Keele University

Identification of palaeotsunamis using ground penetrating radar, sedimentological and micropaleontological techniques; implications for Sri Lankan tsunami risk

H.M. RANJITH PREMASIRI

This thesis is submitted for the degree of Doctor of Philosophy

2012

ABSTRACT

One of the most catastrophic natural hazards which can devastate coastal zone communities is the tsunami. The risk of tsunami devastation can be mitigated by reconstruction and quantification of past tsunamis, but this requires identification and analysis of past tsunami magnitudes and dates even from historical times. The interpretation of geological records of tsunamigenic deposits is the core theme explored in this thesis for the characterisation of palaeotsunamis. Three key elements: identification of palaeotsunamites, dating their deposition and determination of magnitude are needed for reconstruction and quantification of palaeotsunamis. While several studies have described criteria for identification of tsunamigenic sediments, much less research has been carried out on reconstruction of palaeotsunamis.

Sediment characteristics, their depositional configuration and extent of the inundation area on the coast give information on hydrodynamic conditions of tsunami waves. This study has developed a method to estimate tsunami risk by reconstructing and quantifying palaeotsunamis from tsunamigenic sediments on the Sri Lankan coast using sedimentological and paleontological characteristics, Ground Penetrating Radar (GPR), and optically stimulated luminescence (OSL) dating techniques. The 2004 tsunami records were used as a control for the study. Distinctive tsunamigenic sediment signatures were recognised. Three palaeotsunami events were identified and dated at 150 (Krakatua), 2550±190 and 3170±320 years BP and correlated with historical and archaeological records. The recurrence interval of c 600 years postulated for the Indian Ocean was confirmed by this study and the oldest event recorded to date in the Indian Ocean was recognised at 3170±320BP. The method developed here based on reconstruction of palaeotsunamis using sedimentological records, GPR and OSL techniques enables estimation of inundation distance, recurrence interval and consequently the wave characteristics of palaeotsunamis which can be used to estimate tsunami risk for any coast.

ACKNOWLEDGEMENTS

At the outset, I would like to record my deep respect and gratitude for the valuable guidance, excellent supervision and encouragement given to me by my Supervisors, Professors Peter Styles and Victor Shrira. My special thanks must go to Drs Nigel Cassidy and Luigia Nuzzo for their assistance in processing the GPR data. The support and the most willing assistance extended by all members of the Applied and Environmental Geophysics group, the School of Earth Science and Geography and EPSAM, Keele University are acknowledged with utmost gratitude.

Dr. Jean-Luc Schwenninger and the members of Luminescence Dating (OLD) laboratory, Oxford University are also greatly acknowledged for their invaluable support for sediment dating.

I am forever indebted to colleagues and members of academic and technical staff of the Department of Earth Resources Engineering, University of Moratuwa, Sri Lanka for their kind assistance and support extended to me during the field work. I would also like to thank Professor Ana Gunathilake for his constructive ideas and help during the field work.

My special thanks go to Keele University for awarding me a university research scholarship for this study. The valuable guidance and unreserved support offered by many others are remembered with profound gratitude. I regret the inability to mention all of them by name.

CONTENTS **Page**

List of Figures

CHAPTER 2

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

CHAPTER 9

List of Tables

CHAPTER 1

CHAPTER 2

CHAPTER 4

CHAPTER 6

CHAPTER 8

CHAPTER 9

CHAPTER 1

INTRODUCTION AND SCIENTIFIC RATIONALE

1.1 Tsunami Hazard

Most natural hazards in the world cause severe damage resulting in considerable impact on the environment, socio-economic conditions, and finally the country's economy (Finn Løvholt *et al.*, 2012). Natural hazards cannot rarely be controlled or stopped and then the only possible measures are mitigation and management of the hazard. In this process, identification, analysis and management of the risks of natural hazard play an important role. Therefore, research on natural hazards can make great contributions to the process of mitigation and management and can greatly help to minimise the damage caused by hazards.

Though there are many natural hazards which cause severe damage, tsunamis are one of the most destructive natural hazards although less frequent globally than other hazards such as Earthquakes, Landslides etc. (Satake, 2007). However, tsunamis are unfortunately a fairly common natural hazard in the Pacific Ocean, much more than in the Atlantic and the Indian Oceans (although as we will see that perception has changed considerably since 2004) but tsunamis are still an ever-present threat to lives and property along the coasts around all the oceans (Bernard *et al*. 2006; Morrow and Llewellyn, 2006; Okal and Borrero, 2007). Also before 1990, the most people thought that tsunamis originated from large underwater earthquake taking place in the Pacific Ocean. But as the regional distribution of tsunamis in the world shows, only the south Atlantic coast appears to be free from tsunamis (Table 1.1). Further, 2004 Sumatra tsunami waves have hit most of the coasts in the world including the Pacific Ocean revealed that location of the coast is immaterial for occurrence of a tsunami.

Though tsunamis have been recorded along most of the coasts in the world, they are still underrated as a risk and people are not properly aware about this huge potential for disaster. The Tōhoku earthquake and tsunami on 11 March 2011 in Japan which resulted in the largest nuclear disaster since Chernobyl again stressed the necessity of studies on tsunamis and, in particular, the necessity of much longer records (Goto *et al*, 2012; Vita-Finzi, 2012).

Table 1.1 Percentage distribution of tsunami in the world's ocean and seas (Bryant, 2005).

Location	Percentage
Atlantic east coast	1.6
Mediterranean	10.1
Bay of Bengal	0.8
East Indies	20.3
Pacific Ocean	25.4
Japan-Russia	18.6
Pacific east coast	8.9
Caribbean	13.8
Atlantic west coast	0.4

In the recent past, several great tsunamis have occurred in many parts of the world (Table 1.1) causing severe impact for many coastal communities and property. Most of the tsunamis generated during the last 20 years are due to earthquakes having Moment magnitudes of more than seven and are related to subduction at major active tectonic boundaries. But, because there are variations in the direction of movement from even great earthquakes (lateral transcurrent movements are not tsunamigenic) not every large earthquake occurring beneath the sea bed generates a tsunami. Between 1861 and 1948, as few as 124 tsunamis were recorded from more than 15,000 earthquakes (Bryant, 2008). However, all these tsunamis caused great damage to coastal properties as well as killing hundreds to hundreds thousands of people in each event (Morrow and Llewellyn, 2006; Aitkenhead *et al.*, 2007). Therefore, studies on tsunamis have the potential to make very significant contributions to tsunami science and can be enormously helpful in minimising the damage caused by tsunamis and safeguarding the lives of coastal communities and their properties. Not even the UK and the rest of the Northern European Atlantic countries are immune from tsunamis as "*Deposits from the Storegga tsunami have been found in coastal areas around the Norwegian Sea and North Sea, from the northeast coast of England to beyond the Arctic Circle in northern Norway. The tsunami deposits reach onshore elevations of 10–12 m above sea level of their time in western Norway, 3-6 m in northeast Scotland and above 20 m on the Shetland Islands".*

In the aftermath of Japanese Tohoku earthquake and the tsunami in 2011, scientists are greatly considering the risk from such a big event on nuclear plants and the coastal zones in the world, especially from Alaskan-Aleutian Subduction Zone, or even large sub marine slide at any place in the world as the Storegga slide (EOS Transaction America Geophysical Union, 93-*http://www.agu.org/journals/eo/v093/i019/2012EO190001/2012EO190001_brr.pdf*).

Additionally, there has been a suggestion that the 1607 Bristol Channel flood may have been a tsunami (Bryant and Haslett, 2002; Haslett, 2011), but others think that a storm surge superimposed on a very high spring tide is a more likely reason, (*http://www.rms.com/Reports/1607BristolFlood.pdf* - Horsburgh and Horritt, 2006).

1.2 General introduction to tsunamis

Tsunamis are one of the most destructive natural hazards; they take lives, cause severe damage to property and, often literally destroy coastal communities. Tsunamis cannot be controlled, stopped or even predicted precisely, but their impact may be mitigated and /or, to some extent managed. In this context research on identification, analysis and management of the risk of tsunamis could greatly help in minimising the damage caused by this hazard.

1.2.1 What is a tsunami?

Tsunami is a Japanese word with the English translation, "harbour wave," represented by two characters, the top character, "tsu," means harbour, while the bottom character, "nami," means "wave." (Encyclopaedia Britannica). Tsunamis were sometimes referred to as "tidal waves" by the general public and as “seismic sea waves by the scientific community. The term "tidal wave" is a misnomer; although a tsunami's impact upon a coastline is dependent upon the tidal level at the time a tsunami strikes; tsunamis are unrelated to the tides. The term "seismic sea wave" is also misleading because “Seismic" implies an earthquake-related generation mechanism, while tsunamis can also be caused by non-seismic events.

In general, the long wave in the ocean generated by an impulsive disturbance with vertical displacement of the sea floor, which generates giant waves and travels across oceans at a very high speed is referred to as a tsunami. Tsunami waves are a displacement of the sea surface, initiating a series of waves radiating outwards from the initial disturbance. In the deep sea, the wave height of a tsunami wave is less than 1m, the wavelength exceeds 100 km and they travel at a speed of about 800 kmh^{-1}. When tsunamis reach the shallow water the velocity decreases proportional to the depth. As the energy loss in the deep ocean is very low, tsunami waves bring most of their energy to the coastal shallow sea. When the velocity of the wave decreases its wave height dramatically increases, since by virtue of the conservation of wave action, wave energy increases which is inversely proportional to the decrease of wave celerity. As a result, the wave height may increase to 10-50 m causing great damage to the coast line (Berry, 2007; Helal and Mehanna, 2008).

1.2.2 Occurrence of tsunami

Tsunamis are quite unevenly distributed geographically (Table 1.1). Tsunamis are fairly common in the Pacific Ocean, but are much rarer in the Atlantic and the Indian Oceans. However, everywhere along the coast tsunamis are still an ever-present threat to lives and property (Bernard *et al,*. 2006; Morrow and Llewelyn, 2006; Satake *et al.*, 2007). For example, tsunami waves from the 2004 Sumatra event hit most of the coasts in the world including the Pacific Ocean and revealed that regardless of the location much of the world coastline may be susceptible to tsunami risk, and in fact tsunamis have been recorded along most of the coasts in the world. Even the records of the earthquakes are very recent past, they show occurrence of tens of high magnitude earthquakes in the world which generated tsunamis (Table 1.2). The risk is still largely unrecognised and people are not properly aware about the potential for huge disaster. One of the fundamental outstanding problems of tsunami studies is quantifying the risk for each shore. It is worth noting that a smaller probability of tsunamis at a particular coast does not necessarily imply greater safety. The countries subject to frequent tsunami events have incomparably higher level of awareness and are overall much better prepared.

Table 1.2 Tsunamis which have occurred in last two decades in the world

Event Location/ Ocean	Date	Source (Magnitude)
Northern Sumatra	Apr. 11, 2012	Earthquake (M: 8.6)
Raoul Island, Kermadec	Jul. 6, 2011	Earthquake (M: 7.6)
Honshu, Japan	Mar. 11, 2011	Earthquake (M: 9.0)
Bonin Islands, Japan	Dec. 21, 2010	Earthquake (M: 7.4)
Mentawai, Indonesia	Oct. 25, 2010	Earthquake (M: 7.7)
Sumatra. Indonesia	Apr. 6, 2010	Earthquake (M: 7.7)
Chile	Feb. 27, 2010	Earthquake (M: 8.8)
Haiti	Jan. 12, 2010	Earthquake (M: 7.0)
Solomon Islands	Jan. 3, 2010	Earthquake (M: 7.2)
Santa Cruz Islands	Oct. 7, 2009	Earthquake (M: 7.6)
Samoa	Sep. 29, 2009	Earthquake (M: 8.0)
Andaman Islands	Aug. 10, 2009	Earthquake (M: 7.7)
Northern Chile/Pacific	Nov. 14, 2007	Earthquake (M: 7.7)
Sumatra/Indian	Sept. 12, 2007	Earthquake (M: 7.7)
Peru/Pacific	Aug. 15, 2007	Earthquake (M: 7.7)
Solomon Islands/Pacific	Apr. 1, 2007	Earthquake (M: 7.7)
Kuril Islands, Russia/Pacific	Jan. 13, 2007	Earthquake (M: 7.7)
Kuril Islands, Russia/Pacific	Nov. 15, 2006	Earthquake (M: 7.7)
South Java/Indian	Jul. 17, 2006	Earthquake (M: 7.7)
Indonesia/Indian	Mar. 28, 2005	Earthquake (M: 7.7)
Indonesia (Sumatra)/Indian	Dec. 26, 2004	Earthquake (M: 7.7)
Hokkaido /Pacific	Sept. 25, 2003	Earthquake (M: 7.7)
Peru /Pacific	Jun. 23, 2001	Earthquake (M: 7.7)
El Salvador /Pacific	Jan. ,13, 2001	Earthquake (M: 7.7)
Turkey/ Marmara Sea	Aug., 17, 1999	Earthquake (M: 7.7)
Vanuatu /Pacific	Nov. 26, 1999	Earthquake (M: 7.7)
Papua New Guinea /Pacific	Jul. 17, 1998	Earthquake (M: 7.7)

Andreanov/Pacific	Jun. 10, 1996	Earthquake (M: 7.7)
Chimbote (Peru)/Pacific	Feb. 21, 1996	Earthquake (M: 7.7)
Irian Java/Indian	Feb. 17, 1996	Earthquake (M: 7.7)
Sulawasi Island/Indian	Jan. 1, 1996	Earthquake (M: 7.7)
Chile/Pacific	Jul. 30, 1995	Earthquake (M: 7.7)
Mexico/Pacific	Oct. 9. 1995	Earthquake (M: 7.7)
Java Indonesia/Indian	Jun. 2, 1994	Earthquake (M: 7.7)
Mindoro Philippines/ Pacific	Nov. 15, 1994	Earthquake (M: 7.7)
Kuril Island/Pacific	Oct. 4, 1994	Earthquake (M: 7.7)
Japan Okishiri/pacific	Jul. 12, 1993	Earthquake (M: 7.7)
Nicaragua/Pacific	Sep. 2, 1992	Earthquake (M: 7.7)
Flores Island Indonesia/Indian	Dec. 12, 1992	Earthquake (M: 7.7)

Sources: NOAA Centre for Tsunami Research/ International Tsunami Information Centre (ITIC).

1.2 Historical records of tsunamis in the world

Tsunamis have been reported since ancient times. However, in many places in the world the written record of tsunamis is too short to accurately assess their risk. But there are many legends in literature from many parts of the world which are related to tsunamis. Recently, many of them have been proved scientifically as tsunamis. The longest written record of tsunamis is in Japan where monks have kept records on causes of death, including tsunami, since approximately 600 A.D (Nakata and Kawanna, 1995). Since 1900 (the beginning of instrumental location of earthquakes), most tsunamis have been generated in Japan, Peru, Chile, New Guinea and the Solomon Islands (Clague *et al*., 1994; Sato *et al*., 1995; Nishimura and Miyagi, 1995; Minoura *et al*., 1996; Dawson and Shi, 2000). Some historic tsunami events have also been identified in Atlantic Ocean / northwest Europe (Haslett and Bryant, 2007). A much smaller number of tsunamis have been generated in the Atlantic and Indian

Oceans. In the Atlantic Ocean, there are few subduction zones at the edges of plate boundaries to generate such waves except small subduction zones under the Caribbean and Scotia arcs. In the Indian Ocean, however, the Indo-Australian plate is being subducted beneath the Eurasian plate at its eastern margin (Gunathilake, 2005). High magnitude earthquakes occur as a result of this convergence of the Indian and Asian tectonic plates, with the Indian plate moving northeast at around 6 cm per year at an oblique angle to the Java Trench with Sumatra sliding over the top of the subducting Indian oceanic plate (Sandiford *et al*., 2005; Richards *et al.*,2007; Mosher *et al.*, 2008).

The longest continuous tsunami record outside Japan in the Indian Ocean is of the order of several hundred years in India and Sri Lanka. Tsunami event catalogues in the Indian Ocean region from 1750 AD have been produced by Dominy-Howes *et al*. (2002). In Sri Lanka, a number of sea surge events have been recorded in “Mahawamsa “(the Chronicles of Sri Lankan History). However, not all these sea surges may be due to tsunamis, and some storm surges may be included as well (unpublished data). The recorded sea surge in 1883 can be related to the tsunami, which was generated as a result of the volcanic explosion in Krakatau Island, Indonesia (Stromkov *et al.*, 2005).

1.4 Estimation of tsunami risk

Tsunamis are one of the most destructive natural hazards and, therefore, estimation of the risk of the hazard is important in minimizing the damage. Some scales/ intensity scales and magnitudes have been developed to understand the threat of tsunamis as explained in previous paragraphs. Hydrodynamic characteristics (wave/run up heights, inland inundations), energy of waves and damage caused by tsunamis have been used for developing these scales and magnitudes, but they are only based on known recent past tsunamis. Although one major tsunami occurred in 2004 within recent history, the information from this single tsunami alone is not adequate to estimate the risk of tsunamis. Thus these methods of scaling and determining magnitudes cannot be applied, therefore, records form palaeotsunamis are required to estimate real risk of the tsunami disaster.

There are two avenues of investigation:

1) from historical and archaeological records

2) from geological records.

Therefore, in this research, I have studied geological records mainly for estimating the strength of palaeotsunami events (wave characteristics) and historical records for confirmation of the tsunami events. This research was carried out around the Sri Lankan coast, which was greatly affected by the 2004 Sumatra tsunami, even though it is located over 1000 km away from its origin. Also Sri Lanka is an island which is located directly facing the major tsunami generating zone of the Indian Ocean, the Sumatra subduction zone. This subduction zone is always active and triggers large earthquakes, many of which exceed 6 on Moment magnitude scale (United State Geological Survey). Therefore, tsunami studies on the Sri Lankan coast have a unique potential to provide valuable information which can be used to assess the tsunami risk for the whole Indian Ocean because any large tsunamis occurring in the Indian Ocean, will mainly have their origin in the active Sumatra subduction zone. Therefore, all these tsunami records may be preserved in the geological record of the Sri Lankan coast because of its unique location with respect to the tsunami sources.

1.5 General overview of tsunami research; present status

Generally, research on tsunamis has several dimensions such as, tsunami origin, wave propagation, and impact on the coastal zone, geological records of past tsunamis, tsunami prediction and development of warning systems and evaluation of tsunami risk and coastal development strategies. However, much research has been conducted and models developed for tsunami origin, wave propagation and impact on the coastal zone (Latter, 1981; Smith and Dawson, 1990; Brooke *et al*., 1994; Yeh *et al.*, 2006; Liu *et al.*, 2007; Ruiz *et al.*, 2007; Tanioka and Katsumata, 2007; Abe *et al.*, 2008; Thusyanithan and Madabhusi, 2008; Xiao and Huang, 2008). Also, well established tsunami warning systems are being operated at present in the Pacific Ocean by Pacific Tsunami Warning Centre and Japanese Meteorological Agency.

Geological records of tsunami especially for identification criteria, have also been studied in many parts of the world (Atwater, 1992; Clague *et al.*, 2000; Dawson and Shi, 2000; Pinegina, and Bourgeois, 2001; Dominey-Howes *et al.*, 2007; Ramirez-Herrera *et al*., 2007; Tappin, 2007; Wagner *et al.*, 2007). However, for the last 20 years, most tsunami research has been confined to institutes and organizations from areas where tsunamis frequently occur, generally around the Pacific Ocean and in the Mediterranean, but recently organizations across North America, Europe and Australia have been established for tsunami research (Smith, 2005). From these studies, some important geological /sedimentological, chemical and palaeontological characteristics have been defined for identification of tsunami sediments or tsunamites.

After the Indian Ocean mega tsunami occurred on 26th December 2004, tsunami research has increased and some new models of tsunami generation and propagation, near-shore transformation, wave height, run-up and inundation, together with simulation of tsunami have been developed (Hettiarachchi and Samarawickrama, 2005). Also, some research on geological records and identification of tsunami sediments based on various parameters, such as sedimentological, physical, chemical, mineralogical and paleontological have been conducted on several coasts in and around the Indian Ocean (Liu *et al.*,2005; Richmond *et al.*, 2006; Srinivasulu *et al.*, 2007; Dahanayake and Kulasena, 2008). However, the primary objective of any tsunami research, i.e. minimising the damage of the tsunami via evaluating the tsunami risk still has not been addressed properly by these researches. The main focus of all of these researchers was only to model the 2004 tsunami or to identify palaeotsunamis. It is very important that studies of the tsunami recurrence interval and their magnitudes as well as the conditions of sources of origins are carried out. Therefore, studies on developments of methods for reconstruction of palaeotsunamis along the Sri Lankan coast as well as in the countries around the Indian Ocean would play a vital role for safeguarding coastal communities.

1.6 Tsunami Research in Sri Lanka

Before the 2004 Sumatra tsunami event, there were only a few news articles and historical reports in a few books published about tsunami events on the Sri Lankan coast, but no scientific studies on tsunamis had been conducted until 2004 on the Sri Lankan coast.

Immediately after the 2004 tsunami, several international and local scientific teams carried out many studies along the Sri Lankan coasts. The main surveys carried out by different teams just after the tsunami event are:

- United States Geological Survey (USGS)
- Earthquake Engineering Research Institute (EERI)

- National Science Foundation (NSF) ,USA
- Geological Survey and Mines Bureau of Sri Lanka (GSMBSL)
- GeoEnvironmental Consultants of New Zealand (GeoEnv)

However, no research has been carried out which is focused on developing a proper method for estimating tsunami risk in the region. Scientific method has not been developed for estimating wave characteristics or hydrodynamic nature (inland penetration run up heights etc.) of palaeotsunamis and determining the frequency of the occurrence of tsunami events, which are the main tools for estimating tsunami risk, since tsunami risk is defined by severity, frequency and the expose.

1.7 Motivation

Lack of information and memory about tsunami in tsunami-genic areas is a major drawback to understand the risk which can be used to minimise the damage. One major source for ancient tsunamis information is records of tsunami deposits. Location and accurate dating of tsunami deposit are important issues when estimating the tsunami risk for specific areas of coastline. Tsunamis always leave records of sediment depositions/erosion that are normally preserved in the geologic records of the coast. These records are the only form of evidence which can indicate the risk from a tsunami. Where more than one tsunami deposit is preserved in a stratigraphic sequence, the record may help determine how often a tsunami is likely to occur. Tsunami sediments are also important records, which give information on the hydrodynamic nature of palaeotsunamis occurred thousands of years before or even more. Therefore, all past tsunami records can be used to assess the risk and tsunami threatened areas. If there are known recent tsunami records in an area, such as the 2004 tsunami in the

Indian Ocean and the Miyagi Tsunami in Japan, they can be used as a template for interpreting palaeotsunamis. However, the availability of information and studies on tsunami records in Sri Lanka is very limited. Therefore, studies on palaeotsunamis using geological records are vital for estimation of tsunami risk on the Sri Lankan coast.

In the summary of tsunami generation, historical records and the geographical distribution in the world, it is not clear what contribution they can make to the process risk assessment for a single location. Tsunamis generation from different generation mechanisms are reasonable well understood, though some source parameters are still not clear (Okal, 2003). Tsunami propagation in the open sea is well described by several mathematical models (Titov, 1997; Hamouda, 2006; Rabinovich and Thomson, 2007; Liu *et al*., 2008). Knowledge of tsunami interactions with the coastal zone and onshore wave propagation which is the most important part of the tsunami risk assessment is still limited. Tsunami interaction with the coast varies greatly along the coast even from the same tsunami (Shuto, 1985). Physical characteristics (geology, geomorphology, hydrology and ecology) of the coast can have a significant impact on the tsunami wave action on the coast. Near off-shore bathymetry may also play a major role in the nature of tsunami wave/coast interaction In the present study, I have analysed the 2004 tsunami effects all around the Sri Lankan coast (the East, the South and the West coasts) in detail in order to interpret the interaction of the tsunami waves on the Sri Lankan coast with respect to geographical location and characteristics of the coast zone (coastal geomorphology). However, detailed bathymetric data are not available at present which has hampered this study but they can of course become available in the future and a retrospective analysis carried out. The most important other information for the tsunami risk estimation is knowledge of past events and their magnitudes. Thus, the research on past tsunami records seems to be an important task for the tsunami disaster mitigation.

1.8 Aims and Objectives

The aim of the study is to attempt the reconstruction of palaeotsunami events by studying both recent and palaeotsunami sediments, and thereby to estimate future tsunami risk on the Sri Lankan coast.

Specific objectives

i. To study characteristics of the 2004 tsunami sediments on the Sri Lankan coast with the aim of developing a reliable method of identifying palaeotsunami sediments.

ii. To develop an integrated approach for identifying tsunami sediments based on parameters such as the physical, mineralogical, sedimentological and palaeontological characteristics.

iii. To estimate the dates of identified tsunami sediments using the Optically Stimulated Luminescence dating technique (OSL described later) technique, since the OSL technique is the most convenient and accurate for sediments in the age range of interest (from present to a few thousand years).

iv. To investigate the potential of using Ground Penetrating Radar (GPR) for determining the lateral extent of the tsunami deposits.

v. To place the findings on palaeotsunamis on the Sri Lankan coast obtained employing the above methods into historical and geological context using available historical and archaeological records on Sri Lankan tsunamis and other coasts of the Indian Ocean basin.

CHAPTER 2

LITERATURE REVIEW

2.1 Tsunami studies

Before the 2004 Sumatra Tsunami, most `regional' tsunami research was confined to the coasts around the Pacific Ocean. After 2004, there was a surge in tsunami studies focused to the coasts in the Indian oceans. Due to the occurrence of many extremely destructive tsunamis in the world during the last few years, the realisation of the necessity of tsunami researches have grown. Well established models of tsunami generation, propagation and inundation have already been developed as discussed in next paragraphs and there has been significant progress in studies of geological and sedimentological characteristics of tsunamis all around the world. In particular, detailed geological characteristics have been established for recent tsunamis records as well as palaeotsunamis for many coasts around the world.

2.2 Generation of tsunamis

The mechanism and the location of the tsunami generation area are important factors for estimating the risk of tsunamis and predicting the future threat for any particular location. There are several possible mechanisms of tsunami generation, such as high magnitude shallow earthquakes in the sea, submarine volcanic eruption , massive submarine landslide, and impacts of objects from outer space (such as meteorites, asteroids, and comets). Very often tsunami generation involves seismic activity. Therefore, the origin of tsunamis is mostly confined to tectonically active zones in the world and most tsunamis cause severe damage to coastal zones.

a) Earthquake generated tsunamis

The most common cause of tsunamis are earthquakes; over the past two millennia, earthquakes have generated 82.3% of all tsunamis in the Pacific Ocean (Bryant, 2008). Earthquake tsunamis are generated due to disturbance of the seafloor by the vertical component of the displacement on the fault planes of the earthquake. There are several types of fault motions which might generate tsunamis;

1) a strike-slip earthquake on a vertical fault (very low possibility of generating tsunamis)

2) a dip slip earthquake on a vertical fault and

3) thrust earthquake on a dipping plane (Figure 1.1).

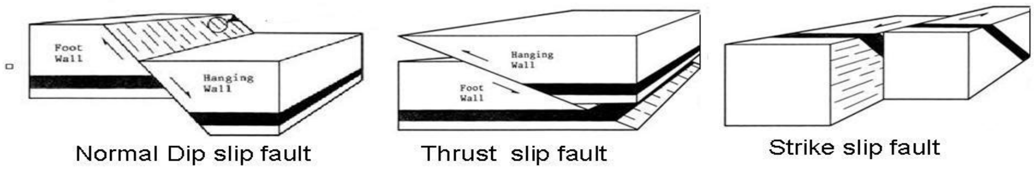


Figure 2.1 Three types of earthquake faults

Tsunami generation is mainly caused by vertical displacement of the seafloor (Lorito *et al.*, 2008). Thus the possibility of tsunami generation is much higher from dip-slip or thrust earthquakes than from strike-slip events. The magnitude of the tsunami is mostly related to the magnitude of the earthquake through the scale of vertical displacement of the sea floor (or slip) and the area of significant displacement. Additionally, the depth of the epicentre and its location with respect to the continental shelf and the shore line are also important factors determining the magnitude. Hence, there is no simple deterministic link between the magnitude of the earthquake (either based on the Richter Scale (M_L) or on the moment magnitude (Mw)) and the magnitude of the earthquake generated tsunami. The Richter scale is no longer in use in the scientific literature, what is used is the moment magnitude (Mw), which is roughly equivalent to the Richter scale (Abe, 1994).

However, there is approximate significant at a moderate statistical level, empirical relationship between the earthquake moment magnitude (Mw) and tsunami generation (Okal *et al*., 2003). It has been found that earthquakes of Mw> 8.6 can generate giant teleseismic tsunamis, which are capable of travelling across the whole width of an ocean (Bryant, 2008). This type of tsunami generation is confined to the major plate boundaries. Since the Pacific Ocean is mainly surrounded by destructive, subducting plate boundaries, it is in these regions that tsunamis are frequently generated by earthquakes.

Moment magnitude is defined as a function of seismic moment (Okal *et al*., 2003; Okal and Kirby, 1998)

$$M_w = 0.67\log_{10}Mo-10.73$$

Where Mo is seismic moment, which is based upon the forces acting along a fault line and unit is Newton meters (Nm). The statistical link between the tsunami height and the moment magnitude has been explored in a number of studies, from the east coast of Japan and Tahiti by Okal (1988) and Kajiura (1983).

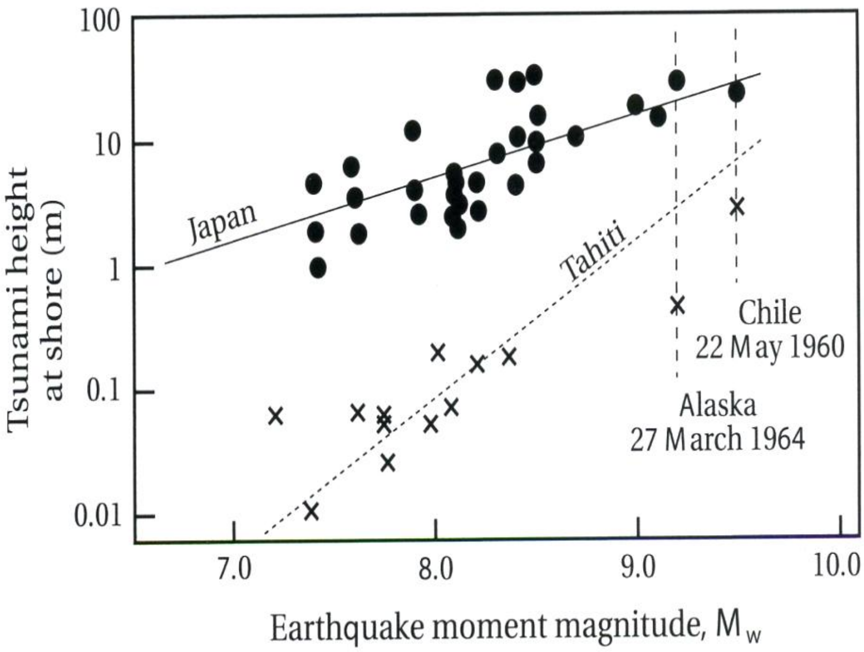


Figure 2.2 Relationship between moment magnitude (M_w) and tsunami height (Okal,1988).

b) Landslide generated tsunamis

Large submarine landslides usually take place on continental slopes. Trench debris avalanches or collapse on mid-ocean ridges can also generate tsunamis. There are many causes for triggering such marine slides. Very often these slides are triggered by earthquakes, but other causes such as rising sea level, overloading of sediments on a slope, turbidity currents and violent volcanic eruptions can trigger a mass submarine slide (Haugen *et al*., 2005).

The tsunamis generated by submarine landslides are different to earthquake generated tsunamis. A major difference is that landslide generated tsunamis are more focused (point sources) and waves propagate both up slope direction and parallel to the slide direction. Waves generated by landslides depend primarily upon the volume of materials moved, the depth of submergence, and the speed of the landslide. The volume of the landslide is normally determined by height, horizontal length and the initial slope of the slide (Figure 2.3). However, the wave period of the tsunami increases with an increase in the length slide and decrease in the slope. It is independent of water depth, the depth of submergence and the mass of the block (Bryant, 2008).

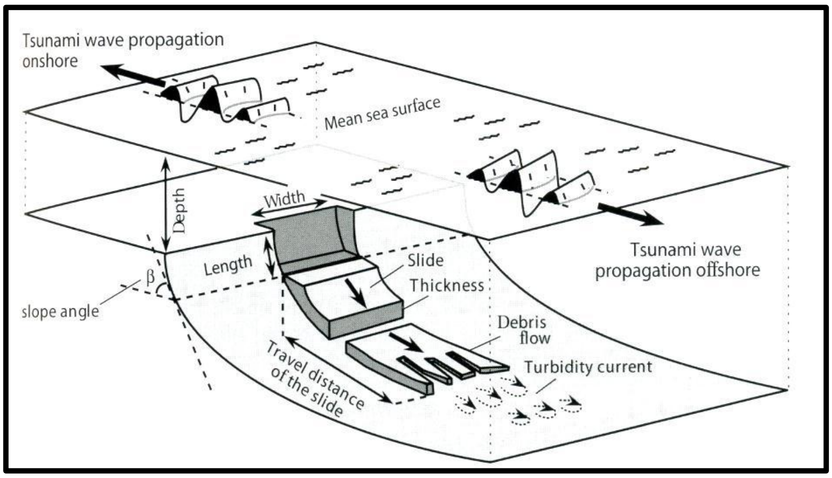


Figure 2.3 Schematic diagram of submarine slide generating tsunami waves (Bryant, 2008).

Some well-known examples of tsunamis generated by submarine landslides are the Storrega tsunami which occurred in 7950BP off Norway, the Grand Bank tsunami Alaska on 18 November 1929, in the Canary Islands, Lituya Bay in Alaska in 1958 and the Hawaiian island tsunamis (Sevendsan and Mangerud, 1987; John *et al.*, 2000; Atwater *et al.*, 2005; Peters *et al*., 2007).

c) Volcanic eruption generated tsunamis

There are many mechanisms for generation of tsunamis by volcanic eruptions such as volcanic earthquake or tremors, pyroclastic flows, submarine explosion, caldera formation, volcano associated landslides, basal surges, avalanches of hot rocks, lahar lava flow (Latter, 1981). Volcano-generated tsunamis occur mainly in the Pacific Ocean (Figure 2.4). Volcanoes erupting on a coastal zone or on the seafloor can generate tsunamis due to rapidly emplaced pyroclastic flow. Landslide and debris avalanches into the sea from the explosive eruption may generate tsunamis. Of 92 volcano-related tsunamis occurring in the world, 16.5 % resulted from tectonic earthquake associated with the eruptions, 20% due to pyroclastic flow, 14 % from submarine eruptions and 7 % from collapse of the volcano.

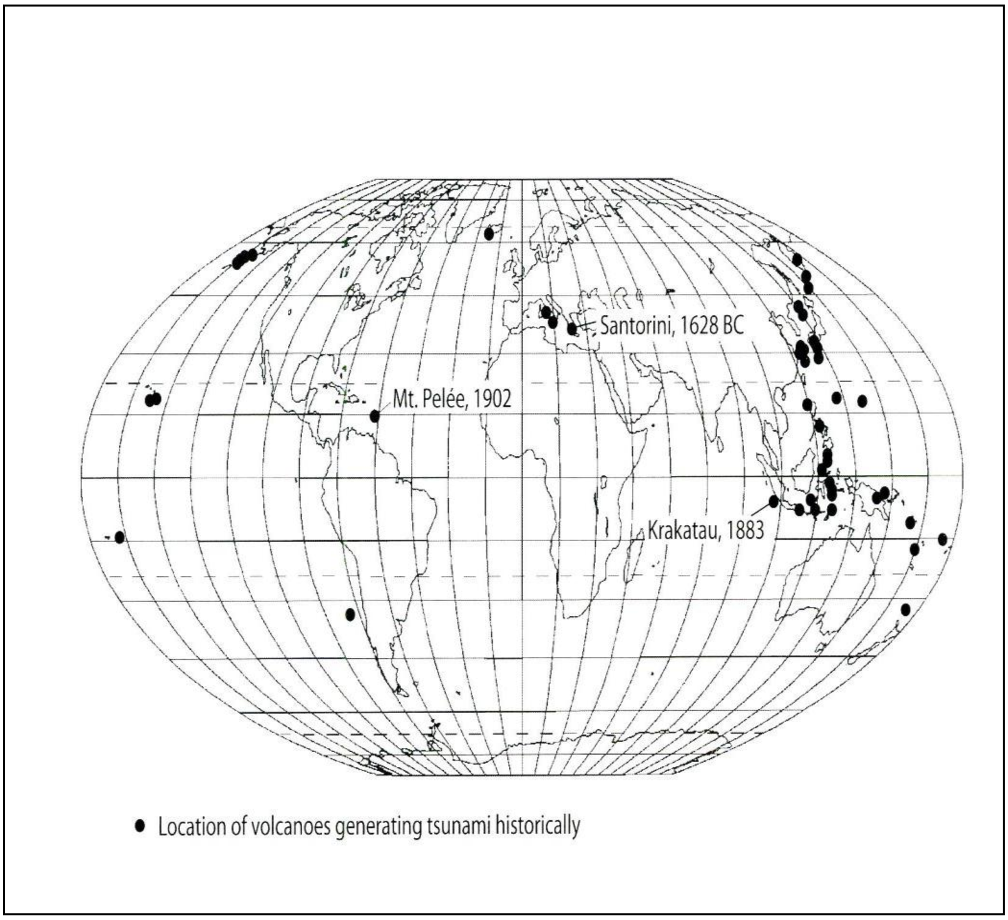


Figure 2.4 Volcano generated tsunamis recorded in the world (Latter, 1981).

d) Underwater Explosion related tsunamis

Sub-sea nuclear tests release huge amount of energy which could cause significant disturbance to the sea floor and may also directly contribute to generating tsunamis. There is evidence that nuclear testing by the United States in the Marshall Islands in the 1940s and 1950s generated tsunamis (Nelson, 2011).

e) Tsunami generation by Meteorite Impacts; Comets and asteroids

While there are no recent historic examples of tsunamis generated by meteorite impacts, there is a real possibility of such a scenario. There is a documented evidence that at the end of the Cretaceous Period, about 65 million years ago, near the tip of what is now the Yucatan Peninsula of Mexico, a huge meteorite impact produced a tsunami that left deposits all along the Gulf coast of Mexico and the United States (Halif and Sabki, 2005).

f) Meteo-Tsunami

Severe meteorological condition in the Oceans also caused tsunami in the world. They are referred as meteo-tsunamis, which are also long-period waves that possess tsunami characteristics but are meteorological in origin (Haslett and Bryant, 2009; Thomson *et al*., 2009).

2.3 Tsunami waves and related physics

2.3.1 Tsunami waves

Tsunami wave dynamics have been explored by many people using mathematical approaches (Iida and Iwasaki, 1983; Von-Baeyer, 1999; Ward, 2002). There are many definitions for tsunami waves from these different researchers. Generally, in the deep sea, tsunami waves are well described as a linear superposition of sinusoidal waves; when they approach the shore, the wave shape changes depending on the local bathymetry. Most tsunamis generated by large earthquakes travel in wave trains containing several large waves having very low amplitude in the deep sea of about 1m or less. The amplitudes increase substantially when they reach the shallow sea environment, potentially up to several tens of meters. Phase velocities of ocean wind waves and swell are about 90 km/h while tsunamis move much more rapidly across ocean basins having phase and group velocities of the order of 800 km/h.

2.3.2 Propagation of tsunami waves

Tsunami waves are characterized as shallow-water waves. These are different from the wind waves most of us have observed on beaches that are caused by the wind blowing across the ocean's surface. Wind-generated waves usually have periods (time between two successive waves) between one to twenty seconds and wavelengths of up to 600 m (for swell). A tsunami can have a period in the range from a few minutes to two hours and wavelengths exceeding 500 km. A wave is characterized as a shallow-water wave when the ratio of the water depth and wavelength is very small. The velocity of a shallow-water wave is also equal to the square root of the product of the acceleration of gravity (g) and the depth of the water, d (Figure 1.5).

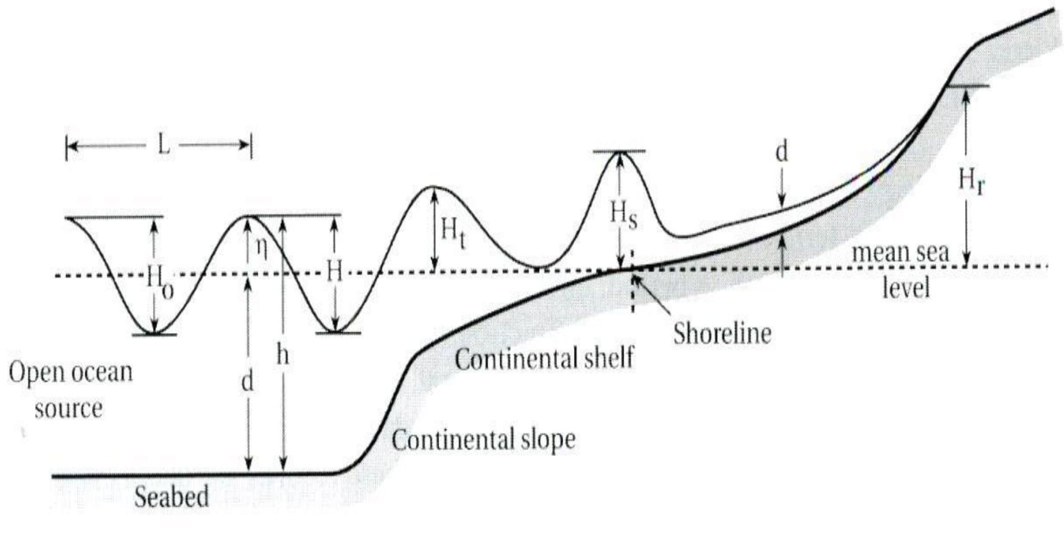


Figure 2.5 Cross section of physical characteristics of tsunami waves from open ocean source to land with common terms used (H_0 - Crest to trough wave height at source point; d- water depth from MSL or water height from the land surface; h- wave height from sea bed; H- Crest to trough wave height; H_t -wave height at shore; H_s-wave height at the shoreline; H_r-tsunami run-up height above MSL; L-wave length and η- is water surface elevation (Bryant, 2008).

The phase and group velocities of long linear waves which coincide in the longwave limit can be described with a very good accuracy by the simple expression:

$C = (gd)^{1/2}$

Where:

C = wave velocity (ms^{-1})

g = gravitational constant (9.81 ms^{-1})

d = depth to the sea bottom (m)

2.3.3 Flood and inland penetration of tsunami waves

The extent of inundation of tsunami waves into the land is critical because a main impact of the tsunami occurs during this inland penetration. There are many parameters which control this impact. However, Hills and Mader (1997) were able to link the maximum inundation to wave height at the shoreline. They showed that the maximum distance, X_{max} is dependent on the maximum depth of the water at the shoreline (wave height at the shoreline), the run-up height (h_0), the slope of the shore away from the coast, and the roughness of the ground that the water moves across. This was further elaborated by Bryant (2008). Theoretically, the cross-sectional area of coastline flooded by a tsunami is equal to the cross sectional areas of water under the wave crest closest to shore. Therefore, the higher the tsunami wave height at the shoreline and the larger the wave period, then the larger is the volume of "perturbed" water and the greater is the extent of the observed inundation.

If there is a flat coastal plain on which the flood depth h has a maximum value h_0, the depth at X inland is given by (Hills and Mader, 1997);

$h/h_o = [1+(X / X_{max})]^{4/3}$

The maximum inundation distance to which the water flows is

$X_{max} = ho^{4/3}/n^2 A$

Where

X_{max} : Maximum inundation distance (m)

n :Manning's roughness number (dependent on the nature of the inundation area)

A : an empirical constant

Here n is variable; it equals 0.015 for very smooth terrain like mud flats and ice, 0.03-0.035 for developed and built-up areas and is 0.07 for areas covered with dense vegetation

The empirical constant A has been estimated to be 0.06 from ensemble averaging of a large sample of past tsunamis.

2.3.4 Depth and velocity of tsunami waves

The height and velocity of the waves inland have also been examined within the framework of various hydrodynamic models (Camfield, 1994; Yeh *et al*., 1994; Nott, 1997).

According to these models, the velocity of tsunami waves onshore can be described as the same square root function of water depth, where the depth, however, should be considered equal to the wave height.

Therefore, $H_t = d$

$v_r = (gH_t)^{1/2}$

v_r : Velocity of run-up (ms^{-1})

d : the depth of water flow overland (m)

2.4 Modelling of Tsunamis

There is an intense on going activity aimed at developing numerical models which are better and computationally faster at describing the origin of tsunamis, wave propagation, inundation or impact on the coastal zone. One of the tasks of these propagation models is to estimate the arrival time and wave heights / run-up for any coast. The inundation models are developed mainly to reproduce wave dynamics during inundation and to make inundation maps. Furthermore, these models are also very important in understanding the behaviour of tsunamis, and thereby to estimate the damage and tsunami risk.

We list here some of the commonly used models:

1 Method of Splitting Tsunamis (MOST) for propagation and run up developed by scientists at the University of Southern California. This model is very commonly used by several institutes currently engaged in tsunami modelling (Burwell et al. 2007).

2 Submarine Mass failure model (SME): Many models have been developed for modelling generation of tsunamis by a landslide based on landslide morphology, materials or dynamics (Hamptom *et al*., 1996)

3 Tsunami propagation and inundation model (Geowave); nonlinear Boussinesq equation (Madsen *et al*., 2002; Fuhrman and Bingham, 2004).

2.5 Quantification of energy wave height and inundation distance of a tsunami

Energy carried by tsunami waves, run-up height and inundation distance (inland penetration) are all dependent on various factors such as the location of and mechanism of the tsunami, offshore condition (bathymetry), the distance the waves have travelled and the geomorphological configuration of the coast and onshore topography. In order to characterise the strength of tsunamis a number of tsunami magnitudes and intensity scale schemes has been developed based on tsunami observations in different parts of the world.

a) The Imamura-Iida scale (m_H): this scale has been developed on the basis of past tsunamis around the Japanese coasts (Abe, 1993; Abe, 1995; Hatori, 1995).

$$m_H = \log_2 H_{max}$$

Where

m_H : Imamura-Iida's tsunami magnitude scale

H_{max} : Maximum tsunami run up height above sea level

Similarly, a few other scales have been introduced using more parameters of the tsunami (Papadopoulos and Imamura, 2001)

b) Magnitude M_t:

$$M_t = a \log H + b \log \Delta + D$$

H: Maximum single amplitude of tsunami waves

Δ : Distance in Kilometre from the earthquake epicentre to the tide station

a, b and D are empirical constants

c) Murty and Loomes scale: A different approach to defining tsunami magnitude (ML) was suggested by Murty and Loomes (1980)

$$ML = 2(\log e\text{-}^{19})$$

Where E: tsunami potential energy

d) Tsunami intensity i_s (Soloviev, 1970):

$$i_s = \log 2 \sqrt{2}^{(H)}$$

Where

H is the mean tsunami height at the coast in meters.

e) Further Soloviev developed the following formula to accommodate the difference in maximum run-up along the coast as:

$$i_s = \log_2 (1.4 H_r)$$

Where

i_s: Solviev's tsunami magnitude

$H_{r:}$ mean tsunami run-up height along stretch of a coast.

f) Though there are many definitions for tsunami magnitude and the intensity, none gives an adequate characterisation of the strength of the tsunami. Therefore, Gerassimos and Imamura (2001) proposed a new tsunami intensity scale in which the scale of earthquake intensity incorporates both magnitude and intensity, and mainly considers the damage caused by the tsunamis. Three main parameters are included in this scale a) the effects on humans; b) the effects on objects, including vessels of variable size, and types; and c) damage to buildings. Based on these three parameters this scale has been divided into twelve divisions as follows.

It is analogous to Earthquake Intensity

i) **Not felt** a) Not felt even under the most favourable circumstance

b) No effect

c) No damage

ii) **Scarcely felt** a) Felt by few people onboard small vessels. Not observed on the coast

b) No effect

c) No damage

iii) **Weak** a) Felt by most people onboard small vessels. Observed by few people on the coast

b) No effect

c) No damage

iv) **Largely observed** a) Felt by all people onboard small vessels and few people onboard large vessels. Observed by most people on the coast

b) Few small vessels move slightly onshore

c) No damage

v) **Strong** a) Felt by all people onboard large vessels and observed by all on the coast. Few people are frightened and run to higher ground.

b) Many small vessels move strongly onshore, few of them crash into each other or overturn. Traces of sand layer are left behind on ground with favourable conditions. Limited flooding of cultivated land.

c) Limited Flooding of outdoor facilities (e.g. gardens) of near shore strictures.

vi) **Slightly damaging** a) Many people are frightened and run to higher ground

b) Most small vessels move violently onshore, crash strongly into each other, or overturn.

c) Damage and flooding in a few wooden structures. Most masonry buildings withstand.

vii) **Damaging** a) Most people are frightened and try to run to higher ground.

b) Many small vessels damaged. Few large vessels oscillate violently. Objects of variable size and stability overturn and drift. Sand layer and accumulations of pebbles are left behind. Few aquaculture rafts washed away.

c) Many wooden structures damaged, few are demolished or washed away. Damage to grade 1 and flooding in a few masonry buildings.

viii) **Heavily damaging** a) All people escape to higher ground, a few are washed away.

b) Most small vessels damaged, many are washed away. Few large vessels are moved onshore or crash into each other. Big objects are drifted away. Erosion and littering on the beach. Extensive flooding. Slight damage in tsunami control forest, stop drifts. Many aquaculture rafts washed away, few partially damaged.

c) Most wooden structures are washed away or demolished or washed away. Damage to grade 2 in a few masonry buildings. Most RC buildings sustain damage to grade 1 and flooding is observed.

ix) **Destructive** a) Many people are washed away

b) Most small vessels are destroyed or washed away. Many large vessels are moved violently ashore, few are destroyed. Extensive erosion and littering of the beach. Local ground subsidence. Partial destruction in tsunami control forest. Most aquaculture rafts washed away, many partially damaged.

c) Damage to grade 3 in many masonry buildings, few RC buildings suffer from damage grade 2.

x) **Very destructive** a) General panic. Most people are washed away.

b) Most large vessels are moved violently ashore, .many are destroyed or collide with buildings. Small boulders from the sea bottom are moved inland. Cars overturned and drifted. Oil spills, fires start. Extensive ground subsidence.

c) Damage to grade 4 in many masonry buildings, few RCbuildings suffer from damage grade 3. Artificial embankments collapse, port water breaks damaged.

xi) **Devastating** b) Lifeline interrupted. Extensive fires, Water backwash drifts cars and other objects in the sea. Big boulders from the sea bottom are moved inland.

c) Damage of grade 5 in many masonry buildings. Few RC buildings suffer from damage grade 4, many suffer from damage grade 3.

xii) **Completely devastating**

c) Practically all masonry buildings demolished. Most RS buildings suffer from at least damage grade 3.

They also correlate their intensity scale with maximum wave height;

Divisions	i - v	Height <1.0 m
	vi	2.0 m
	vii - viii	4.0 m
	ix - x	8.0 m
	xi	16.0 m
	xii	32.0 m

Though, several methods and definitions have been developed for quantifying tsunami threat (Imamura, 2001), there is no suggestion that they can predict or give any idea about future risk of a tsunami for any particular area. Furthermore, most of these methods to find tsunami magnitude or intensity can only be used only for recent well known tsunamis. Therefore, these methods are mainly usable in estimating damages from past tsunamis and to rank the disaster. However, it would be very useful if these scales could be incorporated as a tool into the process of estimation of tsunami risk.

2.6 Geological Records of Tsunamis

Most tsunamis leave geological footprints on the coasts which have an absolutely unique potential for addressing a number of key questions related to past tsunamis (Mamo *et al.*, 2009). Indeed, geological records go back orders of magnitude further than the oldest historical documents and even legends. Because the tsunami pattern in any place is largely determined by local bathymetry rather than the characteristics of its source, geological records at a given location could hold the key to reconstruction of past tsunami events. Presently the success in quantitative reconstruction is very patchy and at best, only partial, but the field is rapidly developing. Once a reasonable reconstruction of past tsunami events for a particular area is achieved, this would greatly advance the understanding of the risk of the tsunamis (Dominey-Howes, 2002).

Usually, the imprints of tsunamis as geological records can be traced for hundreds of kilometres along the shoreline (Atwater, 1992; Clague *et al*., 2000; Nott, 2000; Bryant, 2001; Dominey-Howes, 2002; Scheffers, 2004; Dominey-Howes *et al*., 2007; Hori *et al*., 2007; Paris *et al*., 2007; Fagherazzi, 2008). This chapter explains the importance of tsunamigenic geological records and how they might be discriminated from other similar records formed by other events on the coast.

Two main types of geological record are formed by tsunamis; depositional and erosional. Depositional records which preserve sediment deposits on the coast play a key role in tsunami reconstruction by providing most of the important information about tsunami processes. The characteristics of the sediments provide information on wave height, flow velocity, flow direction and inundation area, all of which are important parameters for reconstructing past tsunamis (Dawson *et al*., 1996; Hutchinson *et al*., 1997; Scheffers and Kelletat, 2003; Scheffers, 2004; Kumar, 2006). Deposition of sediments containing fossils or palaeontological evidence are also potential sources of information for past tsunami events. Erosional records which mainly modify the normal coastal landscape and geomorphology are an indicator of strong wave action which is not related to normal coastal hydrodynamic process. Geological records can be divided into three main categories based on their time of occurrence and available information;

1) Geological records formed by recent, known tsunamis,

2) Records formed by unknown tsunamis but where some historical information or evidence about the tsunamis might be available.

3) Geological records of palaeotsunami events (which may be more than a few thousand years ago) where usually no historical information or archaeological evidence is available.

If category one geological records can be found on any coast, these confirmed tsunami records can be used as templates for identification of past tsunamigenic sedimentary sequences. Very often all these three categories can be studied together allowing more significant conclusions to be drawn.

2. 6.1 Depositional characteristics of tsunami sediments

Tsunami deposits are generally present as thin beds or layers, continuous or discontinuous sheets, pockets or patches of sediment brought from eroded materials from adjacent beaches, land, shallow or deep-sea environments. Tsunami deposits are rarely present over the entire inundated area, but depending on the local topography and tsunami wave action, sediment deposition can be restricted to restricted areas of the coastal zone (Atwater 1992; Benson *et al.*, 1997; Carver *et al.*, 1999; Clague *et al.*, 2000; Dawson and Shi, 2000; Fujiwara *et al.*, 2000).

Tsunami deposits also tend to show less contemporaneous reworking than storm deposits (Atwater and Hemphill-Haley, 1996; Bourgeois and Minoura, 1997). Sometimes, wind-blown sandy deposits also show some similarities with tsunamigenic sandy sediment deposits. Most previous studies illustrate some common characteristics of tsunami deposits as they are typically very well sorted, fine sands, and form wedge-shaped deposits. Other flood deposits from fluvial or alluvial processes are typically browner and muddier and these sediments are commonly less mature and have some characteristic textural features and are generally poorly sorted, with mostly angular grains and the source materials are totally derived from a terrestrial environment. Tsunami sediment also shows fining upwards in grain size of the sequence and fining and thinning inland (Shi *et al.*, 1995; Dawson and Shi, 2000; Goff *et al.*, 2004; Tuttle *et al.*, 2004). Identification of the contact between tsunamite deposits and the adjacent sediment beds is another, very crucial factor aiding further recognition or isolation of tsunami deposits in the field.

Studies on palaeotsunami sediments reveal a number of distinct characteristics for the identification of palaeotsunami deposits using depositional patterns and sedimentological features as discriminators. The most prominent characteristics of tsunami sediments can be summarised as follows; the presence of continuous or discontinuous wedge-shaped deposits of various thicknesses, sheet-like mud, silt and sand deposits, isolated boulder deposits, erosive lower contacts, presence of graded and planar bedding, asymmetric ripple and cross stratification, muddy or peaty rip-up clasts and sub layers, mud drapes inter-bedded with mud layers, cross-bedding, condensed organic beds and angular clasts (Benson *et al*., 1997; Carver *et al.*,1999; Clague *et al*., 2000; Dawson and Shi, 2000; Fujiwara *et al.*, 2000; Grauert *et al*., 2001; Goff *et al.*, 2004; Tuttle *et al*., 2004; Cantalamessa and Celma, 2005; Schnyder *et al*., 2005; Fujino *et al*., 2006; Perez-Torrado *et al*., 2006; Dawson and Stewart, 2007; Dominey-Howes, 2007; Fujiwara and Kamataki, 2007; Kortekaas and Dawson, 2007; Monecke, 2007; Moore *et al*., 2007; Morton *et al*., 2007; Peters *et al*., 2007; Smith *et al*., 2007; Tappin, 2007; Wagner *et al*., 2007).

Very often tsunami sand deposits can be associated with muddy estuarine or lagoonal beds (Atwater, 1987; Clague, 2000).

2.6.2 Signature of Tsunami deposits

Material brought by tsunami waves and deposited on the inundated area can be referred to as tsunami sediment deposits or tsunamites. There are various types of tsunami deposits such as clay, silt or sandy deposits, very coarse boulder deposits and other tsunami-transported debris deposits (Nanayama *et al*., 1993; Bryant and Nott, 2001; Dominey-Howes, 2007). These deposits may either be brought from marine sedimentary environments by direct waves or from the land (terrestrial environment) mostly by backwash flow. Therefore, very often sedimentary heterogeneity is a dominant feature of tsunami deposits. Sediment characteristics and other depositional features of tsunami deposits depend mostly on wave action, coastal geomorphology, onshore and offshore conditions. These deposits are unrelated to other normal coastal deposits due to their unusual depositional conditions compared to normal coastal hydrodynamic process. Because tsunamis are high energy waves and inundate large areas of a coastal plain by sea water (Perez-Torrado *et al*., 2006) they produce distinguishable geological records on the coast.

Tsunami deposits may not always preserve all the discriminating sedimentological characteristics characteristic of tsunami sediments. Particularly, distinguishing between tsunami and other high energy coastal deposits deposit is still a challenge for scientists. Several recent research projects have been carried out aimed at clarifying identification and distinguishing between tsunami sediments and storm deposits (Bryant *et al*., 1992; Shi *et al*., 1995; Dawson *et al*., 1996; Minoura *et al*., 1997; Bourgeois *et al*., 1999; Goff *et al*., 2004; Tuttle *et al*., 2004; Moore *et al*., 2006; Aoibheann *et al*., 2007; McFadgen and Goff, 2007; Nanayama *et al*., 2007; Pariset *et al*., 2007; Scheffers and Scheffers, 2007; Weiss, 2008).

Studies carried out by Hearty (1997); focused on understanding the hydraulic differences between tsunami action and storm action. The most obvious feature of tsunami deposits which has been shown by many studies is the presence of erosive or truncated lower and upper contacts by channelized backwash flow and, deposits having multiple layers corresponding to the number of waves which may extend for several kilometres distance along the coastal zone.

2.6.2.1 Sand and fine grained sediment deposit/ pockets

The most common tsunami deposits are sand and fine grained sediments (Figure 2.6), which display most of the characteristic features and signatures of tsunami events because both the deposits and their sedimentological characteristics are preserved within the coastal geological sequence (Dawson *et al*., 1996). The most common characteristic signatures preserved in tsunami sandy or fine deposits are layering or lamella with textural differences, rip-up clasts, tapering, lens or sheet-like deposits which extend long distances inland on the coast with erosive lower contacts, sandwiched between marshy, clayey beds or between peaty layers (Figure 2.6 and 2.7).

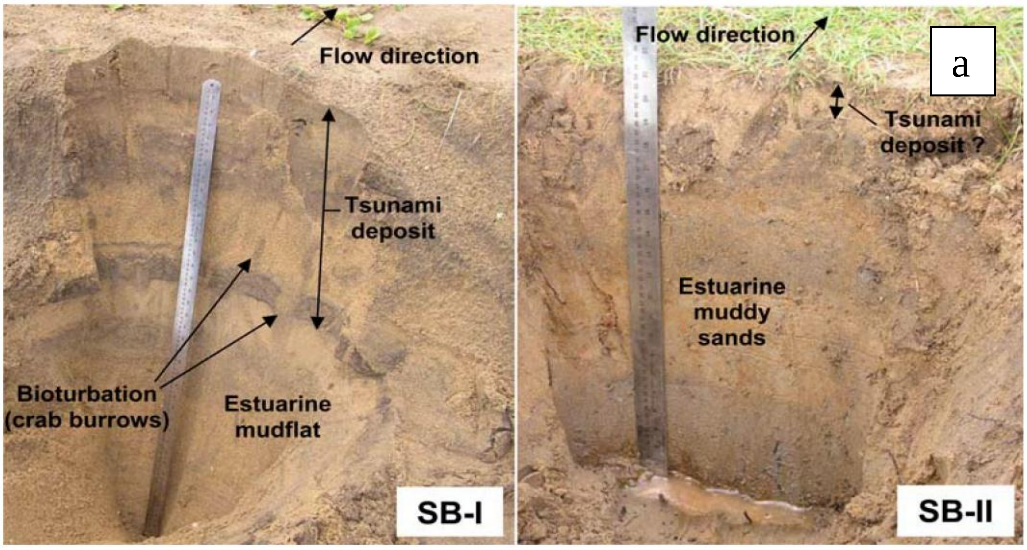
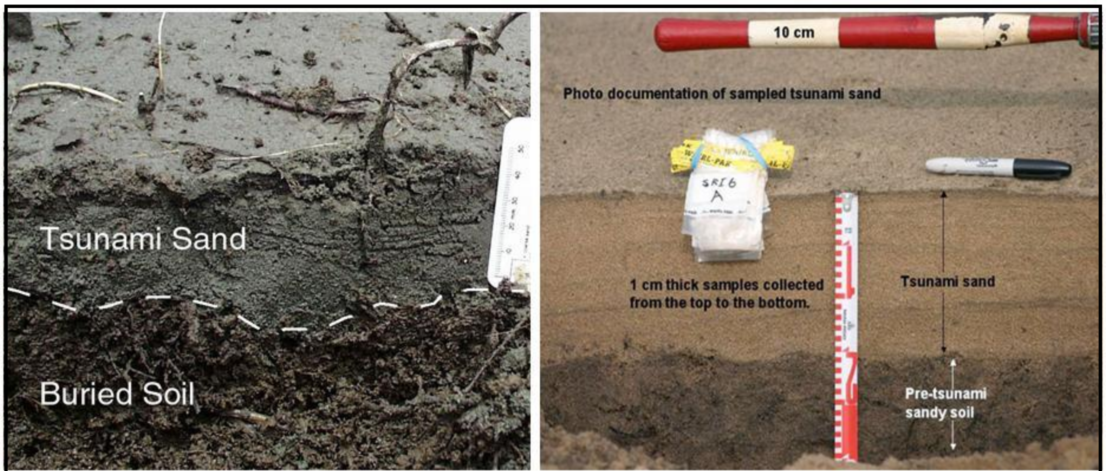


Figure 2.6a Sediment deposited by the 2004 tsunami on Cuddalore SE India (Adam, *et al*., 2012)

Figure 2.6b Sediment deposited by the 2004 tsunami on Cuddalore SE India (Adam, *et al*., 2012)



a)Typical tsunami deposit from Papua New Ginea. The tsunami deposited a gray-coloured sand, here about 5 cm thick, on a brown soil containing roots. (Picture from survey after Yoshinobu Tsuji et al (1998)

b) 2004 Sandy tsunami deposits from the east coast of Sri Lanka. Picture from Tsunami sediment survey conducted by USGS Team (2005)

Figure 2.7 Different features of tsunami deposits; a) clayey deposit and b) sandy deposit.

2.6.2.2 Dumped and debris deposits

Most tsunamis transport a mixture of sediment and/or debris of various materials and deposit them in onshore or near offshore areas of the coast. These deposits are characterized by sediments of various textural groups such as clay, silt, pebble (rounded to angular) rocks or coral fragments, construction materials (concrete, bricks etc.) and plant material. Very often these deposits can be found above the limits of storm waves. But they may be confused with other deposits like glacial head and man-made deposits. Therefore, the signature of these deposits should be correlated with other tsunami deposits and all other available evidence in order to identify them as tsunami debris deposits. Moreover, these chaotic debris deposits can form isolated ridges or mounds even up to few meters high which would not be expected from normal sea waves or currents (Bryant, 2008).

2.6.2.3 Boulder deposits

Boulder deposits on the coast are fairly unusual under normal coastal hydrodynamic processes. But tsunami-like high energy processes can bring large boulders onto the coast (Nott, 2000). The boulder deposits can also be observed in many forms (Figure 2.8). Isolated boulder deposits on a sandy coast are very often considered as a tsunami deposit. Tsunami-transported boulders are mostly imbricated and can be found as isolated deposits. Tsunamigenic boulder deposits may contain large coral boulders, rocky boulders or other debris of construction materials such as pieces of concrete slab or bricks which have been transported far away from their original position.

Figure 2.8 Scattered boulders deposited on a rocky platform in the north-eastern sector of the Maddalena Peninsula, south-eastern Sicily, Italy (Scicchitano *et al.*, 2007).

2.6.2.4 Erosional features of Tsunamis

Generally, some parts of the coast are subjected to erosion by the tsunami waves (Kench *et al*., 2006; Srinivasalu *et al*., 2007; Umitsu *et al*., 2007). Very often, the first part of the coast, up to about 50-75 metres from the shoreline is subject to erosion rather than deposition by tsunamis. This was clearly observed after the 2004 tsunami around the Sri Lankan coast (Figure 2.9).

Figure 2.9 Erosional land forms from the 2004 tsunami on the Sri Lankan coast. All four pictures are from south east coast (Yala), Sri Lanka.

2.6.3 Textural and grain size characteristics of Tsunami sediments

Several studies of both palaeotsunamis and recent tsunamis reveal some common textural characteristics and special features of grain size statistics, which can be used to characterise tsunami sediments. These include: poor sorting and poly-modal grain size distribution (mainly bimodal); decreasing pattern of mean grain size inland and grain size fining upwards in the sequence are common characteristics of palaeotsunami sediments (Scheffers and Kelletat, 2003; Goff *et al.,* 2004; Scheffers and Kelletat, 2004; Cantalamessa and Celma, 2005; Torrado *et al.*, 2006; Kortekaas and Dawson, 2007; Moore *et al*., 2007). Textural analysis (ratios of gravel, sand, silt and clay) was a part or the main thrust of many studies, but did not reveal any meaningful relations except highlighting some increase in the sand portion

(Hindson and Andrade, 1999). The composition of tsunami deposits is mostly dependent on the source of origin, the geographical location and available materials. Therefore tsunami sediments show various physical characteristics; their key distinctive feature is that they are mostly unrelated to the normal coastal sediments on any coast.

Tsunami sediments have some unique grain size statistical features depending on the specific tsunami wave action. This has been shown in tsunamite sandy deposits at Ardmore, Scotland which are associated with the Storegga Slide tsunami. The relationship between sorting index and mean grain size with different tsunami waves from these deposits has been explained by Bryant (2008), demonstrating the energy of each wave and its behaviour (Figure 2.10). In this particular case, but not necessarily for other tsunami, it has been suggested that Wave 1 had the greatest energy and deposited coarse-grained, poorly sorted sediments; subsequently the energy of the waves in the wave train decays, resulting eventually in the deposition of finer grained sediments.

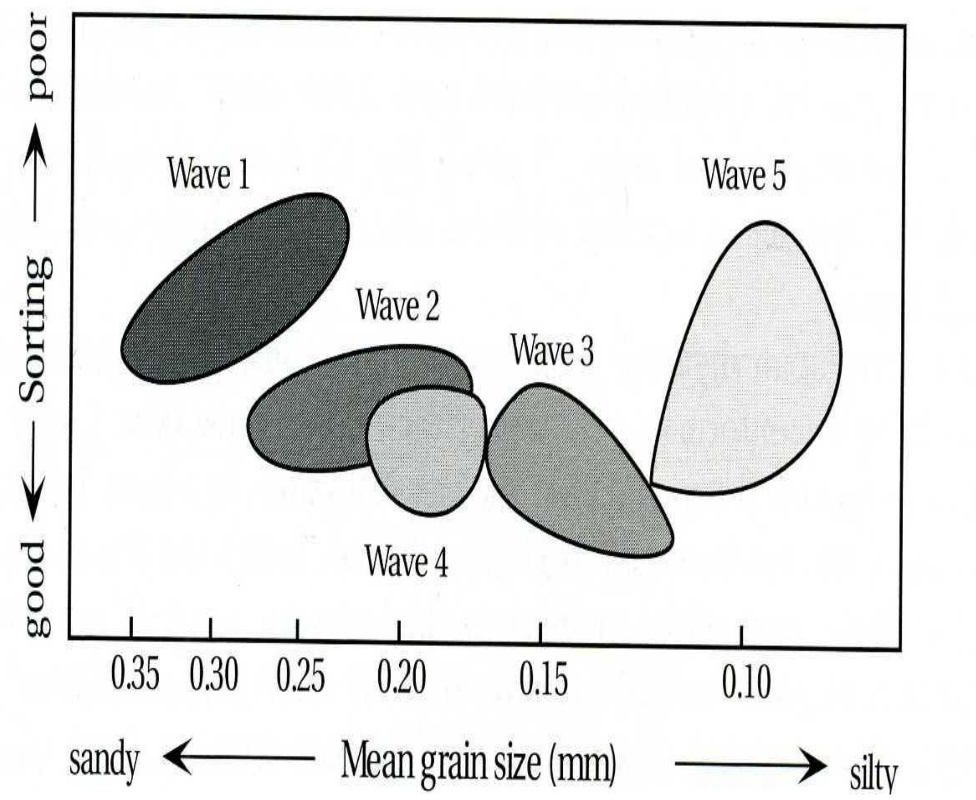


Figure 2.10 Relationship between sorting and mean grain size with regards to different waves of a tsunami, example from Scotland; the Storrega slide tsunami (Bryant, 2008).

2.6.4 Fossil, diatom and pollen records

Some studies have shown that tsunami sediments can be characterised by the presence of marine fossils and pollen. Microfossils species such as foraminifera and diatoms are commonly present in tsunami sediments, but macro-fossils such as bivalves, and other shell or shell fragments may also occur (Kilfether, 2007; Donato, 2008). Generally, foraminifera content is higher in tsunami sediments (Kortekaasa and Dawson, 2007). Also the presence of brackish-marine diatoms can be used as an indicator for tsunami sediments (Hepmill-Haley, 1996). Thus, most studies show that fossil records (diatoms and foraminifera) allow identification of the source of origin of the sediments and their environment (Dawson and

Stewart, 2007). Also analysis of foraminifera assemblage composition has the capacity to enable inferences about the sediments brought by the tsunami waves. The gross assemblage composition and/or individual foraminifera found within a deposit can also provide significant information about local environmental conditions (Mamo *et al*., 2009). Thus tsunamigenic sediments can be isolated based on the foraminifera assemblages.

The composition of the shells and fragments, extension and thicknesses of the shell- beds and presence of angular fragments can also be used to identify tsunami deposits (Donato, 2008; Dawson and Stewart, 2007). Foraminifera assemblages have been used to obtained information on sediment provenance and hence wave characteristics can be determined (Clague and Bobrowsky, 1994; Dawson and Shi, 2000; Hawkes *et al*., 2007). A detailed study conducted on the Malaysia-Thailand peninsula showed that foraminifera assemblages were able to precisely fingerprint the tsunamigenic sediments (Hawkes *et al*., 2007). Thus fossil records are a key factor in the identification of tsunami sediments and reconstruction of palaeotsunami.

A unique characteristic of tsunami sediments is due to their different source of origin as compared to normal coastal deposits. A marine origin is often attributed to tsunami sediments. Therefore, silty, clayey or sandy tsunami sediments may contain characteristic marine fossils brought by high energy tsunami waves. Tsunami sediments may especially contain foraminifera and diatoms of various species (Dawson and Shi, 2000; Williams and Hutchinson, 2000; Dahanayake and Kulasena, 2008). These two types of unicellular animal and plant fossils made from calcium carbonate and silica shells can be preserved in tsunami sediments. The fossil records of different species of foraminifera and diatom are extremely important records, since tsunami waves can mobilise and transport different marine species than normal sea waves or storm surges.

Microfossil assemblages present in known tsunamis such as 2004 may be very useful for understanding the palaeotsunami in the area, because characteristic species may be identified from known tsunami sediments. The 2004 tsunami sediments contain many species of foraminifera microfossils (Figure 2.11).

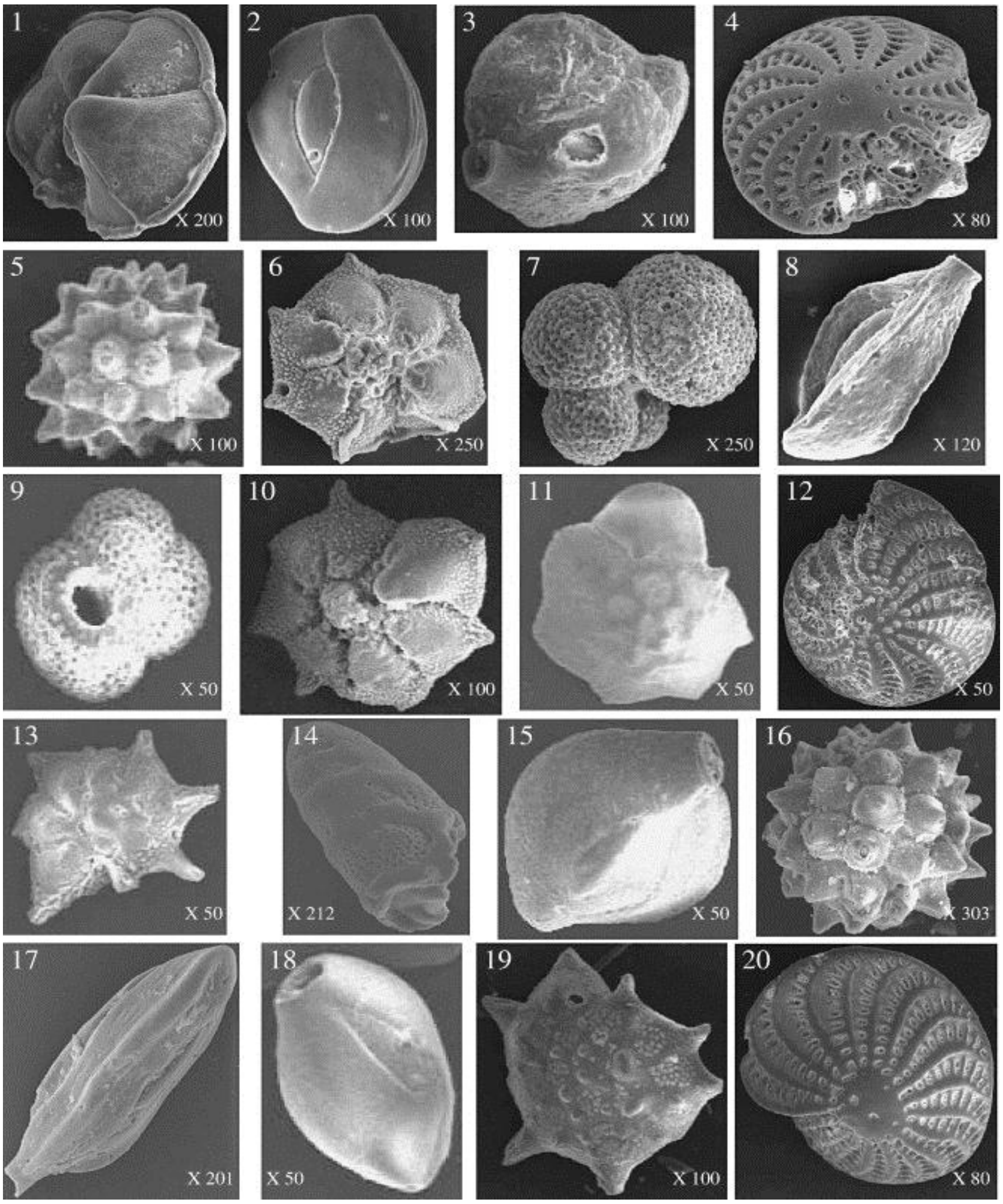


Figure 2.11 Different species of fossils of foraminifera in the 2004 tsunami sediments, deposited on the Sri Lankan coast (Dahanayake and Kulasena, 2008);

On the Figure 2.11, Taxa was formulated after both reflection Microscope and SEM studies (Shorck and Twenhofel, 1953; Braisier, 1980; Mohan Gupta, 2006; Thomau 2005; Satyanarayana, *et al*., 2007; MIRACLE web site UCL) 1. *Globorotalia menardii*: 2. *Milionella subrotunda*: side view. 3. *Quinqueloculina* sp.: side view. 4. *Elphidium advenum*: spiral view (Cushman). 5. *Radiolaria*, *Acantharia*: side view. 6. *Hantkenina* sp.: umbilical view. 7. *Globigerinella calida*: side view. 8. *Quinqueloculina* sp.: side view. 9. *Globigerina* sp.: side view. 10. *Hantkenina* sp. Umbilical view. 11. *Ammonia beccarii*: spiral view (Linne'). 12. *Elphidium macellum*: spiral view (Fichtel and Moll). 13. *Hantkenina* sp.: umbilical view. 14. *Bolivina* sp.: side view. 15. *Quinqueloculina* sp.: side view. 16. *Radiolaria, Acantharia*: side view. 17. *Quinqueloculina* sp.: side view. 18. *Milionella subrotunda*: side view. 19. *Hantkenina* sp.: spiral view. 20. *Elphidium advenum*: spiral view (Cushman).

2.7 Palaeotsunami and their records

Palaeotsunamis leave different types of records which can be used to recognise the event. Tsunamis impact greatly on coastal geology, geomorphology and land-forms, ecology, other physical structures and the whole coastal environment. Therefore, palaeotsunami records may be imprinted in several modes such as geological records, geomorphological records, ecological records, palaeontological records and archaeological records. Thus, the science of palaeotsunamis has links to a large number of other sciences; geology, geomorphology, geophysics, earthquake engineering, marine geology and engineering, geochemistry, seismology, and coastal engineering (Rhodes *et al*., 2006). Hundreds of megatsunamis have been recorded in the past 2000 years with over 2000 tsunamis during the past 4000 years including smaller tsunamis) from different parts of the world (Scheffers and Kelletat, 2003).

Therefore, vast numbers of palaeotsunamis records may be available to develop this science. The most useful and available records of palaeotsunamis are sediment deposits transported by the tsunamis.

Some important observations have been made on palaeotsunami records on the Pacific west coast of Canada and the USA as well as along the Atlantic seaboard of northwest Europe associated with Cascadia earthquakes and the Storegga slide in the UK (Goff *et al*., 2012).

2.7.1 Palaeotsunami records in different parts of the world.

Scotland and Norway

Studies carried out along the eastern, northern and western coasts of Norway provide detailed sedimentological information for a palaeotsunami generated by a submarine slide which took place in the Norwegian Sea in 7590±50 and 7290±50 radiocarbon years BP (Dawson and Smith, 2000). Tsunami deposits from an isostatically uplifted lake basin in western Norway exhibit great stratigraphical complexity while showing a tsunamigenic origin such as resting upon an erosional subsurface, rip-up clasts structures, incorporation of many inter-clasts of eroded materials, sets of fining upwards sedimentary sequences, patterns of chaotic sedimentation with marine sediment resting adjacent to layers of terrestrial turf and twigs, tapering inland and enclosed within peat beds. Large fragments including rocks as rip-up clasts and water-logged wood fragments were concentrated in the lower parts of the organic detritus facies. However, some studies have noticed that fine silts, sands and organic matter in the upper-most part of the deposit was due to sediment deposition after the withdrawal of each major wave (Dawson *et al*., 1988; Dawson and Shi, 2000; Bondevik *et al*., 2005).

Pacific coast

Some sedimentological records from countries around the Pacific Ocean, in particular, Japan and the Pacific west coast of Canada and Washington State, provide detailed information about former occurrences of tsunamis. Tsunami sediment deposits from have been found lying directly upon buried soils and beneath intertidal muds, thus suggesting that the tsunamis took place during or immediately after the episode of co-seismic subsidence (Atwater and Yamaguchi, 1991; Dawson and Shi, 2000; Fujiwara, *et al*., 2000).

Other well marked tsunami deposits discovered along the Cascadia margin of Western North America have also provided important information about palaeotsunamis in the region. These deposits were well preserved and could be identified on the basis of a combination of sedimentary characteristics and stratigraphic features from low energy coastal environments such as tidal marshes, back-barrier marshes and coastal lakes deposits and they all occurred as anomalous layers of sand within peat and mud deposits (Hutchinson *et al*., 2000; Peters *et al*., 2007). These sand sheets were very often continuous and thinning towards land and away from the channel but also have discontinuous lens-like deposits (Atwater, 1987).

Significant observations regarding palaeotsunamis have been made by several studies carried out on the Japanese, Australian, and Indonesian and Papua New Guinea coasts. The main observations made from these studies were:

Generally the deposits

i. have thickness >25cm,
ii. extend over hundreds of meters inland,
iii. have relationships to micro-topographical features,
iv. mostly consist of single homogeneous graded beds,
v. mud inter-clasts and lamina are commonly present

vi. have twig orientations indicating return flow

(Nishimura *et al*, 1999; Dominey-Howes, 2007; Morton *et al*. 2007).

Fujino *et al*, (2006) have note five well-marked characteristics for palaeotsunami sediments on the Japanese coast;

1) Inversely directed imbrications

2) Scour and grading structure

3) Deposition of beach rocks and coral clasts

4) Presence of condensed organic beds

5) Preservation of fossils.

Indian Ocean

There is very little knowledge concerning palaeotsunamis in the Indian Ocean. A few palaeotsunami events have been identified and dated on the Thailand coasts (Jankaew *et al*., 2008; Monecke *et al*., 2008; Brill *et al*., 2011; Prendergas *et al*., 2012). Six events have been identified on the Thailand coast, 350±50 or 380±50 BP, 990±130BP, 1400±190BP, 1600±200BP, 2100±270BP or 2160±280BP, 2200-2400BP, 2500-2800BP (Figure 2.12).

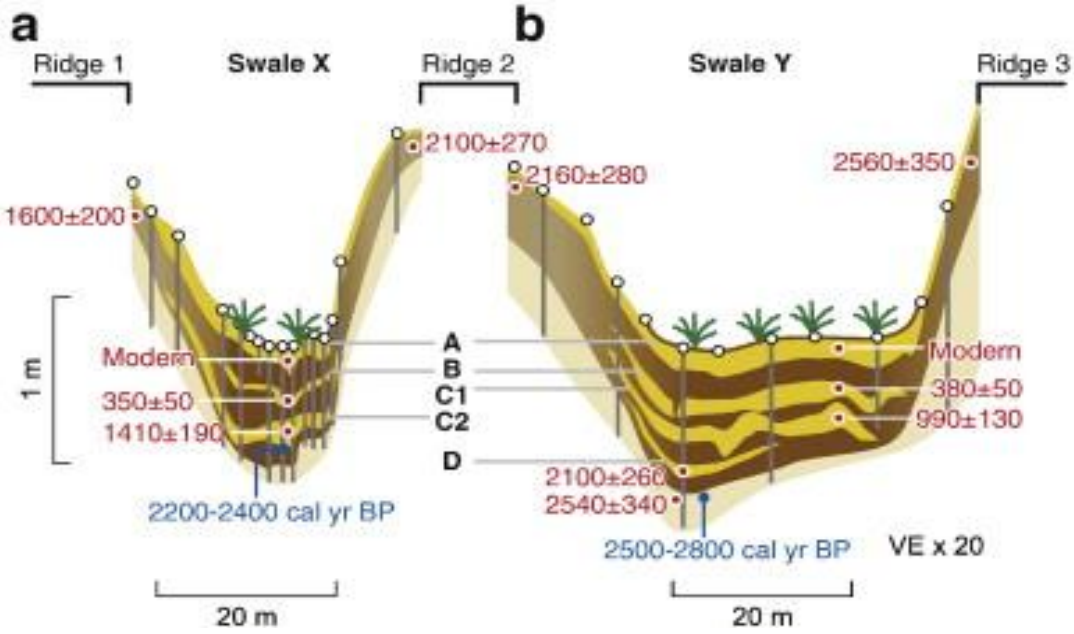


Figure 2.12 Cross sections Palaeotsunami records found in Thailand with dates (After Jankaew *et al*., 2008; Prendergas *et al*., 2012)

2.7.2 Identification of palaeotsunami sediments

Identification of tsunami sediments is mainly based on four criteria;

- Field and depositional characteristics
- Textural and grain size characteristics
- Compositional and physical characteristics
- Fossils, diatoms and pollen records/ Palaeontological evidence

Identification of tsunami sediments is always a challenge since they have diverse character and closely resemble other deposits; flood and coastal storm surge deposits. But in last few decades, several research studies have been conducted at many parts of the world to overcome this challenge (Dawson *et al*., 2000; De Martini, 2003; Fujiwara and; Goff *et al*., 2004; Tuttle *et al*., 2004; Babu *et al*., 2006; Kamataki, 2007; Kortekaas and Dawson, 2007; Nanayama *et al.*, 2007; Peters *et al*., 2007; Tappin, 2007). Three main processes were used in identification of tsunami sediments: sedimentary context, spatial distribution of deposits and the ruling out of other high energy depositional modes (Jaffe and Gelfenbaum, 2002).

Sedimentological context includes stratigraphy and structures from micro to macro scale, grain size statistics or granulometry, paleontological characteristics, mineralogy, chemical constituent and depositional environment. Spatial distribution includes geographical/spatial relation of deposits with respect to coastline, wave actions (the height, the inundation and the flow rate/direction), local topographical and geological features and all other physical features on the coast.

All types of sedimentological analyses such as structural, textural (granulometric), paleontological and stratigraphic can be used to identify tsunami sediments as they represent the hydrodynamics process during the sediment deposition. Very little attempt has been made on using the chemistry and mineralogical composition of the tsunami sediments in order to identify them. Generally, tsunami sediments show geochemical heterogeneity and have some textural and lithological variations. Some studies show that tsunami sand has higher concentrations of SiO_2, CaO and Sr, as they contain higher siliceous sand and calcareous materials. Additionally, they show significant positive anomalies for MgO, Cl, Br and I (Hindson, 1999). Most microfossils studies exhibit a high concentration of foraminifera species and diatoms in tsunami sediments (Dawson *et al*., 2000; Williams and Hutchinson, 2000; Dahanayake and Kulasena, 2008).

2.7.3 Sedimentation Pattern of Palaeotsunami deposits

The sediment deposition pattern and its geographical distribution are also a useful factor in identifying the tsunamigenic deposits. Sediment depositions from tsunamis have their specific characters and conditions such as being confined to some specific parts of the coastal zone, greater inland penetration of deposits, relationship to a tsunami generating source (submarine earthquake, volcano or landslide zone), deposits preserved in swells or marshes rather than other high grounds, thinning inland and distributed greater distances along the coast (hundreds to thousands of kilometres by an event). These particular features are not expected from other coastal deposits.

2.8 Discrimination of tsunami from other high energetic events

Ruling out of other similar events such as storm surge and severe flood deposits which resemble to tsunami sediments is key for identification of tsunami sediments. Therefore, these similar deposits must be clearly identified and distinguished from tsunami deposits.

2.8.1 Differentiation of tsunami and storm action on the coastal zone

Tsunamis are mainly caused by an earthquake, a submarine landslide or a volcanic eruption originating in the sea-bed and providing an impulsive displacement to the seawater column. After this, high speed, long waves travel across the oceans and interact with the coastal zone with very high amplitude. Storms, however, originate from severe weather condition developing from low-pressure zones over the sea as a meteorological process. Since these two processes have two different origins they lead to qualitatively different hydrodynamic processes, although both these natural events are always a catastrophe and cause considerable damage to the coastal environment. While both tsunamis and storms cause damage to coast considerable amounts of sediments are also brought and deposited on the coastal zone or near offshore region. Furthermore, these deposits can be subject to reworking or erosion by the same process or later events resulting in specific types of sedimentary deposits or geological records on the coastal zone or near offshore.

Both tsunami and storm deposits are confined to the coastal zone and differ from normal coastal sedimentary deposits because both processes are associated with high energetic waves which are quite unusual to normal coastal hydrodynamics. However, distinguishing between tsunami and storm deposits is still a scientific challenge since both, as abnormal depositional environment and disturbance to the normal coastal sediment sequence, have some similarities. Occasionally, both of these deposit types can be found on the same coastal stretch and within the same stratigraphic sequence (Goff *et al*., 2004).

Studies of these specific coastal deposits are very important for estimating of risk from these catastrophic events, management of the coastal zone and protection of the coastal environment. Several studies have been carried out on tsunami and storm deposits from different coasts, but very few have attempted to distinguish these two types of deposits from these two processes (Nanayama *et al*., 2000; Goff *et al*., 2004; Morton *et al*., 2007). Some studies have investigated palaeotsunami and palaeo-storm event derived recurrence frequency and estimated intensity based on the stratigraphic records (Atwater and Hemphill-Haley, 1996; Bourgeois and Minoura, 1997; Hutchinson *et al*., 1997; Lue and Ferm, 2000; Morton *et al*., 2007).

The distinction between tsunami and storm deposits is directly related to differences in hydrodynamic process and their behaviour, because, the hydrodynamic process during the whole sediment erosion, transportation and depositional cycle is directly related to all characteristics of the sediments and other geological records. Generally, tsunami sediments deposition results from a few high-velocity long waves, which carry sediments from the offshore, shore-face, beach and inlands (Morton *et al*., 2007). As a rule storm sediments are from near-shore or beach.

2.8.2 Tsunami and storm waves

Although both these natural disastrous events have their origin in or over the sea and cause severe damage to the coastal zone through high energetic conditions, there are great differences in origin, wave type, frequency of occurrence, inundation time period and number of waves. Since storms occur due to a severe weather condition with low pressure zones and wind, they are a fairly frequent event compared to tsunamis and can occur in any coastal zone. However, storm events can be predicted and early warning can be given in advance by meteorologists in order to minimise the damage.

A storm surge is not a normal oceanic gravity wave. Storm surges are caused primarily by high winds pushing the water to pile up higher than the ordinary sea level. The waves can then penetrate further inland since effectively the shoreline is shifted. Thus, storm surges especially when they coincide with the high tide, can inundate most of the low-lying coastal areas. When a storm surge occurs during high tide, in some areas the wave height and the inundation can be very high and may cause severe damage. Therefore it can be not easily distinguishable from tsunami waves and sediments.

In general, tsunami and storm waves can be differentiated as follows;

1) Tsunami waves: Seismically induced waves, individual waves inundate the land in a very short period and are associated with high energy levels in both run up and backwash.

2) Storm waves: Meteorologically induced waves, arriving as a series of waves that can inundate the land almost continuously, for many hours and can have highly variable energy levels (Goff *et al*., 2004)

3) Meteorological tsunamis, or meteo-tsunamis, are long-period waves that possess tsunami characteristics, but are meteorological in origin, although they are not storm surges (Haslett and Bryant, 2009).

Tsunamis are due to huge disturbances of the sea bed and generate very long waves (few hundreds of kilometres) with high energy and travel at very high speed (600-800 km/h). The tsunami waves travel with very high speeds when in deep water, but when they come into the shallow water environment their shape changes; the crests start to move faster than the bulk of the wave; the wave lower part experiences friction from the floor. Most erosion takes place at this point (Halif and Sabke, 2005) and consequently tsunami waves can bring materials from comparatively deep sea environments inaccessible to wind waves; still, we stress, the erosion occurs only in the shelf zone. Tsunamis mostly consist of a single or a relatively small numbers of waves hitting the coast and the run-up and backwash are confined to a comparatively short time period. Therefore, both their hydrodynamics and their geological records can be differentiated from storms, though there is some overlapping of features (Table 2.1).

Table 2.1 Differences in physical characteristics of the flow associated with tsunami and extreme storm (Morton *et al*., 2007).

Flow Characteristics	Tsunami	Coastal storm	Both
Length of coast impacted	10-10,000km	100-600km	Local tsunami and storm can affect similar lengths of coastline
Deep water wave height	<0.5 m	>5 m	
Near shore wave height and period	10-20 m, 100-2000 s	<10 m 10-25 s	
Potential wave run-up height	Most are 10 m, can be a few hundred meters	A few meters	
Inundation depth	0-20 m	<5 m	
Active flow duration	Minutes to hours	Hours to days	
Run up elevation			can have similar run up elevation
Overland flow water velocity	20 m/s	5 m/s	
Flow direction			Tsunami and storms may have similar flood duration, shore normal, can be locally variable
Flow-direction change	Alternating run-up and return during event	Return flow only at end of the event	
Boundary layer structure	Entire water column	Current boundary layer	
Influence of wind stress	Not a factor	Increase water velocity and surge height	
Sediment transport mechanism	Mostly suspension, some traction	Mostly traction some suspension	
Phase of flooding	Repeated rapid rise and fall	Gradual initial rise	
Event frequency	Moderate frequency locally and globally	Frequent locally and globally	

2.8.3 Sediment deposits from tsunamis and storm events

There are some differences in near-shore wave height and period, run-up height, number of overland waves, inundation depth and distance, overland flow velocity, active flow duration, flow-direction change and boundary layer structure between tsunamis and storm (Table 2.1). Additionally, sediment transport mechanisms and depositional characteristics also show great differences. These parameters greatly contribute to the sedimentological characteristics of the deposits. Therefore, tsunamigenic and storm deposits show considerable variation in their characteristics. Many studies have revealed significant differences between tsunami and storm deposits (Table 2.2).

Table 2.2 Summary of the distinguishing characteristics of tsunami and storm deposits (Goff *et al*., 2004).

Tsunami	Storm	References
The deposit is locally extensive, rising in altitude inland, with an abrupt thinning at the margin from moderately ubiquitous thickness of about 30cm. It fines inland and upwards of the sequence within the unit. Inland extension 200m.	The deposit is not locally extensive; it has a minor rise in altitude inland and shows no relationship between distance inland and thickness which varies up to 12cm. There is a marked coarsening at the landward end. Inland extent: 40 m	Atwater *at el*., 1995; Benson *et al*., 1997; Dawson *et al*., 2000; Liu and Fearn, 2000; Nanayama *et al*., 2000; Goff *et al*., 2004
Particle/grain size range from coarse sand to fine silt. Less well sorted than storm deposits, the deposit is generally massive	Particle/grain size range from coarse sand to fine silt. Sorting is better than tsunami.	Dawson and Shi, 2000; Nanayama *et al*., 2000.
Mean grain size is finer than storm.	Mean grain size is coarser than tsunami.	
Lower contact is erosional, and the deposit contains rare rip-up clasts of reworked materials.	Sharp and flat lower boundary.	Dawson *et al*., 1998; Goff *et al*., 1998; Goff and Goff 1999; Clague *et al*., 2000.
Buried/eroded soils present at some locations	Associated with buried vesicular plant materials and /or buried soils.	Atwater,1987; Minoura *et al*., 1996; Clague *et al*., 2000; Lue and Fearn, 2000.
Associated with reworked/ buried archaeological remains.		Fullagar *et al*., 1999; Goff and McFadgen, 2001.
	Shell, wood and debris found as an approximately linear feature, sub-parallel to the shoreline.	Semeniuk, 1996

Some specific characteristics of grain size statistics show clear demarcation between tsunamigenic and storm sediments. Several studies have used bivariate plots between grain-size statistical parameters to explain the difference between tsunamigenic and storm deposits. A bivariate plot of mean grain size against standard deviation (sorting index) for tsunami and storm deposits on New Zealand coasts has been produced by Luque *et al*. (2002) and Goff *et al*. (2004). The plot included data from different trenches with vertical variation and different distances from the coast (Figure 2.13). A notable difference is that storm sediments are slightly better sorted and coarser than tsunamigenic sediments.

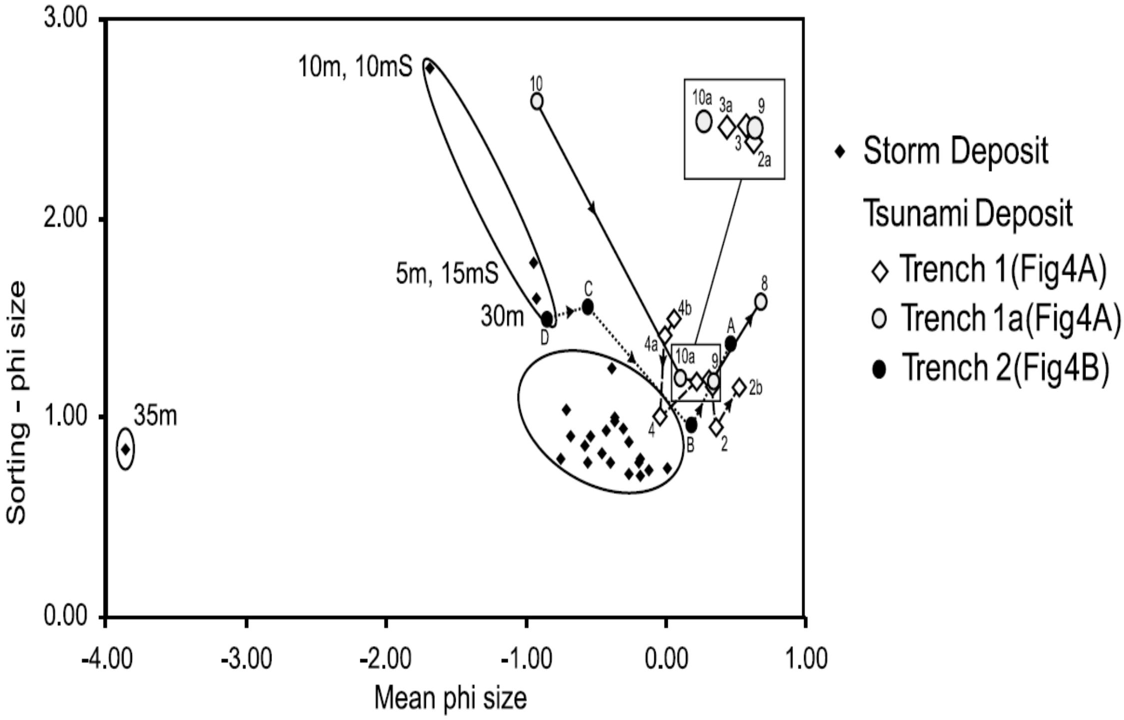


Figure 2.13 Bivariate plot of mean grain size against standard deviation for tsunami and storm deposits (After Luque *et al.,* 2002; Goff *et al.,* 2004).

Goff *et al*. (2004) showed the variation of mean grain size with distance from the coastline of sediments deposited by a tsunami and a storm. Tsunami deposits show a marked fining inland. The sediment depositions from storms do not show any relationship between mean grain-size and distance and the deposits are limited to very short distances inland compared to tsunami deposits (Figure 2.14).

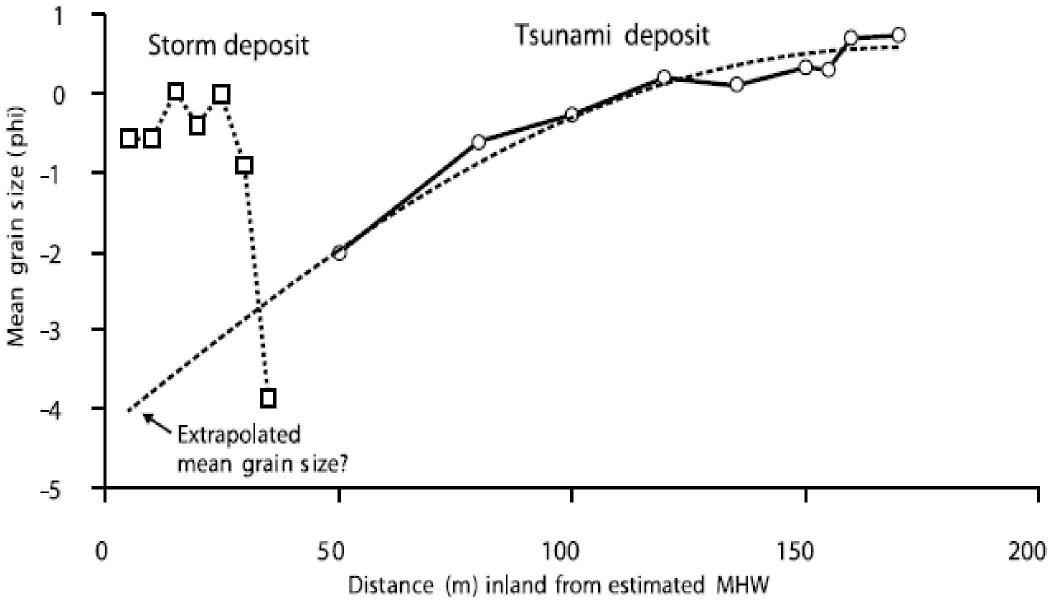


Figure 2.14 Variations of mean grain size with distance from the coast for storm and tsunami sediments (After Goff *et al.*, 2004).

Studies carried out on tsunami and storm deposits on the Papua New Guinea, Peru, Texas and northern Carolina (USA) coasts (Morton *et al.*, 2007) have identified significant characteristics for differentiation of tsunamis from storm deposits. Sedimentological, stratigraphical and morphological differences between tsunamigenic and storm deposits have been explained based on the sediment deposition and the inundation area (Figure 2.15). Tsunamis can deposit sediments further inland than storms, although sometimes storms can have greater inundation distances. Stratigraphical features also show some differences such as tsunami sediment profile, the presence of mud cap, mud clasts, mud lamella and thicknesses up to few tens of centimetres while storm deposit have planar stratification, many lamina sets and thickness up few hundreds of centimetres (Figure 2.16).

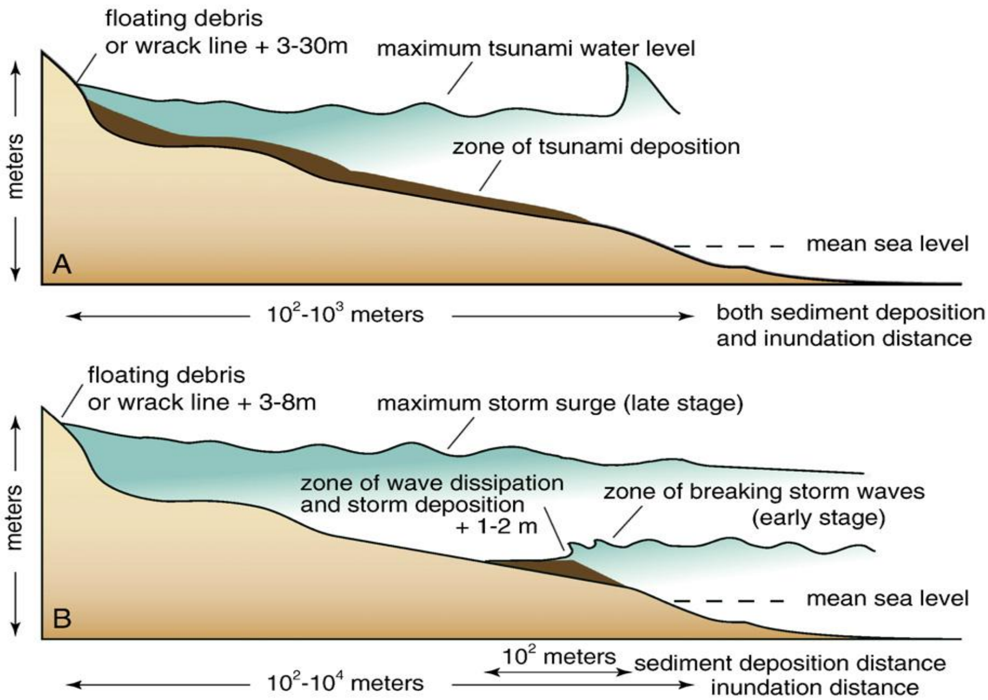


Figure 2.15 Differences in flow depth, inundation distance and sediment-transport distances for sand beds deposited by (A) tsunamis and (B) coastal storms (Robert *et al*., 2007).

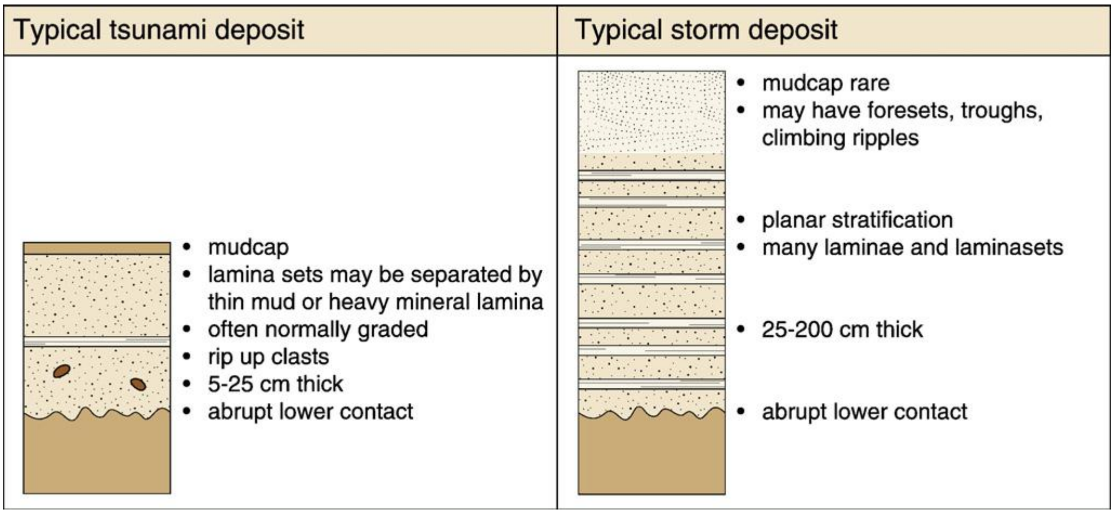


Figure 2.16 Typical characteristics of tsunami sand and storm deposits (Robert *et al*., 2007).

A study carried out by Kortekaas and Dawson (2007) in Martinhal, Southwest-Portugal showed important observations to aid differentiation of tsunami from storm deposits;

- Tsunami deposits extend further inland than other deposits.
- Tsunami deposits contain large boulders.
- Tsunami deposits contain interclasts of fine sediments eroded from the underlying surface.
- Fining upwards sequence and presence of rip-up clasts.
- Tsunami sediments are composed of higher concentration of foraminifera.
- Both tsunami and storm deposits show identical grain size characteristics.

Using these distinguishing characteristics, it is relatively easy to spot the recent deposits exposed over large areas. But it is much trickier to identify, ancient buried deposits exposed over a limited area. Also as tsunami and large- storm deposits have many similarities, it is unlikely that proper diagnosis characteristics are sufficiently well preserved and found by a single observation or site (Morton *et al*., 2007).

2.9 Significance of the tsunami sediment studies

Sedimentological characteristics of any kind of sediment deposits give much information on their depositional environment. Structures (from large scale to microscopic scale), depositional pattern, texture, mineralogy and chemical composition and other constituents are totally dependent on the transport and depositional conditions (Paris *et al.*, 2007). Therefore all conditions of the depositional environment can be read through the sediment characteristics. Tsunami sediment analysis is the only tool available for determining the nature of tsunami actions through reconstruction of tsunami hydrodynamics, and thereby the determination of intensity or magnitude of tsunamis.

Lack of information and memory of past tsunamis in many tsunamigenic areas are the major drawback to estimating tsunami risk and deployment of appropriate remedial measures to minimise damage. Therefore, very often geological records have been considered as the main source of information about ancient tsunamis. The most identifiable and feasible source is sediment deposits. Sediment deposit studies, identification, location and accurate dating are important issues when demarcating the tsunami threatened areas and estimating the risk of tsunami. When more than one tsunami deposit layer is preserved in the stratigraphic sequence, the record may help to determine, records of occurrence of palaeotsunamis and how often tsunamis are likely to occur (Srinivasalu *et al.*, 2007). Additionally, tsunami sediments are also important records for understanding hydrodynamic processes during the inundation time of tsunamis, which is very important information for reconstructing past tsunamis. Major sedimentological characteristics such as thickness and grain size/shape and distribution of tsunami deposits can be used to determine the wave height and the flow velocity of the tsunami waves which are among the most important properties of a tsunami in determining the strength of tsunami waves.

An important step towards a proper estimation of tsunami hazard (probability of occurrence of a tsunami and their intensity or magnitude in a particular period) is an identification of the past tsunami records, generated in, or affecting a particular region. This typically necessitates the setting up of a tsunami catalogue or database established from geologic and historic records. Such a catalogue may then be used to establish a frequency-recurrence curve and to estimate return period for events of different magnitudes (Dominey-Howes *et al.*, 2007). Since most tsunamis are generated related to seismic activities, the seismic history of the area can also be explained using tsunami-related geological records. Thereby, it can be used to interpret tectonic activities in the past and present in the regions and to quantify past tectonic activity.

Known recent tsunami records such as the 1993 Hokkaido, 1998 Papua New Guinea and 2004 Sumatra tsunamis can be used as markers or key for studying past events. If there are no previous recorded tsunami events in an area in known history, attention to tsunami studies is often very low. Before the 2004 tsunami, tsunami studies in most of the countries around the Indian Ocean were totally neglected, and there was no rescue programme or plan for minimising the damage to properties in any coastal area. Therefore, the 2004 Sumatra tsunami caused severe damage to all the countries around the Indian Ocean, which could have been minimised to a large degree in many of them (Gunathilake , 2005). Thus, information on tsunamis or preparation of a tsunami catalogue for any area would be a most useful tool for mitigation of damage caused by tsunamis. A tsunami catalogue/ database for the Indian Ocean have been prepared by Dominey-Howes (2006).

At present no surveying technique has been reported in the literature which can recognise palaeotsunamis without excavation and especially map the inundation extent non-invasively

In this thesis I hope to confirm that palaeotsunamis can be recognised and characterised using geophysical techniques and that their deposits can be dated using luminescence methods. A combination of these methods would be a powerful tool in helping to establish the recurrence interval and the range of tsunami magnitudes which have been encountered on Sri Lanka and demonstrate how these might be deployed elsewhere to give the same important information for risk mitigation.

2.10 Overview of the 2004 Sumatra the earthquake and the Indian Ocean tsunami

The most disastrous tsunami in the known history of the world occurred on the 26^{th} December, 2004 at 00.58 GMT, which was generated by a massive earthquake located beneath the Northern Sumatra, Nicobar and Andaman islands in the eastern Indian Ocean. This enormous earthquake was recorded as having a magnitude of 9.3 and a focal depth of 30 km (Stein and Okal, 2005). It was one of the largest earthquakes to have occurred worldwide in recent history. The event was estimated as having a total rupture length of over 1,150 km and a fault slip of 11m to 15m (Stein and Okal, 2005; Tsai *et al*., 2005; Tanioka *et al.*, 2006; Vita-Finzi, 2008). The rupture speed was calculated as 2.3-2.7 kms^{-1} and the total duration of the rupture to be at least 430s (Kruger and Ohrnberger, 2005). This earthquake occurred in the major subduction zone between the Indo-Australian and the Eurasian plates along the Java trench (Figure 2.17).

The neo-tectonics of the area is shown in Figures 2.17 and 2.18 where the seafloor of the Indian-Australian plate is moving under the Burma micro-plate, towards the northeast at a rate of ~6 cm per year resulting in the most active seismic region in the world (Sandiford *et al*., 2005; Richards *et al*., 2007; Scheffers and Scheffers, 2007; Vita-Finzi, 2008). Therefore, a high accumulation of stress across the subduction zone can be expected, which was released as a large magnitude earthquake on 26^{th} December 2004. This earthquake was followed by several aftershocks and another major earthquake occurred on the 28th February 2005 (after two months) showing there was still sufficient residual potential energy to trigger large earthquakes in the zone (Figure 2.17).

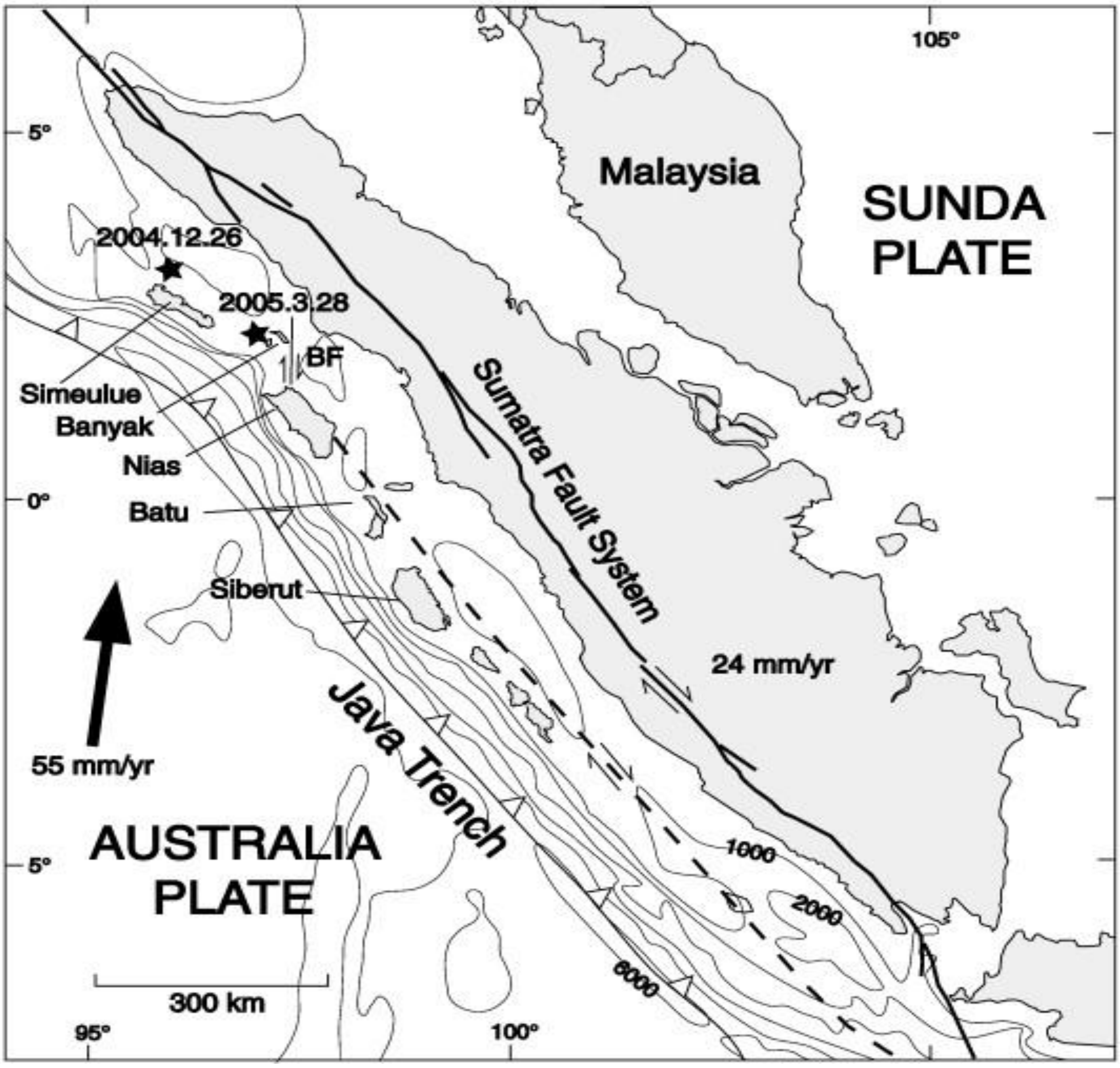


Figure 2.17 Tectonic setting and neo-tectonics of the Sumatra Andaman Island subduction zone (Vita-Finzi, 2008)

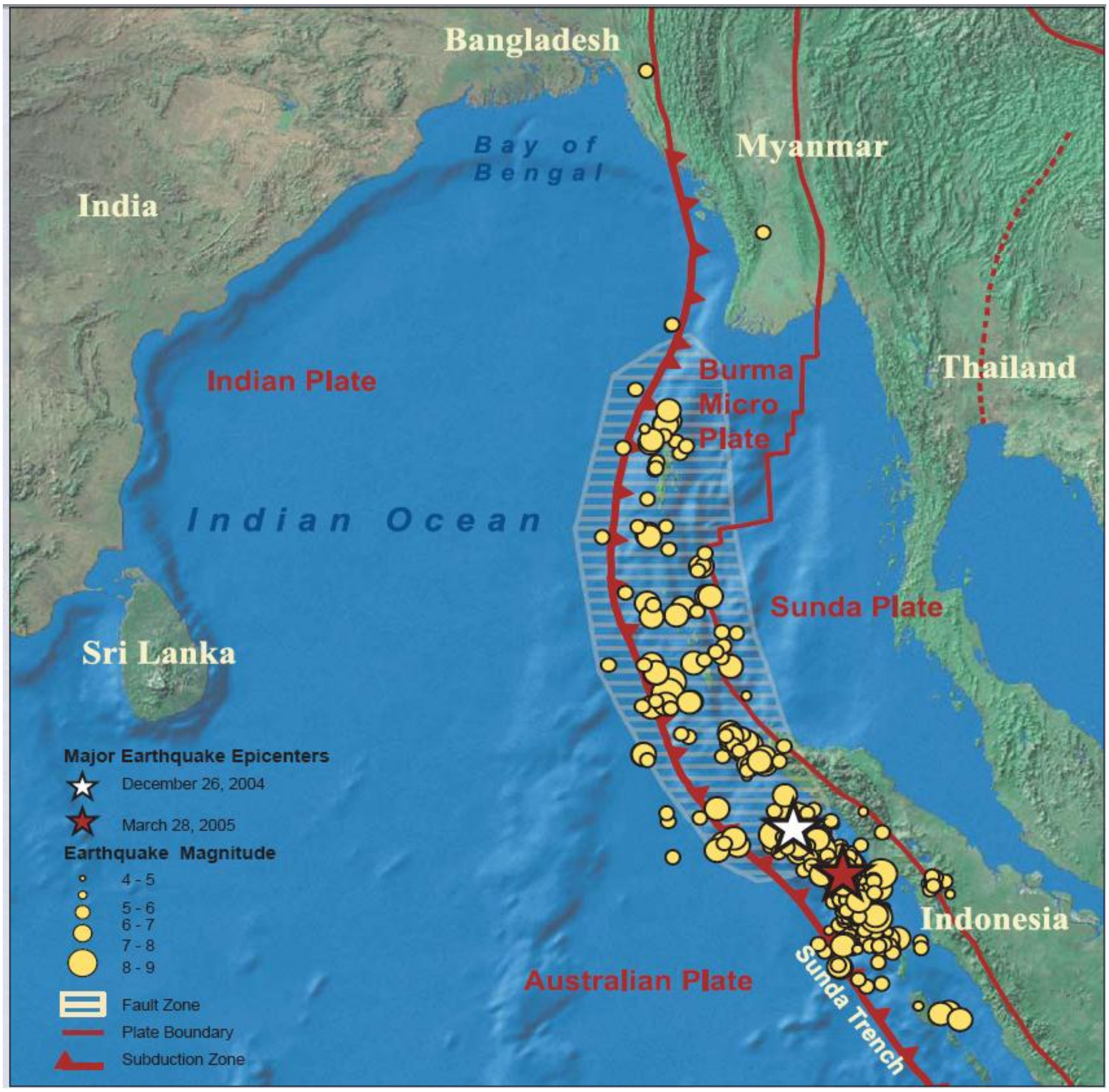


Figure 2.18 Map showing the 26th December 2004, 9.3 earthquake, the 28 February 2005 earthquake and after-shocks along with the regional tectonic setting including the fault zone (Source RMS report USA), (http://www.rms.com/Publications/IndianOceanTsunami).

2.10.1 Energies of the earthquake and the tsunami

It has been estimated that the power of the earthquake itself was equivalent to approximately about 2.0 x 10^8 J, which is more than 1000 times the power of the most powerful nuclear weapon ever detonated (Narayana *et al*., 2007). When we observe the damage and impact caused by the tsunami, even over thousands of kilometres away from its origin, it can be seen that tsunami waves have brought enormous amount of energy to such distances, because, they destroyed concrete structures, ships and boats, highways and railways and moving vehicles and trains etc. on the coast over many thousands of kilometres away.

2.10.2 Damage caused by the tsunami

The 2004 tsunami and the earthquake severely affected most of countries around the Indian Ocean, killing over 226,000 people, displacing over 1.1 million and causing severe damage worth over seven billion US dollars to most of countries around the Indian Ocean (Gunathilake, 2005). Indonesia, Thailand, Sri Lanka, India, Maldives, Myanmar, Malaysia, and Somalia are the countries which suffered both casualties and damage, while Australia, Madagascar, Oman and Singapore experienced only property damage (Greenhough *et al.*, 2005). However, available death records showed that people from most other countries were also affected by this tsunami, as many of them were visiting these severely affected areas. The highest death toll, 131,028 was recorded from Indonesia as it is nearest and directly affected from both the earthquake and the tsunami. Thus, the 2004 tsunami was well documented as the most catastrophic devastation which has occurred on a global scale in known history (Gunathilake, 2005).

Giant waves from this tsunami travelled across the whole Indian Ocean within a few hours and even reached to the Pacific Ocean through the small window between Australia and Indonesia (Figure 2.19). Most coasts near the origin experienced tsunami waves within an hour or a maximum of two hours' time (Rabinovich and Thomson, 2007). However, there was no possibility to give a tsunami warning, since a tsunami warning system had not been established in the Indian Ocean. The tsunami caused unacceptable damage, which could have been mitigated if there had been a warning system; even just pre-experience and awareness could have dramatically reduced the loss of life.

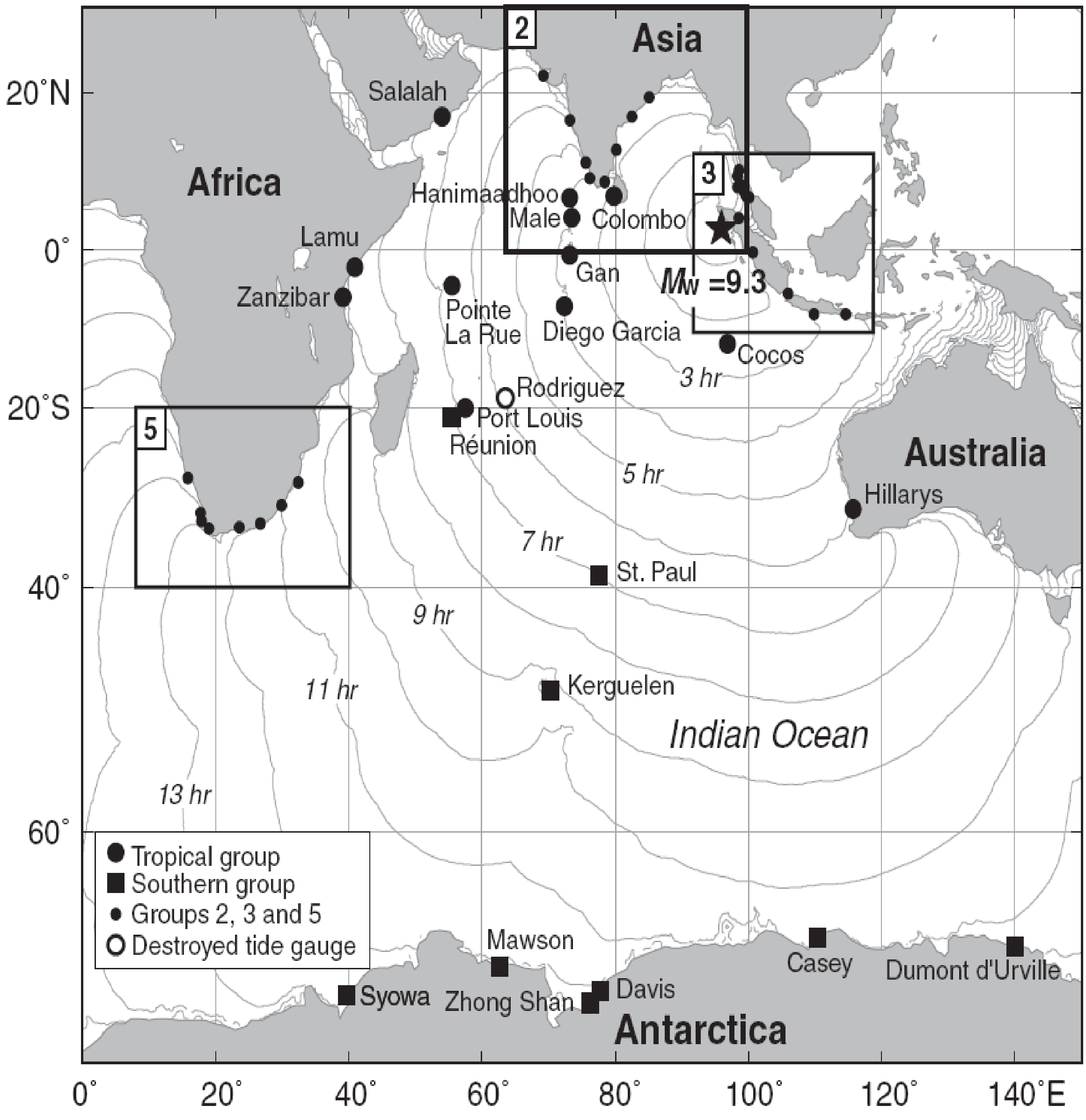


Figure 2.19 Map of the 2004 tsunami origin and hourly isochrones of the tsunami travel time across the Indian Ocean (Rabinovich and Thomson, 2007).

2.10.3 Impact of the 2004 tsunami on the Sri Lankan coast

As Sri Lanka is a small island in the Indian Ocean, it was severely affected by the 2004 Sumatra tsunami, although it is located about 1500 kilometres away from the source. The Island of Sri Lanka is located facing directly towards the Sumatra tsunami linear wave front across the open ocean. Sri Lanka was one of the worst affected countries. Over 75% or a 1000 km length of the coastal stretch and 13 districts out of 14 lying along the coastal belt were affected. Over 35,000 deaths, about 15,000 injuries and over one million homeless were reported. The property damage caused by the tsunami was estimated as over one billion US $ which included ships and boats, harbours, hotels, roads and highways, railways, vehicles and trains, hospitals, schools and other government buildings, cities and towns. Moreover, damage was caused to 89,000 housing units (over 50,000 completely damaged) and 11,000 businesses (Records of Department of Census and Statistics, Sri Lanka, 2005). Therefore, this tragic event created a number of social, cultural and economic problems for most of the coastal community of Sri Lanka, because of orphans, parents who lost their children and most people mainly related to the tourist and fishing industries lost their source of income or jobs and also lack other basic facilities such as school, hospitals etc. This was the most unforgettable devastating event which has taken place in Sri Lanka in its known history.

This tsunami left a considerable geological signature on the coastal zone which is providing extremely useful material for tsunami research. Tsunami related studies have accelerated and many scientists from all over the world have commenced research in this area. Through our interpretation of the 2004 tsunami signature, all other past tsunami records can be read and a full appraisal made of their significance. Therefore, proper understanding and analysis of the 2004 tsunami event is a vital part of tsunami research on the Sri Lankan coast and also in the Indian Ocean. In this chapter, inundation pattern, sediment deposition and other geological records are analysed in detail.

2.10.4 Characteristics of the 2004 tsunami around the Sri Lankan coast

Wave height and inundation distance along all the affected areas of the Sri Lankan coast showed considerable variations even within a very short distance. A generalized picture of the tsunami wave action around the Sri Lankan coast has been modelled (Hettiarachchi and Samarawickrama, 2005). One of the most significant observations from the 2004 tsunami was the severe effect on the western Sri Lankan coast even though it was in the shadow of the direct wave front. Wave impact on the Sri Lankan coasts has been explained as being due to direct waves, reflected waves, diffracted waves or combined waves of all these. Different parts of the Sri Lankan coast were hit by one, two, three or maximum four waves (Figure 2.20).

The number of waves which arrived at the particular location on the coast is dependent on offshore bathymetry, coastal geomorphology, the facing direction of the coastline and the geographical location. Additionally, a complex near-shore transformation and sometimes favourable coastal geomorphology (e.g. combined bay and headlands) also contributed to unexpectedly heavy local devastation.

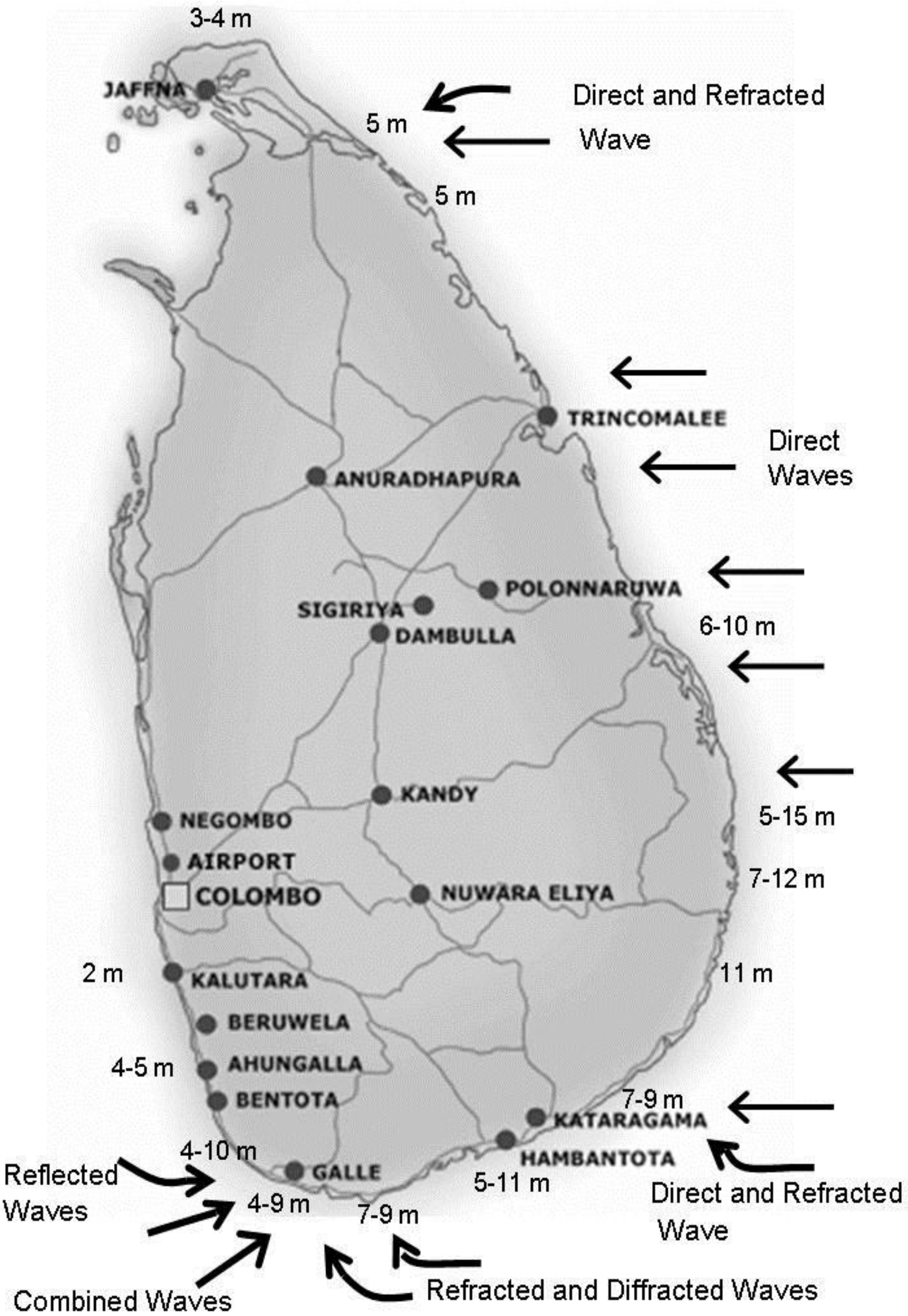


Figure 2.20 Near-shore wave refraction and recorded tsunami heights around Sri Lanka from the 2004 tsunami (Hettiarachchi and Samarawickrama, 2005)

2.10.5 Near-shore transformation of the 2004 tsunami wave around the Sri Lankan coast

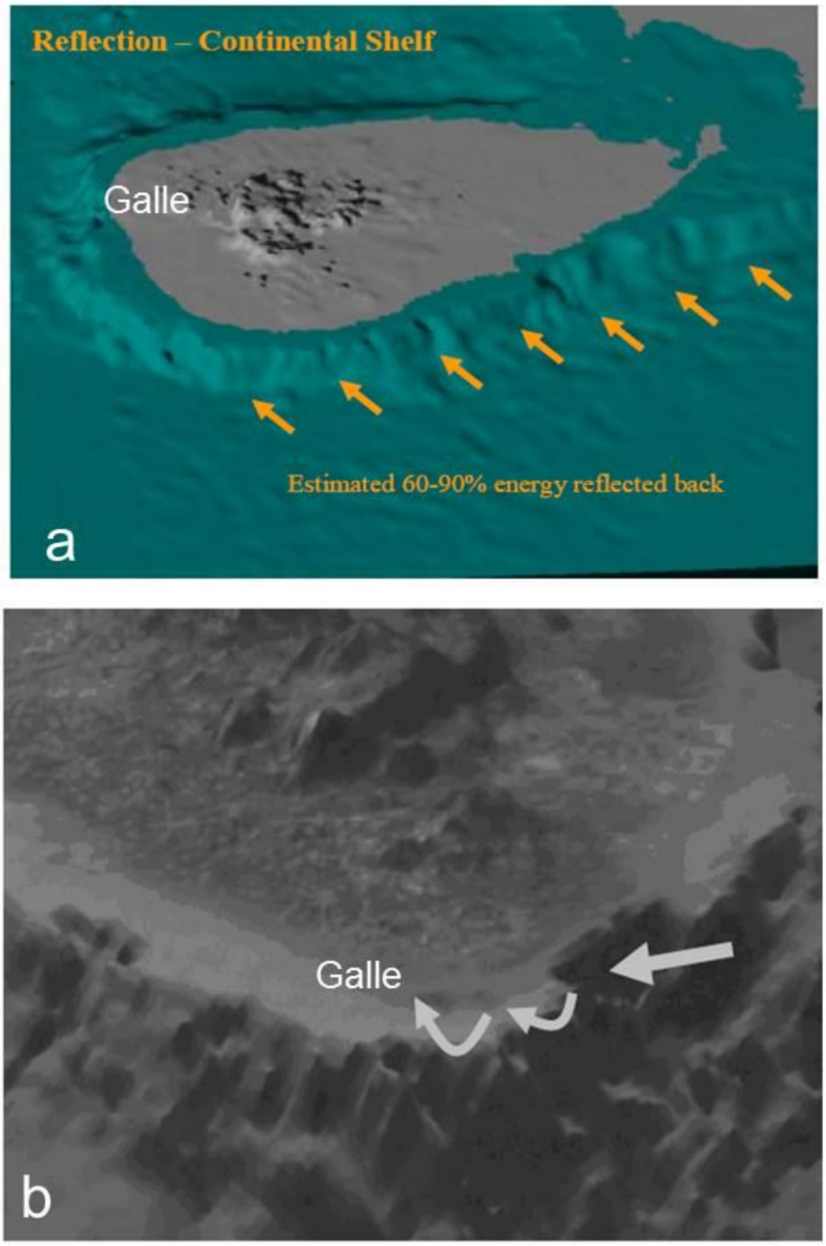


Figure 2.21 The 2004 tsunami wave reflection and transformation from the continental shelf. Plate (a) show planar transformation on the eastern continental shelf and Plate (b) shows the complex nature of the southern continental shelf of Sri Lankan (Hettiarachchi and Samarawickrama, 2005).

Usually a considerable portion of the incoming wave energy is reflected by the continental shelf. Sri Lanka has a very narrow continental shelf with steep slopes and a sudden drop. Further, the presence of discontinuities and irregularities of the southern continental shelf of the Sri Lankan island (Figure 2.21) were responsible for generation of complex wave patterns leading to significantly greater impact (Hettiarachchi and Samarawickrama, 2005).

2.10.6 Inundation pattern of the 2004 tsunami waves along the Sri Lankan coast

The eastern, southern and parts of the west coast of Sri Lanka were affected by the 2004 Sumatra tsunami. Tsunami wave arrival times at Sri Lanka showed significant time differences between the arrival of the first wave on the east coast and on the west coast. The first wave hit the east coast at 08.30am-08.45am (local time), followed by the largest wave around 08.50am-09.15am. On the south and west coasts, the first wave arrived around 09.30am -09.45am and the largest wave arrived around 09.50am-10.30am. According to eyewitness accounts, most parts of the west and southwest coast experienced another wave in the afternoon from 13.00am to 15.00pm, which was due to reflection from the coast of the Maldives (Liu *et al*., 2005; Goff *et al.*, 2006; Wijetunge, 2006; Fagherazzi and Du, 2008).

CHAPTER 3

METHODOLOGY

3.1 Tsunami studies

One of the most promising ways of estimating risk of tsunami in coastal zones is to estimate the frequency and the magnitude of past tsunami events (Nelson *et al*., 1995; Fujiwara *et al*., 2000; Kelsey *et al*., 2005). In most places however, the records are either incomplete or inconsistent or sometime absent (Aoibheann *et al*., 2007). The only material records which can reliably be used to interpret the past tsunami events beyond historical times are sediment deposits or geological records that are preserved on the coastal zone (Dominey-Howes, 2002). The geological signatures / records give valuable information about past history. If these records can be identified properly and dated, the frequency of tsunami events for a particular coast can be determined. The distribution pattern of the geological records especially, sediment deposits, provide more information on hydrodynamic characteristics of the tsunami event such as; the lateral extent of the tsunami sediments gives information on the inundation distance of the tsunami wave. Therefore, in this project many techniques were applied to reconstruct palaeotsunamis, thereby developing methods to determine tsunami risk.

Geological signature recognition tools were developed for identifying tsunami records, with the 2004 Sumatra tsunami records used as a template. The sediments were then dated and the lateral distribution of them traced using geophysical techniques. This multidisciplinary approach was applied for the several sites for this project. Tsunamigenic sediments were identified and distinguished from other depositional events using sedimentological and paleontological characteristics. The sedimentological characteristics of the sediments were analysed using currently available and recognized standard methods (Switzer *et al*., 2012) and micro-palaeontological analyses of microfauna were carried as described in later sections. The lateral extent of the tsunamigenic sediments was mapped using a small number of hand-dug pits and trenches and they were correlated with horizons identified using geophysical methods, namely Ground Penetrating Radar (GPR). This technique was selected as it has been applied to clastic sedimentary sequences very successfully in other depositional environments and this study needs a geophysical method with a high resolution but penetration is only required into the shallow sub-surface (i.e. a few meters). The GPR technique can be used in any terrain having even constructed areas such as; cemented pavement or tarmac roads etc. and the resolution can be selected using different frequencies albeit that penetration is more or less inversely proportional to frequency. Therefore, Ground Penetrating Radar (GPR) was the obvious method of choice for this study. Many published studies show that the GPR technique can be successfully used for coastal sandy deposit studies (Jol and Bristow, 2008).

The frequency and recurrence interval of tsunamis is also an important factor in this study and therefore the determination of the ages of palaeotsunami sediments is a key factor. The most appropriate and relatively recently developed method, is known as Optically Stimulated Luminescence (OSL) and was used for dating the tsunamigenic sediments (Prendergast *et al.*, 2012).

3.2 Study area

The research was carried out on those areas of the Sri Lankan coast where the 2004 tsunami caused severe impact. Sri Lanka is one of the islands, where considerable damage was caused even though it is located over 1000 km away from the origin of the 2004 Sumatra Tsunami (Figure 3.1). About 75% of the coast, nearly 1000 km, was affected (Gunathilake, 2005). The present study mainly concentrates on the south-eastern, southern and western parts of the Sri Lankan coast.

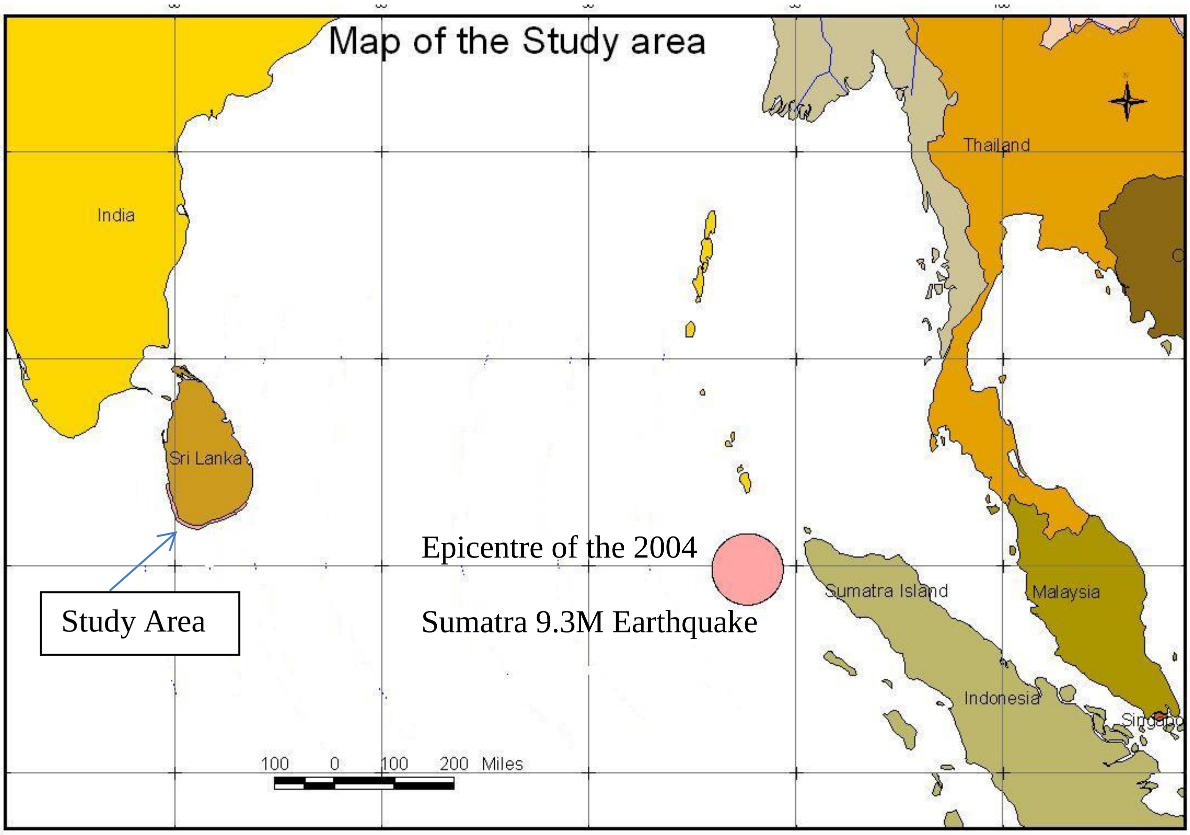


Figure 3.1 Map of the 2004 Indian Ocean tsunami and the surrounding countries affected.

3.2.1 Geography and geology of the study area

The Island of Sri Lanka lies in the Indian Ocean, just south of India, between 5^0-10^0 North and 78^0-82^0 East. Geomorpholgically Sri Lanka is divided in to three units: coastal plains (0 to 90m), Uplands (90- 570m) and Highlands (>570m). The coastal plain is mostly flat and with isolated hills and rocky outcrops. The upland zones are characterized by ridge and valley topography. The highlands are mostly mountain ranges and plateaus. Climatologically, Sri Lankan island is divided into main two parts; a Wet zone and a Dry zone. The western part of the island mostly lies in the wet zone receiving 2500-5000mm annual average rain fall from the southwest monsoon. The dry zone mostly lies in the eastern northern and southeastern parts of the island and receives 900-1200 mm annual average rainfall from inter-monsoon rain and northeast monsoon rains (National Atlas, Sri Lanka).

Geologically, Sri Lankan is composed of Proterozoic high grade metamorphic rock terrain which covers 90% of the island (Kroner *et al.*, 1991). The rest of the area is covered by Miocene limestones, with some Jurassic strata and Quaternary deposits located on the coastal zone and river beds / valleys. The metamorphic rock terrain is divided into main three complexes (Map 3.2) based on the tectonic setting and the metamorphic grade; Highland Complex, Wanni Complex and Vijayan Complex (Kroner *et al.*, 1991). The Highland Complex comprises granulite grade metamorphic rocks (Charnockite, Quartzite, High-grade gneisses) forming high elevated topography. The other two complexes consist of upper amphibolite grade metamorphic rocks of hornblende-biotite-gneisses and granitic and granitoid gneisses and they mainly form low flat elevated topography.

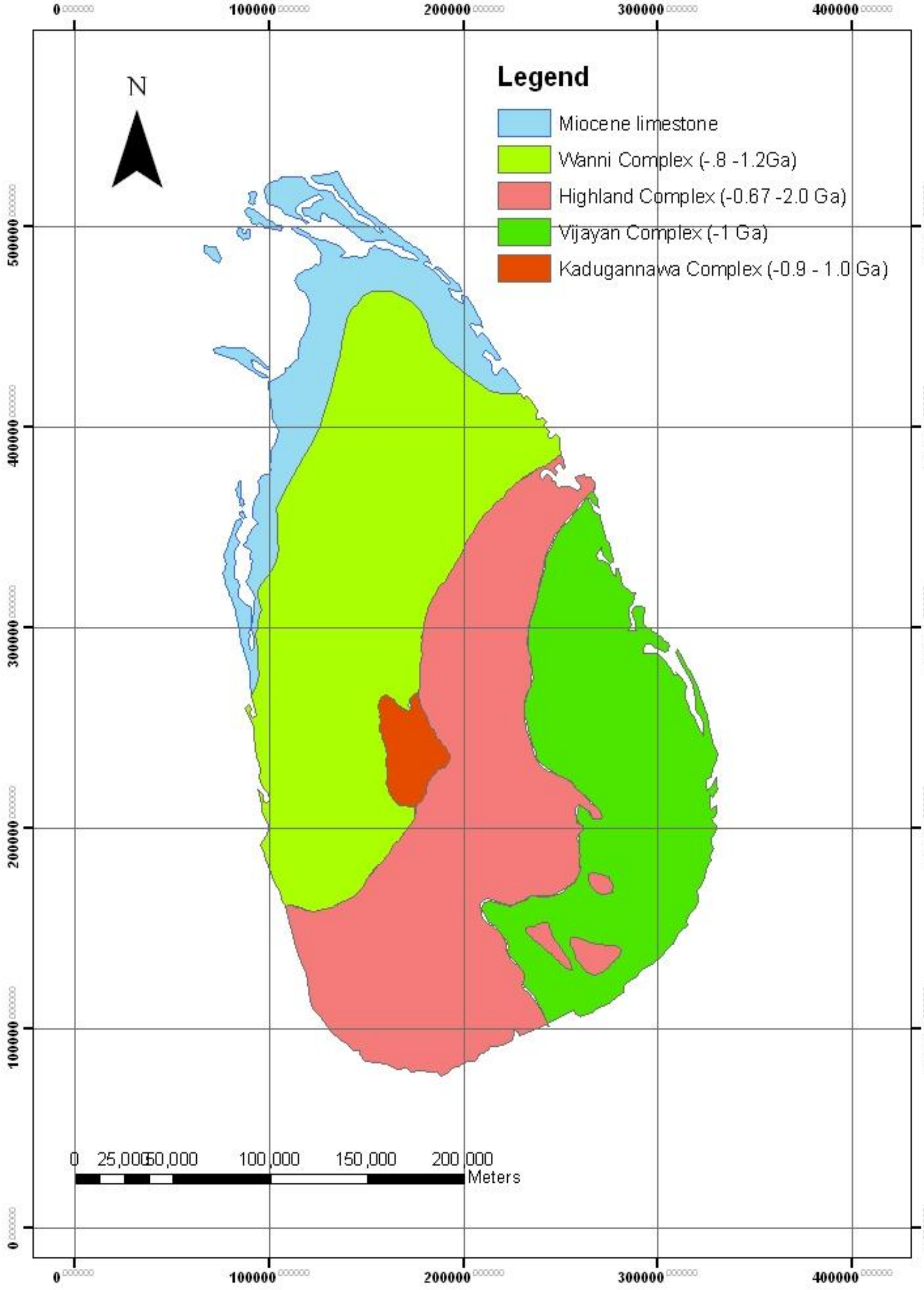


Figure 3.2: Simplified Geological Map of Sri Lanka (Kroner *et al*., 1991)

3.2.3 Locations of the study

Both recent tsunami and palaeotsunami studies were conducted at locations on the western, southern and the southeastern coasts of Sri Lanka. These locations were selected based on the impact of the 2004 tsunami, sediment depositional patterns and the geomorphological characteristics. Three locations (Figure 3.4); Katukurunda, Payagala and Yakgahaela (Bentota) were on the western coast and Dikwella was on the southern coast. These locations fall geologically within the Highland Complex and the climatologically wet zone of Sri Lanka. Other locations on the southeastern coast; Yala and Hambantota fall within the Vijayan Complex and the dry zone of Sri Lanka. Geological records deposited during both the 2004 Sumatra tsunami and Palaeotsunami were studied at different locations as described in the next paragraphs.

3.2.4 The 2004 Sumatra tsunami studies

The characteristics of the inundation patterns of the 2004 tsunami waves and sediment depositional sequences were studied. Inundation distances, run-up heights and the number of waves which impinged on the coast the coasts were analysed using sections around the coast. The whole coastal stretch was divided into three sections representing the east, the south and the west (Figure 3.3). The inundation distance, wave height, number of waves which impacted on the coast and the sediment thickness were plotted for each section.

Section 1: North- South section parallel to the East coast.

Section 2: East-West section parallel to the South coast.

Section 3: North-South section parallel to the West coast.

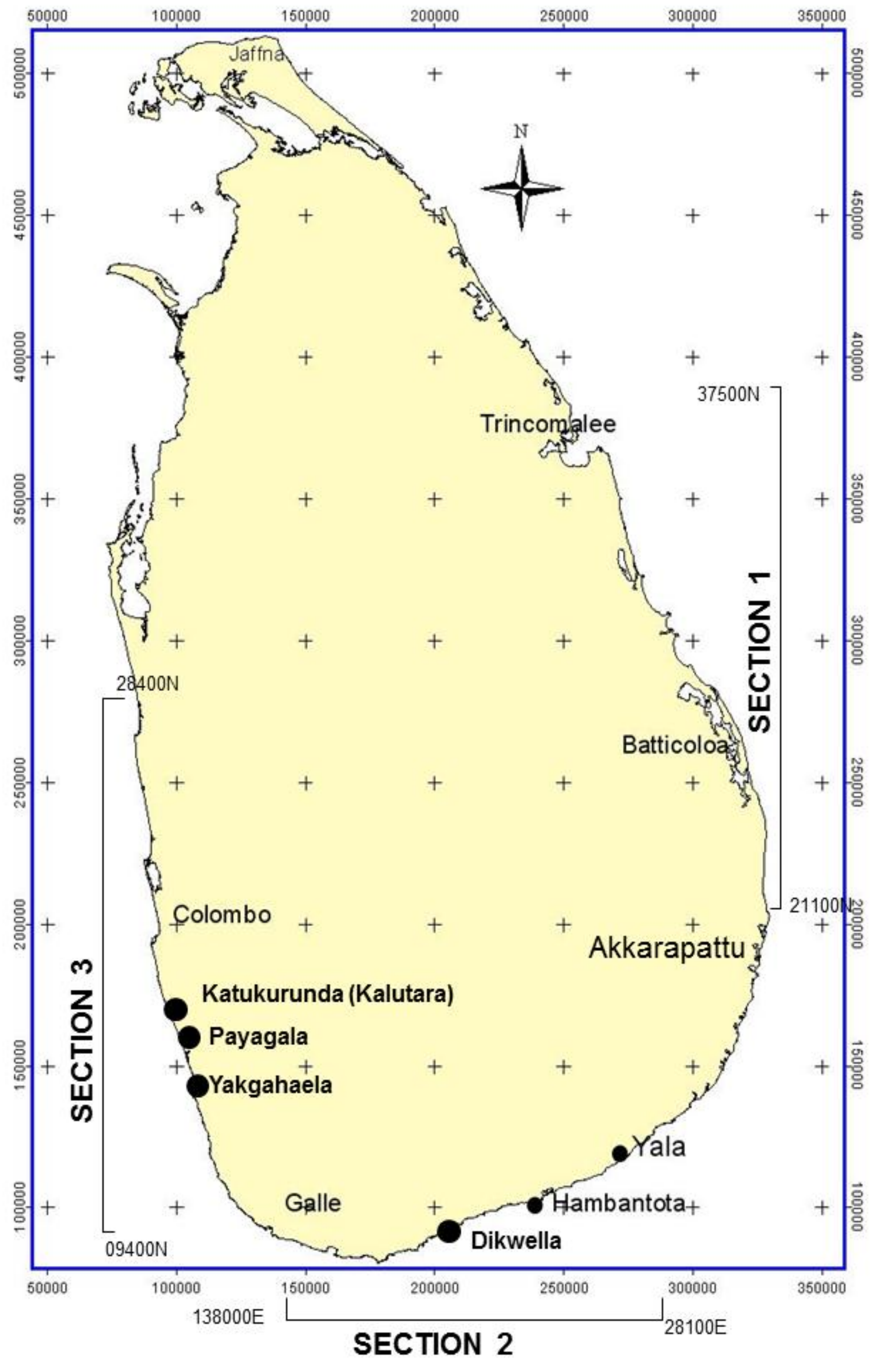


Figure 3.3: Locations map with three sections studied around Sri Lanka.

3.2.5 Sediment deposition studies on four transects

The analysis also included detailed studies of the depositional pattern of the sediments on the coast; here four transects were used, where sediment deposition could be traced along a cross section. Additionally, a few more locations were also selected where good sediment profiles could be observed at a single site and also based on the different geographical, geological and geomorphological conditions. Four transects were planned, normal to the coast representing southeast and west coasts, and named Transect 1, 2, 3 and 4 (Figure 3.4).

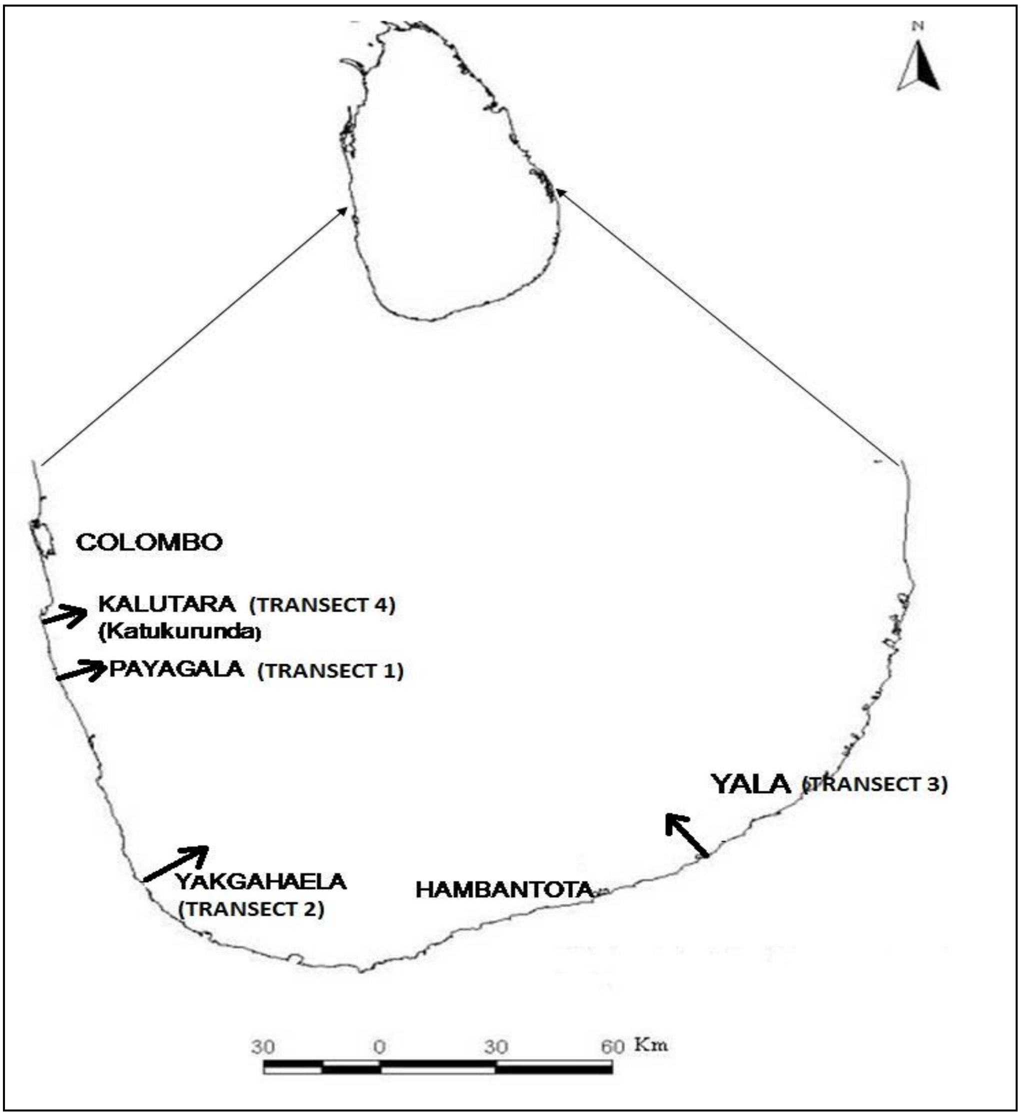


Figure 3.4 Location map of the four Transects of the 2004 tsunami sediment study on the Sri Lankan coast.

Elevation and details of the topography was surveyed along all transects using an optical Dumpy Level. Simultaneously, run-up heights of the 2004 tsunami were measured using available signs such as water marks, debris on trees and water marks on walls or buildings. Sediment deposits were studied by means of thickness, sedimentological characteristics; structures, textures, mineralogy and composition. Representative sediment samples were collected along transects for further laboratory analysis.

Transect 1

Location: Payagala

Geographical Coordinates: 6^0 30.82' N, 79^0 58.93'E

The Payagala site is on a flat coastal stretch on the west coast of Sri Lanka (Figures 3.5). This coastal stretch is straight and oriented in NNW-SSE direction. The location is characterized by the presence of a sandy narrow beach, lateritic high ground and low ground with marshlands and a valley with a stream. Strong wave actions were recorded from the 2004 tsunami in this area generally, with run up heights and inundation distances of the 2004 tsunami waves recorded as 3-5 m and 250-750 m respectively (Figure 3.6).

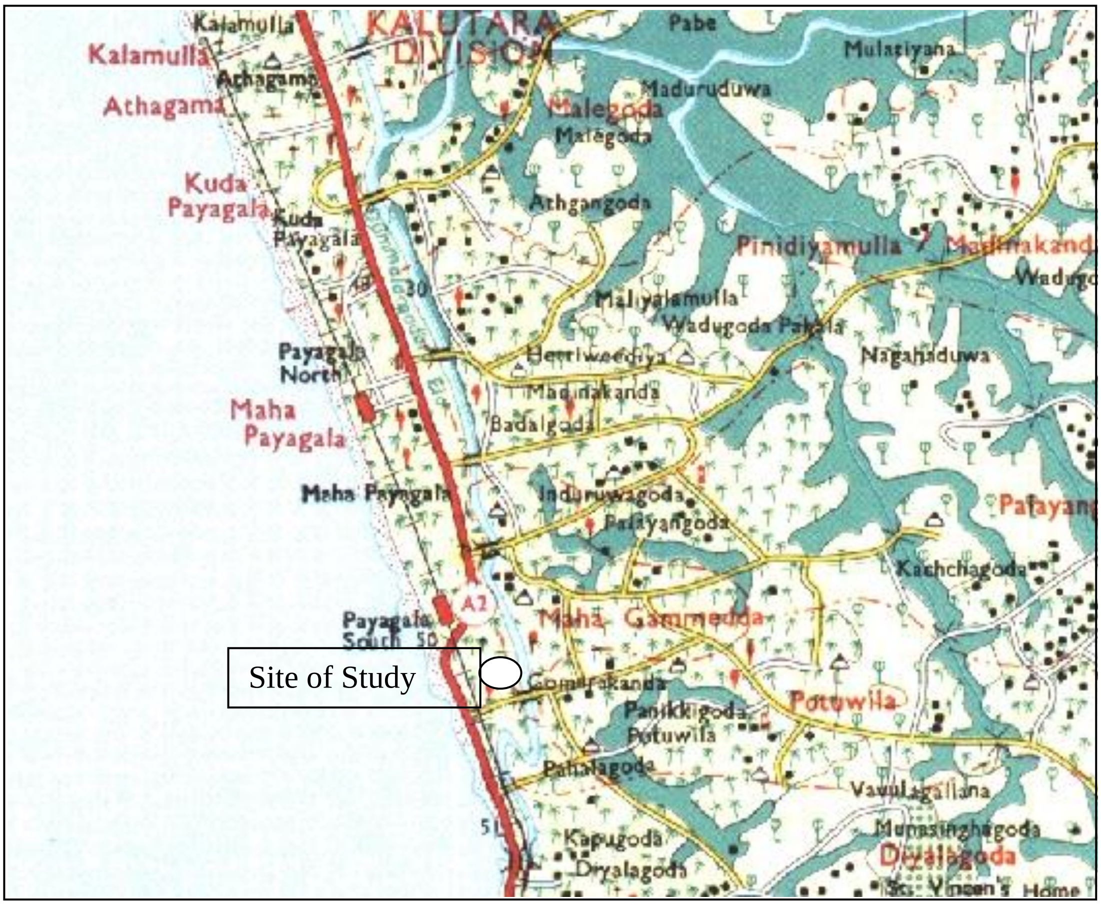


Figure 3.5 Topographic map of Payagala area

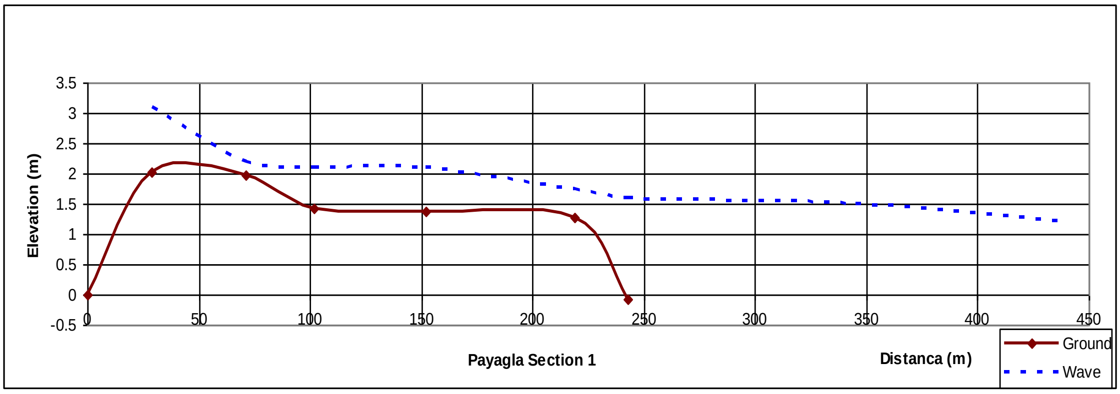


Figure 3.6 Topographic cross section with run up height of the 2004 tsunami along the Transect 1 (Payagala).

Transect 2

Location: Yakgahaela (Bentota

Geographic Coordinates: 6^0 2.04'N, 80^0 00.29'E

This site is located in the south-western part of Sri Lanka (Figure 3.7), and the major topographical features of the area are narrow beach and lateritic high ground having a gentle slope towards the coast. The coastline in this area is straight and oriented NNW-SSE direction. The 2004 tsunami waves in this area have shown 250-300 m inundation and up to 3 m run up height and two waves were recorded in the area.

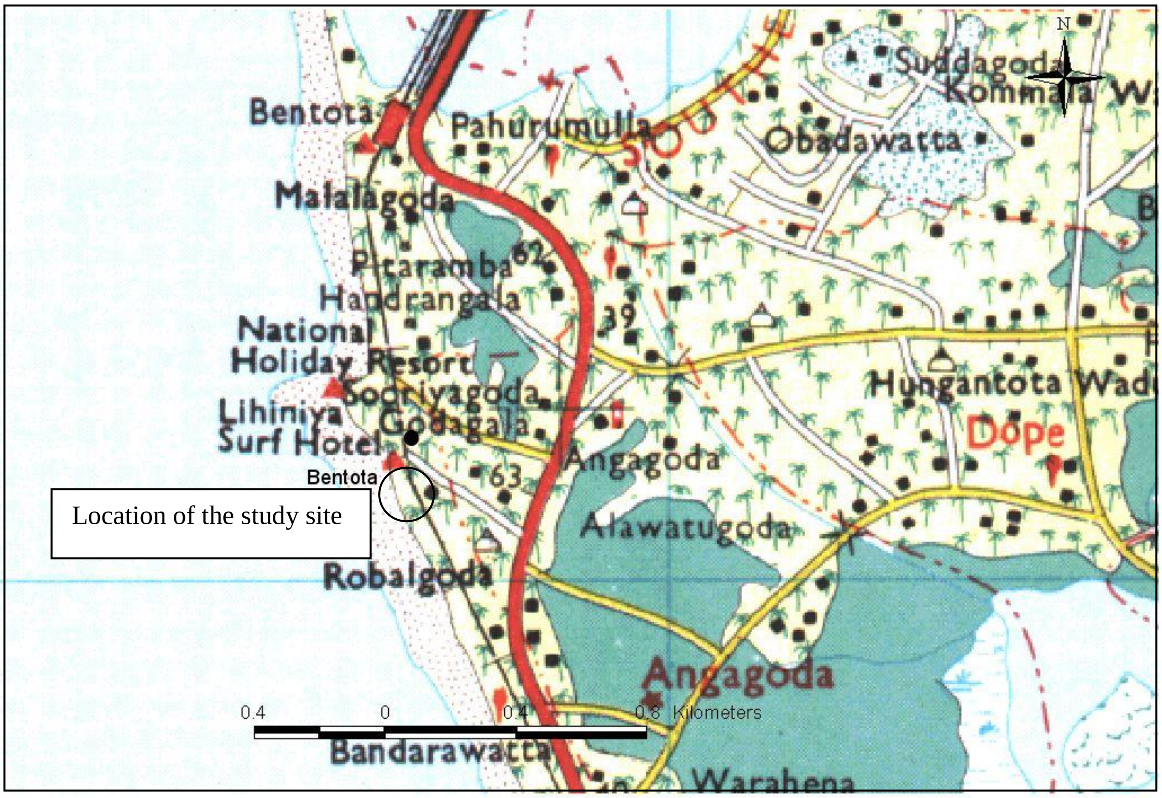


Figure 3.7 Topographic Map of Bentota / Yakgahaela area

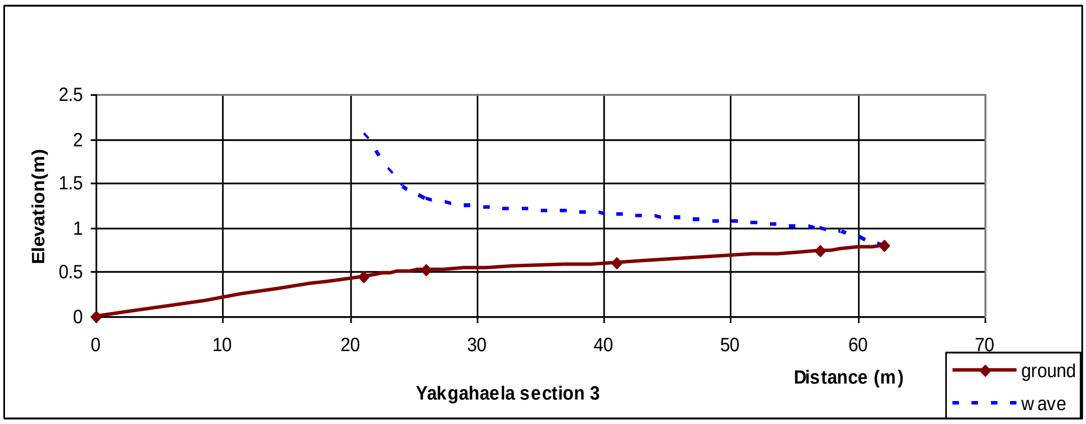


Figure 3.8 Topographic cross section with run up height of the 2004 tsunami along the Transect 2 (Yakgahaela).

Transect 3

Location: Yala, Sri Lanka (Southeast coast)

Geographic Coordinates: 06^{0} 16.39'N, 81^{0} 25.09'E

Yala is located on the southeast coast (Figure 3.3 and 3.9). The major geomorphologcal features observed in the area were wide sandy beach, sand dunes followed by gentle sloping land, irregular rocky outcrops and small hillocks showing hummocky topography. The coastline in the area trends NE-SW and is irregular in shape. An irregular shaped lagoon, (Palatupana) extends over 1 km inland (Figure 3.9). The 2004 tsunami event showed great inundation distances of about 2000-2500 m and 5-8 m high run up in the area with 2 to 3 waves recorded on the coast. Very thick sediment deposition, of up to 30-35 cm comprising several layers with different textural characteristics was observed in the area up to 700 to 800 m inlands. Part of this area belongs to Yala National Wildlife Sanctuary.

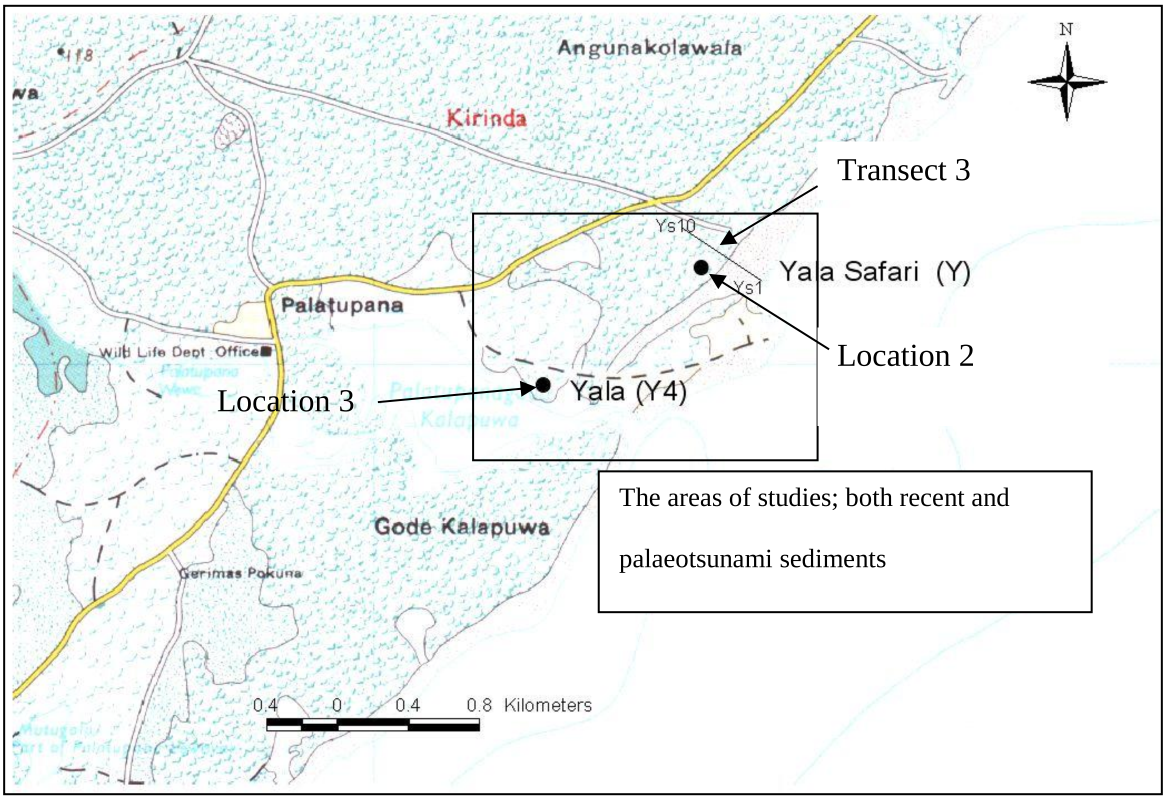


Figure 3.9 Topographic map of Yala area.

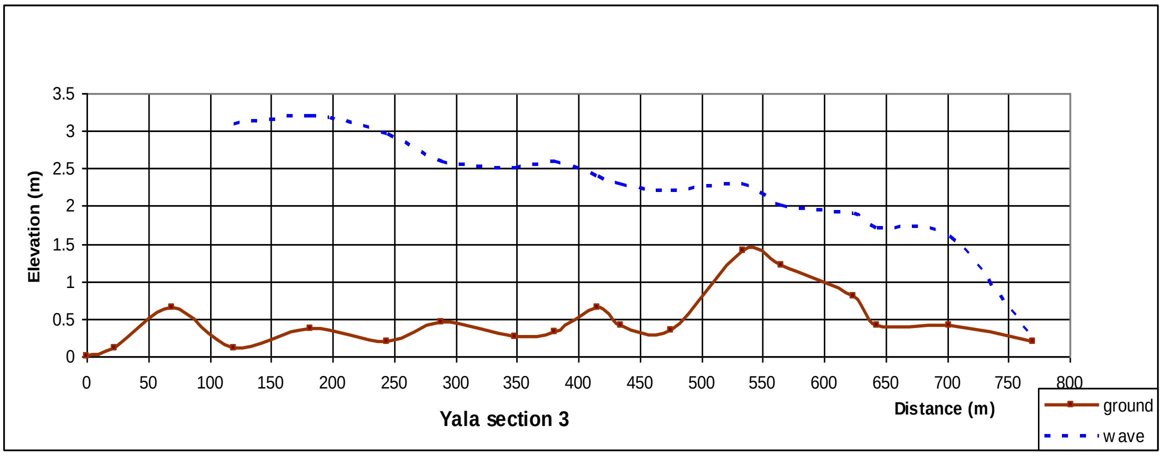


Figure 3.10 Topographic cross section with run up height of the 2004 tsunami along the Transect 3 (Yala).

Transect 4

Location: Katukurunda, Sri Lanka

Geographical Coordinates: 06^0 33.92'N, 079^0 57.70'E

This site is located on a straight coastal stretch on the western coast of Sri Lanka and close to Kalutara lagoon (Figure 3.4 and 3.11). The 2004 tsunami waves caused severe damage to this location. This site is almost flat and presents a lagoon towards the land. A beach over 100m wide is present with a fairly high barrier beach ridge along the shoreline. In this area, about 175-250 m inundation distance, 3-6 m high run ups and 4 waves have been recorded from the 2004 tsunami. The studies were carried out on the sea-side of the lagoon.

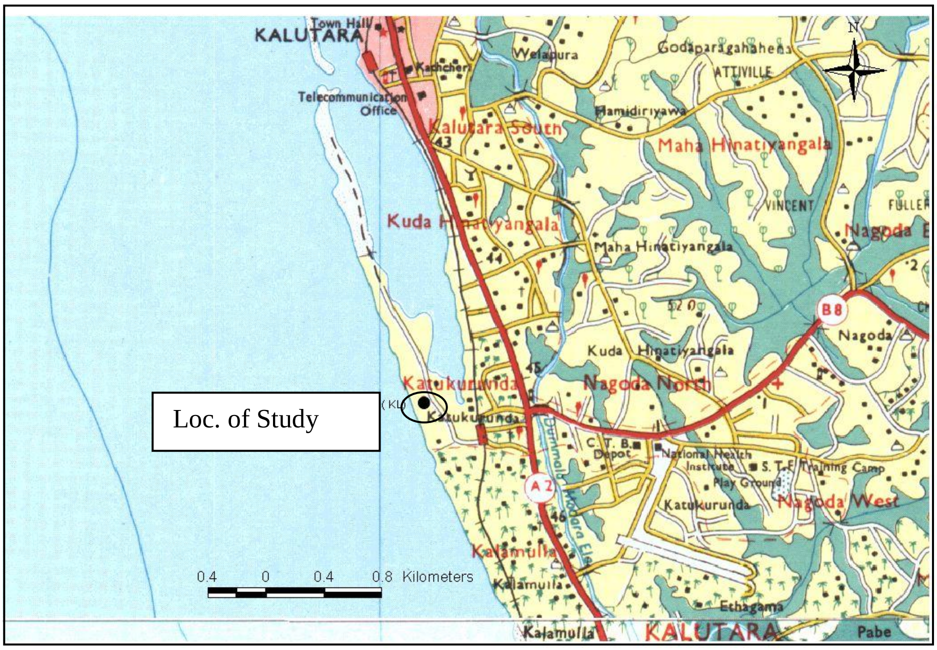


Figure 3.11 Topographic map of Katukurunda area

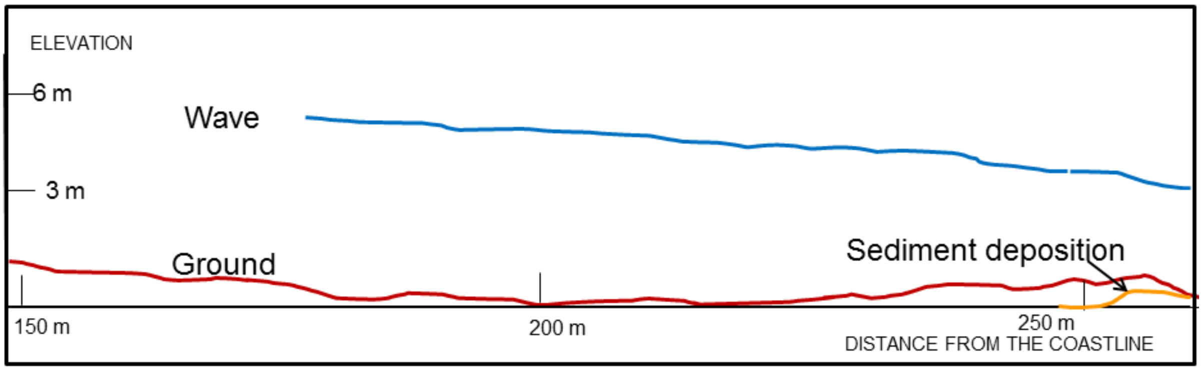


Figure 3.12 Topographic cross section with run-up height of the 2004 tsunami along the Transect 4 (Katukurunda)

3.3 Grain size Statistics analyses

Grain size analyses and statistical analysis were performed for each tsunami sediment sample collected from both the 2004 tsunami and palaeotsunamis. Sediment analyses were performed according to standard method as follows.

About 400-500g samples were collected from each layer and samples were sub-sampled by cone and quartering method and then about 100g were used for the sieve analysis. The samples were fractionated into grain size using standard sieve sizes, described by James and Syvitski (1991). Some sites had extremely fine-grained layers; the 2004 tsunami sediment deposit at Katukurunda samples were studied using a laser grain sizer for grain size analyses using Malvern *Mastersizer X Ver. 1.2b*. Statistical parameters such as mean grain size, standard deviation (sorting index), skewness and kurtosis were determined using the Gradisat software (Blott and Pye, 2001) by means of arithmetic methods as described below.

Mean grain size

$x_a = \sum f m_m / 100$

Standard deviation (sorting index)

$\sigma_a = \sqrt{\sum f (m_m - x_a)^2 / 100}$

Skewness

$sk_a = \sum f (m_m - x_a)^3 / 100\ \sigma_a^{3}$

Kurtosis

$K_a = \sum f (m_m - x_a)^4 / 100\ \sigma_a^{4}$

(f :frequency in per cent, m_m : midpoint of the class in metric)

The correlations and regression among statistical parameters were also studies.

3.4 Palaeotsunami studies

Pits and augur holes were used at three sites for palaeotsunami sediment studies in two locations; Yala and Hambantota where there were huge impacts from the 2004 tsunami. Representative samples were collected from each layer and stored separately for further laboratory analysis.

Site 1

Hambantota lies on the southeastern coast of Sri Lanka (Geographic Coordinates: 06^0 09.23' N, 81^0 1024'E). The site is on a sandy beach adjacent to a marshland, which is used for salt production. The Sand dunes show 2-3 m heights but generally the area is flat ground. The area was severely affected by the 2004 tsunami event. The maximum inundation distance and wave height recorded in the area from the 2004 tsunami were 1500 m and 8 m respectively. The Normal beach sand in the area is rich in garnet and other heavy minerals. A pit (1.5m) was cut on the beach about 175m inland but had to stopped due to reaching the water table (Figure 3.13)

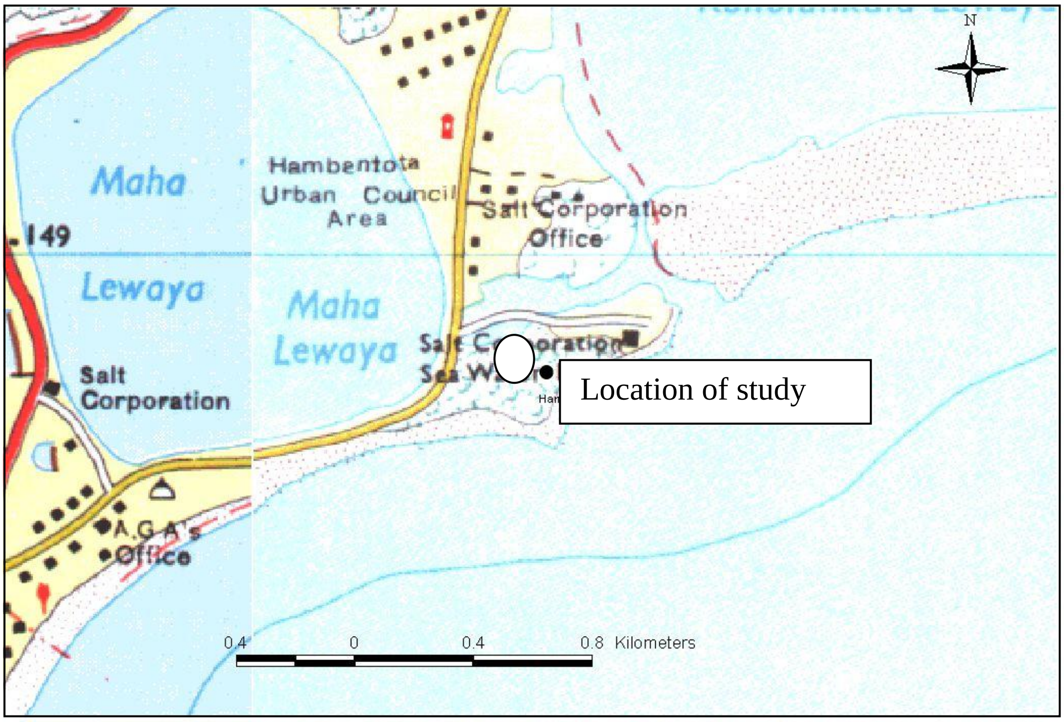


Figure 3.13 Topographic map of the Hambantota area

Site 2

Site 2 was located in the Yala area closer to the Yala Safari Hotel which was destroyed by the 2004 Tsunami. A pit (1.6m depth) was dug at the location which was about 200 m inland and on flat ground (Figure 3.9). The pit had to be stopped due to reaching the water table.

Site 3

Site 3 was also in Yala Area. An augur hole (1 inch diameter) was dug up to 1.5m depth in the Palatupana lagoon (Figure 3.9), and basic sedimentological studies were carried out in the field for samples collected by the augur. However, it was not possible to collect sufficient samples for detailed laboratory analysis due to prevailing shallow water table.

3.5 Micropetrographic and Micro palaeontological analyses

After sieving sediment samples from the 2004 tsunami and palaeotsunamis, 125-500μm fractions of each sample were used for Micropetrographic and Micro-palaeontological analyses. Each sample was dried and mounted on a glass slide using Petroepoxy resin. The sections were observed under a ZEISS Polarising microscope at several magnification powers of 2X, 6.3X, and 25X and observed under both plane and cross-polarized light (PPL). Images were taken for further study using a microscope mounted Canon G5 digital camera. Mineralogical, textural and palaeontological characteristics of each sample (fossils) were studied. Taxa of fossils were based on the foraminifera morphology described by Murray,(1993); Thomas (2005); Dahanayake and Kulasena (2008): University College London (MIRACLE) web site and the Zoological Institute, of the Russian Academy of Sciences web sites (http://www.foraminifera.eu/morphoclass.htm).

3.6 Mapping of Palaeotsunami sediments using GPR technique

In this study, one of the most important aspects was the mapping or tracing of subsurface distribution tsunami sediment layers in the sub-surface geological profile in order to determine the inundation distance of tsunamis and thereby attain an idea of their magnitude. Presently, this is done using auguring, trenching, or cutting pits. However, these methods are very often not applicable due to practical problems such as extensive disturbance to the ground, due to constructions, beach barriers, roads etc., and the high labour, cost and long duration required for these methods. The main intention in this study was the application of appropriate reliable geophysical methods to trace the tsunami sediment layers in the coastal sedimentary profile.

From the field and sedimentological studies, it was observed that structural, textural and mineralogical characteristics differed from other normal beach deposits, which can leads to distinguishable characteristic dielectric properties of tsunami sediments. Also it was observed that tsunami sediment deposits were very thin, mostly in the sub-centimeter to a few centimetres scale and mostly preserved within marshy or lagoonal clayey deposits in the coastal zone. Therefore, a geophysical technique was required which could be capable of application to any ground conditions without excavation. Furthermore, the technique should have appropriate resolution to resolve discrete fine tsunami layers and be an efficient and reliable method for obtaining detailed imaging of the shallow ground profile. Ground penetrating radar (GPR) is a high-resolution electromagnetic geophysical technique which has a wide range of applications for subsurface geological investigations such as sedimentological and stratigraphic studies, burial research, archaeological and environmental studies, hydrological and hydro-geological studies, foundation and geo-engineering studies, tectonics and structural geological studies and most other shallow geological investigations. Due to its numerous military and civil applications the GPR technique has today become a very popular tool for ground investigations, especially for near-surface geological investigation. GPR has become an increasingly popular tool in sedimentological studies as it can provide high resolution 3D profiles of the sub surface (Knight, 2001). The advantages of recently developed GPR systems are that they are light-weight, portable, robust and digital. GPR data can be viewed in real time, allowing both data and its quality to be assessed in the field (Jol and Bristow, 2003) and it can then also be processed and enhanced using appropriate software to enhance the discrimination in the laboratory later.

3.6.1 Basic Theory of GPR Technique

GPR is a very successful too for appropriate geological conditions. However, to fully utilize its capabilities it is essential to understand the limitations placed on it by the Laws of Physics. The energy used in GPR technique is Electromagnetic Energy, which exists as Electromagnetic waves discovered by Hertz in 1886. Radar is the name given to the part of the electromagnetic spectrum which lies between about 10 MHz and 1 GHz, somewhere between TV signals on the low side and microwave ovens on the upper side and with mobile phone frequencies catastrophically right in the middle. Ground Penetrating Radar lies in the same band as Radio, TV and mobile phone communications all of which compete for bandwidth as shown in figure 3.14.

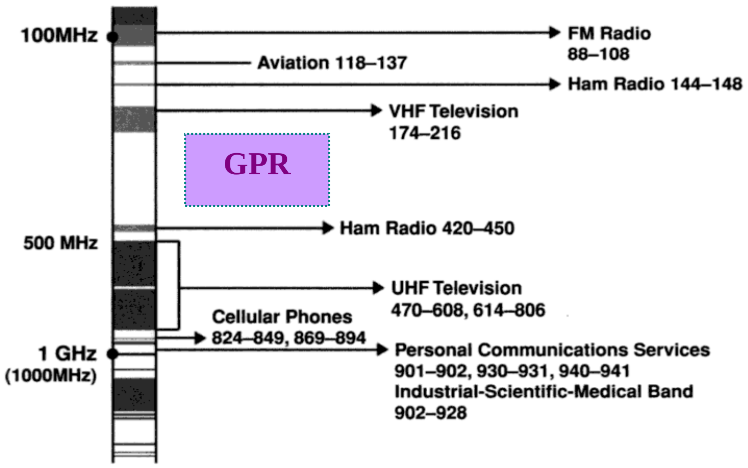


Figure 3.14: Radar band used in GPR techniques and wave bands used for different applications.

Electromagnetic waves penetrate materials because x-rays are used to probe inside bodies, but it probably do not appreciate that not all parts of the spectrum can penetrate far in most materials and that it depends on the frequency of the waves and also the electrical and magnetic properties of the material we are investigating.

The velocity υ of the GPR waves is given by:

$\boldsymbol{\upsilon = c/(\varepsilon_R\mu)^{1/2}}$ (m/s, or more often m/ns),

Where

c is the **velocity** of EM radiation in free space-3.0 x 10^8 m/sec;

$\boldsymbol{\varepsilon_R}$ is the relative **permittivity;**

μ is the relative **magnetic permeability** of the sub-surface materials.

3.6.1.1 Permittivity (εR) or Dielectric Constant

This dimensionless number describes the ability of a material to store and release EM energy in the form of electrical charge. It partly determines the velocity of the GPR wave, as in the equation (1) and is given relative to the value in free air.

Values range from: **1** for air, **3-5** dry sand/rock, **5-20** soils, **15-35** saturated sand/rock and **80** for **fresh** water. Typical values are shown in Figure 3.15.

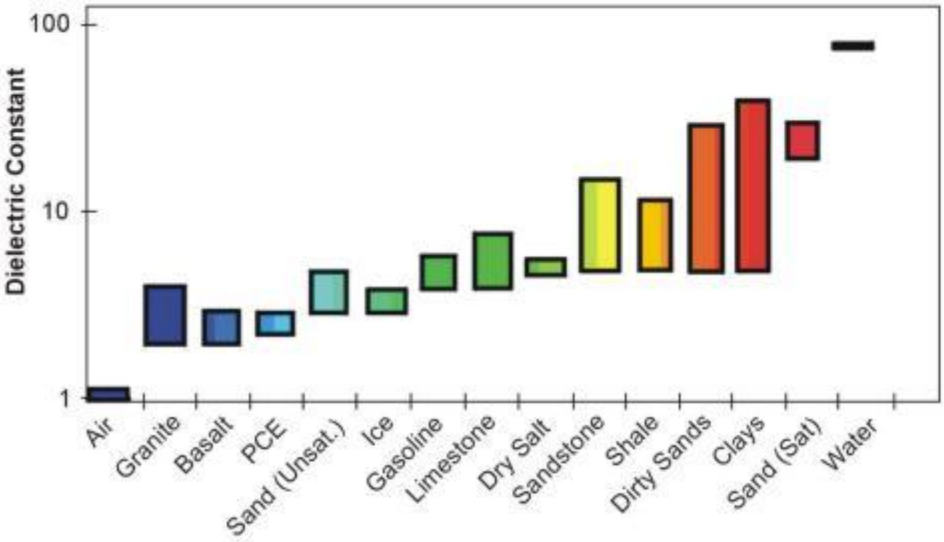


Figure 3.15 Dielectric Constants for a range of common Earth Materials (Courtesy of US Federal Highways Division)

This causes a phenomenon called dispersion of GPR waves – i.e. different frequencies travel at different velocities which causes the pulse to broaden with time and become less capable of imaging smaller size targets.

3.6.1.2 Magnetic Permeability (μ)

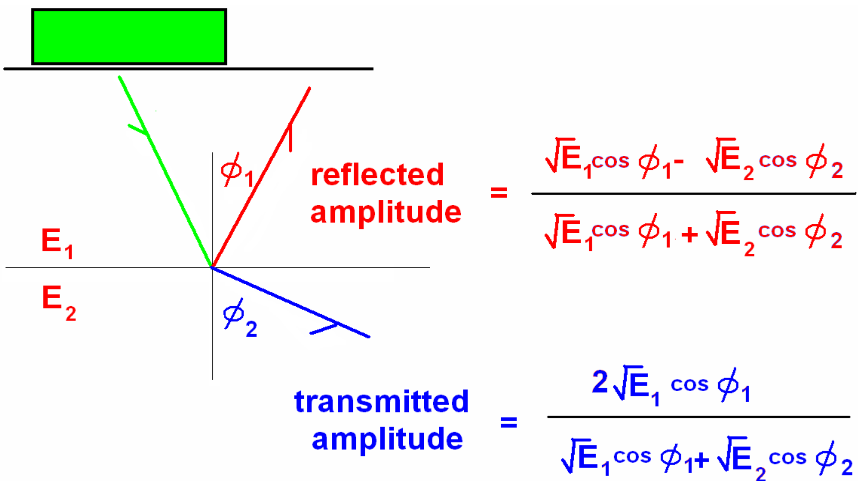
This parameter describes the magnetic response of a material to the GPR wave i.e. how magnetisable the material is. It is very dependent on the mineral content of the rocks and soils. The value is given relative to the free air value and assumed to be very small (i.e. given the relative value of 1) and is dimensionless.

3.6.1.3 Electrical Conductivity (σ)

This parameter, which is the inverse of electrical resistance, describes the ability of the material to transport free electrical charges (electrons, ions, surface charges) under the influence of the GPR wave which is interacting with and attempting to move them. This does not affect the velocity of the radar waves but it causes loss of energy due to charge collisions, resulting in attenuation of the GPR signal. This is the major problem in conductive soils with high clay content which contain conductive minerals or high salt/brine content. Typical values are: **0** for air, **0.01-1** dry sand/rock, **0.1-10** soils, **0.1-1** saturated sand/rock, **0.5** fresh water, **2-1000** clays, **3000** salt water and it is measured in millisiemens/metre (mS/m).

3.6.2 Mechanism of GPR system

The basic mechanism of the GPR system is that high frequency electromagnetic (EM) pulses are radiated into the ground from a transmitter antenna from the surface and the radiated radio-frequency electromagnetic energy which is reflected back to the surface from interfaces of materials having different dielectric properties and energy are recorded using a receiving antenna. EM radiation penetrates into the ground obeying the general physical rules of reflection and refraction theory based on the different dielectric constant (ε) of layers (Figure 3.16).



$$\text{reflected amplitude} = \frac{\sqrt{E_1}\cos\phi_1 - \sqrt{E_2}\cos\phi_2}{\sqrt{E_1}\cos\phi_1 + \sqrt{E_2}\cos\phi_2}$$

$$\text{transmitted amplitude} = \frac{2\sqrt{E_1}\cos\phi_1}{\sqrt{E_1}\cos\phi_1 + \sqrt{E_2}\cos\phi_2}$$

$$\sin\phi_1 = \frac{{E_1}^2}{{E_2}^2}\sin\phi_2$$

Figure 3.16 Reflection and Refraction of EM radiation through different materials.

Electromagnetic waves travel at a specific velocity that is primarily determined by the electrical permittivity of the material. The relationship between the velocity of the wave and material properties is the fundamental basis of the GPR imaging technique. The travel-time in GPR surveys is measured in nanoseconds (1ns = 10^{-9} s). The approximate travel time of electromagnetic waves in air is 3.3333nm/s. The velocity of EM waves is inversely proportional to the square root of the permittivity of the material.

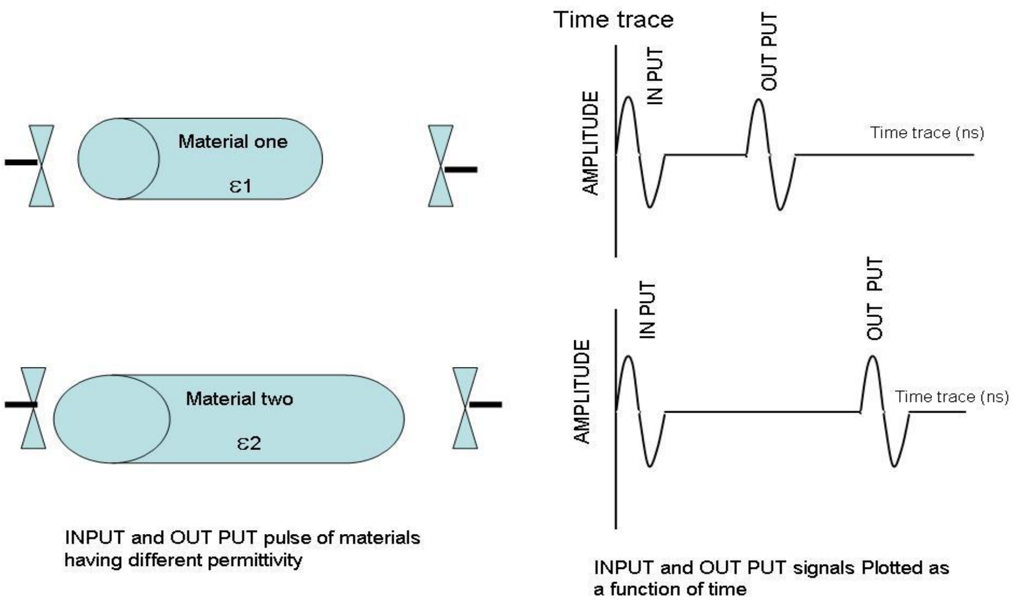


Figure 3.17 EM signals showing travel times of different materials.

A pulse of radar energy is generated from a dipole transmitting antenna that is placed on the ground surface. The resulting wave of electromagnetic energy propagates downward into the ground, where a portion of it is reflected back to the surface whenever it encounters a discontinuity in the ground due to a geological boundary, a buried object or different materials where there is a change of electrical properties or dielectric constant. This is dependent on the composition, porosity and moisture content of the materials. The penetration depth of the radar energy is also controlled by the frequency of the radar energy transmitted. There is a range of antennas which have standard central frequencies ranging from 10 to 1000Mz.

GPR systems can be deployed in three basic modes such as reflection profiling, velocity soundings and trans-illumination. Reflection profiling and velocity sounding are two most common form of GPR surveying in sedimentary environments while trans-illumination is the basis of GPR tomography.

3.6.3 Field Data Acquisition using GPR system

The equipment consists of a generator and receiver of radar pulses and in essence, that is all there is to it. Pulses propagate out from an antenna as polarized electromagnetic pulses with an orientation; i.e. they travel in one particular plane and are then modified by the subsurface and travel back either as reflections from interfaces or as energy scattered from discontinuities in EM properties and are received on another polarized antenna (Figure 3.18).

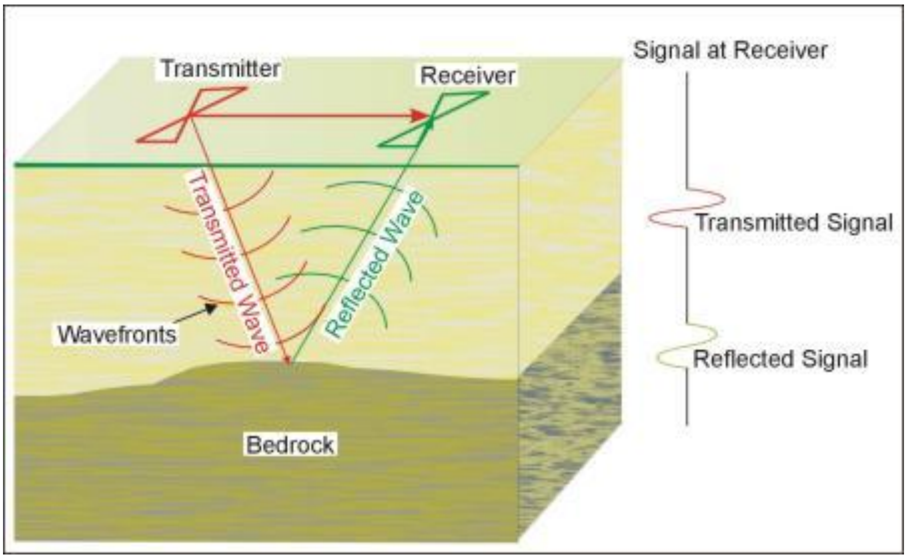


Figure 3.18. Basics of GPR surveying (Courtesy of US Federal Highways Division)

The equipment can be used to acquire data along profiles (giving sub-surface cross-sections) or the profiles can be combined to give coverage of a surface area which will translate into a volume of the sub-surface.

The signal received by the GPR receiver is the train of reflected pulses. Figure 3.19 illustrates the two common acquisition modes: common offset and common midpoint. The typical mode of operation is the common-offset mode where the receiver and transmitter are maintained at a fixed distance and moved along a line to produce a profile. Note that the energy does not necessarily only propagate downward and a reflection will be received from objects off to the side. An added complication with GPR is the fact that some of the energy is radiated into the air, if reflected from above the ground from objects such as street furniture or nearby objects like buildings or support vehicles and will appear on the record as arrivals. The Common Midpoint mode is sometimes used to determine the velocity of propagation within the ground in a similar way to seismic reflection interpretation (Figure 3.19 and 3.20).

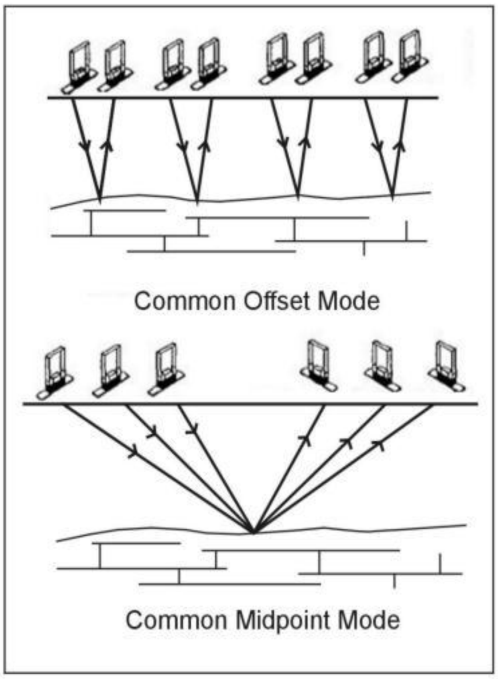


Figure 3.19. Different collection geometries from profiling (Common Offset) and for velocity determination (Common Mid-point) (Courtesy of US Federal Highways Division)

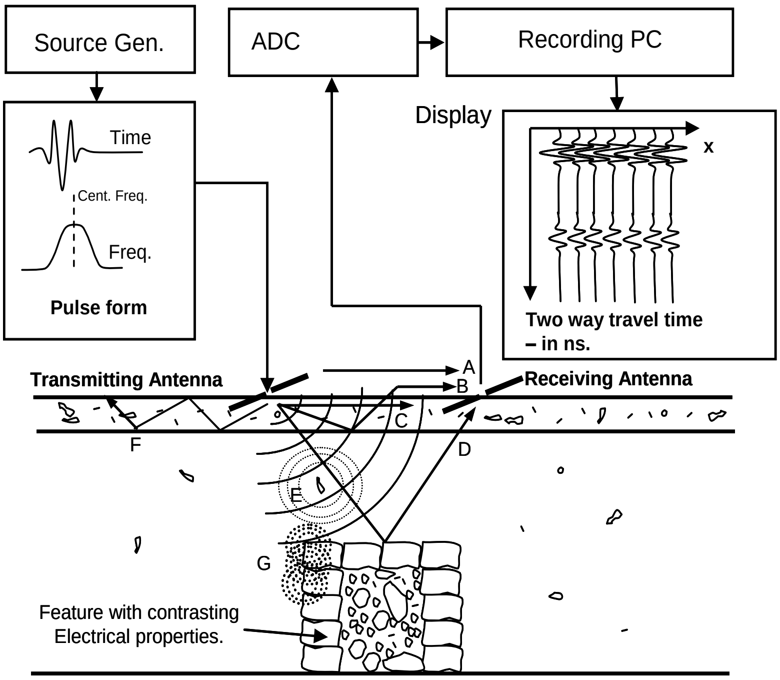


Figure 3.20 Causes of reflections and their typical signatures.
Wave Types: A – Cross antenna leakage, **B** – Refracted air wave, **C** – Direct ground wave, **D** – Reflected wave, **E** – scattered signal, **F** – Multiple reflection, **G** – Diffractions from sharp features in wall

3.6.4 Application of the GPR technique for palaeotsunami sediment mapping

Geological and sedimentological studies reveal that tsunamigenic deposits are confined to certain specific locations on the coastal zone and they have varying thicknesses within continuous or discontinuous sheets or layered deposits. These deposits are preserved within coastal sediment sequences or in low-lying marshy clay beds. The dielectric constants of these sediments were found to differ sufficiently from the surrounding normal beach and lagoonal sediments to provide significantly large EM reflections at the layer boundaries to enable them to be traced using GPR. The lateral extent of the tsunamigenic deposit is a good proxy for determining the magnitude of palaeotsunami events. Recent successful applications of GPR for mapping quaternary deposits and several types of coastal sand deposits are described in many studies (Botha *et al*., 2003; Havholm *et al.*, 2003; Heinz and Aigner, 2003; Jol and Bristow, 2003;Woodward *et al.*, 2003). However, the present work is the first application of GPR for mapping tsunamite deposits.

3.6.5 Dielectric properties Tsunami sediments

The samples collected from a coastal sedimentary profile at Yala, south east coast of Sri Lanka; the samples included a 1.5 m thick complete sequence of both the identified tsunamigenic and non-tsunamigenic layers. These samples were tightly packed into a beaker and the dielectric properties were measured for the fixed percentage of water content. Two sets of samples: dry and 25% wet were tested. This standard set of measurements provided values of the sediment dielectric constant (k) along with lower and upper error limits. To assess EM wave propagation in such sediments EM velocity (m/ns), Loss Tangent, Attenuation (dB/m) were also calculated. Wet samples were used, because the natural conditions of samples were not preserved, when the samples were tested. Two readings were taken for each sample at two locations in the packed beaker. Finally, the radar reflection coefficient at each sediment layer boundary was calculated using equation below.

$$_1R_2 = (\sqrt{k_2}-\sqrt{k_1}) / (\sqrt{k_2}+\sqrt{k_1})$$

Where k_1 and k_2 are measured dielectric constants of adjacent sediment layers one and two.

3.6.6 GPR survey on the Sri Lankan coast for Palaeotsunami studies; locations and methodology

Four GPR surveys were conducted on the southeast, south and the west coast of Sri Lanka, where two sites (1 and 2) were confirmed as palaeotsunami sediment records using excavations and laboratory analyses. The other two sites (3 and 4) were lacking in ground truth data or other evidence for palaeotsunami records (Figure 3.21).

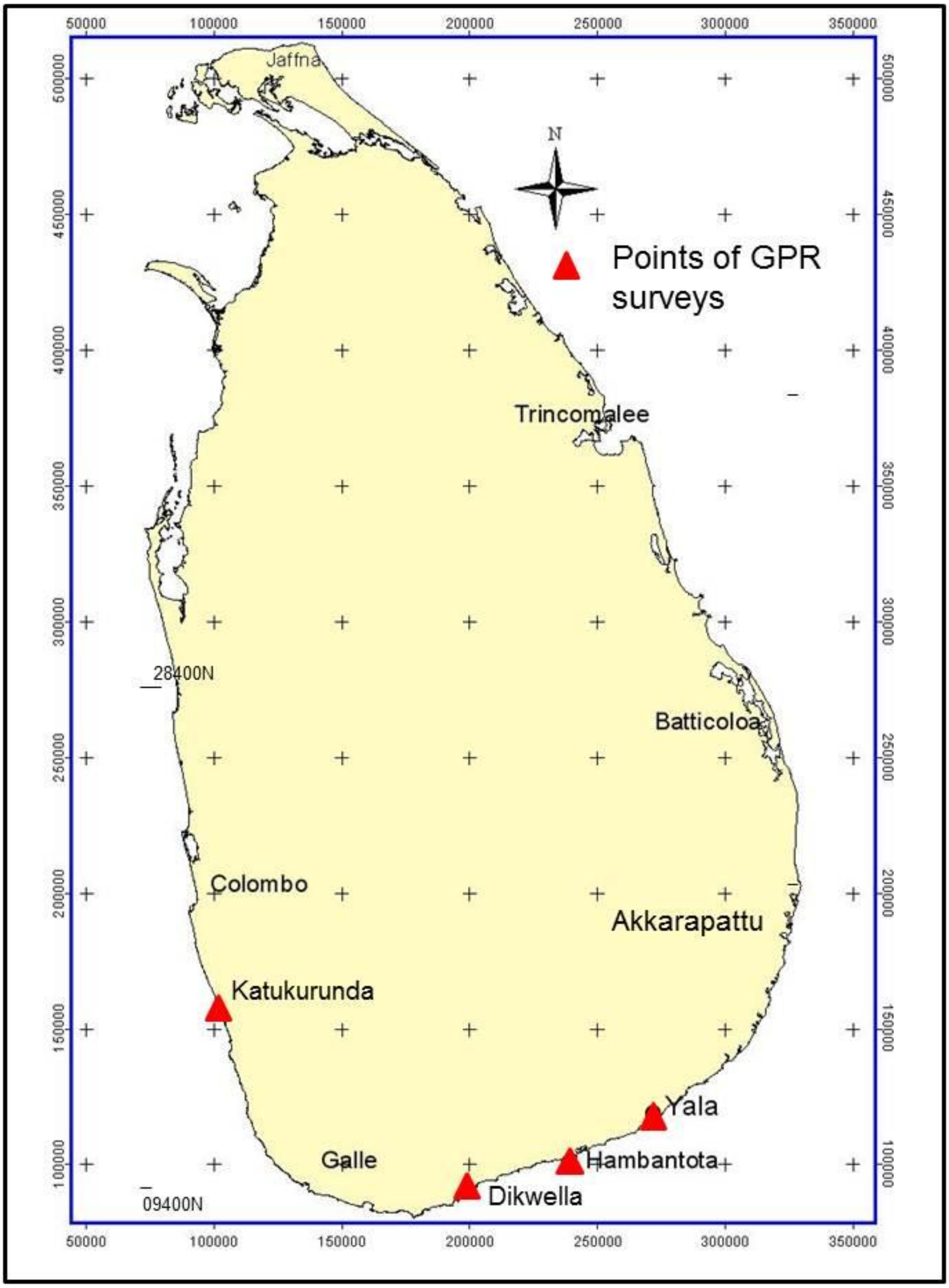


Figure 3.21 Map showing locations of the GPR surveys on the Sri Lankan coast.

(Site 1: Yala, Site 2: Hamabantota, Site 3; Dikwella and Site 4: Katukurunda)

3.6.6.1 Field work

GPR traverses were planned normal to the coast line at each site. The data was collected at step intervals of 2.5 and 5cm using a PulseEkko PE1000 GPR system with 450 and 900 MHz antennas. At sites 1 and 2, traverses were planned close to previously excavated sites for geological studies and sites 3 and 4 were on marshland and sandy beach respectively.

Site 1 Yala southeast coast of Sri Lanka

A GPR traverse was set out normal to the coast up to 300 m inland. The traverse was closer to the previously studied palaeotsunami profile of Yala Safari hotel land (Figure 3.9).

Site 2 Hambantota, southeast coast of Sri Lanka.

Three parallel GPR traverses were set out in this site and the length of each traverse was 50m. The site is also close to the previously studied palaeotsunami site of 175m inland (Figure 3.13).

Site 3 Dikwella, the South coast of Sri Lanka

A GPR survey was carried out in a marshland close to the sea on the southern coast of Sri Lanka (Figure 3.21). In this site there was no evidence for palaeotsunami sediment deposition form other studies. The site is about 100m inland and 30m traverse was set out.

Site 4 Katukurunada (Kalutara), the West coast of Sri Lanka

This site was located on a wide beach where the 2004 tsunami caused severe damage to this area (Figure 3.11). A few centimetre thickness of the 2004 tsunami sand deposit could be observed at this site but there was no evidence for palaeotsunami from other studies.

3.6.7 GPR data processing and interpretation

GPR data collected from all four sites were processed with a standard method using following major steps.

1 Time zero correction.

2) Bandpass filter – to cut-off of 50MHz and upper of 1000MHz).

3) Diffraction stack migration (to collapse hyperbola) based on a diffraction matching-function over 12 traces with a uniform velocity of 0.11 m/ns

4) A user-based gain function (quasi-exponential) was applied for the visual enhancement of the deeper features.

5) Geological boundaries were traced using visual observation and based on reflection coefficient values with the help of ground truth data.

3.7 OSL analysis and Tsunami sediment dating

Proper dating of palaeotsunami sediments is the key factor in finding tsunami recurrence interval. Tsunami sediment dating is challenging due to the wide range of sediment ages from a few hundred to millions of years. A number of techniques are available for sediment dating such as radiometric dating, Luminescence, Cosmogenic nuclides and palaeomagnetic dating. Here I provide a brief comparative review of the methods and justify our choice.

Carbon dating (^{14}C) thermo-luminescence (TL) and optically stimulated luminance (OSL) techniques are most commonly used for recent sediment dating. They are the most feasible and reliable techniques in recent quaternary sediment dating. Because each technique has different accuracy levels, relies upon different physical mechanisms and procedures, applies to different types of materials, employs different sampling, preparation methods and conditions of testing, there are some specific advantages and restrictions and limitations for each technique. For example, the.^{14}C technique uses organic material within the sediment: the ^{14}C fraction of this organic material declines at a fixed exponential rate due to the radioactive decay of ^{14}C, and by comparing the remaining ^{14}C fraction of a sample to that expected from atmospheric ^{14}C the age can be determined. This method is not reliable for recent sediment deposits due to the small period of time over which decay has occurred and the error factor (the standard deviation) may be larger than the date obtained (Richter et al., 2009). Carbon dating cannot be used for inorganic sediments. Also there are many problems which may occur when use C dating such as mixing or reworking of surrounding plant materials, uncertainty about data materials and tsunamites and lack of plant materials within the tsunamite deposits (Huntley and Clague, 1996). In natural conditions the background ionizing radiation is absorbed and stored by sediments in the crystal lattice. This stored radiation dose can be evicted with stimulation and released as luminescence. Luminescence dating (TL and OSL) measures the energy of the photons being released which is proportional to the time since the last exposure to sunlight or intense heat. In OSL and TL techniques, minerals (crystal grains) such as quartz, feldspars etc. are used for the analysis and they have better accuracy levels (Murray and Wintle, 2000).

3.7.1 Thermo Luminescence Technique (TL)

The TL technique relies on the bleaching of crystal grains due to exposure of the sediment grains to sunlight before their deposition. Generally, crystalline mineral materials emit TL signals when they are subjected to progressively increasing temperature. Therefore, during the transportation of sediments prior to their deposition, they may be exposed to sunlight, which causes bleaching of the signal. After deposition, their latent thermal-luminescence slowly regenerates as the material shielded from the light, responds to ambient levels of ionising radiation (Richter *et al.,* 2009). Thus the present-day TL intensity of the sediment reflects both the environmental radiation level and the length of time since deposition. By measuring the TL and radiation intensities, the age of the sediment may be deduced. In this technique a crucial factor is that individual grains are adequately exposed before deposition (Shlukov and Shakhvets, 1986).

3.7.2 Optically Stimulated Luminescence (OSL) techniques

Luminescence dating is based on the time-dependent dosimetric properties of silicate minerals, predominately feldspar and quartz (Bos and Wallinga, 2009). The technique has been used to date sediments usually < 200, 000 old that received sunlight exposure prior to deposition (Hashimoto *et al*., 1986). Exposing sediment to sunlight for hours or heating to >300 ºC eliminates most of the previously acquired luminescence from mineral grains (Bøtter-Jensen and Murray, 2001). After the sediment is buried and shielded from further light exposure ionizing radiation from the decay of naturally occurring radioisotopes of U, Th, and K produces free electrons which are subsequently trapped in crystallographic charge defects in silicate minerals (Helen *et al.*, 2009). Excitation of minerals by heat or light yields in recombination of stored-charge those results in luminescence emissions. The intensity of the luminescence is calibrated in the laboratory to yield an equivalent dose (De, measured in grays (Gy); 100 rads = 1 gray), which is divided by an estimate of the radioactivity that the sample received during burial (dose rate, Dr) to render a luminescence age (Wallinga, 2002).

The OSL techniques is quite similar to the TL technique, as the amount of bleaching of optical luminescence before deposition and its regeneration during the burial time is used to date the sediments (Botter-Jensen and Murray, 2000). The key advantage of OSL over TL technique is that the luminescence of the quartz and feldspar grains is reduced to a low definable level after only a few minutes of sunlight exposure whereas TL need hours of exposure (Godfrey-Smith *et al*., 1988). Another advantage of the OSL technique is that it can be used for a wide range of wavelengths such as blue, green infrared, rapidly releasing the most sensitive trapped electrons from the crystal lattice. Therefore, the OSL technique is good for dating various types of sediments from 0 to 150,000 years. Therefore, OSL has become a very popular technique in quaternary sediments dating especially for aeolian, fluvial, marine and colluvial sediments (Shen *et al*., 2007; Li *et al*., 2007; Shen *et al*., 2007; Schaetzl and Forman, 2008).

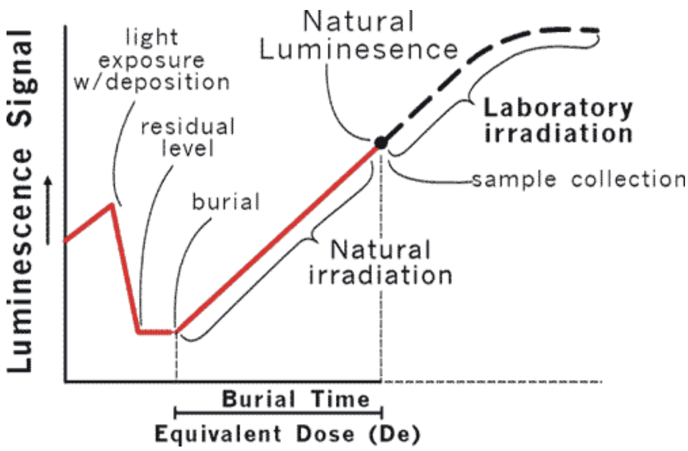


Figure 3.22 Mechanism of OSL dating

3.7.3 Principle of OSL Dating

When sediment is buried, the effects of the incoming solar radiation are removed. With this bleaching effect removed this result in the accumulation of a signal within individual mineral grains (most commonly quartz and feldspars). It is this signal that is the key to luminescence dating techniques (Figure 3.22). Given an estimate of the rate of received ionizing radiation and knowing the total accumulated dose (the palaeodose) it is possible to derive an age since burial (Murray and Wintle, 2000).

Luminescence Age = Equalling Dose (De, Grays) / (a $D_{\alpha}W + D_{\beta}W + D_{\gamma}W + D_c$)

W - water content factor,

De - equivalent dose (De, measured in grays (Gy); 100 rads = 1 gray)

a -alpha radiation attenuation coefficient

D_{α} - alpha radiation contribution to dose rate

D_{β} -beta radiation contribution to dose rate

D_{γ} -gamma radiation contribution to dose rate

D_c - cosmic radiation contribution to dose rate

Currently two major analytical approaches are available that translate the time-stored luminescence to an equivalent dose, and thus to an age. The multiple aliquot additive dose method (MAAD) is used principally on the fine-grained polymineral or the quartz fraction. This method applies additional doses (beta or gamma) to the natural luminescence on separate aliquots of the sample effectively building a dose response curve, simulating future dose and interpolating an equivalent dose to the solar reset level. MAAD is a method that was original developed for TL dating and in largely unaltered form is currently used in OSL analysis (Richter *et al*., 2009). Numerous studies indicate the robustness of this procedure because it has yielded ages in agreement with other chronologic control for at least the past 100,000 years.

The other method is the single aliquot regeneration method (SAR), which determines an age for each aliquot by matching a regenerated signal from the light reset level to the original natural level, while compensating for apparent sensitivity changes. This technique is used on both fine (4-11µm) - and coarse (100-300 µm)-grained fractions containing mono- or poly-mineral separates. The SAR method is particularly useful for sediments < 50,000 old and provides decadal scale resolution for dating sediments (Wellinga, 2002).

Here I have used the OSL technique, since it is the most suitable technique for dating tsunami sediments which are deposited under rapid conditions, and consist mainly of quartz and feldspar sand. Furthermore our required time period is from the very recent (hundreds of years) to thousands of years (Hutt *et al*., 1988; Huntley *et al*., 1985).

3.7.4 Measures to be used in collection of sediments for OSL

Sampling sediment for OSL dating is relatively straightforward though care should be exercised against inadvertent light exposure and the appropriate stratigraphic unit is sampled. It is advised against sampling at night or under a tarp where uncertainty exists on what sediment is sampled. However, following procedure has been explained for the sediment sampling for OSL dating (http://www.uic.edu/labs/ldrl/collection.html).

Weathered horizons exhibiting pedogenic accumulations of iron, clay, silt, carbonate or silica should be scrupulously avoided. Post-depositional weathering detrimentally affects the luminescence time-signal by altering the radionuclide concentration, disrupting the crystal structure of the mineral and by translocating or bioturbating in younger sediment particles. Ideally, at the sampling site, at least 30 cm of homogeneous sediment should surround the collected strata to maximize uniformity in the dose-rate environment. Sampling within 30 cm of boulders or the surface should be avoided to obviate potential inhomogeneities in radioactivity.

Approximately 10-30 g of sediment should be collected, though more or less may be adequate depending on the concentration of the chosen particle size for luminescence dating. Geological OSL of sediment is reduced with brief (<10 seconds) exposure to sunlight, thus great care must be taken to expose the analysed aliquot to no light. It is best to take the sediment intact for OSL.

If the sediment is coarse grained (>2mm), hardened or excessively dried out a variety of other techniques are employed. Cohesive sediment can be sampled by cutting out a block and wrapping it in aluminium foil or by placing in a tin: an internal non-light exposed sample can be analysed. The serrated end of the can is tightly closed with aluminium foil and duct tape. This is a particularly effective method for sampling coarse-grained colluvium. It was recommended that additional 10-20g sample be taken from the same sampled layer for dose rate, mineralogical and granulometric analyses; this sample does not have to be shielded from light exposure.

3.7.5 Sample Collection for OSL analyses of the present study

In the present study, I applied a technique for collecting samples according available methods in the literature. Samples were collected from each suspected tsunamigenic layer at two sites where detailed study was carried out: Hambantota and Yala. It was necessary to collect samples for OSL dating without exposing them to sunlight. I used dark polyvinyl tube (12cm length and 5cm diameter) as sample containers and the sample was collected directly into the tube while inserting the tube horizontally into the geological profile (Figure 3.23), and both ends of the tube were shielded immediately. Thereafter, the samples were analysed at the Oxford University Luminescence Dating Laboratory using the method explained as Single-aliquot procedures (Murray and Wintle, 2000).

Figure 3.23: Sediment sampling for OSL analysis.

CHAPTER 4

GEOLOGICAL RECORDS OF THE 2004 SUMATRA TSUNAMI AROUND THE SRI LANKAN COASTS

4.1 General introduction to geological records of the 2004 tsunami around the Sri Lankan coast.

The most destructive natural hazard of the known history of Sri Lanka is the 2004 tsunami, which affected a stretch of over 1000 km on the East, the South and the West coasts. From which, significant geological signatures and sediment depositions were found to be confined to small parts of the coast. These tsunami geological signatures and sediments on the Sri Lankan coast store vast amount of potentially valuable information about tsunamis affecting Sri Lanka and the whole Indian Ocean. However, some of the records were disturbed or moved out, especially on the highly populated western and southern coasts during the clearing of the debris and development and rehabilitation works in the aftermath. Nevertheless, some records which are sufficient to enable scientific studies were preserved and several studies were carried out to attempt to understand the tsunami event (Liu *et al.*, 2005; Richmond *et al.*, 2006; Goffredo *et al*., 2007; Dahanayake and Kulasena, 2008 ; Morton *et al*., 2008). In the present study, detailed geological study based on both field and laboratory were carried out to establish a signature for tsunami sediments deposited on the Sri Lankan coast by the 2004 tsunami.

4.1.1 The regional pattern of sediment deposition on the East, the South and the West coasts

The sediment deposition pattern around the Sri Lankan coast varied strongly; crucially, with no obvious dependence on wave height, inundation distance or number of waves. Overall, along the West coast significantly less sediment deposition was observed and exceptionally high sediment deposition compared to all other coastal areas was recorded for a small part of the southeast coast. Only at a few places on the east coast was noticeable sediment deposition observed, from a few centimetres to a maximum 16 cm at one location. The maximum 30-35 cm thick deposits were found on the southeast coast, along the Yala National Park. Previous studies have shown that coastal topography plays a key role in tsunami sediment deposition (Shi *et al*., 1995; Bahlburg and Weiss, 2007; Hori *et al*., 2007; Srinivasalu *et al*., 2007) .

The east coast of Sri Lanka is more or less flat with the presence of a few sand dunes. The southeast and south coasts very often show irregular topographic settings, represented by small hillocks, rocky outcrops, lateritic ridges, and sand dunes. Generally, the west coast has flat topography, with a small number of lateritic ridges and sand dunes. However, most of the natural topography on the west coast has not been preserved due to high population density and corresponding intense human activities. The western coastal stretch is mostly covered by buildings (hotels, residential houses and commercial edifices), roads and railways and cities. All of these factors affected tsunami sediment deposition pattern on the coast.

4.2 Analysis of the 2004 tsunami wave action and Sediment deposition around the Sri Lankan coast (in three sections)

4.2.1 Section 1; along the East coast

The eastern coast was mostly affected by the direct waves of the tsunami and the greatest inundation distances up to 1800m and maximum run up heights up to 14m were recorded. Generally, 2-4 cm thick sediment deposition was observed for most of area while a few locations showed over 10 cm thick deposits. Most of the sediment brought by the incoming tsunami waves was washed away by backwash flow. Thus the eastern coastal zone has flattened topography and planar beaches with most sediment washed back (Figure 4.1). Commonly, three waves arrived on the east coast, but at a few locations, four waves were recorded, which may be due to local phenomena like diffraction, refraction or reflection.

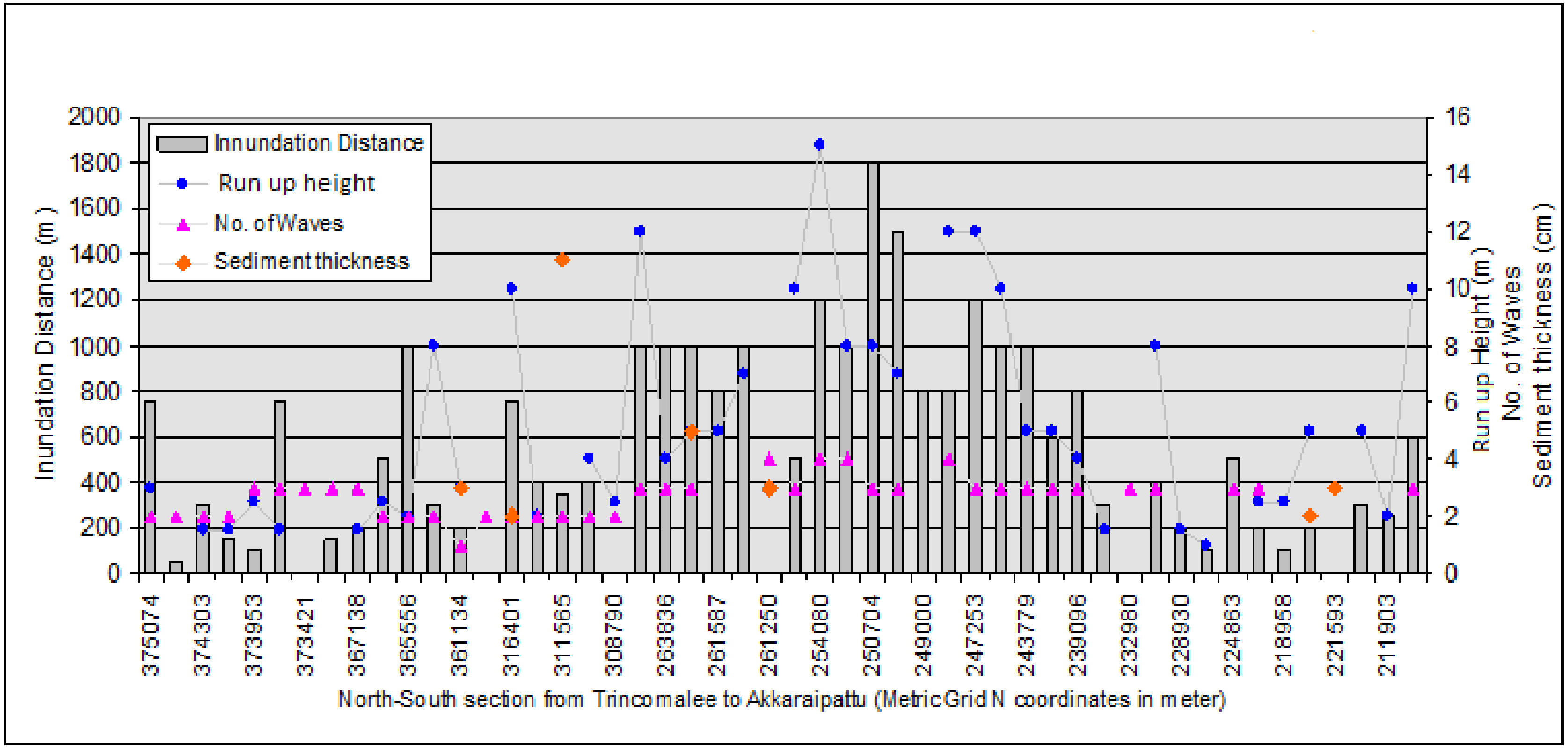


Figure 4.1 Relationship between run up height, inundation distance, number of waves and sediment thickness along the east coast (Section 1); Source unpublished report of Geological Survey and Mines Bureau, Sri Lanka.

4.2.2 Section 2; along the South coast

The southern section shows a clear trend of inundation distance and sediment deposition from the East to the West. The eastern part of the section shows a greater inundation distance than the West and also exceptionally high sediment deposition compared to all other parts. Run up heights were also significantly higher towards the east. The orientation and the coastal topography of the southern coast played a significant role in tsunami inundation and the sediment deposition patterns. The southeast part of the coast was mostly affected by direct waves and refracted waves. The coastal topography is composed of ridges, small hills, sand dunes having flat topography and some bays and headlands representing quite a complexity of coastal geomorphology. Therefore, the tsunami effect varied widely along this coast from the East to the West. Commonly, two waves were recorded on this section while three waves were recorded at a few places from different wave effects such as combined waves (direct, refracted and diffracted waves caused by bays and headlands); for example Galle city. However, sediment deposition shows a significant anomaly with deposition of over 30 cm deposits only occurring on a part of the southeast coast. Towards the West, sediment deposition is almost completely missing (Figure 4.2).

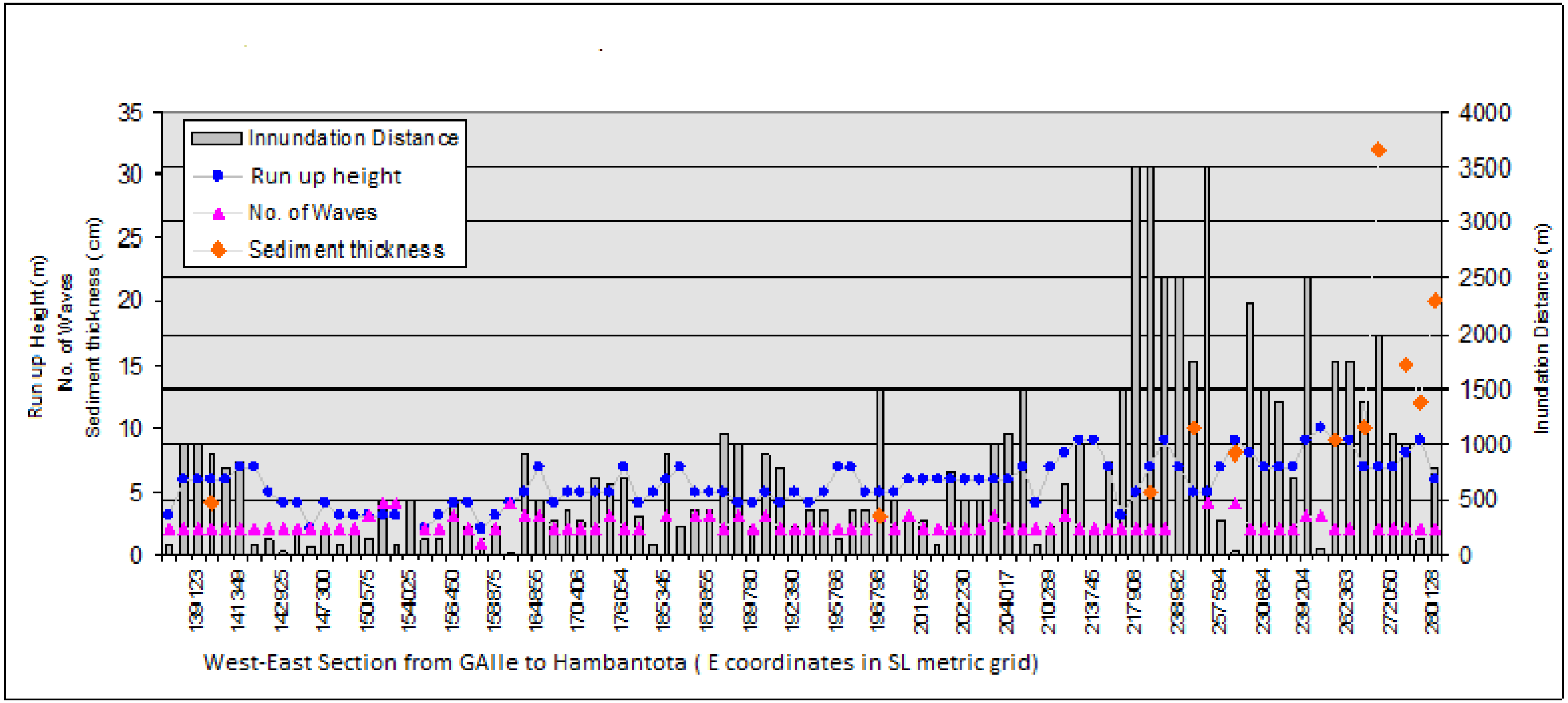


Figure 4.2 Relationship between run up height, inundation distance, number of waves and sediment thickness along the south coast (Section 2). Source unpublished report of Geological Survey and Mines Bureau, Sri Lanka.

4.2.3 Section 3: along the West coast

The West coast of Sri Lanka was in the shadow of the direct tsunami wave front but most of southern part was greatly affected by the tsunami. The southwest part was affected by combined (diffracted and refracted), reflected and direct waves. Inundation distance and the run up heights show a decreasing pattern from the South to the North. Greater inundation distances (shown in the northern part of the section) occur at river mouths. Two or three waves hit this coastal section, but a few locations have recorded four waves. Generally, very much less sediment deposition was observed on the West coast, mostly only a few centimetres. But at one location (Kalutara South) a thick deposit, of over 16 cm was recorded (Figure 4.3).

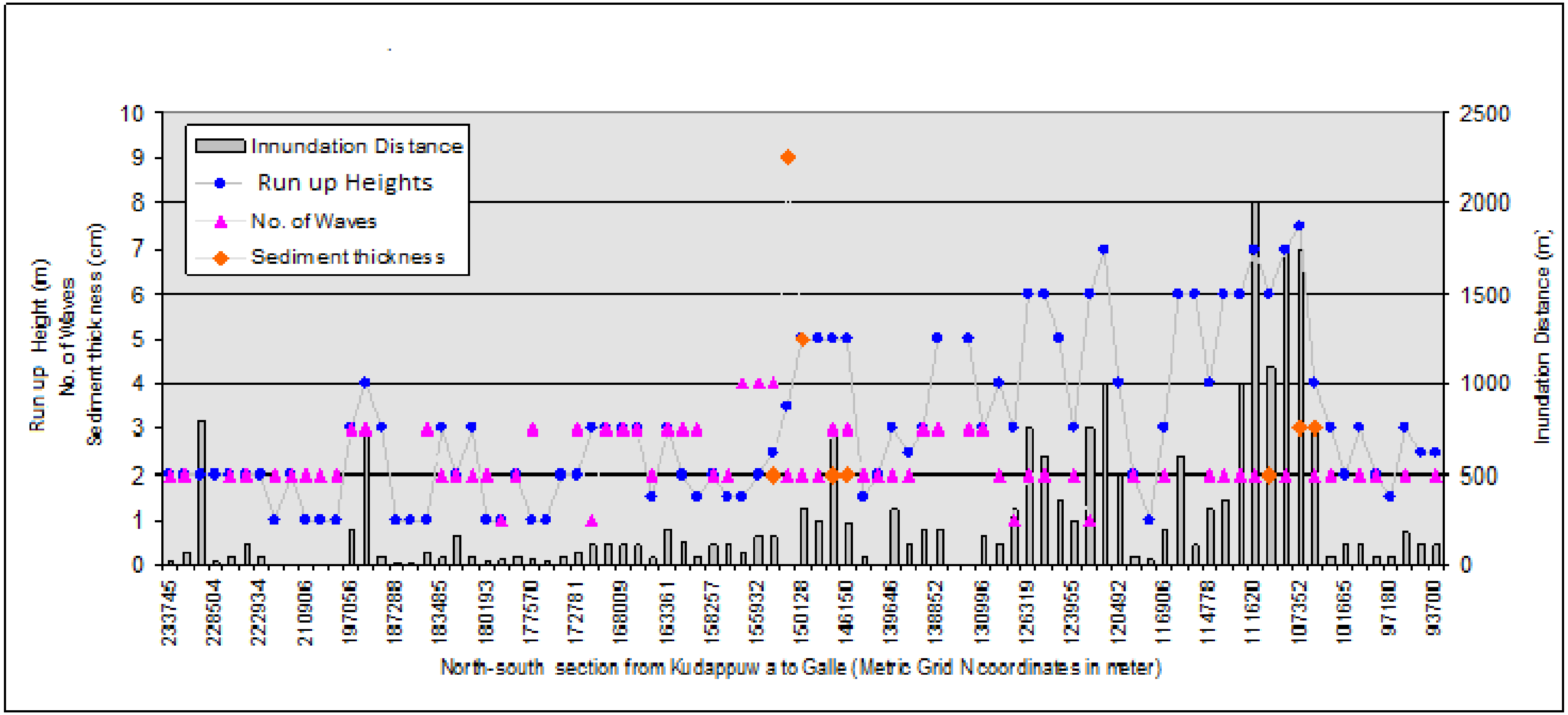


Figure 4.3 Relationship between run up height, inundation distance, number of waves and sediment thickness along the west coast (Section 3).
Source unpublished report of Geological Survey and Mines Bureau, Sri Lanka.

Table 4.1 Maximum inundation distances, run up heights, number of waves and sediment thicknesses of the East, the South and the West coasts of Sri Lanka; Source data from unpublished report of Geological Survey and Mines Bureau, Sri Lanka (2005).

Coast		East	South	West
Inundation distance (m)	Maximum	1800	3500	1750
Run up height (m)	Maximum	15	10	7.5
Sediment thickness (cm)	Maximum	11	32	16
Number of waves	Maximum	4	4	4

4.3 Geological records left by the 2004 Tsunami waves on the Sri Lankan coast

As in other parts in the world, the 2004 tsunami left many geological records on the Sri Lankan Coast. Mainly the records could be recognised as depositional and erosional features.

4.3.1 Erosional features

As mentioned in the literature review, the first part of the coast, up to about 50-75 m from the shoreline is subject to erosion rather than deposition by tsunamis. This was clearly observed after the 2004 tsunami around the Sri Lankan coast (Figure 4.3)

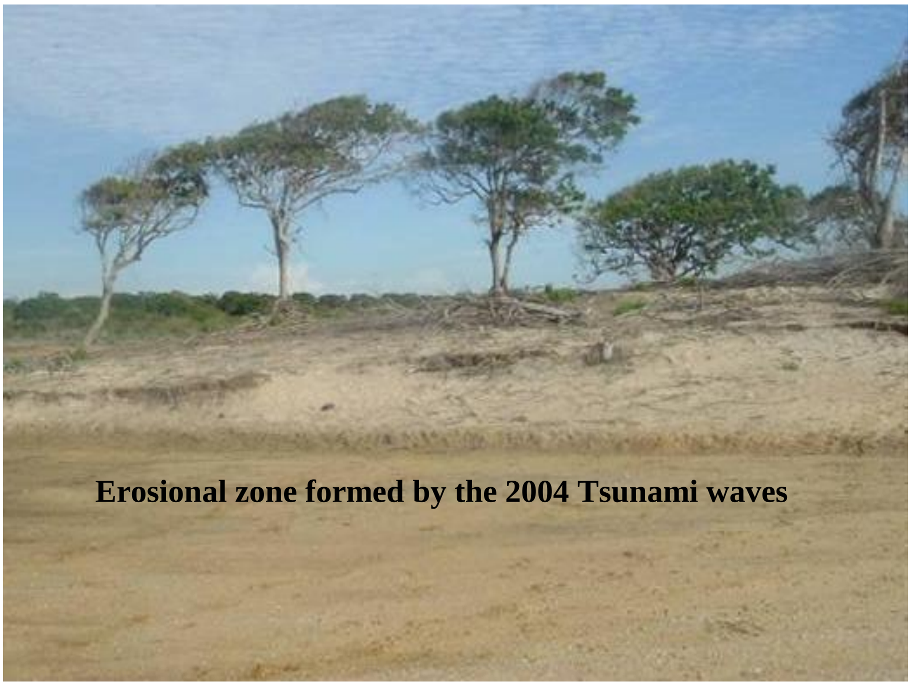


Figure 4.4 Erosional land forms from the 2004 tsunami on the Sri Lankan southern coast.

4.3.2 Depositional Features

Tsunami waves deposit various types of tsunami deposits such as clay, silt or sandy deposits, very coarse boulder deposits and other tsunami-transported debris deposits. On the Sri Lankan coast sand and some boulders were deposited in many parts on the coast by the 2004 tsunami waves.

Characteristically, the most common signatures preserved in tsunami deposits are sandy or fine deposits which have layering or lamella with textural differences, rip-up clasts and sheet-like deposits which extend long distances inland from the coast with erosive lower contacts, sandwiched between marshy, clayey beds or between peaty layers (pre-tsunami and post-tsunami). According my field observation, tsunami sand deposits left by the 2004 tsunamis on the Sri Lankan coast show most of the above features such as layering; rip up clasts, erosive lower contacts and fining-landwards sand deposition (Figure 4.5).

Figure 4.5 Sandy tsunami sediments deposited by the 2004 Sumatra tsunami on the southeast coast of Sri Lanka. a) Massive light sandy deposit showing clear contact with the original ground. b) Well layered tsunami deposit representing different waves with a middle layer containing rip-up clasts of pebbles. c) Preserved tsunami sand layers in between organic materials of pre and post tsunami provenance. d) Fine tsunami sands deposited on high ground over 400 m inland from the coastline.

4.3.3 Boulder deposits

Tsunami- transported boulders are mostly imbricated and can be found as isolated deposits. Tsunamigenic boulder deposits contain large isolated rocky boulders or other debris of construction materials such as pieces of concrete slab or bricks which have been transported far away from their original position. Figure 4.6 shows examples from the 2004 Sumatra tsunami, during which different types of boulders were deposited on Sri Lankan coast.

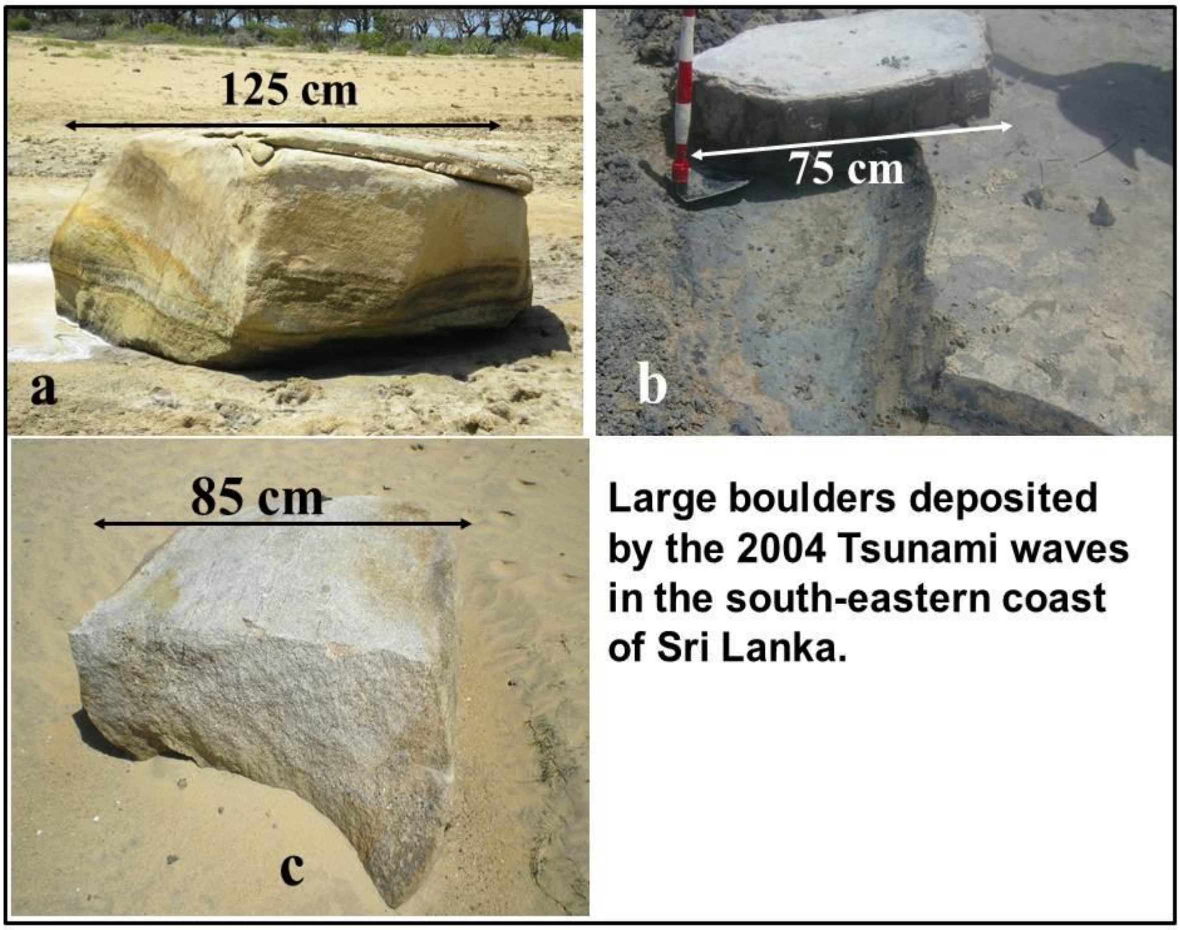


Figure 4.6 Large boulders deposited from the 2004 Sumatra tsunami on the southeast coast of Sri Lanka; **a** and **b** are rocky boulders and **c** is a derby of construction materials.

4.4 Characterization of the 2004 Sumatra tsunami sediments on the Sri Lankan coast

Sediment deposits from the 2004 tsunami around the Sri Lankan coast were studied using 4 transects normal to the coast.

4.4.1 Transect 1: Payagala, west coast of Sri Lanka

Transect one area has a shallow slope in both directions, towards the beach and inland due to the lateritic high grounds and marshland. The coastline in this area was more or less straight and trending in the northwest-southeast direction. Run-up heights and inundation distances of the tsunami recorded in this area were 3-5 m and 250-750 m respectively. Strong wave action and severe damage were recorded in this area. No or very little backwash occurred due to the presence of marshland. Very thin sediment deposition was observed, up to 3-4cm maximum which was totally dependent on the local topographical variations (Figure 4.7). Generally, both run up height and sediment deposition are decreasing inland.

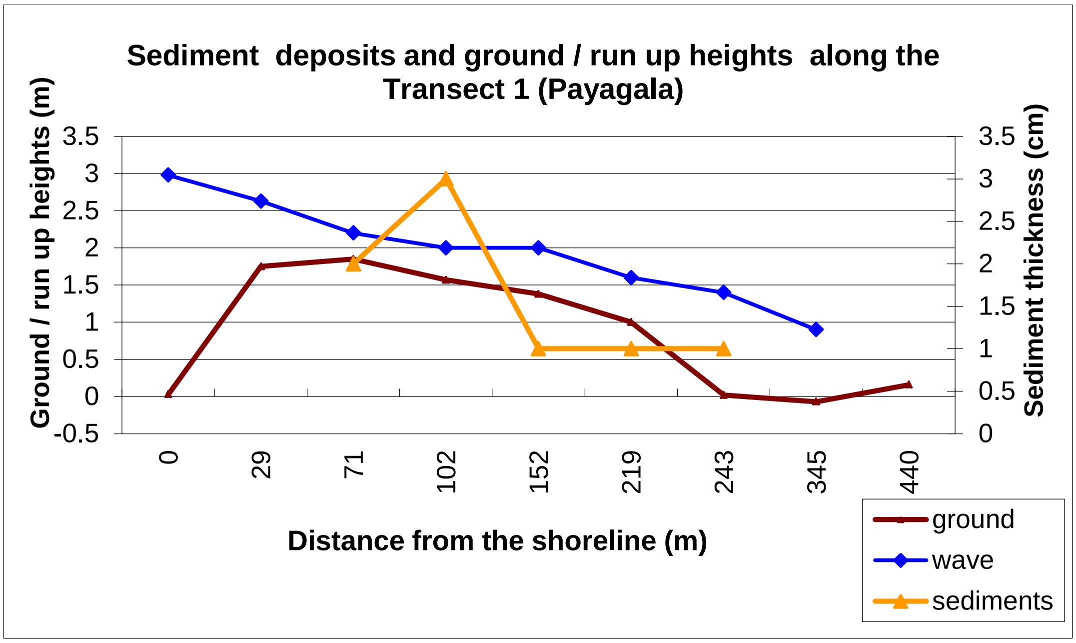


Figure 4.7 The 2004 tsunami wave heights and the sediment deposition along Transect 1 with topography.

Textural and grain size statistics

The textural characteristics of sediments along the Transect 1 showed an overall heterogeneity with clay silt and sand, Grain size distribution patterns showed trimodal (clay, fine and silt and sand), bimodal (clay and sand) and unimodal (silty sand) patterns (Figure 4.8). The sediments were well sorted while fining in grain size inland. On all four transects, the finest sediments were deposited on transect 1.

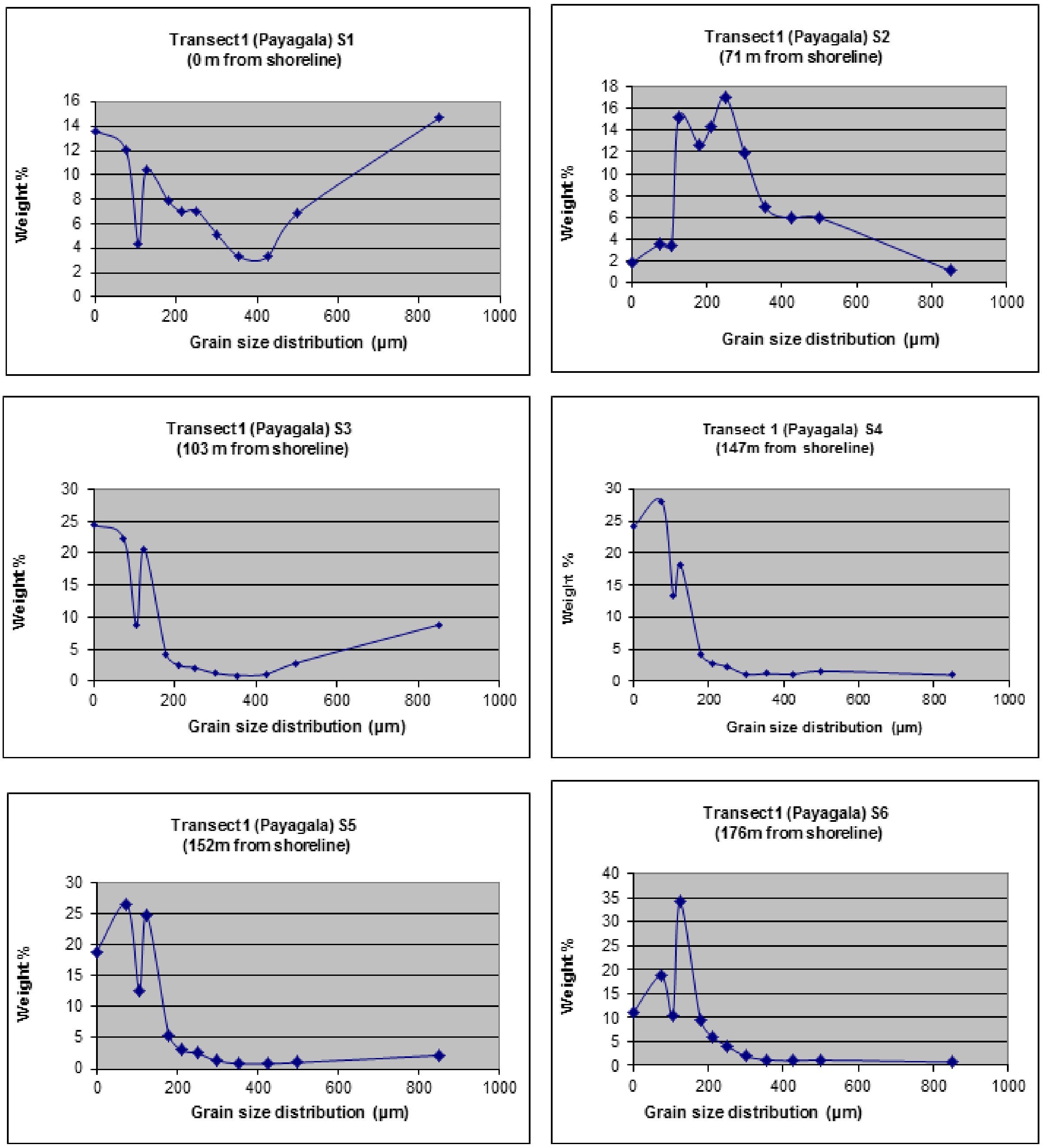


Figure 4.8 Grain size distribution patterns of the 2004 tsunami sediments along Transect 1 (S1 to S6 are samples collected from coast to land); grain size is increasing from left to right from 100-900 (µm) on the X axis and weight percentage on the Y axis.

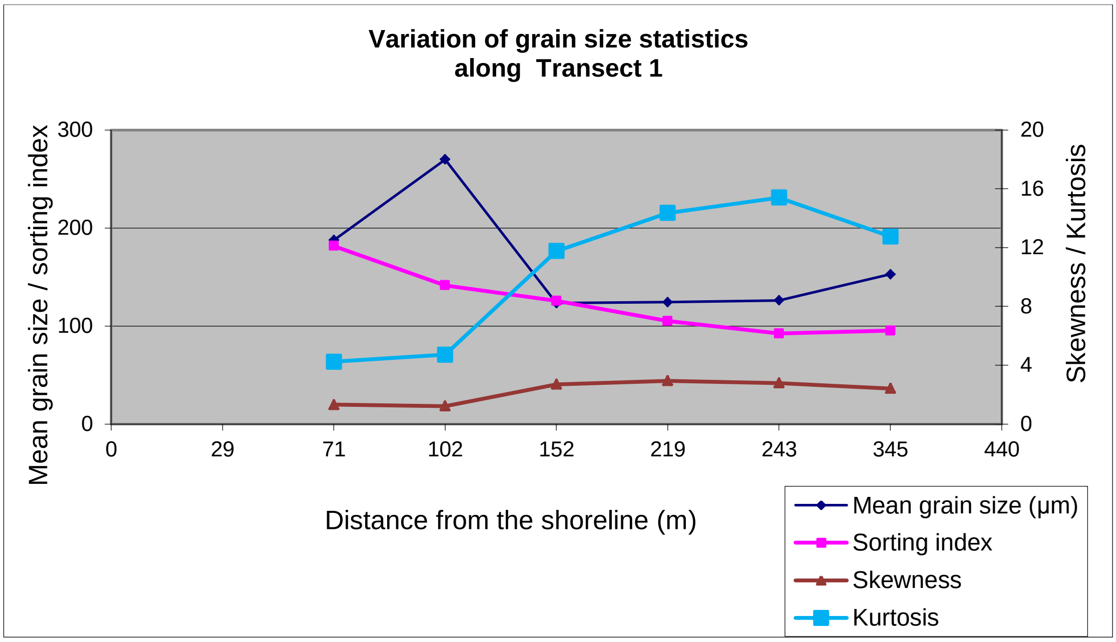


Figure 4.9 Variation of grain size statistical parameters with distance from the coastline along the Transect 1.

The mean grain size of the sediments from Transect 1 showed that, it varies from fine to very fine sand inland. The skewness varies from symmetrical to fine and very fine skewed and kurtosis ranges from leptokurtic to very leptokurtic from coast to land. Mean grain size and the sorting index show overall decreasing trends towards the land (Figure 4.9).

4.4.2 Transect 2; Yakgahawela (Bentota), southwest coast of Sri Lanka

Transect two was on the southwest coast where the 2004 tsunami caused severe impact. The topographic features of the area are a narrow beach and lateritic ridges with fairly high ground having a gentle slope towards the coast (Figure 4.10). The coastline trends in a northwest-southeast direction along a straight coastal stretch. About 300 m inundation distances and up to 3m run up height have been recorded. Only two waves were recorded in the area and, there was no information on the reflected wave which arrived in the afternoon. Very thin sediment deposition was observed within a very short distance inland.

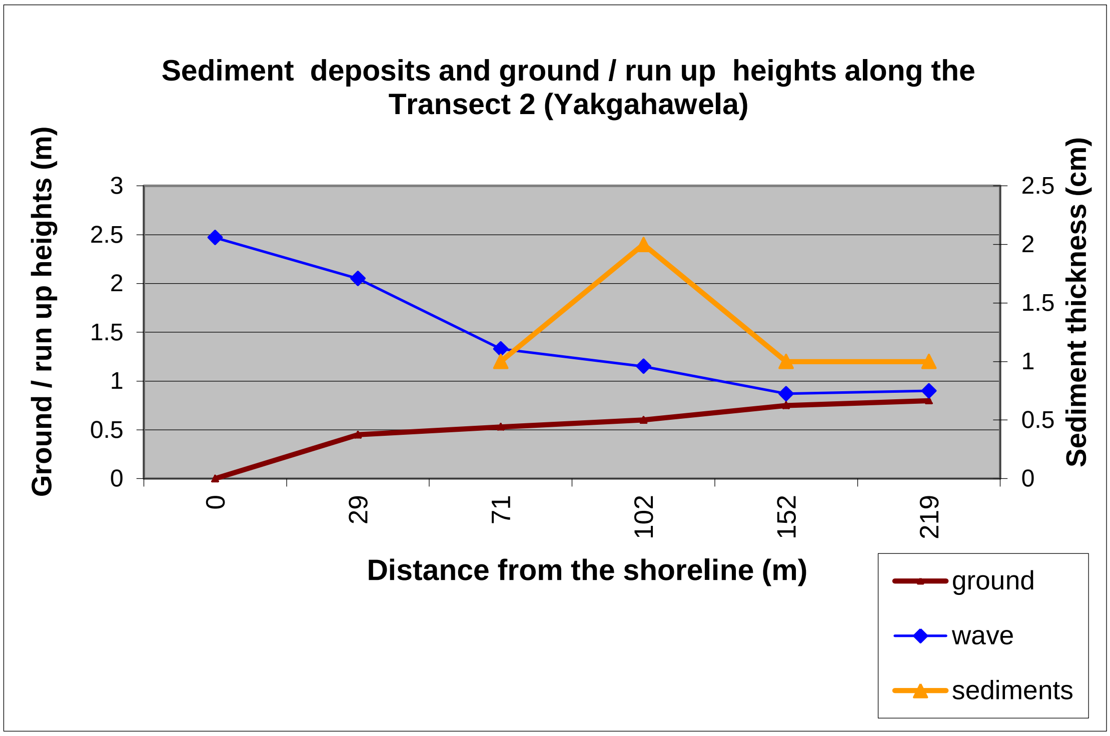


Figure 4.10 The 2004 tsunami wave heights and the sediment deposition along Transect 2 with topography.

Textural and grain size statistics

Along transect two, moderate to well-sorted sediments have been deposited and the sand showed mostly unimodal distribution patterns except for sample 4 (S4). The sediments did not show clear variations of grain size or distribution pattern (Figure 4.11).

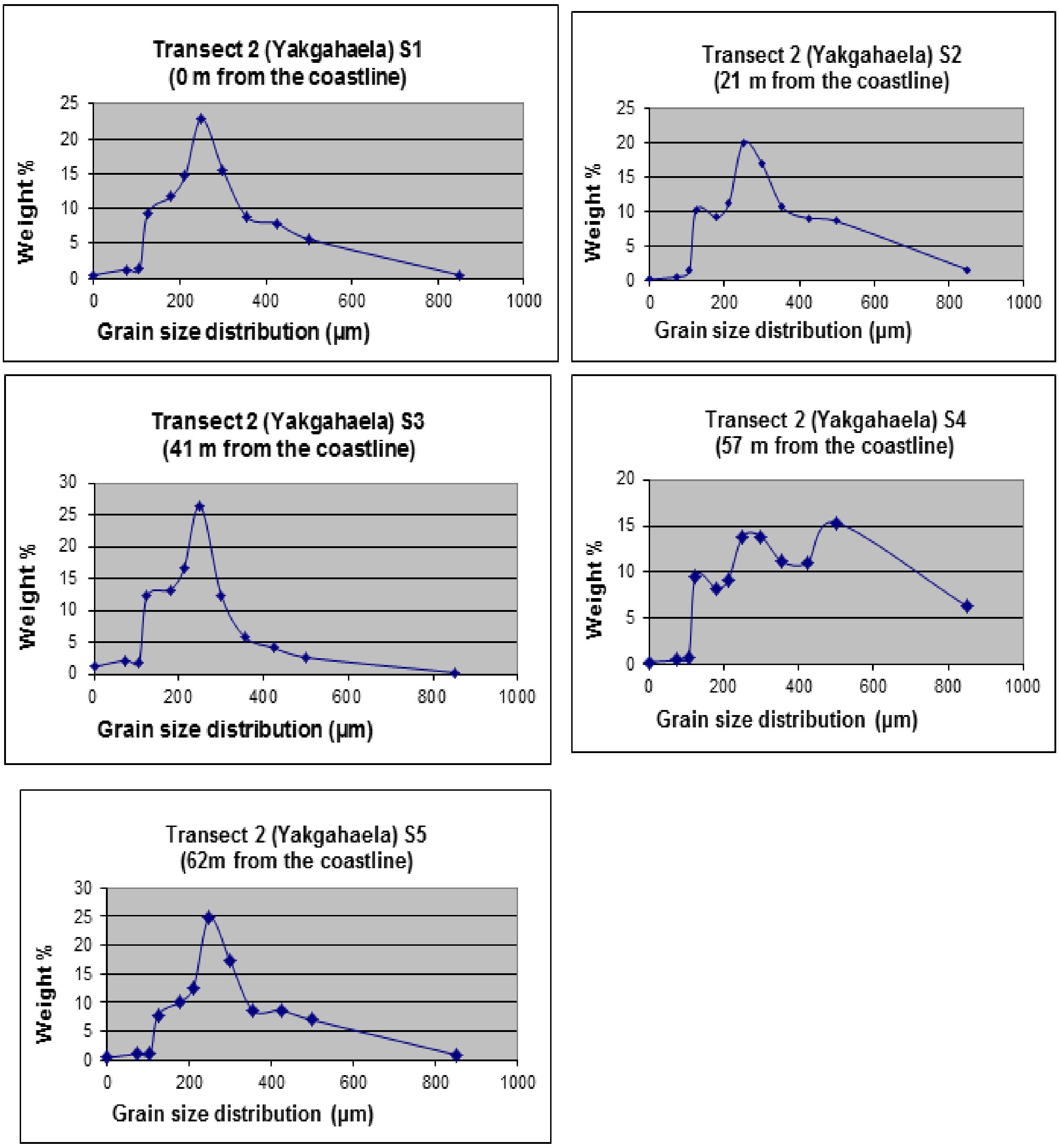


Figure 4.11 Grain size distribution patterns of the 2004 tsunami sediments along Transect 2 (S1 to S5 are samples collected from coast to inland); grain size is increasing from left to right from 100-1000 (µm) on the X axis and weight percentage on the Y axis.

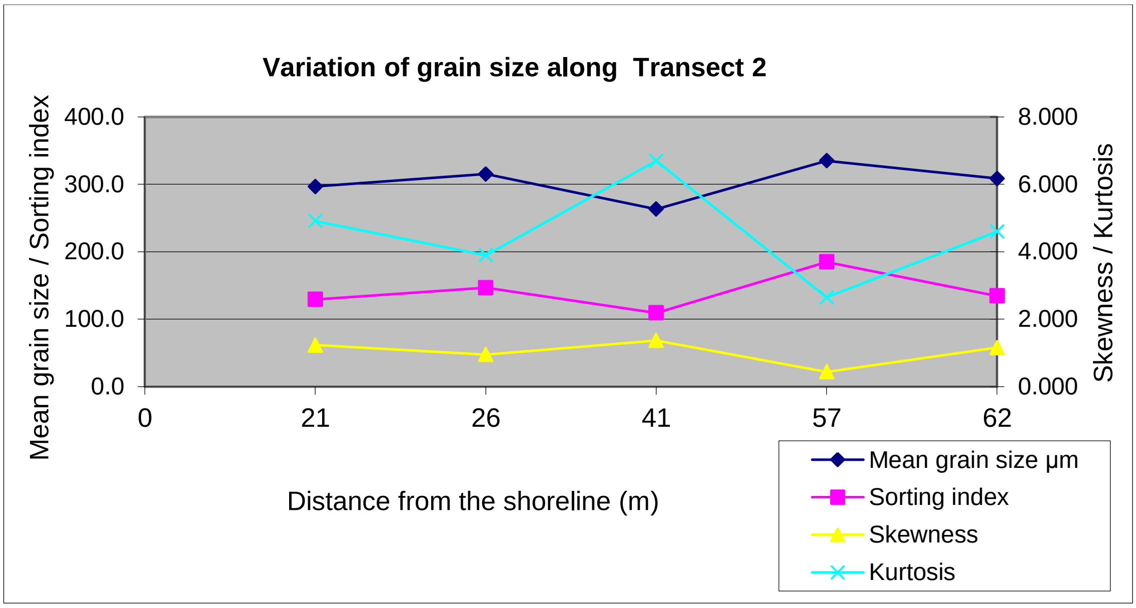


Figure 4.12 Variation of grain size statistical parameters with distance from the coastline along the Transect 2.

The grain size statistical parameters did not show a clear variation along Transect 2 (Figures 4.11 and 4.12). This may be because the area lies on the West coast of Sri Lanka and is highly populated and the sediments may have been disturbed by post-tsunami rehabilitation programmes.

4.4.3 Transect 3: Yala, southeast coast of Sri Lanka

Transect three (Yala) records the greatest inundation distances of over 1500 m and 5-8 m run up heights were recorded with three waves impacting the coast. In this location, the backwash flow of the tsunami waves was very low due to the hummocky topography and most of the incoming waves were dispersed in several directions. Very thick sediment deposition, up to 30-35 cm comprising a few layers with different textural characteristics was observed up to 700 m inland. Wave heights decreased inland, while ground elevation increases, but the thickness of sediment deposit shows an irregular pattern with the distance along the transect (Figure 4.13).

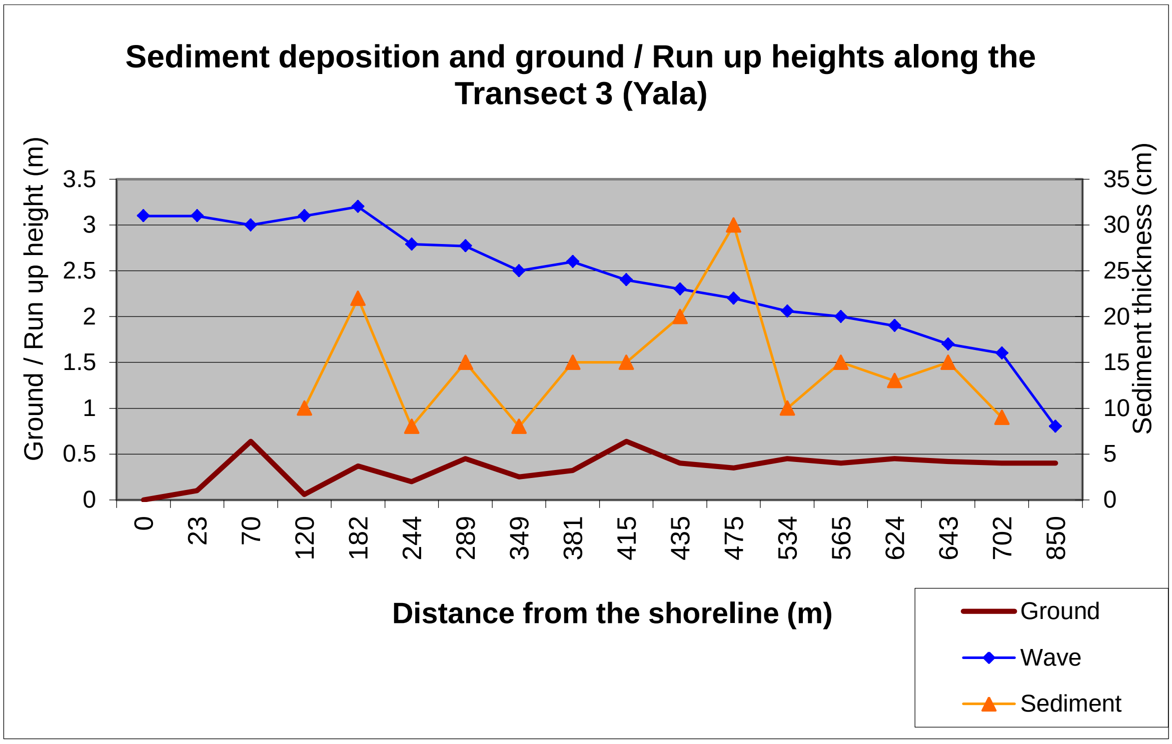
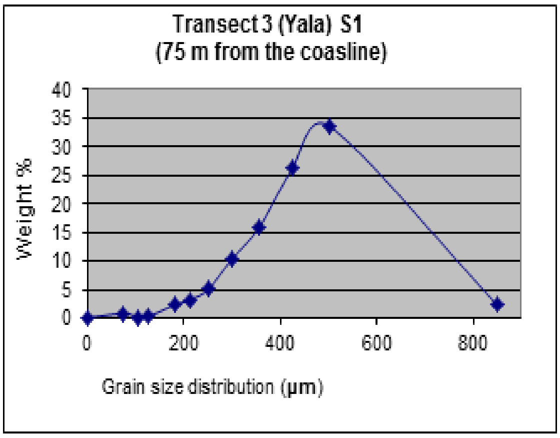
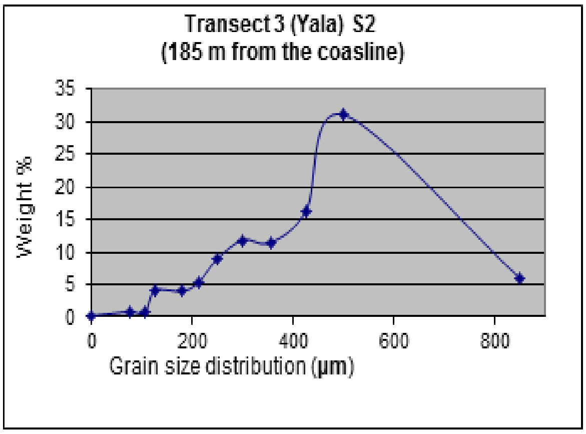


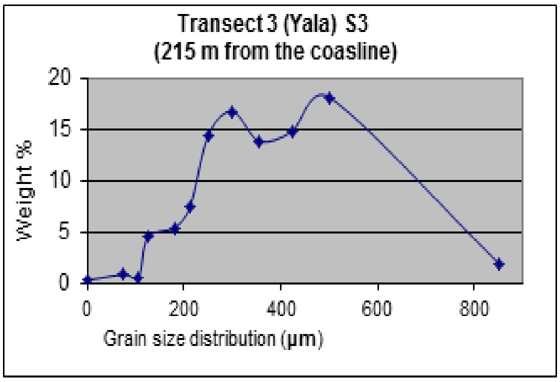
Figure 4.13 The 2004 tsunami wave heights and the sediment deposition along Transect 3 with topography.

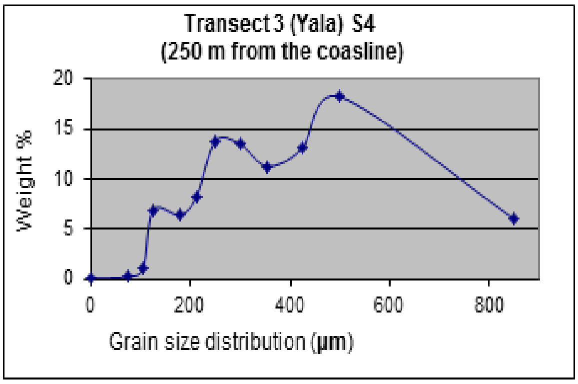
Textural and grain size statistics

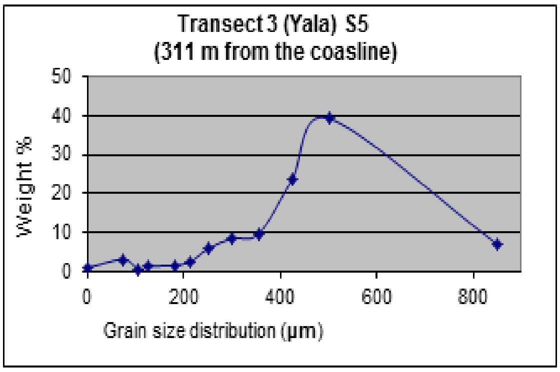
Transect 3 showed a completely heterogeneous and irregular grain size distribution pattern. The distribution patterns mainly exhibit unimodal (medium sand) and bimodal (coarse to medium sand). The sediments on transect three are composed of moderately to well-sorted medium sand and moderately sorted coarse sand (Figure 4.14).

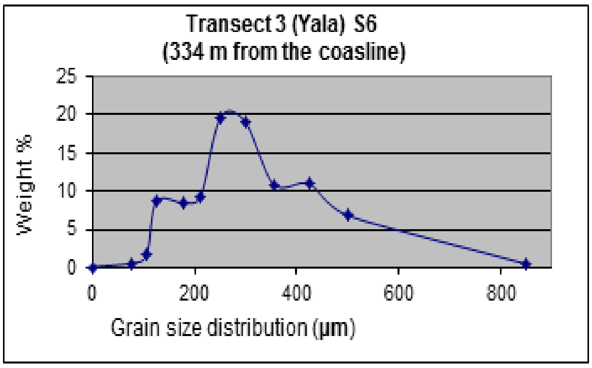

Transect 3 (Yala) S1
(75 m from the coasline)
Weight %
Grain size distribution (µm)

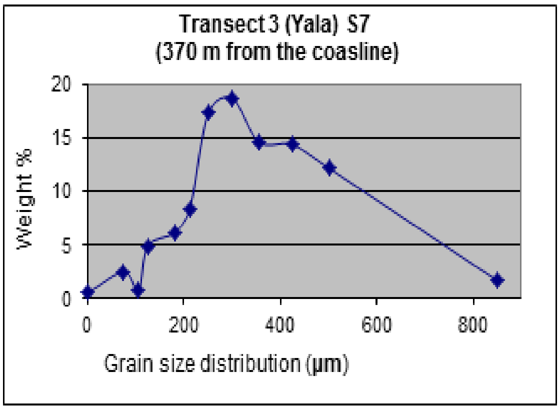

Transect 3 (Yala) S2
(185 m from the coasline)
Weight %
Grain size distribution (µm)

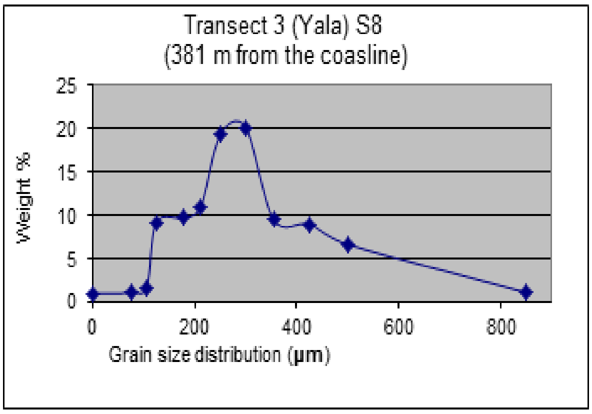

Transect 3 (Yala) S3
(215 m from the coasline)
Weight %
Grain size distribution (µm)


Transect 3 (Yala) S4
(250 m from the coasline)
Weight %
Grain size distribution (µm)


Transect 3 (Yala) S5
(311 m from the coasline)
Weight %
Grain size distribution (µm)


Transect 3 (Yala) S6
(334 m from the coasline)
Weight %
Grain size distribution (µm)


Transect 3 (Yala) S7
(370 m from the coasline)
Weight %
Grain size distribution (µm)


Transect 3 (Yala) S8
(381 m from the coasline)
Weight %
Grain size distribution (µm)

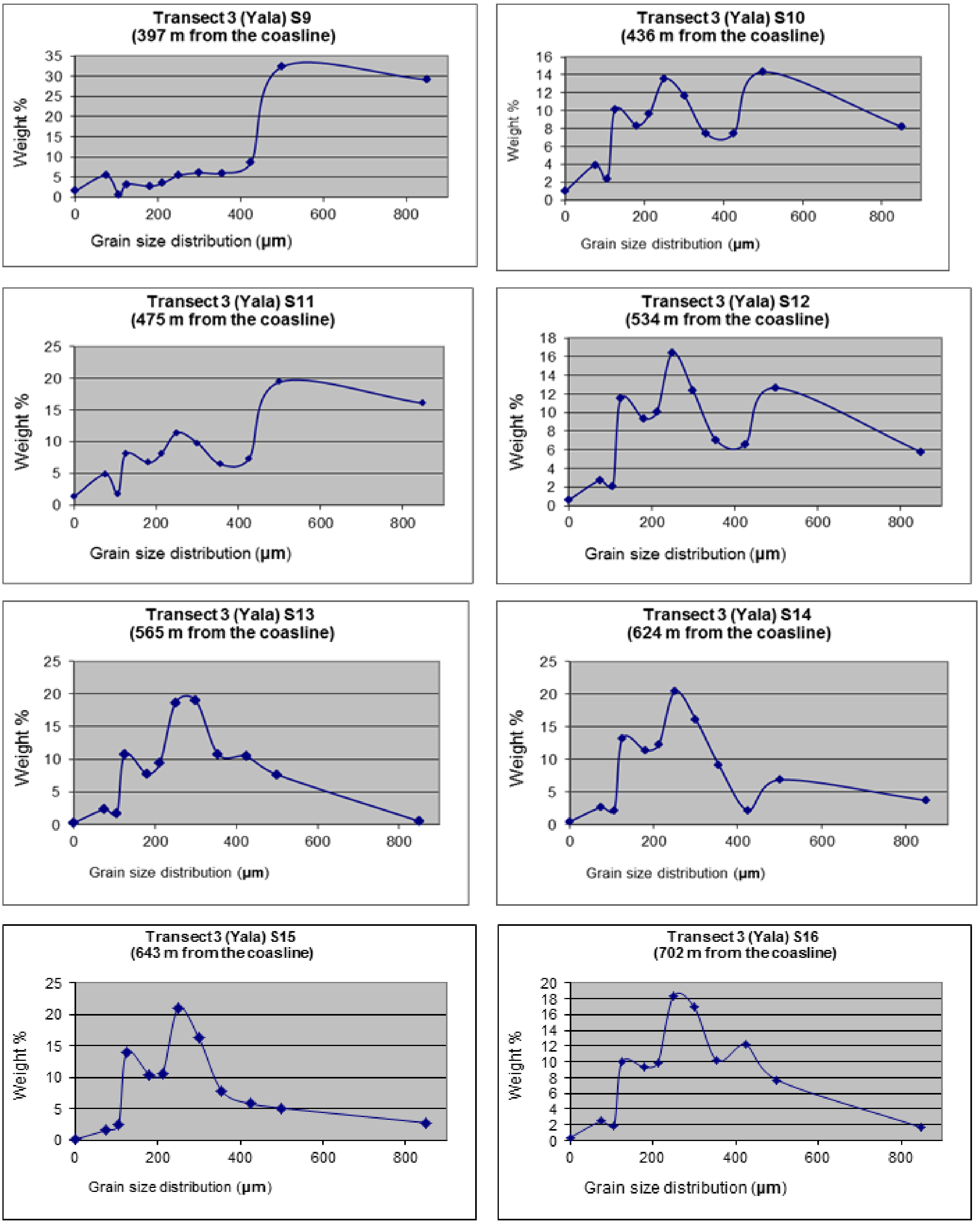


Figure 4.14 Grain size distribution patterns of the 2004 tsunami sediments along Transect 3 (S1 to S16 are samples collected from coast to inland); grain size is increasing from left to right from 100-850 (µm) on the X axis and weight percentage on the Y axis.

Variation of grain size statistical parameters along the Transect 3

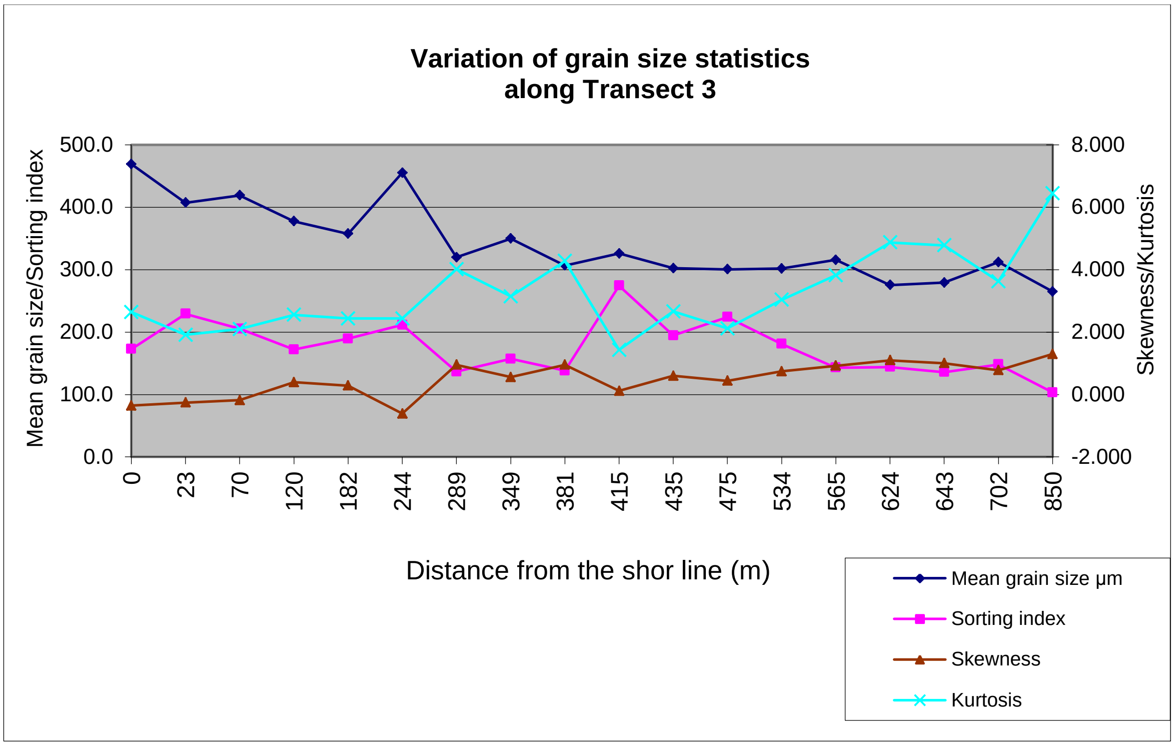


Figure 4.15 Variation of grain size statistical parameters with distance from the coastline along the Transect 3.

Mean grain size and sorting index have decreasing trends towards the land on Transect 3, similar to transect 1. Skewness shows wide variation from very fine skewed, symmetrical to course skewed. Kurtosis also varies from leptokurtic to mesokurtic, but varies irregularly along transect 3 (Figure 4.15).

Generally, the statistical parameters show a variation from coast to inland which is most clearly demonstrated on transect 3. Transect 3 has a greater number of sample points for a longer distance. The overall pattern is that mean grain size and kurtosis decrease, while skewness and sorting index are increasing inland (Figure 4.14 and 4.15). But along transect two these relations are not clear, which may be due to the very thin sediment veneer occurring in this location and possible contamination.

4.4.4 Transect 4; Katukurunda west coast of Sri Lanka

Transect four recorded inundation distance of 250-300 m, 3-6 m high run up and four wave cycles were recorded. According to the available information from eyewitnesses, the first and second waves were weaker and only the third, strongest wave inundated the area. The fourth wave arrived in the afternoon (3.00pm Local Time) as a reflected wave. About 20 cm sediment deposition was observed on this transect at one location in the shadow area of the building (Figure 4.16)

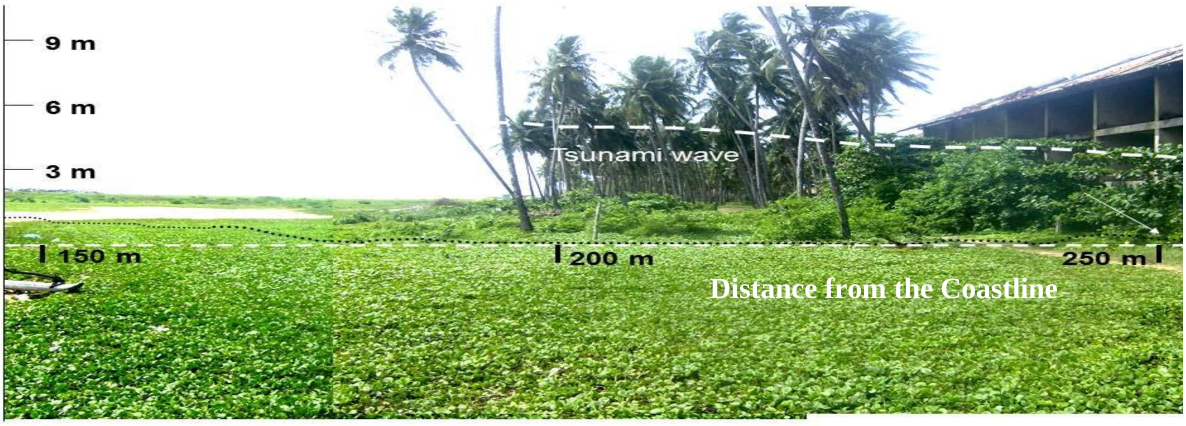


Figure 4.16 The 2004 tsunami run up heights and the sediment deposition along Transect 4 with topography.

The general deposition pattern of the 2004 tsunami deposits did not show any consistent relationship between geographical location and wave parameters such as number of waves and wave height but it did show a strong dependence on the local topography which, in particular, was responsible for the backwash flow and its nature. Sediment deposition was primarily controlled by three main factors: availability of sediment (source), local topography and the backwash flow, but local topography played the key role in sediment deposition. For example normal beach sections could be found having backwash flow, where no thick sediment deposition was observed (Example- Transect 2) and it was also noticed areas with very small backwash flow (Transects 3 and 4) where thick deposits were observed.

4.5 Characteristics of specific sediment deposits observed from the 2004 tsunami around the Sri Lankan coast

Several specific thick sediment deposits observed from the 2004 tsunami were examined in detail within the framework of this study. Most of the deposits were found on the south east coast of Sri Lanka. Tsunami wave actions were interpreted based on the general characteristics of the deposits through detailed sedimentological studies.

4.5.1 Location 1: Katukurunda, on the west coast of Sri Lanka

Tsunami sediments deposits 16 cm thick were observed a 250 m inland in the shadow of a building (Figure 4.16). The deposit was well preserved by vegetation cover and shadow of a building. This deposit was discovered three years after the tsunami and, it was the thickest tsunami sediment deposit recorded on the west coast of Sri Lanka. It shows remarkable sedimentological structures such as layering with textural significance. This sediment deposit is therefore extremely important for studies of the effects of the 2004 tsunami on the Sri Lankan coast. Both detailed field and laboratory studies were undertaken on this deposit. The deposit was carefully examined and all information recorded.

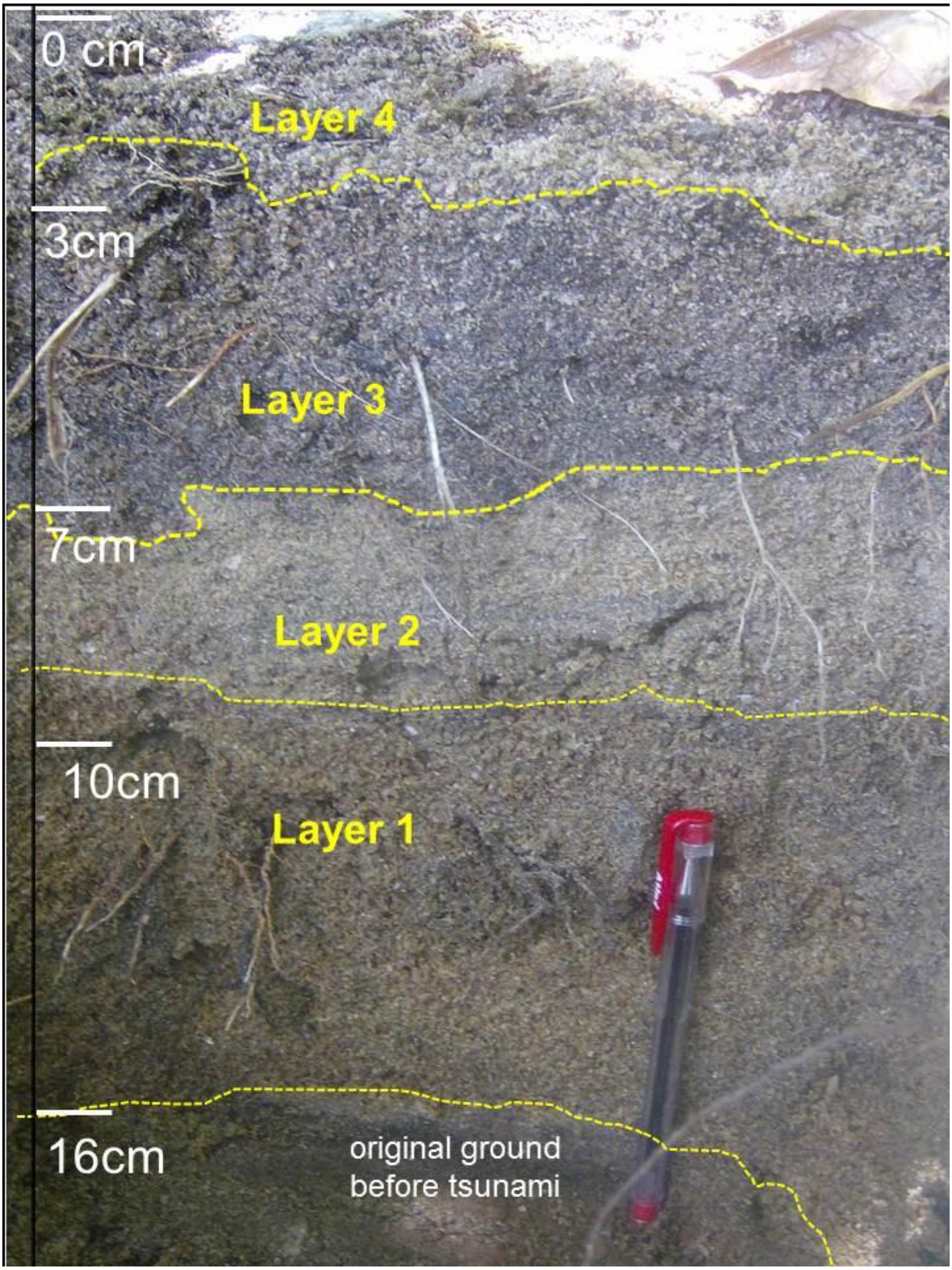


Figure 4.17 Sediment deposited by the 2004 tsunami at Katukurunda, the west coast of Sri Lanka.

The deposit consists of 4 distinctive layers which are readily identifiable using colour, texture and clear boundaries. The boundaries showed some irregularity due to erosional features (Figure 4.17). There was a clear contrast between original ground and the tsunami deposit, because the original ground was hard and comprised dark brown soils. The tsunami sediments here were loose sand. During the past three years, a thick vegetation cover has grown on the location and most of their roots have penetrated into the sandy tsunami layers. However, the original structures were not disturbed by them.

The sedimentological characteristics of the four sediment layers (bottom to top) are as follows;

1st layer : Medium grained massive light brown sand layer, loose sand of thickness about 6 cm.

2nd layer : Light grey colour with medium grained sand with minor amounts of gravel and very coarse grained sands, fine laminations were present and the thickness is about 2 cm.

3rd layer : Dark grey colour medium to coarse sand, massive layer with erosive and irregular top surface, the thickness is about 1-2 cm.

4thlayer : Black and white coloured medium to coarse sand and clay, massive layer, up to 6-7 cm thick, with the top part is mostly washed by rain water with time and remove clay resulting the presence of light sand.

Micro-petrographic studies

Micro-structures and mineralogical studies of these sediment layers were carried out using thin sections under the polarising microscope of each layer.

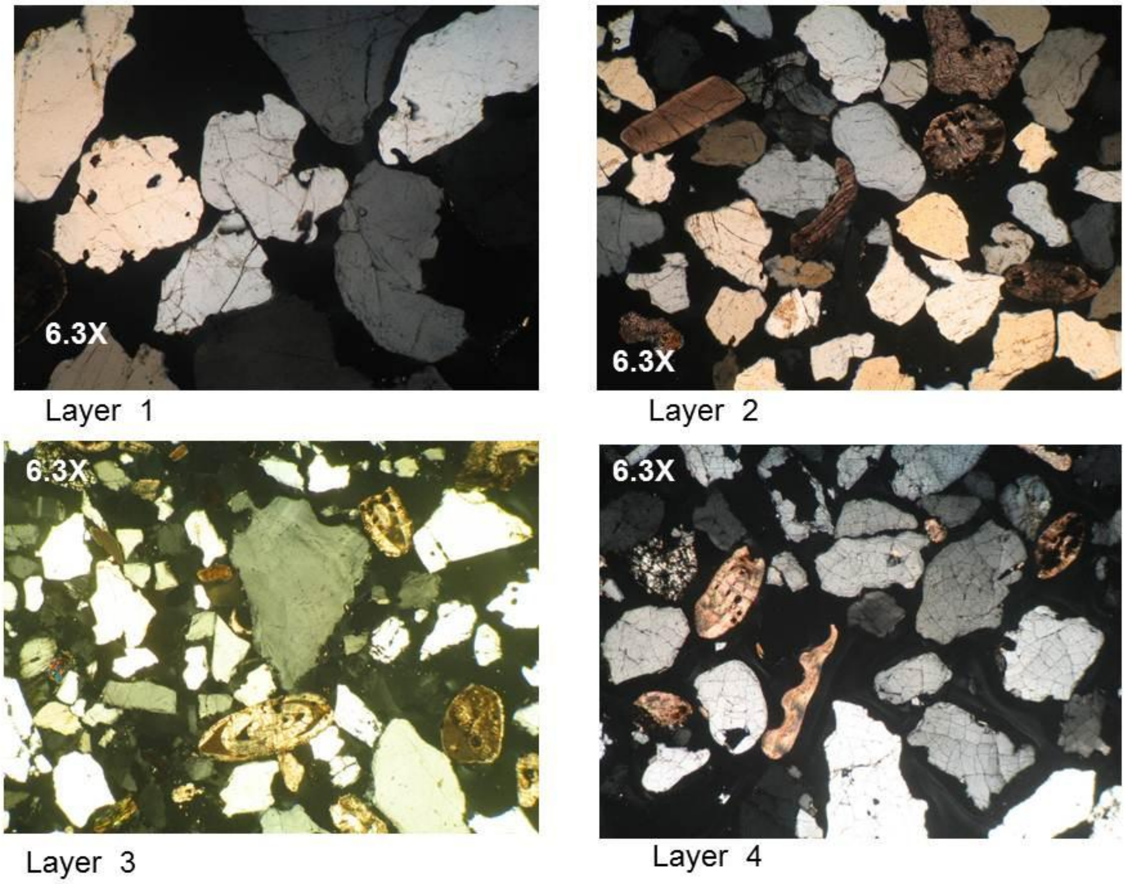


Figure 4.18 Micro-photographs of the 2004 tsunami sediments at Katukurunda.

Layer 1: Medium to coarse sub- rounded well sorted quartz and feldspar sand, slightly fractured grains present.

Layer 2: Fine grained angular to sub-rounded well sorted quartz and feldspar sand, grains are slightly fractured.

Layer 3: Fine to very coarse sub-rounded to angular, poorly sorted quartz and feldspar sand.

Layer 4: Fine to medium moderately sorted sub rounded to angular quartz feldspar sand, highly fractured grains (Figure 4.18).

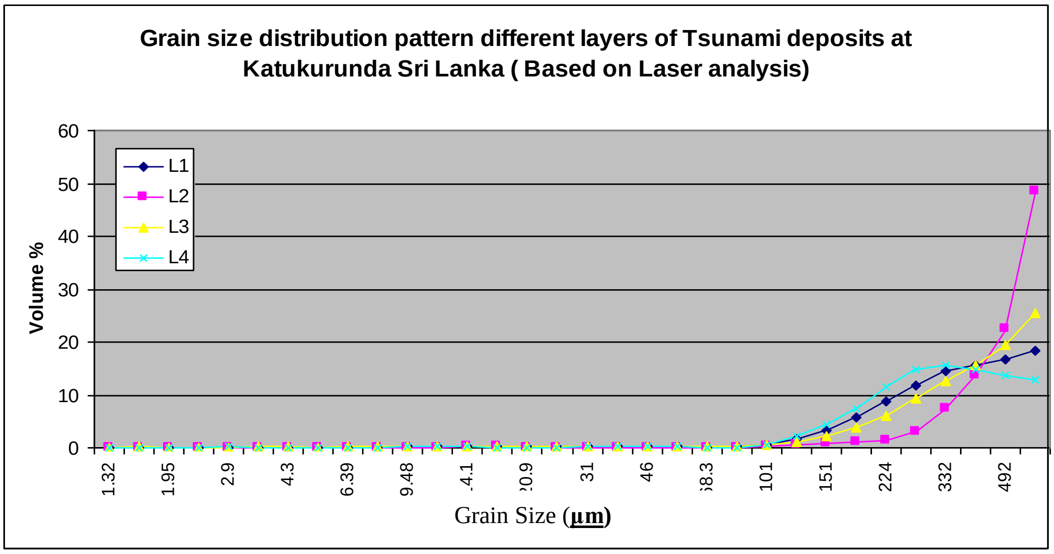


Figure 4.19 Grain size distribution pattern of different sediment layers of the 2004 tsunami deposits at Katukurunda (<500 µm fraction).

The analysis of the grain size distribution pattern of the sediments (<500 µm fraction) showed none of the sediment layers contain very fine sediments, less than 100 µm (Figure 4.19).

4.5.2 Location 2: Yala, southeast coast of Sri Lanka

The thickest sediment deposition from the 2004 tsunami was observed on the south-eastern coast of Sri Lanka 200m inland in the Yala National park. The sediment deposit showed remarkable sedimentological characteristics presenting three distinctive layers with clearly distinguishable textural and stratigraphical characteristics (Figure 4.20). The sediments were deposited on the original dark peaty clayey ground and the boundary between the tsunami deposits and original ground was clearly identified.

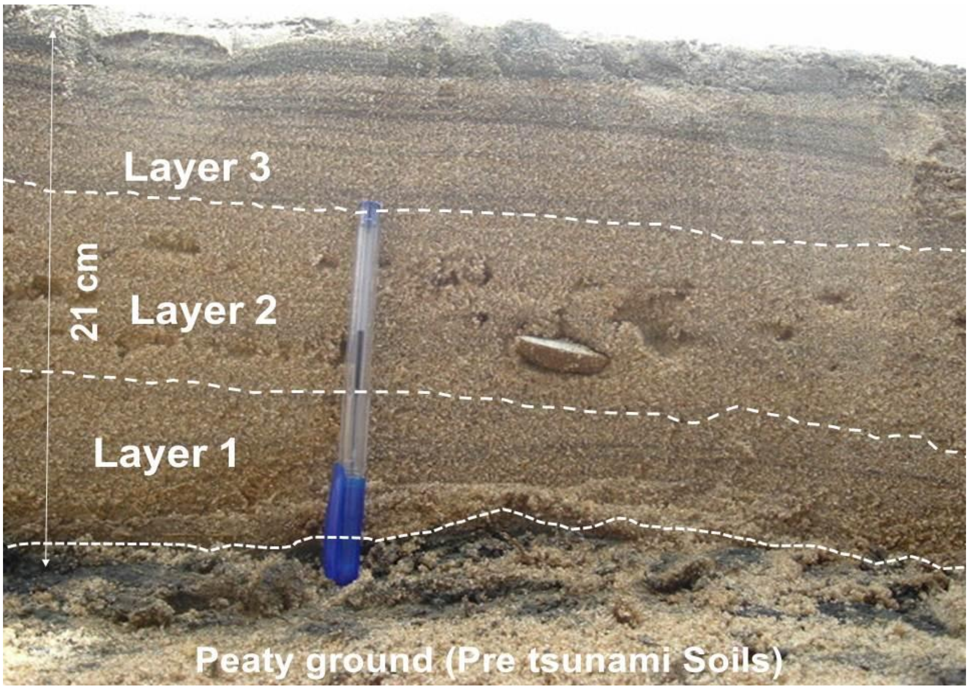


Figure 4.20 The 2004 tsunami sediment deposits showing whole cross-sections from Yala, southeast coast of Sri Lanka.

1st layer is the bottom layer which is massive and consists of medium to fine sand. It has been deposited by the first wave and subjected to reworking by later tsunami waves. The first wave was small at this location, but brought a considerable amount of sediment derived from the beach and near-shore. The first layer comprises of mainly medium to fine sediments due to low energy condition and the source was mainly from the adjacent beach. The estimated run up height of this wave was about 1 m.

2nd layer is also massive and comprises very poorly sorted medium sand to pebbles and rip-up clasts. Therefore, it is clear that second wave was much stronger as very coarse sediments were deposited. Estimated maximum run up height of this wave was 8 m.

3rd layer is the uppermost layer comprised mostly of fine sand with fine laminations deposited by the third wave. The laminations are due to reworking of sediments during the flood phase. However, the third wave was not as strong as the second wave and estimated run up height of this wave was about 0.7m.

Three main waves from the 2004 tsunami hit this coast and all three waves carried considerable amounts of sediments. However, in this location, there was no strong backwash flow and the waves were dispersed in many directions by the irregular topography of the area.

4.5.3 Location 3 The 2004 tsunami deposit at Palatupana-Yala, southeast coast of Sri Lanka

Figure 4.21 The 2004 tsunami deposit at Palatupana, southeast coast of Sri Lanka.

This location is 1 km west of the previous location in Yala (Location 2). A light grey massive fine sand deposit from the 2004 tsunami was observed on the clayey ground. It was located

400m inland in Palatupana lagoon, southeast coast of Sri Lanka. This deposit was a few centimetres (5-6) thick and consisted mostly of sand. The deposit was preserved on low elevated marshy ground and the contact between dark marshy clay and light colour tsunami sand was clearly noticeable (Figure 4.21). Judging from the inundation distance of the sediment deposits, it may have been deposited by the strongest wave of the tsunami.

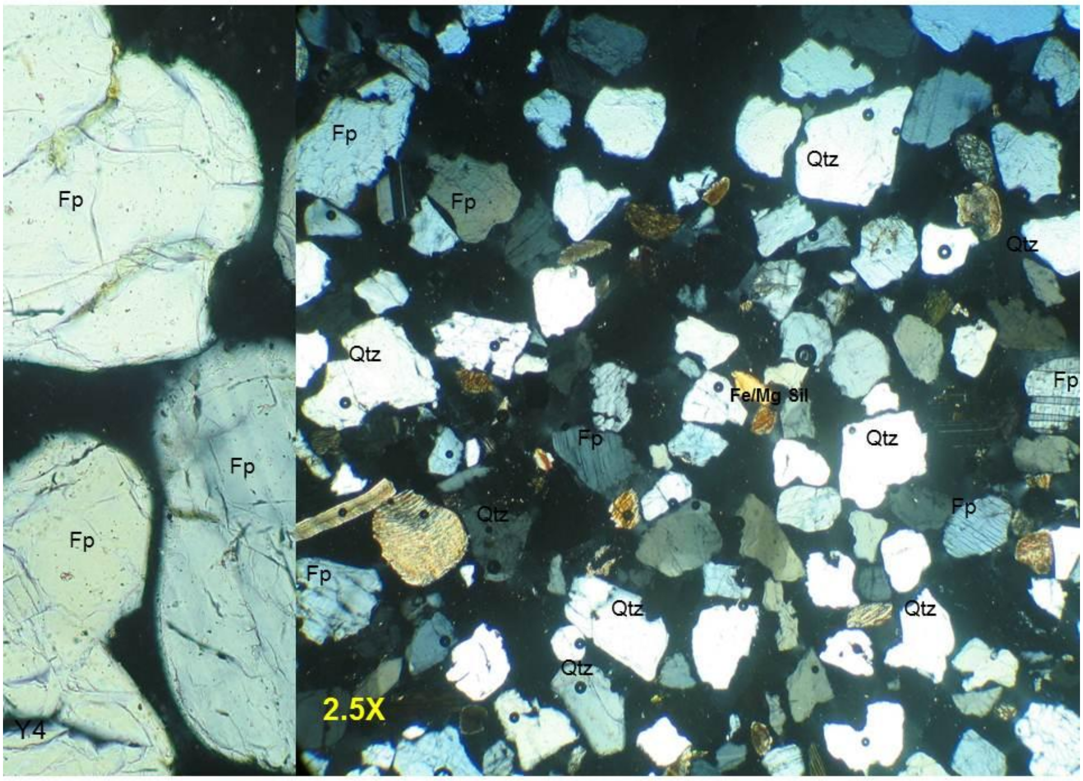


Figure 4.22 Micro-petrographic picture of the 2004 tsunami sand from Palatupana, southeast coast of Sri Lanka (magnification of the imageLeft half; 6.3 and right half; 2.5X).

Micro-petrographic studies showed that, the sand of this deposit was from both the adjacent beach together with some offshore sediment. The sand comprises moderately sorted fine to medium sub rounded sands; mainly quartz and feldspar with minor amount of Fe-Mg and other heavy minerals (Figure 4.22).

4.5.4 Location 4: Godawaya-Hambantota, the south coast of Sri Lanka

A well-preserved deposit was observed about 200m inland at Godawaya, Hambantota, on the south coast of Sri Lanka (Figure 4.23). The thickness of the deposit was estimated as 5 cm. The tsunami waves have penetrated inland to a greater distance at this location through a stream. A single massive loose sand deposit was present overlying clayey ground. The sediments are medium to fine sand and may be from the adjacent coast and brought by the strongest wave experienced at this location. Therefore, it is evident that there was only one strong wave, carrying sediments at this location from the 2004 tsunami.

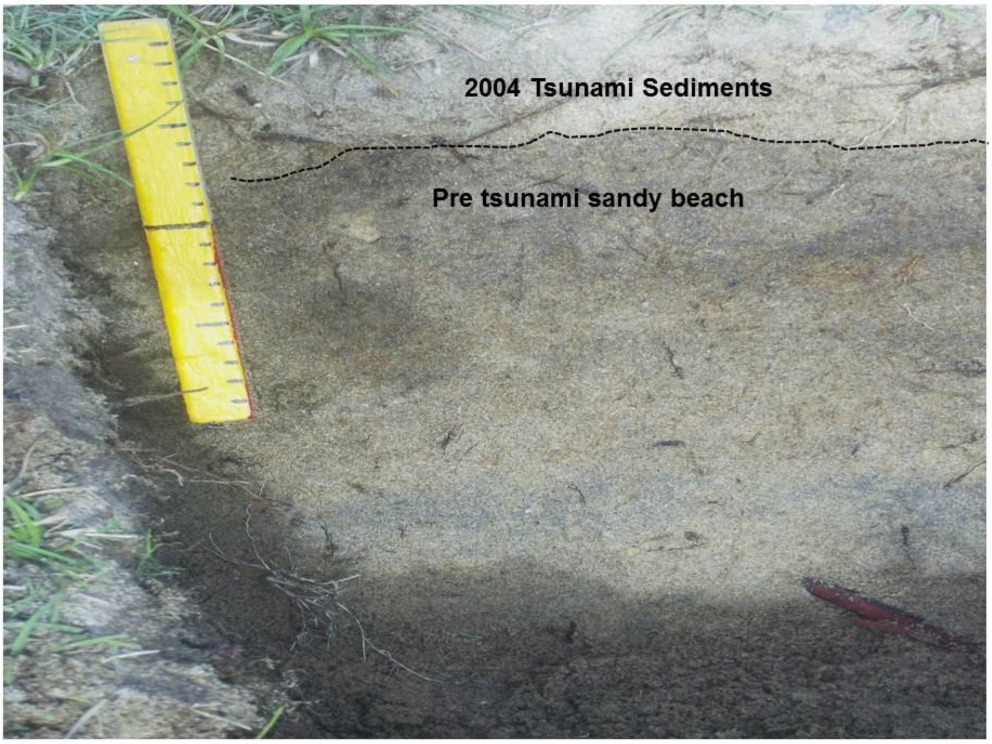


Figure 4.23 A sediment deposit from the 2004 tsunami at Godawaya, south-eastern coast of Sri Lanka.

4.5.5 Location 5: Karaganlewaya- Hambantota, south coast of Sri Lanka

A sand deposit a few centimetres thick was found under a peaty layer in a pine plantation on the Karaganlewaya- Hambantota, south coast of Sri Lanka. The deposit was adequately preserved on a gentle slope facing to inland and about 300m away from the coastline. Both top and bottom margins, of the deposit showed organic layers. The sand deposit was massive and composed of medium grey sand (Figure 4.24).

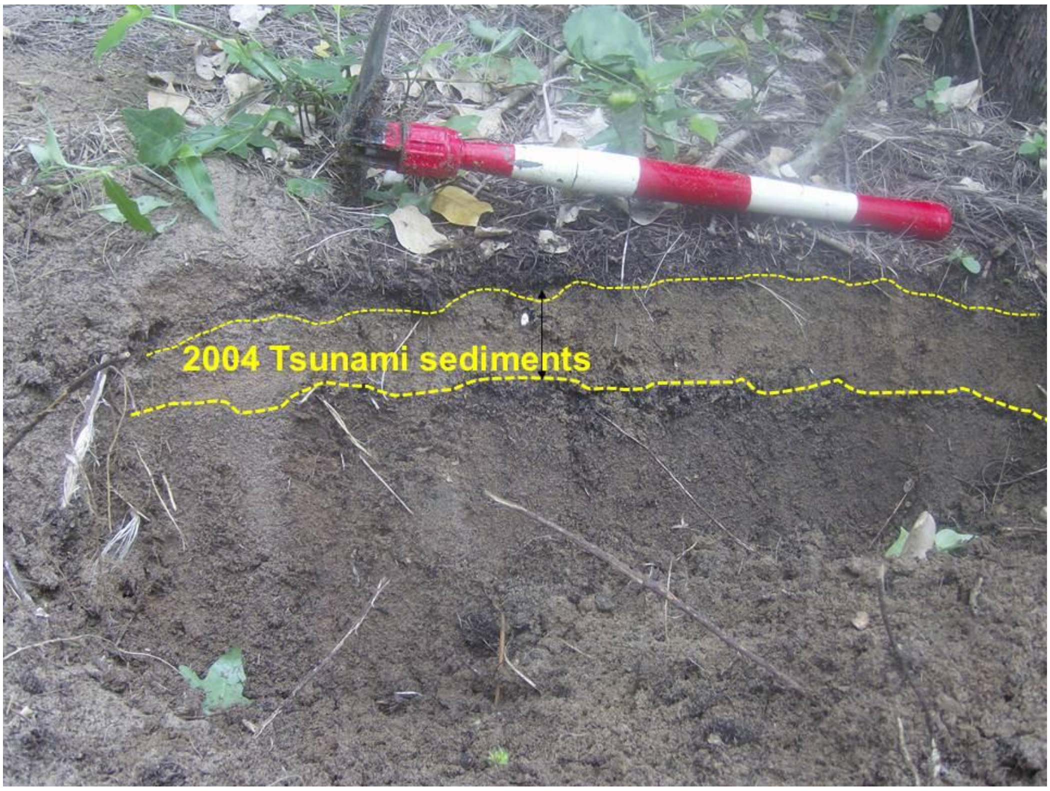


Figure 4.24 A sediment deposit from the 2004 tsunami at Karaganlewaya (Hambantota), south- eastern coast of Sri Lanka.

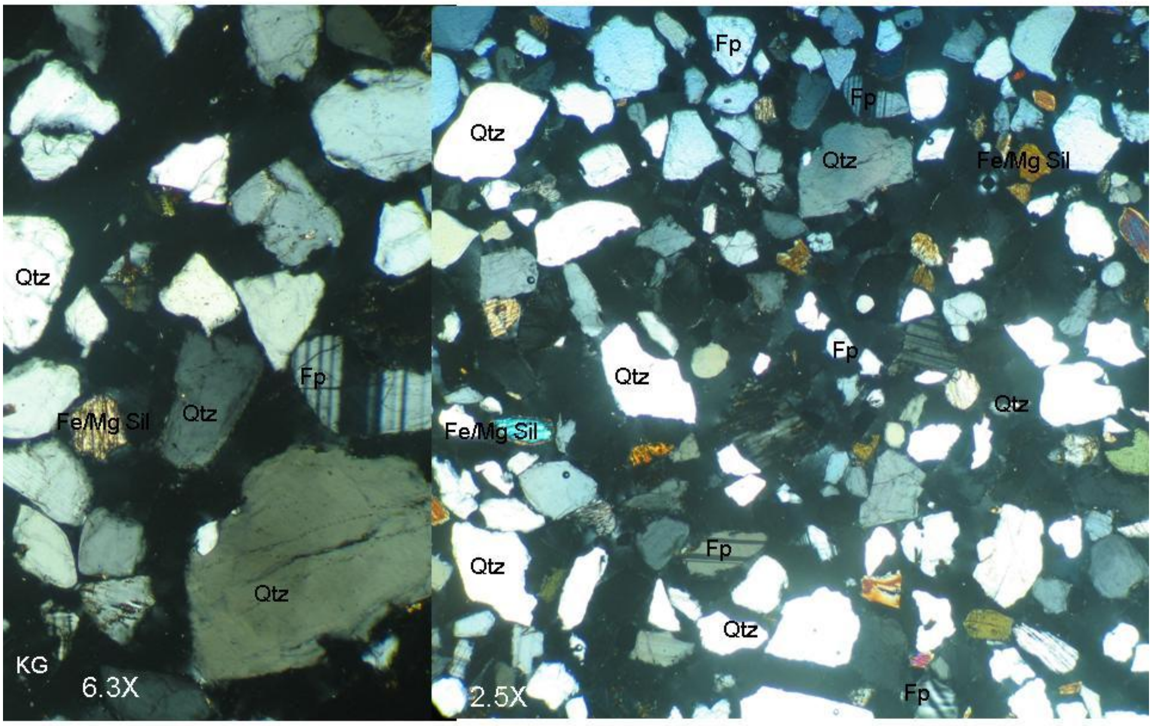


Figure 4.25 Micro-petrographic picture of the 2004 tsunami sand from Karaganlewaya.

Micro-petrographic studies showed that the sediments are fine to medium moderately-sorted sub rounded sand. They comprise mainly quartz and feldspar and minor amount of garnet, other Fe-Mg silicate minerals and heavy minerals (Figure 4.25).

4.6 Correlations of statistical parameters of the tsunamigenic sediments

Quite remarkable correlations are displayed between the grain size statistical parameters, especially between mean grain size and kurtosis / mean grain and skewness. A very distinctive feature of the grain size statistics of tsunami sediments is the strong negative correlation between mean grain size and skewness (r = -0.8 to -0.9) and between mean grain size and kurtosis (r = -0.6 to -0.9). These correlations are shown by sediments on transect 1, and 3 (Figure 4.26 and 4.27).

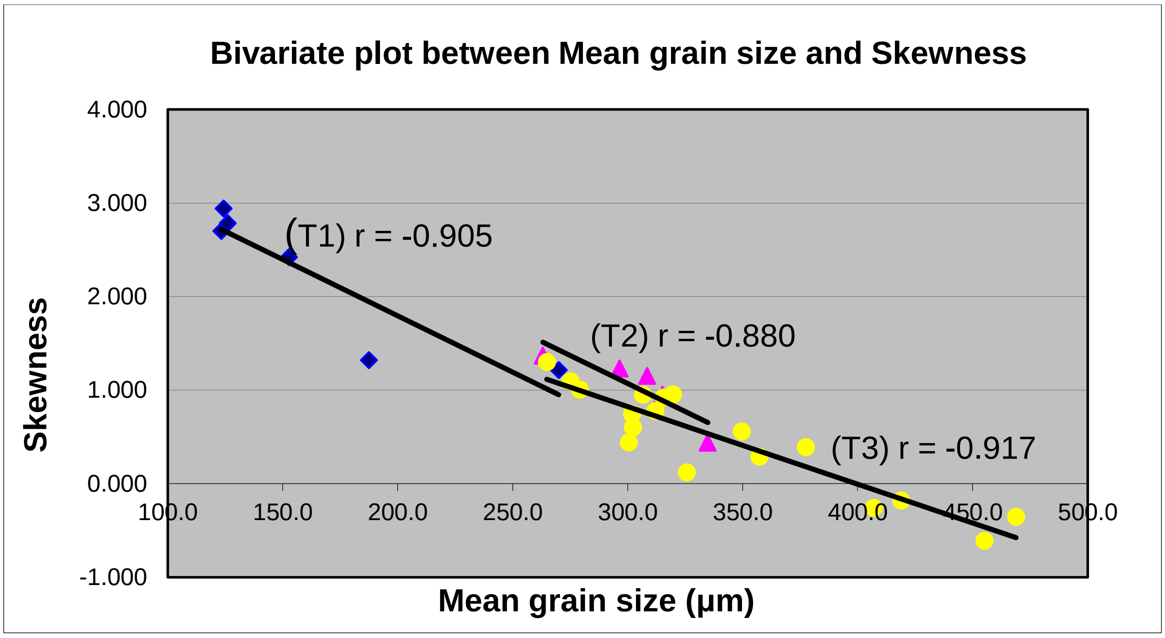


Figure 4.26 Correlation between mean grain size and skewness of data from Transects 1, 2 and 3 (T1, T2 and T3).

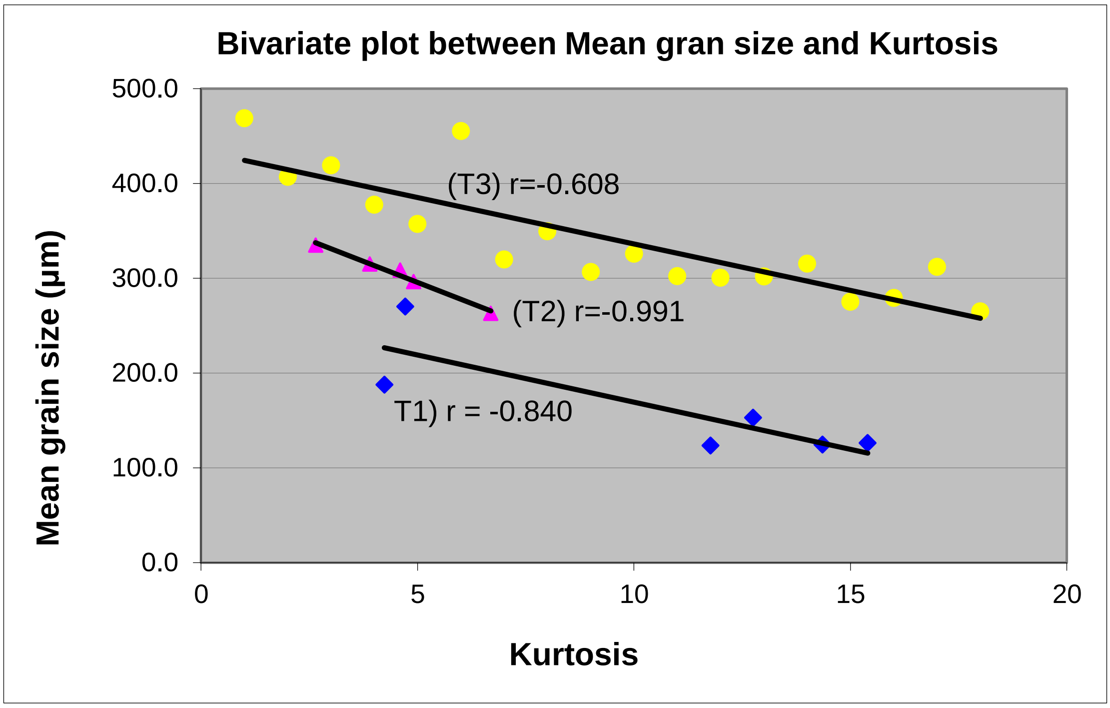


Figure 4.27 Correlation between mean grain size and kurtosis of data from Transects 1, 2 and 3 (T1, T2 and T3).

Similar variations have been observed from tsunami sediments in many parts of the world (Hindson and Andrade, 1999; Gelfenbaum and Jaffe, 2003; Morton *et al*., 2007; Paris *et al*., 2007) but these correlations have not been recognized as a diagnostic signature for characterisation of tsunami sediments from any of those studies (Figure 4.28 and 4.29); example from the Indian coast by Babu *et al*., (2006) but this may be due to the fact those beaches are rich in heavy minerals and tsunami sediments have been contaminated with them.

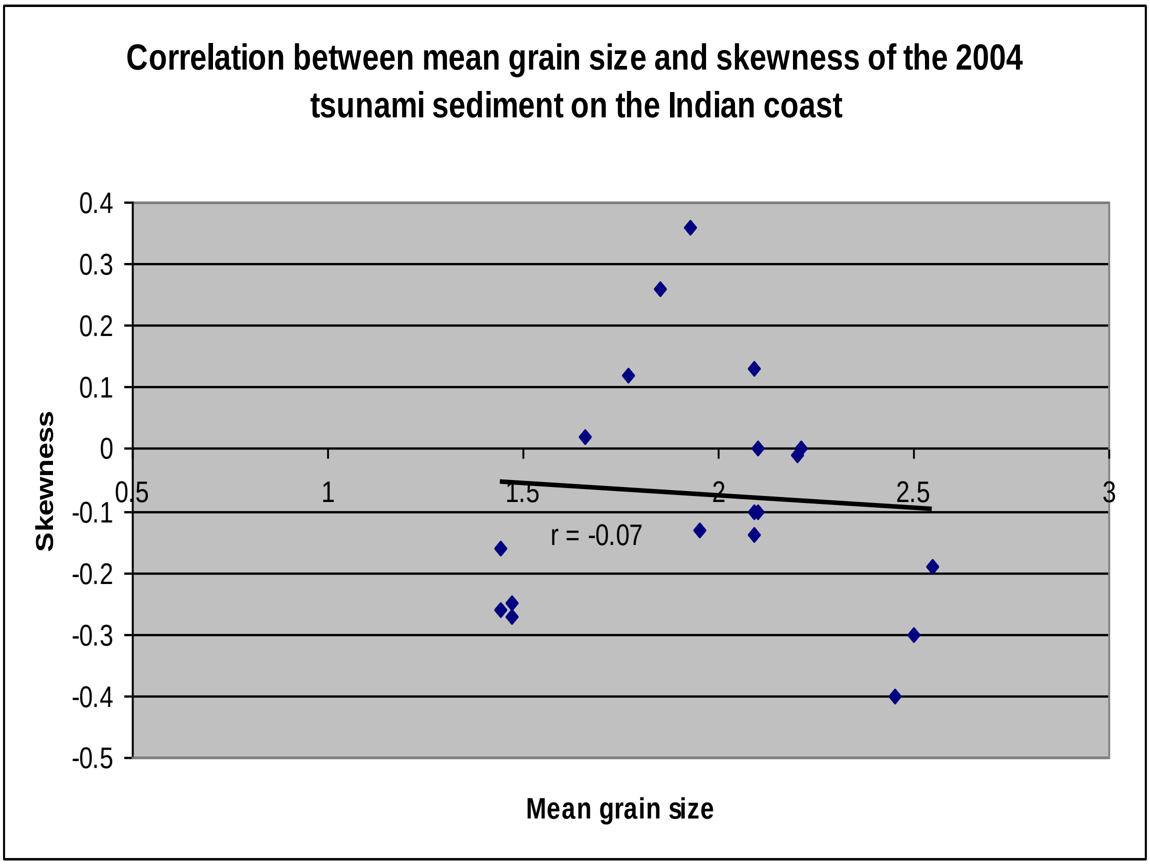


Figure 4.28 Correlations between mean grain size and skewness of the 2004 tsunami sediment on the Indian coast; data from Babu *et al*., (2006).

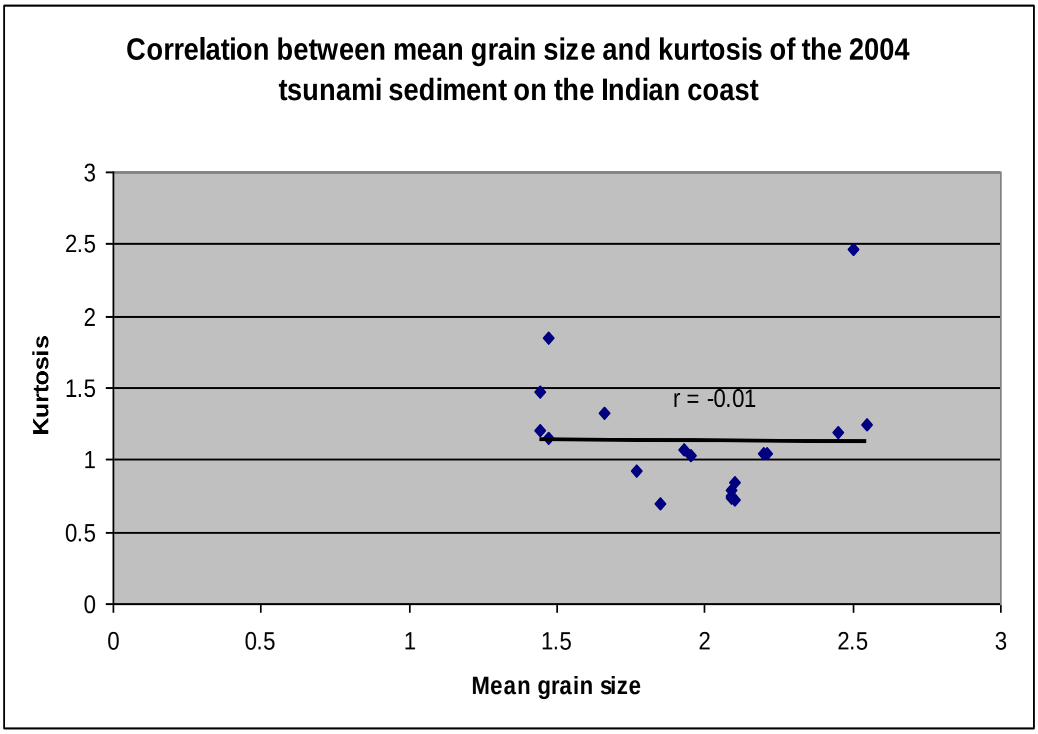


Figure 4.29 Correlations between mean grain size and kurtosis of the 2004 tsunami sediment on the Indian coast; data from Babu *et al*., (2006).

4.7 Preservation of tsunami sediment characteristics on the beach with time

Since our study is mainly focused on palaeotsunami sediments, the preservation of sedimentological signatures of tsunamigenic sediments under natural environmental conditions is an important factor. Therefore, the evolution of grain size statistics of the 2004 tsunami with time was studied. The characteristics of the sediments can change with time due to the action of wind, rain or human activities by means of erosion, deposition and mixing. The character and the rates of such changes have never been studied anywhere; either in the Sri Lanka context or anywhere else. Thus the 2004 sediments along the same Transects 1, 2, and 3 were re-sampled in 2007. However, areas on transect 1 and 2 were totally disturbed and it was not posible to collect representative samples. However, on transect 3, where the thickest sediments were observed, it was possible to collect a proper set of undisturbed samples and carry out further analyses to make a proper comparison.

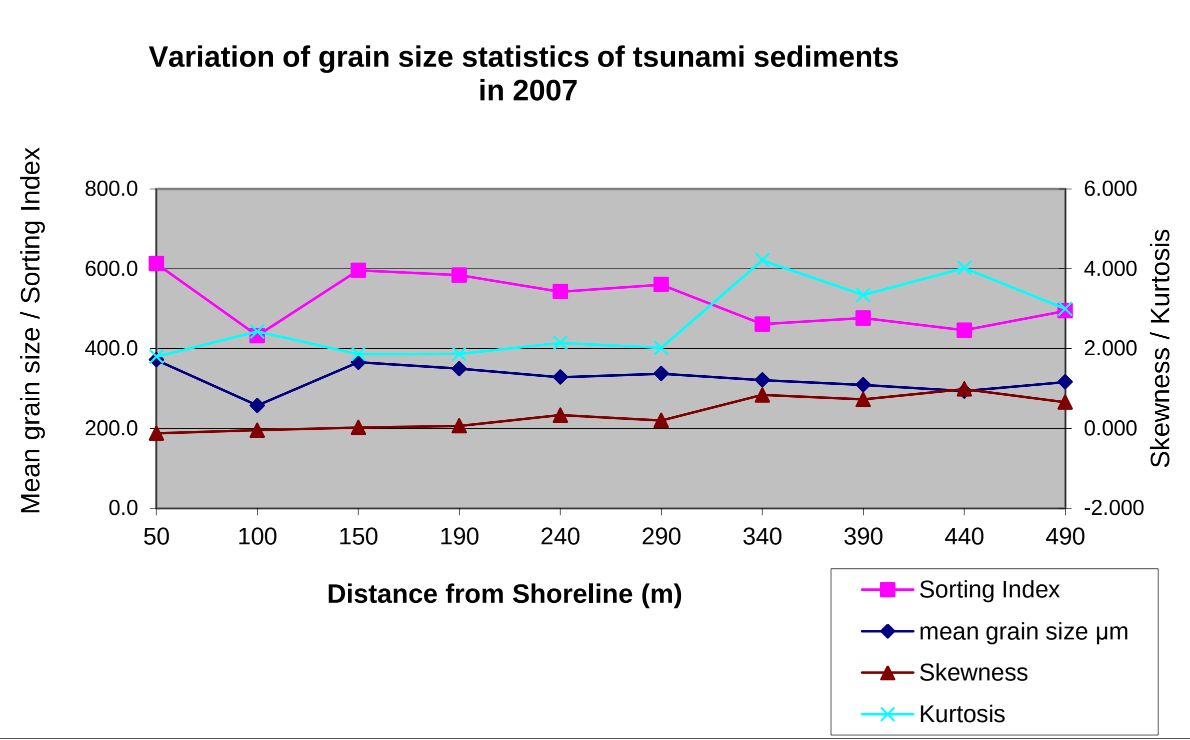


Figure 4.30 Variation of grain size statistical parameters of tsunami sediments with distance from the coast to inland, after three years of the tsunami (in 2007).

The general decreasing trend of the variation of mean grain size and sorting index of the tsunami sediments inland were well preserved after three years (in 2007). Similarly, the increasing trend of skewness and kurtosis was also preserved. However, after three years, the grain size distribution pattern showed some deviations from its original pattern (4 statistical parameters) in year 2004, for distances up to of 300m inland (Figure 4.30). Beyond 400m inland, the grain size distribution pattern remained mostly unchanged during the period. Since the grain size distribution pattern of the sediments soon after deposition (in 2004) showed a unimodal pattern with coarse sand, after three years, the sediment on this stretch showed bimodal distribution richer in fine sand for the first 300m distance of the transect (Figure 4.33). Therefore, I deduce that disturbance to tsunami sediment deposits is higher towards the coast. This may be due to greater wind actions and deposition of finer sand onto the tsunami deposits. However, on transects 1 and 2, no meaningful relations were obtained (Figures 4.31 and 4.32), since these two sites were highly disturbed.

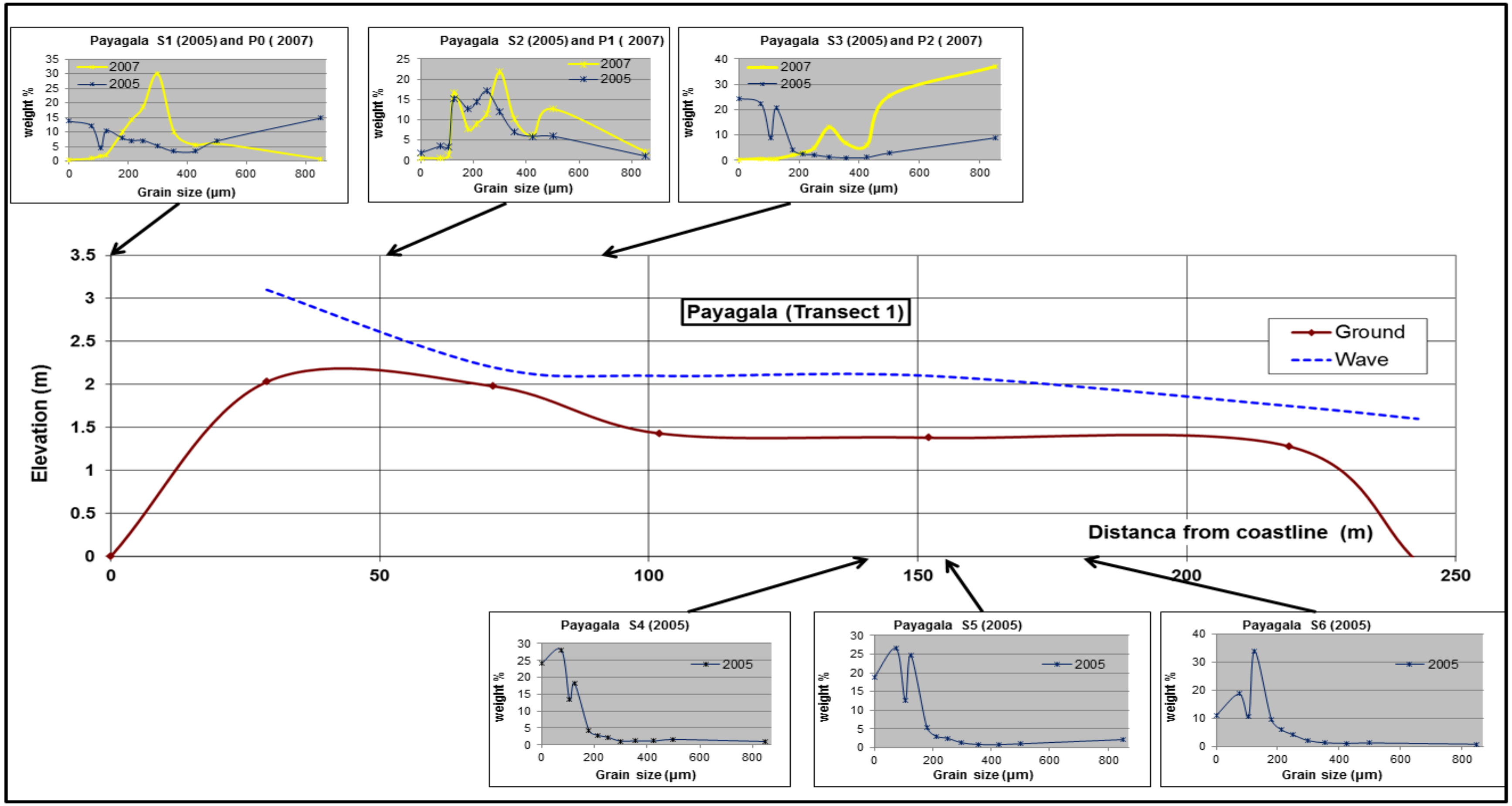


Figure 4.31 Comparison of grain size distribution pattern of the 2004 tsunami sediments along Payagala (Transect 1) between 2004-2007.

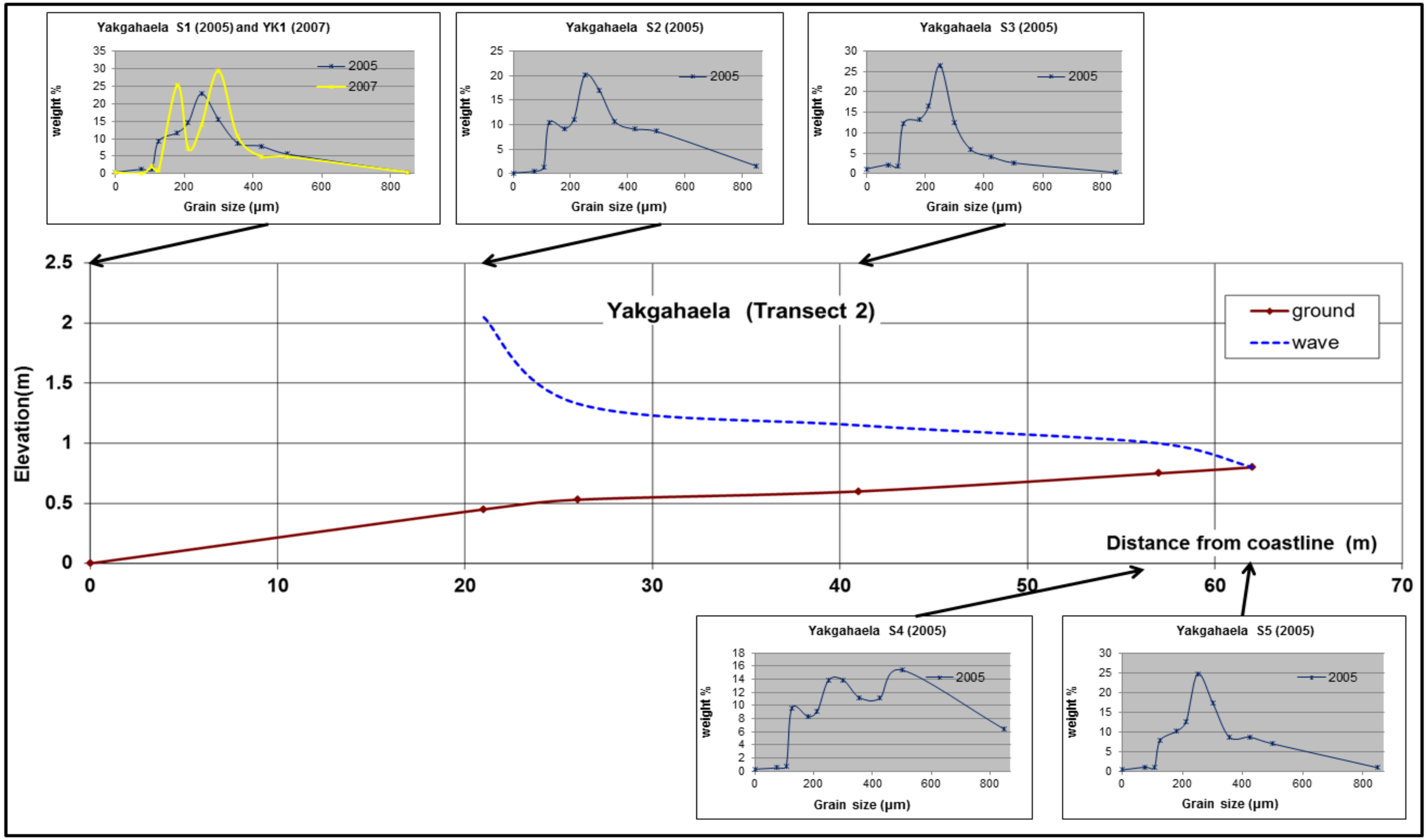


Figure 4.32 Comparison of grain size distribution pattern of the 2004 tsunami sediments on Yakgahaela (Transect 2) between 2004 and 2007.

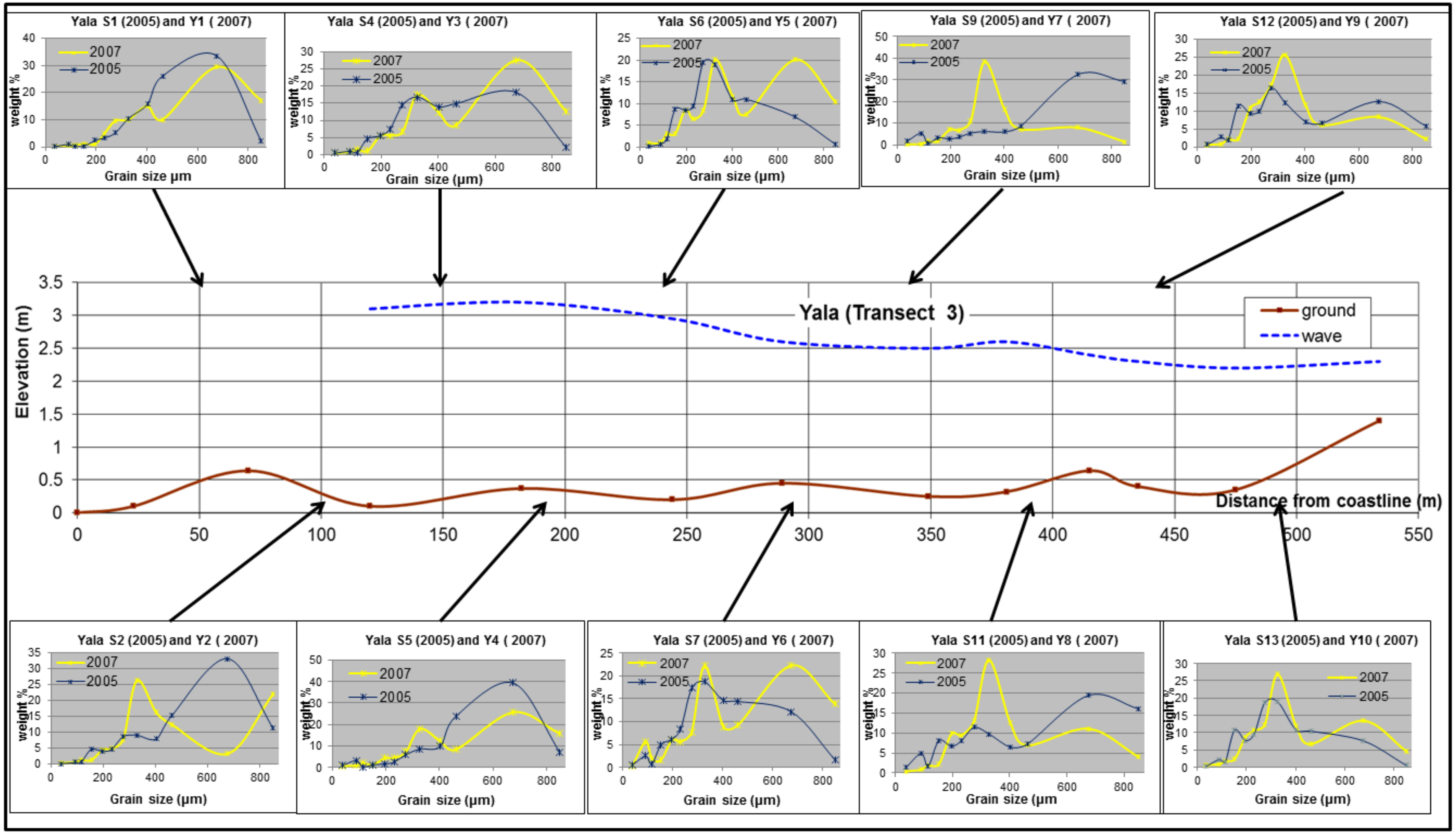


Figure 4.33 Comparison of grain size distribution pattern of the 2004 tsunami sediments on Yala (Transect 3) between 2004 and 2007.

4.7.1 Variation of grain size statistics from 2004 -2007 along the Transects 3

Mean grain size, sorting index, skewness and kurtosis variation along the Transect 3 show some distinguishable characteristics. Mean grain size and kurtosis show significant differences towards the coast in this time interval but inland the sediment is preserved unchanged. Variations of sorting index and skewness do not show much difference (Figures 4.34, 4.35, 4.36 and 4.37).

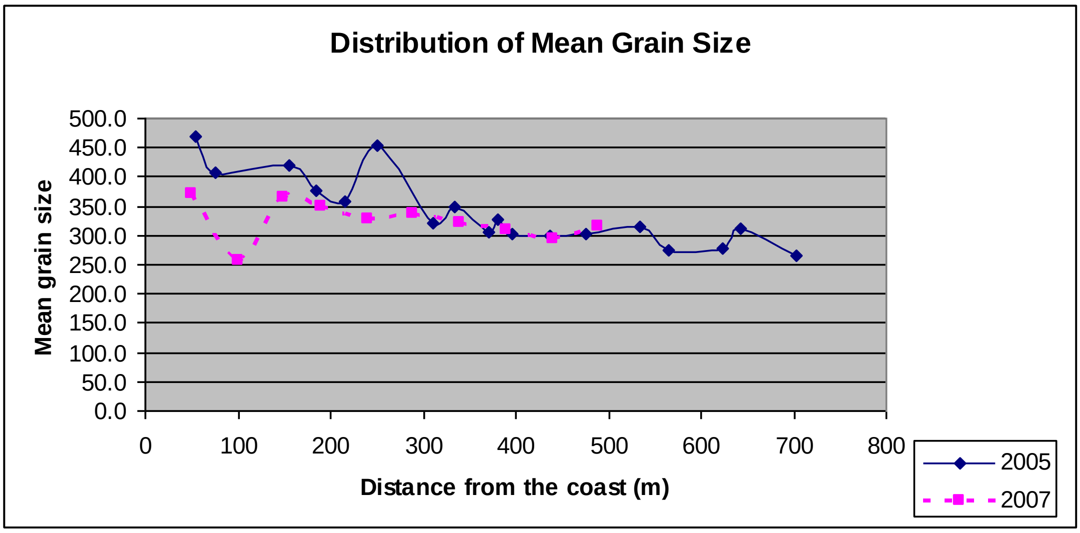


Figure 4.34 Comparison between tsunami sediments in 2005 and 2007 of mean grain size (μm).

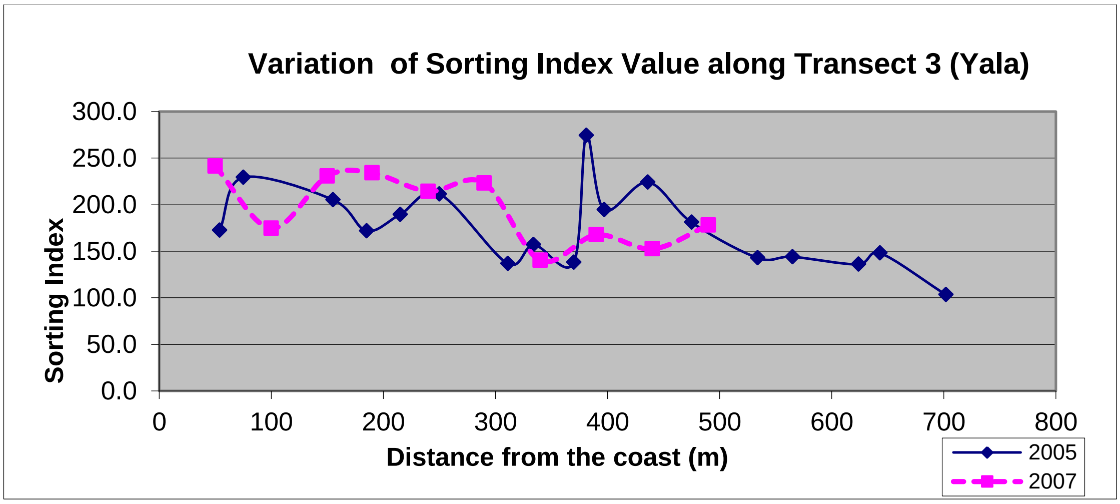


Figure 4.35 Comparison between tsunami sediments in 2005 and 2007 of sorting index.

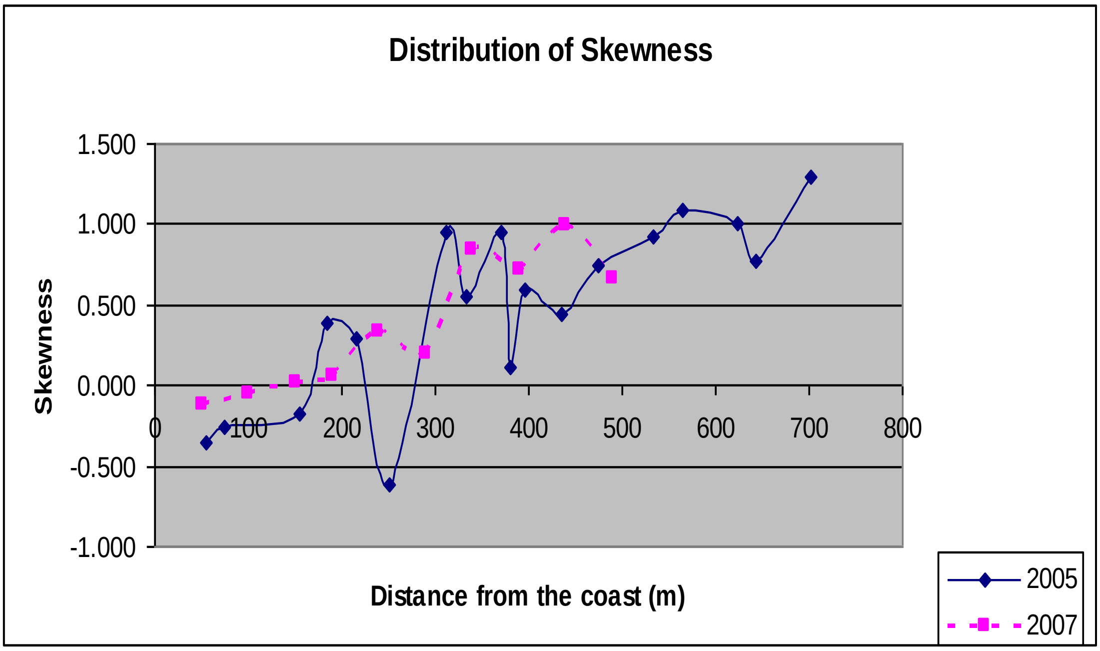


Figure 4.36 Comparison between tsunami sediments in 2005 March and 2007 of skewness.

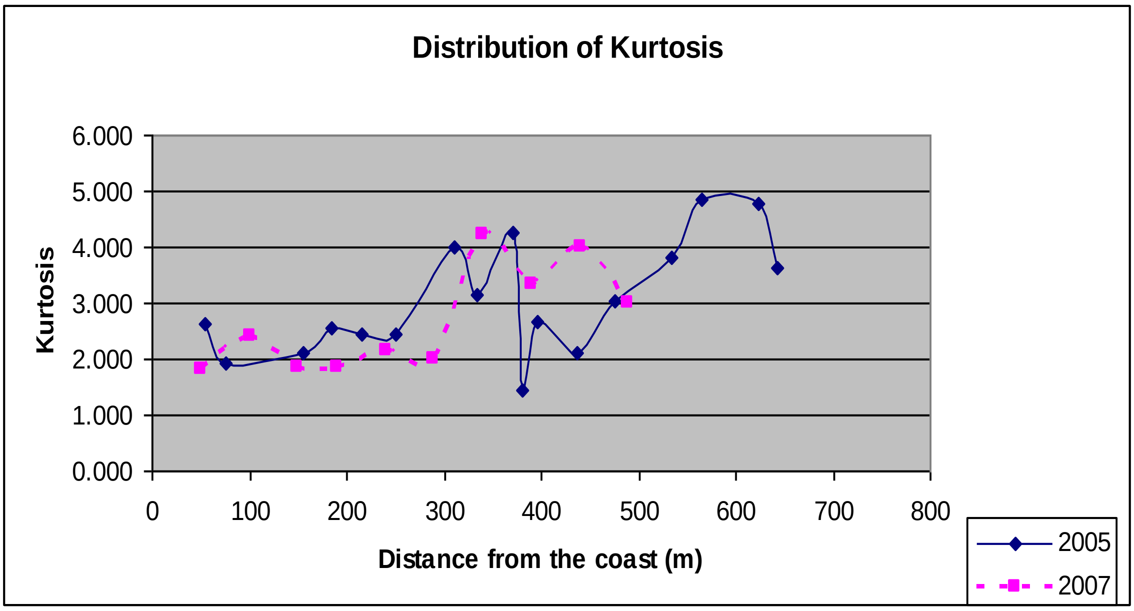


Figure 4.37 Comparison between tsunami sediments in 2005 March and 2007 of kurtosis.

4.7.2 Implications of changing sediment characteristics for palaeotsunami studies

Our observations reveal that the effects of natural processes are higher towards the coast and affect mostly the uppermost parts of the deposits as might be expected. Therefore, the impact of natural causes is very small on thick deposits which were deposited far-inland. Grain size statistical characteristics on transect 3 which had thick sediment deposits were preserved after three years while on transects 1 and 2 the characteristics were not preserved. Our results suggest that, grain size statistics would be the most reliable indicator for the identification of large palaeotsunamis which penetrate further inland and deposit thick sediment deposits.

4.8 Signature of the 2004 tsunami sediments on the Sri Lankan coast

1. Tsunami sediment deposition is greatly dependent on local topographical variation and the nature of back wash flow. The sediment mainly consists of poorly sorted medium to coarse sand.
2. Sediments often show heterogeneity.
3. The first 50 to 75 m distance from the coast was mainly subjected to erosion than deposition.
4. Depositional pattern is mainly dependent on local topographical variations.
5. No strong relationship exists between sediment thickness and wave characteristics such as wave direction or run up heights.
6. Mineralogically, tsunamigenic sands are rich in quartz and feldspars minerals with other heavy or opaque minerals with Fe/Mg silicate minerals present as tracer amount compared to normal beach sand (Herath, 1985).
7. Grain size distribution has a mainly polymodal pattern. Strong negative correlations between mean grain size and kurtosis and mean grain size and skewness are prominent features of the tsunami sediments.

8. Unique grain size statistical correlations exist between mean grain size and skewness (r = -0.8 to -0.9) and between mean grain size and kurtosis (r = -0.6 to -0.9)
9. Grain size distribution patterns show mostly bimodal and polymodal patterns with poor sorting.
10. Tsunami sands showed mechanical fracturing at microscopic scale, how it was hard to explain the mechanism of fracturing from the present study.
11. Tsunami sands are not identical to normal beach sand in composition, texture structure and most other physical characteristics.
12. With time, the uppermost layer of the tsunami sediments can be altered by natural environmental causes. However the effect decreases inland and the impact on thicker deposits is very small.

The specific characteristics of the 2004 tsunami sediments reveal some valuable information about the nature of the tsunami wave action all around the coast. The hydrodynamic conditions during the sediment deposition could be potentially extracted from these characteristics. Furthermore, these characteristics provide a strong identifying signature of the tsunami sediments.

CHAPTER 5

PALEOTSUNAMI SEDIMENTS

5.1 Introduction to palaeotsunami studies

Historic tsunamis are known as palaeotsunamis. A Tsunami is one of the most devastating hazards which may occur on any coastal environment. Information on palaeotsunami records can be derived from archaeological, geological or historical records (Dominey-Howes, 2007). However, archaeological and historical records alone do not provide enough reliable information. Therefore, correlations of the archaeological and historical records with geological records using advanced scientific methods are always necessary. Archaeological and historical records are usually restricted to particular time periods, but geological records may provide information far beyond the time limits of archaeological and historical records.

Three key problems have been identified in palaeotsunami studies as:

(1) Definitive identification of palaeotsunami records

(2) Dating and correlation of events with other records

(3) Quantification of the events

5.2 Identification of palaeotsunami on the Sri Lankan coast; the Indian Ocean

Two main tsunamis have been reported by historical and archaeological records in Sri Lanka (Hardy, 1866; Codrington, 1994). The oldest event was recorded about 200 BC (Mahawamsa; Great Chronicle of Sri Lanka) and the second event was in 1883, the well-known Krakatau eruption tsunami (Choi *et al*., 2003; Pelinovsky *et al*., 2005; Stromkov *et al*., 2005). This was also recorded by the Newspaper "*The Ceylon Observer of 27th August 1883*" as tsunami waves a few meters high hit the Sri Lankan coast within an hour of the eruption. However, these events have not been properly supported by observational scientific evidence from the Sri Lankan coast.

Detailed field and laboratory studies on tsunami sediments from the Sri Lankan coast were carried out in order to recognize palaeotsunami events. This study included surface field mapping, trenching/sampling, sedimentological and palaeontological analyses, dating using OSL technique and mapping of the subsurface distribution of palaeotsunami sediment layers using the GPR technique.

5.2.1 Field, sedimentological / granulometric, mineralogical, textural characteristics of palaeotsunami sediments on Sri Lankan coast

After preliminary field surveys, possible sites for detailed follow-up investigation of palaeotsunami records were selected. Detailed field and laboratory analyses were carried out on two selected sites at Hambantota and Yala on the south and southeast coasts of Sri Lanka (Figure 3.4). Subsequently, stratigraphic and structural analyses in the field and granulometric, mineralogical and textural and physical characteristics analysis were performed.

5.2.1.1 Location 1: Hambantota, south-eastern coast of Sri Lanka

Location one was on a flat beach ridge adjacent to Hambantota-Mahalewaya lagoon showing rich sediment deposition.

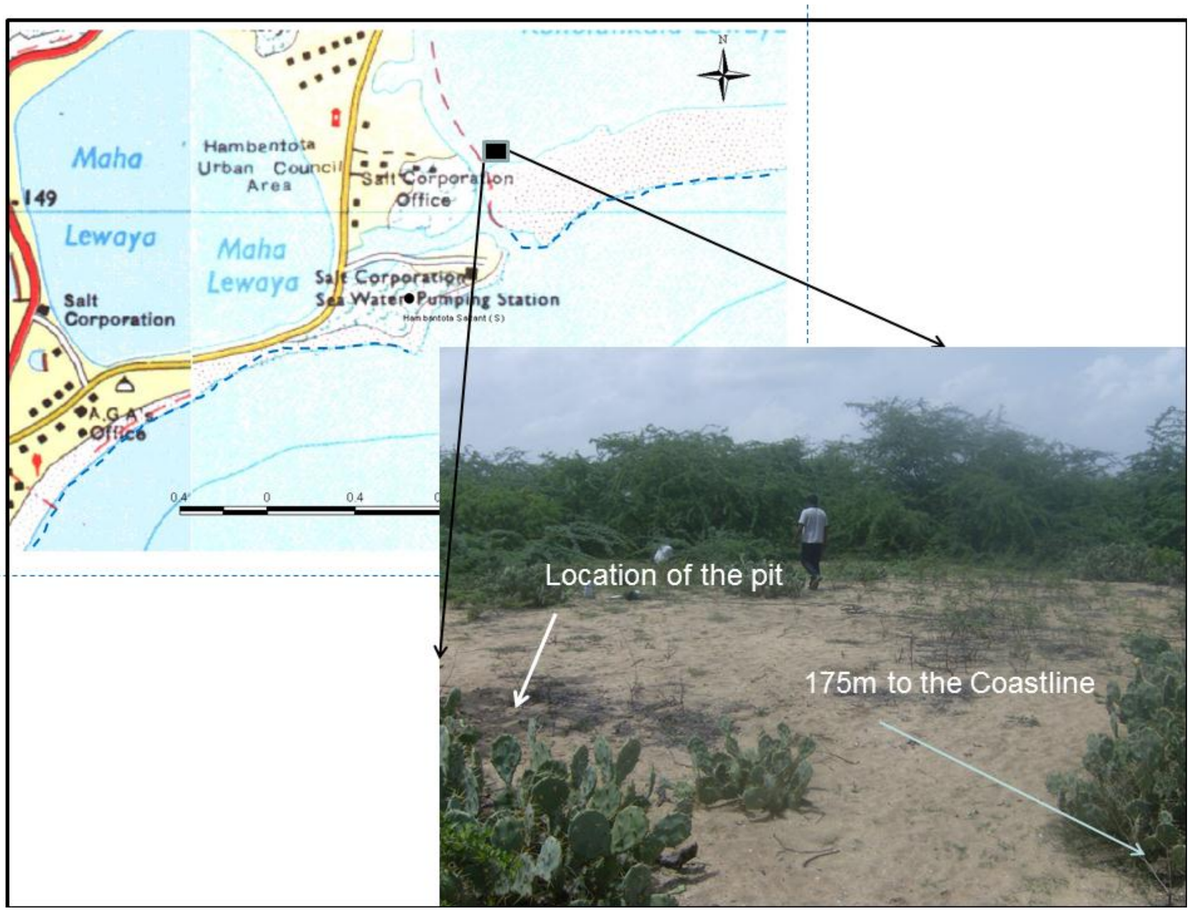


Figure 5.1 Location of the pit dug for palaeotsunami studies at Hambantota (Location 1)

A pit, located about 175m inland, (Figure 5.1) was dug to 1.5m depth until it reached the lagoon clay bed. This area was severely affected by the 2004 tsunami and a few centimetres thick sediment deposit was observed. Then several sequences of sediment layers were observed in the pit. They were closely studied.

The stratigraphic section displays conspicuous layering in the sandy sediments. The 2004 tsunami sediment (S1) was clearly identified lying on top of the peaty original ground. It was also possible to isolate a further two layers (S5 and S7) comprising light coloured, coarse-grained sediments with properties distinct from the background sediments (Figure 5.2).

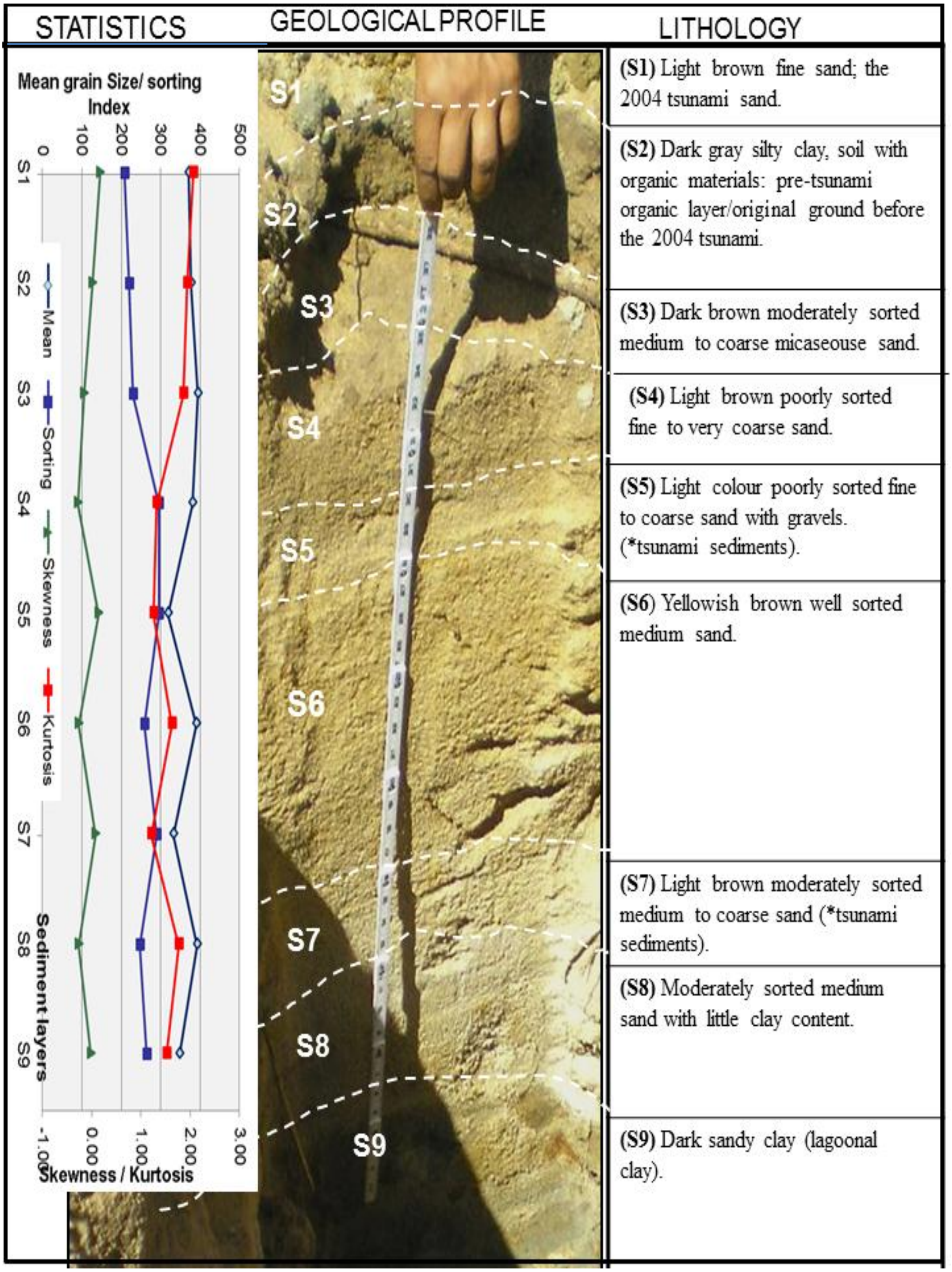


Figure 5.2 Palaeotsunami sand layers associated with normal beach sand and some fluvial sand beds on the lagoonal clayey sand at Location 1, Hambantota, south-eastern coast (different sediment layers of the sequence are labelled as S1, S2 up to S9).

According to the grain size statistical analyses, layers S5 and S7 show meaningful correlations between mean grain size and skewness / kurtosis which are similar to the 2004 tsunami sediment; i.e. when skewness increases, mean grain size and kurtosis decrease (Figure 5.2). There is a negative correlation between mean grain size skewness, while other sediments in the sequence do not show such correlations. The grain size distribution pattern of the tsunamigenic sediments on the profile shows some characteristic patterns, which differ from other sediments on the coast. However, they are not consistent with the general pattern identified from the 2004 tsunami sediment. The 2004 tsunami sediments commonly show a poly-modal distribution, while palaeotsunami sediment at this location does not. An increasing coarsening fraction is exhibited by these sediments (Figure 5.3).

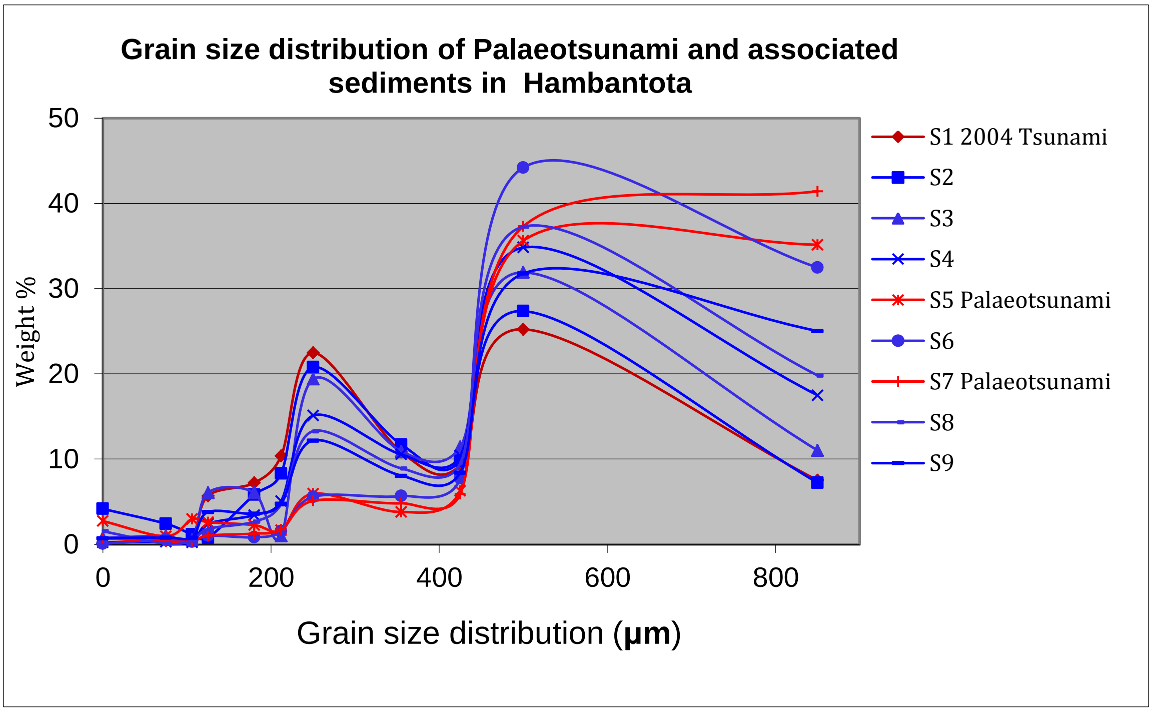


Figure 5.3 Grain size distribution patterns of palaeotsunami sediments with associated other beach sediments, Location 1, Hambantota, south coast of Sri Lanka.

Petrographic Studies at Location 1

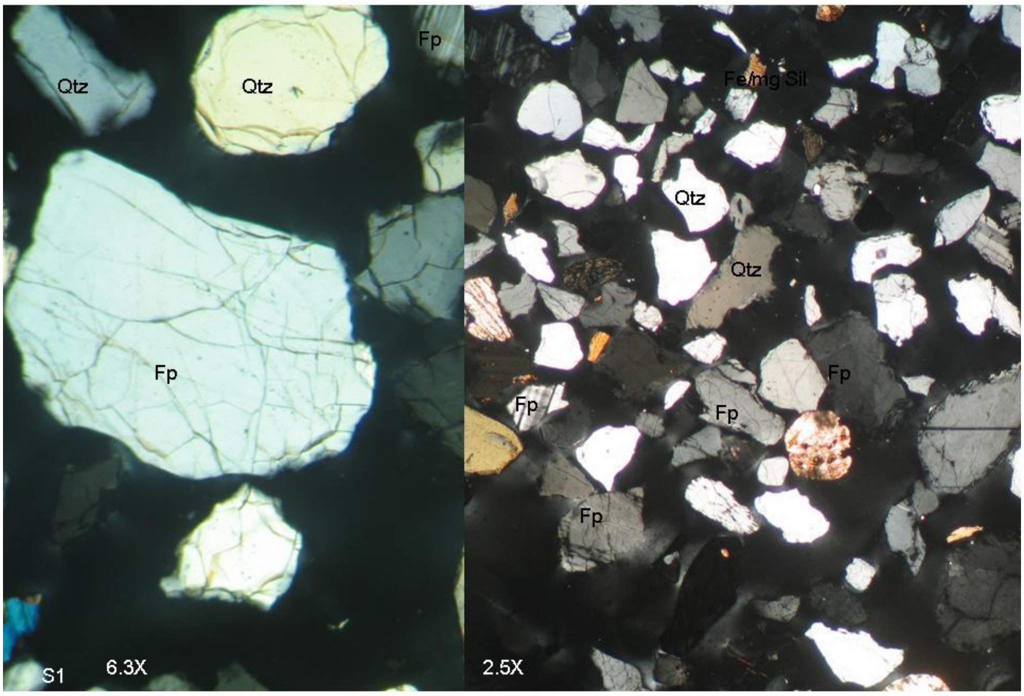


Figure 5.4a: Layer S1

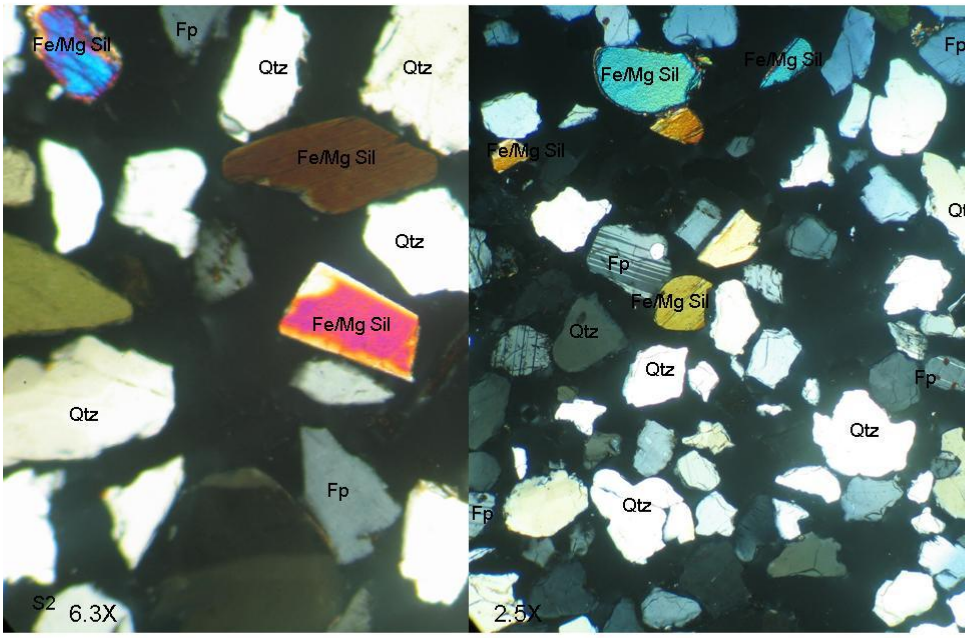


Figure 5.4b: Layer S2

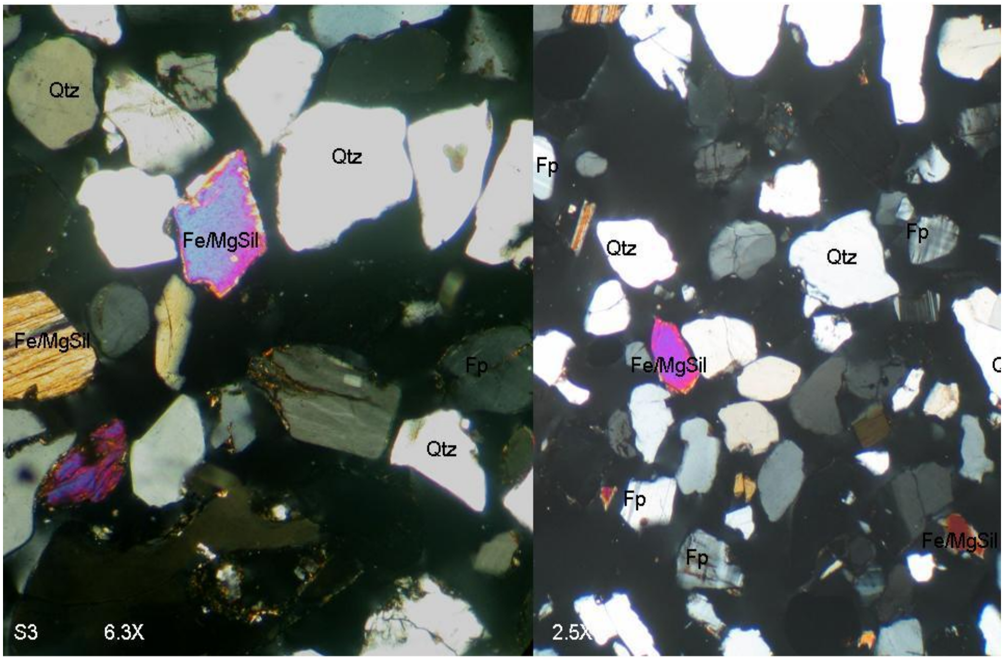


Figure 5.4c: Layer S3

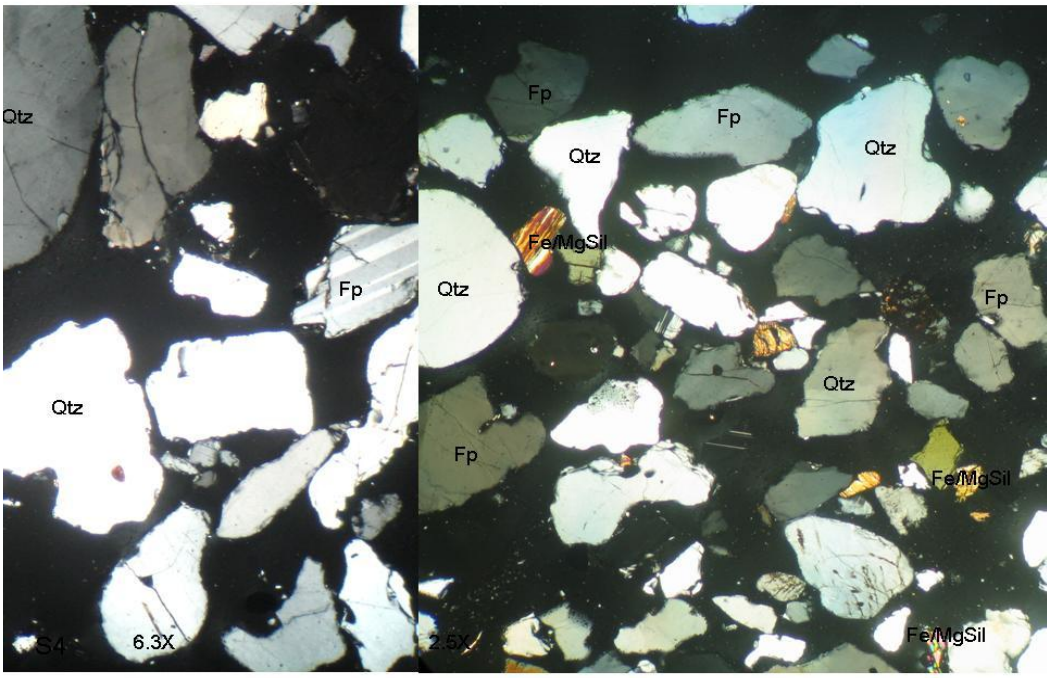


Figure 5.4d: Layer S4

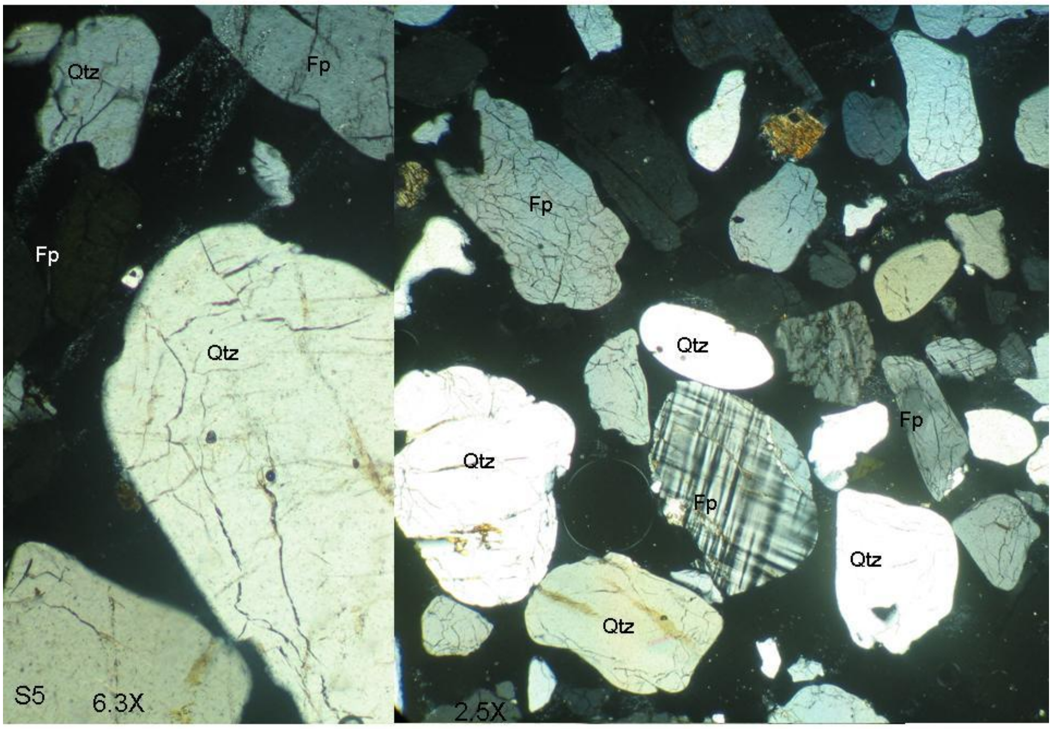


Figure 5.4e: Layer S5

Figure 5.4 (a-e) Micro-petrographic pictures of different sediment layers of coastal sediment sequences at Hambantota (Location 1).

Tsunamigenic sediments of layers S1 and S5 are poorly sorted comprising a wide range of grain sizes from fine to very coarse. Also sediments of S1 and S5 mainly comprise well-rounded to angular grains of quartz and feldspars with trace amounts of opaque and Fe-Mg Silicate minerals. Most of the quartz and feldspar grains present micro-fracturing (Figure 5.5a and 5.4e). Non-tsunami sediment layers of S2, S3 and S4 comprise mainly fine to medium, moderately to well sorted, angular to sub rounded sands. Mineral composition was mainly quartz, and feldspars with it a characteristic feature being that they are more opaque and Fe/Mg-silicate minerals than are seen in tsunamigenic sediments; (Figures 5.4b, 5.4c, 5.4d).

5.2.1.2 Location 2: Yala, southeast coast of Sri Lanka

Location two was on flat ground at the boundary of Yala National Wild Life Park. The location was severely affected by the 2004 tsunami which caused massive damage here (Figure 5.5).

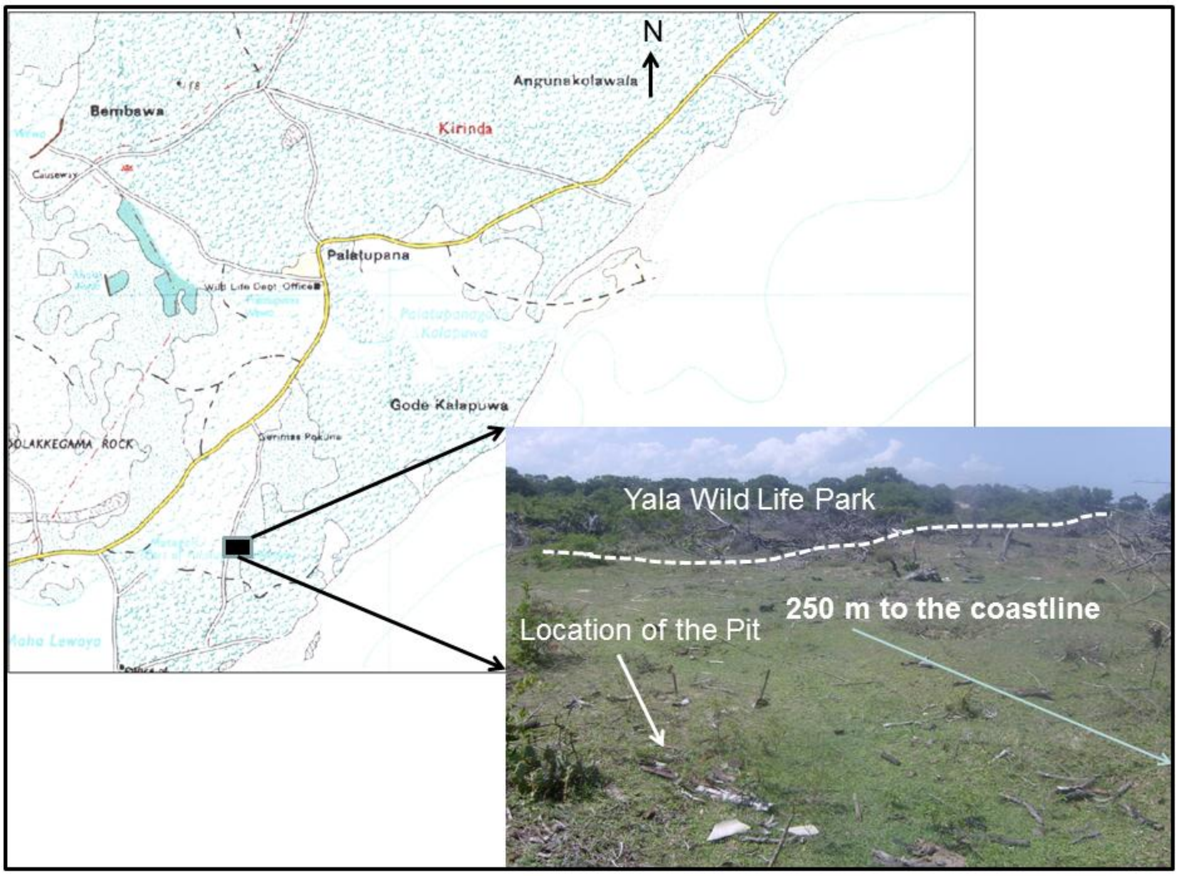


Figure 5.5 Location map of the palaeotsunami studies carried out at Location 2 Yala.

(A Pit was dug to 1.5m depth at 250m inland and studied the sediment profile).

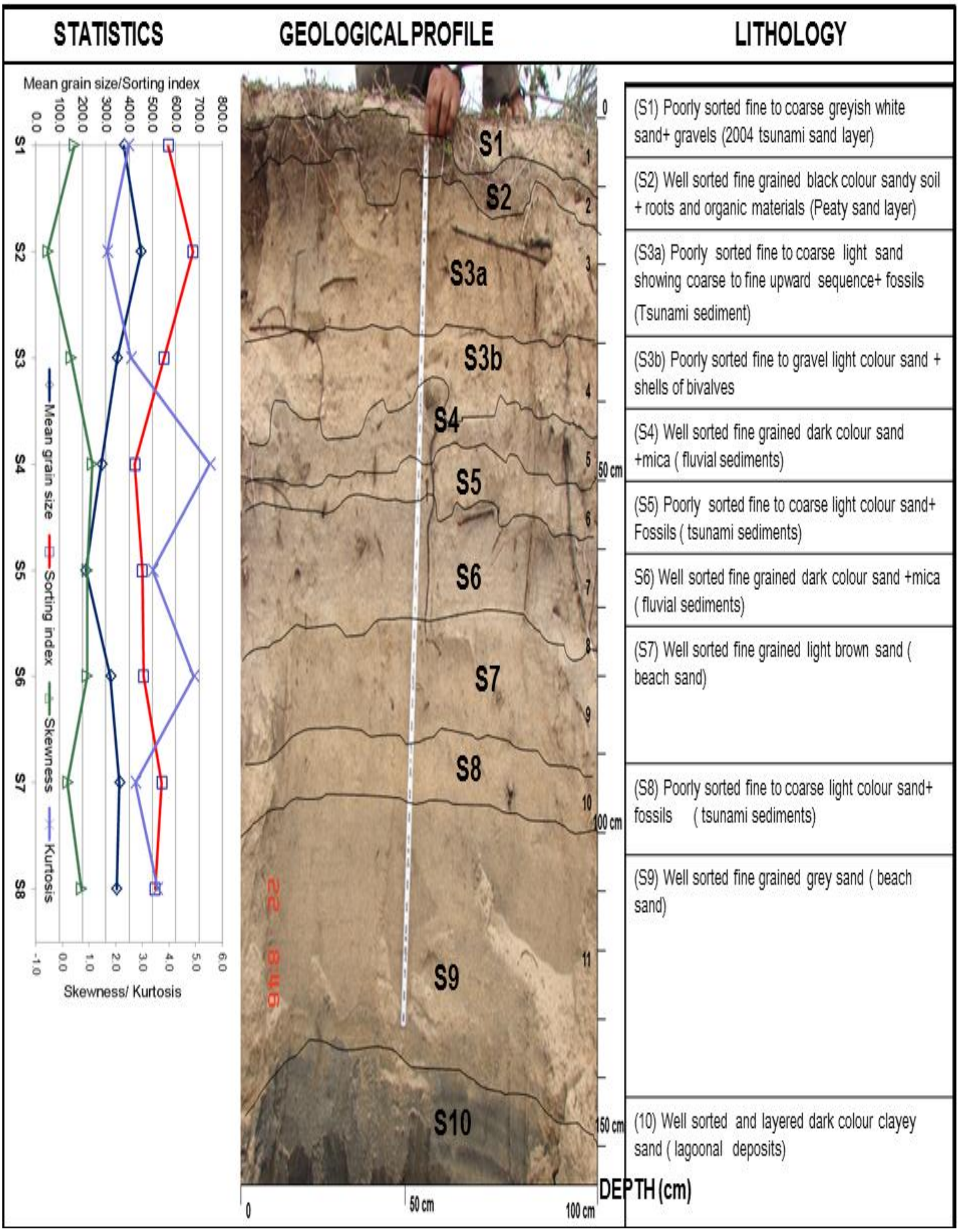


Figure 5.6 Tsunami sand layers associated with normal beach sand and fluvial sand beds overlying the lagoonal clayey sand at Location 2, Yala, south-eastern coast of Sri Lanka.

The sediment sequence at this location shows well-marked sediment layers with different textural/structural properties and colour. The top-most layer of the sequence was the 2004 tsunami sand deposit which was recognised from its erosive lower contact with peaty ground. Three other light colour coarse grained sediment layers (S3, S5 and S8) have been identified as tsunamigenic (palaeotsunami) sediments and are clearly distinguishable from other coastal beach sediments on the profile.

Tsunamigenic sediment layers (S3, S5, and S8) show correlations between grain size statistical parameters, mean grain size, sorting index, skewness and kurtosis which are distinguishable from other sediments on the profile (Figure 5.6). However, the grain size distribution patterns of tsunamigenic sediment do not differ greatly from other sediments, showing similar poly-modal distributions and increasing coarsening fractions (Figure 5.7).

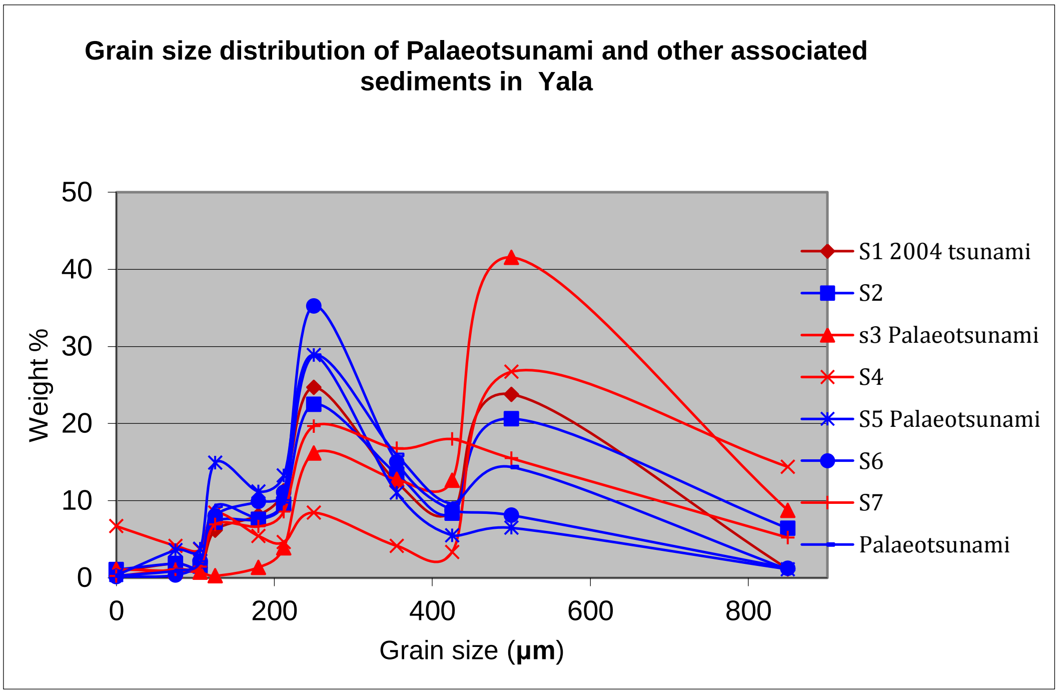


Figure 5.7 Grain size distribution patterns of palaeotsunami sediments and associated other beach sediments, Location 2 (Yala), southeast coast of Sri Lanka.

Micro-petrographic analysis

The tsunamigenic sediments of location 2 show similar micro-petrographic characteristics to those of location 1-a; poor sorting from fine to coarse sand, presence of micro-fracturing, large quartz and feldspar grains, angular to well-rounded mixture of grains and very low Fe-Mg silicate and opaque mineral content (Figure 5.8). The sections of layers 4 and 6 (Figure 5.8b and 5.8d) which are non tsunamigenic sediments show relatively lower grain size and are well sorted nature together with a higher composition of Fe- Mg minerals.

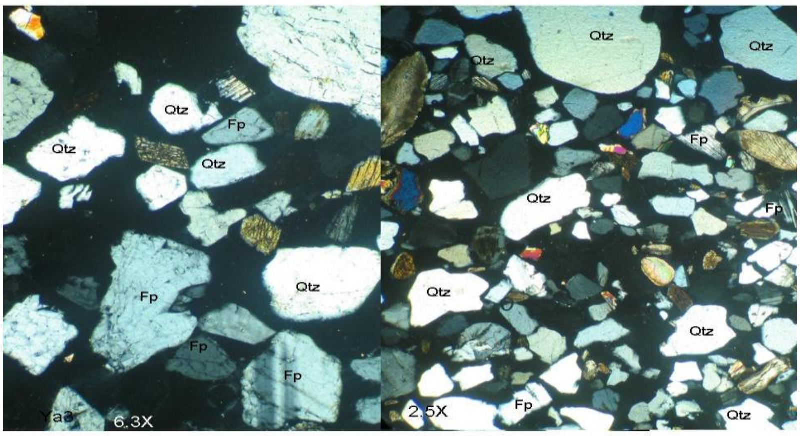


Figure 5.8a: Layer S3

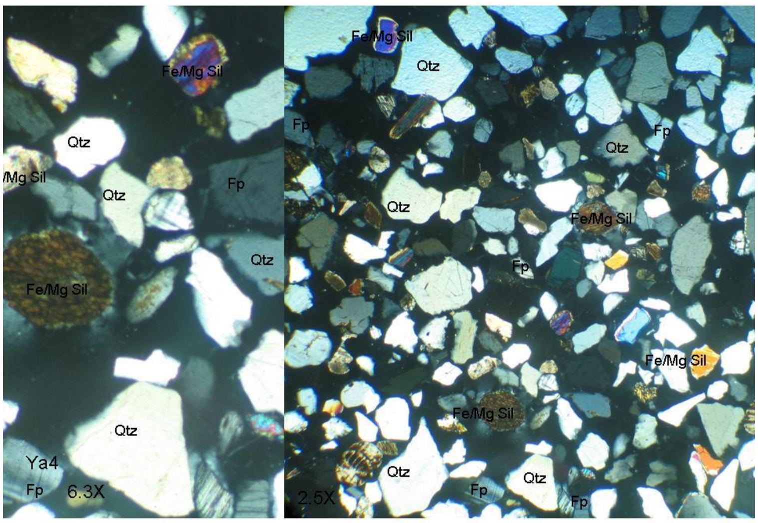


Figure 5.8b: Layer S4

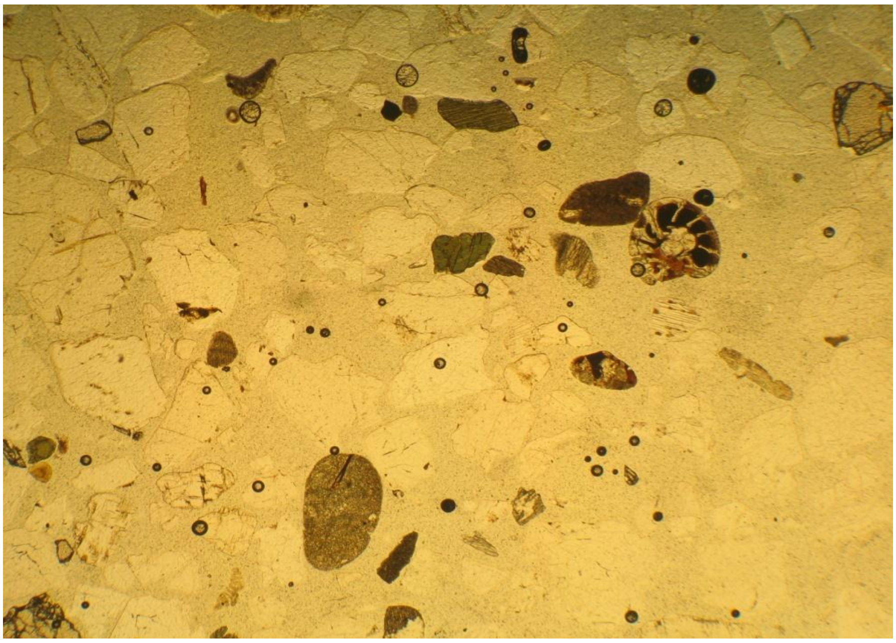


Figure 5.8c: Layer S5

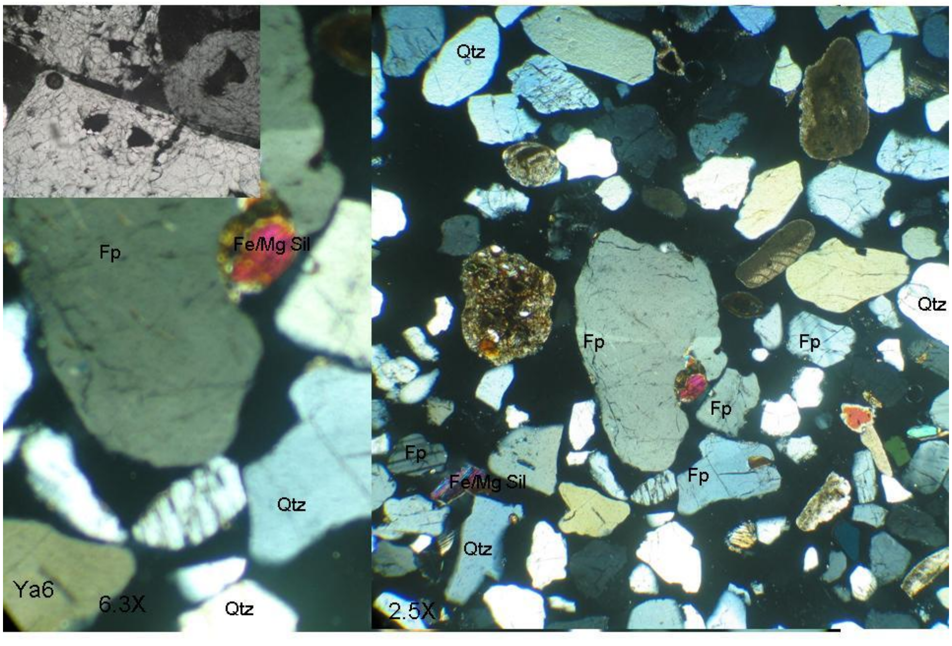


Figure 5.8d: Layer S6

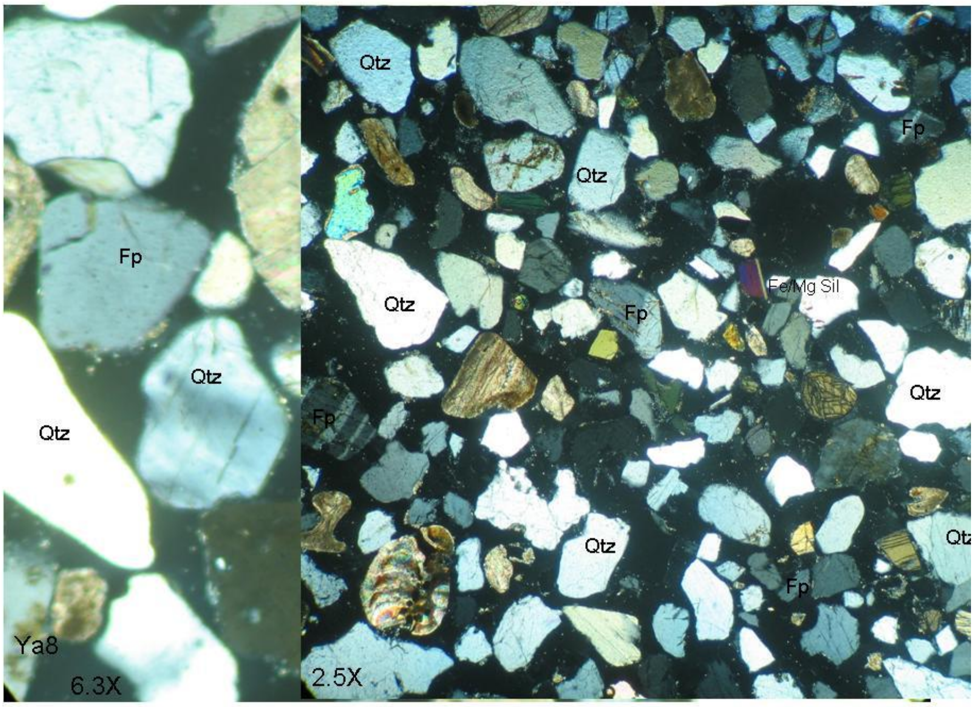


Figure 5.8e: Layer S8

Figure 5.8 a-e Micropetrographic pictures of sediments at the Location 2, Yala.

5.2.2 Sites of suspected palaeotsunami sediments on the Sri Lankan coast

Suspected palaeotsunami sediment deposits were identified at a few more locations from the preliminary field survey but it was not possible to carry out detailed studies at these locations due to security restrictions which were enforced after the tsunami and also within a highly restricted wildlife sanctuary. However, preliminary field observations identified some locations which had potential for palaeotsunami sediment depositions.

5.2.2.1 Location 3: Mahaseelawa, southeast coast of Sri Lanka

A light colour medium to coarse sand layer was identified in a lagoonal clay bed at about 300m inland in Mahaseelawa lagoon (Figure 5.10). The deposit was over 10 cm thick and showed clear contacts between the lower and upper margins. The light coloured sandy deposit contained mud clasts. The 2004 tsunami sand was deposited on the top of this sequence. The suspected tsunami sand deposit was sandwiched within sticky clay bed (lagoonal).

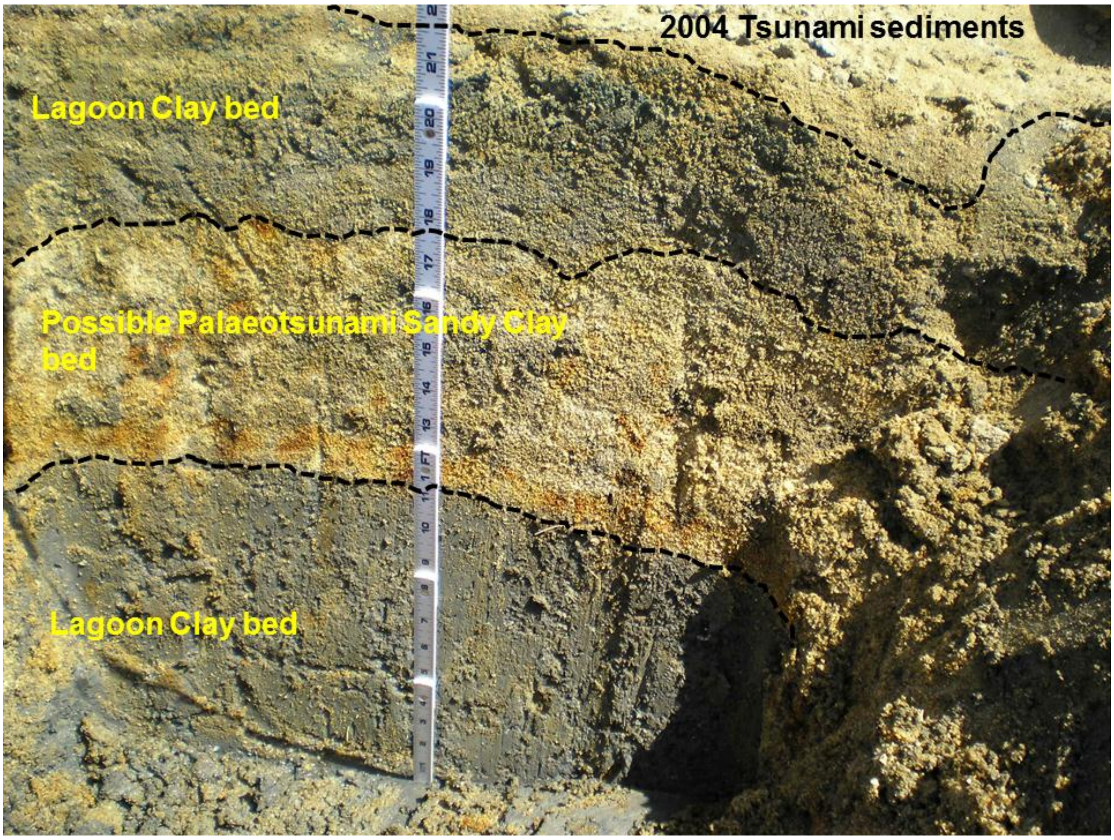


Figure 5.9 Well-preserved light coloured tsunami sand deposits within dark lagoonal clay at Mahaseelawa, southeast coast of Sri Lanka.

5.2.2.2 Location 4: Palatupana lagoon, southeast coast of Sri Lanka

Palatupana lagoon extends a few kilometres inland (Figure 5.10), but presently only the lower part (for a few hundred meters inland) of the lagoon area is under water during high tide. An auger hole (1.5 meter deep) was recovered about 1.6km inland in the lagoon and unmixed samples were collected and examined in the field.

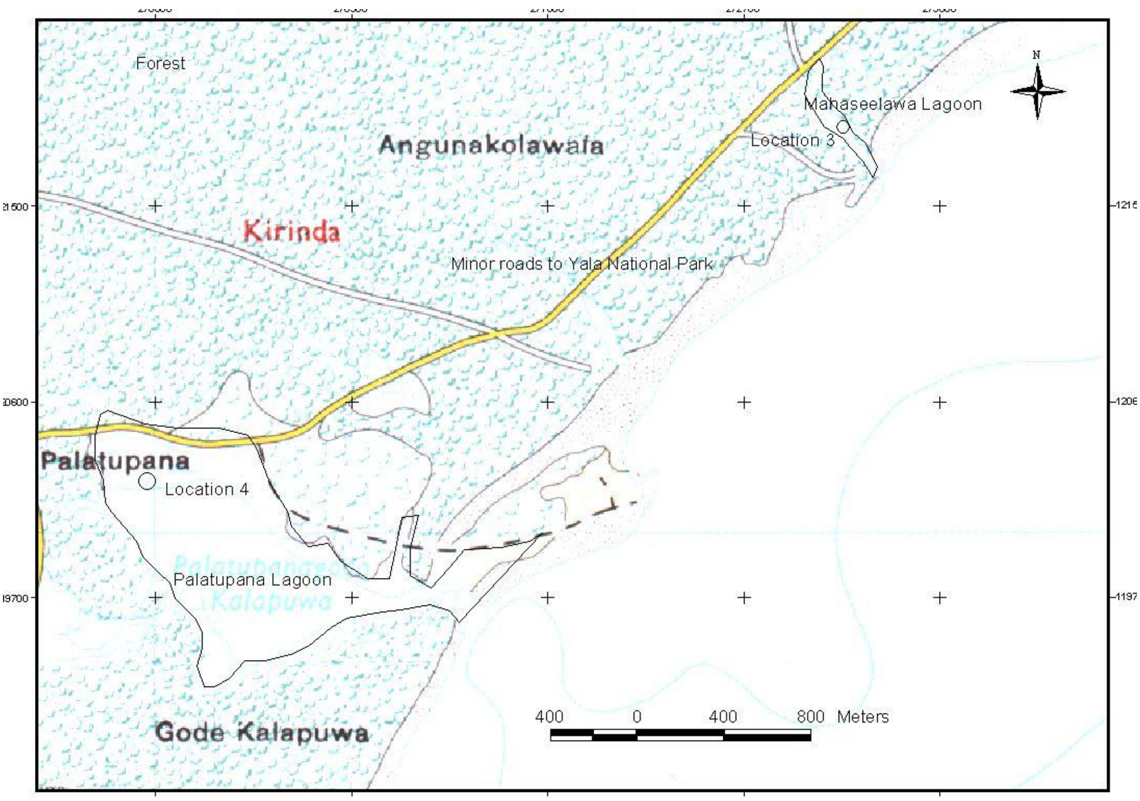
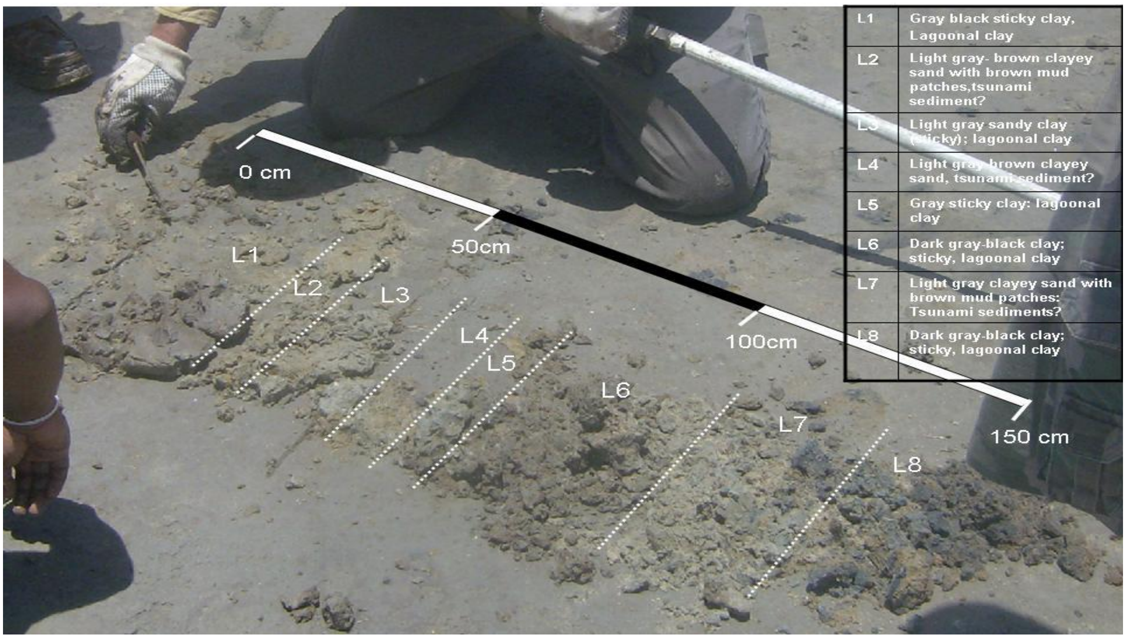


Figure 5.10 Location Maps of Mahaseelawa and Palatupana lagoons.

According to the field observations, three sediment layers were observed which were suspected to be tsunami sediments because all these three layers comprise poorly sorted, light grey clayey sand while all the other sediment layers were sticky lagoonal clay (Figure 5.11). Therefore, the sand deposition in this lagoonal environment must be due to a highly energetic process with the most likely event being tsunami waves as the location is too far from the coastline at this point for storm surges to deposit sediment.



L1	Grey black sticky clay, Lagoonal clay
L2	Light grey- brown clayey sand with brown mud patches, tsunami sediment?
L3	Light grey sandy clay (sticky); lagoonal clay
L4	Light grey brown clayey sand, possible tsunami sediment.
L5	Grey sticky clay: lagoonal clay
L6	Dark grey-black clay; sticky, lagoonal clay
L7	Light grey clayey sand with brown mud patches: Possible palaeotsunami sediments layer.
L8	Dark grey-black clay; sticky, lagoonal clay

Figure 5.11 Lithological log of the auger-hole samples at Palatupana lagoon (1.5 km inland), southeast coast of Sri Lanka showing preservation of possible tsunamigenic sand deposits within lagoonal clay: L1 to L8 are sediment layers recognised in the hole.

5.3 Geological evidence for the occurrence of palaeotsunami on the Sri Lankan coast

According to field and depositional characteristics, textural and grain size characteristics, physical and mineralogical evidence, three palaeotsunami events have been identified, from particular coastal geological profiles around Yala and Hambantota (Figures 5.2, 5.6). All these suspected tsunami sediment layers could be clearly distinguished from the depositional characteristics; very often with light coloured coarse sand layers associated with fine sand or clay beds.

Also, tsunamigenic sediment layers were isolated using grain size statistical characteristics. Tsunamigenic sediment have some distinctive correlations between mean grain size, sorting index, skewness and kurtosis; particularly anti-correlation between mean grain size and kurtosis, but feature poly-modal distributions which are not seen as a characteristic feature from this study. However, increasing coarsening fractions of the sediments could be observed in both 2004 and palaeotsunami sediments. Further micro-petrographic studies reveal that tsunamigenic sediments are mostly poorly sorted and rich in coarse grain fractions and have lower composition of Fe-Mg minerals than beach sands. All the above characteristics could reliably discriminate tsunamigenic sediment layers from other coastal sediments while correlating strongly with the known 2004 tsunami sediment deposits on the same coast.

CHAPTER 6

MAPPING PALAEOTSUNAMI SEDIMENT DEPOSITS USING THE GROUND PENETRATING RADAR (GPR) TECHNIQUE

6.1 GPR survey on the Sri Lankan coast for mapping palaeotsunami sediment beds

Studies of palaeotsunami deposits on the Sri Lankan coast show tsunamigenic deposits are usually confined to certain specific locations on the coastal zone and are preserved within coastal sediment sequences or in low-lying marshy clay beds. As discussed earlier (Chapter 5) these sediments are often coarse-grained and poorly-sorted showing discrete textural character; their physical characteristics differ in many respects from other normal beach and lagoonal sediments. Distinguishable properties (textural and structural) of tsunamigenic sediment from other normal beach sediments, tsunamigenic sediments should give identifiable dielectric constant values. Thus, RADAR reflection could be used to demarcate those sediment beds. The lateral extent of the tsunamigenic deposit is a good proxy for determining the magnitude of palaeotsunami events.

Four GPR surveys were conducted on the southeast, south and the west coast of Sri Lanka, where two sites (1 and 2) were on confirmed palaeotsunami sediment beds using excavations and laboratory analyses. The other two sites (3 and 4) were located where there were no ground truth data or other evidence for palaeotsunami records as explained in Chapter 3 (Methodology).

6.1.1 GPR survey at Site 1: Yala southeast coast of Sri Lanka

At site 1, three palaeotsunami sediment layers were visually identified in the field from the excavated pit and confirmed to be tsunamigenic by laboratory analyses. The GPR survey line was planned normal to the beach crossing the pit which was dug for palaeotsunami studies (Figure 6.1). Three sediment layers could be traced over 250 m inland using the GPR studies (Figures 6.1 and 6.2). The palaeotsunami sediment layers were traced in a 1.5 meter thick sediment profile which comprised beds having varying thicknesses and continuity. The dielectric properties of sediment of each layer of the profile dug at Yala are shown in table 6.1.

Table 6.1 Dielectric properties of tsunamigenic and non-tsunami sediments at Yala, Sri Lanka (TS- Tsunamigenic Layers).

Sediment layer	S1 (TS)	S2	S3 (TS)	S4	S5 (TS)	S6	S7
Dielectric Constant K	6.27	8.53	6.32	9.92	4.19	7.58	7.43
K Upper error limit	7.32	9.77	7.61	11.13	4.66	4.66	8.99
Loss tangent	0.11	0.11	0.11	0.09	0.11	0.11	0.12
Attenuation dB/m	15.46	20.11	15.89	18.45	12.41	12.41	18.76
Velocity m/ns	0.120	0.103	0.119	0.095	0.146	0.146	0.109
Reflection Coefficient (Boundary between adjacent layer)	S1/S2 -0.0768	S2/S3 0.0748	S3/S4 -0.1122	S4/S5 0.2122	S5/S6 -0.1471	S6/S7 0.0049	

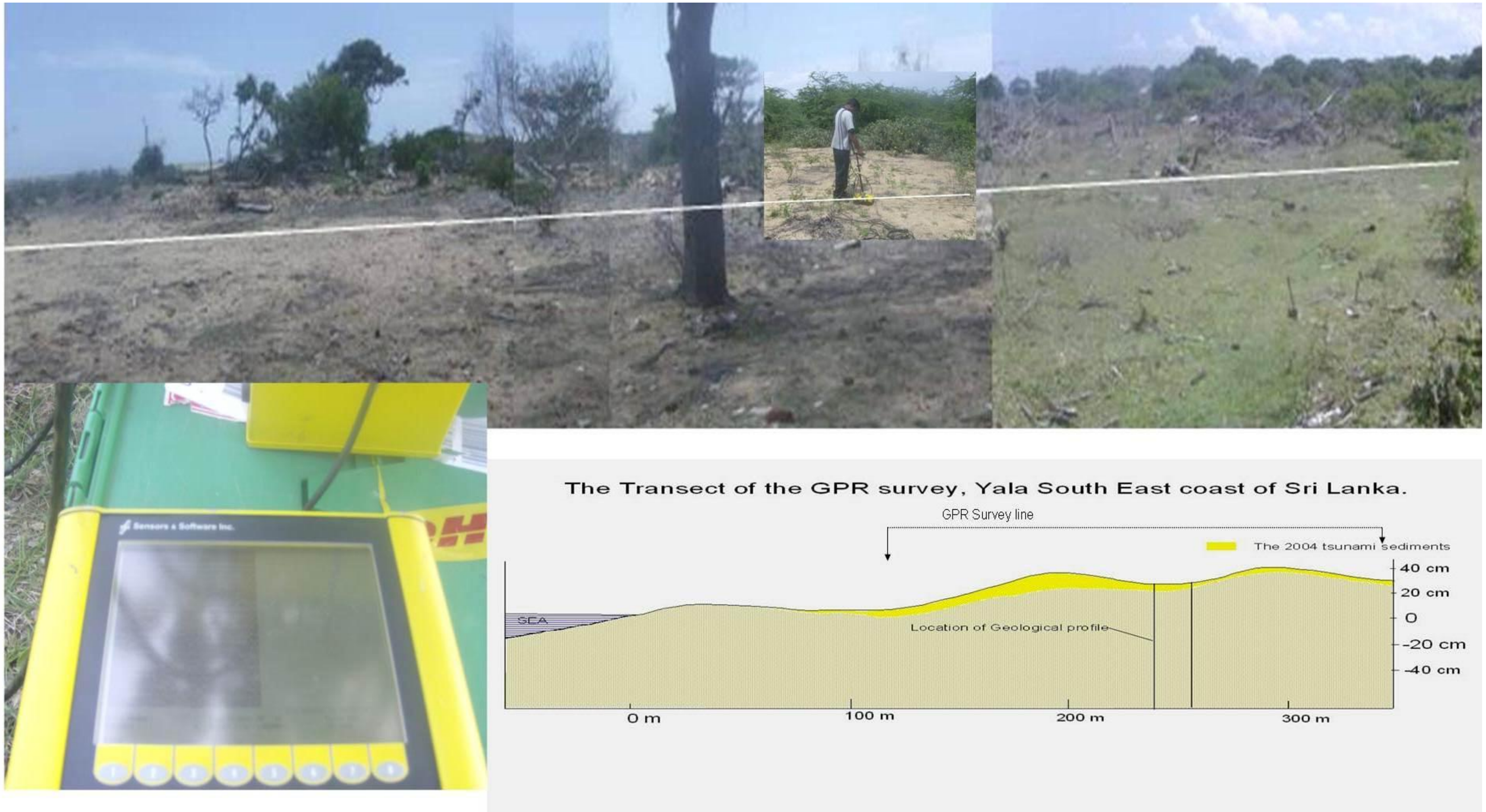


Figure 6.1 GPR survey line of palaeotsunami sediment at site 1-Yala.

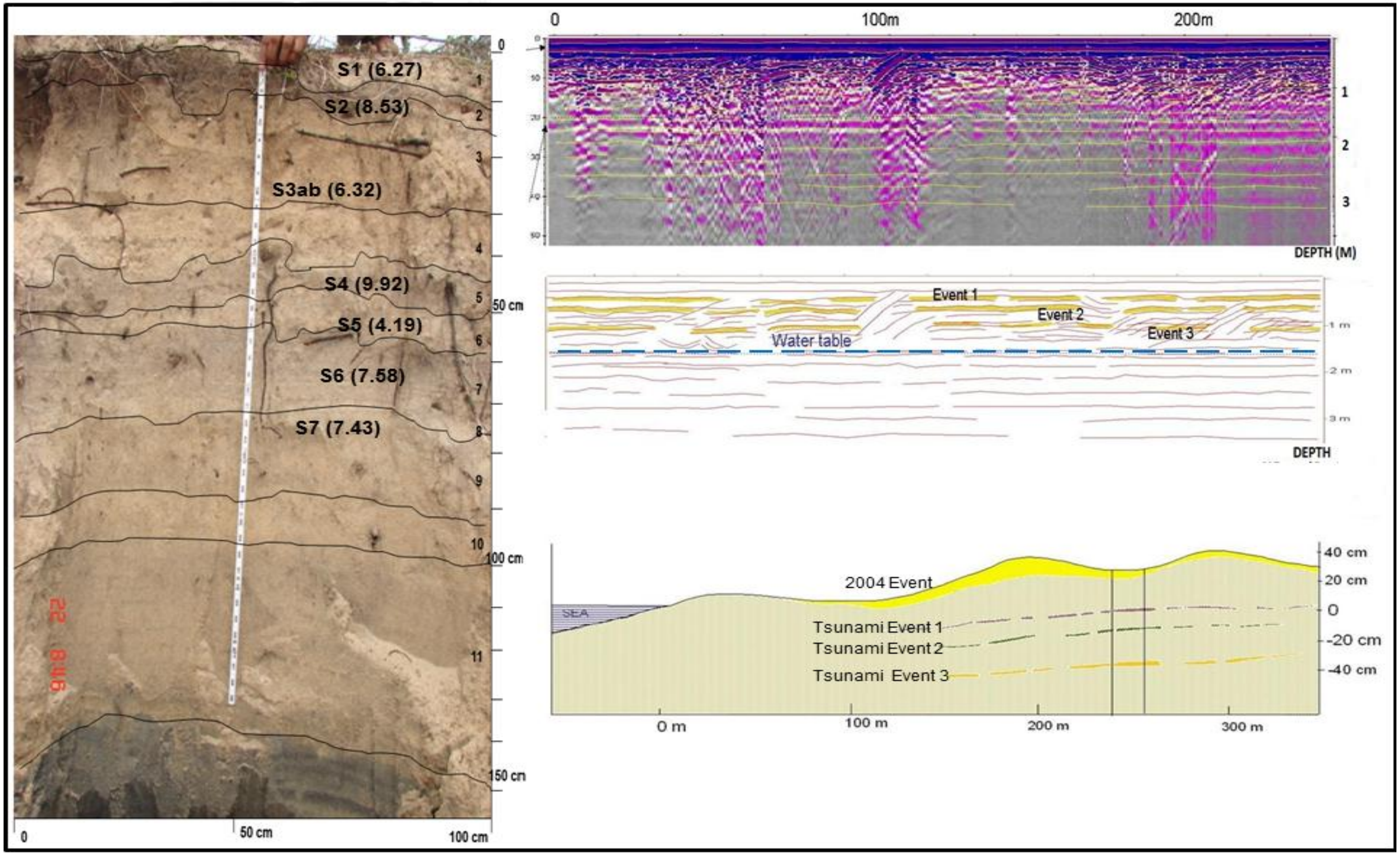


Figure 6.2 Interpretation of palaeotsunami sediment layers using the GPR technique at site 1-Yala ; S1 –S7 are Sediment Layers with Respective Dielectric Constant values (k)

6.1.2 Site 2: Hambantota

This site is situated 275m inland, close to Hambantota salt lagoon. At this location three GPR traverses were carried out at 2m intervals (Figure 6.3). Two tsunamigenic sediment layers (S5 and S7) identified in the trench were clearly traced from all three GPR profiles (Figures 6.4, 6.5 and 6.6), but could not be traced to greater distances due to the presence of marshland and a topographic break.

Figure 6.3 GPR survey Line 1, 2 and 3 at site 2- Hambantota, south-east coast of Sri Lanka.

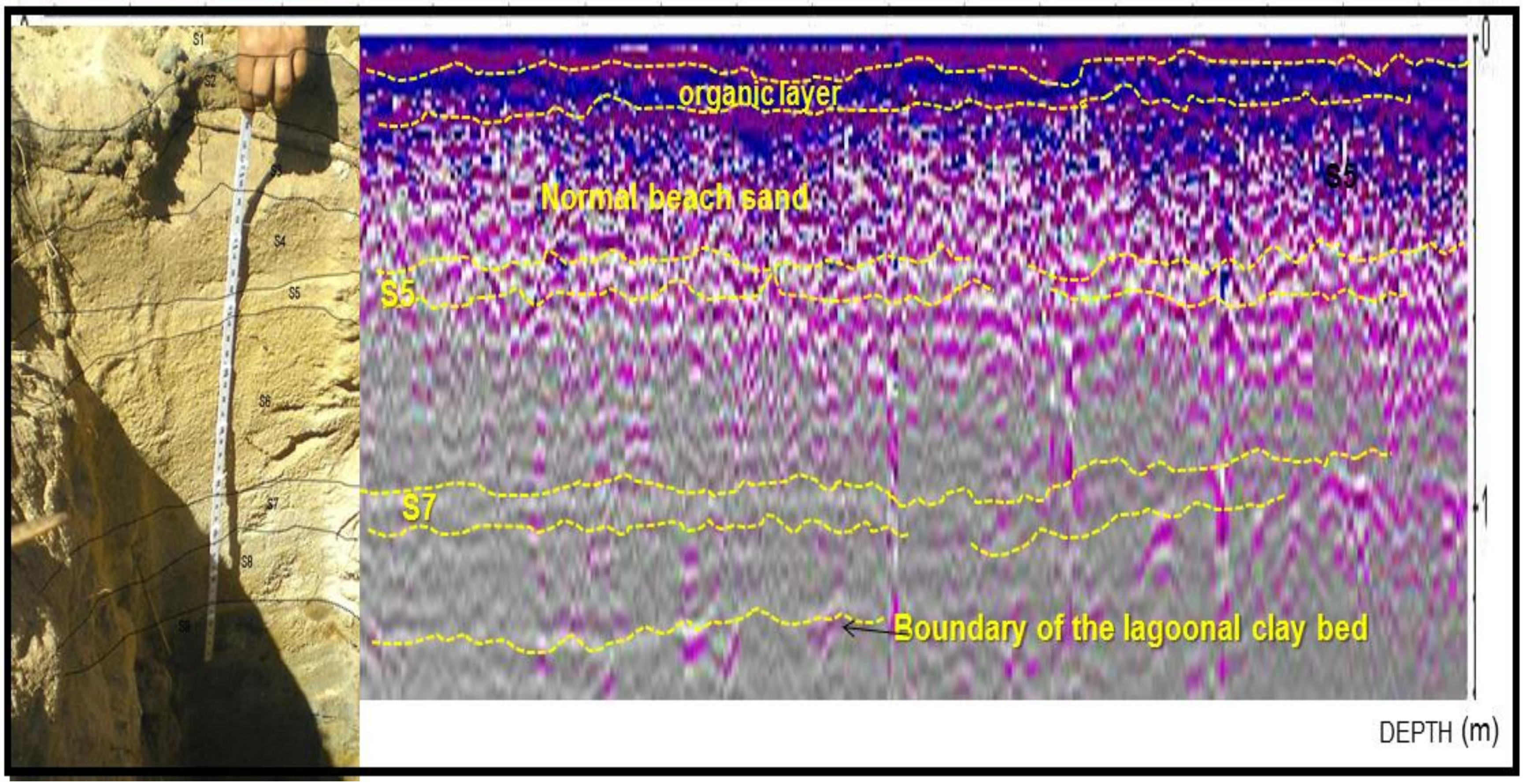


Figure 6.4 Interpretation of palaeotsunami sediment layers using the GPR section (LINE 1) at site 2, Hambantota.

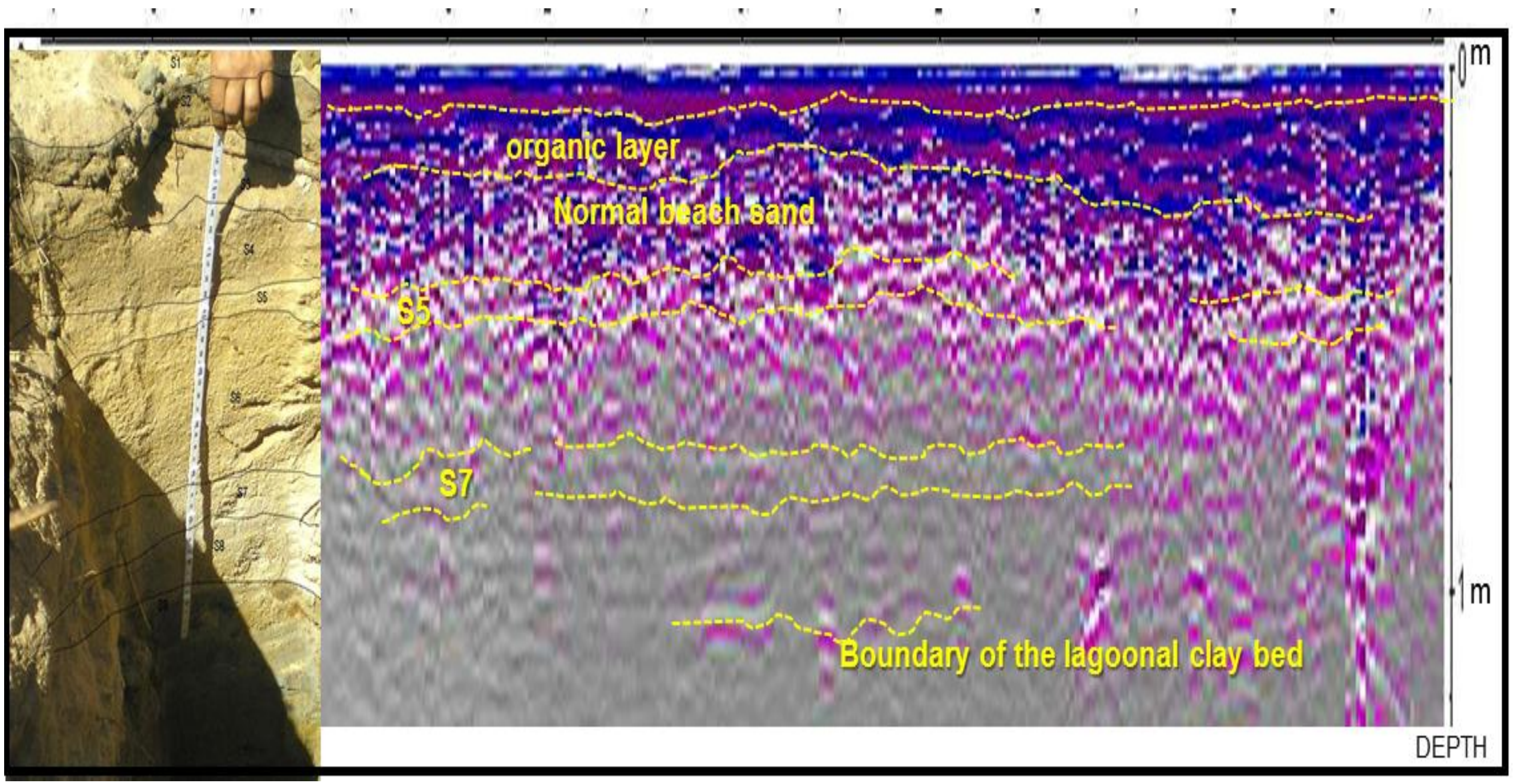


Figure 6.5 Interpretation of palaeotsunami sediment layers using the GPR section (LINE 2) at site 2, Hambantota.

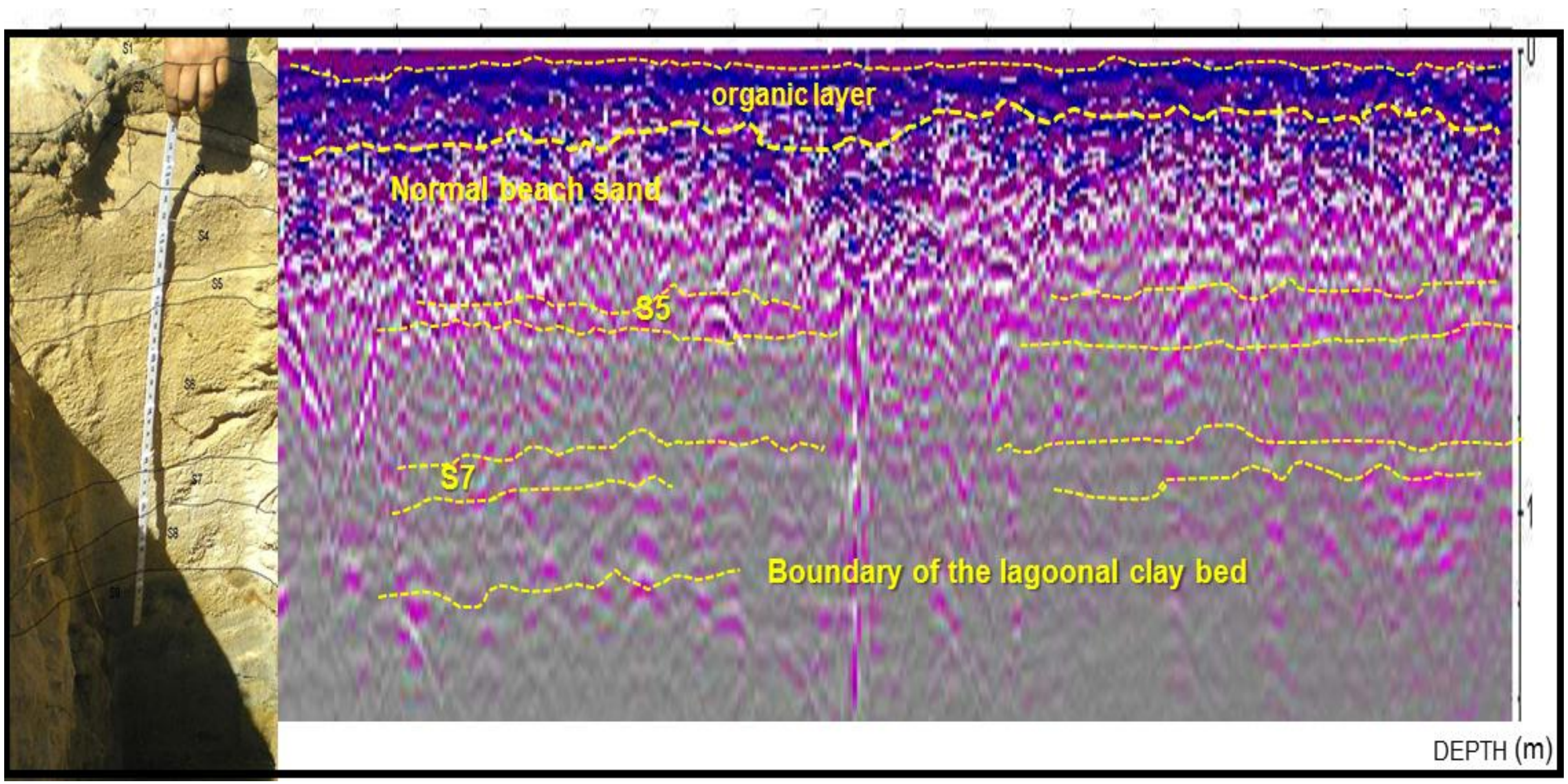


Figure 6.6 Interpretation of palaeotsunami sediment layers using the GPR section (LINE 3) at site 2,

6.1.3 Site 3: Dikwella, the South coast of Sri Lanka

A GPR survey was carried out over marshland close to the sea (Figure 6.7). There was a possibility of depositing tsunami sediment here, since it is low-lying marshland located close to the sea. However, the GPR section, gave no indication of the presence of coarse grained sand deposits inter-layered with the marshy clay beds. The upper-most part of the section showed layering due to man-made compaction on the marshland from a foot path. This is demonstrably different from previous profiles which are clearly tsunamigenic sand deposits.

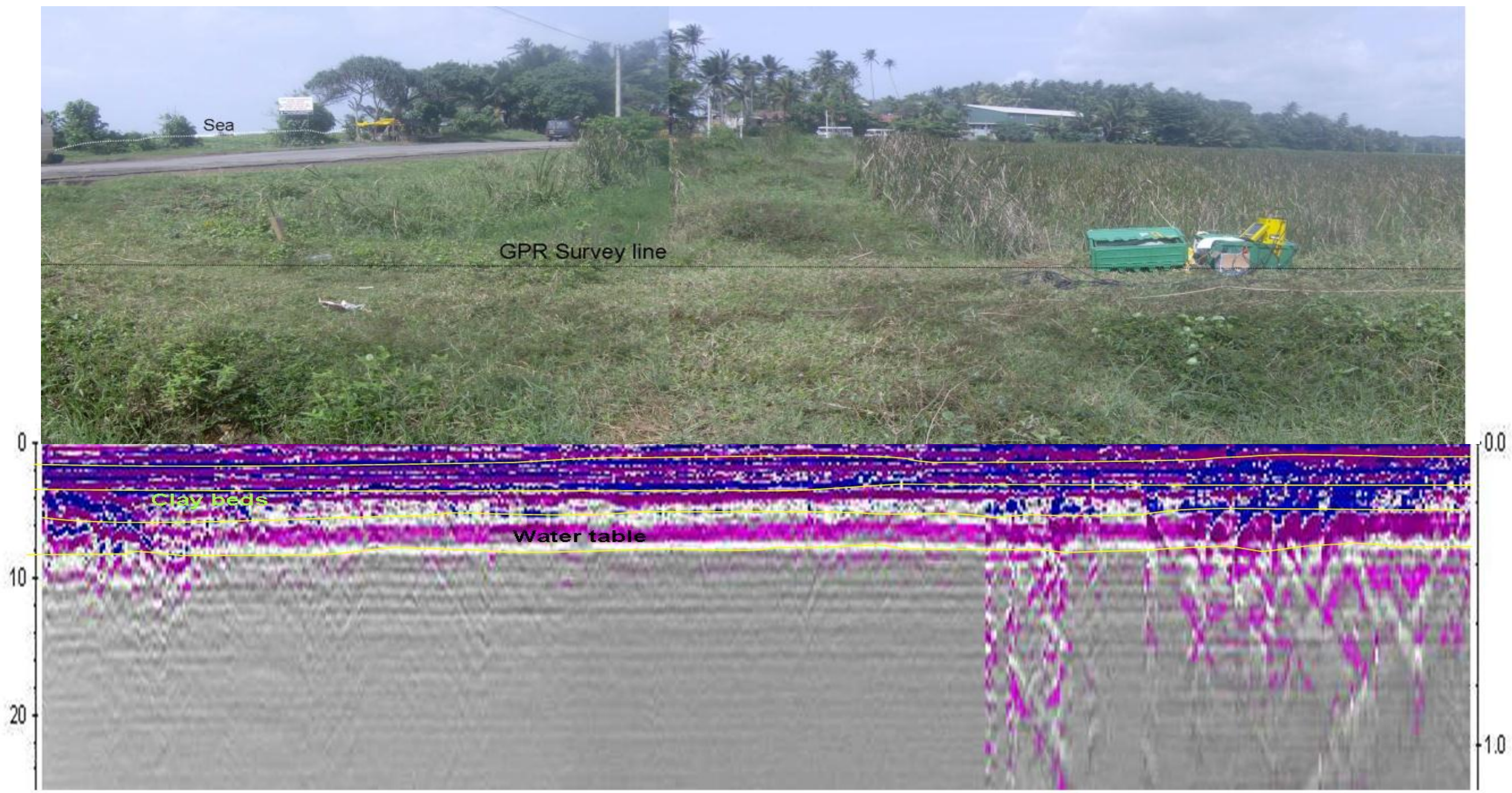


Figure 6.7 GPR section at site 3-Dikwella, on the South coast of Sri Lanka and interpretation of the GPR section.

6.1.4 Site 4 : Katukurunada (Kalutara), the West coast of Sri Lanka

This site was located on a wide beach where the 2004 tsunami caused severe damage (Figure 6.8). A few centimetres thick 2004 tsunami sand deposit could be observed at this site. While this recent event could be clearly seen, the GPR data interpretation, showed no evidence for the occurrence of palaeotsunami sediment layers in the beach sand profile. It was mainly, a normal beach sand deposit exhibiting cross bedding; ripple marks and other poorly differentiated sand layers with textural and mineralogical variations (Figure 6.8).

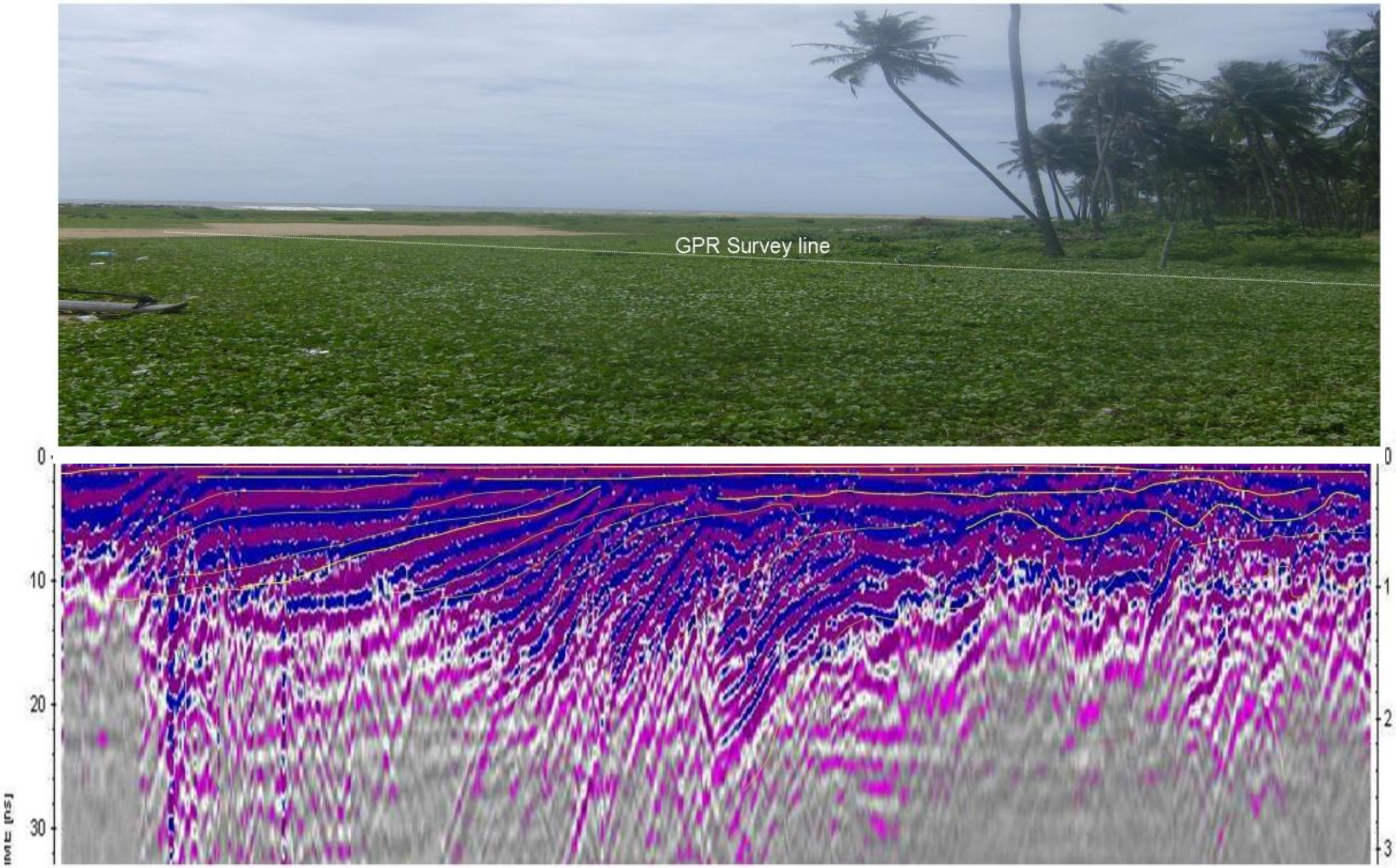


Figure 6.8 GPR section at site 4-Katukurunda, on the West coast of Sri Lanka and interpretation of the GPR section.

From interpretation of the GPR surveys at all four sites, tsunami sediment layers could only be traced at sites 1 and 2. Normal beach profile and marshland clayey beds could be clearly distinguished where there were no tsunamigenic sand deposits at Sites 3 and 4).

The GPR technique along with dielectric measurements has been successfully applied for mapping subsurface extent of tsunamigenic sediment layers at locations 1 and 2. While previously identified tsunamigenic layers using sedimentological, paleontological and age dating could be mapped up to 400 m inland, the radar-grams clearly show the sediment layers extend much further inland at these locations. At locations 3 and 4, tsunamigenic sediment layers could not be identified during geological studies and this is also confirmed by the Radargrams (6.7 and 6.8).

6.2 Conclusions; application of GPR technique for tsunami sediment mapping

1. The results of the laboratory electromagnetic measurements show a clear contrast between the dielectric properties of the tsunamigenic sediments and normal beach sands and lagoonal sediments (Table 6.1), which is the reason for the clearly defined refection signatures observed on the GPR profiles. Inspection of the reflection coefficients shows that for all of the tsunami deposits examined here there is a strong negative reflection coefficient which defines the tsunami event. The lower values of dielectric constant in the tsunami deposits is consistent with a decrease in pore space and, therefore, water content associated with the poorer degree of sorting observed in these sediments.

2. This dielectric contrasts remain sharp over several thousand years which allows this technique to be used for Palaeotsunami sediment mapping.

3. There is also a marked difference in textural, physical and mineralogical properties between normal beach deposits and the tsunamigenic deposits meaning that the GPR technique can be used to map the subsurface extents of tsunamigenic and palaeo-tsunamigenic sand facies.

4. Further developments:
   a. This radar system is unable to see a layer which exits significantly below the excavated depth of 1 m. There is a real possibility (which remains to be checked) of tracing even older palaeotsunamis.
   b. Using gridded GPR surveys with multiple frequency antennae and more sophisticated, specifically tailored processing algorithms might increase the quality and resolution of reconstruction and, in particular, make it possible to see even thinner tsunamite layers and even their geomorphological configurations and relationships.

The water content is the key factor, although others such as magnetic properties and grain morphology may play a part, in producing contrasts in dielectric properties between tsunamites and normal beach / lagoonal sediments, due mainly to the higher porosity of tsunamites. It is therefore anticipated that the technique will be universally applicable, since the contrast in porosity of tsunamites, which is their universal feature, is in no way confined to the Sri Lankan context and should have wide global significance.

CHAPTER 7

MICRO-FOSSIL ANALYSIS

7.1. Significance of micro-fossils studies on tsunami sediments

The signatures of tsunami sediments on the Sri Lankan coast were established using both known 2004 tsunami and palaeotsunami sediment studies and a GPR based method of finding the inundation distance of palaeotsunamis proposed and successfully tested as discussed in previous chapters. One of the limitations of this approach is if the sea level has changed the composition of the beach sediment could be different to normal. For example, in the Sri Lanka context the period of constancy of the present sea level is confined for approximately the last three thousand five hundred years (Katupotha and Fujiwara, 1988). Given the large recurrence period these limitations leads to a lack of statistical significance and, as a result to large error margins in estimating the probability density function of tsunamis on Sri Lankan coast. In this context, it would be of great interest to attempt to find an alternative approach aimed estimating the magnitudes of palaeo-events unconstrained by the requirement of the constancy of sea level. It is always useful to have additional conformation of the identification of tsunami sediment and one additional method is derived from micro-palaeontological evidence.

One of the distinctive features of tsunami sediments is that the tsunamites contain microfossils which are usually absent from the usual beach sediments (Dahanayake and Kulasena, 2008). A possible reason for the presence of the well preserved identifiable microfossils derived from the marine sediments which are undisturbed by normal wind driven waves is that they have been entrained and transported onshore by the deep wave base associated with long-wavelength tsunami waves in the offshore. The tsunami magnitude at the shoreline and its maximum inundation are known to increase with the wave period and wave height at any cross-section at a distance from the shore. The observation that a tsunami disturbs bottom sediments is absolutely uncontroversial (Goto *et al*., 2011). Thus stronger waves bring sediments from deep off shore and smaller waves bring sediment from near shore. The practical implication is that the tsunamigenic sediments can be isolated from other normal sediments and even distinguished from storm deposits which do not access the deep sediment layers.

Micro-paleontological characteristics or assemblages of different fossils species of both the 2004 tsunami sediments and palaeotsunami sediments were studied**.** Firstly, the foraminifera assemblages of the 2004 tsunami deposits were studied. Then these results were used to interpret palaeotsunami sediments.

7.2 Composition of normal beach sands.

Previous studies carried out on Sri Lankan beach sediments show, normal beach sand and near off shore sand are mainly rich in bivalves, radiolarians gastropods and corals (8%). Also the mineralogical composition is quartz (90%) and heavy minerals (2%) and they are well rounded and well sorted (Hearth, 1985). And the beach sediments are lack with marine microfossils (Dahanayake and Kulasena 2008).

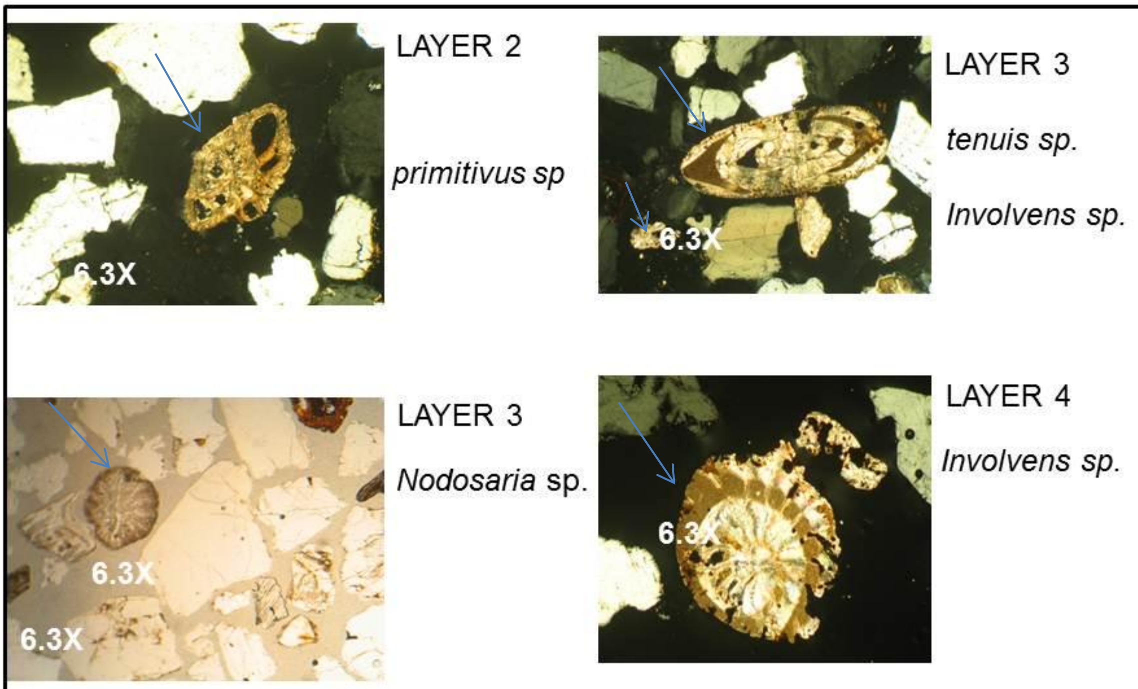
The present study also reveals that the normal beach sediments are free from microfossils. The thin sections studied for micropetrographic analysis in Hambantota -Location 1 and Yala -Location 2 (chapters 5.2.1.1 and 5.2.1.2) were also revealed that the nontsunamigenic sediment layers in the profiles were free from microfossils (Figures 5.4b, 5.4d, 5.8b and 5.8d). Thus, these results were more encouraging to carry out for microfossils studies i.e. presence of microfossils in the beach sand profile gives a better signature for the tsunamigenic origin.

7. 3 Micropalaeotological characteristics of the 2004 tsunami sediments

The sediment collected from the 2004 known tsunami sediments were analysed for studying to observe microfossils content.

7.3.1 Katukurunda (west coast of Sri Lanka)

At this location, four distinct sediment layers were identified and recognised as 2004 tsunami sediment beds (Chapter 4, Figure 4.17) corresponding to the four tsunami waves reported by direct observations. Different sediment layers are composed of different foraminifera species.



Foraminifera Species in different layers of the 2004 tsunami sediments deposit at Katukurunda, west coast of Sri Lanka.

Figure 7.1: Foraminifera species present in different layers of the 2004 tsunami deposits at Katukurunda, Sri Lanka (All sections are at 6.3X magnification of the Microscopic view).

The tsunami deposit observed at Katukurunda was well preserved and recorded most of the information on the hydrodynamics of the tsunami waves. The first layer of light-brown well-sorted sand is sourced from the near beach and deposited by the first wave. The height of the first wave at this location could be estimated as 0.7 m, which was not a particularly strong wave. But the first wave had deposited a thick bed, as the most of the materials are available for the first wave from the adjacent coastal stretch which was a slightly higher sandy ridge. This layer did not show evidence for presence of foraminifera species.

The second layer was deposited by the second wave of the height of approximately 1 m (there were no instrumental measurements of wave height of this wave at this place; the wave height was estimated via several indirect methods including the eyewitness testimonies). This layer comprises few foraminifera species (Figure 7.1). The second wave was not very strong and did not reach the lagoon. A thick sediment layer was deposited by the second wave due to presence of a building as a barrier, where wave flow rates have been reduced at this point. There could also have been a small backwash flow as reflections from the building resulted in an eroded surface on the pre-deposited materials from the same wave.

According to the eyewitnesses the third wave was the largest, with a height of about 3.5 m at this location. The third sediment layer deposited by this strong wave differs from the first two waves. The peculiarity of this particular wave at this location is that there was no backwash flow, this wave flowed directly into the lagoon. The thick sediment deposit and a non-erosive top surface of the third layer provide further evidence of the absence of a backwash flow for the third wave. This layer was characterised by presence of foraminifera species; nodosaria sp, *tenuis sp.* and *involvens sp.* (Figure 7.1).

The fourth layer is black sandy clay from near offshore mixed with sediment brought by the third wave. The sediment in that layer was also comprised foraminifera species; *involvens sp.* (Figure 7.1).

7.3.2 Yala (Palatupana) southeast coast of Sri Lanka

Micro-fossils were similarly analysed for tsunami sediments collected at the *Yala* location (On the Transect 3 in Chapter 4). Foraminifera species; *ammonia beccarii sp.*, *secans sp*, *circanata sp.* were observed from the sediments (Figure 7.2). Sand samples location was at 400m inland and only the strongest wave has reached the place of sampling. Micro-petrographic studies showed that the sand of this deposit was from both adjacent beach and offshore sediment. The sand comprises moderately sorted fine to medium sub rounded sands; mainly quartz and feldspar with minor amount of Fe-Mg and other heavy minerals (as explained in Chapter 4).

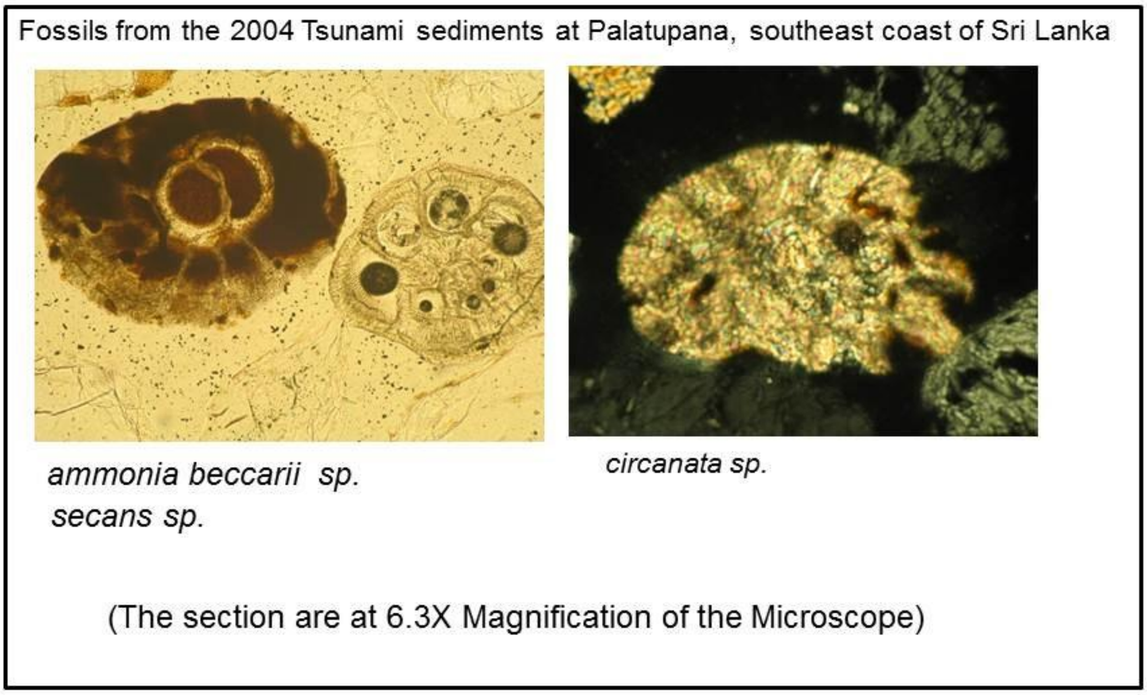


Figure 7.2: Fossil records of the 2004 tsunami deposit at Yala (Palatupana), southeast coast, Sri Lanka.

From the foraminifera fossil records of the 2004 tsunami sediments and the data on the wave parameters, microfossil evidence can also be used for identifying tsunamigenic sediments.

7.4 Micro fossil records of palaeotsunami sediments

Yala (Location 2)

Micro- fossils were analysed for the samples taken from this location (Yala) where three palaeotsunami sediments layers were identified using sedimentological studies (Location 2 in Chapter 5). All palaeotsunami sediment deposits (S3, S5 and S8- Figure 5.6) in the profile contain different species of foraminifera species. Other normal sediment layers in the profile did not contain the fossils.

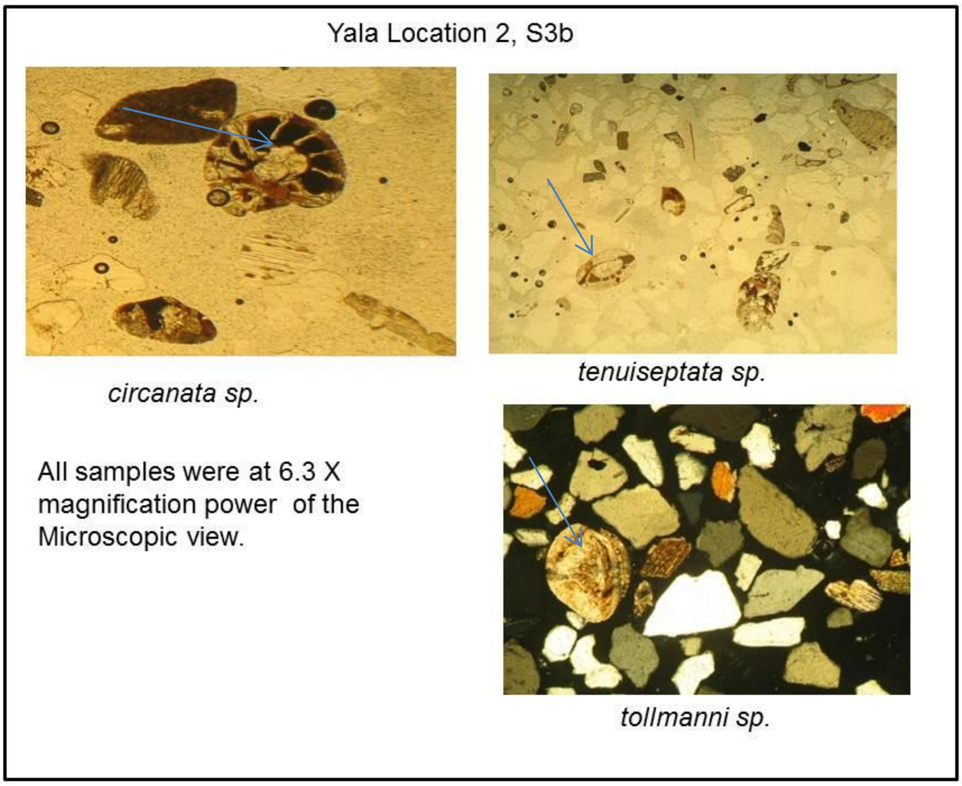


Figure 7.3a: Layer 3 (S3)

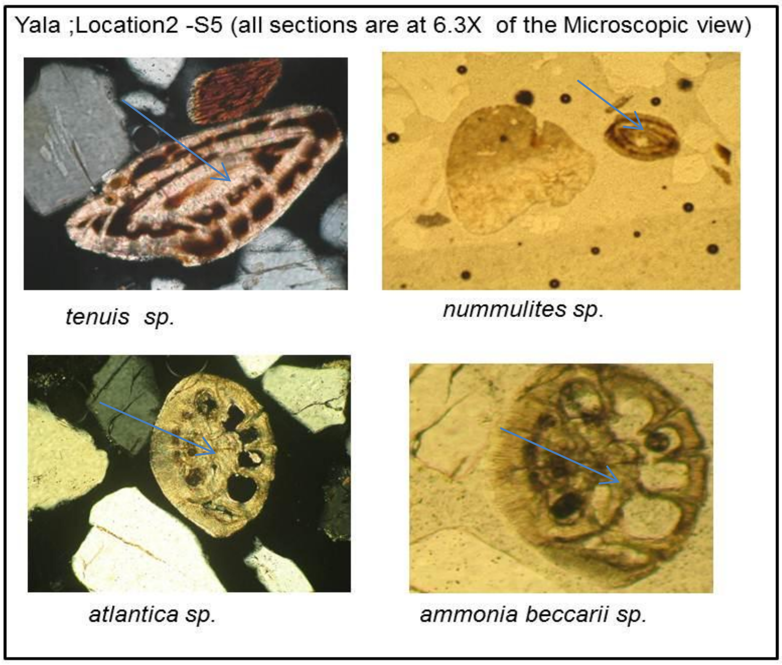


Figure 7.3b: Layer 5 (S5)

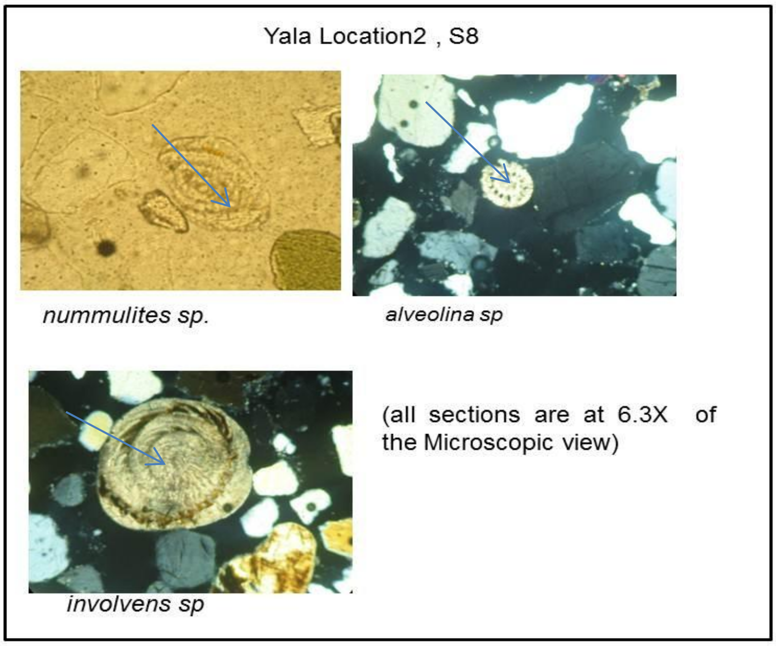


Figure 7.3c: Layer 8 (S8)

Figure 7.3a-c: Micrographs of foraminifera species found in palaeotsunami sediment layers (S3, S5 and S8) at location 2 (Yala).

CHAPTER 8

PALAEOTSUNAMI SEDIMENTS DATING AND IMPLICATION OF HISTORICAL RECORDS

8.1 Dating of Palaeotsunami sediments

Proper dating of palaeotsunami sediments is the key factor in finding tsunami recurrence interval. Tsunami sediment dating is challenging due to the wide range of sediment ages from a few hundred to millions of years. A number of techniques are available for sediment dating such as radiometric dating, and Carbon dating (^{14}C) Thermo-Luminescence (TL) and Optically Stimulated Luminance (OSL) techniques are most commonly used for recent sediment dating (Gonçalves *et al*., 2005). They are the most feasible and reliable techniques in recent quaternary sediment dating. Because each technique has different accuracy levels, relies upon different physical mechanisms and procedures, applies to different types of materials, employs different sampling, preparation methods and conditions of testing. There are some specific advantages and restrictions and limitations for each technique. For example, the ^{14}C technique uses organic material within the sediment; ^{14}C fraction of this organic material declines at a fixed exponential rate due to the radioactive decay of ^{14}C, by comparing the remaining ^{14}C fraction of a sample to that expected from atmospheric ^{14}C (Wilkins, 2012). Luminescence dating (TL and OSL) measures the energy of photons being released which is proportional to the time since the last exposure to sunlight or intense heat. In OSL and TL techniques, minerals (crystal grains) such as quartz, feldspars etc. are used for the analysis and they have better accuracy levels (up to 5%) with different age limit up to 150, 000 years than Carbon-14 method.

8.2 OSL dating for Palaeotsunami sediments on the Sri Lankan coast

Samples were collected from two sites where detailed studies has been carried out, at Hambantota (Location 1) and Yala (Location2) as explained in Chapter 3. Three Palaeotsunami events have been identified based on the OSL dating at 150 to 200BP, 2550±190BP, 2710±310BP and 3170±320BP years from the two profiles (Figure 8.1), this permits further correlation of the palaeotsunami deposits between the two sections exposed in the pits.

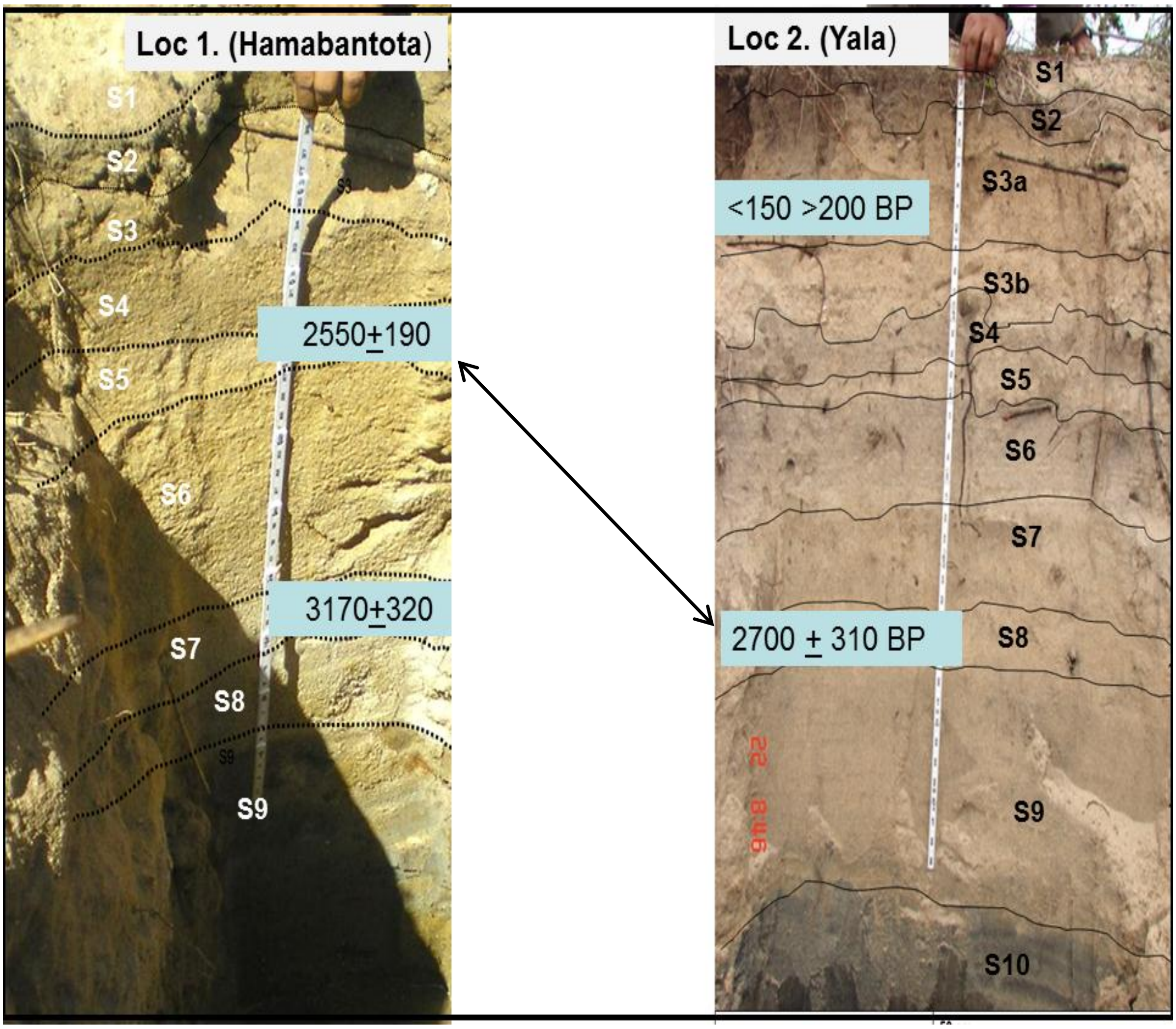


Figure 8.1 OSL dating records of palaeotsunami sediment at Location 1(Hambantota) and Location 2 (Yala)

8.3 Recurrence interval and tsunami risk on the Sri Lankan coast

The recurrence interval of tsunami hazards is very often considered to be a regional-scale parameter. The determination of tsunami risk for the Indian Ocean basin is critically important for the issue of tsunami recurrence on the Sri Lankan coast even though it is situated far from seismically active areas. The island of Sri Lanka lies directly facing towards the main wave front of the major tsunami generating zone in the Indian Ocean; the Andaman-Sumatra-Java islands subduction zone. Previous studies (based on carbon dating) on the coast of Thailand and Sumatra have showed a recurrence interval for the Indian Ocean of nearly 600 years. They recorded three palaeotsunami events in 100-130BP, 540-600BP, 966-1170BP, 2200 BP (Bondevik, 2008; Jankaew *et al*., 2008; Monecke *et al*., 2008; Brill *et al*., 2012).

Table 8.1: Palaeotsunami records for the Sri Lankan coast and the Indian Ocean from the present study and previous studies.

event	Literature	This study	Historical records
1	2004 (Sumatra Tsunami)	2004 (Sumatra)	2004 Sumatra Mega Tsunami
2		150-200 BP	Krakatau Eruption 1883
3	100-130BP (Brill *et al*., 2012)	Not recognised	Rupture of the Sunda Arc occurred in 1881
4	540-600 BP (Jankaew *et al*., 2008; Monecke *et al*., 2008) 500-700BP (Brill *et al*., 2011) 380±130BP (Prendergast *et al*., 2012)	Not recognised	-
5	966-1170BP (Monecke *et al*., 2008) 990-1400 BP (Prendergast *et al*., 2012)	Not recognised	-
6	2200 BP (Monecke *et al*., 2008) 2100±260 (Prendergast *et al*., 2012)	2500 ±190 BP	Viharamahadevi Event (Sri Lanka)
7	Not recognised	3170 ±320 BP	Not Reported

Events one and two are the 2004 tsunami and the 1883 Krakatau eruption tsunami respectively. However, event two does originate from the Sumatra subduction zone which is considered to be the most significant potential tsunami generating source in the Indian Ocean. The 6th event matches reasonably with both previous studies and the present study (Table 8.1). However, three younger events (3, 4 and 5) recorded by previous studies have not been recorded on the Sri Lankan coast from this study. It may be that those tsunamis did not affect the Sri Lankan coast (they were local events to the Andaman area) or that they deposited thin sediment layers which were not preserved.

Of particular note is the 7th event at 3170±320 years BP recorded from the present study which is the oldest event recorded on the Sri Lankan coast and significantly also the oldest ever recorded from the entire Indian Ocean.

8.4 Reconciliation of palaeotsunami events recorded on the Sri Lankan coast with available historical and archaeological records.

As shown in table 8.1 two palaeotsunami events recorded from the present study can be confirmed with historical records of Sri Lanka. The 1883 Krakatau eruption tsunami was reported in a newspaper article in the Sunday Observer on *27th August 1883* which reported that a tsunami wave hit the southwest coast of Sri Lanka after one hour of its origin. Another, and possibly the most famous tsunami event which occurred around 200BC (i.e. 2200BP and potentially associated with event 6 in Table 8.1 was reported by several Sri Lankan chronicles (*Mahawamsa and Rajawaliya*) and the story has subsequently been recorded in some books (Hardy, 1866; Codrington, 1994).

It is now important to see whether the oldest event at 3170 can be verified elsewhere in the Indian Ocean as if it was sufficiently large to reach Sri Lanka, it would have been large enough to be experienced at many other regions within the Indian Ocean.

CHAPTER 9

SYNTHESIS OF THE STUDY

9.1 Impact of the 2004 tsunami on the Sri Lankan Coast

Though, Sri Lanka is situated over 1000 km from the main tsunami source region (Sumatra Trench), the 2004 tsunami hit all around the island devastating most of the coastal zone. Run up heights and inundation distances along all of the affected areas of the coast showed considerable variations even within a very short distance. Geological records, specially erosional and depositional features showed very wide variation along the coast, The maximum inundation distance record from the tsunami was 3500 m while the maximum run up height was 15m (mainly on the eastern and south-eastern coasts). Generally, at most locations, 3-4 discrete waves impacted on the Sri Lankan coast (Chapter 4).

9.2 Major Geological / Sedimentological signature of the 2004 tsunami records on the Sri Lankan coast.

Regional sediment deposition patterns on the island showed great variation all around the coast; maximum recorded thicknesses of the sediment bed deposited on the eastern coast were about 11 cm, on the southern / south-eastern coast, 32 cm and on the western coast about 16 cm. From the present study, the following major depositional characteristics were found from the 2004 tsunami around the Sri Lankan coast.

9.2.1 Major sedimentological characteristics observed from the 2004 Tsunami

- Mainly sand deposits in varying thickness (from few centimetres to over 30 cm deposits were observed all around the island.

- Sediment deposition was higher in southeast and eastern coast compared to the western coast. The tsunami sediment deposits are mainly confined to low relief topographical features like swells or marshlands. Sediment deposition patterns were more often controlled by local topographical features than by the tsunami wave characteristics (Figures 4.1, 4.2 and 4.3).
- The extent of deposition of tsunami sediment inland depends on the inundation distance (note the 2004 tsunami sediment deposition pattern with wave characteristics on the east, south and west coasts of Sri Lanka; Figures 4.1, 4.2 and 4.3). The sediment deposition was observed over 700m inland (maximum) as continues beds, discontinues sheets, lenses, pocket like deposits (Figure 4.13)
- Very often layered deposits were observed and layering mainly comparable with the number of waves and their hydrodynamic nature (Figure 4.5b).
- Massive sandy deposits also found at some places (Figure 4.5d)
- The sediment deposits laid on the coastal zone from the tsunami were simply identified alone from other normal beach sediments (Figure 4.5) with the aids the contacts (erosive and always lower contact with peaty or normal dark colour top soils) and textural characteristics (often coarse grained and light colour).
- Isolated boulder deposits demonstrate the high- energy hydrodynamic regimes which were present.
- Sandy deposits contain rip-up clasts showing agitated environment during the deposition (Figure 4.20).
- Very often, the near part of the coastline was subject to erosion rather than deposition (Figure 4.4).
- Some tsunamigenic deposits were inter-bedded with marshy clay/ organic beds and hence were well preserved (Figure 4.5c).

The resulted characterises of the 2004 tsunamigenic sediments observed from 2004 tsunami around the Sri Lankan coast provided a firmed signature for the tsunami sediments as a marked event.

Most of the above characteristics are well established as discriminators for a tsunamigenic origin from most of previous studies (Atwater, 1992; Clague *el al*., 2000; Dawson and Shi, 2000 ; Fujiwara *et al*., 2000; Nott, 2000; Bryant, 2001; Dominey-Howes, 2002; Gelfenbaumand Jaffe, 2003; Goff *et al*., 2004 ; Scheffers, 2004; Dominey-Howes *et al*., 2007; Hori *et al*., 2007; Hawkes et al., 2007; Paris *et al*., 2007; Srinivasalu *et al*., 2007; Fagherazzi, 2008; Morales *et al.*, 2008; Matsumoto *et al.*, 2010). Thick bedded deposits were found on the southeast coast of Sri Lankan (Chapter 4, Figure 4.9) and similar sand deposits were studied on the Indian coast by Adam *et al* (2012). Isolated boulders (Figure 2.7) have been found in many parts of the world transported and then re-deposited by tsunamigenic deposits (Nott, 2000; Scicchitano *et al.*, 2007).

9.2.2 Granulometric and textural and mineralogical characteristics of the 2004 tsunamigenic sediments.

A detailed study on four transects and at five more individual locations on the Sri Lankan coast has allowed characterising the tsunamigenic sediments from the 2004 tsunami. Tsunami sediments have specific textural and structural characteristics showing a discrete signature. They were always present as poorly sorted sands with varying grain shapes (angular to well rounded). Tsunami sediments were light coloured and coarse grained. The minerals present in these sediments were dominantly quartz and feldspars with trace amounts of Fe-Mg minerals and opaque metallic minerals (heavy minerals) compared to other normal coastal sediments. Most of the normal coastal beach sediments on the Sri Lankan coast contain much higher amount of heavy or opaque and Fe-Mg minerals (Herath, 1988). Coarse grained quartz and feldspars present in tsunamigenic sediments showed micro-fracturing which was not observed in the other sandy sediment deposits, but the reason cannot be fully explained but may be due to the high energy flows. These particular mineralogical and micro-structural characteristics have not been recorded in other studies as a discriminative tsunami signature. All these characteristics were described fully in Chapter 4, often with micro-petrographic analyses. Tsunamigenic sediments showed some heterogeneity as a result of mixing of sediment from different sources and rapid deposition without the sorting which occurs during most normal beach sedimentation processes.

Grain size statistical parameters of tsunami sediments showed some characteristic relationships. In particular, strong anti-correlation between mean grain size and skewness / kurtosis was shown by tsunamigenic sediments (Figures 4.26 and 4.27), which has not been recorded by any previous study as a characteristic signature for tsunamites. However, it was possible to see these relationships from the results of some previous studies, but they were not identified as signatures for tsunami sediment. For example, a previous study was carried out on tsunami sand deposits on the Sri Lankan coast by Morton *et al*. (2008). They plotted mean grain size and skewness with depth of the 2004 tsunami sediment deposit, from which results similar relations can be seen for the sediment (Figure 9.1; sections 141and 300), though they have not recognised that characteristics as the signature. However, the sample method they used in that study was to sample at equal intervals (4 cm) irrespective of the layering of the sediment beds. Thus, the characteristics of different beds deposited by different waves could not be identified and could not give sensible correlations. Similar variations have been observed from tsunami sediment in many other parts of the world (Hindson and Andrade, 1999; Gelfenbaum and Jaffe, 2003; Morton *et al*., 2007; Paris *et al*., 2007) but these correlations have not been recognized as a diagnostic signature for characterisation of tsunami sediments from any of those studies. Granulometric studies were carried out for the 2004 tsunamigenic sediments on the Indian coast by Babu *et al*., (2006) and did not show these particular correlations at all (Figure 4.28 and 4.29). This may be due to the fact those beaches are rich in heavy minerals and the tsunami sediments have been contaminated with them.

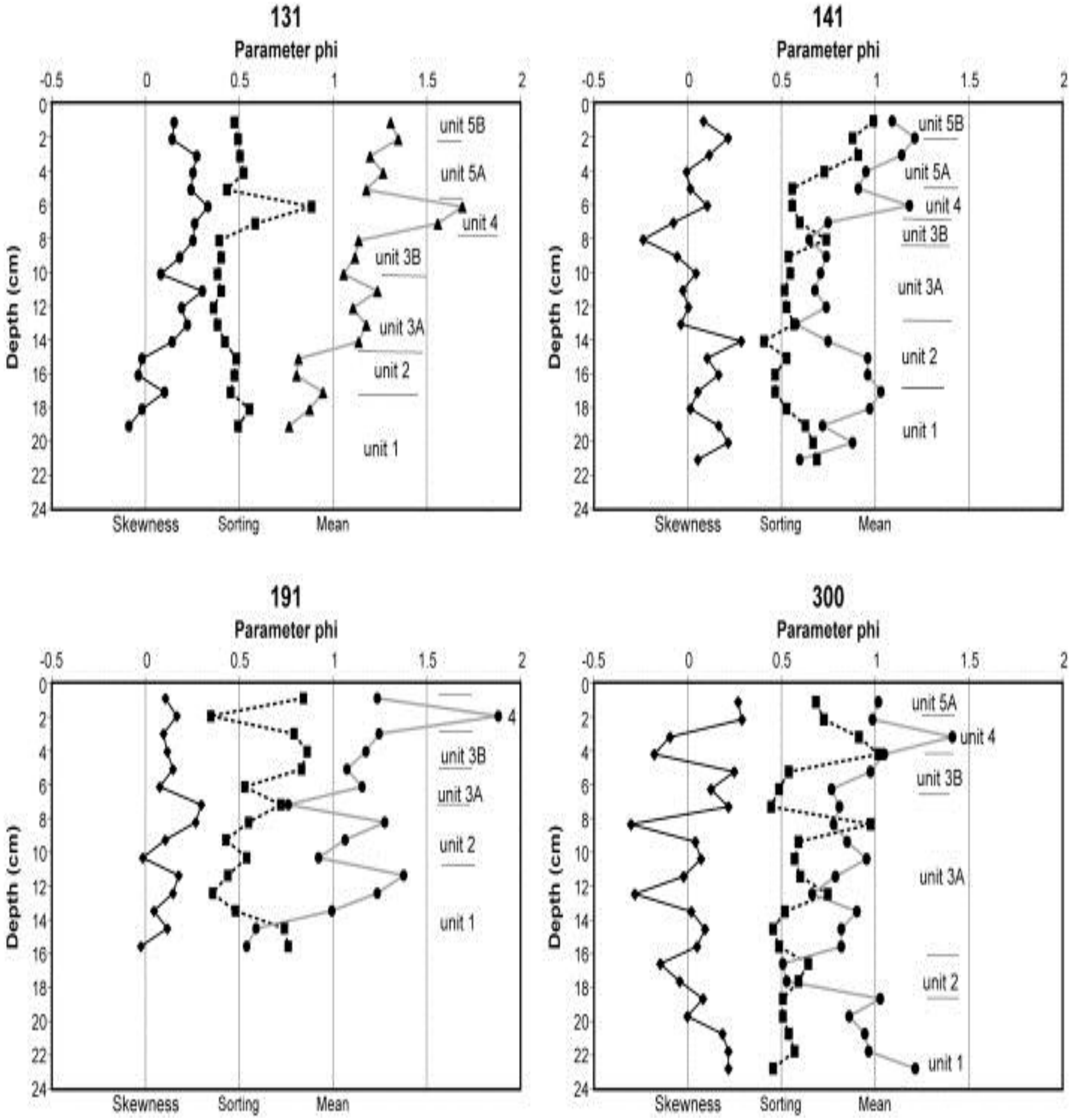


Figure 9.1 Variation of mean grain size, sorting and skewness at 1-cm intervals for the 2004 Indian Ocean tsunami deposit of four sections at Yala (After Morton *et al*., 2008).

Polymodal or mostly bimodal grain size distribution is also a characteristic feature of tsunami sediments (Figure 4.14). The poly-modal or bimodal distribution patterns were due to the tsunami sediments being characteristically heterogeneous in nature due to mixing of sediments from different sources.

9.3 Palaeotsunami records on The Sri Lankan coast

After detailed studies were carried out in two pits located Hambantota and Yala on the south-eastern coast of Sri Lanka and at two more isolated locations**.** Three palaeotsunami events have been recognised based on sedimentological studies. Two palaeotsunami layers (S5 and S7 of Figure 5.2) from location 1 (Hambantota) and three layers (S3, S5 and S8 of Figure 5.6) from Location 2 (Yala) were identified in this study. However, Location 1 (S5) and Location 2 (S8) sediment record probably from a same event (from ages and historical records). All available sedimentological characteristics such as textural, structural (from macro to micro scale), mineralogical, micro-paleontological and depositional characteristics were used in an integrated effort to identify tsunamigenic sediment deposits precisely.

9.3.1 Distinctive characteristics of Palaeotsunami sediments;

- Presence of light colour minerals poorly sorted comprising a wide range of grain sizes from fine to very coarse (Figure 5.6).
- Sandwiched between marshy clayey deposits or normal fine grained sand deposits (Figures 5.2, 5.6, 5.9 and 5.11).
- Overall grain size statistical pattern of the tsunamigenic sediments on the profile showed some characteristic patterns, which differ from other sediments on the coast.
- Negative correlation between mean grain and skewness while some positive correlation between mean grain size and kurtosis (Figure 5.2).
- Poorly sorted and rich in coarse grain fraction and lesser composition of heavy minerals (Figure 5.8b and 5.8c), but normal beach sediments are rich in heavy bearing/ heavy minerals; as explained in chapter 7.2.
- Presence of microfossils (foraminifers' species) and absence of other macro fossils such as bivalves which are present in normal beach sand ; as explained in chapter 7.2.

This is likely to be a key criterion for tsunamigenic sediment identification in the other coasts of the world (Goff *et al*., 2001; Scheffers and Kelletat, 2003; Hawkes *et al*., 2007; Kortekaas and Dawson, 2007; Brill *et al*., 2012).

- Poly-modal distribution was not a characteristic feature of palaeotsunami from this study though it was a significant feature of the 2004 tsunami sediments.

Most of the characteristics identified in this study were comparable with other tsunamigenic deposit from the coasts of the rest of the world (Clague *et al*., 1994; Gelfenbaum and Jaffe, 2003; Tuttle *et al*., 2004; Dawson and Stewart, 2007; Sugawara *et al*., 2008).

9.3.2 Micropalaeontological evidences of palaeotsunamigenic sediments

It was observed microfossils (Foraminifera) from both recent 2004 and palaeotsunami sediments (Table 9.1). The presence of foraminifera in tsunamigenic sediment could also be used as diagnostic criteria. It was also noted that the normal beach sand profile did not contain microfossils (Palaeotsunami studies at Hambanatota –Location 1 and Yala –Location 2 in Chapter 5.2.1.1 and 5.2.1.2).

Table 9.1 Foraminifera species observed in both recent (the 2004 tsunami) and palaeotsunami sediments.

2004 Tsunami Sediments		
Location	Layer	Species
Katukurunda	L1	Not recognised
	L2	*primitivus sp*
	L3	*nodosaria* sp. *tenuis sp.* *involvens sp.*
	L4	*involvens sp.*
Yala (Palatupana)		*ammonia beccarii sp.* *secans sp.* *circanata sp.*
Palaeotsunami Sediments		
Yala	Layer (S3)	*circanata sp.* *tenuiseptata sp* *tollmanni sp.* *ammonia beccarii sp*
	Layer (S5)	*tenuis sp.* *atlantica sp.* *nummulites sp.*
	Layer (S8)	*nummulites sp.* *involvens sp* *alveolina sp*

9.4 Subsurface mapping Palaeotsunami sediment beds using GPR technique.

Several studies have been carried out for identifying palaeotsunami deposits and their characteristic. Mostly they have used pits, trenches or drill holes for sampling and sediment profile studies. However, not much emphasis has been given to mapping the lateral distribution of the tsunamigenic deposits, which gives valuable information about the strength of the tsunami. In the process of reconstruction and quantification of palaeotsunamis, inundation distance of tsunami wave is a key parameter. Thus, the extent of the tsunamigenic sediments on land on the coastal zone is an important parameter to characterise a tsunami inundation.

In this study, four GPR surveys have been carried out on the coast as explained in Chapter 6. From two sites (Site 1 (Yala) and 2 (Hambantota) with identified tsunamigenic sediment layers based on trenches/pits and geological studies (Figure 6.2 and 6.3), it was possible to trace tsunamigenic sediment layers unequivocally with the help of ground truth data (Figures 6.2, 6.4, 6.5 and 6.6). From the GPR survey, three sediment layers of palaeotsunami events could be traced up to 400 m inland at the location 1 (Figure 6.2). At the location 2, two tsunami events identified from sedimentological studies could be traced from all three GPR sections (Figures 6.3, 6.4 and 6.5). Another two GPR surveys were carried out at two sites where there were not any clear indications for tsunamigenic sediment geological field studies. One location (Site 3-Dikwella) in a marshland close to the beach and site 4 (Katukurunda) was also near the beach and there was some sediment deposition by the 2004 tsunami on this site. GPR profiles from these two sites do not show any positive indications of tsunamigenic sediments as were recognised at sites 1 and 2. The GPR section at site 3 did not give indication of the presence of coarse grained sand deposits inter-layered with the marshy clay beds (Figure 6.7). Additionally, GPR data interpretation of site 4 showed no evidence for the occurrence of palaeotsunami sediment layers in the beach sand profile. It is mainly a normal beach sand deposit exhibiting cross bedding, ripple marks and other poorly differentiated sand layers with textural and mineralogical variations (Figure 6.8). Since the tsunamigenic deposits occur in the coastal deposits as very distinctive geological layers compared with the normal beach deposits, the GPR technique can be invaluable for mapping them.

9.5 Age dating of Palaeotsunami events in the Indian Ocean

From this study three palaeotsunami events were identified from two beach profiles as (Event 2) 150-200BP, (Event 6) 2500±290BP and (Event 7) 3170±320BP. When these results were compared with the Indian Ocean palaeotsunami events (Table 8.1), Event 2 and Event 6 have been recognised by previous studies on Thailand and Indonesian coasts (Monacke *et al*,, 2008; Jankaew *et al*., 2008; Brill *et al*., 2011; Brill *et al*., 2012; Prendergast *et al.*, 2012). However, three events (Event 3, 4 and 5) which were identified by previous studies were not recognised in the present study and were probably not present potentially as they may have been deposited by a smaller tsunami event which did not reach Sri Lanka.

The oldest palaeotsunami tsunami events ever recorded in the Indian Ocean is 3170±320, which is only from this study. Most of the younger palaeotsunami events recorded on the Thailand coast are unlikely to be as large tsunami as the 2004 event. Thus they produced no effect on the Sri Lankan coast since the location of Sri Lanka island is much farther from the sources of tsunamis compared to Thailand/ Indonesia which lie close to the major source region; Sunda trench (Figure 9.2)

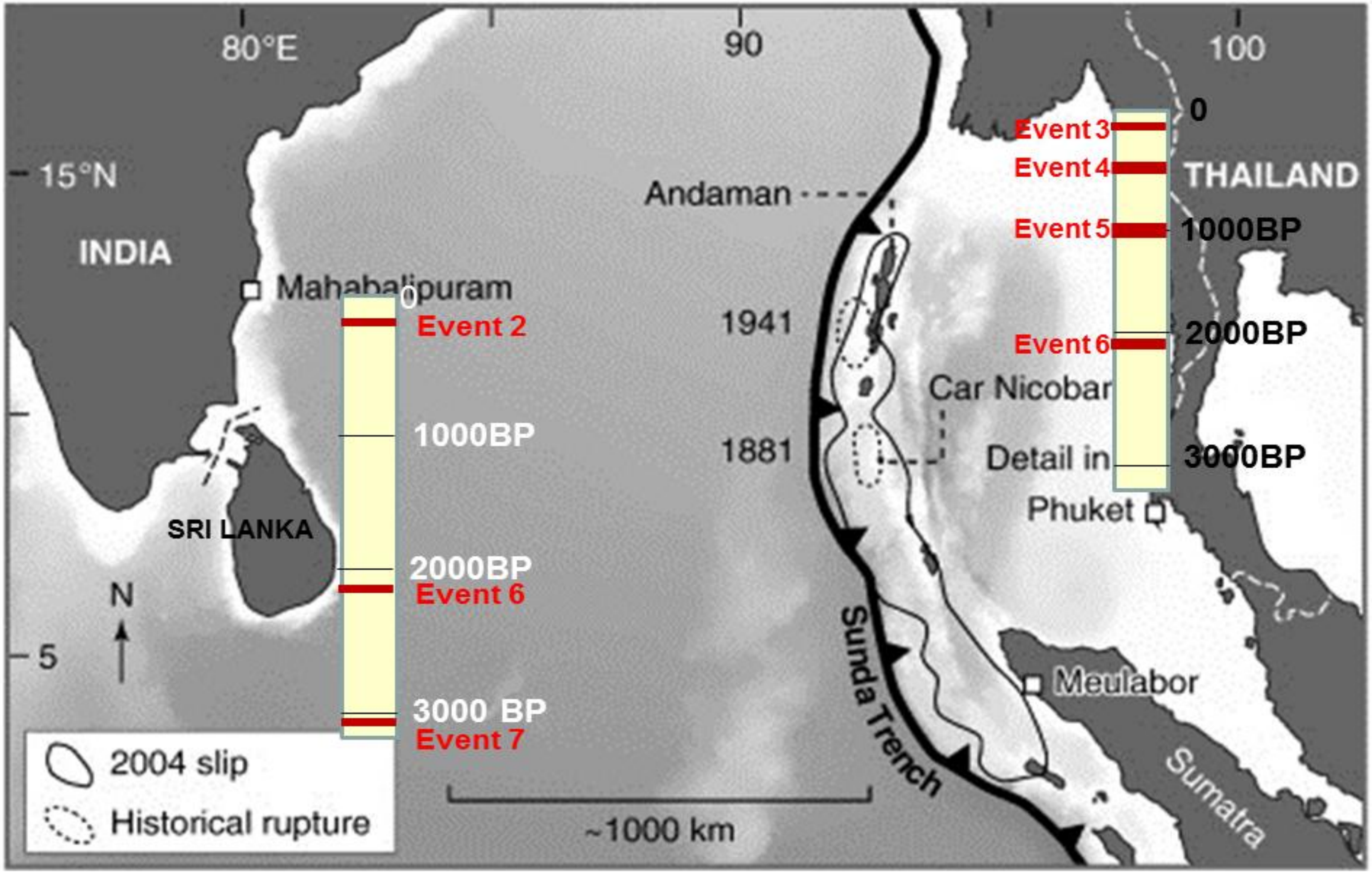


Figure 9.2: Regional correlation of palaeotsunami events recorded in the Indian Ocean; Events with reference to Table 8.1 (Source map After: Prendergast *et al*., 2012).

9.6 Key Findings

- Establishing a signature for the tsunami sediments on the Sri Lankan Coast based on, depositional, sedimentological, statistical, mineralogical, textural and palaeontological characteristics.
- Identification of three palaeotsunami events and dated them (150-200BP, 2500±190BP and 3170±320 BP).
- Two palaeotsunamis have been matched with historical events (legend stories).
- Recording of the oldest Palaeotsunami event in the Indian Ocean (3170±320BP).
- Introduction of novel methods for mapping a of tsunamigenic sediment beds in the subsurface using GPR technique.
- Introduction of methodologies to determine recurrence interval of tsunami disaster and to find the strength of the disaster by mean of inland penetration.

CHAPTER 10

DISCUSSION AND CONCLUSIONS

10.1 Discussion

Though tsunamis are not very frequent events compared to other natural disasters which occur in the world, they cause severe impact and enormous loss of life in low-lying coastal zones. In this study, geological records of palaeotsunamis have been identified using sedimentological, paleontological, depositional and physical characteristics. Though the geological signature of palaeotsunami events has been established by several studies in the world, there were no such studies carried out to determine the precise signature for tsunami sediments on the Sri Lankan coast. Also there were well marked tsunami deposits signatures on the Sri Lankan coast from the 2004 tsunami. Thus the tsunami signature for both recent and palaeotsunamis could be established from this study. Three palaeotsunami events have been identified and dated using the OSL technique which is the most reliable method for estimating the date of recent to several thousand years old sediments. The identified palaeotsunami events were reconciled with available archaeological and historical records from the Sri Lankan chronicles. Another result of the present work is the discovery that dielectric properties of tsunami sediments differ substantially from those of the surrounding soil. This enables the Ground Penetrating Radars (GPR) to be applied for outlining the palaeotsunami deposits. The GPR technique was effectively tested and applied for mapping the subsurface extent of palaeotsunami deposits. Using the onshore extent of the palaeotsunami sediment deposits the inland penetration of the tsunami events could be estimated and this inundation can be used to estimate the magnitude of palaeotsunamis.

10.1.1 Identification of tsunamigenic geological records/ sediment deposits

In palaeotsunami studies, identification of tsunamigenic geological records are a critical and perhaps the most important and challenging task. Tsunami sediment deposits are the most useful records which store most of the information about the event. Other sediment deposits or records can resemble tsunamigenic geological records and deposits causing some confusion in identification, and it is critical to be able to distinguish between these and true tsunamites. Therefore, all available sediment characteristics such as textural, structural (from macro to micro scale), mineralogical, micro-paleontological and depositional characteristics have been used in an integrated effort to identify tsunamigenic sediment deposits precisely. While the geological signature of palaeotsunamis have been identified by previous studies using these factors individually elsewhere in the world (Clague *et al*., 2000; Dawson and Shi, 2000; Gelfenbaum and Jaffe, 2003;Goff *et al*., 2004; Hori *et al*., 2007; Paris *et al*., 2007 Peters *et al*., 2007; Srinivasalu *et al*., 2007; Morales *et al*., 2008), the power of using them in an integrated method for the identification palaeotsunamis is clearly demonstrable.

10.1.2 Application of the GPR technique to reconstruct palaeotsunami events

In the process of reconstruction and quantification of palaeotsunamis, tsunami wave characteristics such as inundation distance, wave height and flow velocity are key parameters to be determined. As explained in chapter 6, the inundation distances of past tsunamis were determined using GPR techniques based on the inland extent of the tsunamigenic sediment deposits recognised in the radar cross-sections. Conventional methods which have been available to determine the subsurface distribution of tsunamigenic sediment deposits are drilling/coring and digging trenches and pits, which are mostly impracticable and are not reliable methods because they require a large and available labour force and extensive excavation, which is unlikely to be possible in constructed and built areas. These areas are precisely of most interest for tsunami risk assessment due to continuity of human settlements. Also there is a risk that tsunami deposits could be locally disturbed just in the location of the probing and thus lead to false picture of the palaeotsunami. Previous studies have shown the successful application of the GPR technique for coastal sediment mapping (Bristow and Jol, 2003) and therefore, it is a major breakthrough to be able to use GPR which is one of the advanced and sophisticated geophysical techniques. In this study the use of GPR was justified on the basis of laboratory study of dielectric properties of sediments, and then GPR has been applied to trace tsunamigenic sand layers in the coastal geological profile.

In the present study, the GPR technique was successfully applied to trace tsunamigenic layers at two sites (1 and 2 of Chapter 6) where tsunami sediment deposits were previously identified by geological studies. Additionally, GPR surveys were carried out at another two sites where there were not any clear indications for tsunamigenic sediment deposits in the subsurface. Also there were no indication that tsunamigenic sediment deposits could be traced on Sites 1 and 2. The GPR technique provided additional information which enabled tsunamigenic sand layers with variable thicknesses to be traced using appropriate GPR frequencies.

Some limitations on the application of GPR technique for tsunami sediment deposit mapping on the coastal zone were encountered. It was not possible to utilise this technique in regions with very shallow water table, on inland saline water bodies (although it may be possible in fresh or brackish conditions) or in marshland and saline water environments. However, tsunami sediments deposits are very often preserved in dry marshland, swells or within other sandy sediments. Therefore, the GPR technique can be effectively applied with proper site selection and during suitable weather conditions. Furthermore, it was possible to distinguish discrete tsunami sediment layers based on differing dielectric properties and reflection coefficients. Therefore, these dielectric characteristics were also helpful in processing and interpretation of GPR data to trace the sediment layers precisely.

10.1.3 Determination of recurrence interval and tsunami sediment dating

The other most important part of tsunami risk estimation is the determination of the frequency of past tsunami events. Properly identified past tsunami events should be dated accurately. Since few methods are available for sediment dating, the OSL technique, because of its higher accuracy level for dating recent sediments has been used. Tsunami sediments are ideal for this technique because they are rich in quartz and feldspar and they are rapidly buried with very low bleaching. Furthermore, OSL has a wide range of time scale from very recent to 150,000 years. Tsunamis bring deposit which remains onshore for quite a while and therefore are exposed to sunlight adequately to bleach them for OSL analysis.

The present study has dated three tsunami events at two sites at 150-200, 2550±190 and 3170±320 years BP. The first two events have been correlated with available historical records giving enhanced confidence that the dating is reasonably reliable. From previous studies on the Thailand and Indonesian coasts, the recurrence interval of major tsunamis in the Indian Ocean has been established as 600 years (Bondevik, 2008; Jankaew *et al*., 2008; Monecke *et al*., 2008). Other researchers have recorded the following events; 100-130, 540-600/500-700/380±130, 966-1170, 990-1400, and 2220/2100±260 years ago based on carbon dating (Monecke *et al*., 2008; Jankaew *et al.*, 2008; Brill *et al*., 2011; Brill *et al*., 2012; Prendergast *et al.*, 2012). The lack of recording of the other two younger events from this study indicates they may not have been strong enough to imprint geological records on the much more distant Sri Lankan coast or that the records have not been preserved adequately.

The oldest event recorded by the present study at 3170±320 years BP is the first record of the oldest event which has ever been recorded anywhere in the Indian Ocean.

10.1.4 Tsunami risk on the Sri Lankan coast

The main cause of tsunamis in the Indian Ocean is the triggering of large earthquakes along the active Andaman-Sumatra subduction zone. Geological records indicate that not all large earthquakes occurring along this subduction zone generate tsunamis, especially large tsunamis which affect the whole Indian Ocean mainly because of variations in the orientation of the fault plane. Therefore, geological records provide information only about the largest tsunamis with particular focal mechanisms associated with thrust earthquakes which uplift the ocean floor extremely rapidly by significant amounts, since only these giant tsunamis can leave significant geological records on the remote coast. However, despite the great risk and the impact caused by large tsunamis, others are sometimes not noticed by humans, and are only detected by buoys and wave gauges. Therefore, the application of geological records together with GPR and OSL dating for tsunami risk estimation appears to be the most feasible and successful approach.

10.2 Conclusions

- The use of sedimentological characteristics for tsunami sediment identification is the most effective method. Tsunami sediments show distinct grain size statistical, textural, structural (macro to micro level) and mineralogical characteristics.
- The anti-correlation between mean grain size and skewness / kurtosis appears to be a strong diagnostic signature for tsunamigenic sediments.
- Poor sorting, with higher coarse grain fractions and the presence of angular to well-rounded grains with poly-modal grain size distribution pattern are also significant signatures for tsunamigenic sediments.
- Depositional characteristics of tsunami sediments on the Sri Lankan coast exhibit appropriate signatures of tsunamigenic origin which are mostly comparable with already established characteristics of tsunami sediment deposits from the previous studies.
- The other most conclusive evidence of tsunamigenic sediments was their micro-paleontological characteristics. This study reveals that tsunami sediments were present with microfossils especially marine foraminifera species.
- Tsunami sediments on the Sri Lankan coast did not contain fossil bivalves, although normal beach sand is rich in bivalve fossils. This suggests that tsunami sediments were not related to normal beach sand.
- The off the shelf GPR technique can be easily used for mapping the subsurface distribution of tsunami sediments and distinguishing them from other coastal deposits although there are some limitations when there are saline water bodies and topographical breaks.

- The circa 600 year recurrence interval for major tsunamis in the Indian Ocean, established by previous studies was further corroborated by our results and we have also recorded the oldest event in the 3170 years BP, which has not previously been recorded in the Indian Ocean.
- The methods developed in this thesis for the quantification and reconstruction of palaeotsunamis using GPR, the OSL dating techniques and microfossil analysis have appropriately filled a gap in tsunami risk estimation in the tsunami sciences.

5. The results of the laboratory electromagnetic measurements show a clear contrast between the dielectric properties of the tsunamigenic sediments and normal beach sands and lagoonal sediments (Table 6.1), which is the reason for the clearly defined refection signatures observed on the GPR profiles.

- There is also a marked difference in textural and mineralogical properties between normal beach deposits and the tsunamigenic deposits meaning that the GPR technique can be used to map the subsurface extents of tsunamigenic and palaeotsunamigenic sand facies.

10.3 Future prospects and further works

Tsunami generation, their propagation across oceans and their impact on very distant coasts are now reasonably understood. Furthermore, the problem of identification of the tsunami records on these coasts has been practically resolved by the work in this study. Therefore, after the present study the following research areas are suggested for further consideration and development.

- Application of 3-D imaging with GPR techniques to determine the spatial morphology and inundation distance of palaeotsunamis to obtain more information on tsunami sediment distribution within the coastal geological sequence.
- Application of this method to the other coasts in the Indian Ocean as well as other places in the world to test tsunami risk.
- Studies on offshore tsunamigenic sediment characteristics using presently identified signatures.
- Use of other appropriate geophysical techniques such as electrical resistivity tomographic imaging in conjunction with GPR to map tsunami sediment deposits in an integrated approach which should enable the methods to be applied in any of the environmental conditions and deeper levels than presently tested. Then, even older tsunami events might be identified globally and tsunami risk estimation improved with the consequent improvement in mitigation strategies and protection of property and most importantly reduction in mortality and injury to coastal dwelling nations.

- Microfossils studies of the 2004 tsunami sediments at Katukurunda suggested that there is some relationship between type of species and the respective waves brought the sediments. Thus, further studies will be able to developed proper model for wave dynamics using microfossil studies.

REFERENCES

Abe, K. (1993) Modelling of the run up heights of the Hokkaido-Nansei-Oki tsunami of 12 July 1993 *Pure and Applied Geophysics*, **144**, pp735-745.

Abe, K. (1994) Instrumental Magnitudes of Historical Earthquakes,1892 to 1898. *Bulletin of the Seismological Society of America*, **84,** pp415-425.

Abe, K. (1995) Modeling of the Run-up Heights of the Hokkaido-Nansei-Oki Tsunami of 12 July 1993 *Pure and Applied Geophysics*, **144**, pp735-745.

Abe, I., Goto, K., Imamura, F. and Shimizu, K. (2008) Numerical simulation of the tsunami generated by the 2007 Noto Hanto Earthquake and implications for unusual tidal surges observed in Toyama Bay. *Earth Planets and Space*, **60**, pp133-138.

Aoibheann, K.A, Blackford, J.J. and Meer, J.J.M. (2007) Micromorphological Analysis of Coastal Sediments from Willapa Bay, Washington, USA: A Technique for Analysing Inferred Tsunami Deposits. *Pure and Applied and Applied Geophysics*, **164**, pp519-525.

Aitkenhead, M.J., Lumsdon, P. and Miller, D.,R. (2007) Remote sensing-based neural network mapping of tsunami damage in Aceh, Indonesia, *Disasters,* **31**,pp 217-226.

Atwater, B.F. (1987) Evidence for great Holocene earthquakes along the outer coast of Washington State. *Science*, **236**, pp 942-944.

Atwater, B.F., and Yamaguchi, D.K. (1991) Sudden, Probably Coseismic Submergence of Holocene Trees and Grass in Coastal Washington-State. *Geology,* **19**, pp706-709.

Atwater, B.F. (1992) Geologic Evidence for Earthquakes during the Past 2000 Years Along the Copalis River, Southern Coastal Washington. *Journal of Geophysical Research-Solid Earth*, **97**, pp1901-1919.

Atwater, B.F., Nelson, A.R., Clague, J.J., Carver, G.A., Yamaguchi, D.K., Bobrowsky, P.T., Bourgeois, J., Darienzo, M.E., Grant, W.C., Hemphill-Haley, E., Kelsey, H.M., Jacoby, G.C., Nishenko, A.P., Palmer, S.P., Peterson, C.D. and Reinhart, M.A. (1995) Summary of coastal geological evidence for past great earthquakes at the Cascadia subduction zone. *Earthq. Spectra*, **11**, pp1-18.

Babu, N., Babu, D.S. and Das, N.M. (2006) Impact of tsunami on texture and mineralogy of a major placer deposit in southwest coast of India. *Environmental Geology*, **52**, pp71-80.

Bahlburg, H., and Weiss, R. (2007) Sedimentology of the December 26, 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya. *International Journal of Earth Sciences*, **96**, pp1195-1209.

Benson, B.E., Grimm, K.A. and Clague, J.J. (1997) Tsunami deposits beneath tidal marshes on north-western Vancouver Island, British Columbia. *Quaternary Research*, **48**, pp192-204.

Bos A.J.J. and Wallinga J (2009 Analysis of the quartz OSL decay curve by differentiation *Radiation measurements*, **44**, pp88-53

Bernard, E.N., Mofjeld, H.O., Titov, V., Synolakis, C.E. and Gonzalez, F.I. (2006) Tsunami: scientific frontiers mitigation, forecasting and policy implications. *Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences*, **364**, pp1989-2006.

Berry M.V. (2007) Focused tsunami waves, proceeding of Royal Society *,Mathematical,Physical and Engineeering Sciences*, **463**, pp3055-3071.

Blott, S.J. and Pye, K. (2001) Gradisat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, **26**, pp1237-1248.

Bondevik, S., Dawson, S., Dawson, A. and Øystein, L. (2003) Record-breaking Height for 8000-Year-Old Tsunami in the North Atlantic, EOS, *Transactions American Geophysical Union*, **84** (31)

Bondevik, S., Lovholt, F., Harbitz, C., Mangerud, J., Dawson, A. and Svendsen, J.I. (2005). The Storegga Slide tsunami - comparing field observations with numerical simulations. *Marine and Petroleum Geology*, **22**, pp195-208.

Botha, G.A., Bristow, C.S., Porat, N., Duller, G., Armitage, S.J., Roberts, H.M., Clarke, B.M., Kota, M.W. and Schoeman, P. (2003) Evidence for dune reactivation from GPR profiles on the Maputaland coastal plain, South Africa. *Geological Society, London, Special Publications,* **211**, pp29-46.

Bourgeois, J., Petroff, C., Yeh, H., Titov, V., Synolakis, C.E., Benson, B., Kuroiwa, J., Lander, J. and Norabuena, E. (1999) Geologic setting, field survey and modeling of the Chimbote, northern Peru, tsunami of 21 February 199, *Pure and Applied Geophysics*, **154**, pp513-540.

Brill D., Brückner H., Jankaew K., Kelletat D. Scheffers, A and Scheffers S. (2011) Potential predecessors of the 2004 IndianOcean Tsunami Sedimentary evidence of extreme wave events at Ban Bang Sak, SW Thailand, *Sedimentary Geology*, **239,** pp146-161.

Brill D., Klasen N., Brückner H., Jankaew K., Scheffers, A., Kelletat D. and Scheffers S. (2011) OSL dating of tsunami deposits from Phra Thong Island, Thailand, Quaternary Geochronology, **(** *in press)***.**

Bristow, C.S. and Jol, H.M. (2003) An Introduction to ground penetrating radar (GPR) in sediments, *Ground Penetrating radar in sediments* (*ed. Charles S Bristow, and Harry M Jol),* Geo Soc London, 1-9.

Brooke, B.P., Young, R.W., Bryant, E.A., Murraywallace, C.V. and Price, D.M. (1994) A Pleistocene Origin for Shore Platforms Along the Northern Illawarra Coast, New-South-Wales. *Australian Geographer*, **25**, pp178-185.

Bryant, E. (2005) Natural Hazards (2nd Edition) Cambridge University Press, UK.

Bryant, E.A. (2008) Tsunami ;The Underrated Hazard. Springer link publications.

Bryant, E.A. and Nott, J. (2001) Geological indicators of large tsunami in Australia. *Natural Hazards*, **24**, pp231-249.

Bryant, E.A. and Haslett, S.K. (2002) Was the AD 1607 coastal flooding event in the Severn Estuary and Bristol Channel (UK) due to a tsunami? *Archaeology in the Severn Estuary,* **13**, pp163-167.

Bryant, E.A., Young, R.W., Price, D.M. and Short, S.A. (1992) Evidence for Pleistocene and Holocene Raised Marine Deposits, Sandon Point, New-South-Wales. *Australian Journal of Earth Sciences*, **39**, pp481-493.

Burwell, D, Tolkova, E and Chawla A (2007) Diffusion and dispersion characterization of a numerical tsunami model, *Ocean Modellin*g,**19.**

Camfield, F.E. (1994) Tsunami effects on coastal structures. *Journal of coastal* research special issue no. **12**, pp177-187.

Cantalamessa, G. and Di Celma, C. (2005) Sedimentary features of tsunami backwash deposits in a shallow marine Miocene setting, Mejillones Peninsula, northern Chile. *Sedimentary Geology*, **178**, pp259-273.

Carver, G.A., Abramson, H.A., Garrison-Laney, C.E. and Leroy, T. (1999) Paleotsunami evidence from northern California for repeated long rupture (M 9) of the Cascadia Subduction Zone. *Annual Meeting of the Seismological Society of America*, USA.

Choi, B.H., Pelinovsky E., Kim K.O., and Lee, J.S. (2003) Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatau volcanic eruption. *Natural Hazards and Earth System Sciences,* **3,** pp321-332.

Clague, J.J. and Bobrowsky, P.T. (1994) Evidence for a Large Earthquake and Tsunami 100-400 Years Ago on Western Vancouver-Island, British-Columbia. *Quaternary Research*, **41**, pp176-184.

Chague, J.J. and Goff, J.R. (1999) Geochmical and sedimentological signature of catastrophic sea water inundation (tsunami), New Zealand. *Quaternary Australia*, **17**, pp38-48.

Clague, J.J., Bobrowsky, P.T. and Hutchinson, I. (2000) A review of geological records of large tsunamis at Vancouver Island, British Columbia, and implications for hazard. *Quaternary Science Reviews*, **19**, pp849-863.

Codrington, H.W. (1994) Short History of Ceylon. *Asian Educational Services*.

Dahanayake, K and Kulasena, N. (2008) Recognition of diagnostic criteria for recent- and paleo-tsunami sediments from Sri Lanka. *Marine Geology*, **254**, pp180-186.

Dawson, A.G., Long, D. and Smith, D.E. (1988) The Storegga Slides - Evidence from Eastern Scotland for a Possible Tsunami. *Marine Geology*, **82**, pp271-276.

Dawson, A.G., Shi, S., Dawson, S., Takahashi, T. and Shuto, N. (1996) Coastal sedimentation associated with the June 2nd and 3rd, 1994 tsunami in Rajegwesi, Java. *Quaternary Science Reviews*, **15**, pp901-912.

Dawson, A.G. and Shi, S.Z. (2000) Tsunami deposits. *Pure and Applied Geophysics*, **157**, pp875-897.

Dawson, S. and Smith, D.E. (2000) The sedimentology of Middle Holocene tsunami facies in northern Sutherland, Scotland, UK, *Marine Geology*, **170**.

Dawson, A.G, Lockett, P., Shi, S. (2004) Tsunami hazards in Europe, *Environment International*, **30**(4), pp 577-585

Dawson, A.G. and Stewart, I. (2007)Tsunami deposits in the geological record. *Sedimentary Geology*, **200**, pp166-183.

De Martini, P.M., Burrato, P., Pantosti, D., Maramai, A., Graziani, L. and Abramson, H. (2003) Identification of tsunami deposits and liquefaction features in the Gargano area (Italy): paleoseismological implication. *Annals of Geophysics*, **46**, pp883-902.

Dominey-Howes, D. (2002) Documentary and geological records of tsunamis in the Aegean Sea region of Greece and their potential value to risk assessment and disaster management. *Natural Hazards*, **25**, pp195-224.

Dominey-Howes, D., Cummins, P. and Burbidge, D. (2007) Historic records of teletsunami in the Indian Ocean and insights from numerical modelling. *Natural Hazards,* **42**, pp1-17.

Dominey-Howes, D.T.M., Humphreys, G.S. and Hesse, P.P. (2006) Tsunami and palaeotsunami depositional signatures and their potential value in understanding the late-Holocene tsunami record. *Holocene*, **16**, pp1095-1107.

Donato, S.V., Reinhardt, E.G., Boyce, J.I., Rothaus, R. and Vosmer, T. (2008) Identifying tsunami deposits using bivalve shell taphonomy. *Geology,* **36**, pp199–202.

Fagherazzi S. and Du X. (2008) Tsunamigenic incisions produced by the December 2004 earthquake along the coasts of Thailand, Indonesia and Sri Lanka. *Geomorphology*, **99**, pp120-129.

Finn Løvholt, Sylfest Glimsdal, Carl B. Harbitz, Natalia Zamora, Farrokh Nadim, Pascal Peduzzi, Hy Dao and Helge Smebye (2012) Tsunami hazard and exposure on the global scale , *Earth-Science Reviews*, **110** (1–4), -73.

Fujino, S., Masuda, F., Tagomori, S. and Matsumoto, D. (2006) Structure and depositional processes of a gravelly tsunami deposit in a shallow marine setting: Lower Cretaceous Miyako Group, Japan. *Sedimentary Geology*, **187**, pp127-138.

Fujiwara, O., Masuda, F., Sakai, T., Irizuki, T. and Fuse, K. (2000) Tsunami deposits in Holocene bay mud in southern Kanto region, Pacific coast of central Japan. *Sedimentary Geology*, **135**, pp219-230.

Fujiwara, O. and Kamataki, T. (2007) Identification of tsunami deposits considering the tsunami waveform: An example of subaqueous tsunami deposits in Holocene shallow bay on southern Boso Peninsula, Central Japan. *Sedimentary Geology*, **200**, pp295-313.

Fullagar, R., Head, L., Bryant, E.A., Beaman, S. (1999) Tsunami disturbance on coastal middens, McCauleys Beach, New South Wales. In *Australian Coastal Archaeology*, ed, J. Hall, & I. McNiven, pp. 235-238. Canberra :ANH Publication, Department of Archaeology and Natural History, Australian National University.

Fuhrman, D.R and Bingham, H.B. (2004) Numerical solutions of fully non-linear and highly dispersive Boussinesq equations in two horizontal dimensions, *International Journal for Numerical Methods in Fluids,* **44,** pp231–255.

Gehrels, W.R. and Long, A.J (2007) Quaternary land–ocean interactions: Sea-level change, sediments and tsunami, *Marine Geology*, **242** (1–3)

Gelfenbaum, G., and Jaffe, B. (2003) Erosion and sedimentation from the 17 July, 1998 Papua New Guinea tsunami. *Pure and Applied Geophysics*, **160**, pp969-1999.

Gerassimos, A.P. and Imamura, F. (2001) A proposal for a new tsunami intensity scale. (*ed*), Ryan Layne Whitney, *International Tsunami Symposium 2001, Publisher; NOAA.*

Goff, J., Chagué-Goff, C. and Nichol , S (2001) Palaeotsunami deposits: a New Zealand perspective., *Sedimentary Geology*, **143**(1-2).

Goff, J.R., Crozier, M., Sutherland, V., Cochran, U. and Shane, P (1998) Possible tsunami deposits of the 1855 earthquake, North Island, New Zealand. In *Coastal Tectonics, ed.* I.S. Stewart and C.,Vita-Finzi, pp. 353–374. *Geol. Soc. Spec. Publ. No. 133*.

Goff, C. and Goff, J.R. (1999). Geochemical and sedimentological signature of catastrophic saltwater inundations (tsunami), New Zealand. *Quat. Aust.* **17**,pp38–48.

Goff, J., Liu, P.L.F., Higman, B., Morton, R., Jaffe, B.E., Fernando, H., Lynett, P., Fritz, H., Synolakis, C. and Fernando, S. (2006) Sri Lanka field survey after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, **22**, pp155-172.

Goff, J.R., McFadgen, B.G., (2001). Nationwide tsunami during prehistoric Maori occupation, New Zealand. *Proceedings of the International Tsunami Symposium 2001*, NOAA/PEML, *Seattle*, pp469–476.

Goff, J., McFadgen, B.G. and Chague-Goff, C. (2004) Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology*, **204**, pp235-250.

Goff, J, Chagué-Goff, C., Nichol,S, Jaffe, B,. Dominey-Howes, D. (2012) Progress in palaeotsunami research , *Sedimentary Geology*, **243–244,** pp70-88

Goffredo, S., Piccinetti, C. and Zaccanti,F. (2007) Tsunami survey expedition: Preliminary investigation of Maldivian coral reefs two weeks after the event. *Environmental Monitoring and Assessment*, **131**, pp95-105.

Godfrey-Smith D.I., Huntley D.J. and Chen W.H. (1988) Optical dating studies of quartz and feldspar sediment extracts. *Quaternary Science Reviews* **7,** pp373-380.

Gonçalves, J.A.N., Sandonato, G.M., Meléndrez, R., Chernov, V. , Pedroza-Montero, M., De la Rosa, E., Rodríguez, R.A., Salas, P. and Barboza-Flores , M. (2005) OSL and TL dosimeter characterization of boron doped CVD diamond films, *Optical Materials***,** **27(7)**, pp1231-1234.

Goto, K., Catherine Chagué-Goff, Shigehiro Fujino, James Goff, Bruce Jaffe, Yuichi Nishimura, Bruce Richmond, Daisuke Sugawara, Witold Szczuciński, David R. Tappin, Robert C. Witter and Eko Yulianto (2001) New insights of tsunami hazard from the 2011 Tohoku-oki event , *Marine Geology*, **290**(1–4), pp46-50

Goto, K., Jun Takahashi, Takayuki Oie and Fumihiko Imamura (2011) Remarkable bathymetric change in the nearshore zone by the 2004 Indian Ocean tsunami: Kirinda Harbor, Sri Lanka, *Geomorphology*, **127**(1–2).

Grauert, M., Bjoerck, S. and Bondevik, S. (2001) Storegga tsunami deposits in a coastal lake on Suouroy, the Faroe Islands. *Boreas*, **30**, pp263-271.

Greenhough, B., Jazeel, T. and Massey, D. (2005) Introduction: Geographical encounters with the Indian Ocean tsunami. *Geographical Journal*, **171**, pp369-371.

Gunatilake, A. (2005) The Indian Ocean megatsunami of December 2004: the scientific basis of the Catastrophe. *Journal of National Science Foundation, Sri Lanka*, **33**, 69-80**.**

Hayir, A., (2004) Ocean depth effects on tsunami amplitudes used in source models in linearized shallow-water wave theory , *Ocean Engineering*,**31**(3–4) pp353-361.

Halif, M.N.A. and Sabki, S.N. (2005) The physics of Tsunami: basic understanding of the Indian Ocean disaster, *American Journal of Applied Sciences*, **2** (8), pp1188-1193.

Hamouda, A.Z. (2006) Numerical computations of 1303 tsunamigenic propagation towards Alexandria, Egyptian Coast. *Journal of African Earth Sciences*, **44** *(1)*, pp37-44.

Hampton, M.A., Lee H.J. and Locat, J. (1996) Submarine Landslides. *Reviews of Geophysics*, **34**, pp33–59.

Hardy, R.S. (1866) The Legends and Theories of the Buddhists. *Williams and Norgate.*

Haslett, S.K. and Bryant, E.A., (2007) Reconnaissance of historic (post-AD 1000) high-energy deposits along the Atlantic coasts of southwest Britain, Ireland and Brittany, France, *Marine Geology*, **242**(1–3), pp207-220

Haslett, S.K., Mellor, H.E. and Bryant E.A.(2009) Meteo-tsunami hazard associated with summer thunderstorms in the United Kingdom, *Physics and Chemistry of the Earth, Parts A/B/C*, **34** , pp1016-1022.

Haslett, S. K. (2011) Earthquake, tsunami and nuclear power: Relevance of the 1607 flood in the Bristol Channel, Blackbarn Books, Usk.

Hatori1, T. (1995) Magnitude scale for the Central American tsunamis. *Pure and Applied Geophysics*, **144**, 471-479.

Havholm, K.G., Bergstrom, N.D., Jol, H.M. and Running, G.L. (2003) The use and application of GPR in sandy fluvial environments: methodological considerations. In *Ground Penetrating Radar in Sediments*, ed. C.S. Bristow and H.M. Jol, Editors, pp. 47-55**,** Geological Society London, Special Publications 2003.

Haugen K, Løvholt F and Harbitz C (2005) Fundamental mechanisms for tsunami generation by submarine mass flows in idealised geometries". *Marine and Petroleum Geology,* **22**: pp209-217.

Hawkes, A.D., Bird, M., Cowie, S., Grundy-Warr, C., Horton, B.P., Hwai, A.T.S., Law, L., Macgregor, C., Nott, J., Ong, J.E., Rigg, J., Robinson, R., Tan-Mullins, M., Sa,T.T., Yasin, Z. and Aik, L.W. (2007) Sediments deposited by the 2004 Indian Ocean Tsunami along the Malaysia-Thailand Peninsula. *Marine Geology*, **242**, pp169-190.

Hearty, P.J. (1997) Boulder Deposit from large waves during the large interglaciation on North Eleunthera Bahamas. *Quaternary research*, **48**, pp326-338.

Heinz, J and Aigner, T. (2003) The use and application of GPR in sandy fluvial environments: methodological considerations. In *Ground Penetrating Radar in Sediments*, ed. C.S. Bristow and H.M. Jol, Editors, pp. 99-111**.** Geological Society London, Special Publications 2003.

Helal, M.A. and Mehana, M.S. (2008) Tsunami from nature to physics, *Chaos, Solitons & Fractals*, **36**(4) pp787–796.

Hemphill-Haley,E. (1996) Diatoms as an aid in identifying late-Holocene tsunami deposits. *The Holocene*, **6** (4) pp439–448.

Herath, J.W. (1985) The Economic Geology of Sri Lanka, Natural Resource Series No 1, NARESA Publication.

Herath, M M J W (1988) Sri Lankan beach mineral sands, Geological Survey Publication. Sri Lanka.

Hettiarachchi, S.S.L. and Samarawickrama, S.P. (2005) Experience of the Indian Ocean Tsunami on the Sri Lankan coast. *International Symposium Disaster Reduction on Coasts, Monash University, Melbourne, Australia*.

Hills, J.G. and Mader, C.L. (1997) Tsunami produced by the impact of small asteroids. *Annals of the New York Academy of Science,* **822**, pp381-394.

Hindson, R.A. and Andrade, C. (1999) Sedimentation and hydrodynamic processes associated with the tsunami generated by the 1755 Lisbon earthquake. *Quaternary International*, **56**, pp27-38.

Hori, K., Kuzumoto, R., Hirouchi, D., Umitsu, M., Janjirawuttikul, N. and Patanakanog, B. (2007) Horizontal and vertical variation of 2004 Indian tsunami deposits: An example of two transects along the western coast of Thailand. *Marine Geology*, **239**, pp163-172.

Horsburgh, K.J. and Horritt, M. (2006) The Bristol Channel floods of 1607 – reconstruction and analysis, *Weather*, **61**(10), pp272–277.

Helen M. Roberts, Julie A. Durcan, Geoff A.T. Duller (2009) Exploring procedures for the rapid assessment of optically stimulated luminescence range-finder ages, *Radiation Measurements*, **44** (5–6) pp582-587

Hutchinson, I., Clague, J.J., and Mathewes, R.W. (1997) Reconstructing the Tsunami record on an emerging coast: A case study of Kanim Lake, Vancouver Island, British Columbia. Canada, *Journal of Coastal Research*, **13**, pp545-553.

Hutchinson, I., Guilbault, J.P., Clague, J.J. and Bobrowsky, P.T. (2000) Tsunamis and tectonic deformation at the northern Cascadia margin: a 3000-year record from Deserted Lake, Vancouver Island, British Columbia, Canada. *Holocene*, **10**, pp429-439.

Iida, K. And Iwasaki T. (1983) Tsunami: Their Science and Engineering. *Reidel*, 61-76.

Jaffe, B.E. and Gelfenbaum, G. (2002) Using tsunami deposits to improve assessment of tsunami risk, *(ed). Jaffe, B. E. and Gelfenbaum G.), Solutions to Coastal Disasters Conference*.

Jankaew, K., Atwater B.F., Sawai, Y., Choowong, M., Charoentitirat, T., Martin, M.E. and Prendergast, A. (2008) Medieval forewarning of the 2004 Indian Ocean tsunami in Thailand. *Nature*, **455**, pp1228-1231.

James P. and Syvitski, M. (1991) Principles, Methods and Application of Particle Size Analysis, *Cambridge University Press*.

Jol, H.M. and Bristow, C.S. (2003) GPR in sediments: Advice on data collection, basic processing and interpretation, a good practice guide. In *Ground Penetrating Radar in Sediments*,ed. C.S. Bristow and H.M. Jol, Editors, pp. 9-27**.** Geological Society London, Special Publications 2003.

Jol, H.M and Smith, D.G. (1991) Ground penetrating radar of northern lacustrin deltas. *Canadian Journal of Earth Sciences*, **28**, 1939-1947.

Katupotha, J. and Fujiwara, K. (1988) Holocene sea level change on the southwest and south coasts of Sri Lanka, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **68,** pp189-203.

Kench, P.S., Mclean, R.F., Brander, R.W., Nichol, S.L., Smithers, S.G., Ford, M.R., Parnell, K.E. and Aslam, M. (2006). Geological effects of tsunami on mid-ocean atoll islands: The Maldives before and after the Sumatran tsunami. *Geology*, **34**, pp177-180.

Kharif,C and Pelinovsky, E.N. (2005) Asteroid impacttsunami ,*Comptes Rendus Physique*, **6,** pp361–366.

Kilfeather, A.A**.** Blackford, J.J and van der Meer, J.J.M. (2007) Micromorphological analysis of coastal sediments from Willapa Bay, Washington, USA: a potential technique for analysing inferred tsunami deposits. *Pure and Applied Geophysics*, **164**, pp509-525.

Knight, R. (2001) Ground penetrating radar for environmental applications. *Annual Review Earth Planet Science*, **29**, pp229–255.

Komatsubara, J. and Fujiwara, O. (2007) Overview of Holocene tsunami deposits along the Nankai, Suruga, and Sagami troughs, southwest Japan. *Pure and Applied Geophysics*, **164**, pp493-507.

Kortekaas, S. and Dawson, A.G. (2007) Distinguishing tsunami and storm deposits: An example from martinhal, SW Portugal. *Sedimentary Geology*, **200**, pp208-221.

Kruger, F. and Ohrnberger, M. (2005) Tracking the rupture of the M: 9.3, Sumatra earthquake over 1,150 km at teleseismic distance. *Nature*, **435**, pp937-939.

Kroner A., Cooray P.G. and Vitanage P.W. (1991) Lithotectonic Subdivision of the Basement in the Sri Lanka. The crystalline crust of Sri Lanka part 1, Professional Paper No.5, Geological Survey Department, Sri Lanka, pp5-21.

Kumar, K.A. and Achyuthan, H. (2006) A record of palaeo-tsunami in the Indian Ocean, *Marine Geodesy,* **29**, pp253-263.

Latter, J. H. (1981) Tsunamis of volcanic origin: Summary of causes, with particular reference to Krakatoa, 1883. *Bulletin of Volcanology,* **44**, pp 467-490.

Leclerc, J.P., Berger, C., Foulon, A., Sarraute, R. and Gabet, L. (2008) Tsunami impact on shallow groundwater in the Ampara district in Eastern Sri Lanka: Conductivity measurements and qualitative interpretations. *Desalination*, **219**, pp126-136.

Le Méhauté,B. and Wang S (1996) Water Waves Generated by Underwater Explosion *World Scientific, Singapore* .

Liu, K.B. and Fearn, M.L. (2000) Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records, *Quaternary Research*, **54**, pp238-245.

Liu, P.L.F., Lynett, P., Fernando, H., Jaffe, B.E., Fritz, H., Higman, B., Morton, R., Goff, J. and Synolakis, C. (2005) Observations by the International Tsunami Survey Team in Sri Lanka. *Science*, **308**.

Liu, Y.C., Santo S, A., Wang, S.M., Shi, Y.L., Liu, H.L. and Yuen, D.A. (2007) Tsunami hazards along Chinese coast from potential earthquakes in South China Sea. *Physics of the Earth and Planetary Interiors*, **163**, pp233-244.

Luque, L., Lario,J., Civis, J., Silva, P.G., Zazo, C., Goy, J.L. and Dabrio, C.J. (2002) Sedimentary record of a tsunami during Roman times, Bay of Cadiz, Spain. *Journal of Quaternary Science*, **17**, pp623-631.

Madsen, H.B., Bingham, and Liu, H. (2002) A new Boussinesq method for fully nonlinear waves from shallow to deep water, *Journal of Fluid Mechanics*, **462**, pp1–30.

Mamo, B., Strotz, L. and Dominey-Howes, D. (2009) Tsunami sediments and their foraminiferal assemblages, *Earth-Science Reviews*, **96** (4).

Matsumoto, D., Toshihiko Shimamoto, Takehiro Hirose, Jagath Gunatilake, Ashvin Wickramasooriya, Jeffrey DeLile, Sansfica Young, Chaminda Rathnayake, Jay Ranasooriya, Masafumi Murayama (2010) Thickness and grain-size distribution of the 2004 Indian Ocean tsunami deposits in Periya Kalapuwa Lagoon, eastern Sri Lanka *Sedimentary Geology* **230 (3–4)**,pp95-104.

Mamo, B, Strotz, L. and Dominey-Howes, D (2009) Tsunami sediments and their foraminiferal assemblages, *Earth-Science Reviews*, **9** , pp 263–278.

McAdoo, B.G. and Watts, P. (2004) Tsunami hazard from submarine landslides on the Oregon continental slope , *Marine Geology*, **203** (3–4), pp235-245.

McFadgen, B.G. and Goff, J.R. (2007) Tsunamis in the New Zealand archaeological record. *Sedimentary Geology*, **200**, pp263-274.

Minoura, K., Gusiakov, V.G., Kurbatov, A., Takeuti, S., Svendsen, J.I., Bondevik, S. and Oda, T. (1996) Tsunami sedimentation associated with the 1923 Kamchatka earthquake, *Sedimentary Geology*, **106**(1–2).

Minoura, K., Imamura, F., Takahashi, T. and Shuto, N. (1997) Sequence of sedimentation processes caused by the 1992 Flores tsunami: Evidence from Babi Island. *Geology*, **25**, pp523-526.

Minoura, K., Gusiakov, V. G., Kurbatov, A., Takeuti, S., Svendsen, J. I. , Bondevik, S. and Oda, T. (1996) Tsunami sedimentation associated with the 1923 Kamchatka earthquake, *Sedimentary Geology*, **106** (1–2),pp145–154.

Monecke, K. A. (2007) Palaeotsunami Record from Marshlands in West Aceh Province, Indonesia. *2007 Fall Meeting of the American Geophysical Union San Francisco, California (USA*).

Monecke, K., Finger, W., Klarer, D., Kongko, W., Mcadoo, B.G., Moore, A.L. and Sudrajat, S.U. (2008) A 1,000-year sediment record of tsunami recurrence in northern Sumatra. *Nature*, **455**, pp1232-1234.

Moore, A.L., Nishimura, Y., Gelfenbaum, G., Kamataki, T. and Triyono, R. (2006) Sedimentary deposits of the 26 December 2004 tsunami on the northwest coast of Aceh, Indonesia. *Earth Planets and Space*, **58**, pp253-258.

Moore, A.L., McAdoo, B.G. and Ruffman, A. (2007) Landward fining from multiple sources in a sand sheet deposited by the 1929 Grand Banks tsunami, Newfoundland. *Sedimentary Geology*, **200**, pp336-346.

Morales, J.A., Borrego, J., Miguel, E.G.S., Lopez-Gonzalez, N. and Carro, B. (2008) Sedimentary record of recent tsunamis in the Huelva Estuary (south-western Spain). *Quaternary Science Reviews*, **27**, pp734-746.

Morrow, R.C. and Llewellyn, D.M. (2006) Tsunami overview. *Military Medicine*, **171**(5-7).

Morton, R.A., Gelfenbaum, G. and Jaffe R.E. (2007) Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology*, **200**, pp184-207.

Morton, R.A., Goff, J.R. and Nichol, S.L. (2008) Hydrodynamic implications of textural trends in sand deposits of the 2004 tsunami in Sri Lanka. *Sedimentary Geology*, **207**, pp56-64.

Mosher, D.C., Austin, J.A., Fisher, D. and Gulick, S.P.S. (2008) Deformation of the northern Sumatra accretionary prism from high-resolution seismic reflection profiles and ROV observations. *Marine Geology*, **252**, pp89-99.

Murthy, T.S. and Loomis, H.G. (1980) A new objective tsunami magnitude scale. *Marine Geodesy*, **4**, pp267-282.

Murray, A.S. and Wintle, A.G. (2000) Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol, Radiation *Measurements*, **32,** pp57–73.

Murray, J.W (1993) Distribution and Ecology of Living Benthic Foraminifera, Heinamann Educational Books, London.

Nanayama, F., Furukawa, R., Shigeno, K., Makino, A., Soeda, Y. and Igarashi, Y. (2007) Nine unusually large tsunami deposits from the past 4000 years at Kiritappu marsh along the southern Kuril Trench. *Sedimentary Geology*, **200**, pp275-294.

Nanayama, F., Shigeno, K., Satake, K., Shimokawa, K., Koitabashi, S., Miyasaka, S. and Ishii, M. (2000) Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. *Sedimentary Geology*, **135**, pp255-264.

Narayana, A.C., Tatavarti, R., Shinu, N. and Subeer, A. (2007) Tsunami of December 26, 2004 on the southwest coast of India: Post-tsunami geomorphic and sediment characteristics. *Marine Geology*, **242**, pp155-168.

Nelson S.A. (2011) http://www.tulane.edu/~sanelson/geol204/tsunami.htm (visited; April 2012).

Nishimura, Y., Miyaji, N. and Suzuki, M. (1999) Behaviour of historic tsunamis of volcanic origin as revealed by onshore Tsunami deposits. *Physics and Chemistry of the Earth Part A-Solid Earth and Geodesy*, **24**, pp985-988.

Nott, J. (1997) Extremely high wave deposits inside the Great Barrier Reef, Australia; determining the cause tsunami or tropical cyclone, *Marine Geology*, **141**, pp193–207.

Nott, J. (2000) Records of prehistoric tsunami from boulder deposits evidence from Australia. *Science of Tsunami Hazards*, **18**, pp3–14.

Okal, E. A. (1988) Seismic Parameters Controlling Far-field Tsunami amplitude. *Natural Hazards*, **1**, pp67-96.

Okal, E.A., Alasset, P.J., Hyvernaud, O. and Schindele, F. (2003) The deficient T waves of tsunami earthquakes. *Geophysical Journal International*, **152**(2), pp416-432.

Okal, E.A. and Kirby, S.H. (1998) Deep earthquakes beneath the Fiji Basin, SW Pacific: Earth's most intense deep seismicity in stagnant slabs. *Physics of the Earth and Planetary Interiors*, **109**, pp25-63.

Papadopoulos, G.A., Caputo, R., McAdoo, B., Pavlides, S., Karastathis,V., Fokaefs, A., Orfanogiannaki, K. and Valkaniotis, S. (2006) The large tsunami of 26 December 2004:

Field observations and eyewitnesses accounts from Sri Lanka, Maldives Is. and Thailand. *Earth Planets and Space*, **58**, pp233-241.

Paris, R., Lavigne, F., Wassmer, P. and Sartohadi, J. (2007) Coastal sedimentation associated with the December 26, 2004 tsunami in Lhok Nga, west Banda Aceh (Sumatra, Indonesia*)*. *Marine Geology*, **238**, pp93-106.

Pelinovsky, E., Choi, B.H., Stromkov, A., Didenkulova, I. And Kim, H.S. (2005) Analysis of Tide-Gauge Records of the 1883 Krakatau Tsunami. In *Tsunamis,* ed. K.Satake, pp.55-78.

Perez-Torrado, F.J., Paris, R., Cabrera, M.C., Schneider, J.L., Wassmer, P., Carracedo, J.C., Rodriguez-Santana, A. and Santana, F. (2006) Tsunami deposits related to flank collapse in oceanic volcanoes: The Agaete Valley evidence, Gran Canaria, Canary Islands. *Marine Geology*, **227**, pp135-149.

Peters, R., Jaffe, B. and Gelfenbaum, G. (2007) Distribution and sedimentary characteristics of tsunami deposits along the Cascadia margin of western North America. *Sedimentary Geology*, **200**, pp372-386.

Pinegina, T. K. and Bourgeois, J. (2001) Historical and paleo-tsunami deposits on Kamchatka, Russia:long-term chronologies and long-distance correlations, *Natural Hazards and Earth System Sciences*, **1**, pp177–185.

Poppe, L.J., Eliason, A.H., Fredericks, J.J., Rendigs, R.R., Blackwood D. and Polloni, C.F. (2003) Grain size analyses of marine sediments: Methodology and data processing. *US Geological Survey Open Report*, **358**.

Premasiri, H. M. R., Styles, P. and Shrira, V. (2007) Sumatra tsunami signature in sediment characteristics on the Sri Lankan coast. *Geophysical Research Abstracts*.

Prendergast A. L., Cupper, M.L., Jankaew K. and Sawai,Y. (2012) Indian Ocean tsunami recurrence from optical dating of tsunami sand sheets in Thailand, *Marine Geology*, **295–298**, pp20-27.

Rabinovich, A.B. and Thomson, R.E. (2007) The 26 December 2004 Sumatra tsunami: Analysis of tide gauge data from the World Ocean Part 1. Indian Ocean and South Africa. *Pure and Applied Geophysics*, **164**, pp261-308.

Ramirez-Herrera, M.T., Cundy, A., Kostoglodov, V., Carranza-Edwards, A., Morales, E. and Metcalfe, S. (2007) Sedimentary record of late-Holocene relative sea-level change and tectonic deformation from the Guerrero Seismic Gap, Mexican Pacific Coast. *Holocene*, **17**, pp1211-1220.

Rhodes, B., Tuttle, M., Horton, B., Doner, L., Kelsey, H., Nelson, A. and Cisternas, M. (2006) Paleotsunami Research. *Eos,* **87**, pp205–209.

Richards, S., Lister, G. and Kennett, B. (2007) A slab in depth: Three-dimensional geometry and evolution of the Indo-Australian plate. *Geochemistry Geophysics Geosystems,* **8** *(12).*

Richmond, B.M., Jaffe, B.E., Gelfenbaum, G. and Morton R.A. (2006) Geologic Impacts of the 2004 Indian Ocean Tsunami on Indonesia, Sri Lanka, and the Maldives, *Z. Geomorphology*, **146**, pp235-251.

Richter, D., Tostevin, G., Škrdla, P. and Davies, W. (2009) New radiometric ages for the Early Upper Palaeolithic type locality of Brno-Bohunice (Czech Republic): comparison of OSL, IRSL, TL and ^{14}C dating results ,*Journal of Archaeological Science*, **36** (3), pp708-720.

Robert, A. Morton, Gelfenbaum, G. and Jaffe,B.E. (2007) Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples.
Sedimentary Geology, **200** (3-4), pp184-207.

Rossetto,T., Peiris, N., Pomonis, A., Wilkinson, S.M., Del Re, D., Koo, R. and Gallocher, S. (2007) The Indian Ocean tsunami of December 26, 2004: observations in Sri Lanka and Thailand. *Natural Hazards*, ***42***, pp105-124.

Ruiz, F., Borrego, J., Lopez-Gonzalez, N., Abad, M., Gonzalez-Regalado, M.L., Carro, B., Pendon, J.G., Rodriguez-Vidal, J., Caceres, L.M., Prudencio, M.I. and Dias,M.I. (2007) The geological record of a mid-Holocene marine storm in southwestern Spain. *Geobios*, **40**, pp689-699.

Sandiford, M., Coblentz, D. and Schellart, W.P. (2005) Evaluating slab-plate coupling in the Indo-Australian plate. *Geology*, **33**, pp113-116.

Satake, K., Okal, E.A. and Borrero, J.C. (2007) Tsunami and its hazard in the Indian and Pacific Oceans: Introduction. *Pure and Applied Geophysics*, **164**, pp249-259.

Satake, K. (2007) Tsunamis, *Treatise on Geophysics*, **4,** pp483-511.

Scheffers, A. (2004) Tsunami imprints on the Leeward Netherlands Antilles (Aruba, Curacao, Bonaire) and their relation to other coastal problems, *Quaternary International*, **120**, pp163-172.

Scheffers, A. and Kelletat, D. (2003) Sedimentologic and geomorphologic tsunami imprints worldwide - a review. *Earth-Science Reviews*, **63**, -92.

Scheffers, A. and Kelletat, D. (2004) Bimodal tsunami deposits – a neglected feature in paleo-tsunami research. *T.Dolch. Geographie der Meere und Küsten. Coastline Reports*, **1**, pp67-75.

Scheffers,A. and Scheffers, S. (2007) Tsunami deposits on the coastline of west Crete (Greece). *Earth and Planetary Science Letters*, **259**, pp613-624.

Schnyder, J., Baudin, F. and Deconinck, J.F. (2005) A possible tsunami deposit around the Jurassic-Cretaceous boundary in the Boulonnais area (northern France). *Sedimentary Geology*, **177**, pp209-227.

Scicchitano, G., Monaco, C. and Tortorici, L. (2007) Large boulder deposits by tsunami waves along the Ionian coast of south-eastern Sicily (Italy) , *Marine Geology*, **238**(1–4) pp75-91.

Semeniuk, V. (1996) Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. *Palaeogeogr. Palaeoclimatol. Palaeoecol*, **123**, pp49-84.

Shen, Z.X., Mauz, B., Lang, A., Bloemendal, J. and Dearing, J. (2007) Optical dating of Holocene lake sediments: Elimination of the feldspar component in fine silt quartz samples. *Quaternary Geochronology*, **2**, pp150-154.

Shi, S.Z., Dawson, A.G. and Smith, D.E. (1995) Coastal Sedimentation Associated with the December 12Th, 1992 Tsunami in Flores, Indonesia. *Pure and Applied Geophysics*, **144**, pp525-536.

Shlukov, A., I and Shakhvets, S.A. (1986) Kinetic studies of quartz thermolunescence as applied to sediment dating. *Conference: Methodologies for TL Dating in Tallinn.*

Simon K. Haslett, Holly E. Mellor, and Edward A. Bryant (2009) Meteo-tsunami hazard associated with summer thunderstorms in the United Kingdom *Physics and Chemistry of the Earth*, **34**(17–18), pp1016-1022.

Siriwardana, C.H.E.R. (2005) Final Report of the Tsunami Mapping Programme Conducted in the eastern, southern and western Regions in Sri Lanka, Geological Survey and Mines Bureau Sri Lanka (Unpublished Report).

Smith, D. (2005) Tsunami: a research perspective, *Geology Today*, **21 (**2 **),** pp64-68.

Smith, D. and Dawson, A. (1990) Tsunami Waves in the North-Sea. *New Scientist*, **127**, pp46-49.

Smith, D.E., Foster, I.D.L., Long, D. and Shi, S. (2007) Reconstructing the pattern and depth of flow onshore in a palaeotsunami from associated deposits, *Sedimentary Geology*, **200**, pp362-371.

Soloviev, S.L. (1970) Recurrence of Tsunamis in the Pacific.In *Tsunamis in the Pacific Ocean,*ed.W.M. Adams, pp149-163.

Srinivasalu, S., Thangadurai, N., Switzer, A.D., Mohan, V.R. and Ayyamperumal, T. (2007) Erosion and sedimentation in Kalpakkam (N Tamil Nadu, India) from the 26th December 2004 tsunami. *Marine Geology*, **240**, pp65-75.

Stein, S. and Okal, E.A. (2005) Speed and size of the Sumatra earthquake, *Nature*, **434**, pp581-582.

Stromkov A., Kim, S.H., Choi, B.H., Pelinovsk, E. and .Didenkulova. I. (2005) Analysis of tide-gauge records of the 1883 Krakatau tsunami. *Advances in Natural and Technological Hazards Research*, **23**, pp57-77.

Sugawara, D., K. Minoura, F. Imamura (2008) Tsunamis and tsunami sedimentology ed T. Shiki, Y. Tsuji, T. Yamazaki, K. Minoura (Eds.), Tsunamites Features and Implications, Elsevier.

Switzer, A.D., ,Srinivasalu, S., Thanadurai, N. and Ram, V. (2012) Bedding structure in Indian tsunami deposits that provide clues to the dynamics of tsunami inundation, Geological Society, London, Special Publication, **361**.

Tanioka, Y. and Katsumata, K. (2007) Tsunami generated by the 2004 Kushiro-oki earthquake. *Earth Planets Space,* **59** el e3 (E-letter).

Tanioka, Y., Kususose, T., Kathiroli, S., Nishimura, Y., Iwasaki, S.I. and Satake, K. (2006) Rupture process of the 2004 great Sumatra-Andaman earthquake estimated from tsunami waveforms. *Earth Planets and Space*, **58**, pp203-209.

Tappin, D.R. (2007) Sedimentary features of tsunami deposits - Their origin, recognition and discrimination: An introduction, *Sedimentary Geology*, **200**, pp151-154.

Thomson, R.E., Rabinovich, A.B., Fine, I.V., Sinnott, D.C., McCarthy, A., Sutherland, N.A.S. and Neil, L.K.(2009) Meteorological tsunamis on the coasts of British Columbia and Washington *Physics and Chemistry of the Earth, Parts A/B/C,* **34**, (17–18), pp971-988.

Thusyanithan, N.I. and Madabhusi, S.P.G. (2008) Tsunami wave loading on coastal houses: a model approach. *Proceedings of the Institution of Civil Engineers-Civil Engineering*, **161**, pp77-86.

Torrado, F.J.P., Paris, R., Cabrera, M.C., Luc Schneider, J., Wassmer, P., Carracedo, J., Rodríguez-Santana, A. and Santana, F.(2006) Tsunami deposits related to flank collapse in oceanic volcanoes: The Agaete Valley evidence, Gran Canaria. Canary Islands, *Marine Geology,* **227**(1-2), pp135-149.

Tsai, V.C., Nettles, M., Ekstrom, G. and Dziewonski, A.M. (2005) Multiple CMT source analysis of the 2004 Sumatra earthquake. *Geophysical Research Letters,* **32**.

Tuttle, M.P., Ruffman, A., Anderson, T. and Jeter, H. (2004) Distinguishing tsunami from storm deposits in eastern North America: The 1929 grand banks tsunami versus the 1991 Halloween storm. *Seismological Research Letters*, **75**, pp117-131.

Tuttle, M.P., Ruffman, A., Anderson, T. and Jeter, H. (2004) Tsunami or storm deposits? The 1929 `Grand Banks' tsunami versus the 1991 Halloween storm. 2004. Moncton, New Brunswick -Canada, *Atlantic Geoscience Society Colloquium & Annual General Meeting. 2004.*

Umitsu, M., Tanavud, C. and Patanakanog, B. (2007) Effects of landforms on tsunami flow in the plains of Banda Aceh, Indonesia, and Nam Khem, Thailand. *Marine Geology*, **242**, pp141-153.

Vita-Finzi, C. (2008) Neotectonics and the 2004 and 2005 earthquake sequences at Sumatra. *Marine Geology*, **248**, pp47-52.

Von Baeyer, H.C. (1999) Catch the wave. *The Science*, **29**, (3) pp10-13.

Wagner, B., Bennike, O., Klug, M. and Cremer, H. (2007) First indication of Storegga tsunami deposits from East Greenland, *Journal of Quaternary Science*, **22**, pp321-325.

Ward, S.N. (2002) Tsunami. In *The Encyclopaedia of Physical Science and Technology* 173rd Edition, ed. R.A. Meyers, pp. 175-191. Academic Press.

Weiss, R. (2008) Sediment grains moved by passing tsunami waves: Tsunami deposits in deep water. *Marine Geology*, **250**, pp251-257.

Wellanga, J. (2002) On the detection of OSL age overestimation using single-aliquot techniques, *Geochronometria*, **21,** pp17-26

Wijetunge, J.J. (2006) Tsunami on 26 December 2004: Spatial distribution of tsunami height and extent of inundation in Sri Lanka. *Science of Tsunami Hazard*, **24**, pp225-239.

Wilkins,D., Patrick De Deckker, L. Keith Fifield, Chris Gouramanis and Jon Olley (2012) Comparative optical and radiocarbon dating of laminated Holocene sediments in two maar lakes: Lake Keilambete and Lake Gnotuk, south-western Victoria, Australia, *Quaternary Geochronology,* **9**.

Williams, H. and Hutchinson, I. (2000) Stratigraphic and microfossil evidence for late Holocene tsunamis at Swantown Marsh, Whidbey Island, Washington. *Quaternary Research*, **54**, pp218-227.

Woodward, J., Ashworth, P.J., Best, J.L., Smith, G.H.S. and Simpson, C.J. (2003) The use and application of GPR in sandy fluvial environments: methodological considerations. In, *Ground Penetrating Radar in Sediments* vol. 211. ed. C.S. Bristow and H.M. Jol, pp. 127–142. Geological Society London. Special Publications 2003.

Xiao, H. and Huang, W.R. (2008) Numerical modelling of wave run up and forces on an idealized beachfront house. *Ocean Engineering*, **35**, pp106-116.

Yeh, H., Chadha, R.K., Francis, M., Katada, T., Latha, G., Peterson, C., Raghuraman, G. and Singh, J.P. (2006) Tsunami run up survey along the southeast Indian coast. *Earthquake Spectra*, **22**, pp173-186.

Yeh, H.H., Liu, P., Briggs, M. and Synolakis, C. (1994) Propagation and implication of tsunamis at coastal boundaries. *Nature*, **372**, pp352-355.

Web sites

Sri Lanka Department of Census and Statistics (2005). Housing and non-housing building units damaged by the Tsunami 2004; www.statitics.gov.lk/(visited may 2007)

The national atlas of Sri Lanka (1988) Published by the Survey Department of Sri Lanka. www.adb.org/Documents/Reports/Tsunami/sri-lanka-tsunami (visited April 2009)

http://walrus.wr.usgs.gov/tsunami/srilanka05/ (visited March 2009)

(http://www.rms.com/Publications/IndianOceanTsunami (visited January 2010)

http://nctr.pmel.noaa.gov/database_devel.html (visited April 2012)

http://www.foraminifera.eu/morphoclass.html(Valeria I. Mikhalevich et al) Zoological Institute. Russian Academy of Sciences (visited April 2012)

http://www.uic.edu/labs/ldrl/collection.html (visited April 2012)

http://www.rms.com/Reports/1607_Bristol_Flood.pdf (visited April 2012)

http://www.agu.org/journals/eo/v093/i019/2012EO190001/2012EO190001_brr.pdf (visited April 2012

ANNEXTURES

Annexure 1

Sieve analysis data (Transect 1) Payagala

Sample locations	Grain size in (µm) % by weight												Total
	850	500	425	355	300	250	212	180	125	106	75	0	
S1	8.827	2.879	1.102	0.950	1.273	2.132	2.491	4.199	20.637	8.733	22.278	24.465	99.972
S2	0.984	1.608	1.130	1.195	1.106	2.276	2.875	4.216	18.208	13.338	28.111	24.224	99.277
S3	2.137	1.0109	0.768	0.822	1.276	2.505	3.026	5.396	24.759	12.674	26.499	18.859	99.738
S4	0.707	1.156	1.0127	1.23	1.991	4.105	5.919	9.491	34.050	10.580	18.694	11.025	99.970
S5	2.137	1.0109	0.768	0.822	1.276	2.505	3.026	5.396	24.759	12.674	26.499	18.859	99.738
L6	0.707	1.156	1.012	1.233	1.991	4.105	5.919	9.491	34.050	10.580	18.694	11.025	99.970

Sieve analysis data at Yakgahagala (Transect 2)

Sample locations	Grain size in (µm) and % by weight												Total
	850	500	425	355	300	250	212	180	125	106	75	0	
S1	0.472	5.6270	7.872	8.8148	15.495	22.882	14.702	11.739	9.3116	1.309	1.280	0.470	99.979
S2	1.566	8.6478	9.073	10.681	17.077	20.075	11.152	9.1902	10.369	1.359	0.542	0.158	99.894
S3	0.296	2.688	4.182	5.9331	12.525	26.530	16.611	13.341	12.310	1.919	2.253	1.209	99.803
S4	6.303	15.337	11.058	11.155	13.825	13.794	9.082	8.2564	9.552	0.783	0.494	0.283	99.927
S5	0.829	6.9187	8.588	8.6422	17.355	24.738	12.609	10.100	7.736	0.989	0.974	0.304	99.788

Cumulative percentage values of sieve analysis data at yakgahagala (Transect 2)

Sample location	Grain size (µm) and % by weight											
	850	500	425	355	300	250	212	180	125	106	75	0
S1	99.979	99.507	93.880	86.008	77.193	61.697	38.814	24.112	12.372	3.060	1.750	0.470
S2	99.894	98.327	89.679	80.606	69.924	52.847	32.772	21.619	12.429	2.060	0.700	0.158
S3	99.803	99.506	96.817	92.635	86.702	74.176	47.646	31.034	17.693	5.382	3.463	1.209
S4	99.927	93.623	78.286	67.227	56.071	42.246	28.451	19.369	11.113	1.560	0.777	0.283
S5	99.788	98.959	92.040	83.452	74.809	57.453	32.715	20.105	10.004	2.268	1.279	0.304

)

Sieve analysis data at Yala (Transect 3)

Size (μm) and % wt (g)	850	500	425	355	300	250	212	180	125	106	75	0	Total (g)
S1	6.906	39.342	23.836	9.706	8.521	5.882	2.444	1.576	1.212	0.199	0.279	0.085	99.989
S2	11.229	33.156	15.276	7.868	9.021	8.572	4.643	3.922	4.557	0.743	0.863	0.112	99.963
S3	5.855	31.033	16.343	11.432	11.832	9.000	5.327	3.978	4.069	0.631	0.445	0.039	99.985
S4	2.067	18.183	14.917	13.927	16.816	14.530	7.526	5.519	4.611	0.705	0.786	0.182	99.768
S4	5.987	18.193	13.068	11.257	13.484	13.745	8.146	6.406	6.900	1.123	0.965	0.403	99.676
S5	6.905	39.334	23.831	9.704	8.519	5.881	2.443	1.576	1.212	0.199	0.279	0.085	99.968
S6	0.569	6.879	10.965	10.879	18.931	19.546	9.324	8.444	8.676	1.746	3.163	0.847	99.970
S7	1.654	12.166	14.408	14.621	18.703	17.289	8.378	6.137	4.909	0.774	0.640	0.133	99.813
S8	1.067	6.607	8.936	9.462	20.126	19.297	10.948	9.667	9.182	1.598	2.468	0.523	99.880
S9	29.157	32.339	8.612	5.986	6.066	5.370	3.481	2.725	3.202	0.656	1.054	0.955	99.602
S10	8.199	14.319	7.431	7.424	11.648	13.525	9.645	8.341	10.135	2.322	5.380	1.575	99.944
S11	16.028	19.393	7.281	6.457	9.780	11.404	8.098	6.676	8.091	1.787	3.891	1.034	99.921
S12	5.778	12.657	6.575	7.062	12.339	16.396	10.025	9.334	11.500	2.046	4.875	1.383	99.972
S13	0.491	7.647	10.432	10.757	18.981	18.649	9.422	7.727	10.778	1.667	2.705	0.620	99.877
S14	3.713	6.857	2.163	9.137	16.111	20.369	12.297	11.391	13.219	2.112	2.305	0.251	99.925
S15	2.823	5.159	5.840	7.917	16.288	20.977	10.561	10.496	13.952	2.482	2.644	0.487	99.627
S16	1.673	7.715	12.191	10.153	16.959	18.338	9.890	9.281	9.949	1.884	1.622	0.170	99.828
S18	0.550	1.980	4.099	6.730	14.885	24.549	13.216	12.337	15.906	2.788	2.469	0.387	99.896

Cumulative percentage values of sieve analysis data at Yala

Sample locations	grain size (μm) and % by weight											
	850	500	425	355	300	250	212	180	125	106	75	0
S1	99.989	93.082	53.741	29.904	20.198	11.677	5.795	3.3516	1.775	0.562	0.363	0.084
S2	99.962	88.733	55.577	40.301	32.433	23.412	14.840	10.197	6.274	1.717	0.975	0.112
S3	99.984	94.129	63.095	46.753	35.321	23.488	14.489	9.162	5.183	1.114	0.483	0.038
S4	99.768	97.701	79.518	64.601	50.674	33.858	19.328	11.802	6.284	1.673	0.967	0.181
S4	99.675	93.689	75.496	62.427	51.170	37.686	23.942	15.796	9.391	2.491	1.368	0.403
S5	99.968	93.063	53.729	29.898	20.194	11.675	5.794	3.350	1.774	0.562	0.363	0.084
S6	99.969	99.400	92.521	81.556	70.677	51.745	32.199	22.875	14.431	5.756	4.0101	0.846
S7	99.813	98.159	85.992	71.584	56.963	38.260	20.971	12.593	6.456	1.547	0.773	0.133
S8	99.879	98.812	92.205	83.269	73.807	53.681	34.384	23.437	13.770	4.588	2.990	0.522
S9	99.602	70.445	38.106	29.494	23.508	17.442	12.072	8.591	5.867	2.665	2.008	0.954
S10	99.943	91.744	77.426	69.994	62.570	50.922	37.398	27.752	19.412	9.276	6.954	1.575
S11	99.920	83.892	64.499	57.218	50.761	40.982	29.577	21.479	14.804	6.7126	4.925	1.034
S12	99.971	94.193	81.536	74.961	67.898	55.559	39.163	29.137	19.803	8.303	6.257	1.382
S13	99.877	99.386	91.739	81.307	70.550	51.569	32.919	23.497	15.770	4.992	3.325	0.620
S14	99.924	96.211	89.354	87.191	78.055	61.944	41.575	29.279	17.887	4.668	2.556	0.251
S15	99.626	96.804	91.645	85.804	77.887	61.599	40.622	30.061	19.565	5.613	3.131	0.486
S16	99.827	98.154	90.439	78.248	68.095	51.135	32.797	22.907	13.626	3.677	1.792	0.170
S18	99.896	99.346	97.366	93.268	86.538	71.652	47.103	33.887	21.550	5.644	2.856	0.387

Grain Size analysis in 2007 Sampling Yala Location 3

Distance from coast (m)	50	100	150	190	240	290	340	390	440	490
Loc. No.	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
850 (µm)	17.23	22.11	12.57	15.65	10.29	13.82	1.4	4.01	2.18	4.62
500	29.55	3.18	27.67	25.68	20.13	22.29	7.94	11.08	8.34	13.49
425	10.16	12.36	8.64	8.32	7.57	9.31	7.23	6.91	6.08	6.75
355	15.12	16.14	12.3	12.36	11.64	8.9	16.77	12.45	11.6	11.89
250	10.12	26.24	17.51	17.98	20.09	22.19	38.34	28.26	25.68	26.93
212	9.63	7.69	6.69	7.23	8.32	7.75	10.85	13.1	17.29	12.41
180	4.83	4.82	5.66	4.41	6.38	5.6	6.82	9.42	12.54	10.6
125	1.09	4.39	5.5	4.32	8.54	5.95	7	9.81	10.74	8.68
106	1.17	1.15	1.07	1.15	2.97	1.65	1.66	2.22	2.31	2.33
75	0.61	1.26	1.57	1.99	3.03	1.96	1.54	1.89	2.18	1.87
0	0.44	0.65	0.8	0.9	1	0.56	0.42	0.85	0.86	0.95

Grain Size analysis Payagala 2007

Distance from coast (m)	0	30	20
Location	P1A	P2	P1
850 (µm)	0.76	37.05	2.15
500	6.05	25.51	12.69
425	5.54	5.96	6.16
355	10.03	6.79	10.23
250	29.96	13.06	21.86
212	18.49	4.89	11.57
180	14.3	3.06	9.11
125	9.94	2.06	7.71
106	2.16	0.61	16.79
75	1.86	0.38	1.21
0	0.89	0.61	0.53

Palaeotsunami Sediment; Gain size analysis

Location 1 Hambantota

Layer	850(µm)	500	425	355	250	212	180	125	106	75	0
S1	7.51	25.23	9.29	10.83	22.47	10.36	7.21	5.69	0.8	0.47	0.11
S2	7.23	27.36	9.79	11.7	20.77	8.31	5.82	0.76	1.17	2.42	4.16
S3	11.02	31.9	11.42	10.9	19.38	0.98	6.06	6.06	0.51	0.98	0.75
S4	17.49	34.82	10.39	10.54	15.1	5.08	3.43	2.39	0.22	0.3	0.22
S5	35.15	35.62	6.29	3.8	5.94	1.66	2.26	2.61	2.97	0.95	2.73
S6	32.46	44.2	7.74	5.67	5.57	1.55	0.83	1.02	0.31	0.55	0.06
S7	41.42	37.3	5.9	4.82	5.1	1.73	1.26	1.03	0.37	0.33	0.7
S8	19.82	37.26	9.49	8.92	13.28	4.69	2.66	1.81	0.44	0.07	1.54
S9	25.03	31.77	8.41	8.06	12.19	4.79	3.61	3.79	0.8	0.8	0.73

Location 2 (Yala) Palaeotsunami sediment analysis

Layer	850 (µm)	500	425	355	250	212	180	125	106	75	0
S1	7.51	25.23	9.29	10.83	22.47	10.36	7.21	5.69	0.8	0.47	0.11
S2	7.23	27.36	9.79	11.7	20.77	8.31	5.82	0.76	1.17	2.42	4.16
S3	11.02	31.9	11.42	10.9	19.38	0.98	6.06	6.06	0.51	0.98	0.75
S4	17.49	34.82	10.39	10.54	15.1	5.08	3.43	2.39	0.22	0.3	0.22
S5	35.15	35.62	6.29	3.8	5.94	1.66	2.26	2.61	2.97	0.95	2.73
S6	32.46	44.2	7.74	5.67	5.57	1.55	0.83	1.02	0.31	0.55	0.06
S7	41.42	37.3	5.9	4.82	5.1	1.73	1.26	1.03	0.37	0.33	0.7
S8	19.82	37.26	9.49	8.92	13.28	4.69	2.66	1.81	0.44	0.07	1.54
S9	25.03	31.77	8.41	8.06	12.19	4.79	3.61	3.79	0.8	0.8	0.73

Annexure 3

THE LEGENDS AND THEORIES

OF THE

BUDDHISTS,

COMPARED WITH

HISTORY AND SCIENCE:

WITH INTRODUCTORY NOTICES OF THE LIFE AND SYSTEM OF GOTAMA BUDDHA.

BY

R. SPENCE HARDY, HON. M.R.A.S.,

AUTHOR OF "EASTERN (BUDDHIST) MONACHISM," "A MANUAL OF BUDDHISM," ETC.

WILLIAMS AND NORGATE,

14, HENRIETTA STREET, COVENT GARDEN, LONDON;

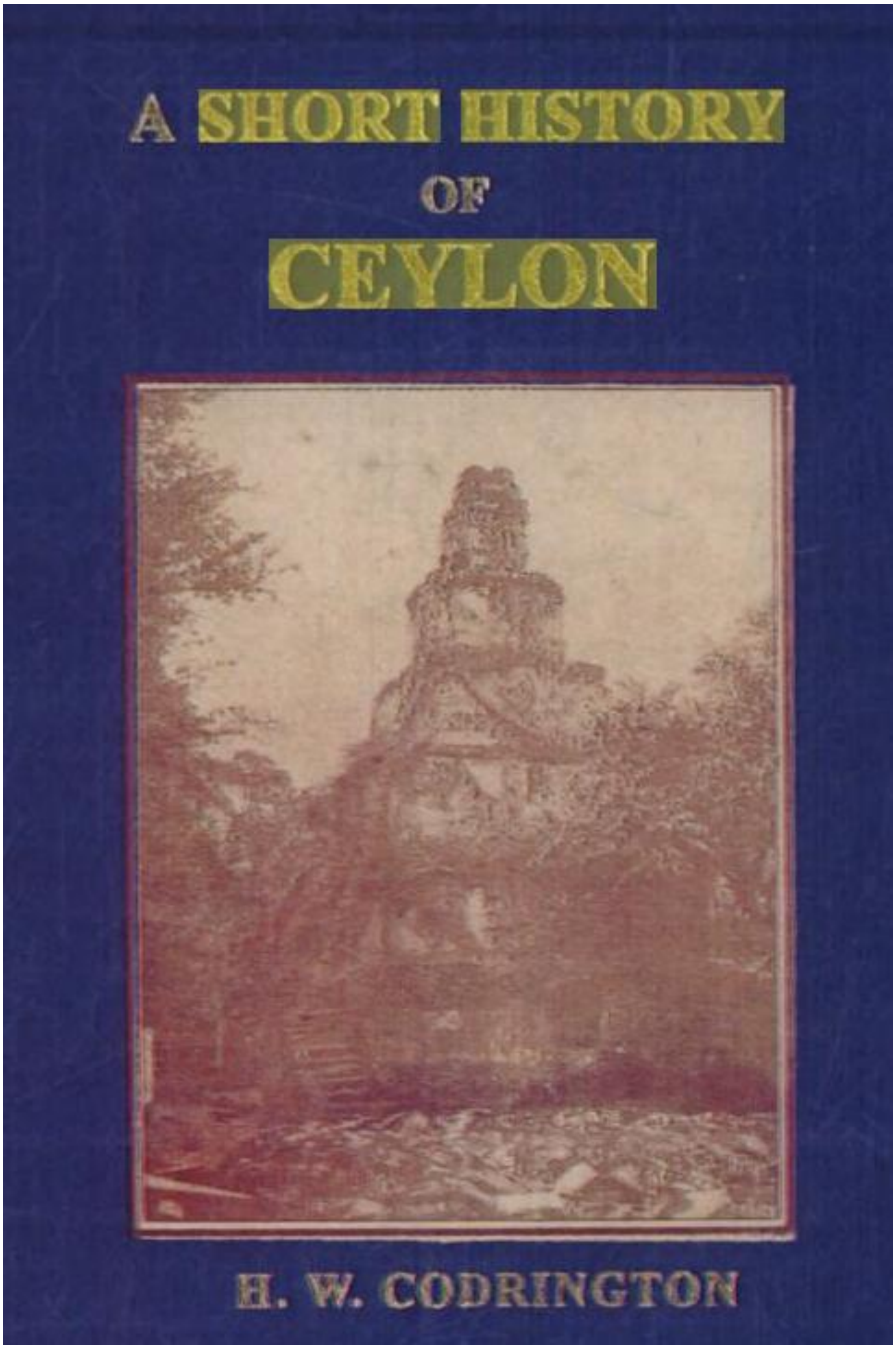
AND

20, SOUTH FREDERICK STREET, EDINBURGH.

1866.

3. THE SINGHALESE LEGEND OF KALYANI.

To show more clearly still the manner in which these conclusions are arrived at, I will apply the same process to one of the earliest of the Singhalese legends, in itself not without interest, and in some respects resembling the story I have just repeated from the traditions of Rome. About the middle of the third century after the death of Buddha, Ceylon was divided into several petty states, and among the rest was that of Kalyáni (Calány), of which Tissa was king. His wife was beautiful; his brother, Uttiya, was a libertine; and there was evil committed in the royal household. But the king having heard of the wrong that was done, sent secretly for a Rodiyá, and spoke to him thus: "I will call together my retinue, including my younger brother, and I will say to thee, in their presence, Is there any one of lower caste than thou art? and the reply thou must make is, The king's younger brother is a meaner man than I am." This was accordingly done; and the prince, thus put to shame, fled to Udagampala; but he contrived to send a letter to the queen, by a messenger disguised as a priest, who was to enter the palace with the rest of the priests when they went to receive the usual alms. The letter was filled with the common topics of a guilty lover; but it had no name, nor was the place mentioned whence it came. The queen was accustomed to assist at the giving of alms; and as she was looking towards the messenger, he took the opportunity to let the epistle fall on the ground. Its fall, however, caused a rustling noise, which attracting the notice of the king, he took it up; and on reading it he saw that his queen was unfaithful to her exalted position. Uttiya had been the pupil of the high priest of Kalyáni, and their hand-writing was alike. The king charged the high priest with having written the letter; listened to no protestations of his innocence; and commanded him to be put to death by being cast into a caldron of boiling oil. For seven days the attempt was made to heat the oil, but it still remained cold; but the priest, when a herdsman in a former age, had acted contrary to the precept, by drowning a fly that fell into some milk he was boiling, and for this offence, though he escaped the death appointed by the king, he was turned into a heap of ashes. The queen was thrown into the river, and the messenger was cut in pieces. But to punish the king for this act of impiety towards an innocent priest, the déwas who protect Ceylon caused the sea to encroach on the land, and much damage was done to the country. To appease their wrath, as it was supposed that the country could be saved in no other way, the king resolved to sacrifice his virgin daughter. Placing her in a golden vessel, on which was inscribed the word "rájadhítáti," which signified that she was a royal maiden, the vessel was committed to the waves of the sea. But the flood still raged, until 100,000 towns, 970 fisher villages, and 470 villages inhabited by divers for pearls, had been submerged.* As the king, from the back of his elephant, was watching the progress of the devastation, the earth opened, flame burst forth from beneath, and he was no more seen by his people. By this time twenty miles of the coast, extending inland, had been washed away, and the distance from Kalyáni to the sea was reduced to four miles. The royal virgin drifted towards the dominions of the king of Mágam, when the vessel was seen by some fishermen, who brought it to land. The monarch Káwantissa, having heard of the wonderful capture made by the fishermen, went to examine it; and when he had read the inscription upon it, he released the princess from her confinement, and she became his queen.


A SHORT HISTORY
OF
CEYLON
H. W. CODRINGTON

CHAPTER II

DUTTHA GĀMANI TO KASSAPA OF SIGIRIYA

THIRD CENTURY B.C.–SIXTH CENTURY A.D.

ELĀRA, or as he is called in Sinhalese Elāla, was a Ṭamil from the Chōla country, of which Tanjore was the capital in mediaeval times: he invaded Ceylon and put Asēla to death. Though a Hindu, his justice commanded the respect of his Sinhalese subjects. Concerning this the *Mahāvansa* relates that the king had a bell with a rope attached at the head of his bed, so that all who sought redress might ring it. Among other instances of the royal justice the chronicle tells how a calf was killed unintentionally by the chariot wheel of the king's son, and how, on the mother cow ringing the bell, the father had the prince's head struck off by the same wheel. The story is also told in Tamil literature of the Chōla king Manu.

At this period there were branches of the royal family established at Kelaniya and at Māgama in the present Hambantota District. The queen of Dēvānampiya Tissa tried to poison her brother-in-law, the sub-king Mahānāga, who thereupon fled towards Ruhuna. On the way his wife gave birth to a son, Tissa, at the Yatthāla Vihāra, whence, proceeding to Ruhuna, he established himself at Māgama. The site of Tissa's birthplace usually is identified with a temple near Galle, but it is clear from the narrative that it was not in Ruhuna: possibly it was the vihāra of the same name in Kēgalla District.

Tissa is said in the *Pūjāvaliya* to have built the Kelani Dāgaba: he, his son Gōthābhaya, and his grandson Kākavanna Tissa (Kāvan Tissa, 'Crow-colour Tissa'), succeeded to the government of the principality or kingdom of Māgama; the last named ruler's wife was the daughter of Tissa, king of Kelaniya. The queen of this king Tissa had carried on an intrigue with her brother-in-law, who on being detected fled and corresponded with her by a messenger disguised as a priest. The man attached himself to the attendants of the chief priest who was visiting the palace, and catching the eye of the queen dropped his master's letter. Unfortunately the palm-leaf missive made a noise in falling; the correspondence was detected, and the king in his fury slew not only the messenger but the chief priest, whose complicity he suspected. Thereupon the sea, which according to the *Rājāvaliya* was then about seven gaus (some fifteen miles) from Kelaniya, overwhelmed the land, submerging many towns and villages. To put an end to this the king placed his daughter Dēvī in a golden vessel and launched it into the sea: she was carried southwards and cast ashore near a temple (vihāra), when she became the queen consort of Kākavanna Tissa under the name of Vihāra Dēvī. Their sons were Gāmani Abhaya, the future hero, and Tissa.

Annexure 4

Details of GPR traverses

07/09/2007 09:13   Yala Safari hotel site Line 1

NUMBER OF TRACES   = 872
NUMBER OF PTS/TRC = 900
TIMEZERO AT POINT = 60
TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000
FINAL POSITION   = 9.2750
STEP SIZE USED   = 0.0250
POSITION UNITS   = metres
NOMINAL FREQUENCY = 450.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS   = 32
SURVEY MODE   = Reflection

17/09/2007 10:59 Payagala Line 2

NUMBER OF TRACES   = 472
NUMBER OF PTS/TRC = 700
TIMEZERO AT POINT = 82
TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000
FINAL POSITION   = 11.7750
STEP SIZE USED   = 0.0250
POSITION UNITS   = metres
NOMINAL FREQUENCY = 450.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS   = 32
SURVEY MODE   = Reflection

18/09/2007 05:11 Dikwella Line 3

NUMBER OF TRACES = 498
NUMBER OF PTS/TRC = 700
TIMEZERO AT POINT = 83
TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000
FINAL POSITION = 12.4250
STEP SIZE USED = 0.0250
POSITION UNITS = metres
NOMINAL FREQUENCY = 900.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS = 32
SURVEY MODE = Reflection

18/09/2007 08:57 Hambantota Line 4

NUMBER OF TRACES = 413
NUMBER OF PTS/TRC = 700
TIMEZERO AT POINT = 69
TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000
FINAL POSITION = 10.3000
STEP SIZE USED = 0.0250
POSITION UNITS = metres
NOMINAL FREQUENCY = 900.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS = 32
SURVEY MODE = Reflection

18/09/2007 09:43 Hambantota Line 5

NUMBER OF TRACES = 285
NUMBER OF PTS/TRC = 700
TIMEZERO AT POINT = 69
TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000
FINAL POSITION = 7.1000
STEP SIZE USED = 0.0250
POSITION UNITS = metres
NOMINAL FREQUENCY = 900.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS = 32
SURVEY MODE = Reflection

18/09/2007 09:28 Hambantota Line 6

NUMBER OF TRACES = 421
NUMBER OF PTS/TRC = 700
TIMEZERO AT POINT = 68

TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000

FINAL POSITION = 10.5000
STEP SIZE USED = 0.0250
POSITION UNITS = metres
NOMINAL FREQUENCY = 900.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS = 32
SURVEY MODE = Reflection

21/09/2007 04:57 Kaluthara line 7

NUMBER OF TRACES = 805
NUMBER OF PTS/TRC = 700
TIMEZERO AT POINT = 86
TOTAL TIME WINDOW = 70
STARTING POSITION = 0.0000
FINAL POSITION = 20.1000
STEP SIZE USED = 0.0250
POSITION UNITS = metres
NOMINAL FREQUENCY = 900.00
ANTENNA SEPARATION = 0.2000
PULSER VOLTAGE (V) = 200
NUMBER OF STACKS = 32
SURVEY MODE = Reflection