Paleoseismic Investigations on the Central West Coast of Vancouver Island, British Columbia, Canada: Pre-historic Tsunami Deposits in Coastal Lacustrine Environments.

by

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ABSTRACT

The use of diverse analytical techniques, new to the field of Paleoseismology, proved to be an effective tool to depict and determine geophysical, biochemical and structural parameters of tsunami deposits. Such techniques were applied on seven percussion cores from unconsolidated freshwater lacustrine sediments from Kakawis Lake, central west coast of Vancouver Island, British Columbia. The objective was to identify and characterise sedimentologically tsunami deposits emplaced in low-elevation lakes based on a diversity of parameters, with the exclusion of microfossil identification.

Six inferred tsunami events (deposits) were depicted at Kakawis Lake suggesting past inundations by tsunamis of either local or distant sources. Each tsunami deposit was identified based on an association of lithofacies, which are specific to individual stages of any given tsunami inundation in lakes. Two stages were defined (tsunami pulse and tsunami inter-pulse). Based on multiple analyses and observations, more detailed characteristics of lacustrine tsunami deposits are proposed. Theories concerning emplacement of tsunami-transported sediments are reviewed.

Multiple sizes, shapes, species, and types of materials characterise the clastic, carbonate (marine shells) and terrestrial plant detritus fractions common to all Kakawis Lake tsunami deposits. The coarsest tsunamigenic grain-size sedimentation evidenced to date in a lake from Vancouver Island is associated with these paleotsunami inundations. All fractions are from local provenance and two of them are undoubtedly marine in origin.

Kakawis Lake tsunami deposits are believed to be the oldest tsunami events evidenced to date in coastal lakes on western Vancouver Island. From a ~15,500 year old sedimentological record (longest core from Kakawis Lake), tsunamigenic evidence spans from ~4500 to 2384 cal years BP (datum = AD 2000). The three most recent historic tsunami events known to have inundated coastal areas along the Pacific shores of southern British Columbia and northern U.S.A. were not recovered at Kakawis Lake. Such absence establishes a <4 m above mean sea level (at normal tide) as the newest possible maximum tsunami run-up for areas located on rugged-rocky indented coasts, ~ 9 km inland from open-ocean shores, but away from fjord heads on Vancouver Island.

Chrono-stratigraphical correlations between tsunami deposits from other tsunamigenic lakes located on the western shores of Vancouver Island are considered. Other possible counterparts (i.e. tsunami sand sheets buried in tidal marshes) are overlooked. The ages of Kakawis Lake tsunami events may correlate with the oldest three mega-thrust earthquake identifiers from the well-established Atwater – Hemphill-Haley chronology for the west coast of North America.

Radiocarbon dates obtained from previously studied archaeological sites on western Vancouver Island may constrain the radiocarbon dates obtained from diverse terrestrial plant material mixed within Kakawis Lake pre-historic tsunami deposits. In the Pacific Northwest, there is a substantial lack of both scientific and written historic data related to Cascadia great earthquakes that may help elucidate paleoseismic investigations. Archaeological evidence may help constrain paleoseismic evidence, which in turn may constrain seismic, geodetic and tsunami simulation models suggested for the Cascadia Subduction Zone region. Such information is basic to enhance hazard and prevention/emergency-response plans of any given coastal community neighbouring tectonically active continental margins like Cascadia.

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DEDICATION

I would like to dedicate this "part of my life" to the strong and gracious; powerful and humble; adventurer and cautious; the true roots of my tree: my grandparents. The Geo-Scientist who I never knew; the Peace Preacher with a never-ending happiness, a guitar and many songs; the Big Hand that despite his great appearance was gentle of heart, full of joy and knowledge; and the Great Mother always protecting, helping and guiding her children along the trails of life. From you I learned some of the most valuable lessons ever taught. Lessons of life, lessons of courage and commitment, lessons of perseverance, lessons of heart, lessons of happiness, lessons of humbleness. The small and simple things gather the true meaning of life.

Eduardo Cadavid Ochoa (January 15, 1911 – July 13, 1963)
Amparo Mejía Puerta de Cadavid (January 4, 1915 – March 28, 1998)
Juan de Dios López Rojas (March 4, 1916 – June 27, 2000)
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Abuelos, gracias por haberme dado a mis padres.

CHAPTER 1

INTRODUCTION

Since ancient times, tsunami, the Japanese word for "harbour wave", has been considered one of the world's most destructive forces of nature. Many names have been associated with this impulse-generated type of wave, or train of waves, the most common the erroneously named "tidal wave". Tsunamis are water waves that in the open ocean, have unusually long periods (up to 33 minutes), small amplitudes (<1 m) and velocities ranging from 500 to 1000 km/h (Murty, 1977; Steinbrugge, 1982; Myles, 1985; NGDC, 2000). Once tsunamis reach shallower waters and/or coastal areas, friction with the ocean bottom causes their velocities to decrease (<10 m/s). However, their amplitudes increase considerably producing impressive wave crests or bore-like fronts and, less commonly, breaking waves (Murty, 1977; Myles, 1985; Morton, 1988; Komar, 1997; Pelinovsky *et al.*, 1998).

Tsunamis may reach dramatic run-up heights and inundate vast coastal areas depending on the geometry and bathymetry of the nearshore water basin, the topography of the targeted coastal lowland and the state of the tide at the time of the tsunamigenic event (Miller, 1964; Pelinovsky *et al.*, 1998; Matsuyama *et al.*, 1999). The initial magnitude of a tsunami is directly related to the magnitude and closeness of the triggering event, as well as the number of obstacles encountered during the wave's propagation across any given basin. Some of the energy of a tsunami can be dissipated through effects such as refraction, diffraction, scattering and shoaling, as with any given water wave (Miller, 1964; Murty, 1977; Thomson, 1981). Fjords and funnel-type coastal waterways may create a resonance effect on tsunamis, thereby amplifying their heights once reaching shore.

Tsunamis are generated by large-scale, sudden disruptive events of either seismic or non-seismic origin. Subduction zone earthquakes, great landslides, underwater slumps, volcanic eruptions (next to or under the ocean) and less commonly meteorite impacts are effective mechanisms for tsunami generation (Myles, 1985; Abbot, 1996;

McCalpin, 1996; Yeats *et al.*, 1997). Most documented tsunamis have been triggered by great seafloor disturbances along the Pacific Ocean margins (mega-thrust earthquakes M_w >8), where vertical tectonic displacements cause vertical disruption of the water column (Soloviev and Go, 1974, 1975; IOC, 1999; UNESCO/IOC, 1999; NGDC, 2000). However, small to moderate earthquakes may trigger small tsunamis which are confined to areas close to the source and/or large landslides/slumps which in turn can trigger tsunamis with a much greater reach.

Tsunamis can be classified as local, regional or distant, depending on their reach and spread pattern. Local tsunamis affect coasts within 100 km from the tsunamigenic source. Regional tsunamis confine their destructive effects to coasts within ~1000 km reach-range. Distant tsunamis (or tele-tsunamis) are sufficiently powerful to cross an entire ocean basin, and reach coasts located more than 1000 km away, often within hours (UNESCO/IOC, 1999; NGCD, 2000).

Given their great energy and devastating effects, tsunamis have been responsible for numerous disasters and deaths. Predicting tsunami inundation limits and run-up heights help to diminish loss of life and property damage. Approximately one third of the world's population lives along coastal zones, including many of the most important cities. Tsunamis have been documented since ancient times, depending on the availability of the written history in a region; that is particularly extensive for China, Japan and the Middle East. In the ancient Mediterranean, the disappearance of the Minoan civilization has been linked with the prehistoric eruption of the Santorini volcano (*ca.* BC 1470) and subsequent enormous tsunami (Cita and Aloisi, 2000; Driessen and MacDonald, 2000). Historically, the most destructive tsunami was triggered by the eruption of the Krakatau volcano (Indonesia) in 1883, reaching heights > 40 m and killing 36,500 people (Myles, 1985). In 1958, an earthquake triggered a massive landslide that fell into Lituya Bay (Alaska, U.S.A.), generating a monstrous tsunami wave that reached a 525 m run-up height (Cox and Pararas-Carayannis, 1976). More recently, prehistoric tsunami deposits have been evidenced on several coasts around the North Sea region and have been attributed to major submarine slides likely generated by paleoearthquakes. The second of the Storegga Slides dates back to *ca.* 7000 yrs BP. It displaced ~1700 km^3 of sediments of the continental slope off western Norway and triggered a tsunami that reached nearby coastal lakes located at elevations up to 11 m above contemporary high water tide (Dawson *et al.*, 1988; Bondevik *et al.*, 1997b).

In the Pacific Ocean, ~82% of the tsunamis have been attributed to earthquakes (IOC, 1999). From the early 1800's until 1965, the seventeen most destructive Pacific-wide tsunamis have caused over 50,000 fatalities (UNESCO/IOC, 1999). The AD 1960 Chilean (M 8.6) and AD 1964 Alaskan (M 8.4) mega-thrust earthquakes generated two of the most documented tsunami inundations in history, damaging coastal areas around the Pacific Ocean basin. Over the past 10 years, ten modern tsunamis have claimed over 4000 lives for areas located around the Pacific Ocean, from coastal Peru to Eastern Java, and all were products of earthquakes (González, 1999). Among these modern tsunamis, the most devastating was the 1998 Papua New Guinea event that reached heights up to 15 m on shore and caused more than 2200 fatalities (González, 1999).

In Canada, there are historical records of tsunamis of diverse origins on both the Atlantic and Pacific coasts. In 1929, the M_w 7.2 Grand Banks earthquake, off the southern shores of Eastern Canada, triggered an enormous submarine slump which generated a tsunami that destroyed some coastal areas of Newfoundland and Nova Scotia (Whelan, 1994; Clague, 2001). The tsunami, which unfortunately coincided with a high tide, claimed 28 lives, inundated areas as far away as 2 km inland and may have reached heights up to 12 m close to shore. In the intricate waterways of the Canadian Pacific coast, the destructive effects of tsunamis may be amplified by the confined geometry of the many fjord basins. Such was the case when in 1975 an 8 m-tsunami was triggered following a large underwater failure in the Kitimat Arm, British Columbia (Murty, 1979). However, the west coast of Canada may also be affected by tsunamis of seismic origin, generated by both local and distant tectonic movements along active subduction zones (Dunbar *et al.*, 1991).

RESEARCH OVERVIEW

On the Pacific coast of Canada and west margin of Vancouver Island (Figure 1.1), British Columbia, tsunami impacts are likely especially when the Cascadia Subduction Zone ruptures (Heaton and Hartzell, 1987; Savage *et al.*, 1991; Hyndman and Wang, 1993; Dragert *et al.*, 1994). Geodetic measurements, thermal and dislocation models as well as analyses of sea level fluctuations have provided evidence about the current deformation pattern along Cascadia (Hyndman and Wang, 1993, 1995; Dragert and Hyndman, 1995; Flück *et al.*, 1997). The west coast of Vancouver Island is continuously uplifting and compressing. Given this pattern of deformation, a locked behaviour and earthquake deformation cycle both has been attributed to Cascadia. Once the strain built during several hundreds of years is released (great earthquake M_w >8), potential devastating tsunamis are triggered.

However, tsunamis of local origin are not the only tsunamigenic hazard for the Pacific coast. Distant tsunamis (or tele-tsunamis) may also surge onto the low-lying coastal areas of Vancouver Island as happened with the AD 1964 Alaska earthquake and tsunami (White, 1966). Tele-tsunamis are capable of crossing large basins (e.g. Pacific Ocean) and damage distant coastal areas, because they conserve their energy and momentum. The size of a given tsunami is relatively proportional to the magnitude of the triggering earthquake (Murty, 1977).

Although the Cascadia Subduction Zone has not experienced a mega-thrust earthquake since AD 1700 (Satake *et al.*, 1996), a variety of geological evidence suggests that several similar events have occurred throughout the Holocene (Figure 1.2) (Hyndman *et al.*, 1996). The most convincing paleoseismic evidence occurs in the form of sedimentary deposits and sequences of deposits (paleosols) found buried in estuaries and tidal marsh environments along the western coasts of Vancouver Island, Washington, Oregon and northern California. Such deposits consist of associations defined by "peat – intertidal mud – peat" or "peat – tsunami sand – intertidal mud – peat" couplets, suggesting episodes of coseismic subsidence followed or not by subsequent tsunami inundation (Clague and Bobrowsky, 1994a, 1994b; Darienzo *et al.*, 1994; Atwater *et al.*,

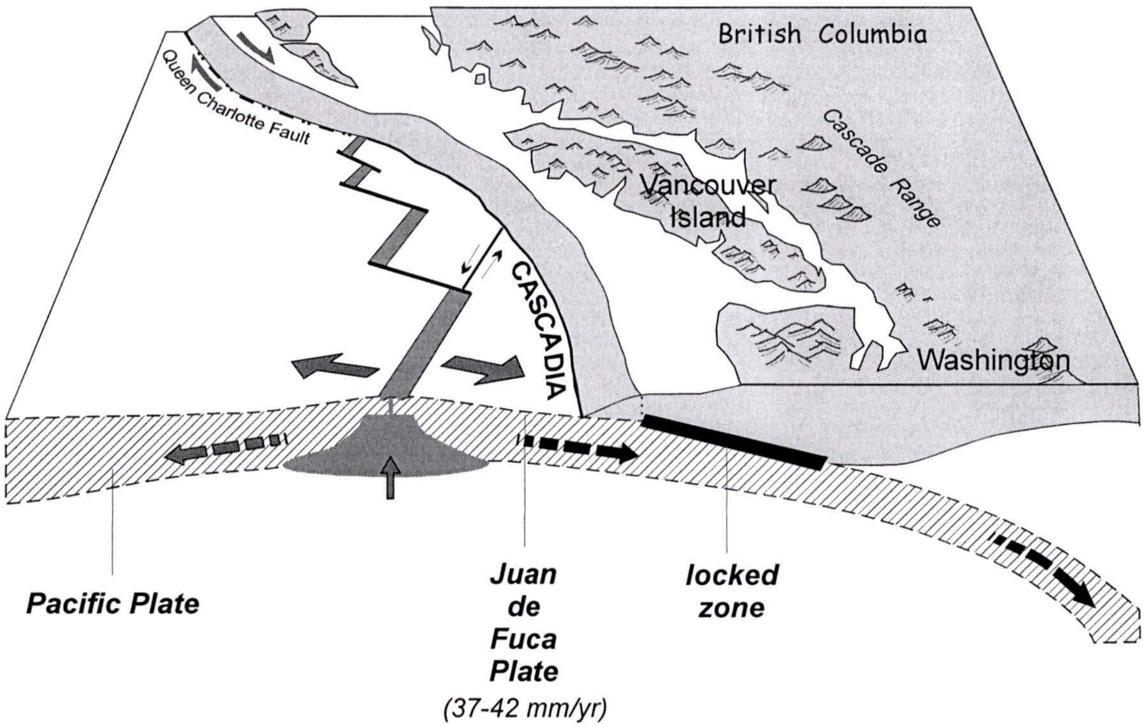
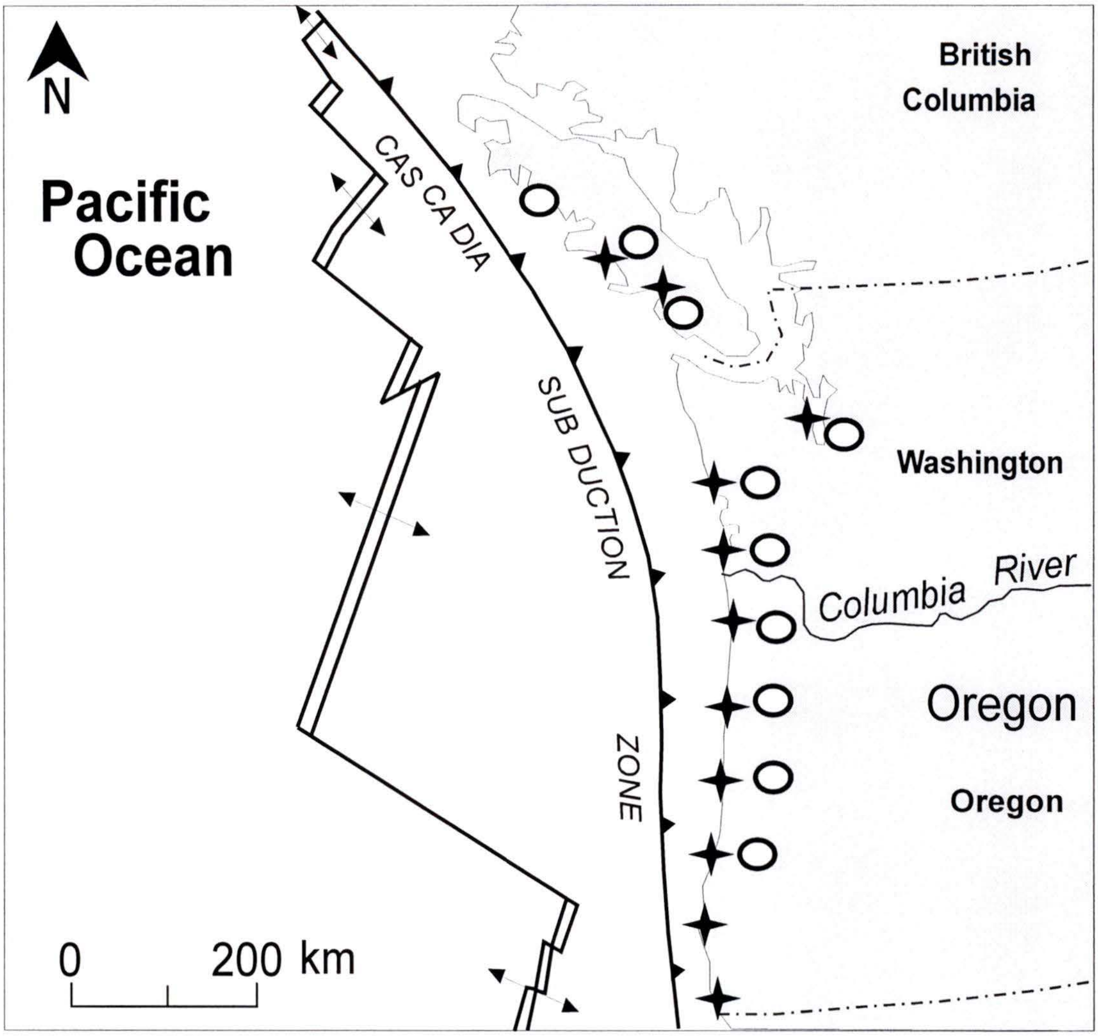


Figure 1.1: Tectonic setting of southwestern British Columbia and northern Washington, showing the Cascadia Subduction zone, potential source for mega-thrust earthquakes and tsunamis (modified after Hyndman *et al.*, 1996, and Clague and Bobrowsky, 1999).



Type of evidence at paleoseismic site

✦ Coseismic subsidence (buried soil/peat)

○ Tsunami sand / deposit

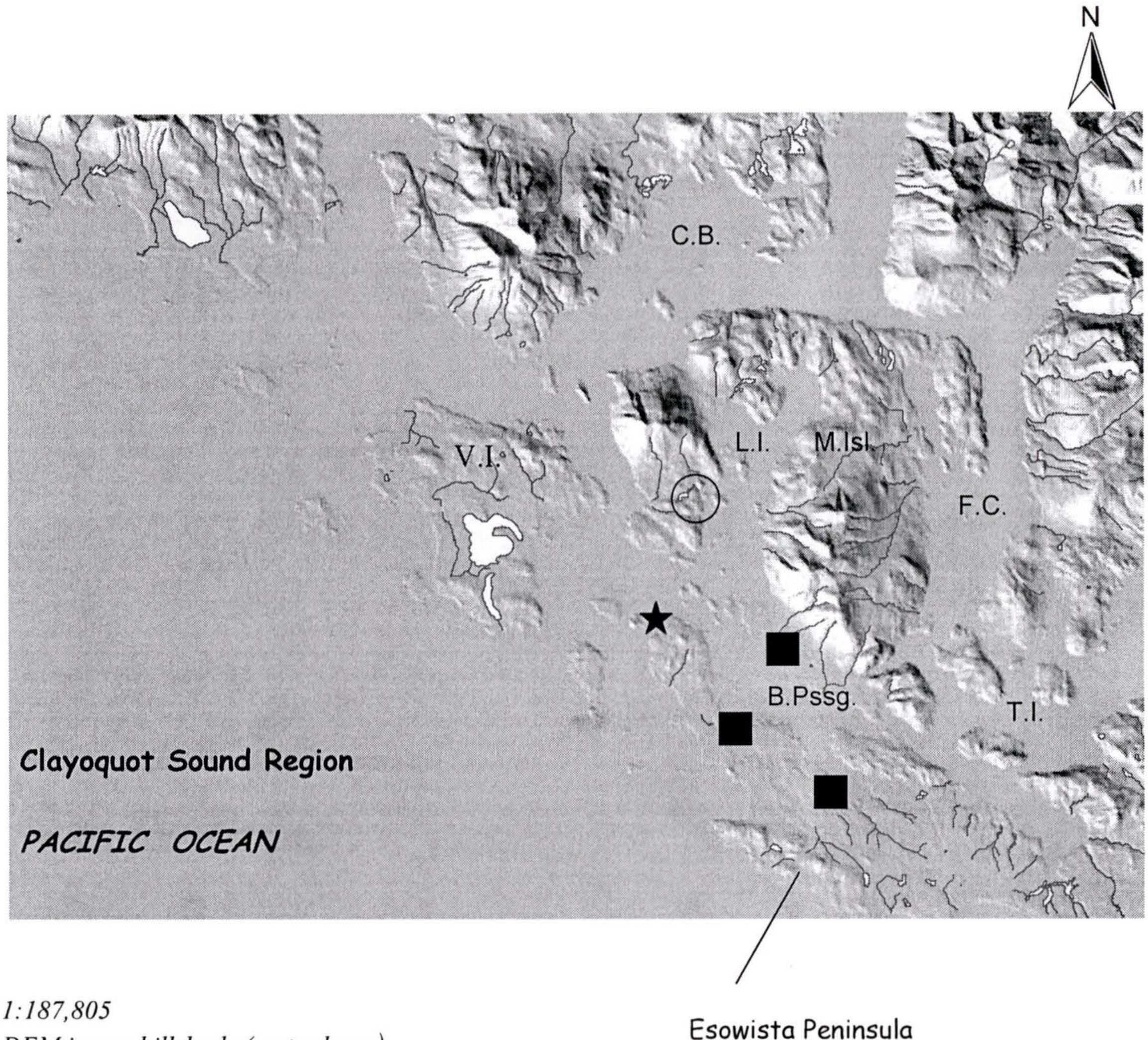
Figure 1.2: Tectonic setting of the Pacific Northwest and a broad range of locations showing some primary paleoseismic evidence. (Source: modified from Atwater *et al.*, 1995; Clague *et al.*, 2000 and present research).

1995; Nelson *et al.*, 1995; Carver and McCalpin, 1996; Atwater and Hemphill-Haley, 1997; Benson *et al.*, 1997).

In previous investigations Bobrowsky and Clague (1991), Clague and Bobrowsky (1994a, 1994b) and Guibault *et al.* (1995, 1996) found tsunami sand sheets embedded in several tidal marsh sedimentary sequences in the vicinity of Tofino and Ucluelet in association with coseismic subsidence (paleosols) (Figure 1.3). Such sites are the closest previously studied areas to the present study area. Intertidal muddy flats on both sides of Browning Passage have trapped tsunami sand sheets, preserving the couplet association mentioned above. Such stratigraphic couplets suggest past coseismic subsidence in the Clayoquot Sound region, in accordance with the tectonic deformation cycle defined for Cascadia. The extensive sand sheets recorded within the tidal marshes suggest widespread tsunami inundation that may also have been recorded in other nearshore depositional environments such as neighbouring low-elevation lakes (i.e. Kakawis Lake).

In recent years, several low-elevation coastal lakes have been targeted along the western shores of Vancouver Island to enhance the paleotsunami history of the region. Among those lakes, paleotsunami evidence has been found in Catala, Deserted and Kanim lakes (Figure 1.4) (Hutchinson *et al.*, 1997, 2000; Clague *et al.*, 1999). There, a detailed paleoenvironmental evolution of the lakes was obtained from microfossil analyses which constrain sea level history in addition to uplift rates of the regions surrounding the lakes. Evidence recovered from low-lying lakes give quantitative parameters that provide information on tsunami inundation limits and run-up heights along the west coast of Vancouver Island.

The purpose of this investigation is to examine, describe and interpret inferred Holocene tsunami deposits found embedded in previously unstudied unconsolidated lacustrine sedimentary sequences from the low to mid-elevation coastal region of Clayoquot Sound, central west coast of Vancouver Island, British Columbia (Figures 1.3 and 1.4). This research provides new information on tsunami sedimentation in coastal lakes, based on comparisons between both observed and analysed characteristics from the recovered tsunami deposits and published theoretical aspects involving such deposition. Using stratigraphic studies and extensive analyses of diverse published data, this research



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DEM image hillshade (raster layer)

Legend:

○ Kakawis Lake location

■ Tidal Marshes with paleoseismic evidence
★ Tofino

C.	Channel	B.Pssg.	Browning Passage
C.B.	Cypress Bay	F.C.	Fortune Channel
L.I.	Lemmens Inlet	M.Isl.	Meares Island
T.I.	Tofino Inlet	V.I.	Vargas Island

Figure 1.3 DEM topographical map of the Clayoquot Sound region showing location of Kakawis Lake, as well as the low elevation of the entire region. Squares represent previously studied sites where evidence for paleotsunamis has been found. Names of principal islands, channels, inlets and bays are shown (Source: modified from BCGS, 2000, Trim Map 92F / 92E)

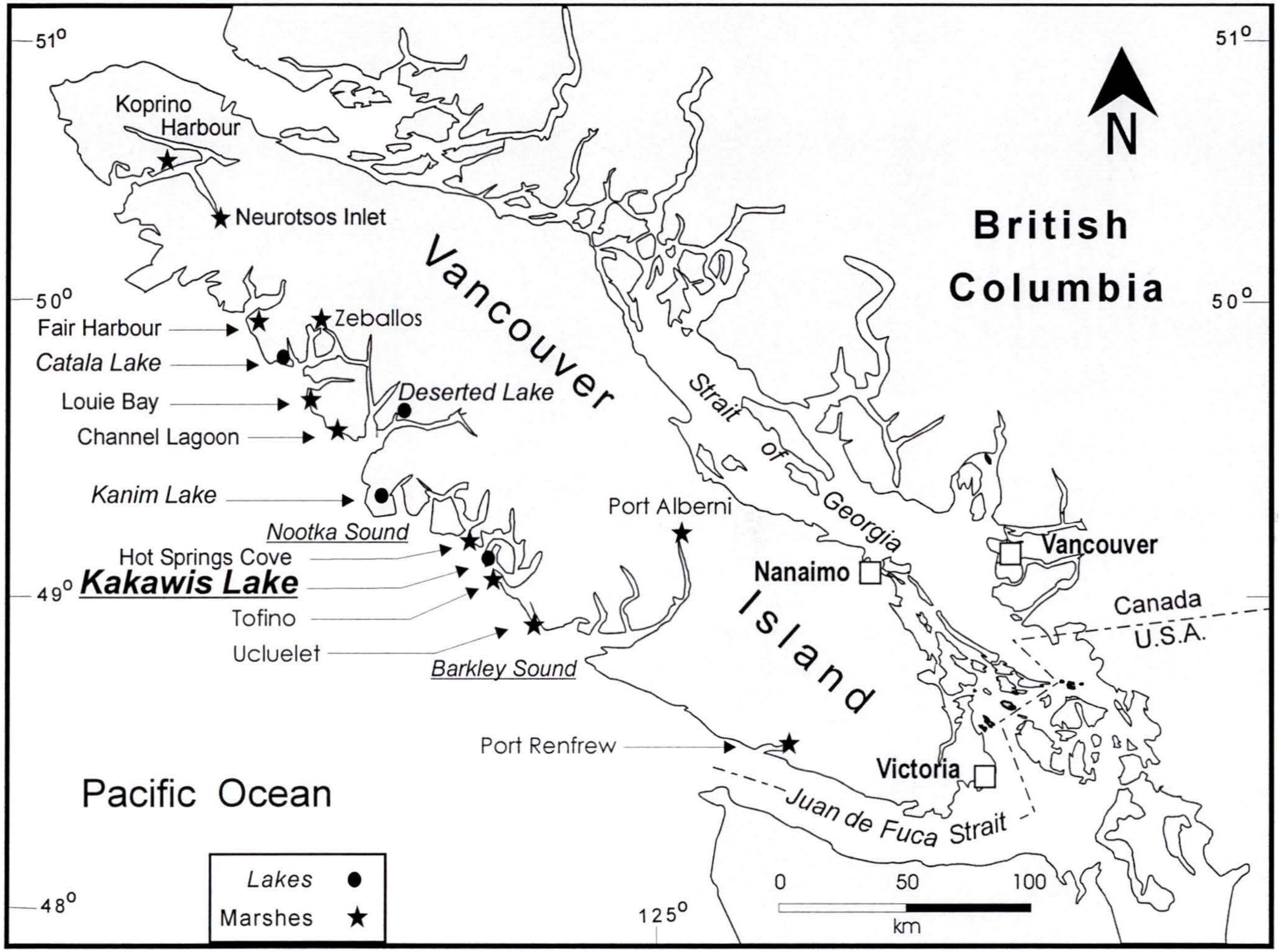


Figure 1.4: Location of Kakawis Lake and sites with geological evidence of tsunami deposits in marshes and lakes on the west coast of Vancouver Island, British Columbia (Sources for sites other than this research: Clague *et al.*, 2000).

provides a broader understanding of the characteristics and implications of tsunami deposits in lacustrine environments on the coastal western margin of Vancouver Island.

Some examples of the available data that were analysed include tectonic deformation models; sea level curves; post-glacial history; Pacific-wide earthquake and tsunami inventories; tsunami recurrence intervals for the Pacific Northwest; radiocarbon age data bases; sedimentologic characteristics of marsh and lake-type tsunami deposits (not always published data); tide gauge data for tsunami and storm heights; storm surge recurrence intervals for the Pacific Northwest; bathymetric data; marine shell inventories for the Pacific Northwest; oral traditions; historical written records; and archaeological data. Detailed objectives and purposes of this research are summarized below.

To start, there were several questions concerning the efficiency and accuracy of the analytical techniques to pursue, given the diversity and limited amounts of the cored material recovered from lacustrine environments (gyttja, anomalous sandy-detrital-shelly layers and glaciomarine clays). Collection, preparation and analysis of primary data were performed. Several of the techniques used herein are new to this type of research and were shown to be efficient approaches in the identification and characterisation of anomalous coarse layers, as well as in depicting the provenance of the materials incorporated within the deposits.

A detailed analysis of stratigraphic sequences in addition to a sedimentologic determination of character, nature and lateral extent of the inferred tsunami deposits were undertaken. A characterisation of the architecture and geometry of inferred tsunami deposits in lakes was obtained.

Other questions concerned the reliability of radiocarbon dating techniques when dealing with re-worked and re-deposited material such as the plant detritus mixed with the tsunami deposits. Several new radiocarbon dates were obtained and constrained to other radiocarbon data sets from both paleoseismic and archaeological investigations on the Pacific Northwest coast, and estimates of tsunami return intervals were subsequently inferred. Identification of the macro-fraction (>0.5 mm) of various materials forming the inferred tsunami deposits constrained the origin of the materials. In addition, such identification provided insights into the paleoenvironmental reconstruction of the study area. Additional objectives such as establishing a maximum run-up limit, maximum inundation limit as well as possible energy level of the tsunami waves that had inundated the study area were estimated.

STUDY AREA

The study area focuses on the Clayoquot Sound region, intricate fjord waterways of the Tofino municipality district, shaped by several channels, inlets, bays, islands, sandy shallow waters and vast intertidal muddy flats. The coastal geomorphology was an important factor when selecting the location of the targeted sites bearing in mind tsunami and extreme ocean wave physical properties. One small coastal lake (Figure 1.3) served as coring site during two field campaigns carried out in the fall of 1998 and the summer of 1999. Kakawis Lake, at just 4 m above mean sea level, was expected to have evidence of past tsunami inundations.

Kakawis Lake located on the west peninsula of Meares Island at ~4.5 km north of Tofino, played an important role in this research because of its geographical location and its elevation (Figure 1.5). Kakawis Lake has only one outlet stream (~200 m-long) that connects the freshwater basin to saline coastal waters. This isolated outlet stream flows into the protected Lemmens Inlet, whose entrance neighbours Browning Passage just north of Tofino. The only natural pathway for a given tsunami surge would be this year-round active outlet stream, whose mouth is located 9 km east from the outer ocean coast, thereby avoiding facing the Pacific Ocean.

SIGNIFICANCE OF PALEOSEISMIC RESEARCH

By understanding the sedimentological history of a particular depositional environment, much can be said about the geological evolution of a region. Paleoseismology focuses on the fact that earthquakes may produce permanent and recognizable changes on natural environments and human settlements, which permit a study of the distribution of individual paleoearthquakes in space and time (Solonenko, 1973; Wallace, 1986; McCalpin, 1996; Michetti and Hancock, 1997). Such changes can

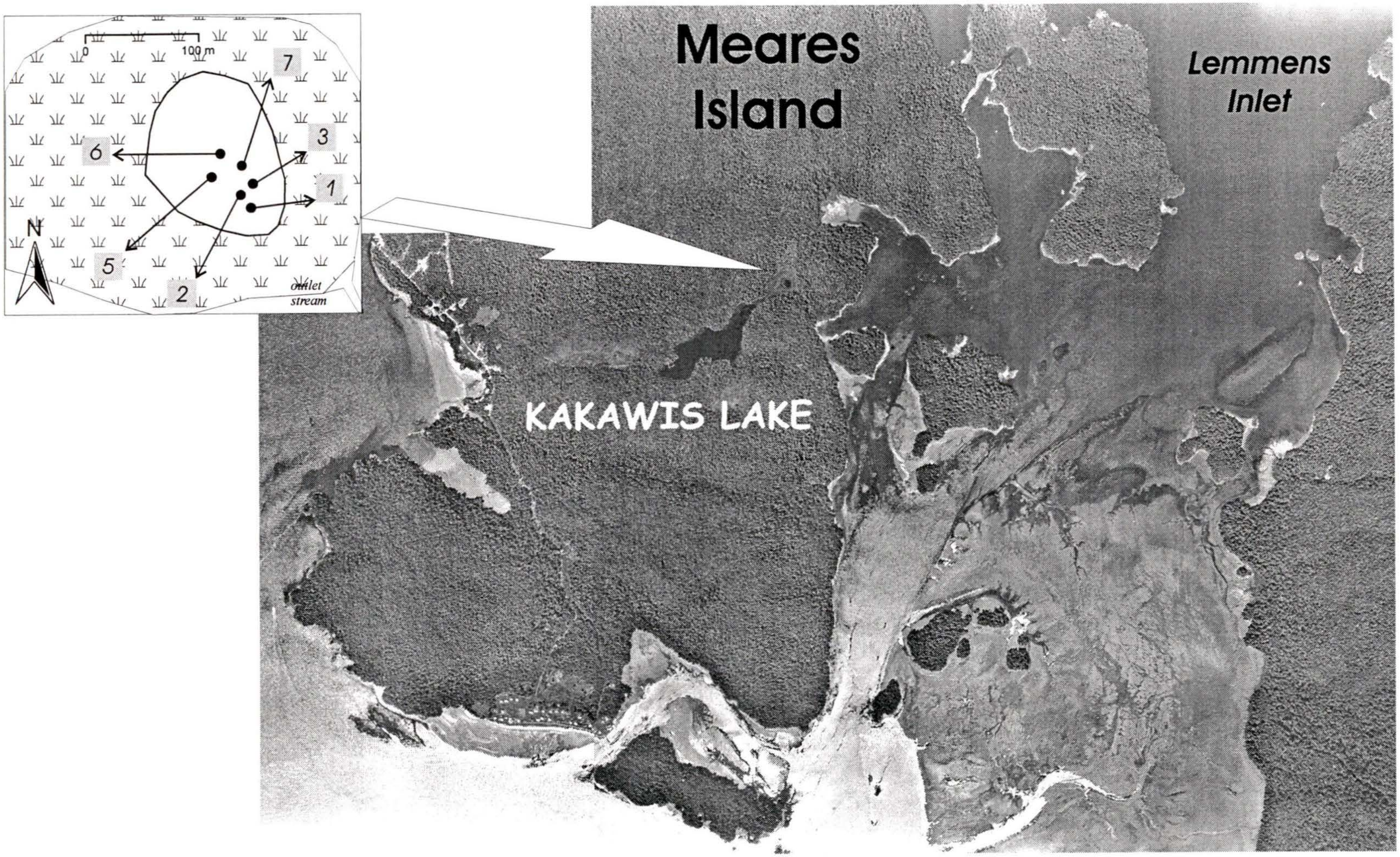


Figure 1.5 Lemmens Inlet entrance and SW peninsula of Meares Island (BC Ministry of Env., Lands & Parks, air-photo C-020-F1-96 / 30BCC9600, org. scale 1:15.000). The core basin is shown by an arrow. The area is protected by numerous islands, passages, shallow waters and vast intertidal mud-flats as seen in this photograph. Very narrow areas are channels deep enough to hold volumes of incoming ocean water. Inset shows location of cores.

be morphological and/or stratigraphic (formation of new deposits) depending on the geological setting (Allen, 1986; McCalpin, 1996). Hence, paleoseismology is an interdisciplinary field of research that borrows concepts from disciplines such as seismology, structural geology, tectonics and sedimentology, and methods and techniques from geomorphology, soil mechanics, sedimentology, stratigraphy, archaeology, paleoecology, photogrammetry, radioisotope dating and pedology as well as history. In synthesis, "paleoseismology is a successful example of applied Quaternary Geology" (Wallace, 1986). This broad spectrum of areas of knowledge makes paleoseismology a unique science.

Near the surface, the most easily created and best preserved effects are associated with large disruptive seismic events (i.e. great magnitude ($M_w \geq 8$) earthquakes) (McCalpin and Nelson, 1996; Michetti and Hancock, 1997). The type of paleoseismic evidence varies greatly depending on parameters such as distance from the seismic source, magnitude and regional influence of the event on the geology and stratigraphy of any given area. Landslides, rockfalls, liquefaction of soils and tsunamis are often products of earthquakes. Tsunamis are direct products of tectonic deformation produced during a seismic disruption, and they may generate geomorphic features (produced by the erosive process of the tsunami waves) and/or stratigraphic expressions (produced by the deposition of the material transported by the tsunami waves) (McCalpin, 1996).

Tsunami deposits are often defined as stratigraphic expressions of coseismic origin located off-fault, and are considered primary evidence of any tectonic displacement of the sea floor (McCalpin and Nelson, 1996). The world-wide abundance of this type of deposit is considered moderate compared to secondary evidence produced by the seismic shaking (i.e. landslides, turbidites and liquefaction of soils) (Einsele *et al.*, 1996; McCalpin, 1996). The study and interpretation of the sedimentological record left by a given tsunami is one of the less developed but yet most interesting sub-fields of paleoseismology (Shiki, 1996; Michetti and Hancock, 1997; Shiki *et al.*, 2000).

The contribution of tsunamis to various depositional environments may be very significant in the sedimentological record, and depends on the magnitude and periodicity of the event (Einsele *et al.*, 1996; Shiki *et al.*, 2000). Sedimentologically, tsunami deposits are considered depositional "episodes" or "events", and given the catastrophic aspect of the depositional mechanism, they are also defined as "convulsive geologic events" (Dott, 1983; Clifton, 1988).

Sedimentary records generated by tsunami inundation provide accurate quantitative data that may identify precise limits of tsunami inundation and geographical extent. Maximum tsunami run-up heights may be best established based on paleotsunamigenic stratigraphic records found in lake environments situated a few metres above mean sea level. An interdisciplinary study of paleoseismic evidence provides additional information that may constrain geophysical and seismic studies in general, and may, as well, give additional information about uplift rates in tectonically deformed convergent margins (McCalpin, 1996; Michetti and Hancock, 1997). Paleotsunami investigations may help better predict future trends of tsunami inundation and tsunami effects on diverse coastal settings. Tsunamis are devastating not only to the physical environment but also to the civil communities and human infrastructure built in coastal areas. This type of understanding may aid in planning regarding tsunami hazard prevention and emergency response, as well as establishment of more accurate tsunami simulation models and tsunami inundation/run-up maps (UNESCO/IOC, 1999; Priest, 2001).

The extent and regional coverage of tsunami deposits suggest widespread wave propagation and inundation. However, tsunami behaviour in coastal shallow waters greatly depends on the complex geometry and bathymetry of coastal areas which may enhance diffraction, refraction, resonance and shoaling effects of any given approaching tsunami wave (Miller, 1964; Murty, 1977; Pelinovsky, *et al.*, 1998; Matsuyama *et al.*, 1999). Modelling such a variety of conditions may provide only an approximation to the real tsunami behaviour at a specific nearshore location. However, erroneous inundation simulation may result, given the lack of detailed shallow water surveys and the uncertainty of earthquake source parameters which are the triggering mechanism of such tsunamis (Dunbar *et al.*, 1991; Whitmore, 1993; Priest, 2001).

Valuable information has been obtained from historical written records regarding paleotsunami extent, inundation limits and run-up heights based on eyewitness accounts

(Soloviev and Go, 1974, 1975; Ramírez, 1975; Cox and Pararas-Cayannis, 1976; Myles, 1985), in addition to timing and age of the events, especially for regions with short written recorded history such as the Pacific coast of North America (Satake *et al.*, 1996). Such information is considered empirical evidence that may contribute to prediction and may constrain tsunami simulation models as well as geophysical models. Because tsunamis occur rarely, any reliable information should be considered important given the devastating results that this oceanic phenomenon implies. Modern tsunami deposits are now being studied in detail as they are still close or on the surface, hence more easily to analyse compared to those that are already buried and that have occurred hundreds or thousands of years ago.

SIGNIFICANCE OF THIS RESEARCH

Besides providing information that increases the paleotsunamigenic record of the Pacific coast of North America, this research provides some of the most detailed sedimentological work to date completed on tsunami deposits emplaced in lacustrine environments on Vancouver Island. Moreover, it establishes important basic patterns of deposition generated by tsunamis in lakes. This work is also beneficial for practical purposes given the number of new techniques applied to paleotsunami research with a focus on stratigraphic evidence.

Data presented herein not only detail the sedimentology of numerous inferred tsunami deposits but also present the implications in a regional post-glacial evolutionary context. Because of its elevation and evolution throughout the Holocene, Kakawis Lake recorded several disruptive events which generated six anomalously coarse sandy-detrital-shelly layers, all inferred to be deposited by tsunamis.

New radiocarbon dates were obtained from the inferred tsunami deposits at Kakawis Lake and were correlated with other radiocarbon data sets for the Pacific coast of North America. From this study it was possible to obtain a middle to late Holocene tsunami history for the central west coast of Vancouver Island. Correlations between Kakawis Lake tsunami events and other geologic evidence found in several insular coastal lakes and tidal marshes on the western shores of Vancouver Island were also possible. These chrono-correlations may imply widespread tsunami inundation. A broader chrono-stratigraphical correlation and recurrence interval discussion elucidates the relationship between the events encountered at Kakawis Lake and the tsunami chronology established for the Pacific Northwest of North America (c.f. Atwater and Hemphill-Haley, 1997). In addition, radiocarbon dates obtained from Kakawis Lake sediments were compared to previously published radiocarbon ages obtained from archaeological sites along the west coast of Vancouver Island and northern shores of Washington. Striking similarities were observed between such dates, constraining the time of emplacement of the inferred tsunami deposits at Kakawis Lake.

Statistical and textural analyses of terrigenous clastic material were undertaken to enhance probable correlation factors and to define the sedimentological characteristics of tsunami deposits emplaced in lacustrine environments. A comparison between the textural characteristics of lacustrine and tidal marsh tsunami deposits was attempted to determine differences in energy level and depositional patterns of tsunami surges when interacting with different coastal settings. Based on the observations, as well as comparisons with suggested "theoretical" characteristics defining tsunami sedimentation (mostly from washover settings), a new set of depositional and textural parameters are proposed for tsunami deposits in lakes.

THESIS OUTLINE

The first chapter introduces the reader to the work undertaken in this thesis. The thesis consists of three main chapters, written as individual papers. General introduction and main conclusions chapters are also provided.

Each chapter focuses on individual themes targeting one or more specific objectives of the research. Each objective is described in the corresponding chapter and the theme is kept separate to enhance the goal of this multidisciplinary research. For a better understanding of the context of this thesis, an introduction to the remaining chapters is also provided in Chapter 1. The citations referenced in each chapter are listed at the end of the thesis. Appendices containing detailed data are included at the end of the thesis.

Chapter 2 focuses on the field and laboratory methods (protocols) used in this research. Six percussion cores were recovered from one coastal lake in the Clayoquot Sound region, central west coast of Vancouver Island. Explanations of modifications made to the percussion coring system are described. An array of laboratory techniques is described. Different analytical approaches such as various geophysical and biochemical analyses, new to the field of paleotsunami study, were targeted. More than 300 samples were analysed for various purposes.

Chapter 3 examines data and results from the analyses of six stratigraphic sequences obtained at Kakawis Lake. This chapter is dedicated to compositional, structural and textural characteristics of the sedimentary sequences which were divided into four main correlative units. Special attention is given to the sedimentology of the inferred tsunami deposits. A discussion about the origin of such deposits is provided.

Chapter 4 establishes a chrono-stratigraphical correlation between the different tsunami deposits found in four (including Kakawis Lake) low-elevation coastal lakes of the west coast of Vancouver Island. Aspects such as sea level fluctuations and tsunami run-up heights are discussed. This last chapter discusses regional correlation by introducing and relating the well-established Atwater - Hemphill-Haley tsunami chronology for the Pacific Northwest to the events preserved at Kakawis Lake (based on radiocarbon dates). Recurrence intervals for tsunamis are also discussed as new scientific trends argue that tsunami recurrence along Cascadia Subduction Zone and the entire Northwest Coast of the North American continent could be over-estimated.

CHAPTER 2

TSUNAMI SEDIMENTS: METHODS AND THEIR INTERPRETATION

ABSTRACT

Ten analytical protocols were successfully used to identify anomalous layers interpreted to be deposited by tsunamis that may have been triggered by mega-thrust earthquakes at both local and/or distant subduction zones. The sedimentological characterisation of the inferred tsunami deposits from Kakawis Lake (central west coast of Vancouver Island, British Columbia, Canada) required a detailed analysis of over 300 samples from six different percussion cores. Because of the diversity of lithology and variety of types of materials involved, several of the laboratory techniques had to be modified and adapted from the original standard methods.

The main focus of this investigation was to identify and characterise lacustrine tsunami deposits based on the analysis of macro-components (not involving micro-fossil assemblages). Five methods used in this study are new to this branch of paleotsunami research. Two geophysical techniques (magnetic susceptibility and electrical resistivity), two biochemical methods (loss-on-ignition and C/N ratios) and a radiographic approach were used to corroborate the allochthonous provenance of the anomalous sediments and to present different analytical approaches for this type of study. The results obtained were positive and each inferred tsunami layer was depicted, corroborating the results of textural analyses. The results are constrained by dates and sedimentation rates determined by ^{14}C and ^{137}Cs analyses.

INTRODUCTION

Tsunami sediments are deposited directly by a high energy wave (tsunami) triggered by a mechanism such as a great earthquake, volcanic eruption or a large scale landslide (terrestrial and/or subaqueous). Tsunamigenic deposits can occur only where a tsunami (either local or trans-oceanic) has flooded coastal lands. They are formed when a powerful sea wave inundates coastal regions, loses its energy, and deposits its load. Moderately-well to poorly-sorted extra-local sands, often mixed with marine organisms and a variety of plant detritus, are the most common features in any given tsunami layer. Such characteristics are relatively easy to recognize if the enclosing depositional environment lacks such features and its' lithology is significantly different.

For paleoseismic studies, tsunami deposits are often analyzed to evaluate tsunami hazard potential, to identify possible past earthquakes (direct or indirect tsunami trigger), and to establish the recurrence interval between large seismic events. Characterisation of tsunami deposits is also important sedimentologically because little is known about the detailed features or attributes of such deposits. Documenting the properties of tsunami deposits and observing their depositional environment is fundamental in the understanding of their nature and distribution.

Enclosed bays, inlets, estuaries, beaches, marshes and low-elevation lakes adjacent to the coastline are appropriate depositional environments for tsunami deposits to be preserved. In particular, low-elevation lakes are considered ideal environments as they promptly respond to significant changes in depositional conditions. Lakes are considered primary sedimentological features from which geological evolution models can be defined and applied to decipher events that have occurred throughout the past (Gray, 1988). When dealing with major natural catastrophic events, such as tsunamis, low-elevation coastal lakes are recognized as ideal study targets. Tsunami waves are different from regular waves in that they can over-run morphological obstacles thereby enriching their suspended load with organic and inorganic material from the surrounding landscape. A wealth of information regarding tsunamis and earthquakes can be recovered from a single lake, although one must always consider its elevation above mean sea level (amsl) (Carver and McCalpin, 1996; Atwater and Hemphill-Haley, 1997; Clague *et al.*, 2000).

This chapter provides a summary of techniques and methods specifically designed for detailed research on anomalously coarse layers such as tsunami deposits. The following laboratory techniques are well-suited for the study of tsunami deposits collected using percussion coring type techniques in lacustrine environments. The analytical methods discussed herein are not unique to the analysis of this type of deposit, but yield the best results when dealing with varying quantities and types of sediment. Moreover, all techniques are cost and time effective.

REGIONAL SETTING AND STUDY AREA

The study area occurs within the limits of the West Vancouver Island Fjordland and the Estevan Lowlands physiographic regions of Vancouver Island, British Columbia (B.C.), Canada, and is covered by dense coniferous temperate rainforests (Holland, 1976). The region of interest is located on the central west coast of the Vancouver Island, on the western edge of the North American plate and is juxtaposed against the Juan de Fuca and Explorer oceanic plates along the northern end of the Cascadia Subduction Zone (CSZ) (Figure 2.1). Paleoseismic evidence found along the Pacific Northwest indicates that numerous tsunami events have occurred in the past. Most are probably due to thrust activity occurring along the CSZ, whereas others may have originated from diverse sources including distant tectonic activity.

The west coast of B.C. has a deeply indented coastline with numerous fjords. Such fjords are the product of past glaciations and are prone to tsunami wave funnelling. Like the fjords of this region, lake formation was also controlled by past glaciation. All the lakes post-date the late Wisconsinan (Fraser) Glaciation of B.C. (Clague, 1989a) and as a result show the affects of post-glacial sea level change.

One coastal lake, Kakawis Lake (4 m amsl) was chosen for study given its short outlet stream and strategic geographical position on the central west coast of Vancouver Island. Located at ~4.5 linear kilometres north of Tofino (Figure 2.1), the lake is not

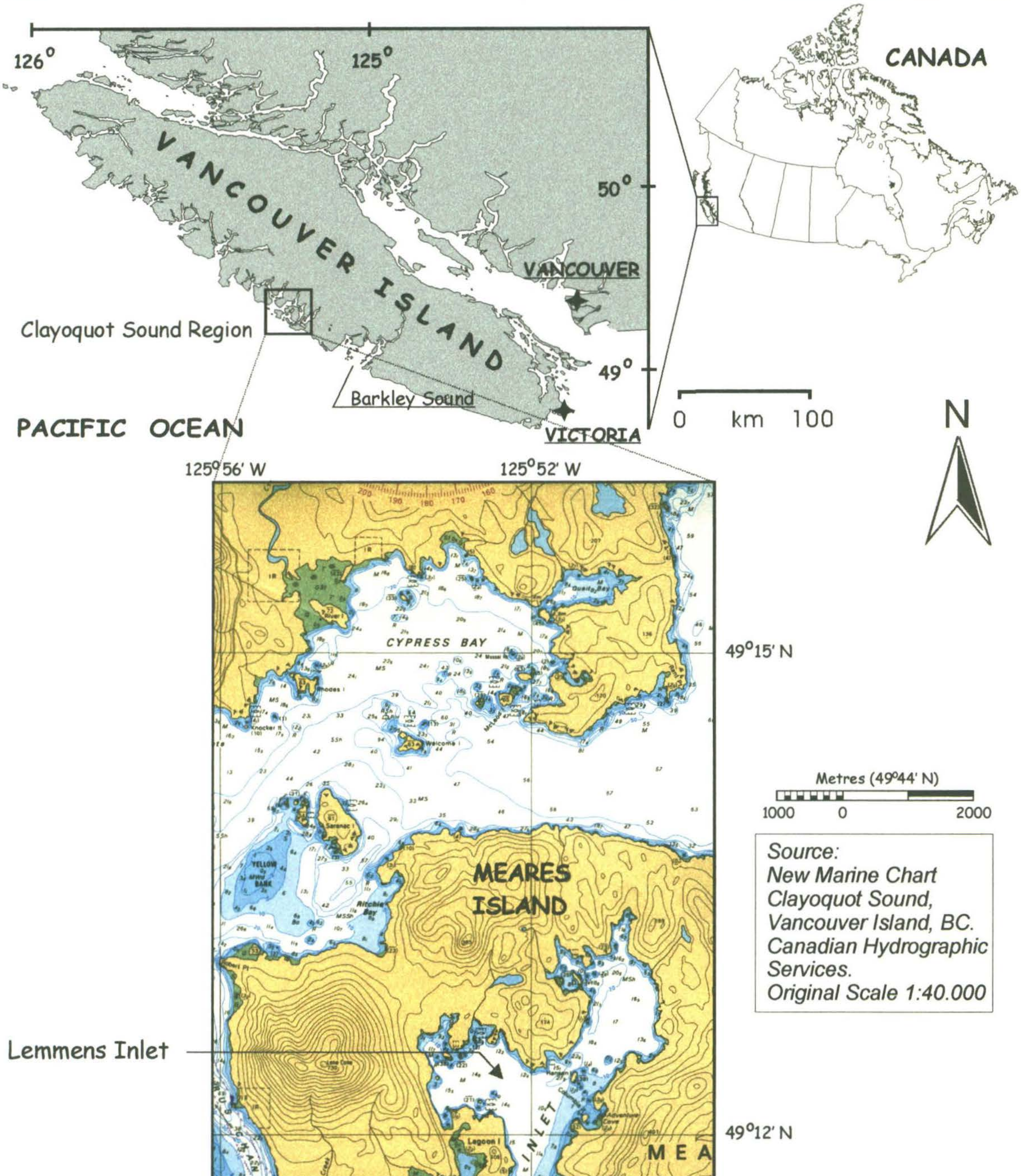


Figure 2.1 Location of study area on Vancouver Island, British Columbia, Canada. Kakawis Lake is located on the Clayoquot Sound region, west central coast of Vancouver Island. Names of locations cited in the text are highlighted in the figure.

affected by direct oceanic waters, an important factor when studying possible tsunami inundation patterns and wave refraction in coastal environments. Also, no steep slopes surround the immediate margins of the lake, diminishing direct terrestrial input from land movements (e.g. landslides). Kakawis Lake does not have permanent streams flowing into the system, hence the fluvial input is low in the both lake.

METHODS

Six sediment cores varying in length from 2.72 to 5.43 m were recovered from Kakawis Lake. Glaciomarine clays defined the basal stratigraphic unit in the lake. Three cores (K1, K2 and K3) were recovered during the summer of 1998, a fourth (K5) was collected in September 1998 and two additional cores (K6 and K7) were obtained in July 1999. All six cores were recovered from a small NE basin (180 m in diameter and 3 m deep) that has a direct outlet stream to saline waters. Tsunami run-ups were suspected to inundate this part of the lake basin. The cores were collected from the central part of the lake, facing the entrance to the outlet stream (Figure 2.2).

FIELD METHODOLOGY

A percussion coring system modified from Reasoner (1993) was used to recover continuous cores of lacustrine sediments from Kakawis Lake. This lightweight system can be used in varying depths of waters, is relatively simple to operate and can be constructed at a very low cost. The system described by Reasoner (1993) is operated from a frozen lake surface. In the absence of a frozen lake surface, we constructed a raft as an alternative coring platform (Figure 2.3). Modifications to the Reasoner (1993) sampling system involved the removal of the attached weight to the core head and the one way valve of the core barrel. This percussion method is a technique that can be used in soft to moderately compacted sediments, but is not recommended for water-saturated or highly porous sediments.

The coring platform consists of two secured and adjacent inflatable rafts overlain by a plywood base (Figure 2.4). The centre of the plywood coincides with a 30 cm gap

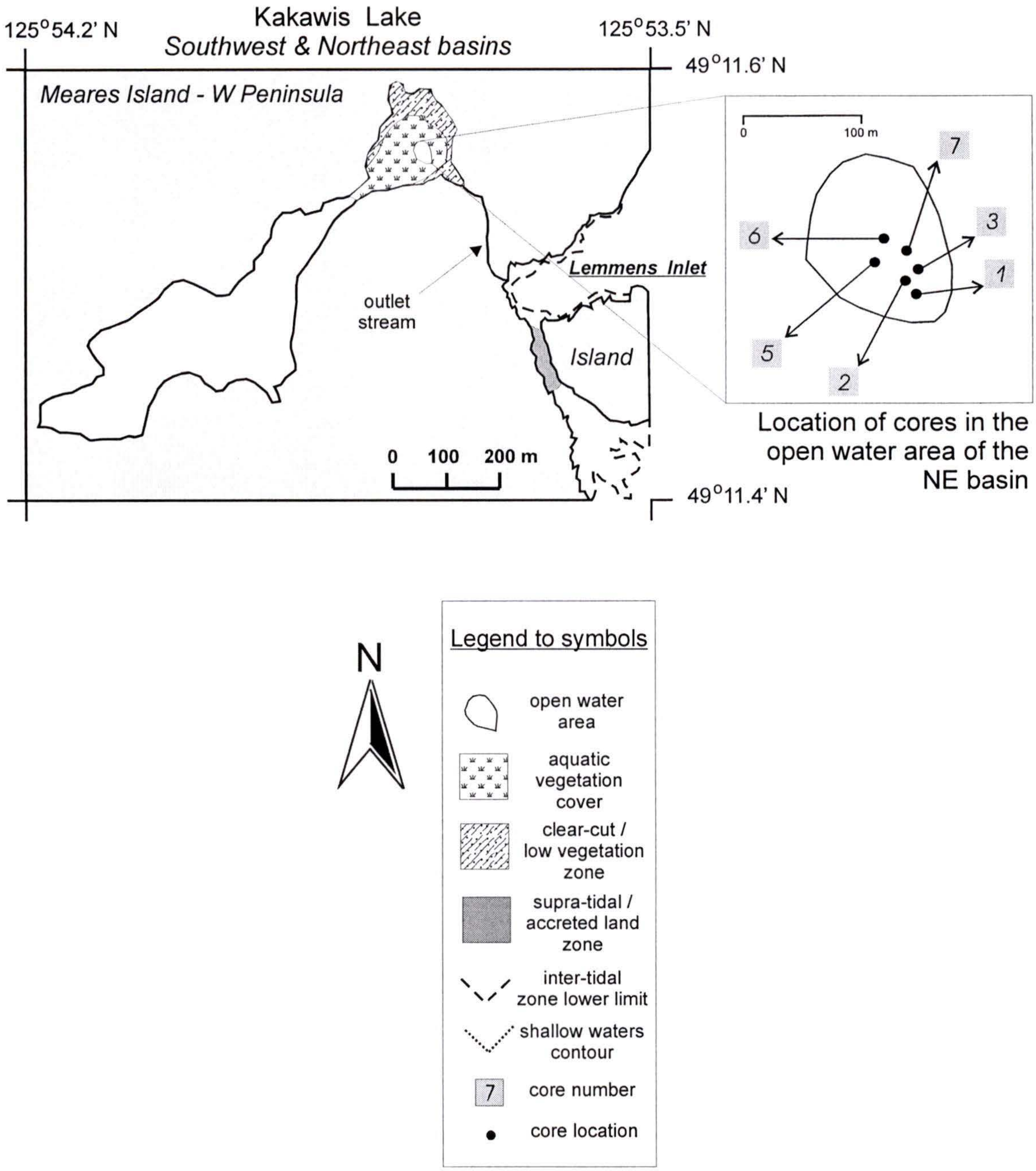


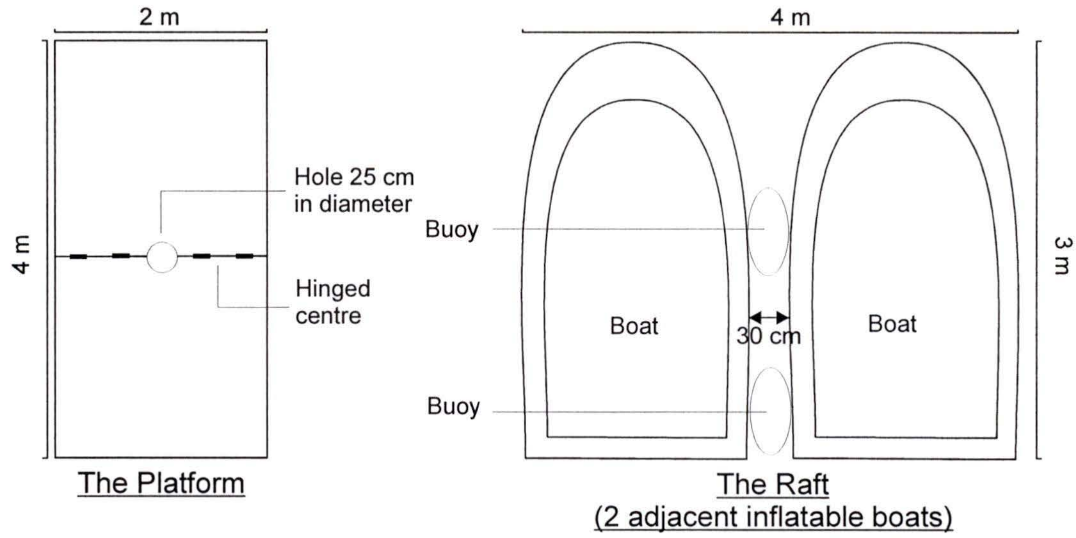
Figure 2.2: Kakawis Lake map showing both basins. The NE basin was the target of the study. The inset shows the location of the cores (cores 1 to 7). Cores were recovered from the open water area of the lake, following the main direction of the outlet stream.

a)

b)

Figure 2.3 Operational platform. a) Assemblage of the plywood that serves as the base from which coring takes place (Photograph taken on the south shore of the NE basin of Kakawis Lake). b) General view of the platform. Note there is a gap between the rafts to insert the coring device (Photograph taken on the waters of Quait Bay, in front of the main inlet entrance).

a)



b)

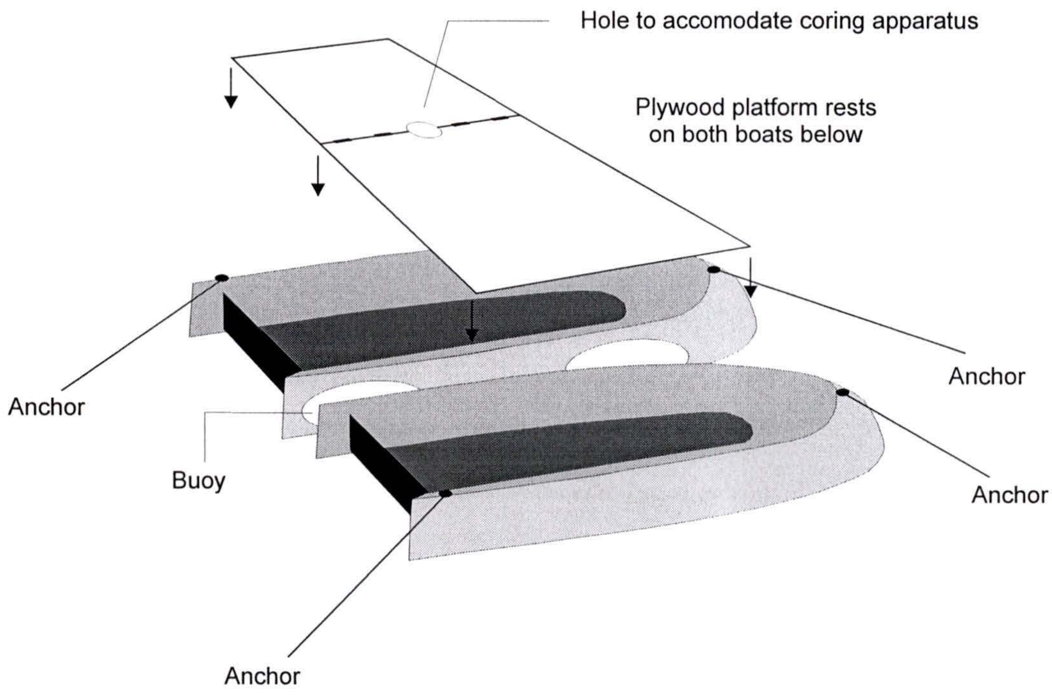


Figure 2.4 Sketches showing the assemblage of floating platform. a) Plan view of both the platform and set of boats that form the raft. b) Perspective view of the whole assemblage.

between the two rafts maintained by two buoys wedged between the rafts. A hole is cut in the middle of the plywood coinciding with the gap below, through which the coring device is placed. To prevent drifting, four cement anchors are lowered to the bottom of the basin once the coring platform is in position.

Figure 2.5 outlines the principal sections of the coring system. The core barrel consists of one or more polyvinyl chloride (PVC) pipes (3 m in length and 7.62 cm in diameter) drilled at their joints and joined with screws. A core catcher, made with 30 gauge aluminum sheet is attached to the first PVC pipe (bottom end of core barrel) and a pounding core head to the last (top end of core barrel). The core catcher (Figure 2.6) was riveted and duct-taped to the lowermost PVC pipe (Reasoner, 1993). The core head, a PVC pipe (76 cm in length) of equal diameter to the core barrel, is used to support the weight of the percussion hammer during pounding. It has three attachment bolts at each end: the top bolts support the main rope of the system whereas the bottom bolts support the core barrel. The percussion hammer (driver) is made of PVC pipe (10 cm in diameter and ~80 cm long) filled with cement or sand. The hammer has a lengthwise hole in its centre through which the main rope extends. This rope in turn has to support and maintain the core tube in a vertical position and at the same time guide the driver onto the top of the core head (Reasoner, 1993).

Once the desired depth is reached for the core, it is extracted with a winch and a step-ladder for support. Drilling into the top of the core barrel (above the sampled core) drains excess water above the sediment, decreasing the overall weight of the core. Empty sections of the core tube are cut off and discarded, and the remaining sediment core is further cut in 1-1.5 m sections whose ends are capped. A detailed succession of photographs showing the coring procedure is displayed in Figure 2.7.

ANALYTICAL PROTOCOLS (LABORATORY METHODS, DATING TECHNIQUES AND IDENTIFICATION OF MATERIALS) AND THEIR INTERPRETATION

Ten different analytical protocols were applied to the samples collected from the six sediment cores recovered from Kakawis Lake. These included three non-destructive techniques: two geophysical and one radiographic. The remaining seven protocols

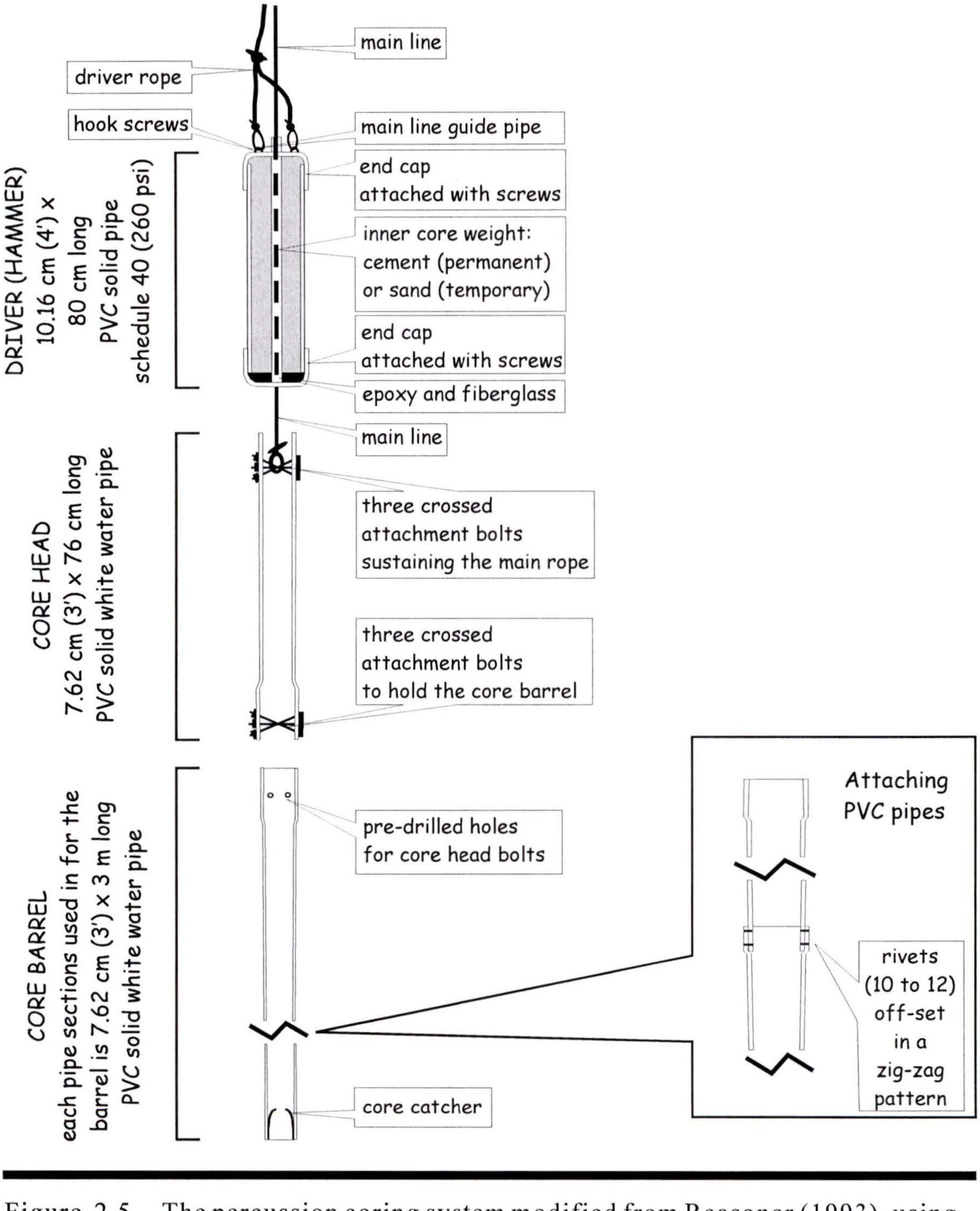


Figure 2.5 The percussion coring system modified from Reasoner (1993), using same nomenclature to describe the three main sections (on the left). On the right, an enlarged view of the PVC pipes when assembled and riveted together. It is suggested to assemble only three pipes for the Core Barrel section (for a total of nine meters of sediment core) to facilitate retrieval and overall handling of the whole structure. With the exception of the rivets, all required holes are pre-drilled in the pipes. Note that no weight is added into the Core Head section and the ends are open.

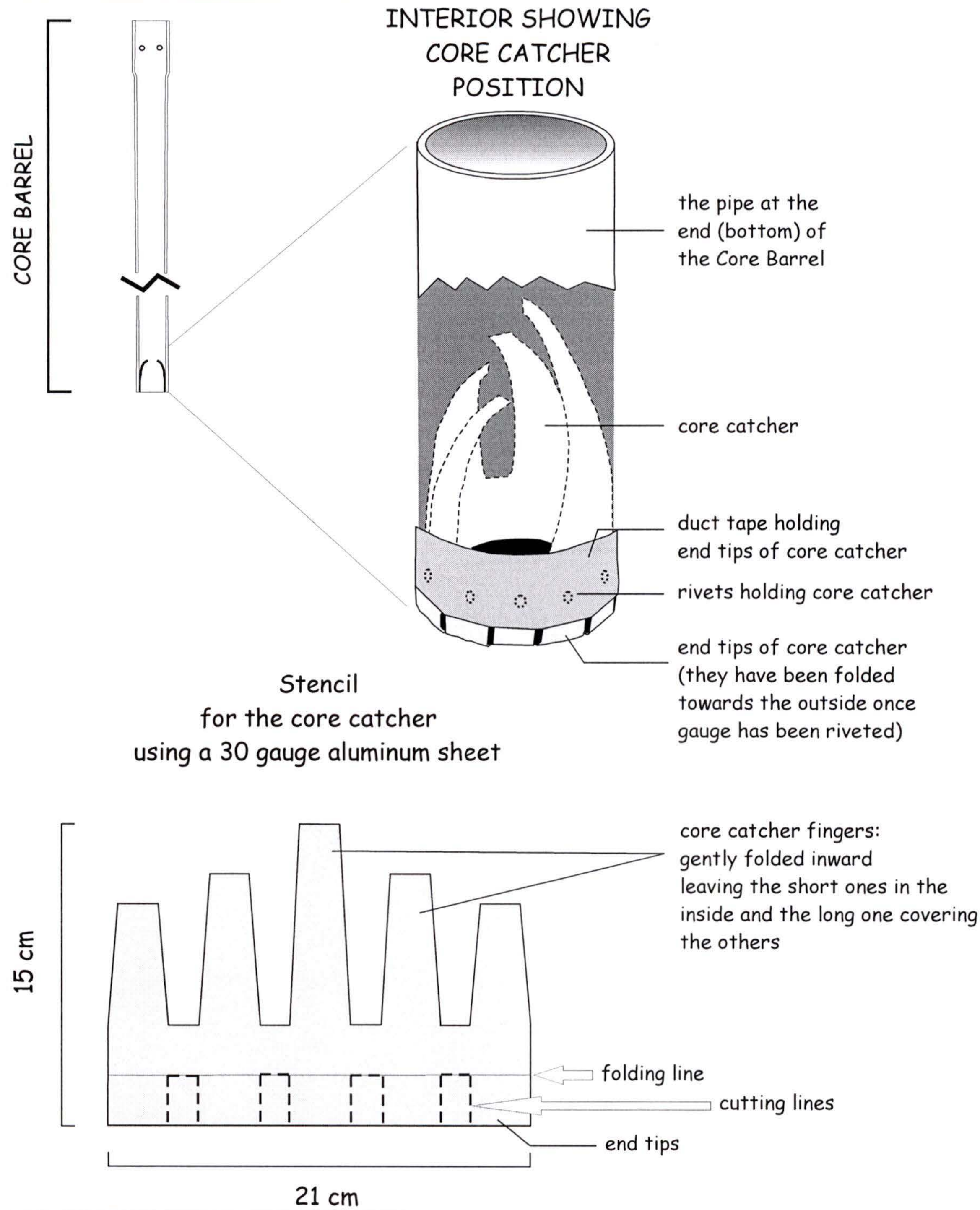


Figure 2.6 Detail showing the core catcher. The top figure shows the core catcher in place, inside the first pipe of the Core Barrel. The five fingers of the catcher are gently folded towards the inside to prevent sediments from escaping. The bottom sketch shows the stencil used to cut the catcher using a 30 gauge aluminum sheet.

Figure 2.7 Sequence of photographs illustrating the percussion coring technique used in this research: (a) Stabilizing the coring platform with anchors on the four corners; (b) Introducing the first PVC pipe into the waters and surficial sediments of the lake bottom; (c) The initial percussion coring is carefully achieved with a sledge hammer until the pipe structure is at an accessible height to use the cement hammer shown in (d) and (e); (f) and (g) show the initial retrieval of the sediment core with a winch hooked to a step ladder, after coring is complete. Once the sediment core is released from the entrapping lake sediments, manual retrieval is possible (h), and subsequent cutting is performed. (Photographs taken at Kakawis Lake during field seasons 1998 and 1999).

involved sample preparation and material collection. Standard approaches commonly used in descriptive/documentary sedimentology were also applied. A total of 305 samples from both inferred tsunami layers and lacustrine sediments were analyzed for loss-on-ignition, index parameters, C/N ratios, textural analyses, radiocarbon dating, ^{137}Cesium analysis as well as organic and inorganic material identification and characterisation.

The recognition of a given anomalously coarse layer (e.g. tsunami layer) within a muddy lacustrine sequence is often relatively easy due to the pronounced sedimentological difference between the two types of materials. However, the actual laboratory procedures to obtain textural patterns, element concentrations, as well as the separation of different materials are difficult and time consuming given the large quantities of fine organic matter.

The following is a summary description of the laboratory techniques used to extract information from the tsunami deposits. An overview of the successes and problems encountered is also presented. Some of the protocols used during the laboratory analyses are standard techniques that required little modification. However, some methodologies were modified and these are justified here. A detailed discussion of the results and data are presented in Chapter 3. Up to six inferred tsunami layers were found embedded within gyttja and organic-rich muds from Kakawis Lake.

General descriptive procedures

For best preservation, the core sections were kept intact and refrigerated at a temperature of 4 $^{\circ}$C until analyses began. It is important to clearly establish the sequence of analytical techniques prior to splitting. For instance, magnetic susceptibility must be performed on an intact core, whereas electrical resistivity needs to be determined using the split sediment core.

The sediment cores were split into two equal longitudinal halves instead of extruded from their original holding pipe. Longitudinal sections were split by sawing the sediment core with either a single bone-saw or a pair of mounted saws on a rolling "boat" enabling both sides of the pipe to be cut simultaneously (Figure 2.8). One half of every split core was archived.

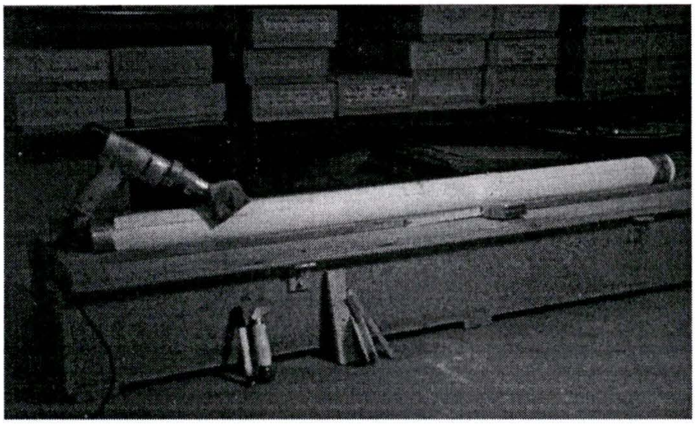
All core sections were photographed with tungsten film and lighting to ensure a consistent quality of the photographs (Figures 2.9, 2.10 and 2.11). Non-reflective 20 cm long scale cards were used to maintain reference points for depth increments. The cores were photographed using a cubic metal frame tripod to which the camera was fixed 80 cm above the core, ensuring the focal length between the lens and the sediment was equidistant. Direct sunlight was avoided, as well as fluorescent artificial light as they both interfere with photography.

The initial core descriptions followed standard sedimentologic and stratigraphic criteria (c.f. Krumbein and Sloss, 1963; Pettijohn and Potter, 1964; Pettijohn *et al.*, 1973; Folk, 1974; Tucker, 1988). All cores were thus described in detail before any sampling was conducted. Observing the split sediment cores when covered with a plastic wrap is a technique particularly useful when changes in an almost monochromatic sequence are difficult to discern. This technique highlights any small change in colour, structures, laminae, and contact boundaries.

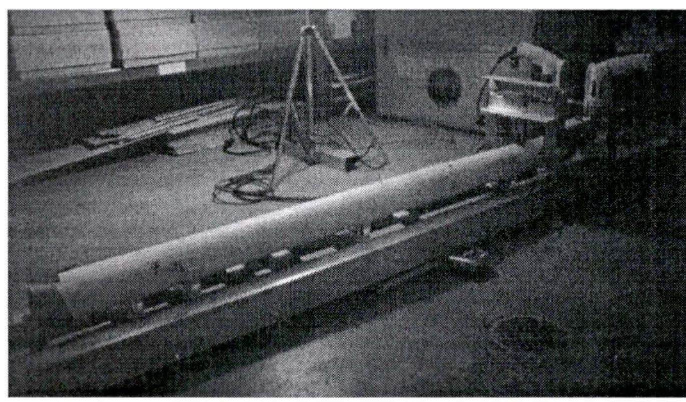
Protocol 1 - Magnetic Susceptibility

Magnetic susceptibility provides a preliminary interpretation of the depositional sedimentary environment. It is used to determine downcore variations in iron-bearing minerals and grain size. Magnetic minerals are extremely useful paleoenvironmental indicators, especially when studied in bulk (Gale and Hoare, 1991). However, caution must be used because organic matter reduces susceptibility and is further directly proportional to the packing, shape and size of strongly magnetic minerals (Grimley *et al.*, 1998). Magnetic susceptibility from coil inductance measurements establishes a correlation between the value obtained and the relative porosity of the material, defined as the ratio of the inductance used.

The procedure followed operational instructions described in Hewitt (1998). This protocol was applied to two non-split cores (K6 and K7) from Kakawis Lake. It was measured at 2 cm intervals, using a Sapphire Instruments' SI2 coil-meter of 10.5 cm in



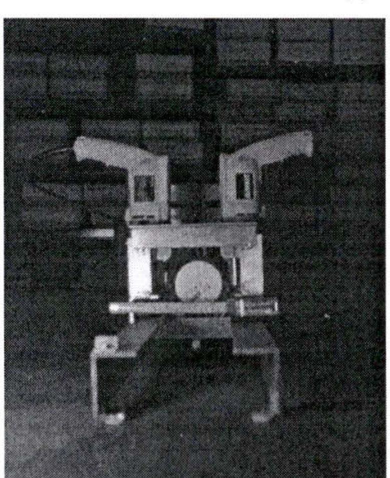
a.



c.

Figure 2.8 Core Splitting techniques: (a) Core splitting procedure with a single bone saw and a box-cutter. (b) Close-up of the pair of saws mounted on an aluminum frame that slides along an aluminum "boat" that holds the core barrel. (c) General picture of the entire apparatus prior to splitting a core. Both saws are manipulated by one person while sliding the mounted saws along the entire length of the core. The arms that hold the saws are mobile, permitting the blades to get closer to (or away from) the core. (PGC Sedimentology Laboratory).

b.



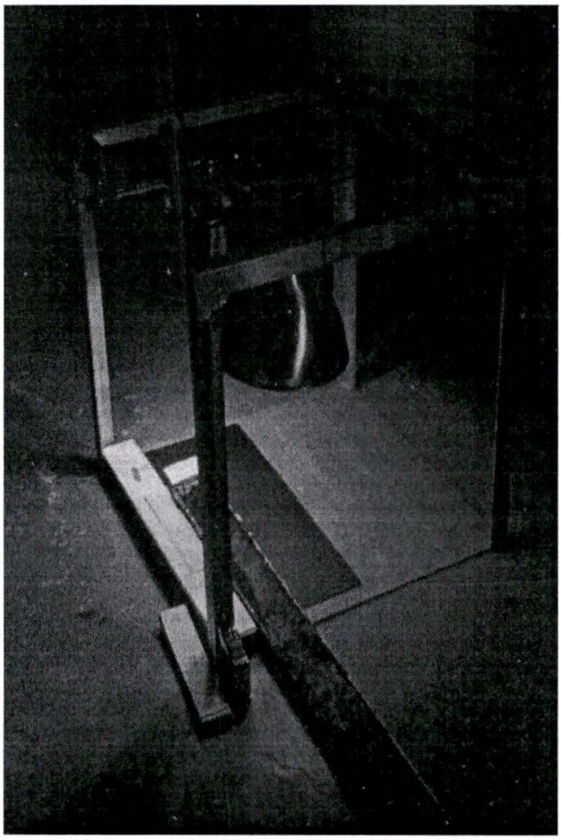
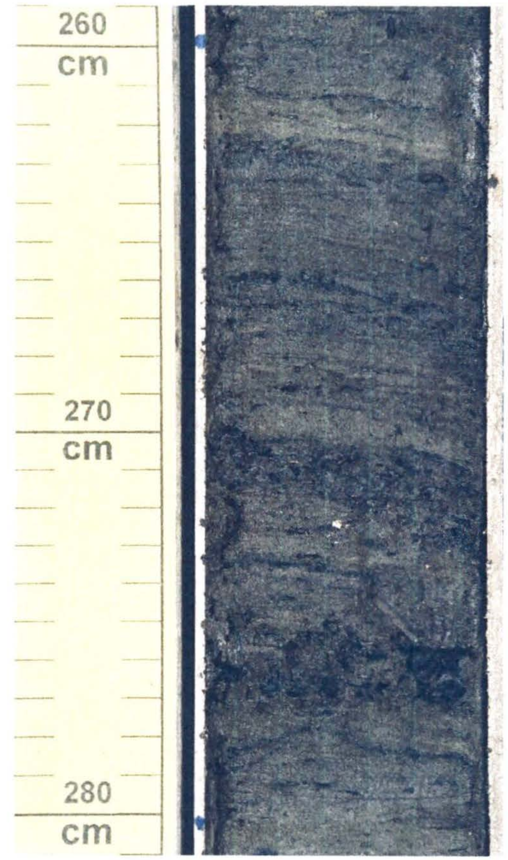


Figure 2.9 Photographing the split sections of each core. Tungsten light bulbs and film are used to obtain high resolution. The camera is mounted on a box-tripod ensuring the lens and sediment to be equidistant throughout the entire shooting of the core sequence. Scale cards are 20cm in length.

Gyttja

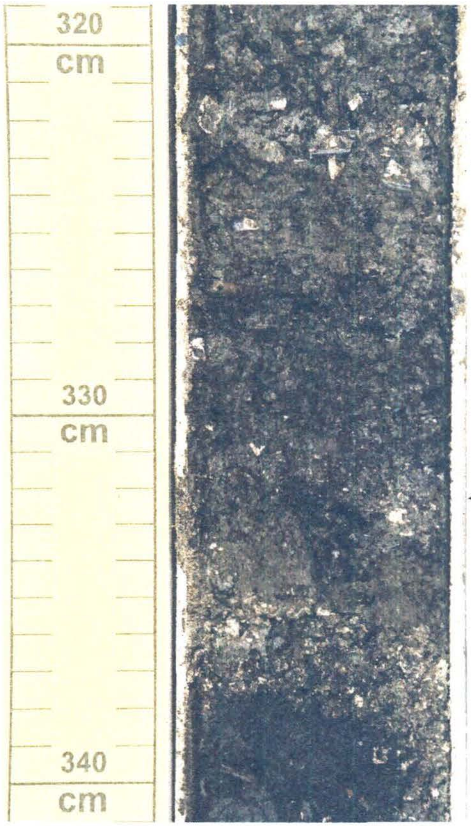
Tsunami layer: correlated with oldest tsunami event in Kakawis Lake

a) Bottom end of core K3: the catcher is not removable after sediment cores are recovered.



b) Example of lacustrine sedimentation in core K5: laminated gyttja. The darker laminae are highly rich in organic material. This type of gyttja is common to sections located in between different tsunami events. At the bottom and top of the sequence, gyttja is massive.

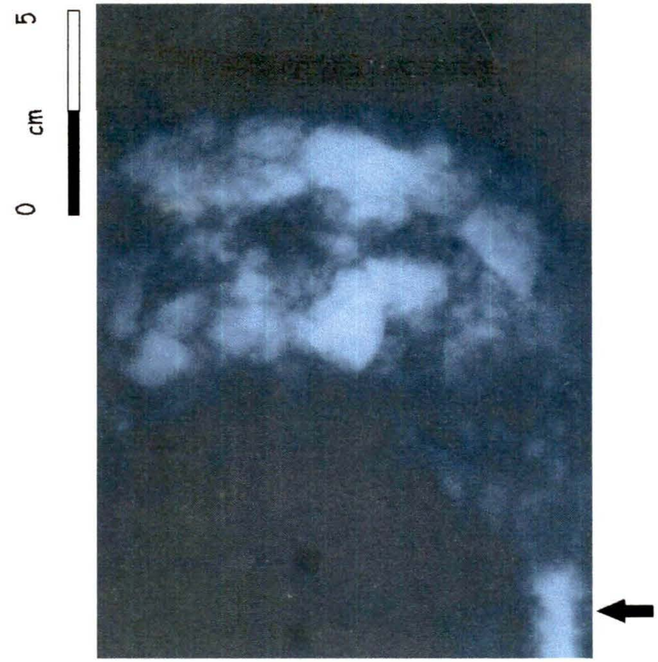
Figure 2.10 Examples of photographs taken from the sediments of split cores.



Tsunami deposit: at least three pulses (sandy layers) were recorded in core K5 corresponding to the oldest tsunami event to hit the lake. Inferred tsunami pulses (run-ups) are marked by the arrows.

Downward movement of material due to cobble pushed during core penetration

a) Example of tsunami layer found in core K5.



b)

Example of a section of the X-radiograph sequence taken from core K5:
Detail showing the first pulse (run-up) of the first (oldest) tsunami deposit found in this core. (The same pulse is shown of photograph b above). The light material corresponds to terrigenous and carbonate particles. The "un-focused" appearance is due to the thickness (3D) of the material.

Figure 2.11 Examples of photographs taken from the sediments of split cores. For comparison, a detail of the X-radiograph images obtained is shown (b).

diameter and 5 cm in width, running a LabVIEW program based on CORESUSC version 1.0 (1996) (Enkin, 1996), provided by the Pacific Geoscience Centre -PGC- (Sidney, B.C.). When applying this technique to such cores it is important to remember: a) magnetic susceptibility is extremely sensitive to sediment temperature, therefore the cores should be brought to room temperature (18-20 °C) at least 12 hours prior to any measurements; and, b) the nearby presence of metallic objects, such as screws and the core-catcher, interfere with the measurements.

Method Interpretation (Magnetic Susceptibility)

The results obtained for cores K6 and K7 were impressive. Each individual inferred tsunami layer reacted positively to the method. A peak value was generated around each of the layers (Figure 2.12). Poorly-sorted tsunami layers with clast sizes up to -4 Φ had susceptibility values up to 780 x10^6 SI/vol, marking the highest measurements recorded for any of the anomalous sandy-detrital-shelly rich layers in the cores. Moderate to moderately-well-sorted tsunami layers showed the lowest susceptibility values, near 160 x10^6 SI/vol. All tsunami layers had susceptibility values near the limits mentioned above. Interestingly, in the cases where the top section of the tsunami layer (the detritus cap) was thick enough (7.5 to 10 cm) to be intercepted by the magnetic field, the susceptibility values showed a slow but steady decrease from 140 x10^6 SI/vol at the bottom to 0.00 SI/vol at the top of the section. As for thick (up to 22 cm) detrital rich layers (plant detritus content >70%), the susceptibility values were also high (*ca.* 300 x10^6 SI/vol).

For lacustrine sediments (gyttja and organic-rich muds), magnetic susceptibility is particularly sensitive to water content and lamination. The values obtained for the massive gyttja sections were inconsistent and quite variable with maximums of 160 x10^6 SI/vol and minimums of 40 x10^6 SI/vol. The finely laminated gyttja sections of the sedimentary cores showed smooth curves ranging from 100 to 160 x10^6 SI/vol or steady curves maintained around the highest value. The coil-meter (magnetic field) could not easily depict individual layers less than five centimetres thick.

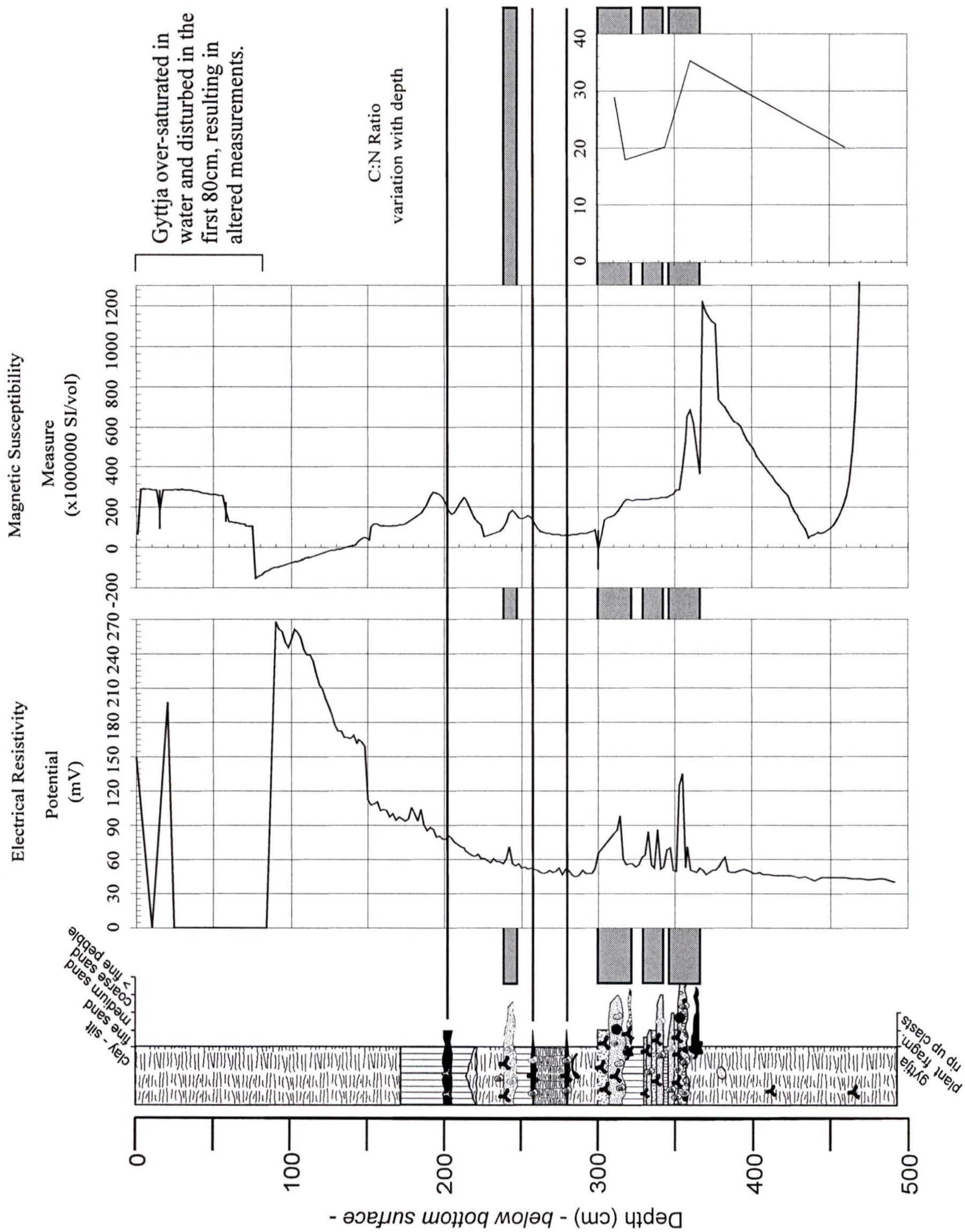


Figure 2.12 Graphic log of core K6 depicting all lithologies encountered. Example of curves obtained from Electrical Resistivity and Magnetic Susceptibility measurements. A profile of the C/N ratios obtained from the lower part of the core is also shown. Inferred tsunami layers are highlighted by the black and thick grey lines.

The gyttja at the top of the cores, which had relative water content up to 95%, showed particularly anomalously high values (around 280 $x10^6$ SI/vol), probably due to excess water, mixing of the material during transportation of the cores and general handling. In contrast, the values obtained on the last 70 cm of the cores were extremely altered by the presence of the core catcher attached to the end of the core, and showed measurements greater than 1200 $x10^6$ SI/vol.

Protocol 2 - Electrical Resistivity

Electrical resistivity was measured directly on the sediments of cores K6 and K7 immediately after splitting. Because it does not involve sampling, electrical resistivity is still considered a non-destructive geophysical technique. For comparison, resistivity was also measured on two other cores (K2 and K5) that had been opened and properly preserved the year before.

Resistivity measures the resistance of sediments to the passage of an electric current. It is a proxy indicator for the degree of porosity of any given sediment as well as for the presence of saline pore water (highly conductive) within the sediment. However, fine sediments oversaturated with freshwater may show altered values. The technique is very sensitive to the sediment surface, temperature and dryness of the material. To complicate matters, electrical resistivity senses any distortions in the subsurface such as troughs and/or crests within the sediment, and invisible on the surface. Low readings are expected from moist soils, whereas coarse-grained layers show higher electrical values (Renfrew and Bahn, 1996). Moreover, stony layers may show as high resistivity values as super-saturated unconsolidated sediments. Resistivity may also vary from layer to layer, due to fluctuating pore water characteristics. Measurements were completed on a smooth sediment core surface and sediment sections were brought to room temperature (18-20 °C) six hours before the measurement.

The procedure followed operational instructions described in Hewitt (1998). The conductivity meter consisted of a 4 pin Wenner array, each pin 2 mm long and separated 2 mm from the other, connected to a Fluke voltmeter (the two inner electrodes measured temperature, whereas the two outer electrodes measured voltage). The signal applied to the material was a ± 5 V 160 Hz square wave through both 4.99 K resistors. The cell constant has to be adjusted until the resulting resistivity is 0.209 Ohm (and the formation factor is 1.000). After every measurement the probe was carefully calibrated with Standard Sea Water (S = $35^{o}/_{oo}$) to prevent errors in the readings. The data handling program under Lab VIEW (RESISTIVITY.vi version 5.0) was used (Heffler, 1992). The equipment was provided by PGC.

The probe pins are very delicate and need to be handled with care because minor bending could alter results. Consistency regarding measurement intervals and probe position also has to be maintained. Measurements were taken every two centimetres downcore and in between two consecutive magnetic susceptibility measurements. A probe position transverse to the core axis (parallel to the stratigraphy) was chosen to better characterise the selected layers.

Method Interpretation (Electrical Resistivity)

Like magnetic susceptibility, the results obtained from the resistivity measurements were also useful. Inferred tsunami layers containing more terrigenous and carbonate material than detritus material were defined by high resistivity values as compared to the enclosing organic-rich sediments (Figures 2.12 and 2.13). This partly reflects the low degree of porosity and/or high saline pore water content of tsunami layers.

Since some tsunami layers were no thicker than five centimetres, the resistivity probe had to be used parallel to bedding. However, when measuring layers enriched in coarse (particles sizes greater than -2 Φ) terrigenous material or coarse plant detritus, it was difficult to obtain accurate values because of the irregularity of the sediment surface and the size of the material. Resistivity measurements are most reliable in materials that have regular or consistent matrix, so the probe can be introduced uniformly in the sediments. As a consequence, layers highly enriched in plant detritus were not easily identified, compared to clastic and finely laminated gyttja layers.

Clastic layers (particles sizes ranging from 5 Φ to ~ -2 Φ) enriched in marine shells and plant detritus were well depicted by the probe. For moderate to moderately-

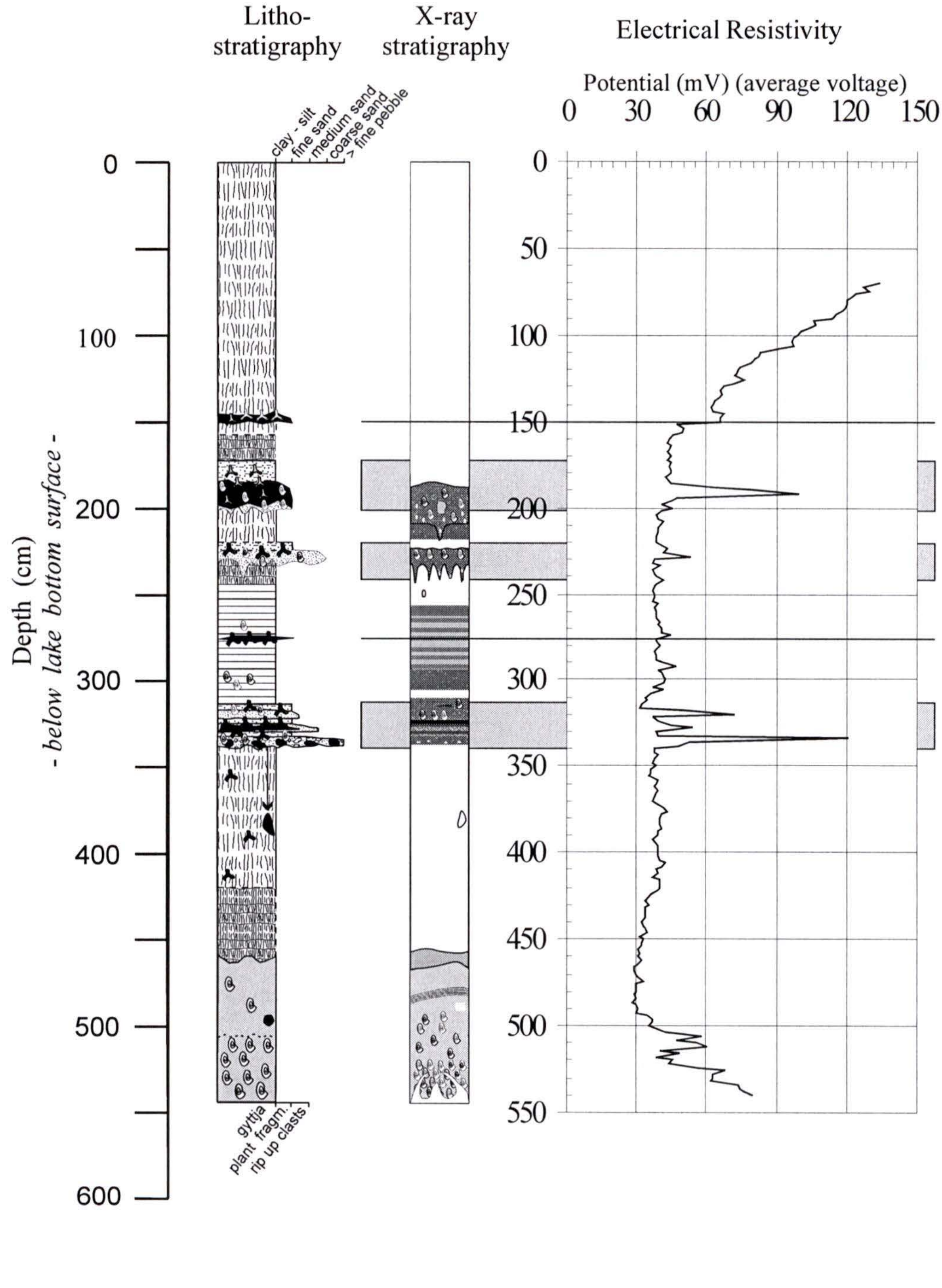


Figure 2.13 Graphic logs showing lithology and x-radiograph sequence obtained for core K5. The correlations between physical analyses and geophysical properties match accordingly. The inferred tsunami events are highlighted by the black lines and grey boxes. For practical purposes, the gyttja layers (black in the x-rays) that did not show structures are represented in white in the x-ray log.

well-sorted tsunami layers, the resistivity values oscillated near 70 mV. Generally, the coarser the terrigenous material, the higher the resistivity values. A maximum value of 135 mV was obtained for a tsunami layer with clasts up to -4 Φ.

Similar to the results obtained with the coil-meter, gyttja with relative water content >90% showed resistivity values up to 270 mV. However, resistivity values gradually decreased with decreasing water content and increasing depth. This was particularly evident in the top 150 to 250 cm of the sediment cores. The gyttja trapped below the earliest tsunami layer (approximately 300 to 350 cm depending on the core) is stratigraphically older than the one at the top. Nevertheless, the relative water content did not vary much in comparison with the younger gyttja. However, the resistivity values were significantly lower than those at the top (between 35 and 45 mV) (Figures 2.12 and 2.13).

Protocol 3 - X-Radiographs

X-rays are an invaluable guide to understanding detailed textural organisation, without disturbing the sediment itself. Conventionally, x-rays are performed on thin (<3 cm) sediment slabs collected directly from the depositional environment or extracted from recovered sediment cores (Jackson *et al.*, 1996; Orsi *et al.*, 1996). However, x-ray images from slabs only provide an in-plane resolution (two dimensions -2D-) of the sediments.

To obtain an insight of the internal nature of the sediment cores, x-radiographs were taken of one whole half of the split core K5 (Figure 2.11). The PVC pipe does not interfere with the reading. However, the thickness of the material, hence the diameter of the pipe, may confuse the image, but an insight of the three-dimension structure of the sediment can be obtained.

The x-ray technique followed a "trial-and-error" principle as no previously established dosage and exposure values were known for such type and thicknesses of material. The radiographs were taken with a traditional veterinary 2D x-ray machine at the McTavish Pet Hospital in Sidney, B.C. Four sections of the split core were x-ray imaged simultaneously using a sheet of industrial x-ray film (35.4 cm x 43 cm). The cone-shaped diverging beam of the x-ray machine covered the width of the sheet. The core sections were placed side by side, covering the width of the sheet. A 1 cm gap was retained between each core. Each sheet enclosed 43 cm of the length of all core sections per photograph, hence three sheets of x-ray film were required to x-ray the 543.3 cm-long core.

Exposure rates vary depending on the type of sediment and given the pronounced lithological differences of the core several shots of trial and error had to be performed to obtain an image that best highlighted the tsunami deposits. Dosages of 62 kV (acceleration potential) for 1/20 seconds (exposure rate) and 100 S (parameter that specifies that the subject has not movement) were used. A 1:1 scale was maintained.

Method Interpretation (X-rays)

Although x-rays are unable to clearly distinguish organic-rich sediments, a complete radiograph of a continuous half of the split core K5 was taken to define the internal organization of the inferred tsunami layers and any other sedimentary structures that might have been overlooked during the visual description. Here, the experiment of x-raying the whole half core yielded excellent results despite the variability in thickness across the core (as it is U shaped).

Areas of the sediment core coinciding with tsunami layers and glaciomarine clays, as well as other beds with sparse clastic material were well-highlighted by x-rays (Figures 2.11 and 2.13). Terrigenous grains and marine organisms such as shells or any other carbonate material have high impedance to x-rays, and are thus well-defined.

Although little detail was recovered from the organic-rich layers, some differences could be observed in the sequence. Layers with more than 50% organic content (both organic matter and macro-plant detritus) showed a much darker pattern in the x-ray image than the bounding sediment units. Minor laminations could also be distinguished within the organic-rich layers, concordant with the observed thinly laminated gyttja sections. Although higher resolution of micro-structures can be obtained from thin sediment slabs, the experiment in this study still yielded valid results, concordant with the lithology and geophysical measurements.

Protocol 4 - Loss-On-Ignition (LOI)

The LOI technique was used to measure the total amount of organic and inorganic carbon present in each sample. The ignition of organic carbon initiates at 200 °C and total combustion is achieved by 550 °C. Inorganic carbon, present in calcium carbonate material, ignites after reaching temperatures of 850 °C. Loss-on-ignition is a method used widely and the principles described by Dean (1974), Hakanson and Jansson (1983), Menounos (1997) and Maher (1998) were applied.

LOI was performed on 64 stratigraphical volumetric samples (10 cc) extracted from different layers of cores K1, K2, K5, K6 and K7 using a syringe (serving as a mini-corer). It is a simple technique to evaluate the organic and inorganic content stratigraphy of a core and it also facilitates correlations.

The equipment used was a Perfect Fire II-563 furnace with KILN DTP-56 electronic control at PGC. Samples were ignited at a ramp rate of 150 °C/hr, up to 550 °C to obtain the Total Organic Carbon (TOC) content. The same procedure was used to reach the 1100 °C temperature to obtain the Total Inorganic Carbon (TIC) content. Samples remained at each crucial temperature for one hour.

Method Interpretation (LOI)

Organic carbon content implies direct values of primary productivity within a system as well as any nutrient input from land. It is a helpful tool when establishing possible variations in paleoenvironments. Nevertheless, caution has to be taken especially with the inferred tsunami deposits as they may concentrate large amounts of allochthonous plant material.

TOC and TIC values behaved proportionally to the variations in the organic matter and carbonate concentrations throughout the sedimentary sequences of Kakawis Lake. No particular values were depicted for the inferred tsunami layers because the measurements depended on the $CaCO_3$ and plant detritus content of individual anomalous layers. However, TOC values for tsunami layers never decreased below 20% or exceeded 70%. In contrast, TIC values were continuously low, varying between 5 and 10% throughout the sequence.

Protocol 5 - Index parameters

Index properties such as wet and dry bulk densities and water content are primary in the determination of physical parameters that define any given sediment. Calculated physical parameters like porosity and permeability can be obtained knowing the density of the pore water. Water content is also an inexpensive way of correlating cores from a single lake (Hakanson and Jansson, 1983; Catt, 1990; Menounos, 1997). The values were obtained from the lyophilization process performed as the initial drying treatment for all the samples both the small samples (used for LOI) and the large samples (used for the textural analyses).

Protocol 6 - C/N Ratios

Total Nitrogen and total Carbon provide details on the degree of nutrient elements input in any given system. The analysis of organic compounds present in the elemental composition of lake sediments can offer a good perspective of events in the history of the system (Hakanson and Jansson, 1983).

Twenty-two stratigraphical volumetric samples were taken directly adjacent to those samples removed for LOI analysis. The C/N ratio analysis was undertaken by the Analytical Chemistry Laboratory, a component of the Research Branch - Ecology and Earth Sciences section of the British Columbia Ministry of Forests (Victoria, B.C.), using a Fisons (Carlo-Erba) NA-1500 NCS elemental analyser. The samples were first ground to 100 mesh (<150 μm) and a moisture factor determination was made at 105 °C to obtain an equal oven-dried basis correlation parameter.

Method Interpretation (C/N Ratios)

Organic matter in general is a dynamic biogeochemical component in lacustrine systems. Usually the primary sources of organic matter in lacustrine sediments are the autochthonous plant detritus (algae) to the lake and the surrounding terrestrial environment (Meyers and Ishiwatari, 1995). By analysing the C/N ratios, it is possible to determine: a) whether or not the sedimentary organic matter at a particular depth within the sedimentary sequence is from vascular (terrestrial) plants or non-vascular aquatic plants; b) if the sediments have suffered some form of mixing or perturbation; or, c) if the plant detritus of a layer is relatively modern or has been buried for a longer time.

The C/N values obtained for the inferred tsunami layers from cores K6 and K7 were particularly interesting, ranging from 17 to 35. The higher values corresponded to the earliest (older) inferred tsunami layers implying that both the source of the plant detritus involved was mainly terrestrial, and that at the time of deposition and burial, the majority of the detritus may have not been necessarily obtained from previously buried material but rather from living material at the time of the tsunami inundation. However, the organic matter incorporated within the inferred tsunami deposits can also have a minor marine component that would not interfere with the high C/N values obtained.

The C/N ratio profile of lacustrine sediments ranged between 14 and 17. However, the recent sediments at the top of the sequence (first 70 cm) showed a variation between 13 and 14, suggesting organic provenance is a mixture of both main sources of organic matter (vascular and non-vascular plants). Such values are expected for most lakes (Meyers and Ishiwatari, 1995).

Protocol 7 - Textural Analyses

A meticulous routine of sedimentological descriptive procedures was applied to the samples collected. Some existing methodologies, techniques and conventions were modified and adapted in this protocol (e.g. Krumbein and Sloss, 1963; Folk, 1974; PGC, 1982; Hakanson and Jansson, 1983; Middleton and Southard, 1984; McManus, 1988; Tucker, 1988; Catt, 1990; Gale and Hoare, 1991; Lewis and McConchie, 1994).

The grain size and individual characteristics of the sediments were of primary importance because variations in the particle size distributions help in the interpretation of changes in hydrodynamic conditions of any given depositional environment. This was certainly the case for the inferred tsunami deposits found within the lacustrine sequences of Kakawis Lake. The determination of sediment texture also helps to establish differences between individual tsunami deposits.

Sixty-six stratigraphical non-volumetric samples were collected from different lithological layers of cores K1, K2, K5, K6 and K7. An additional sample collected from a sandy tsunami layer buried in the marshes near Port Alberni, B.C. (AD 1700 Cascadia tsunami) was also analysed for comparative and correlation purposes. Unfortunately, factors such as high fine organic matter contents, macro plant detritus and carbonate content impeded development of an easier laboratory procedure.

Moreover, the sedimentary sequences of Kakawis Lake comprised three very different lithological groups of materials: 1) organic-rich layers (gyttja and organic muds); 2) sandy-detrital-shelly layers (inferred tsunami layers); and, 3) clay-rich layers (glaciomarine clays). Because of the range of materials and compositional differences, a number of different sample preparation techniques had to be used. A summary of the methods used in this protocol is described below.

Grain Size Determination Procedure

Prior to any analysis, lyophilization was conducted on all 66 samples. Treatment procedures were dependent on the type of sample. Analysis of organic-rich and sandy-detrital-shelly rich samples required that all organic matter and carbonate fragments be extracted. Clay-rich samples were treated as typical marine samples with mud content >5% and these underwent sedigraph analysis (PGC, 1982; Gale and Hoare, 1991; Lewis and McConchie, 1994).

Samples underwent an initial gentle mortar disaggregation to ease the preliminary mechanical separation of the different materials >4 mm. Twigs, bark, shells, and other detrital materials were used in later biological/ecological analyses. Next, each sample was individually dry-sieved using a #10 mesh (2 mm) and two major size fraction groups were thus obtained.

Several methods were used to extract organic matter from material in the finer fraction (<2 mm). Digestion with hydrogen peroxide was attempted but this method required a large volume of solution because most samples had significant amounts of organic matter. Mechanical separation was impossible, so separation was achieved using density differentials. The samples were submerged in a heavy-liquid solution of sodium polytungstate (2.0 density). Lighter organic material was kept on the surface by specific gravity differences. The organic material and heavy liquid were then poured onto a #230 mesh (63 μm) sieve, and washed using very little de-ionised water to recover the heavy liquid.

Occasionally, some organic material may remain attached to sediments. Therefore, a second gravity separation technique was used. First, the sediment is exposed to a sonic bath to enhance separation (in beaker with a 0.5% sodium hexametaphosphate solution) and then it is gently washed several times over a 63 μm sieve with tap water. Water is allowed to overflow the beaker and less dense organic material is collected by the sieve. All wet organic material was oven-dried at 80 °C for 12 hours.

The fine fraction (<2 mm), free of organics, was then treated to extract the carbonate material. If any clay is present, the material was sonicated with a 0.5% sodium hexametaphosphate solution. An adaptation of the Milliman carbonate method (Milliman, 1974) was used to eliminate the carbonate fragments. Approximately 50 ml of 10% HCl were used to digest the carbonates using an oscillating hot plate (~30 minutes). To remove all HCl from the sediments, each sample was rinsed with distilled water. The samples were then oven-dried at 80 °C for 12 hours.

The "clean" clastic material was analysed for grain size using either the standard dry sieving method or a settling tube. The computerized settling tube used (PGC, 1982) required two runs of at least 2 g of sediment per sample. Although several samples were analysed using the settling tube technique, the preferred method proved to be the dry sieving given the limited presence of terrigenous material (<2 g). Although maintaining a ¼ ϕ unit interval between the 63 μm and 2 mm size fractions is statistically preferable in dry-sieving (McManus, 1988; Gale and Hoare, 1991), logistics dictated that only ½ ϕ unit intervals were used.

Grain size statistics are dependent on the accuracy of measurement. Controversies arise when dealing with shaking times in dry-sieving procedures because sediment separation is also dependent on the period of shaking time. A wide range of time values, varying between 5 and 25 minutes, are recommended by different authors (Pettijohn *et al.*, 1973; McManus, 1988; Tucker, 1988; Gale and Hoare, 1991). In this study, a 20 minute standard shaking time was used to minimise statistical errors.

Method Interpretation (Textural Analyses)

In the laboratory, it is often impossible to extract one sample and apply several different analytical techniques. Neither uniform (regular sampling intervals) or random sampling was employed because, such approaches do not give a fully representative sample of the "parent" population especially because the quantity of the material available per layer was often very limited (Dean, 1974; Hakanson and Jansson, 1983; McManus, 1988; Tucker, 1988; Catt, 1990; Gale and Hoare, 1991). Two sedimentological principles were followed for sampling whenever possible: stratigraphic (following the core stratigraphy) and volumetric (enabling a constant volume to allow the determination of the index properties) extraction.

For the protocols requiring sample analyses, two types of samples were taken. The first consisted of small volumetric samples (10 cc and 10 g wet weight) used for the determination of index properties, TOC, TIC and C/N ratios. The second type of sample, representative of a larger portion of any given lithological layer, was typically between 120 and 130 cm^3, with a minimum weight of 90 g (wet weight) and this was exclusively used for the textural analyses.

Moisture content was measured for each sample using both freeze-drying (at least -50 $^{\circ}C$ for 12-48 hours) and oven-drying (105 $^{\circ}C$ for 12 hours) methods to document potential variability. The results showed minor changes, likely due to water being driven from mixed-layer clay minerals. This is a problematic issue when dealing with a rapid determination of organic content in lake sediments and relying on loss-in-mass measurements (Dean, 1974; Hakanson and Jansson, 1983; Gale and Hoare, 1991). Some samples had a total moisture content variability up to 1% between the two methods, resulting in lower values for the oven-dry procedure. To this end, lyophilization was the preferable technique to dry the samples. However, this method required more time to process (12 hours for the small samples and in excess of 48 hours for larger samples).

Other factors affecting freeze drying rates include total water content and mean grain size of the sample. Additionally, lyophilization was chosen over oven drying because it preserves organic material and prevents oxidation. Freeze-drying also enhances the separation and grinding ability of the material for later analyses.

In total, 32 samples contained terrigenous sediment but only 13 had sufficient material to be analysed by settling-tube (a minimum of 2 g per run for a required set of two runs was needed). The other 24 samples were analysed by dry sieving. The samples containing terrigenous material corresponded to the anomalous layers inferred to be tsunami deposits.

The inferred tsunami layers found within the lacustrine sequences of Kakawis Lake varied in grain size from 6 to -7 Φ. Some layers proved to have clastic (terrigenous) material up to 80% of the total composition, and had a particularly large coarse fraction (between -3 and -7 Φ). The coarsest anomalous layers tended to be the lowest in the sedimentary sequence, hence the oldest tsunami deposits. Vertically throughout the sequence, clast sizes decreased in general from bottom to top and sorting increased. This implies that either Kakawis Lake had gradually emerged from its initial forming level that was more accessible to incoming waves and their load, or the energy of the tsunami waves that reached this lake was lower for the younger tsunami layers than for the older ones. A detailed analysis and discussion of the grain size results obtained for the inferred tsunami layers is discussed in Chapter 3, as well as the identification and characterisation of the macro-organic component (shells and plant detritus), made possible to lyophilization.

Protocol 8 - Radiocarbon Dating

The most commonly used method for age determination covering the last 50,000 years is radiocarbon dating. AMS ^{14}C dating was done in individual organic samples selectively and strategically extracted from two cores (K5 and K1). Twenty-three samples were analysed for ^{14}C at the Geological Survey of Canada Radiocarbon Dating Laboratory in Ottawa and the IsoTrace Radiocarbon Laboratory - Accelerator Mass

Spectrometry (AMS) Facility at the University of Toronto. Twenty samples comprised bark fragments, cone brats, twigs, needles and three samples were shell fragments, all embedded in the gyttja, organic muds, inferred tsunami layers and glaciomarine clays.

Radiocarbon was used to establish crude sedimentation rates and chronology of the inferred tsunami events. Carbon contamination and reservoir effects can be problematic and cause errors in the results obtained. Cases of contamination especially in peat and lacustrine samples are discussed in Blystad and Selsing (1989).

Method Interpretation (AMS Radiocarbon dating)

The radiocarbon dates obtained in this study were calibrated using the data sets provided by Stuiver and Pearson (1993) and Stuiver *et al.* (1998). The oldest dates were obtained from marine shells recovered from the glaciomarine clay, basal unit of core K5, and fell between 15,379 – 15,784 and 14,204 – 14,444 cal yrs BP ranges (0 cal yrs BP = AD 2000). Dates were also obtained for the gyttja unit below the oldest inferred tsunami deposit, and ranged between 13,664 – 13,864 and 7984 - 8029 cal yrs BP. Only one value did not reach the expectations. A relatively young age (2969 - 3124 cal yrs BP) was obtained for a gyttja section dated between 8219 and 8469 cal yrs BP.

Special care has to be taken when dealing with radiocarbon ages on detrital wood or plant organics, as they provide an upper age limit for the time of deposition of the enclosing sediment. A range of radiocarbon values varying between 8029 and 2384 cal yrs BP was obtained throughout the core for the different inferred tsunami deposits. The dates were used to establish a chronology of possible tsunami events in the area. Samples were carefully collected from both bottom and top areas of each visible inferred tsunami deposit, as well as from areas above or below the respective contacts; organic availability permitting. For this study, only the youngest ages of the material collected in the same stratigraphical level were selected. Such dates would be the closest ages to the true age of the deposit or event itself (in the case of possible tsunami inundations) and would logically be the less reworked material. Plant detritus with much higher values is certainly older than the enclosing sediment and may be relevant to an earlier layer and/or destroyed tsunami deposit, or another depositional environment nearby. A more detailed interpretation of the values obtained for the different inferred tsunami deposits is presented in Chapters 3 and 4.

Crude sedimentation rates were calculated for Kakawis Lake based on radiocarbon dates obtained for the glaciomarine clays unit and the oldest gyttja unit (pre-dating any inferred tsunami deposition). A low sedimentation rate of ~0.02 cm/a was obtained for this lake which implies that the system has very little input from the surroundings, and the inferred tsunami deposits may be among the oldest ones recovered to date on the west coast of Vancouver Island. The rate is also concordant with the values obtained in the ^{137}Cs analysis.

Protocol 9 - ^{137}Cs Activity Analysis

Cesium-137 is an artificial radionuclide produced by atmospheric nuclear testing performed by the former U.S.S.R. and U.S.A. between 1952 and 1972. It is a good chronometer to support correlations, characterise environments, and determine sedimentation rates of particularly stable and enclosed ecosystems such as lakes. ^{137}Cs is a ^{235}U fission product that was substantially introduced into the atmosphere in AD 1954, had a peak production between the years AD 1962 and AD 1964, and a minor peak in April 1986 caused by the Chernobyl accident (Naidu *et al.*, 1999). ^{137}Cs is a short-lived isotope (half-life of 30 years) and complete atmospheric fallout is nominally achieved within a year (Krishnaswami and Lal, 1978). If the event is recent (< AD 1952-1954), or estimates of modern sedimentation rates are the goal, this isotopic dating technique provides exceptional precision (Woodward, 1964; Miller and Heit, 1986; Wan *et al.*, 1987; Ku *et al.*, 1998).

The ^{137}Cs procedure was performed according to Lewis (1974) at the Spectrometry Laboratory, PGC, and assisted by Drs. Trevor Lewis and Tark S. Hamilton. This limnochronological technique was used only on samples from K3. Eight samples ranging from about 9-15 g were taken from the top 65 cm of the core, corresponding to the gyttja layers. The freeze-dried samples were analysed for Cs, U, Th and K using a gamma-ray spectrometer with a solid state Ge (Li) detector which constrains any interference coming from Tl and Bi. The samples were counted for a minimum of 43 hours to enhance the reading.

Method Interpretation (^{137}Cs)

For this research, ^{137}Cs was used to assess more accurate sedimentation rates but also to verify the existence of any deposit left by the latest tsunami known to have impacted the coast of West Vancouver Island. Sampling for ^{137}Cs was undertaken in an attempt to define anomalous layers in the sequence corresponding to the AD 1964 Alaska tsunami and to evaluate if the youngest tsunami found in the cores (at depths between 151.6 and 87.1 cm, depending on the core) corresponded to that particular event.

Because of their very small size (≤ 1 μm), the ^{137}Cs particles are easily trapped within the finer sediments (e.g. gyttja) but can also move at ease through porous sand-size layers (Francis and Brinkley, 1976; Ashley and Moritz, 1979; Frignani and Langone, 1991; Clague *et al.*, 1994; Clague, 1996). Bioturbation and other sediment mobilisation can result in problems with interpretation because ^{137}Cs can migrate, resulting in erroneous evaluations. To this end, ^{137}Cs analysis is most effective when rapid and autochthonous sedimentation occurs in a system with minimal bioturbation (Ashley and Moritz, 1979; Hakanson and Jansson, 1983). Under such conditions, the radionuclide pattern within the stratigraphic column can be compared directly to the atmospheric fallout; hence the shape of the profile can be use to correlate the lithology with the 1954 and 1963/1964 markers.

Unfortunately, Kakawis Lake did not show a rapid sedimentation rate that could enhance the values obtained from the ^{137}Cs counting. The curve obtained had a peak value of 1.35 pCi/g at the top of the sedimentary sequence and gradually decreased to 0 pCi/g at the depth of 25 cm. Below this depth, the counting was erroneous given the very low concentrations of ^{137}Cs. It is not believed that bioturbation altered the Cesium accumulation because no evidence of such perturbation was recorded in the top sections of the lithology. However, the absence of defined markers could also have been caused by destruction of the uppermost gyttja section during initial emplacement and/or recovery of the core.

Protocol 10 - Identification and characterisation of Organic Material and Clastic Particles

All organic and inorganic material that remained from the laboratory procedures was meticulously identified and characterised. Three resultant types of material were obtained: clastic material; macro plant detritus (>2 mm); and, macro shell and carbonate fragments (>2 mm). Identification of macro-particles was part of the correlation control and paleoenvironmental interpretation of sediment cores from Kakawis Lake. This protocol helps in the correlation and identification of the tsunami layers and may provide insight into hypothetical provenances of the anomalous / allochthonous layers. The potential for obtaining identifiable material was another reason for selecting the lyophilization procedure when drying the samples.

CONCLUSIONS

The most accessible, cost-efficient and effective techniques or protocols were applied to 305 samples collected from six split sediment cores recovered from Kakawis Lake. The methods described here are not unique to this type of research, but are effective for potential paleotsunami investigations pursued in lacustrine systems.

In this study, a range of the techniques applied to the sediment cores recovered for paleotsunami research has been employed to examine the variety of materials and anomalous deposits (inferred to be tsunamigenic) found in this lacustrine environment. No single method is proposed as absolute to analyse such unique and complex deposits. A series of techniques were combined, modified and applied, to provide a complete analysis of the tsunamigenic sediments.

Non-destructive techniques (geophysical and radiographic) yielded remarkable results that highlighted the different tsunami deposits found within the lacustrine sequences of the various cores. However, caution has to be taken especially with magnetic susceptibility and electrical resistivity as results depend upon a variety of parameters and not only the generally coarse grain size of the tsunami deposits.

Several standard and unconventional methods were employed to extract organic matter and recover the terrigenous material: hydrogen peroxide digestion; manual separation of the <1 mm size fraction; gravity grain-size separation; and finally, reuse of the burnt material left after the completion of the LOI method. For the latter, dispersion with $(NaPO_3)_{13}$ and continual heating of the remnant material proved unsuccessful.

Lyophilization was the preferred method of drying because it was found that the samples could yield more information than those oven-dried (i.e. more organic material separated from clastic component; preservation of any organic material).

It is often not possible to extract one sample and use it in several techniques as there is a limit to the quantity of material that is obtained from the cores (i.e. textural analyses are dependent on the amount of sample). To this end, it is recommended to extract as much information as possible from available sampled material. For example, the identification of biologic detritus was possible because the freeze-drying procedure preserves organic particles from a sample.

In the samples containing terrigenous material, grain-size analysis was determined by settling tube and dry-sieving procedures. Such procedures were only possible when sufficient material was available from the anomalous layers. Sediment sieving was performed to determine size ranges. Such data are essential for statistical analyses and characterisation of tsunami layers.

The tsunami deposits from Kakawis Lake presented a variety of clast sizes, ranging from mud to small cobbles, remarkable sizes for a system presently located 4 m amsl. A variety of species and sizes of marine shell fragments, as well as different types and sizes of plant detritus were found associated with each inferred tsunami deposit. More details about the lithology, sedimentological characteristics and chronology of such allochthonous layers are found in Chapters 3 and 4.

CHAPTER 3

EVIDENCE FOR MID TO LATE HOLOCENE PALEOTSUNAMI DEPOSITS, KAKAWIS LAKE, VANCOUVER ISLAND, BRITISH COLUMBIA

ABSTRACT

Kakawis Lake, situated on Meares Island, nine kilometres from the open shoreline of western Vancouver Island, British Columbia, was studied to obtain evidence of possible tsunami inundations and to determine possible tsunami recurrence and run-up. Six percussion cores recovered from this lake contain six anomalous deposits interbedded within the unconsolidated lacustrine sediments. Detailed sedimentological, geophysical and macro-fraction analyses were performed. The methods, new to paleoseismic approaches proved to be successful tools to characterize the anomalously coarse layers enriched in terrestrial plant detritus and marine shells.

Based on at least eight types of evidence, six tsunami inundations are suggested as mechanisms responsible for the anomalous deposition, spanning from 3634 to 2534 cal yrs BP. Each tsunami event consists of a combination of different lithological facies resulting from different stages of tsunami inundation and settling of the material in the lake basin (pulses and inter-pulses). Tsunami deposits in lakes are shown to be less vulnerable to erosional and bioturbation processes than tsunami layers in marshes. However, few paleoseismic studies have been carried out in low-elevation lakes along the Cascadia Subduction Zone region.

The three last tsunami events known to have inundated areas along the Pacific shores of southern British Columbia and northern U.S.A. are not present at Kakawis Lake, establishing a <4 m above mean sea level vertical limit (at normal high tide) as possible maximum tsunami height for areas located away from fjord heads on Vancouver Island.

The anomalous deposits found in Kakawis Lake may be the oldest geological evidence of inferred tsunamis on Vancouver Island, providing a possible recurrence interval between 200 and 400 years.

INTRODUCTION

Deposits produced by natural catastrophic events of seismic origin have been the focus of flourishing sedimentological research over recent years. Such events release extraordinary energy and often have regional scale repercussions given their great magnitude. Some of the most impressive events are mega-thrust earthquakes (moment magnitude M_w >8) and their triggered tsunamis. Because deposits generated by catastrophic events occur rarely, their characterisation is generally inadequate, leading to poor or equivocal interpretations. Tsunami sediments are also part of this poorly known database: they have not been intensively studied, neither the sedimentological processes nor the depositional patterns produced in different depositional environments.

Tsunamis, also called "marine flood waves", "marine gravity waves", "seismic sea waves" or erroneously "killer waves" (Soloviev and Go, 1974, 1975; Murty, 1977; Myles, 1985) are among the world's most complex physical phenomena. They are not "tidal waves". Over the past 30 years, several mathematical models computing wave generation, propagation, inundation and run-up heights for tsunamis have been developed to illustrate their potential hazard and to improve preventive measures for tsunami prone regions (e.g. Pacific continental margins) (Miyoshi, 1977; Gusiakov, 1999; Ivelskaya, 2000; Mofjeld *et al.*, 2000).

Although tsunamis are infrequent, their effects can be devastating. Most large tsunamis in the Pacific Ocean have been caused by great rapid tectonic disruptions along subduction zones (IOC, 1999; NGDC, 2000). The west coasts of southern Canada and northern U.S.A. are subject to episodic seismic events generated by sudden movements of the Cascadia Subduction Zone (CSZ). As a thrust lineament where both the North America (NA) continental plate and the Juan de Fuca (JdF) oceanic plate collide, CSZ is known for its potential to generate great interplate earthquakes, capable of producing large tsunamis (Ng *et al.*, 1992; Whitmore, 1993; Satake *et al.*, 1996; Priest *et al.*, 1997) (Figure 3.1). Less frequent, but equally characterised by their great hazard potential, distant tsunamis generated in other subduction zones along the Pacific Rim of Fire can also impact the Northwest Coast, as well as tsunamis triggered by non-seismic mechanisms such as great landslides and/or great underwater slumps (Thompson, 1981; Dunbar *et al.*, 1991; UNESCO/IOC, 1999; Clague, 2001).

Tsunamis are considered repetitive processes and to some extent cyclic, if the associated triggering mechanism responds to regular recurrence. Evidence of tsunami occurrences within the geologic record can be geomorphic and/or stratigraphic. Both types of evidence are considered primary geo-indicators (directly related to the tectonic deformation) of a given seismic event (McCalpin, 1996). Sedimentologically, an event of such magnitude is short in time span and rapid in generation (Clifton, 1988; Einsele *et al.*, 1996; Shiki, 1996). However, the contribution of tsunamis to the gradual sedimentation of any given depositional basin can be significant.

In order to understand the significance and recurrence of any catastrophically produced event, it is important to understand the sedimentologic product (Dott, 1983; Clifton, 1988; Einsele *et al.*, 1996). Deposits directly reflect their transport and depositional mechanisms. However, the sedimentary products may only be analysed if their preservation is successful. If any given sedimentary unit caused by an extreme ocean level event (e.g. tsunamis and storm surges) is deposited in open coastal areas, flood plains or shallow seas, it may be vulnerable to constant reworking processes common to those areas. Estuaries, fjords, marshes, wetlands, enclosed bays, lagoons and beaches are areas often affected by tsunamis in the Pacific coast of North America but are not necessarily favourable environments for the preservation of tsunami deposits, unless coseismic subsidence and immediate burial occur (Atwater *et al.*, 1995; Clague, 1997; Clague and Bobrowsky, 1999).

Low-elevation coastal lakes are more favourable preservation environments because (Figure 3.2): a) they may lie within reach of tsunami run-up; b) oceanic currents and other marine erosive/transport processes are not prevalent; c) they are enclosed low-energy environments; d) the rate of burial of anomalous layers depends on the lake's

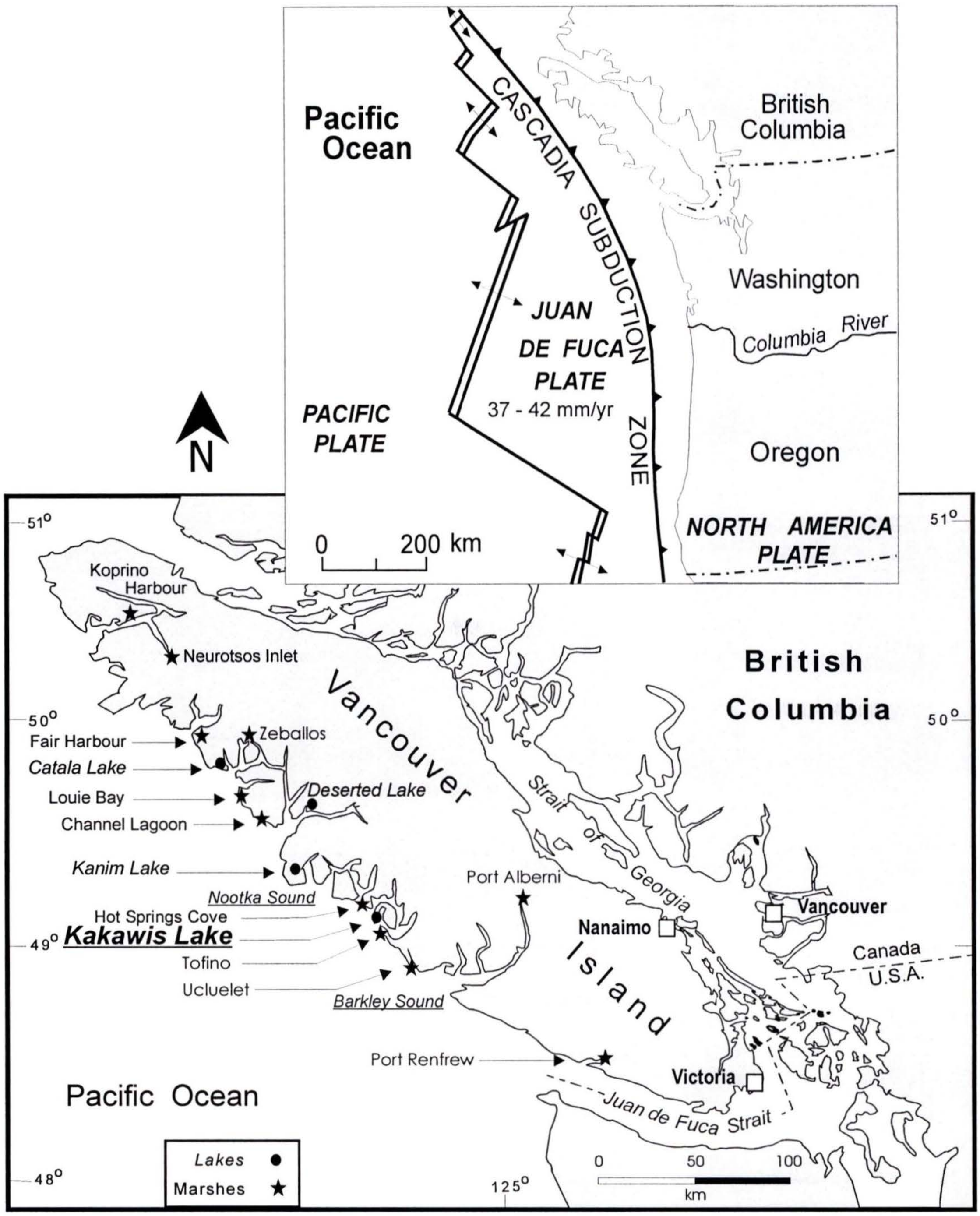


Figure 3.1: Maps showing the tectonic setting of the Pacific coast of southern Canada and northern U.S.A. (inset); and the location of Kakawis Lake and sites with geological evidence of tsunami deposits in marshes and lakes on the west coast of Vancouver Island, British Columbia (Sources for sites other than this research: Clague *et al.*, 2000).

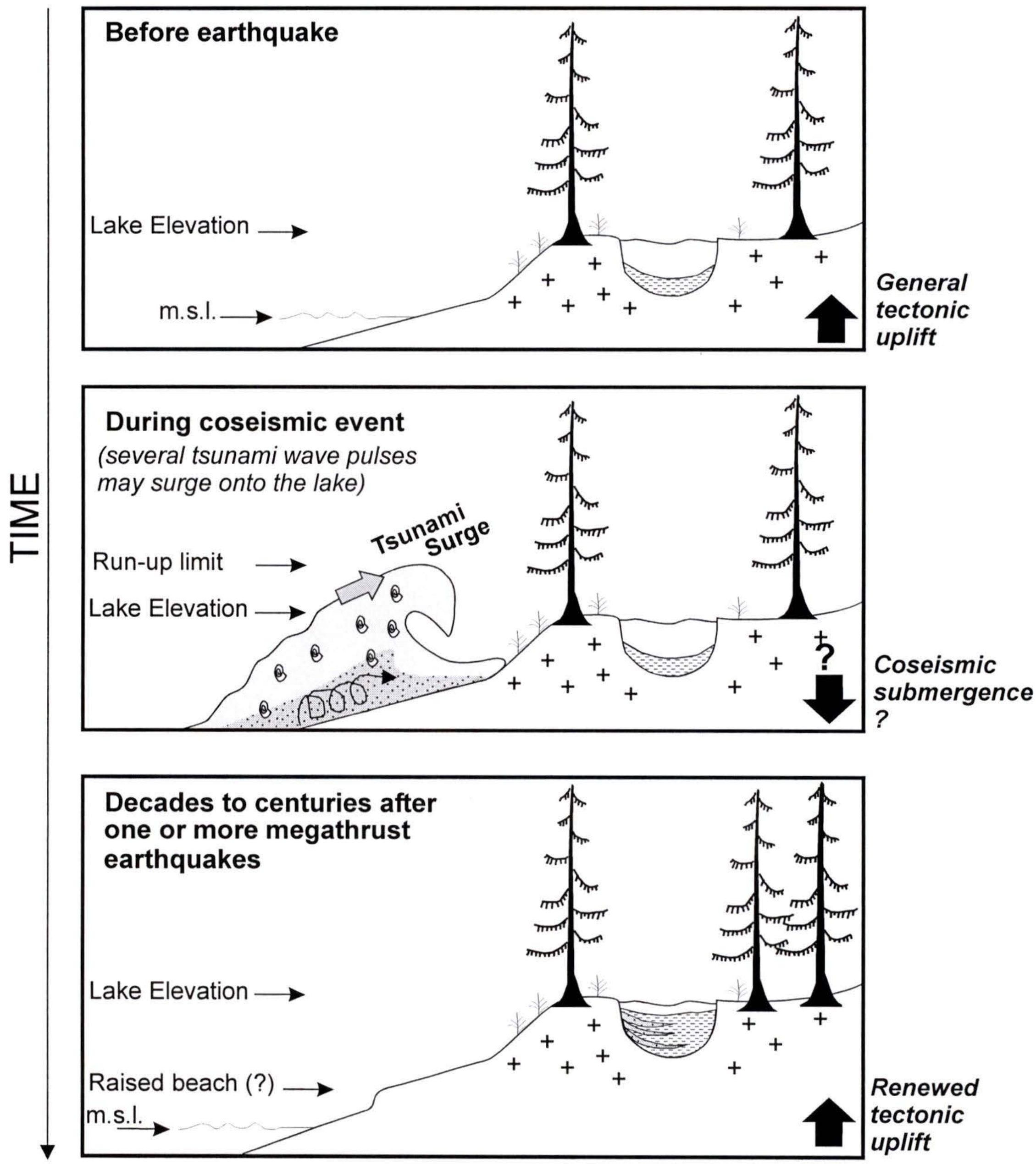


Figure 3.2: Conceptual model for generation of paleotsunamigenic evidence in low-lying coastal lakes on tectonically deforming coasts (i.e. Cascadia Subduction Zone region). The model does not apply for lakes located in flat low-lying coasts, susceptible to washover by extreme ocean water levels. The diagrams are based on paleoseismic evidence found in unconsolidated sedimentary sequences from Kakawis Lake. Given the continuously uplifting coast, tsunami waves may not be able to reach again the once lower-lying coastal lake, setting new maximum tsunami run-up heights for these types of rugged, steep walled and rocky coasts.

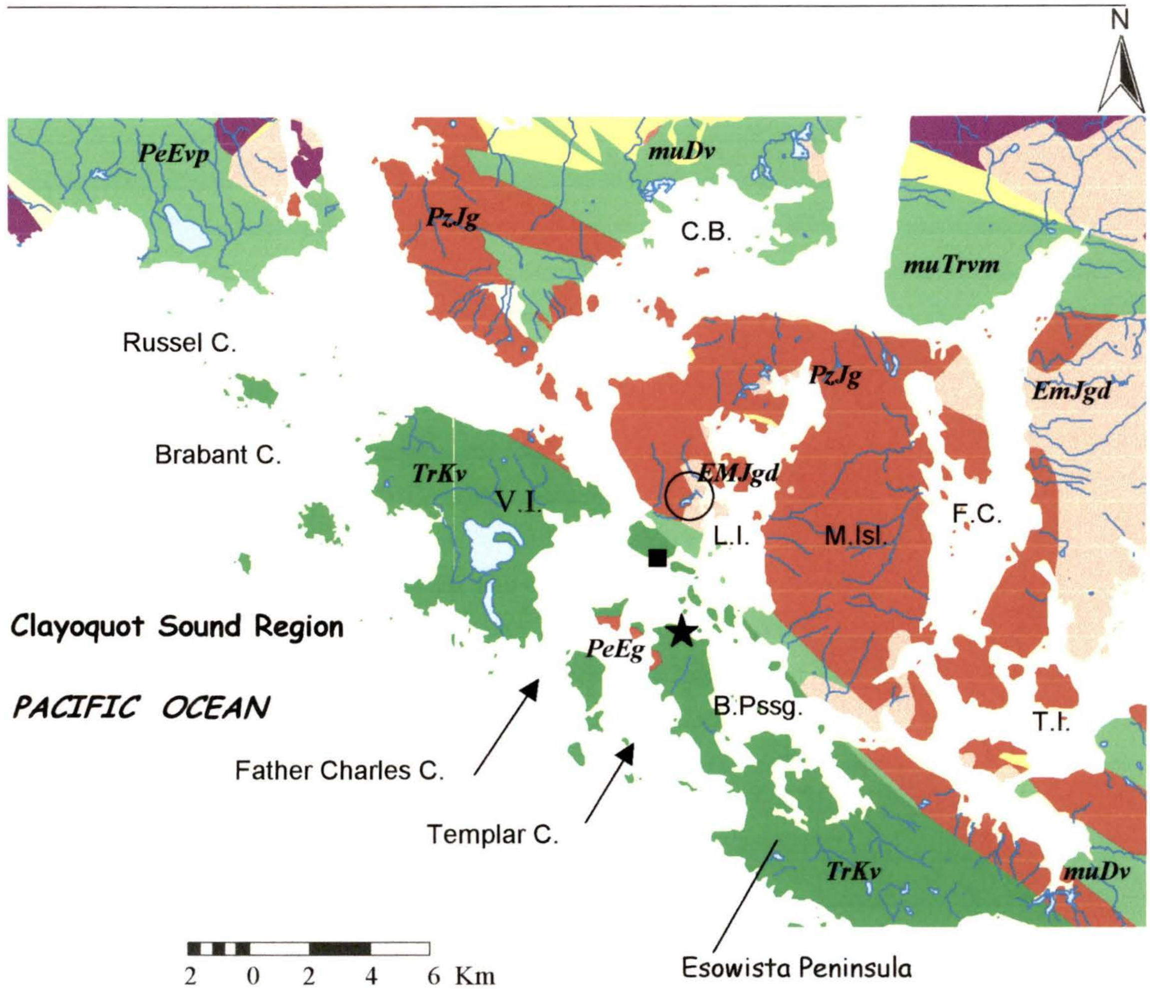
sedimentation rate; e) successful preservation does not necessarily require coseismic subsidence; f) identification of anomalous layers is easier given the contrast to typical lacustrine sediments; and g) coastal lakes are efficient sediment traps.

BACKGROUND RESEARCH

Several North American researchers have identified numerous tsunami deposits along the Pacific coast of Canada and U.S.A., from the northern tip of Vancouver Island, British Columbia (B.C.) to northern California (Bobrowsky and Clague, 1991; Darienzo *et al.*, 1994; Atwater *et al.*, 1995; Clague, 1996; Clague, 1997; Clague *et al.*, 2000). Despite the importance of lacustrine paleotsunami research for estimating maximum run-up heights and inundation limits, few lakes have been studied in the Pacific Northwest. The importance of such research is the sedimentological aspect such as knowing the possible textural differences between anomalous layers deposited in lakes versus those deposited in intertidal salt marshes.

Stratigraphic sequences within some low-elevation coastal lakes (Hutchinson *et al.*, 1997, 2000; Clague *et al.*, 1998, 1999; López and Bobrowsky, 2001) provide convincing evidence of historic and prehistoric tsunamigenic events triggered by mega-thrust earthquakes along CSZ and neighbouring tectonic deformation settings (Figure 3.1). These studies have involved basic textural analyses and detailed microfossil taxonomic identification to produce a precise biostratigraphic, paleoenvironmental and paleotsunami history of the targeted lakes. In some cases, identification of plant macrofossils corroborates biostratigraphical correlation. Radiocarbon dating provides age constraints and is common to all studies.

To enhance the existing evidence regarding indications about the potential recurrence interval of tsunamis, the magnitude of the paleotsunamis that surged this region, and to maintain the continuity of lacustrine tsunami investigations, one coastal lake located on the central west shores of Vancouver Island was targeted for study (Figure 3.3). The aim of this paper is to present new data and discuss the results of analyses completed on six percussion cores recovered from unconsolidated sediment sequences at Kakawis Lake.



Legend:

○ Kakawis Lake location

■ Opitsat Native Community
★ Tofino

C.	Channel	B.Pssg.	Browning Passage
C.B.	Cypress Bay	F.C.	Fortune Channel
L.I.	Lemmens Inlet	M.Isl.	Meares Island
T.I.	Tofino Inlet	V.I.	Vargas Island

Figure 3.3 Geological map of the Clayoquot Sound region showing the location of Kakawis Lake. Principal communities in the area are also shown. Bold letters in italics correspond to the geological formations detailed in the text. Names of principal islands, channels, inlets and bays are shown. (Modified from BCGSB, 2000).

The analyses presented here are exclusively geophysical, sedimentological and biochemical, and represent the results of field work and innovative laboratory studies conducted between the fall of 1998 and the spring of 2001. This research focuses on the sedimentological characteristics of inferred tsunami deposits encountered in organic-rich lacustrine sedimentary sequences. The main goal is to evaluate tsunami deposits by exclusively using the macro-fractions (materials) obtained, as well as introducing new analytical approaches to paleotsunami investigations. The discussion of recurrence and regional correlations between anomalous layers in this study and those found elsewhere along the Northwest Coast are detailed in Chapter 4.

REGIONAL SETTING AND STUDY AREA

The western margin of Vancouver Island is a deeply indented coast with numerous fjords shaping the shore, rugged flanks and impressive steep-sided rocky slopes. A narrow strip of land extending from the mouth of JdF Strait to Brooks Peninsula, along the west side of the island (Figure 3.1), is considered the lowest (<50 m) topographic region on Vancouver Island. The Estevan Coastal Plain is home to extensive openly exposed beaches and broad intertidal flats (Holland, 1976; Clague and Bornhold, 1980), which provide important sources of loose surficial materials. The study site is located within this geomorphological narrow coastal lowland.

One coastal lake protected from direct ocean water action was targeted for research. Kakawis Lake is located 4 m above mean sea level (amsl). The lake has a short (<500 m) but permanently active outlet stream flowing into Lemmens Inlet; fjord waters irrigating Clayoquot Sound, southward of the historically famous Nootka Sound (Figure 3.3).

Kakawis Lake has two water basins (Figure 3.4) surrounded by low (<10 m) topography and a thick coniferous temperate rain forest. Research efforts were focused on the smaller system. This small basin is only three metres deep and is connected to the year-round active outlet stream. In general, Kakawis Lake has calm waters with elevated concentrations of dissolved organic matter and an intense development of aquatic

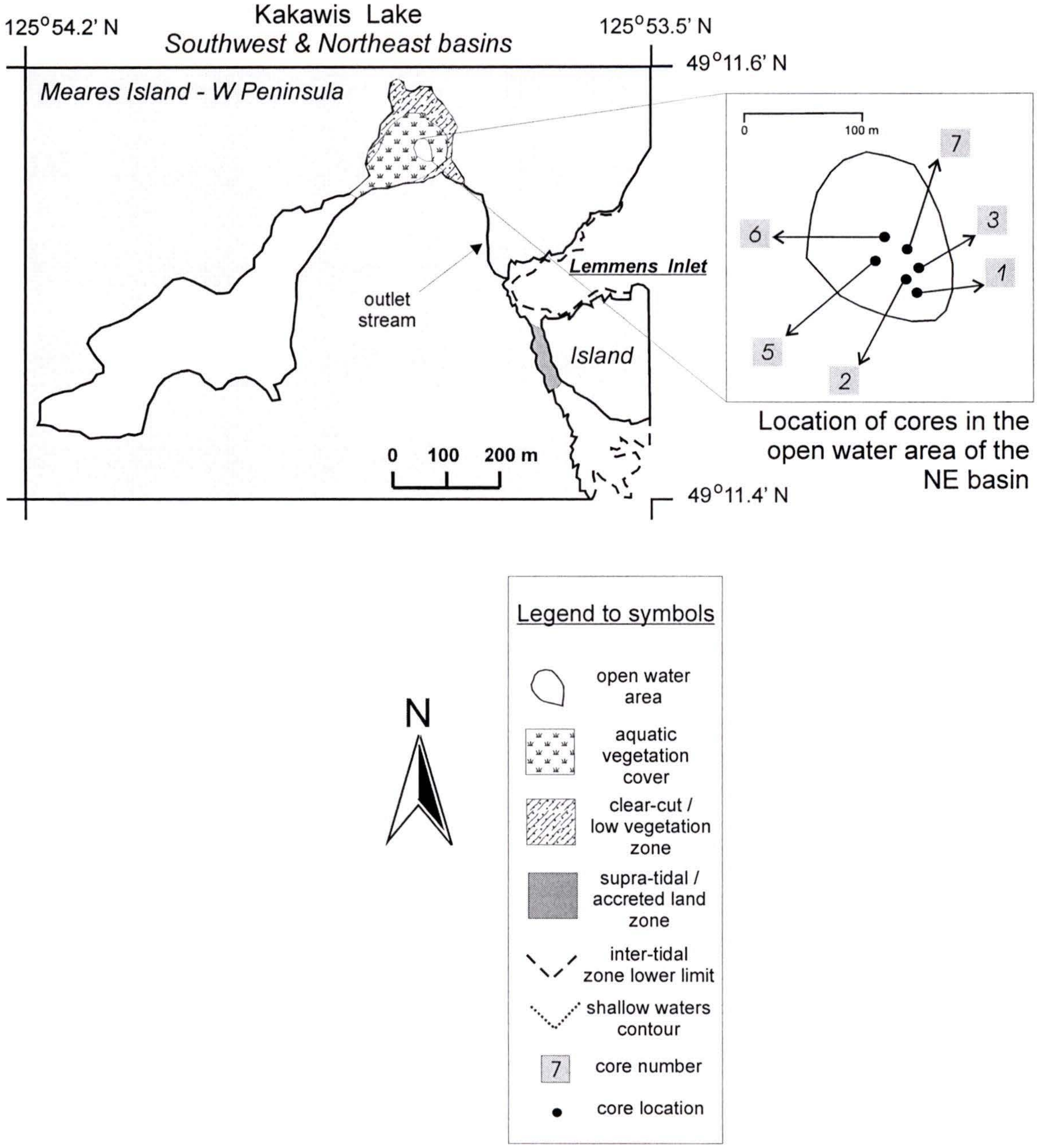


Figure 3.4: Kakawis Lake showing the NE basin, the target of the study. Inset shows the location of the cores (cores 1 to 7).

vegetation. Kakawis Lake can be described as a stratified system with an anoxic bottom, allowing the preservation of organic matter. The geographical position of the mouth of the outlet stream is of particular interest (Figure 3.5). It is the only natural pathway (200 m long) for a run-up of any given extreme wave. However, natural obstacles (island and supra-tidal areas) facing the mouth may diminish the energy of an incoming great wave (c.f. Figure 3.3).

METHODS

Details regarding data acquisition and analytical protocols used in this research are described in Chapter 2. The lakes were cored during the autumn of 1998 and summer 1999. Six percussion cores were recovered from the sub-bottom lacustrine sediments of Kakawis Lake (cores K1, K2, K3, K5, K6 and K7) (Figure 3.4). The sediment cores varied in length from 2.72 to 5.43 m. Ten analytical protocols were applied to all the sedimentary sequences obtained. The protocols varied from non-destructive methods to quantitative analyses of different components including dating methods and identification of the different materials (terrigenous, carbonate and vegetation materials).

Correlations between the sediment cores were possible by relating magnetic susceptibility and electrical resistivity values, relative water content, total organic carbon (TOC), total inorganic carbon (TIC), C/N ratios, relative porosity and density, compositional differences, grain-size statistics and textural variations, and identification of vegetation, carbonate and clastic macro-particles (i.e. coarse sand, pebbles and cobbles). The initial visual description and schematisation of the cores was improved with detailed x-radiograph imagery and photographic analyses.

The age of the tsunami deposits was obtained through radiocarbon-dating of needles, cone bracts, twigs, bark and wood fragments. Twenty-three ^{14}C ages were obtained from cores K1 and K5. Table 3.1 shows the radiocarbon ages. The ages are based on the Libby meanlife for ^{14}C of 8033 years and are referenced to both AD 1950 and AD 2000 (c.f. Stuiver and Pearson, 1993) as well as the uncalibrated age. Calibration into calendar years was computed using the data set INTCAL 98 and CALIB 4.3 program (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). Caution was taken when

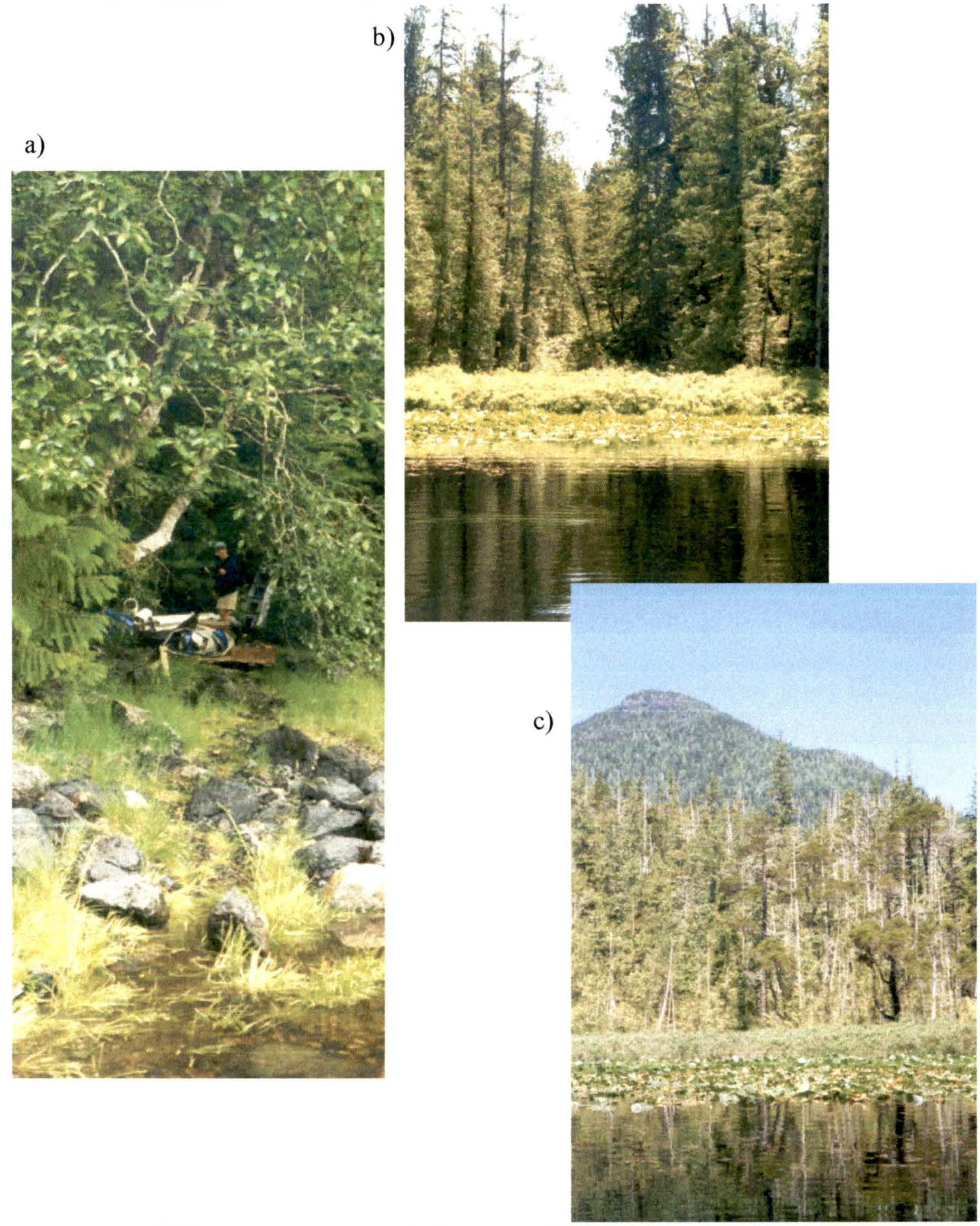


Figure 3.5: Photographs of Kakawis Lake showing the outlet stream. (a) Entrance to lake, looking upstream. Mouth of the outlet stream located in the western corner of a small bay on Lemmens Inlet waters. Note the low flow of water and rocky shore. (b) The outlet stream seen from the lake (towards the SE). A thick rain forest cover surrounds the lake. (c) A view to the N from Kakawis Lake, showing the closest topographic high. The lake was cored in the open water area from which the photographs were taken.

determining the age of inferred tsunamigenic deposits because radiocarbon ages on detrital wood are maxima for the time of deposition of the enclosing sediment.

Crude sedimentation rates were also obtained from the ^{14}C dates and constrained by ^{137}Cs analyses. Moreover, ^{137}Cs was also used to corroborate the existence of a possible tsunami layer deposited by the AD 1964 Alaska tsunami. If an anomalous tsunami layer was deposited at that time, relatively high concentrations of ^{137}Cs are expected in the bounding finer organic-rich sediment which limits mobility of the radionuclide (c.f. Chapter 2). ^{137}Cs was produced by atmospheric nuclear testing between 1952 and 1972, with peak productions in 1963-1964 (Woodward, 1964; Wan *et al.*, 1987; Naidu *et al.*, 1999).

To establish a sedimentologic comparison, a tsunami sand sample from Port Alberni marsh was also taken and analysed using the procedures applied to samples with similar characteristics from Kakawis Lake. The marsh tsunami sample is related to the AD 1700 tsunami triggered by the last great Cascadia earthquake (c.f. Clague, 1996).

COASTAL GEOLOGY AND GEOMORPHOLOGY

The geological framework of western B.C. is a complex collage of terranes accreted to the North American craton during the Mesozoic and Cenozoic (Silver and Smith, 1983; Chamberlain and Lambert, 1985; Engebretson *et al.*, 1992). The Insular Mountains of Vancouver Island (Holland, 1976; Clague and Bornhold, 1980) consist of a series of deformed Paleozoic and Mesozoic volcanic and sedimentary rocks with some Tertiary plutonic intrusions. Pre-Jurassic metamorphic complexes and Jurassic intrusions form most of the central-west coastal lands (Yorath and Nasmith, 1995).

An understanding of the type of bedrock and the composition of the surficial sediments neighbouring the study sites provide a basis for the sediment-source analyses undertaken on the terrigenous macro-particles found within the lacustrine sequences. Figure 3.3 shows the different geologic rock types surrounding the study sites.

The vast intertidal areas of Lemmens Inlet are carpeted with colluvial deposits, derived from Quaternary deposits overlying the bedrock geology of Clayoquot Sound region. This material consists of blocks and rubble with sand and silt derived from the crystalline bedrock, medium grade metamorphic and cemented sandstone in the surrounding area (Fulton, 1995). The residual materials have also been deposited as blankets of debris via downslope movement and *in situ* disintegration of bedrock over Meares Island, Tofino and the main insular land north and east of Meares Island (Figure 3.3).

Another common type of Quaternary material is the glaciomarine and marine deposits formed by meltwater and floating ice in marine waters during the last deglaciation and subsequent regression sequence (Fulton, 1995). Vargas Island and the Esowista Peninsula are covered with coarse grained glaciomarine and marine deposits, consisting of sand and gravel deposited as sand sheets and extensive beach veneers.

The NE basin of Kakawis Lake is located on an intrusive granodioritic body pertaining to the Island Plutonic Suite (*EMJgd*) (c.f. Figure 3.3). One of the principal rock types likely to appear in the terrigenous fraction of a tsunami deposit at Kakawis Lake is the granodioritic rock, given its proximity to the lake. Other potential bedrock sources are located in outcrops around the passages, channels and inlets surrounding Kakawis Lake. These include: a) rocks of the Westcoast Crystalline Complex (*PzJg*) (granitic, metamorphic and metasediments); b) the granitic rocks forming the Clayoquot Plutonic Suite (*PeEg*); c) the Pacific Rim Complex (*TrKv*) rocks varying from volcanic flows to dioritic intrusions; and d) volcanic rocks (andesite to rhyolite tuff, tuff breccia, minor basalt dykes) pertaining to the Flores Volcanics Formation (*PeEvp*).

ANALYSES OF SEDIMENTARY SEQUENCES – DESCRIPTION OF RESULTS

Based on lithological differences, four main units from older to younger (Units A, B, C and D) were identified within the sedimentary sequences of Kakawis Lake. A general description of the units follows.

The possibility of finding inferred tsunami deposits in a lacustrine system with a natural barrier now 4 m amsl was realized when five (possibly six) anomalously coarse-grained layers were found embedded within organic-rich muds from Kakawis Lake. Unit C encloses the inferred tsunamigenic deposits, which are described below.

DESCRIPTION OF UNITS AND LITHOFACIES

The sub-bottom sediments of Kakawis Lake are classified into 11 facies. The results obtained from the analytical protocols support such a classification and are the basis for the correlation. For convenience, the facies are grouped into four major units, not necessarily present in each of the cores. Unit A hosts the lowermost facies assemblage and is related to the last deglaciation and subsequent sea level fall in the region. Unit B hosts the bottom organic-rich sediments linked with lacustrine facies. Unit C groups the sediments hosting the anomalously coarse layers, inferred to be the product of tsunami deposition. Unit D corresponds to the organic-rich sediments related to present day lacustrine deposition that span until today.

Unit A – Post-Glacial Maximum Sediments

Unit A consists of two facies (Figure 3.6), distinctly different from the rest of the overlying sediments. At Kakawis Lake, it was only observed in core K5 (the longest core obtained from this lake), showing a thickness of 81 cm from the bottom of the core upwards. The presence of this unit and its thickness may give insights to the elevation of the lake above mean sea level, at the time its deposition (discussed in Chapter 4).

Facies 1: Glaciomarine with abundant marine shells

Grey (Munsell chart colour 2.5 Y 7/1) massive marine sandy silty clay with sporadic pebbles and abundant marine shells is found at the bottom 37 cm of core K5. The bivalve species *Yoldia sp.* is typical of this facies, as well as of the entire unit. A radiocarbon date of 13,810 ± 90 yrs BP (Table 3.1), documents this pre-Holocene glaciomarine stage of the basin. Facies 2, also glaciomarine, overlies the shelly clay.

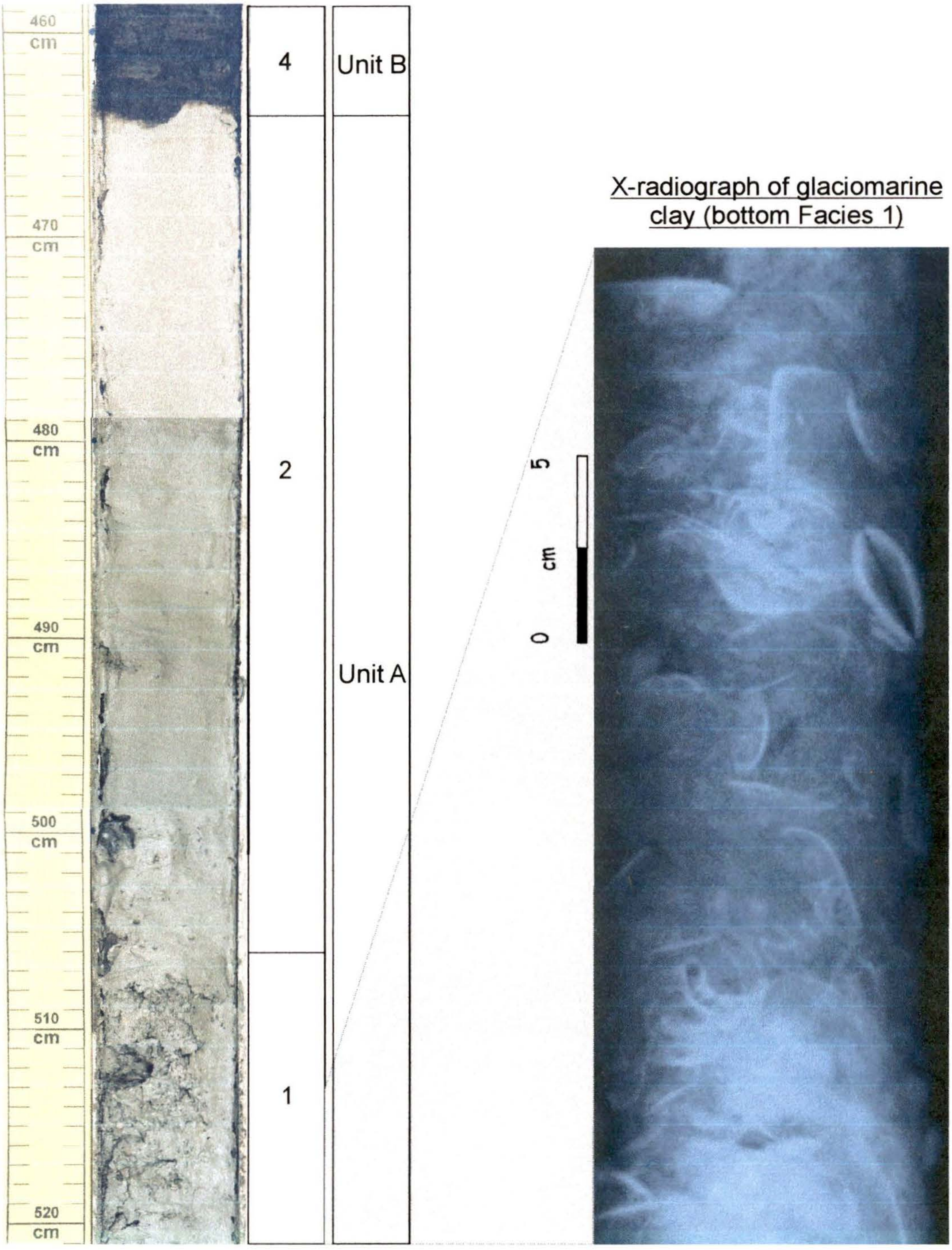


Figure 3.6 Photograph of part of Unit A (glaciomarine clays) in contact with Facies 4 of Unit B (sharp wavy contact) in core K5 from Kakawis Lake. Facies numbers are shown. The inset image is an example of X-radiographs of the glaciomarine bottom facies, showing (3D) the great quantity of marine bivalves (e.g. *Yoldia sp.*) present. The X-ray image represents the lowermost 20cm of core K5 (543cm-long core), not shown in the photograph (the brighter shadow at the bottom of the X-ray reflects the metallic influence of the core catcher).

Table 3.1: Radiocarbon ages on plant and shell remains collected from sub-bottom sediments of Kakawis Lake showing depths below core top (Cores K5 and K1) (BP calculations after Stuiver & Pearson, 1993).

Core No.	Depth (cm)	Dated Material	Radiocarbon Age (14C yr BP)	Cal. Age (cal BC)	Calibrated Age Range 68.3% c.i. (cal yr BC)		Calibrated Age Range cal yr before AD 1950 cal BP = 1949+cal BC		Calibrated Age Range cal yr before AD 2000 cal BP = 1999+cal BC		Tsunami Event No.	Location of Detrital Material above / below / within tsunami layer	Laboratory Name & Lab. No.
					min	max	min	max	min	max			
5	147	twigs	2510+- 50	605	535	720	2484	2669	2534	2719	TE6	top contact	Isotrace TO-7633
5	169-171	twigs	2340 +- 50	395	385	409	2334	2358	2384	2408	TE5	above top contact	Isotrace TO-7634
5	169-171	needles	2470 +- 110	540	400	790	2349	2739	2399	2789	TE5	above top contact	Isotrace TO-7635
5	203-205	cone	3220 +- 50	1465	1430	1520	3379	3469	3429	3519	TE5	below bottom contact	Isotrace TO-7636
5	224-225	bark frags.	3540 +- 50	1835	1805	1840	3754	3789	3804	3839	TE4	top contact	Isotrace TO-7637
5	229-230	twig	3410 +- 60	1715	1680	1750	3629	3699	3679	3749	TE4	bottom contact	Isotrace TO-7638
5	320	twig	3450 +- 50	1740	1689	1775	3638	3724	3688	3774	TE1	within (3rd layer)	Isotrace TO-7639
5	331-332	twig	3580 +- 50	1920	1880	1975	3829	3924	3879	3974	TE1	within (2nd layer)	Isotrace TO-7640
5	335	twig	3300 +- 50	1565	1515	1635	3464	3584	3514	3634	TE1	within (1st layer)	Isotrace TO-7641
5	335	twig	4120 +- 120	2645	2550	2880	4499	4829	4549	4879	TE1	within (1st layer)	Isotrace TO-8186
5	340	twig	7160 +- 60	6015	5985	6030	7934	7979	7984	8029	TE1	bottom contact	Isotrace TO-7642
5	341-342	wood frag.	7430 +- 80	6245	6220	6395	8169	8344	8219	8394		pre- TE1	Isotrace TO-8187
5	351	twig	2880 +- 60	1030	970	1125	2919	3074	2969	3124		(gyttja)	Isotrace TO-7643
5	361	twig	7560 +- 120	6425	6330	6470	8279	8419	8329	8469		(gyttja)	Isotrace TO-8188
5	458-460	wood frag.	11 620 +- 80	11 780	11665	11865	13614	13814	13664	13864		(above glaciomarine)	Isotrace TO-7644
5	500	shell frag.	13 260 +- 80	12 375	12205	12445	14154	14394	14204	14444		(glaciomarine clay)	Isotrace TO-7645
5	530	shell frag.	13 810 +- 90	13 600	13380	13785	15329	15734	15379	15784		(glaciomarine clay)	Isotrace TO-7646
1	193	cone	7870 +- 70	6665	6640	6820	8589	8769	8639	8819	TE1	within	Isotrace TO-7647
1	193	twig	6990 +- 90	5860	5735	5920	7684	7869	7734	7919	TE1	within	Isotrace TO-7648
1	193	wood frag.	9690 +-70	9210	9135	9230	11084	11179	11134	11229	TE1	within	Isotrace TO-7722

Facies 2: Glaciomarine with scattered marine shells

Light grey (2.5 Y 7/1) to grey (2.5 Y 6/1), massive silty marine clay with sporadic concentrations of coarse sand and fine pebbles defines Facies 2. It has a thickness of 44 cm in core K5. In contrast with Facies 1, Facies 2 has much less carbonate material (~1.4% out of a ~30 g bulk sample) and shows minor oxidation mottles. Facies 2 has 67.78 to 75.88% clay, 23.63 to 28.75% silt, 2.77 to 0.33% sand, and 0.12 to 0.60% gravel. Surface analyses on the gravel clasts imply a glacial provenance. Clasts are striated and exhibit one to three flattened surfaces (facets), typical of glacial transport. The rock type is mainly granodioritic with some metamorphic clasts. A pre-Holocene radiocarbon date of 13,260 ± 80 yrs BP (Table 3.1) was obtained for this facies.

Facies 3: Transitional facies

It is hypothesised that a transitional facies, between the glaciomarine clays and the lacustrine sediments must have existed, but the exact period of time is unknown. According to cores recovered from other nearby studied sites, this facies may consist mainly of porous massive glaciomarine clay interbedded with organic mud. Unfortunately, this transitional facies does not exist in Kakawis Lake sequences where Facies 2 is directly overlain by Facies 5.

<u>Units B and D – Organic-rich sediments</u>

Very dark brown (7.5 YR 2.5/2) to dark greyish brown (10 YR 3/2) massive to discontinuously horizontal semi-laminated organic mud form most of Units B and D. This organic-rich mud may vary to black (10 YR 2/1) in some sections. It has sporadic macro-plant detritus (<1 cm) and no evidence of bioturbation. Unit B overlies Facies 2 at Kakawis Lake along a sharply undulated contact, only evident in core K5 (Figure 3.6) and underlies Unit C. Unit D is the uppermost lithological unit which corresponds to organic-rich sediments post-dating Unit C, related to modern gyttja deposition.

Facies 4: Gyttja

Facies 4 is the massive organic-rich gyttja that defines the modern fresh water gyttja forming the uppermost sections of the sedimentary sequences at Kakawis Lake (Figure 3.7). It overlies Unit C, but is not believed to exist below Unit C. At Kakawis Lake, Facies 4 varies in thickness from 39 to 134.5 cm, depending on core length.

Facies 5: Gyttja with small broken shells

Facies 5 occurs in the bottom layer of cores K1, K2, K6 and K7; and is absent in core K3. In core K5, Facies 5 is thought to overlie Unit A and underlie Unit C. A radiocarbon age of 11,620 ± 80 yrs BP (Table 3.1) marks the beginning of Facies 5.

Facies 5 would be identical to Facies 4 but for the presence of a few randomly scattered, small, broken and badly preserved marine shell fragments. The shell fragments do not exceed 3% of the overall organic composition of the mud and are all smaller than 0.5 cm. Facies 5 cannot be differentiated from Facies 4 visually, which is why thickness was difficult to define. Maximum thickness for this facies is about 60 cm. No embedded lenses were found that could help explain the existence of the shells. Electrical resistivity curves did not show higher values for this possible brackish environment. Resistivity values ranged between 40 and 60 mV similar to the "non-shelly" Facies 4. However, magnetic susceptibility values for Facies 5 were higher than for the Facies 4 gyttja that overlies Unit B. The values averaged between 400 and 800 $x10^6$ SI/vol, suggesting the presence of particles coarser than fine organic matter.

Four radiocarbon ages help define the top of the Unit B, before the base of the overlying inferred tsunami deposits from Unit C. Only three of the four ages are considered reliable (Table 3.1). Facies 5 may range between 7560 ± 120 and 7160 ± 60 yrs BP.

Facies 6: Gyttja with in situ fossil plants

Facies 6, found in core K1 is interpreted to represent a marginal threshold of Kakawis Lake (Figure 3.7). It resembles a marsh environment due to the overwhelming quantity of *in situ* marsh-type herbaceous remnants (<1 cm long). The lower contact is marked by the presence of an 8 cm-thick piece of wood crossing the core, directly above

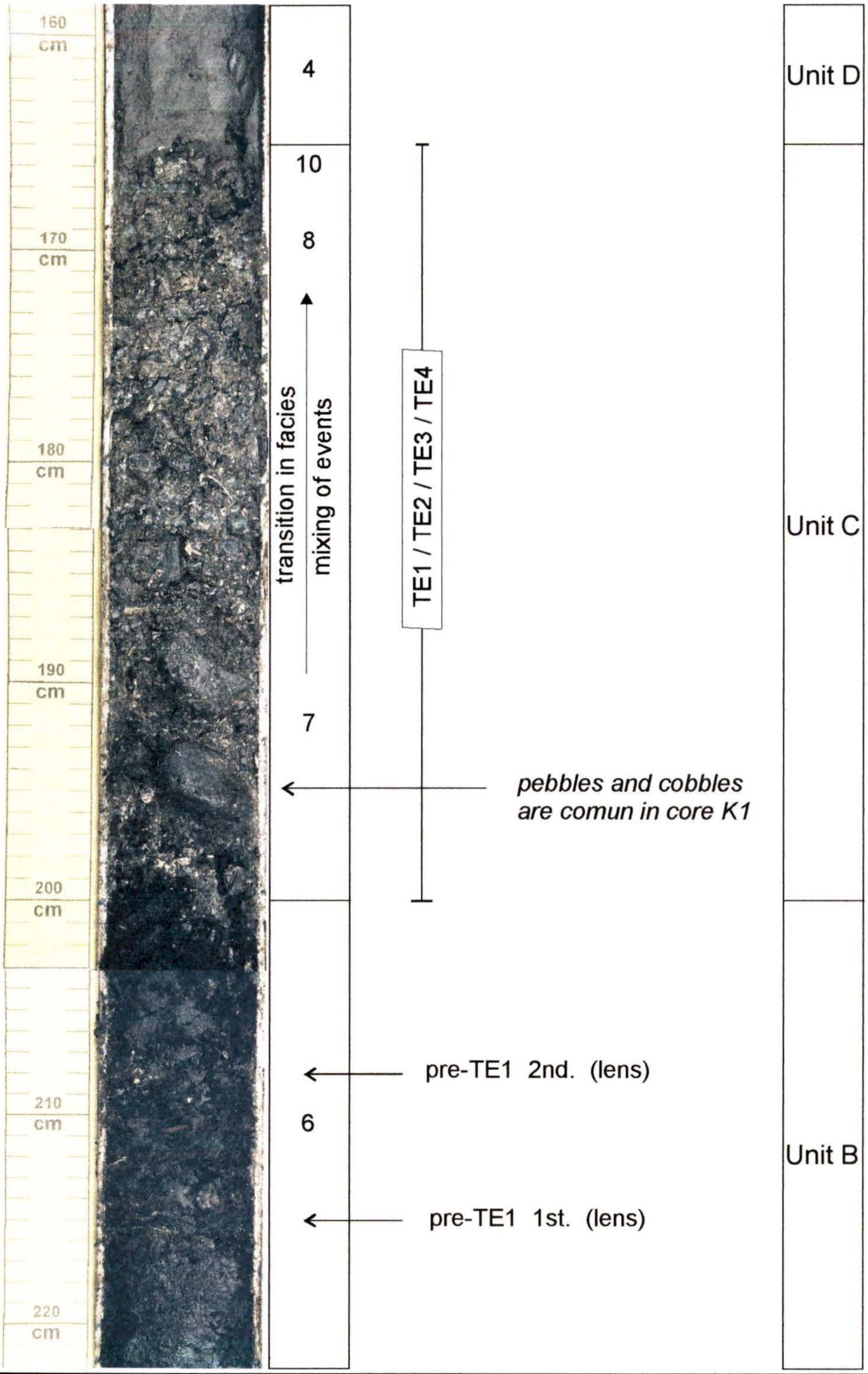


Figure 3.7 Photographs of core K1 showing Facies 4, 6, 7, 8 and 10 as well as the pre-tsunami layers (pre-TE1 1st. and 2nd.)from Kakawis Lake. Facies 6 is present only in this core. K1 had the thickest tsunami deposits of all the cores, and are a combination of several successive event inundations. It is believed that Tsunami Events TE1, TE2, TE3 and TE4 are inter-mixed forming this thick deposit.

Facies 5. Facies 6 is a massive 33 cm thick, very dark brown (7.5 YR 2.5/2) organic-rich mud (78% of ~12 g bulk sample) enriched in macro-plant detritus (70% of overall composition) and marine shell fragments (25%) with minor sand-size clasts (<5% of the overall composition). No age determination was possible for emplacement of this facies. This facies may also exist in core K3, directly overlying Unit C.

Two small (<1 cm) sandy pebbly shelly lenses were found towards the top of Facies 6 in core K1 and embedded within Facies 5 in core K2. Compositionally, 40% is plant detritus, 25% are marine shells, 20% are fine pebbles, and 5-15% is sand-size clastic particles.

Unit C – The Anomalous Deposits

Unit C groups the anomalous sequences of strata enriched in a diversity of allochthonous materials enclosed by organic-rich sediments from Unit B below and Unit D above from Kakawis Lake. A sharp erosional unconformity marks the beginning of the unit. Unit C may have been emplaced while the lake was emerging by isostatic rebound of the western margin of Vancouver Island during the late to mid Holocene. The time of emplacement of the inferred tsunami deposits is constrained by radiocarbon dates and is discussed in a later section of this chapter as well as in Chapter 4.

Four facies have been attributed to tsunami deposition based on a variety of characteristics. Although the anomalous tsunami layers are relatively easy to recognise along the lacustrine sequences, their characterisation and identification was complex given their variability. Each layer has been classified as a distinct facies. Each facies is thought to be associated with different settling velocities and pulses of wave inundation during a tsunami event. The facies described below characterise the various conceptual stages of deposition of allochthonous materials during tsunami events at Kakawis Lake.

Facies 7: Massive gravel

Facies 7 consists of a very poorly to poorly-sorted, very dark greyish brown (2.5 Y 3/2) sandy gravel that varies laterally to cobbly sand, enriched in shell fragments (Figures 3.7 and 3.8). It has a clear erosive basal contact and lacks internal structure.

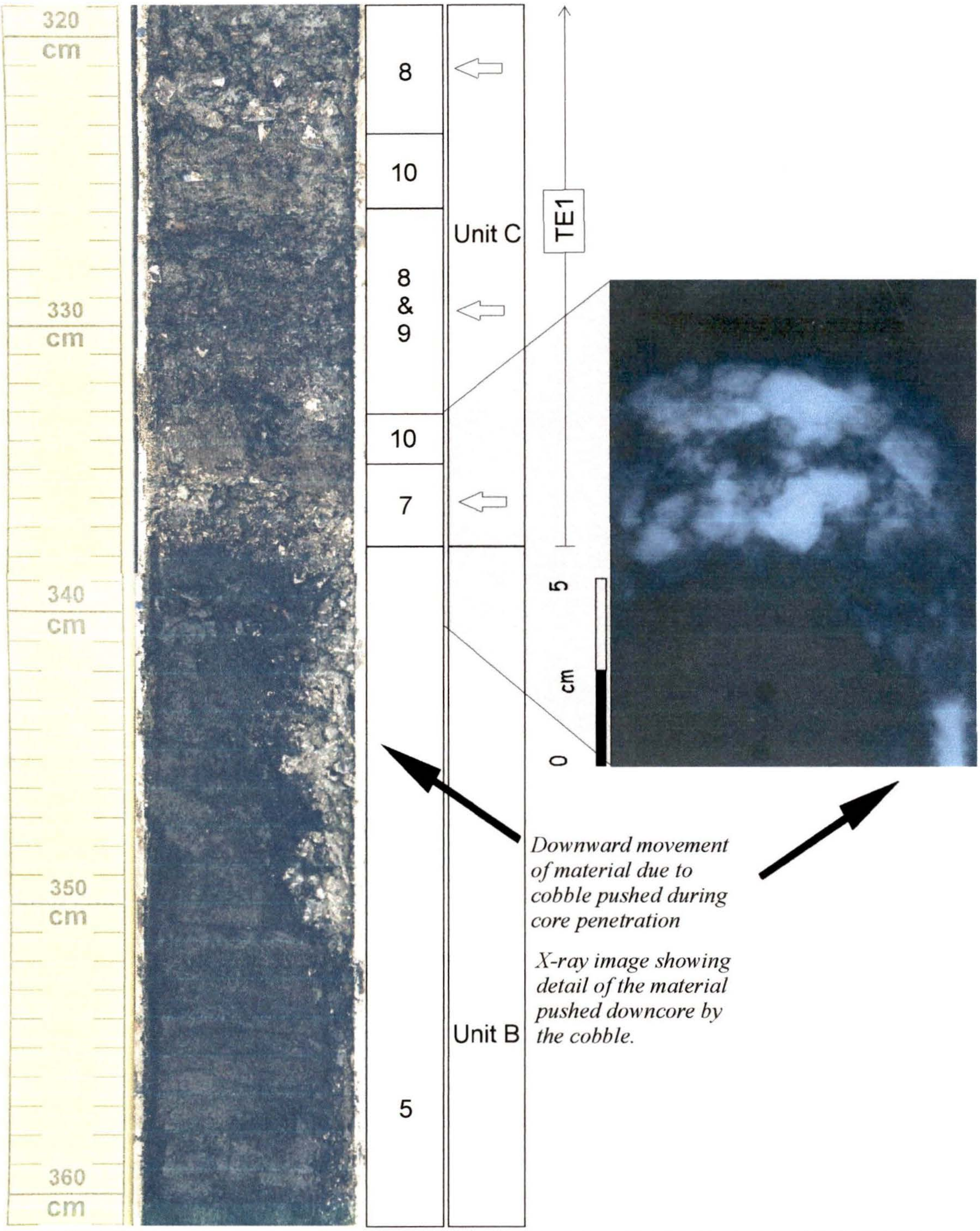


Figure 3.8 Photograph of lowermost tsunamigenic facies of Unit C in core K5 from Kakawis Lake, from Tsunami Event 1 (TE1). Inferred pulses of tsunami inundation are marked by white arrows. The inset image is an example of the X-radiographs taken on this core, detailing Facies 7. The light grey shadows are terrigenous and carbonate particles.

The massive character of Facies 7 is characterised as chaotic, as seen in the x-radiograph imagery.

This tsunami layer is present in all cores, but is clearly distinct in cores from the central area of the lake (K5, K6 and K7) where it has an average thickness of 6.45 cm. Rip-up clasts are commonly associated with the bottom section of this facies or are embedded in the underlying material, suggesting an energetic emplacement.

Facies 7 has a strong polymodality and it is the facies showing the largest terrigenous particle sizes. The number of modal peaks varies between 4 and 8. The coarsest clastic particle has a diameter of -6.5 Φ and mean sizes ranges from -6 to 0 Φ. In general, 30-50% of its composition is marine shells, 5-10% plant detritus, 35-40% sand-size terrigenous particles, and 18-25% coarse clastic material (<-1 Φ particles). In the terrigenous fraction alone, 40-80% is sand, whereas 10-50% is gravel; mud is minimal. This facies showed the highest geophysical values of all the tsunamigenic facies. Electrical resistivity values ranged between 40 and 138 mV and magnetic susceptibility values ranged between 240 and 760 $x10^6$ SI/vol, suggesting the presence of very coarse clastic particles in these layers. C/N ratio analyses showed high values between 21 and 35.

Plant fragments up to 5 cm long are common in this facies. Twigs, small barks, needles, broken cone brats, seeds, remnants of leaves and others characterise the vegetation component of all tsunami facies. This material likely comprises arboreal elements of the coniferous forest common to Vancouver Island.

An interesting feature characteristic to Facies 7 is the abundance and variety of carbonate material. Although most of the shells are fragments of different species, it is common to find fragments up to 4 cm long in pristine condition (Figure 3.9). Such large and well preserved fragments may suggest that transport was minimal. Identification of the shells confirmed their marine provenance. Marine shell species are detailed in Table 3.2 according to core site, depth of occurrence, corresponding facies and associated tsunami event.

Special focus was given to *Balanus sp.* specimens due to their abundance, distinct structure and association with the clastic material. Moreover, this species of crustacean,

Figure 3.9 Examples of terrigenous, vegetation and carbonate material found in different tsunami facies of cores recovered from Kakawis Lake. Coarser clasts often showed fossil marks of barnacles (typical intertidal crustacean species). The particles shown here are part of the macro- (>2mm) elemental fraction forming any given tsunami event at this particular lake.

Table 3.2: Different species of marine shells according to the core site and depth at which they were found. Species here enounced correspond to marine shells found in sedimentary sequences from Kakawis Lake.

Phylum / Class	Subclass /Order /Suborder	Family	Species	Relative to shells found in sediment cores: Core #	Depth range in core (m) min	max	Facies #	Tsunami Event #	Comments on shell fossils
Mollusca / Bivalvia	Protobranchia / Mtilioida	Mytilidae	*Mytilus sp.*	6	240	244	8	TE4	v.little, frags, small
				6	259	263	9	TE3	little, frags, small
				6	313	316	8	TE2	little, frags, small
				7	80	84	10	TE6?	v.little, broken, v.small
				7	202	206	9/10	TE3	little, frags, small
				7	280	284	7	TE1	lot, frags, big
			Mytilus trossulus	1	206	210	7	TE1	little, broken, small
				2	193	200	9	TE4	v.little, frags, v.small
				6	339	342	8	TE1	lot, frags, big
				7	250	254	8	TE2	lot, frags, big
	Heterodonta / Veneroida	Veneridae	*Venus sp.*	1	206	210	7	TE1	little, broken, small
			Protothaca staminea	2	193	200	9	TE4	v.little, frags, v.small
				2	253	259	7	TE1	lot, frags, big
				6	313	316	8	TE2	little, frags, small
				6	354	357	7	TE1	little, broken, small
				7	80	84	10	TE10	v.little, broken, v.small
				7	280	284	7	TE1	lot, frags, big
		Tellinidae	*Macoma sp.*	7	280	284	7	TE1	lot, frags, big
		Cardiidae	*Clinocardium sp.*	7	280	284	7	TE1	lot, frags, big
		Lucinidae	*Parvalucina tenuisculpta*	6	240	244	8	TE4	v.little, frags, v.small
				6	313	316	8	TE2	little, frags, small
	Pteriomorphia / Ostreoida / Pectinina	Anomiidae	*Prododesmus machrochisma*	2	193	200	9	TE4	v.little, frags, v.small
		Pectinidae	*Chlamys Rubida*	2	193	200	9	TE4	v.little, frags, v.small

Phylum / Class	Subclass /Order /Suborder	Family	Species	Core #	Depth range in core (m) min	max	Facies #	Tsunami Event #	Comments on shell fossils
Mollusca / Gastropoda	Protobranchia/ Mesogastropoda/Taeniogrossa	Trichotropididae	*Trichotropis cancellata*	2	193	200	9	TE4	v.little, frags, v.small
		not recognizable	*(gastropods)*	6	354	357	7	TE1	little, broken, small
Arthropoda / Crustacea	Cirripedia / Thoracica / Balanomorpha		*Balanus sp.*	1	206	210	7	TE1	little, broken, small
				2	193	200	9	TE4	v.little, frags, v.small
				6	259	263	9	TE3	little, frags, small
				6	313	316	8	TE2	little, frags, small
				6	339	342	8	TE1	lot, frags, big
				6	382	386	5	gyttja	little, broken, small
				7	250	254	8	TE2	lot, frags, big
				7	280	284	7	TE1	lot, frags, big
Mollusca / Bivalvia	Protobranchia / Nuculoida	Sareptidae	*Yoldia sp.*	5	510	515	1,2	glaciom.	intact shells

v.: very
little: little quantity of material
broken: shell material is highly fractured, broken and destroyed
small: material is small in size (generally < 5 mm)

lot: good & high quantity of material
frags: entire shells or recognizable fragments of shells
big: material is big in size

glaciom.: glaciomarine clays

common to the Pacific Northwest Coast, is exclusive to marine intertidal zones, lives attached to hard bottoms and has rocky shores for habitats. Numerous fossil-ring marks and some calcareous wall plates that compose the barnacle's rigid exoskeleton were found on clast surfaces (Figure 3.9). All were firmly attached to -6.5 to -1 Φ clasts and were more common on pebbles and cobbles than finer material. The presence of acorn barnacles on pebbles and cobbles implies that the clasts were originally related to a marine intertidal environment where the existence of the crustacean species was possible.

Facies 8: Massive sand

Facies 8 varies laterally from areas around the outlet stream to the centre of Kakawis Lake, from poorly to well-sorted gravelly sand. This variation can be associated with different settling velocities and erosive processes that depend on the proximity of the outlet stream. The closer the facies is to the outlet the more susceptible it is to erosion and reworking processes; as well textural sorting decreases. Facies 8 has a sharp basal contact, less irregular than the one shown by Facies 7 (Figure 3.10). Similar to Facies 7, it has a chaotic internal structure. Its colour is generally dark grey (2.5 Y 4/1).

This type of layer is clearly distinguishable in cores from the central area of the lake (K5, K6 and K7). It normally ranges in thickness from 1 to ~10 cm, but can reach up to 20 cm depending on site. Two rip-up clasts were found in cores K2 and K6, directly below basal contacts of Facies 8.

Facies 8 is texturally polymodal, showing 1 to 4 modal peaks. The largest particle associated with this facies has a diameter of -2.5 Φ; however, these isolated pebbles are not common to all tsunami events. Mean sizes generally fall between -1 and 4 Φ. The composition of this facies consists generally of 10-55% marine shells, 28-50% plant detritus, 2-34% sand-size terrigenous particles, and 0-2% coarse clastic material (<-1 Φ particles). However, when analysing the terrigenous fraction separately from any biologic material, Facies 8 is characterised by 2-54% silt, 34-100% sand and 0-36% gravel.

This facies had the second highest geophysical values among tsunamigenic facies. Electrical resistivity values ranged between 35 and 102 mV and magnetic susceptibility

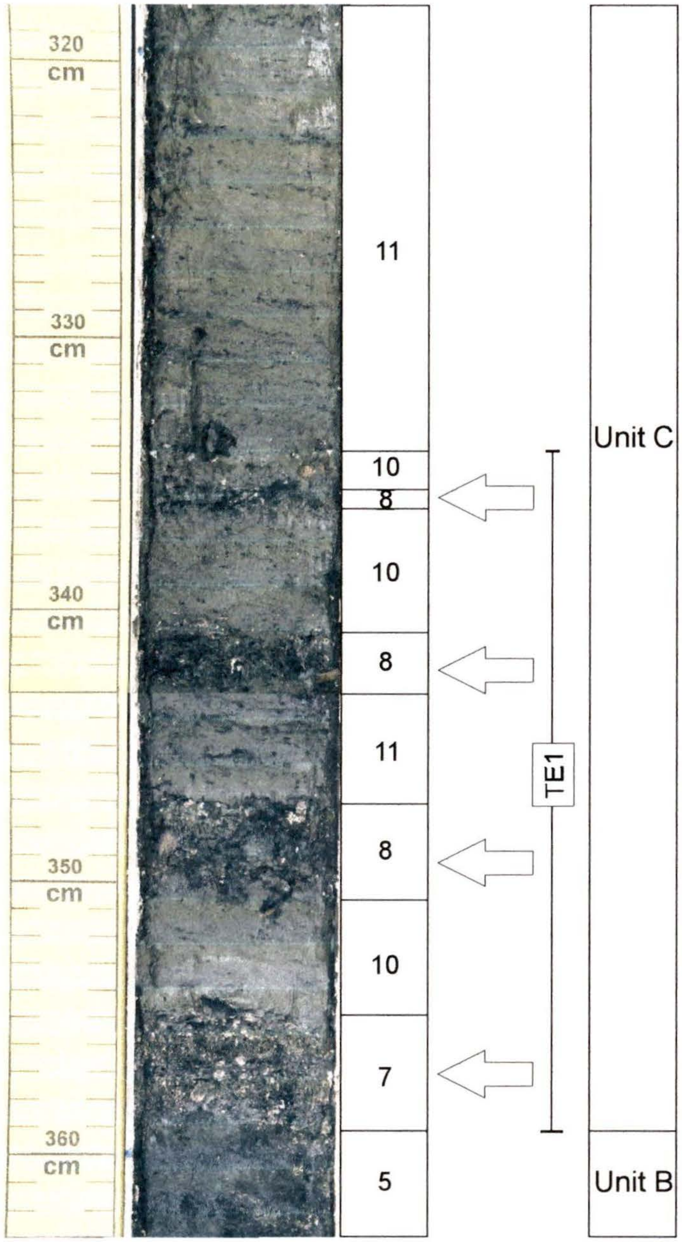


Figure 3.10 Photographs of Facies 5, 7, 8, 10 and 11 in core K6 from Kakawis Lake. Tsunamigenic layers (facies) toward the centre of the lake are much better defined within the stratigraphy than layers in cores located closer to the shores of the lake. Different tsunami pulses are marked by the arrows.

between 80 and 260 x10^6 SI/vol, indicating presence of terrigenous particles and coarseness of composition, although slightly finer than Facies 7. C/N ratio varied between 17 and 29, still showing high values.

Like Facies 7, all carbonate material is marine in origin (Table 3.2). The variety of species is similar to Facies 7. However, in comparison with Facies 7, the abundance and size of the shell fragments diminishes by 50%.

Facies 9: Chaotic organic conglomerate

Facies 9 is anomalously rich in macro-plant detritus with some shell fragments and minor sand and gravel fractions (Figures 3.8 and 3.11). This chaotic, very dark dusky red (10 R 2.5/2) facies has irregular contacts. It has the coarsest plant detritus of the tsunami facies. Wood and bark fragments are characteristic in this facies and reach sizes up to 9 cm-long and 2 cm-thick. Thick (0.5 cm) and long (up to 3 cm) twigs are also found. Few large unbroken cone bracts (up to 3 cm long) and few fish bones (up to 0.3 cm) are common to this facies. Diverse plant seeds (up to 0.5 cm in diameter) are also present. Shell fragments embedded within the plant detritus have a marine origin but are smaller than 2 cm.

Facies 9 is present in all Kakawis cores, and has variable thickness. It varies from thin 2 cm lenses to thick 22 cm layers depending on the position in the lake and the tsunami event. This variation may also be caused by different settling velocities as well as spreading behaviour of the material across the water basin.

Compositionally, this facies is characterised by 55-100% plant detritus, 0-52% marine shells, 0-17% terrigenous sand, and 0-2% mud. Occasionally Facies 9 is mixed with Facies 8, which is why it was difficult to establish the boundary between the two facies. Given the low concentration of terrigenous particles, it was difficult to determine grain size parameters. However, most of the terrigenous component is sand (33-100%) with little mud-fraction (0-33%) and no gravelly material. The largest clastic particle associated with this facies has a diameter of -1 Φ. The mean size generally ranges between 0 and 6 Φ.

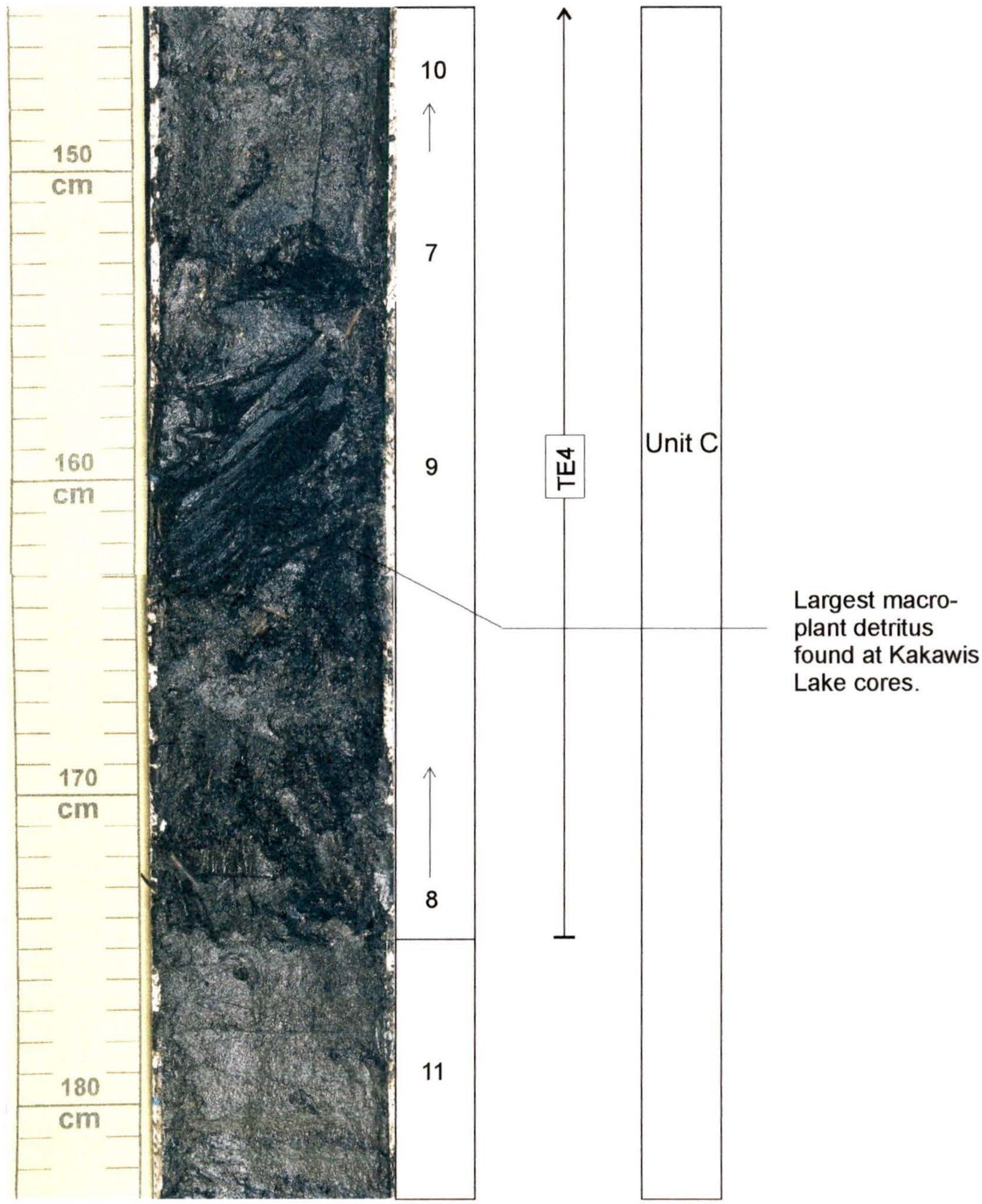


Figure 3.11 Composite of photographs of the coarsest plant detritus layer (Facies 9) in core K7 from Kakawis Lake. Transition between facies is difficult to define due to mixing between layers. Thick fragments of wood and bark are principal components of Facies 9.

Electrical resistivity values ranged between 35 and 170 mV, probably due to the coarse size of the detritus and high porosity. Magnetic susceptibility values ranged between 0 and 300 $x10^6$ SI/vol also indicating coarseness. C/N ratio varied narrowly between 16.5 and 17, values much lower than the ones obtained for clastic Facies 7 and 8, but higher than for the gyttja facies.

Facies 10: Organic detritus cap

Facies 10 resembles Facies 9 compositionally, but differs because of the finer sizes of all components (clastic, carbonate and plant detritus), the low quantities of the clastic fraction and that both contacts are gradational. This facies is described as a massive sandy-shelly organic mud enriched in plant detritus (Figures 3.8, 3.10 and 3.11). Because of the gradational character of the top contact with overlying Facies 11 and/or 4, the thickness of this facies was difficult to establish. Facies 10 is generally 3 cm thick when overlying Facies 7 or 8, but can reach up to 10 cm when overlying Facies 9. Facies 10 resembles Facies 4, 5 and 11 in colour (very dark greyish brown 2.5 Y 3/2), overall texture and the fine plant detritus affinity. Facies 10 was given the name "organic detritus cap" because it generally covers the coarser tsunami facies. It is interpreted as an inter-pulse stage between wave surges as well as the end of the tsunami event (i.e. last tsunami ebb flow).

Similar to Facies 9, plant detritus and organic matter are the major components (50-85%) of Facies 10, that consists of a variety of small (<2 cm) fragments of wood, bark, twigs, needles, broken cones and other material. Marine shell fragments (15-52%) are usually <1 cm as well as highly fragmented. Sand-size clastic fraction ranges between 0 and 20% and the mud fraction does not surpass 5%. Occasionally, a small gravel-fraction (<2%) component may appear in layers close to the outlet stream (i.e. cores K1, K2 and K3). Low concentration of terrigenous particles made grain size determination difficult. However, it was found that most of the terrigenous component consists of sand-size particles (0-100%) with little gravel (0-20%) and mud (0-50%). The largest clastic particle associated with this facies has a diameter of -1 Φ. The mean size generally ranges between 0.5 and 6 Φ.

Electrical resistivity values were lower than Facies 9. They ranged between 33 and 75 mV. Magnetic susceptibility values ranged between 0 and 240 $x10^6$ SI/vol. Both geophysical analyses suggest the presence of fine particles although coarser than the watery gyttja. C/N ratio varied between 15 and 19 in core K7 but between 29 and 32 in core K6. These high values suggest terrestrial provenance of the plant detritus and organic matter, although some organic matter may also come from a marine source.

Facies 11: Laminated Gyttja

Facies 11 has the same characteristics of Facies 5 with the only difference that it is laminated (Figure 3.10). Laminations (0.5-1 cm thick) reflect small changes in colour and composition between black (2.5 Y 2.5/1) laminae enriched in organic particles and olive brown (2.5 Y 4/3) to greyish brown (2.5 Y 5/2) laminae with less organic particles. This facies is only found enclosed by consecutive tsunami deposits, although it is not believed as part of the tsunami inundations but rather a calm depositional period elapsed between those events. Its thickness varies between 3 and 67 cm. Facies 11 is absent in core K1 but present in all remaining cores.

TSUNAMI EVENTS AT KAKAWIS LAKE

Anomalous, coarse-grained, clastic-shelly-detrital layers enclosed within Unit C are interpreted to represent different stages of deposition of a tsunami event. When a given tsunami wave surges into an enclosed basin such as a coastal lake, the deposition of the load follows basic settling rules based on density of the material, quantity of influx and the periodicity of the wave pulses (Bondevik *et al.*, 1997a, 1997b). This depositional pattern is evident at Kakawis Lake (Figure 3.12). Based on this pattern of deposition as well as the chronostratigraphy, six inferred tsunami events have been recognized. Each tsunami event consists of an assemblage of the different tsunami facies described earlier. Each tsunami facies is associated with a different stage of tsunami run-up making it possible to recognize different tsunami pulses (inundations).

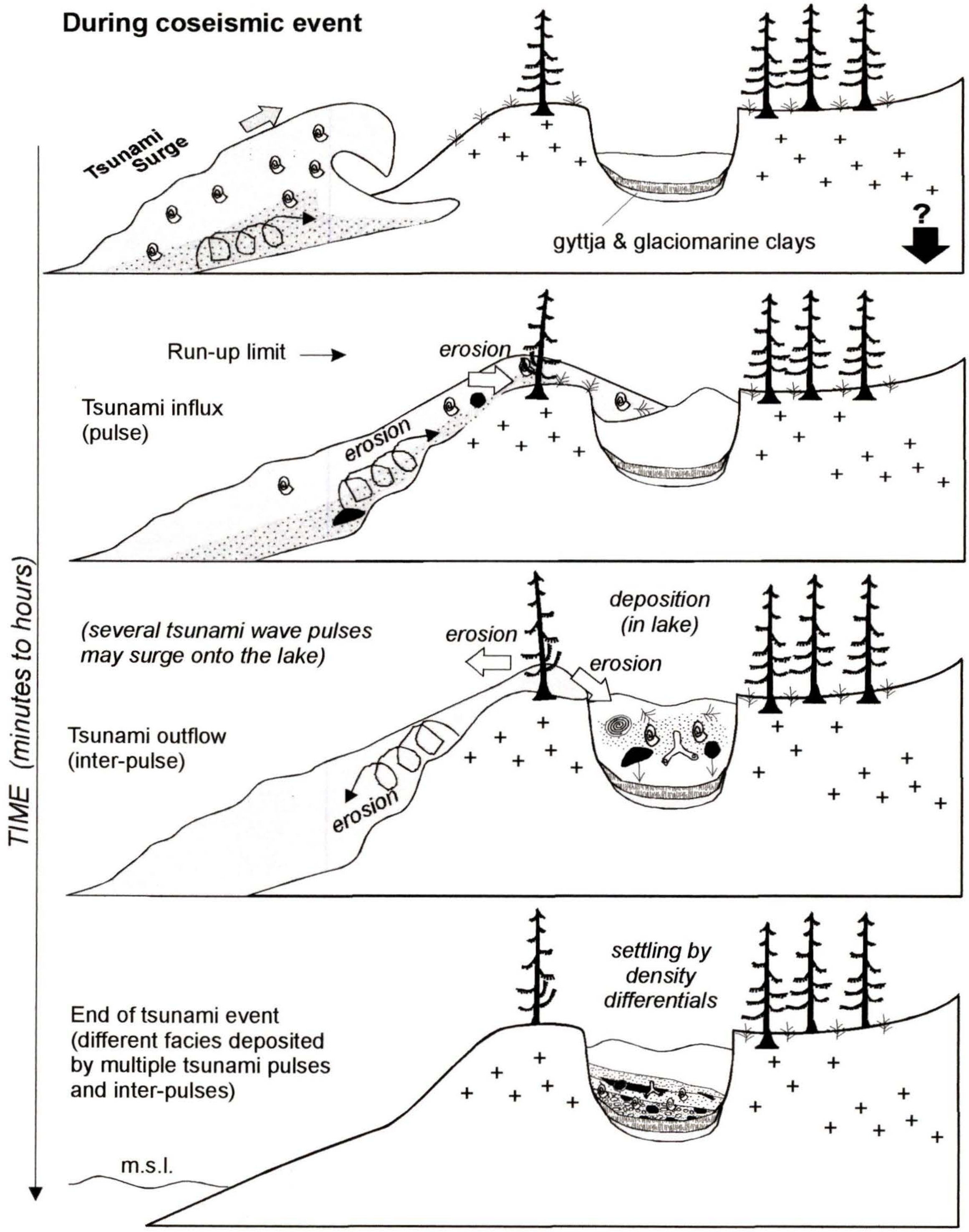


Figure 3.12 Conceptual model of erosion and deposition during tsunami surge in tectonically uplifted rugged, steeped-walled rocky shores like the one surrounding Kakawis Lake. Influx and deposition of coarse material is generated during tsunami pulses. Deposition of suspended fine particles is done during tsunami inter-pulses and after the tsunami. Saline waters may accumulate in the bottom of the lake after tsunami inundation, generating lamination of the bottom sediments.

Figure 3.13 shows the overall hypothesised correlation between the different inferred tsunami events found at Kakawis Lake (Figure 3.4). Symbols, sedimentary structures and patterns shown in the core logs are detailed in Figure 3.14. Although it was not possible to obtain radiocarbon dates from all cores and all tsunami events to enhance the correlation, a valuable chronology was nonetheless established for likely times of emplacement of the tsunamigenic sediments. All radiocarbon values mentioned in this section are related to an AD 2000 datum, showing the age range (68.3% confidence interval) of selected tsunami events and other facies. The bases for such correlation are discussed below. A summary of each tsunami event is given, based on the facies analyses described earlier. The time of emplacement of the six inferred tsunami events at Kakawis is discussed below and a tentative explanation for their formation is suggested. However, there is no record evidencing the stage of the tide at the time of the inferred tsunami deposits.

CHRONOLOGY OF EMPLACEMENT OF TSUNAMI EVENTS

The oldest of several trapped tsunami deposits enclosed by the Unit B organic-mud sequence of Kakawis Lake was Tsunami Event #1 (TE1). It was defined from cores K5, K6 and K7, and consists of an association of Facies 7, 8 and 10. However, the farthest core (K7) does not show Facies 8. TE1 is interpreted to have been generated by at least three to four wave pulses of which the first wave transported and deposited the coarsest material. Well-defined pulses (Facies 7 and 8) and maximum sizes of the overall components (Figure 3.9) indicate that the lake was within reach of oceanic waves, either by being at a lower elevation above mean sea level than today or that the convulsive waves had enormous energy and heights. TE1 is believed to have been emplaced between 3514–3634 and 3688–3774 cal yrs BP. However, much older radiocarbon dates were also obtained throughout this event, especially in core K1, possibly suggesting high mixing, reworking, erosion and probably "cannibalistic" behaviour for the tsunami waves that emplaced TE1 (Table 3.1).

The second tsunami event (TE2) is also present in cores K5, K6 and K7 and consists of an association of Facies 8 and 10, with isolated pebble-size terrigenous grains

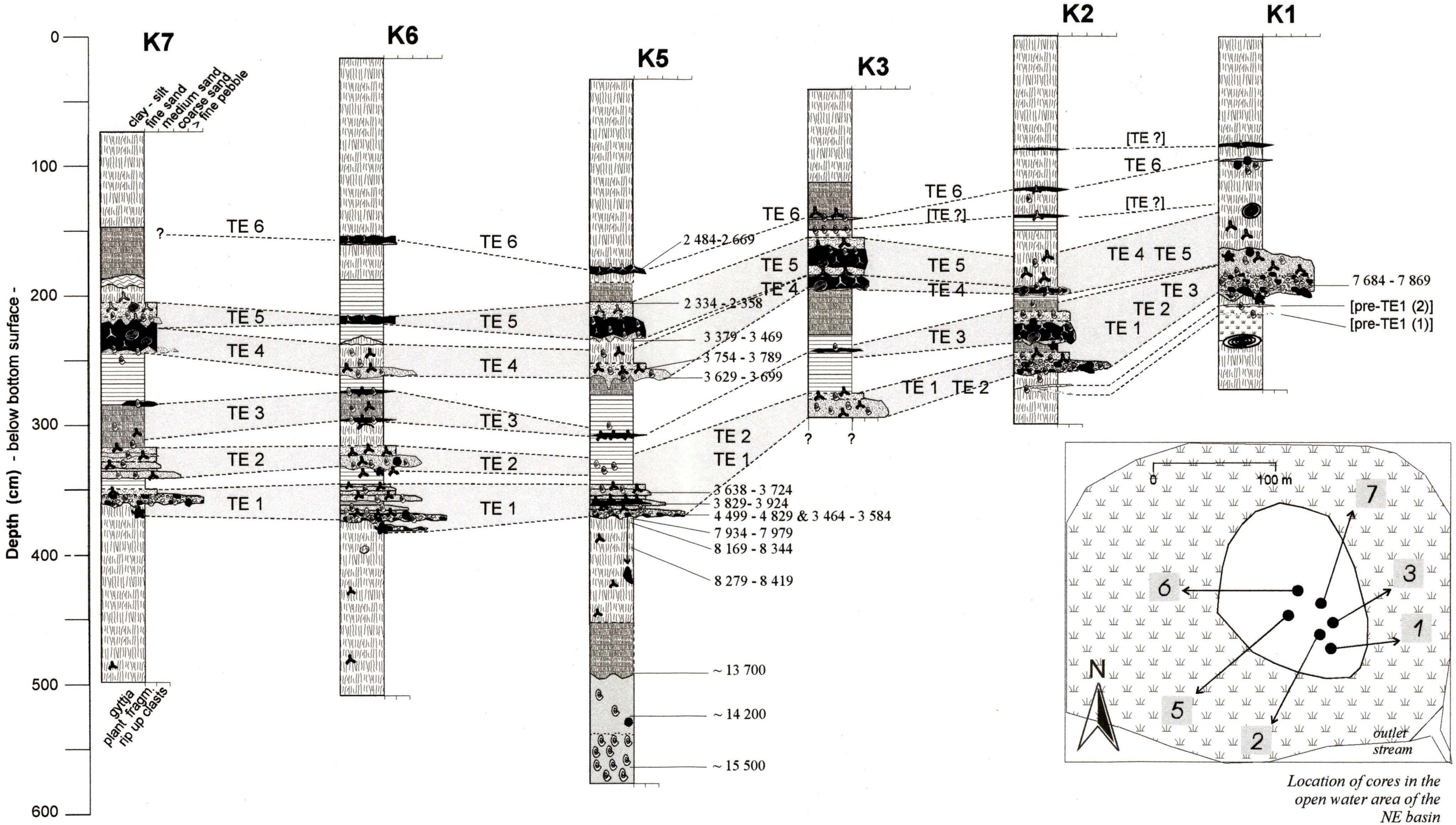


Figure 3.13 Graphic logs of sediment cores recovered from Kakawis Lake. The cores are organized from northwest (left) to southeast (right). The lake is deeper near cores K5, K6 and K7. Based on thickness of tsunami layers, core K1 is the closest to the tsunami run-up source. Tsunami deposits farther away (northwest) from the outlet stream contain less gravel- size particles and also grain-sizes generally decrease. However, tsunami beds (pulses) are better defined towards the central part of the lake where organic detritus caps are generally thicker. This is most probably due to differences between settlement velocities of suspended particles at the time of tsunami inundation. Radiocarbon ages are shown in age ranges 14C calibrated years BP (datum = AD 1950). Tsunami events are designated by numbers (1 for the oldest and 6 for the youngest). Finer anomalous layers are designated by a question mark.

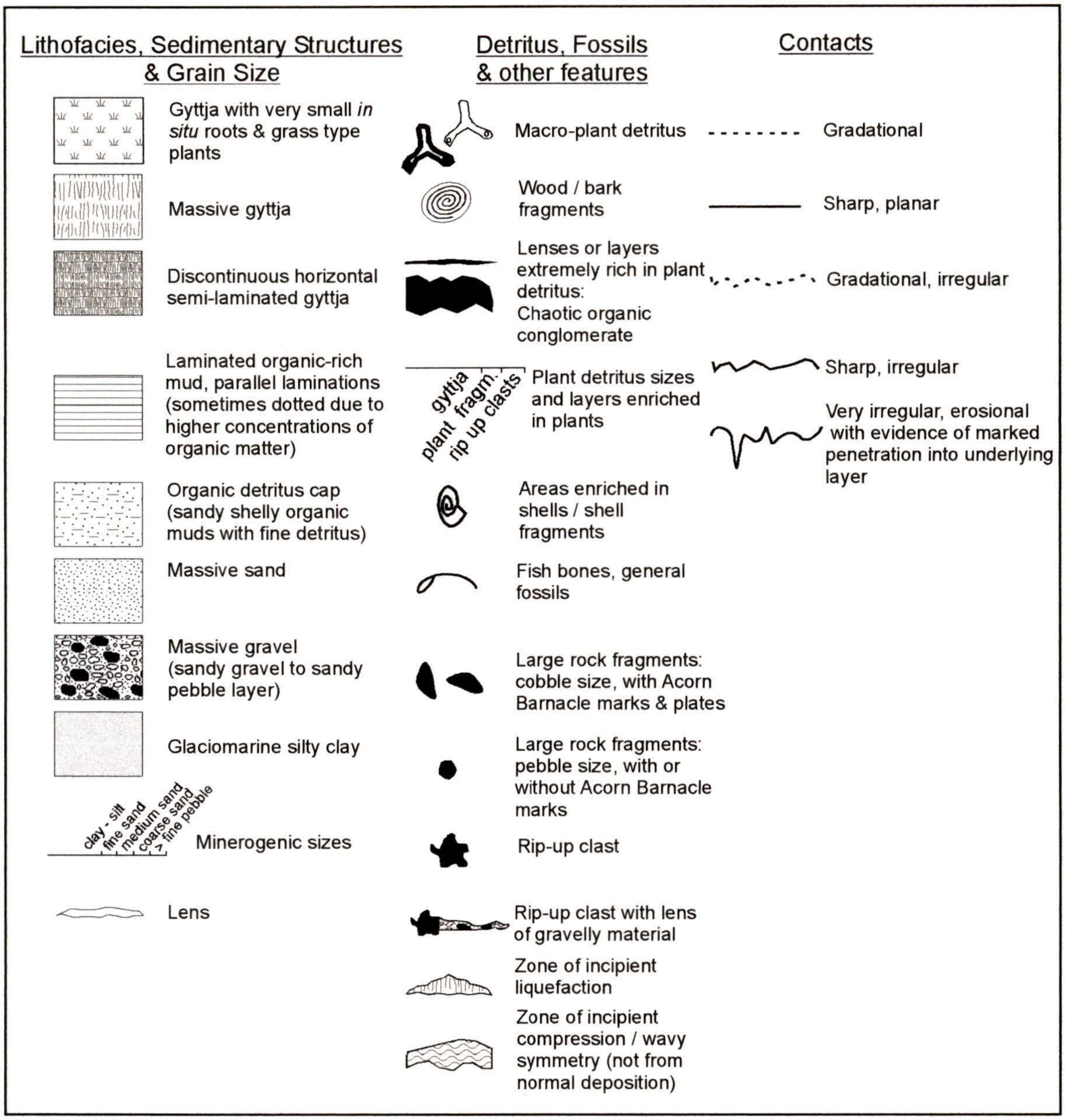


Figure 3.14: Explanatory legend for logs of sedimentary sequences of cores from Kakawis Lake.

that may be part of the lowest part of Facies 8. TE2 may have been generated by at least two wave pulses that dispersed material unevenly across Kakawis water basin, because the second wave pulse is not present in all cores. This may be explained by some sort of reworking/erosive process that occurred in the lake at the time of influx of the second pulse. TE2 may have been emplaced shortly after TE1, based on the thinness (5 cm) of Facies 11 between both events.

The next tsunami event was TE3, which was defined from all cores except K1. This facies mainly incorporates biologic material grouped either in lenses or layers described as Facies 9. In core K2 this tsunami event includes a basal Facies 8 and an uppermost Facies 10. TE3 may have been generated by one or two wave pulses. However, since the coarser and heaviest material (Facies 8) involved in this event is located in core K2, close to the outlet stream, it is suggested that the lake basin was above the level of all but the largest of ocean waves. Moreover, the thickness of Facies 9 is greater compared to the lens-type Facies 9 scattered across the rest of the basin. Organic detritus is a relatively light component and can be easily dispersed in the water column. For this not to happen, an obstacle must have existed to impede the wave run-up.

The first three events show an overall decrease in size and increase in sorting of the different components. However, TE4 has some of the coarse-size grain characteristics of TE2. TE4 consists of an association of Facies 8 overlain by Facies 9. Sometimes Facies 10 appears overlying either Facies 8 or 9. In core K7, Facies 9 shows considerable thickness. In addition, Facies 9 is only present in cores K2, K3 and K7. The distribution of this facies implies that the macro-plant detritus involved may have spread only across the eastern margin of Kakawis Lake. Another possibility is that the lake water may have been pushed onto that side of the lake as a result of the incoming oceanic run-up wave, washing over forest surface and returning into the lake with high concentrations of terrestrial plant detritus. As a result, cores K5 and K6, located slightly to the west (Figures 3.4 and 3.13) do not have this facies associated with event TE4. TE4 may have been generated by one great wave pulse that dispersed material unevenly across Kakawis water basin and/or generated an internal lake wave that washed over surrounding forest surfaces. Because of the coarse fraction of TE4 (compare to TE3), Kakawis Lake may have been situated, again, at a lower elevation than today and within greater reach of any great wave. This may suggest coseismic subsidence of the lake. An age of 3679 to 3749 cal yrs BP was obtained from the basal contact of TE4 (Table 3.1).

The penultimate anomalous event (TE5) contains basal Facies 7 or 8, overlain by either Facies 9 or 10. Because it directly overlies TE4, this event may have been produced by the great waves that deposited TE4. However, the coarse layer (Facies 7) in core K7, overlying Facies 9 corresponds to TE4 and may suggest that this is not the case. TE5 is inferred to have been generated by one or two wave pulses. Because of the coarse size and the uneven dispersal of the facies (more accumulation towards the east side of the basin), the lake basin could, again, have been within reach of oceanic great waves, possibly implying coseismic subsidence. An age of 2384-2408 cal yrs BP was obtained from the uppermost contact of TE5 (Table 3.1).

TE6 is possibly the youngest event recorded at Kakawis Lake. It is also the thinnest of all tsunami deposits. TE6 comprises a thin (1-3 cm) lens of Facies 8 with a few isolated pebble-size clasts, and thin layers of Facies 9 deposit spread across the lake basin. The small size of this event suggests it may not be associated with a great tsunami event. However, the facies must have had a marine origin given the presence of marine shells. Tsunami waves may have been almost out of reach while emplacing TE6 within Kakawis Lake. The transition between Facies 8, closest to the outlet stream, to Facies 9, across the rest of the basin can be explained by settling densities of the material and dispersal behaviour of the organic fraction in the water column. An age of 2534-2719 cal yrs BP was obtained for this event (Table 3.1).

DISCUSSION: DEFINITION OF TSUNAMI EVENTS AT KAKAWIS LAKE

The following are the bases used to define and distinguish the numerous tsunami deposits found at Kakawis Lake, besides the outstanding lithological differences from the lacustrine medium. The bases are determined by the patterns seen on curves and data obtained from the multiple laboratory analyses, new to paleoseismic research. Because radiocarbon ages are absolute values, they are not discussed here.

Detailed lithostratigraphic analyses of six cores recovered from Kakawis Lake have identified six tsunami events within lacustrine (and estuarine?) basin sediments. New subheading criteria for recognition of tsunami deposits were laboratory methods such as electrical resistivity, magnetic susceptibility, x-radiograph imagery, C/N ratios, clast and marine shell identification.

X-radiographs taken of core K5 show the internal and chaotic three-dimensional (3-D) structure of the coarsest tsunami facies (Figures 3.6 and 3.8). Magnetic susceptibility curves show a gradual decrease in values for tsunami deposits with a basal coarse facies (clastic or detrital) and a much finer top layer (texturally better sorted). Such a trend implies a general gradation within the tsunami deposit, but not necessarily within an individual facies (Figure 3.15). Electrical resistivity curves show pronounced peaks at each clastic-rich tsunami facies (Figure 3.15). Peaks associated with Facies 7 and 8 made their recognition within a single tsunami event relatively straightforward. Individual coarse facies may correspond to a pulse (tsunami surge); whereas finer organic facies relate to an inter-pulse (tsunami ebb) during a given tsunami event (Figure 3.12) (c.f. Bondevik *et al.*, 1997a). Since coarser materials have higher resistivity values, electrical resistivity is particularly useful for recognition of tsunamigenic facies (Figure 3.15). However, if overlying finer facies are <2 cm, they may not be well depicted in resistivity curves. Organic-rich gyttja and layers enriched in macro-plant detritus also show high resistivity values due in part by the size of the detritus and water saturation. The highest values are found in the top sections of the cores where water content is greatest.

Textural and statistical analyses of terrigenous fractions did not show gradation within Facies 7 and 8. However, when analysing each tsunami event as an assemblage of different facies, the deposit is normally graded. Grain sizes tend to diminish in general towards the top of Unit C, so that the youngest tsunami events (deposits) are generally finer and better sorted than the older ones.

Thick and texturally variable tsunami deposits located closer to the outlet stream may be a combination of several successive tsunami events. Cores K1 and K2 contain fewer anomalous layers than other cores, but anomalous beds reach thicknesses up to ~40

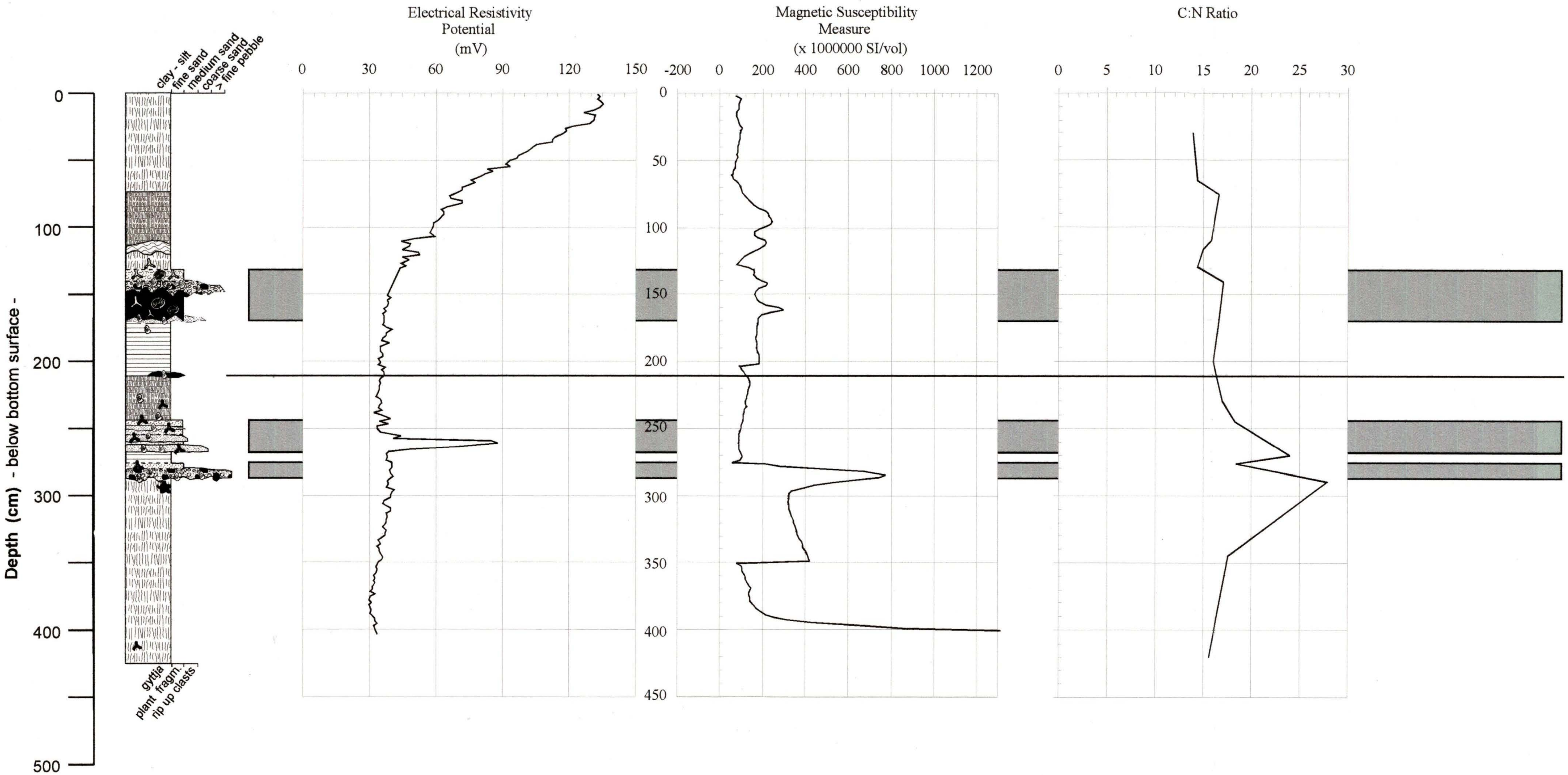


Figure 3.15:
Stratigraphic sequence of core K7 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Electrical resistivity and magnetic susceptibility measures were performed on the entire core. C/N analyses were run on the whole core.
The top horizontal axis in the log represents grain size for clastic facies. For organic rich layers and rip-up clasts, the bottom horizontal axis indicates sizes of plant fragments and association with coarse-sized particles. In the electrical resistivity curve, the continuous increase in values towards the top is caused by a excess of water. The bottom measures on the magnetic susceptibility curve are highly influenced by the metallic core catcher.

cm. The anomalous deposits contain the coarsest clasts (-6.5 Φ), the highest number of grain-size modes and highest clast-barnacle association (Figures 3.7, 3.9 and 3.16). Some of the coarsest plant detritus and shell fragments are found embedded in these sequences, together with the highest diversity of marine shell species.

In comparison, data from cores located in the centre of the lake indicate tsunami deposits thin away from the outlet stream and increase in sorting (Figure 3.16). Furthermore, the resolution of individual events is better closer to the centre of the lake, an observation consistent with what is expected.

When compared with the enclosing sediments, the lowest TOC percentages are associated with tsunami deposits, with the exception of tsunami facies enriched in macro-plant detritus. There is a direct relationship between TOC and mineral content coefficients for tsunami layers.

Carbonate and plant detritus contents are inversely related in the tsunami deposits (Figure 3.17). At Kakawis Lake, the oldest tsunami events contain the highest concentrations of carbonate material as well as the largest diversity of marine shell species (Figures 3.17 and 3.18; Table 3.2). TE1 and TE2 contain much less organic detritus than TE3, TE4 and TE5. This implies that the tsunami waves that generated TE1 and TE2 easily reached Kakawis Lake without having to flood much surface land. Around the time of these events, some ~500 m (horizontal distance) of land present today between Lemmens Inlet and Kakawis Lake was likely partly submerged.

C/N values imply that the origin of the vegetation fraction associated with the different tsunami events is of terrestrial origin (Figure 3.15). Vascular land plants have C/N ratios higher than 20 (Meyers and Ishiwatari, 1995). This suggests that most organic matter and plant detritus mixed within the tsunami facies is of terrestrial provenance. However, a marine origin for some of the organic matter can not be discounted. C/N ratios for Unit B were above 10, suggesting a mixed source for the organic matter forming the gyttja. When organic matter is formed exclusively by autochthonous non-vascular plants, C/N values range between 4 and 10 (Meyers and Ishiwatari, 1995).

The existence of Facies 11 between TE1, TE2, TE3 and TE4 was important for the correlation. If all the anomalous layers found within the sedimentary sequences of

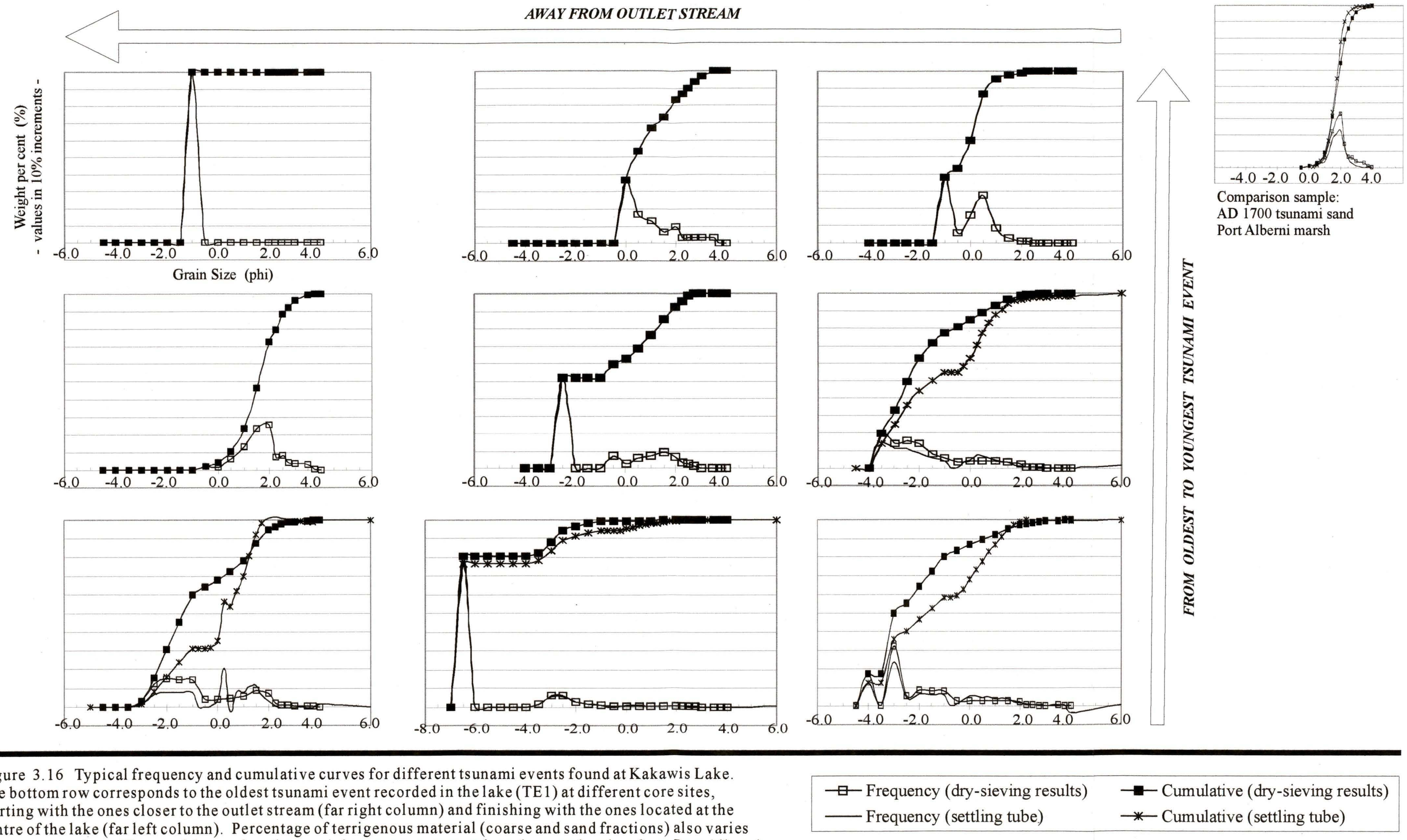
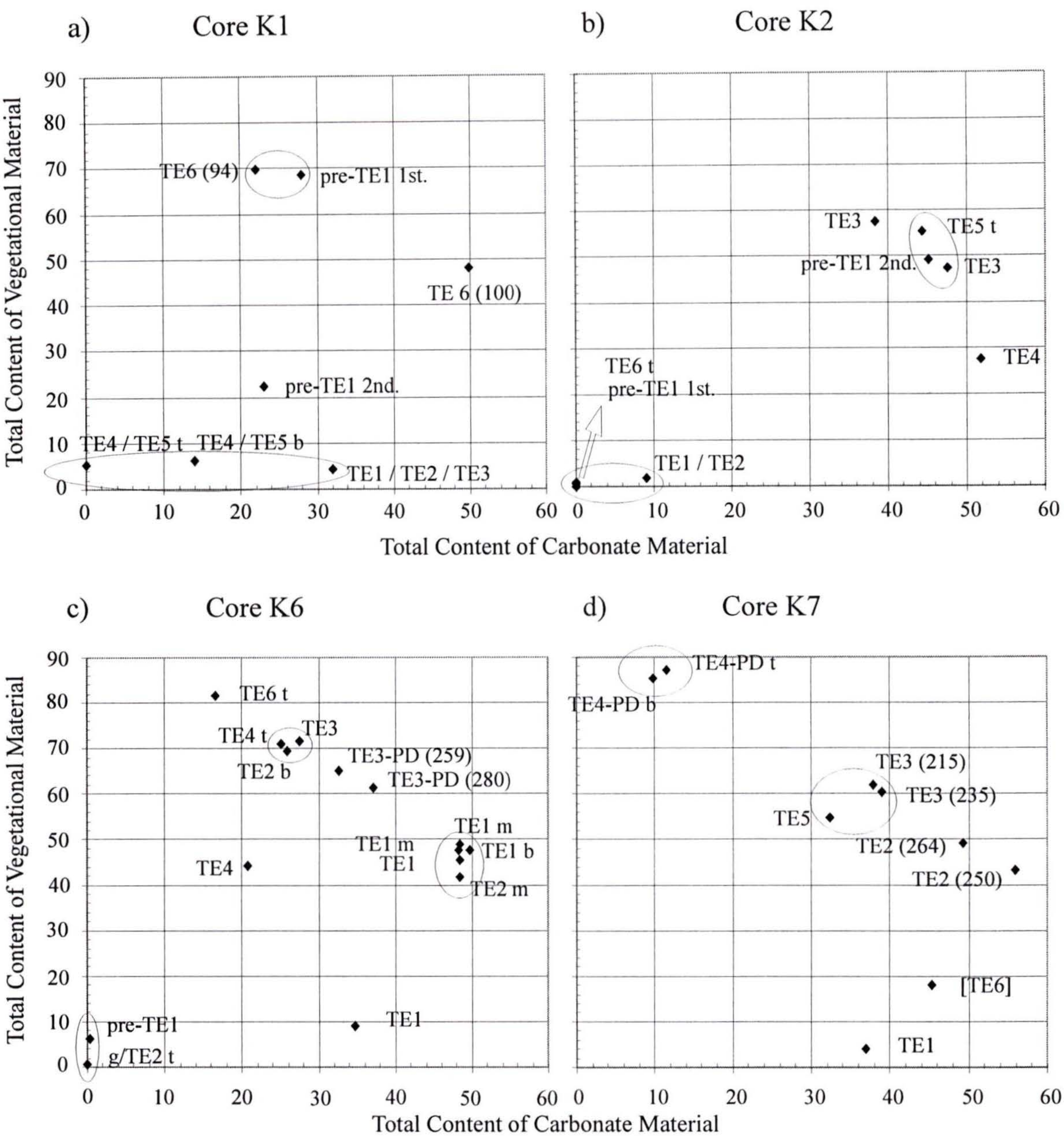


Figure 3.16 Typical frequency and cumulative curves for different tsunami events found at Kakawis Lake. The bottom row corresponds to the oldest tsunami event recorded in the lake (TE1) at different core sites, starting with the ones closer to the outlet stream (far right column) and finishing with the ones located at the centre of the lake (far left column). Percentage of terrigenous material (coarse and sand fractions) also varies between core sites. The graph located on the top right corner corresponds to the sample taken from Port Alberni marsh only for comparison purposes.



Legend for abbreviations:

TE	- tsunami event (deposit) and number (1 for earliest and 6 for latest)		
g/T	- contact between gyttja and underlying tsunami deposit		
PD	- plant detritus layer	t	- top of the layer in question
pre-TE	- layer deposited prior to the latest tsunami deposit	m	- middle of the layer in question
(123)	- depth (in cm) at which sample was taken	b	- bottom of the layer in question

Figure 3.17: Relation between total contents of Vegetational Material (fine organic matter and macro-plant detritus) and Carbonate Material (marine shell fragments) for individual tsunami deposits (TE) from Kakawis Lake. K1 is the closest core to the outlet stream and K7 the furthest. Values are in percentages and are based on total composition (entire elemental fraction).

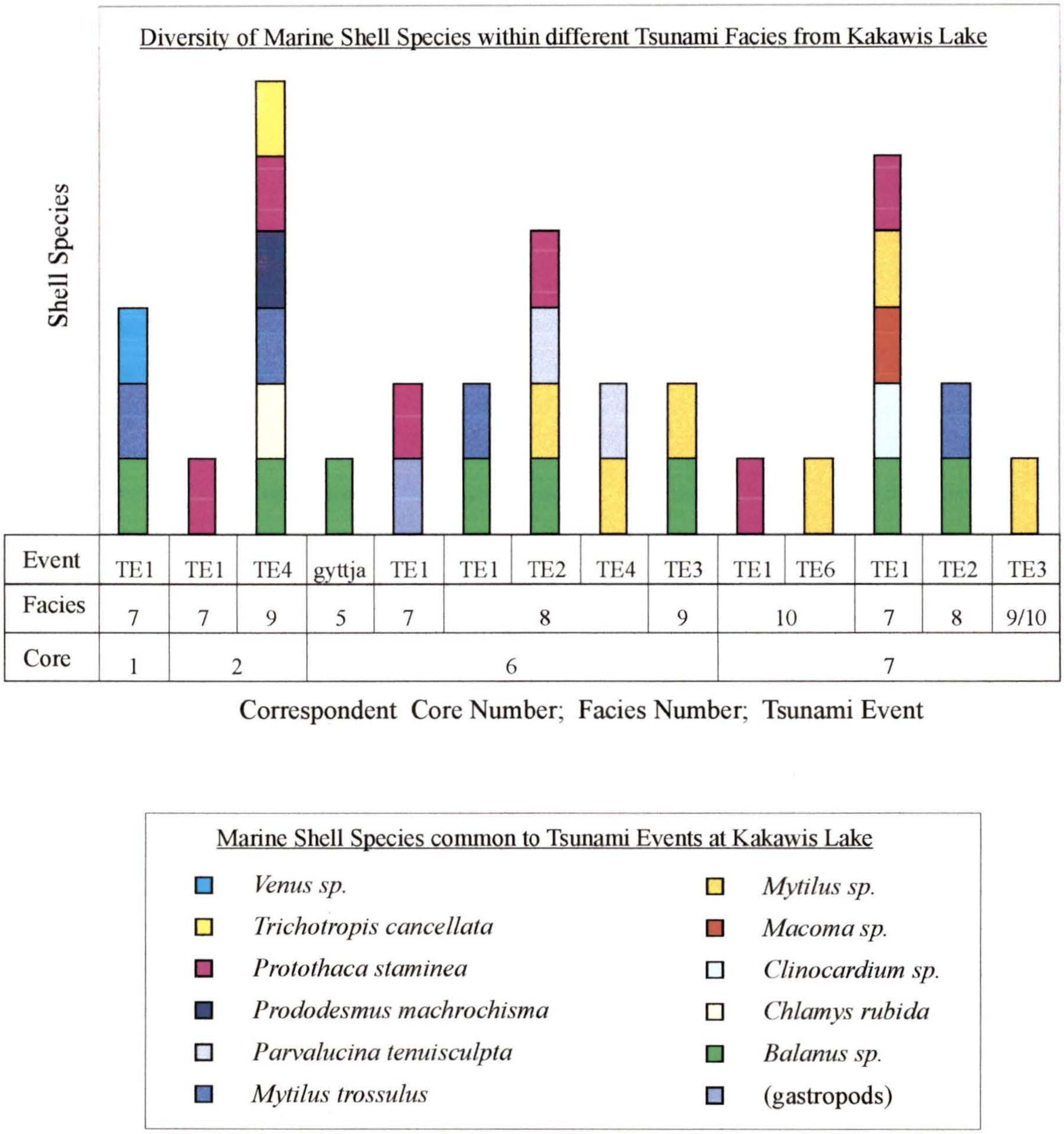


Figure 3.18: Marine shell species identified from different facies associated with several Tsunami Events (TE) from Kakawis Lake. TE1 is the oldest and deepest event found within the lacustrine sequences and TE6 is the youngest. Facies 7 and 8 are composed of the coarsest clastic material. Facies 9 and 10 are composed of vegetation detritus. Very few shells were found intact.

Kakawis Lake were to represent a single tsunami event, it would consist of a ~2.5 m thick tsunami deposit with at least 10 pulses, very well-preserved, implying extreme sedimentation rates. The thickness of this deposit is unprecedented for the Pacific west coast of Canada. Maximum thicknesses for tsunami deposits found in coastal lakes on western Vancouver Island average 40 cm (Hutchinson *et al.*, 1997; Clague *et al.*, 1999; Hutchinson *et al.*, 2000).

An approximate sedimentation rate of 0.02 cm/a was established for Kakawis Lake based on ^{14}C cal BP ages obtained from pre-tsunami units (lowermost organic-mud from Unit B). No dating was possible from the youngest Facies 4 (post-dating Unit C) that presently forms the surface gyttja sediments of the lake floor. However, it is difficult to estimate accurate accumulation rates for tsunami deposits to establish possible chronology for emplacement of the allochthonous layers and evolution of the lake. A sudden great influx of allochthonous material overruns the gradual sedimentation pattern of any given enclosed basin.

The top 60 cm of unconsolidated gyttja from Kakawis Lake were analysed to determine ^{137}Cs concentrations and constrain sedimentation rates and time of deposition of the upper sediment. The lowermost 30 cm did not show any Cesium concentration. ^{137}Cs values increased gradually from 27 to 7.5 cm average depths, followed by an apparent peak starting at 7.5 cm average depth up to the bottom surface (Figure 3.19 and Table 3.3). The top 5 cm showed a high 1.35 pCi/g value compared to the ^{137}Cs values obtained from nearby marshes (c.f. Clague *et al.*, 1994). However, this gyttja is the uppermost material of Facies 4, which is considered the modern sediment of the basin. If the peak covering the first 5 cm of sediment is assumed to be related to the 1963-1964 fallout, the linear sediment accumulation rate obtained for Kakawis Lake would be 0.14 cm/a. However, the rate increases to 0.56 cm/a if the whole uppermost ^{137}Cs-active 25 cm are taken into consideration, as well as the initial 1954 fallout. This latest sedimentation rate is not compatible with the radiocarbon ages.

The tsunami deposit left by the AD 1964 Alaska tsunami, triggered by the second largest mega-thrust earthquake of the 20th century, is known to exist in the nearby marshes of Meares Island, Tofino and Ucluelet (Bobrowsky and Clague, 1991; Clague

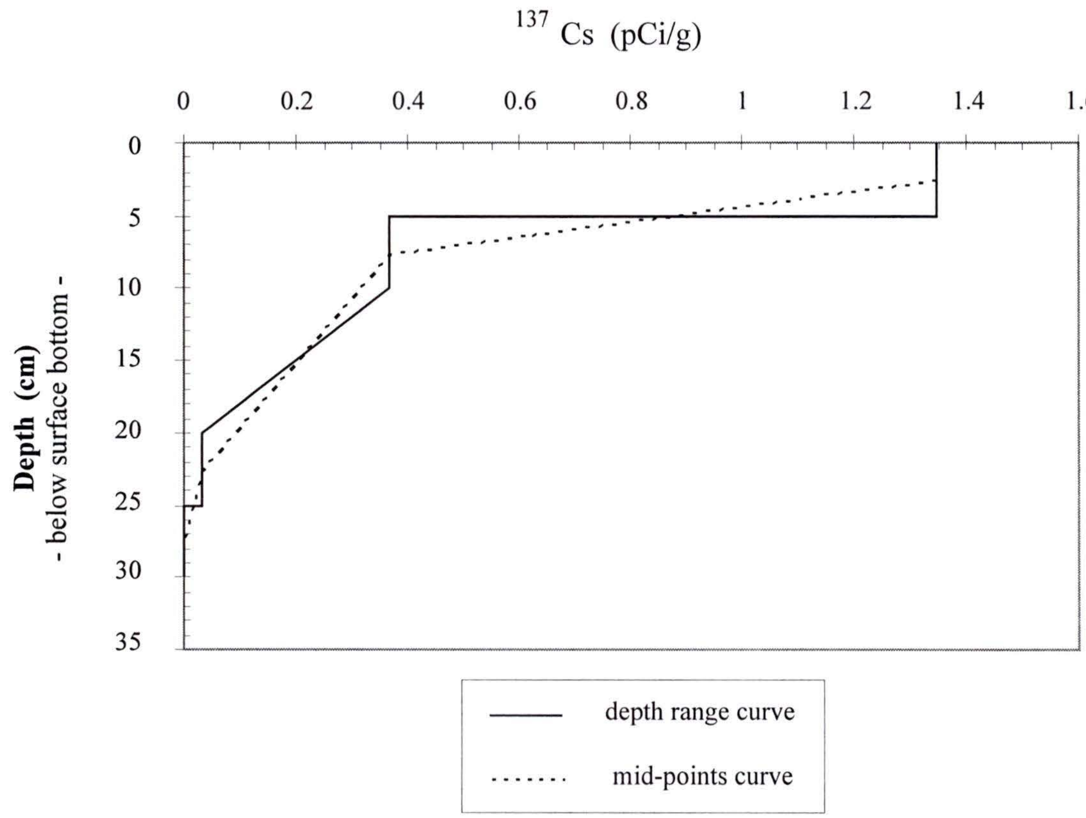


Figure 3.19: 137-Cesium concentrations (picocuries per gram) as a function of depth in core K3 at Kakawis Lake (see Figure 3.4 for location of core). At this site, the first 100cmofthe top of the core are gyttja. 137-Cs concentrations below 20cm are very low. Note: absence of data between 10 - 20 cm and >25 cm intervals (see Table 3.3).

Table 3.3: Analytical data for 137-Cesium obtained from core K3 from Kakawis Lake.

Depth interval in core min (cm)	Depth interval in core max (cm)	Plotted depth mean (cm)	Analysed Sample Dry mass (g)	Type of Material	137Cs count	Standard deviation (%)	137Cs (pCi/g)	Count time (sec)	Count time (min)
0	5	2.50	9.540	Gyttja	34816.9000	3.5700	1.3471	170385.0000	2839.7500
5	10	7.50	12.460	Gyttja	9407.9000	9.6100	0.3683	94328.0000	1572.1333
10	15	12.50	9.900	Gyttja	error	-151.2500	0.0000	76998.0000	1283.3000
15	20	17.50	9.000	Gyttja	error	-74.8900	0.0000	error	
20	25	22.50	13.490	Gyttja	721.0000	30.3100	0.0337	349968.0000	5832.8000
25	30	27.50	12.420	Gyttja	error	-80.6500	0.0000	95647.0000	1594.1167
Standard Cs sample			34.200	Cs	494980.5000	0.8400	18.9983	89185.0000	1486.4167

and Bobrowsky, 1994b; Clague *et al.*, 1994). Ideally, rapid autochthonous fine-grained sedimentation and minimal bioturbation should occur to compare the ^{137}Cs profile directly with the stratigraphic column. The depth axis could then be interpreted as a time axis, enhancing the use of the 1954, 1956, 1959, 1963/1964 and 1986 ^{137}Cs peaks as markers (Ashley and Moritz, 1979; Hakanson and Jansson, 1983; Miller and Heit, 1986; Naidu *et al.*, 1999). No such tsunami event was recorded at Kakawis Lake. Furthermore, the youngest anomalous layer to be found at the lake is located between the 87.1 and 151.6 cm depth, and ranges in age between 2534 and 2719 cal yrs BP, so it can not be related to the AD 1964 Alaskan tsunami.

The weakness in the ^{137}Cs curve could either mean that a) there is constant mixing and mobilization of nuclides in the upper-most fine organic-rich lake sediments; b) there is downward diffusion in the surface sediments; c) there is very little autochthonous and allochthonous sediment input; d) the width range (every 5 cm) used for each sample analysed was too large to detail any major variations in the ^{137}Cs profile; and/or, e) the last 46 years of watery gyttja were not recovered during coring.

DEPOSITIONAL CHARACTERISTICS OF TSUNAMI DEPOSITS AT KAKAWIS LAKE

Paleotsunami deposits embedded in unconsolidated lacustrine sediments are strikingly clear within the organic-rich muds. Moreover, in tectonically emerging coastlines, tsunami deposits are better preserved in lacustrine environments than tidal marshes, because external factors such as re-forestation or erosion due to emergence do not affect lakes.

The six tsunami events recorded at Kakawis Lake showed the general landward and upward thinning and fining trend typical of tsunami inundation (c.f. Benson *et al.*, 1997). The thickest, most chaotic and coarsest event was observed in core K1, the closest core to the outlet stream. All events decreased in thickness away from the outlet stream. The best defined facies were found in cores K5, K6 and K7, at the centre of the lake. All events showed sharp undulating bottom contacts. The first event (TE1) showed the sharpest undulating contact implying an erosional unconformity indicative of turbulent flows (i.e. tsunamis). A few rip-up clasts associated with the coarsest layers are also evidence of erosive and turbulent conditions. The contacts between the different facies varied from sharp to gradational. The contact between the top of the tsunami event and the overlying gyttja is gradational.

Another general architectural characteristic of tsunami deposits is the rising landward and away from shore indicative of landward surges of water (c.f. Atwater and Moore, 1992; Benson *et al.*, 1997), mainly associated with intertidal and washover settings. However, this characteristic does not apply to lacustrine settings because of the general concave geometry of these basins. In lakes, tsunami deposits may follow the lake's bathymetry.

Associations of different layers (couplets) are indicative of deposition by successive waves of a tsunami wave train, rather than a storm surge (c.f. Nelson *et al.*, 1996b; Atwater and Hemphill-Haley, 1997; Benson *et al.*, 1997). However, in lakes couplets are best described as facies resulting from different stages and periodicity of successive tsunami inundations in addition to differences in the settling velocities of materials brought into the basin (c.f. Bondevick *et al.*, 1997a, 1997b). This same pattern of deposition has been evidenced in small protected lagoons on the coast of Japan, although the associated grain sizes are finer (Minoura and Nakaya, 1991). At Kakawis Lake, the influx (swash/flood) due to a tsunami pulse is apparent by deposition of coarse material (Facies 7 and 8), whereas the return flow (backwash/ebb) is associated with the deposition of the finest and lighter material (Facies 9 and 10), during a much "calmer" inter-pulse period.

At Kakawis Lake, tsunami facies (tsunami pulse and inter-pulse) lacked internal structure. This implies that in lakes, tsunami facies associated with coarse material (<0 Φ) have chaotic structures with no indications of flow directions. X-radiographs of massive gravel facies in core K5 associated with tsunami event TE1 show chaotic structures. All other facies with clasts sizes <0 Φ are massive. However, when grouping different facies that define a single tsunami event (coarsest facies at the bottom and finer at the top), lacustrine tsunami events fine upwards.

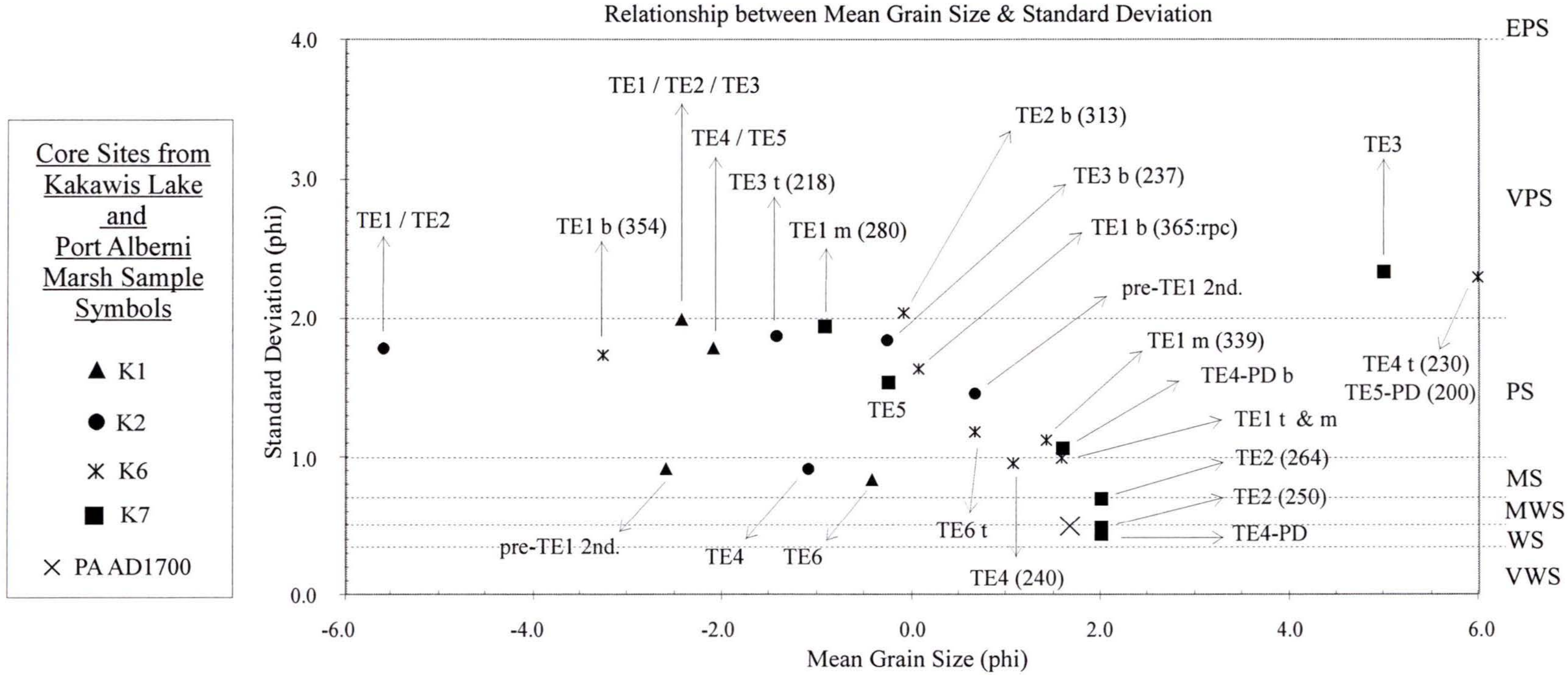
Grain-size distributions in tsunami deposits from Kakawis Lake range from coarse silt (+6 Φ) to small cobbles (-6.5 Φ). The typical clastic range of tsunami deposits found along the Cascadia coastal region is generally fine to very coarse sand. Tsunami deposits in Kakawis Lake are distinctly polymodal and poorly to very poorly-sorted (Figures 3.16 and 3.20). Due to their polymodality, the analysis of modal distributions may give more information about the grain distribution and genesis of the sediment bodies than mean or median analyses (c.f. Friedman *et al.*, 1992).

The sizes of clasts associated with the tsunami deposits generally diminishes away from the outlet stream, with the exception of two events (TE1 and TE5), where cobble-size particles were found throughout the cores (Figures 3.13 and 3.20). Particle sorting increases away from the outlet stream, as well as from oldest (bottom) to youngest (top) tsunami event.

Compared to the AD 1700 tsunami sand sheet recovered from an intertidal marsh at Port Alberni, tsunami deposits emplaced in Kakawis Lake are generally coarser and more poorly-sorted. As described by Clague and Bobrowsky (1994a) and Clague (1996), the massive AD 1700 Port Alberni sand sheet has medium to very fine sand with minor silt and is moderately well-sorted. Similar textural characteristics were obtained from analyses in this study. Additionally, minor macro-carbonate material was found and plant detritus was smaller than 1.5 cm; markedly different from similar material in Kakawis Lake tsunami deposits.

HYPOTHESIS OF EVOLUTION OF KAKAWIS LAKE

The basin in which Kakawis Lake presently lies was formed sometime prior to the last glacial maximum and was influenced by the action of the Cordilleran Ice-Sheet during its early retreat stages (Unit A). The presence of the deep water *Yoldia sp.* bivalve species within the glaciomarine clays suggests that the lake must have been submerged below relative sea level. Kakawis Lake may have been experiencing a distal glacial sedimentation during Facies 2 due to the fine size of its sediments. The transitional Facies 3 may correspond to the interval when the Cordilleran Ice-Sheet retreated from the



Legend for abbreviations:

K	- Kakawis core (numbers designate core sites)		
TE	- tsunami event (deposit) and number (1 for earliest and 6 for latest)		
PD	- plant detritus layer	t	- top of the layer in question
pre-TE	- layer deposited prior to the latest tsunami deposit	m	- middle of the layer in question
PA AD1700	- AD 1700 tsunami from Port Alberni marsh	b	- bottom of the layer in question

Figure 3.20: Relation between mean size and standard deviation for tsunami deposits from K1, K2, K6 and K7 from Kakawis Lake. A sample taken from the AD1700 tsunami layer at a marsh in Port Alberni (Vancouver Island, BC) was also analysed for comparison purposes and it is marked by the "X" symbol. Note the poor sorting of most of the tsunami events. Folk's (1974) sorting limits were used. Values of grain size parameters were obtained from graphical analyses.

region and parts of the western margin of Vancouver Island, before 12,600 yrs BP (Blaise *et al.*, 1990). By the end of Facies 3, between ~13,700 and ~14,370 cal yrs BP, Kakawis basins began to evolve under less saline and organic-rich conditions probably reflecting rebound of the coastline and subsequent drop in relative sea level.

The organic-mud accumulation at Kakawis Lake has been interrupted several times since the end of the last glacial maximum. Over the past ~13,864 years (cal yrs BP), Kakawis Lake has undergone episodic alternations between freshwater and brackish/intertidal environments. These events, defined by anomalous layers interbedded with the muddy organic-rich sequence, may be a result of episodic tsunami inundations of either local or distant source.

At least five to six tsunami events are thought to have most probably surged into Kakawis Lake basin during its history. Based on radiocarbon ages, the tsunami events may be considered the oldest tsunami deposits found to date in low-elevation coastal lakes in western Canada. The three youngest ones are tentatively correlated to event identifiers N, L and J, corresponding to the oldest Cascadia mega-thrust earthquakes recorded in buried soils at Willapa Bay, SW Washington (Atwater and Hemphill-Haley, 1997). Moreover, the tsunami events from Kakawis Lake could be correlative with the oldest (5000 to 2000 cal yrs BP unconfirmed ages) sand layers buried within Port Alberni marshes (c.f. Clague and Bobrowsky, 1994a; Clague, 1996). The older sand layers do not have counterparts at Tofino and Ucluelet marshes (Clague, 1996), probably due to erosion and bioturbation caused by uplift of the outer coast of Vancouver Island.

Continuous uplift during the late Holocene around Tofino is assumed for Meares Island and Kakawis Lake. This may account for why the AD 1964 (Alaska), AD 1700 (Cascadia) and ~AD 1200 (Cascadia?) tsunamis could not reach Kakawis Lake, although they are known to have hit the outer coasts of British Columbia, Washington and Oregon. Unfortunately, there is no record of the rebound history of Kakawis Lake or the W peninsula of Meares Island. Estimates for the elevation of the lake at the time of the tsunami events are local and regional scale models based on late Quaternary sea-level change (Clague *et al.*, 1982; Bobrowsky and Clague, 1992; Friele and Hutchinson, 1993), in addition to regional postglacial rebound models for the southern Canadian West Coast

(James *et al.*, 2000). The changes in late Quaternary sea-level for this part of Vancouver Island are further discussed in Chapter 4.

ORIGIN OF TSUNAMI EVENTS AT KAKAWIS LAKE

At least two of the three components (clasts, marine shells and terrestrial plant detritus) found in the anomalous deposits from Kakawis Lake have a marine origin. Shell species identified are restricted to marine environments, more specifically intertidal to sub-tidal zones. Species such as *Mytilus sp., Venus sp., Protothaca staminea, Macoma sp.* and *Clinocardium sp.* (Figure 3.18 and Table 3.2) are typically associated with surf and intertidal zones surrounding coastal waters of Vancouver Island (Harbo, 1997). The presence of fragile (*Mytilus trossulus*), rare (*Chlamys rubida*) and strong-current immune (*Trichotropis cancellata*) shells may imply waves capable of both accessing secluded water areas and transporting material collected from deeper sub-tidal areas, probably only reachable by tsunami waves.

All shell species are associated with mud-sand to rocky substratum common to the waterways around Meares Island. The presence of permanently fixed fossil calcified exoskeletons of adult balanomorph barnacles to most clasts larger than -1 Φ, is also indicative of marine provenance for the terrigenous fraction. These adult acorn (volcano-type exoskeleton) barnacles are exclusive to marine environments (Kaestner, 1970; Walker, 1992) spanning from the intertidal zone down to depths of 90 m.

The probable sources of the terrigenous particles are along shores and shallow waters surrounding Lemmens Inlet, and the small bay into which Kakawis Lake outlet stream flows. The coarsest clastic fraction is mostly composed by granodioritic lithics and metamorphic fragments. The finer sand-size fraction is composed of (from most to least abundant) granitic lithics, quartz grains, metamorphic lithics, feldspar, hornblende, apatite, epidote and garnet grains with other accessory minerals. All materials are from local provenance.

Coarse-grained layers are not believed to have a terrestrial origin (e.g. landslide). There are no traces of mass movements on the slopes of the closest topographical high (~700 m amsl) located 3 km north of Kakawis Lake. Various aerial photographs dating back to 1960 were analysed for evidence of headscarps on the slopes of that particular hill that may have reflected a slide, but no evidence was found. As for subaqueous landslides, no documentation exists on potentially damming slides at Lemmens Inlet. Moreover, the area of Lemmens Inlet near Kakawis Lake outlet stream is covered (~85%) by vast intertidal mud flats with depths <3 m below mean sea level (according to chart; Canadian Hydrographic Service, 1995). The deepest and closest bathymetric value close to the outlet is 4 m depth (datum = mean sea level). A bathymetrical chart of Lemmens Inlet was analysed in order to depict potential steep subaqueous slopes in deep waters that could generate a subaqueous slide (see chart from Canadian Hydrographic Service, 1995). An enclosed and isolated area, 4.4 km north of Kakawis Lake, in the northern margin of the inlet showed depths of 23 m with close contour lines (Figure 3.3). However, the distance as well as the wide intertidal mudflats surrounding the embayment entrance to Kakawis Lake may prevent any slide-generated wave from surging into the lake. However, distant giant landslides or subaqueous landslides are not discounted as the potential sources of the tsunamis that may have deposited the oldest anomalous layers in Kakawis sedimentary sequence.

Other possible sources for coarse-grained material include fluvial sedimentation. The basins that form Kakawis Lake do not have significant streams entering the lake, so the possibility for a fluvial origin of the anomalous deposits can be discounted. Furthermore, all anomalous layers found at Kakawis Lake thin and fine away from the outlet stream, implying influx from the outlet (Figures 3.13 and 3.16).

Another possible depositional mechanism that could explain the anomalous layers is a non-seismic extreme ocean level such as a storm surge. Storm surges are temporary extreme ocean levels caused by severe climatological phenomena generated over a long fetch of water (Pugh, 1987). The emplacement of the anomalous layers by storm surges is unlikely, even if the anomalous records extend to prehistoric times, for the following reasons. The mouth of the outlet stream from Kakawis Lake is located in a much protected geographical area ~9 km east from the outer open coast (Figure 3.3) and the many smaller islands, channels and passages would scatter and diminish the impact of wind-driven waves. In contrast, a tsunami origin for some anomalous layers buried on marshes and coastal lagoons may be overestimated for some regions of the Pacific Northwest because storm surge recurrence events may have not been extensively considered (Witter *et al.*, 2001). However, such over-estimation applies to low-lying flat coastal areas with shores openly exposed to oceanic waters hence susceptible to washover, and may not apply to rugged, steep-flanked, bedrock-exposed shorelines like those surrounding Kakawis Lake.

Western Vancouver Island has a continental shelf ~200 m deep. Around the Clayoquot Sound latitude the shelf is relatively wide (~100 km) compared to northern areas of the island. This configuration may be appropriate for generation of great ocean waves caused by onshore storm winds, but storm surges break once near shore (contrary to tsunami waves) (Murty, 1977; Komar, 1997; Pelinovsky *et al.*, 1998; Bryant, 2001). Moreover, storm surges can not explain the existence of multiple defined layers (facies) associated with a single extreme ocean level event (c.f. Nanayama *et al.*, 2000). In addition, tide gauge records from the Tofino have shown maximum water levels of 0.9 m associated with storm surges that may occur every 100 years. Inferred levels up 1.5 m, extrapolated from the gauge data (Hutchinson *et al.*, 1997), are associated with recurrence intervals of 1000 years. This interval is much larger than the one suggested by the Atwater – Hemphill-Haley chronology (300-540 years) for Cascadia tsunamis, and does not match the events associated with Kakawis Lake.

Lastly, analyses of clast surfaces showed collision marks on some particles implying a possible turbulent flow as transporting mechanism, a property of tsunami waves. Moreover, the size of the coarsest terrigenous particles (cobbles and pebbles) implies an elevated energy to move and transport such load from the source area.

SUMMARY AND CONCLUSIONS

A detailed lithostratigraphic investigation has recognized allochthonous deposits enclosed by lacustrine sediments in Kakawis Lake, a small low-elevation lake located on protected coastal waters on the central west margin of Vancouver Island (B.C., Canada).

Analytical protocols employed in this study effectively depicted tsunami deposits in lacustrine environments. Methods such as electrical resistivity, magnetic susceptibility and x-radiograph imagery, and analyses such as C/N ratio, TOC, as well as identification of macro-biological and clastic material, were successfully combined and related to characterise the deposits. Most of these methods are new to paleoseismic investigations.

The chaotic, shelly and anomalously coarse deposits mixed and/or capped with terrestrial organic detritus, are interpreted as deposits emplaced by tsunamis of distant and/or local provenance. Five to six tsunami events are evident at Kakawis Lake and likely define the oldest tsunami deposits found to date on Vancouver Island. The tsunami events spanned throughout late to mid Holocene, post-date 7984 cal yrs BP but pre-date 2408 cal yrs BP (datum = AD 2000).

The diversity of radiocarbon ages obtained for the oldest tsunami event (TE1) and the absence of anomalous layers between the glaciomarine clays and TE1 may tentatively suggest that event TE1 could have truncated and re-worked previously deposited older tsunami layers, showing the erosive ("cannibal") aspect of tsunami waves.

Kakawis Lake tsunami events consist of a series of facies, representing different stages of tsunami run-up. For instance, tsunami inundations (pulse) and tsunami outflows or ebbs (inter-pulse) are interpreted in several tsunami events. Plant detritus layers can be found as individual facies mixed and/or capping the tsunami event.

The general architectural characteristic recognized in tsunami deposits present in salt marshes, and estuarine and intertidal environments can also be implied for tsunami deposits emplaced in lacustrine environments. The deposits also thin and fine landwards. However, the thickness and coarseness related to tsunami layers deposited in a lake may be greater than those emplaced along washover settings (Figures 3.2 and 3.12).

In marsh environments, tsunami layers are generally moderately well-sorted and tend to have gradation. In lacustrine environments, individual tsunami layers (facies) are massive and to some extent chaotic if the material is coarse ($<0\ \Phi$). If a single tsunami event (assemblage of facies) is analysed, normal gradation is observed. Moreover, the general succession of tsunami events at Kakawis Lake fines and thins towards the top of the cores.

Although sand layers deposited by tsunamis and extreme storms may be indistinguishable on the basis of lithological characteristics, the existence of a very coarse fraction (<-5 Φ) and the geographical position of the lake suggest tsunamis as depositional mechanism rather than storm surges.

Based on the sediment cores recovered from Kakawis Lake, the lake lacks any geological evidence of the past three most recent tsunamis known to have inundated nearby areas of western Vancouver Island (a ~800 cal yrs BP event, the 300 cal yrs BP latest great Cascadia event and the AD 1964 most recent Alaska mega-thrust event). This suggests that tsunamis that can penetrate enclosed waters around Lemmens and Tofino Inlets may be unable to reach basins presently located at 4 m amsl (at normal high tide), and implies a new vertical limit for tsunami run-up in this region. This limit also depends on the stage of the seasonal and daily tides at the time of the tsunami event.

Radiocarbon ages on plant detritus from the youngest tsunami events are consistent with at least the three oldest ages established for mega-thrust events along the Cascadia Subduction Zone, according to the Atwater – Hemphill-Haley chronology. The three oldest tsunami events recovered from Kakawis Lake may have also been triggered by seismic mechanisms, although a non-seismic origin can not be discounted.

CHAPTER 4

IMPLICATIONS OF TSUNAMI INUNDATION IN LACUSTRINE ENVIRONMENTS ON THE WEST COAST OF VANCOUVER ISLAND, BRITISH COLUMBIA

ABSTRACT

The average recurrence interval for great earthquakes at the Cascadia Subduction Zone oscillates around 500 years. Large tsunamis may have followed such large tectonic disruptions, inundating vast low-lying coastal areas along SW Canada and NW U.S.A. However, due to complex coastal bathymetry and shoreline geometry, tsunamis may not inundate all coastal areas.

Tsunamis likely the result of local mega-thrust earthquakes have left six recognizable and unique deposits in Kakawis Lake, a coastal low-elevation freshwater basin located on the central coast of west Vancouver Island, British Columbia. However, the possibility of other sources for the different tsunami events is also recognized. Sedimentological analyses have determined that such deposits contain some of the largest particle sizes (up to -7 Φ) to date recovered from lacustrine environments from this region, possibly implying complex lake elevation, tsunami run-up and tsunami energy settings.

The tsunami deposits are believed to be the oldest tsunami events recorded to date on this west coast, dating back to the middle Holocene. Very few tsunami deposits evidenced at other low-lying lakes and tidal marshes on western Vancouver Island can be correlated with these deposits. Chrono-stratigraphically, the youngest Kakawis Lake tsunami events may correlate with three of the oldest identifiers from the Atwater – Hemphill-Haley chronology for the west coast of North America. Such lack of counterparts may validate the use of archaeological data to constrain the dates of paleotsunami inundation at Kakawis Lake.

Kakawis Lake lacks evidence for the last three major tsunamis that struck the British Columbia coast (AD 1700, AD 1100-1200, AD 1964). Such lack of evidence together with analyses of sea-level changes may imply a new maximum tsunami run-up limit of 4 m above mean sea level (at normal tides) for the west coast of Vancouver Island.

INTRODUCTION

Although tsunamis have been experienced since ancient times and are considered the greatest and feared of ocean waves, scientific investigation began only at the turn of the 20th century (Soloviev and Go, 1974; NGDC, 2000). Their impact on past coastal communities and civilizations can be found in oral traditions and written histories, in addition to their archaeological record (Cox and Pararas-Carayannis, 1976; Myles, 1985; Vita-Finzi, 1986; Stiros, 1988; Minoura and Nakaya, 1991; Robinson, 1993; Stiros and Pirazzoli, 1995; Satake *et al.*, 1996; Driessen and MacDonald, 2000; Altinok *et al.*, 2001; Goff and McFadgen, 2001). Large disruptive events such as subduction zone earthquakes are effective tsunami generators. Most documented tsunamis have been triggered by great seafloor disturbances along Pacific Ocean convergent margins (Soloviev and Go, 1974, 1975; IOC, 1999; NGDC, 2000).

Tsunamis are defined as ocean waves (or a train of waves) with unusually long periods and long wavelengths generated by large-scale, short duration disruptive events (Soloviev and Go, 1974, 1975; Pickering *et al.*, 1991; Soloviev *et al.*, 1992; Abbot, 1996; Carver and McCalpin, 1996; McCalpin and Nelson, 1996; Yeats *et al.*, 1997). With velocities varying between 500-1000 km/h in the deep ocean waters, tsunamis propagate outward from their source. The energy of a tsunami is directional rather than radial (Murty, 1977; Streinbrugge, 1982). It concentrates in a direction perpendicular to the axis of the tectonic deformation, allowing the wave to travel over long distances, hence impacting distant coastlines. A tsunami wave acts as any given shallow water wave, refracting, diffracting, reflecting, scattering and shoaling when possible (Miller, 1964; Miyoshi, 1977; Murty, 1977; Thomson, 1981). In shallow waters the energy of the wave is conserved, amplitudes grow larger and the height of the tsunami increases dramatically developing bore-like fronts (Murty, 1977).

Tsunami deposits are a result of tsunami inundation, coastal conditions and availability of material permitting. Tsunami deposits are defined as off-fault stratigraphic expressions of tectonic deformation, and are generated coseismically (McCalpin and Nelson, 1996). The world-wide abundance of this type of coseismic deposits is considered moderate compared to common secondary types of coseismic evidence resulting from the shaking of an earthquake (e.g. liquefaction of soils, sand blows, landslides and turbidites). Because of their genesis and timing, tsunami deposits, in addition to shoreline uplift/submergence, are considered primary paleoseismic features used as evidence of paleoearthquakes and relative sea level changes in a region. However, paleoseismology may be constrained to the middle (4-6 ka) and early (7-10 ka) Holocene time in which different types of evidence may still be well preserved (Wallace, 1986; McCalpin, 1996).

Geological paleoseismic evidence found along the low-lying coasts on the eastern margin of the Pacific Ocean basin have led to important contributions to the history and prehistory of this tectonically active region of south-western Canada and north-western United States (Figure 4.1). Sedimentary evidence in coastal intertidal, estuarine, lagoonal and washover environments from the southern tip of Queen Charlotte Islands in British Columbia to northern California confirm the great earthquake cycle model attributed to the Cascadia Subduction Zone (CSZ) (Adams, 1990; Darienzo *et al.*, 1994; Atwater *et al.*, 1995; Clague, 1996). More recently, findings in low-elevation lakes have confirmed past episodic disruptive events (Kelsey *et al.*, 1994, 1998; Nelson *et al.*, 1996a; Hutchinson *et al.*, 1997, 2000; Clague *et al.*, 1998, 1999; López *et al.*, 1999a, 1999b; López and Bobrowsky, 2000, 2001). Great seismic events have occurred during the geologic history of the Northwest Coast of North America. These disruptive events are associated with subduction zone earthquakes (M_w>8) capable of soil liquefaction, sudden land subsidence and tsunami generation. To date, the paleoseismic geologic evidence found consists of several types of geomorphic features and sedimentary deposits that can

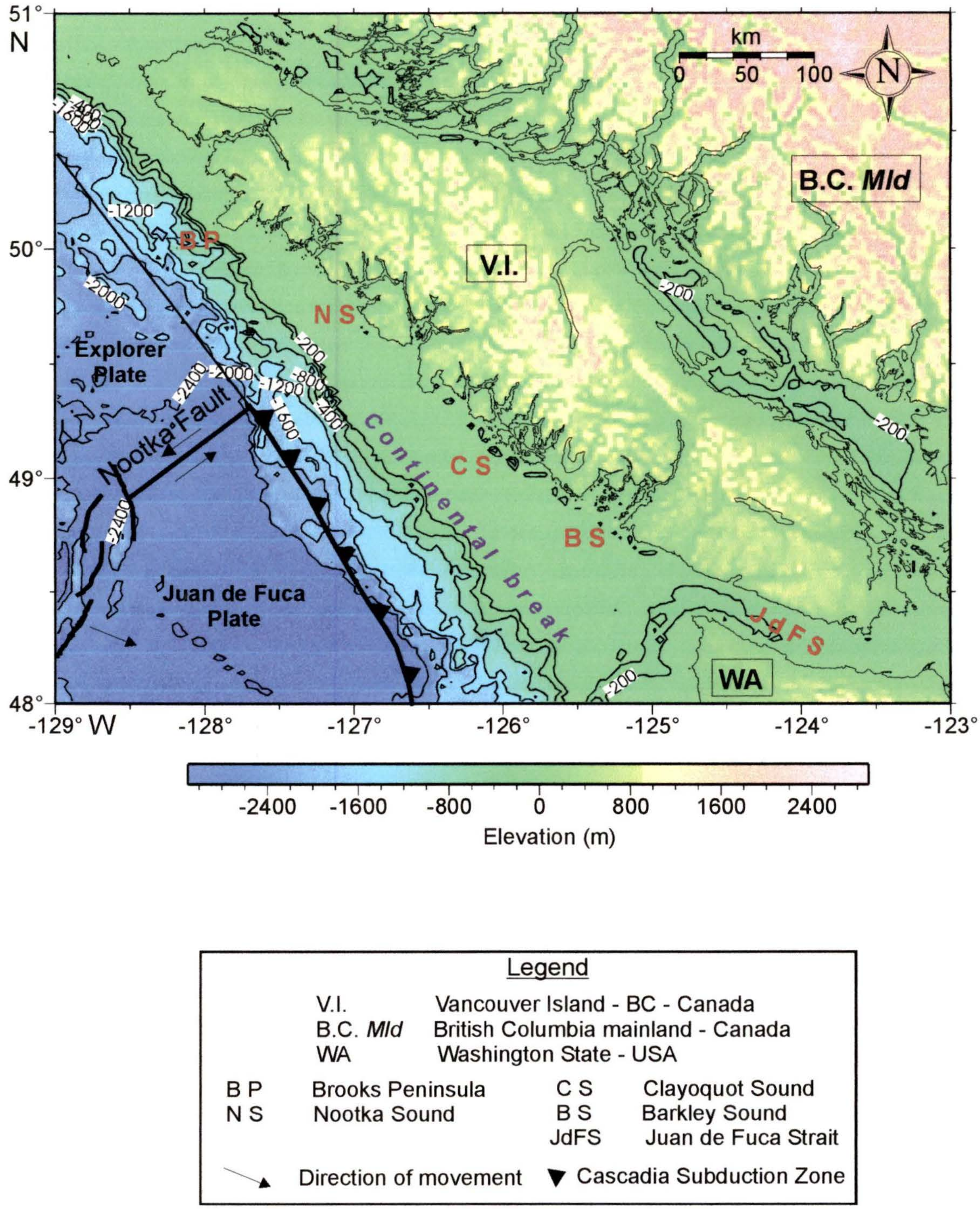


Figure 4.1 Bathymetric map offshore Vancouver Island, British Columbia, Canada. Locations mentioned on the text are noted. The tectonic setting of this northern part of the Pacific Northwest is also marked. Note the 200 m iso-bathymetric contour line denoting the Continental break: the width of the shelf increases continually to the south of BP and reaches its maximum at the entrance of JdFS (Source: modified from GMT, 2001).

only be explained by the occurrence of great earthquakes and subsequent tsunami inundation.

The last mega-event at CSZ was a great interplate earthquake ($M_w \sim 9.0$) that occurred on January 26, 1700 (Satake *et al.*, 1996), dating based on Japanese written records and rating based on tsunami propagation model. The lack of a record of interplate seismicity is due to the relatively short documented history (~200 years) of this part of the "New World", compared to other areas around the Pacific Ocean (i.e. Japan and South America). For the Pacific North America, written records began with Captains Don Juan José Pérez Hernández (in 1774) and James Cook (in 1778), on their arrival in this region (Moziño, 1792). Despite the sometimes fabulous or mythical connotations of aboriginal oral traditions, evidence of both earthquakes and tsunamis are also reported by the Northwest Coast aboriginal peoples (Clague, 2001). Archaeological findings confirming village abandonment along the west coasts of Vancouver Island in British Columbia, Washington and Oregon (Connolly, 1992; Cole *et al.*, 1996; Hutchinson and McMillan, 1997) are also important for the interpretation of Cascadia seismic events and to corroborate recurrence intervals.

Reliable seismic instrumental records for this northern portion of Cascadia were not available until 1948. Prior to this date much of the information was obtained from older international seismic reports (Rogers, 1983). In addition, tide metres were only installed on the British Columbia coast in 1910 (Philip, 1982). Such lack of historic numerical data enhances the value of older written records and aboriginal traditions, as well as paleoseismic evidence. In addition, paleoseismic data may constrain tectonic parameters such as width and length of the fault rupture based on the extensiveness of correlated tsunamigenic deposits along coastal lands neighbouring subduction zones.

Several coastal lakes on the west coast of Vancouver Island have been investigated for records of paleoseismicity, but few have shown evidence of tsunami inundation (Figure 4.2). To provide further information on the paleoseismology of the outer Pacific west coast of Canada, one coastal lake protected from direct ocean water washover were targeted. The aim of this research was to provide detailed information on the sedimentological characteristics of tsunami deposits found in lacustrine environments,

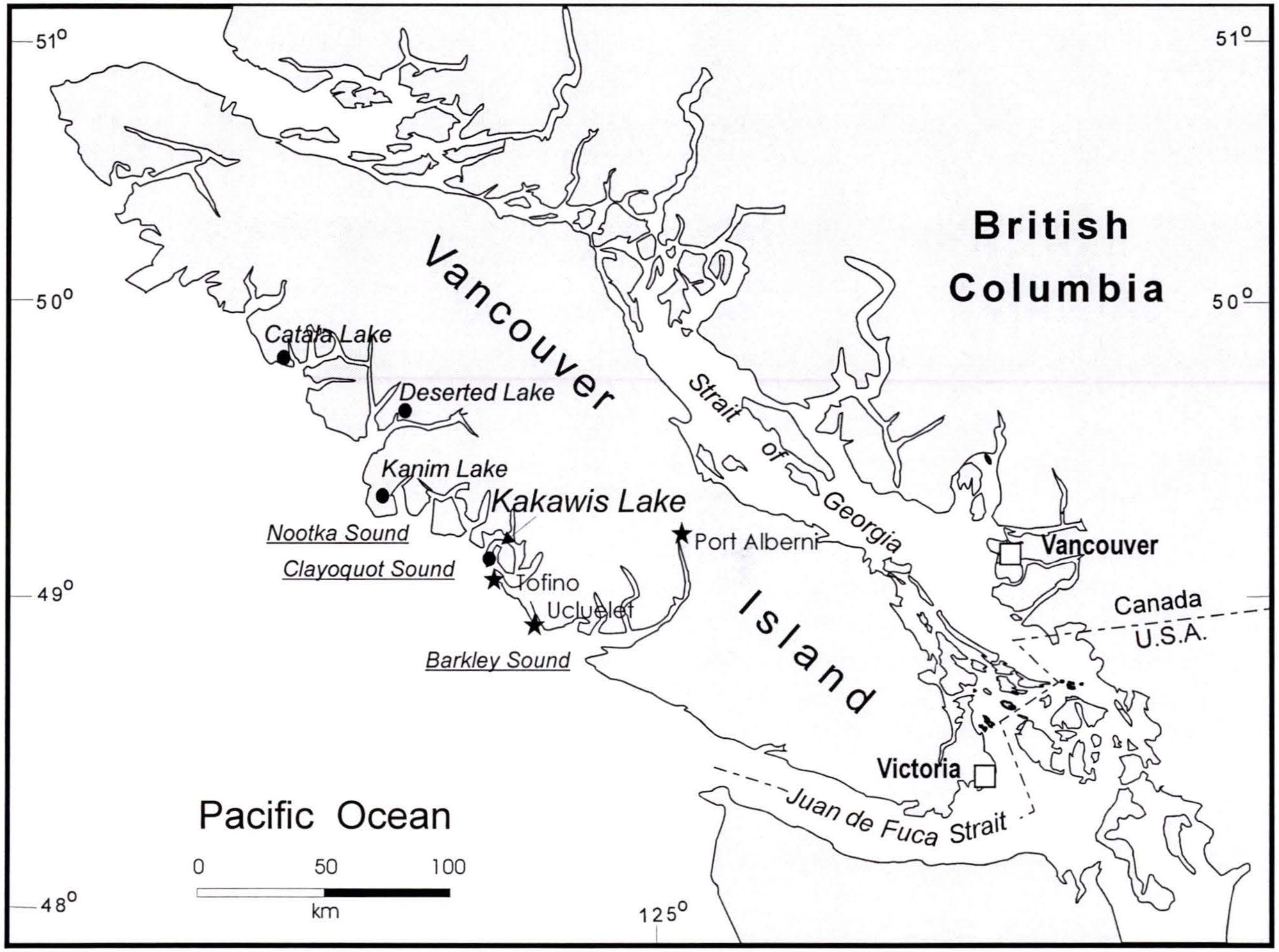


Figure 4.2: Location of principal sites referenced in the text. The circles represent low-elevation lakes where paleoseismic investigations have evidenced paleotsunami events. The stars locate the closest sites to the study area (Clayoquot Sound region) where paleotsunamigenic evidence as well as coseismic subsidence have been found in tidal marshes(Sources for sites other than this research: Clague *et al.*, 1999; Hutchinson *et al.*, 1997, 2000).

and provide further information on tsunami sedimentation in such depositional systems. Tsunami deposits were distinguished on the basis of their macro-particles and by multiple geophysical and biochemical analyses (c.f. Chapters 2 and 3). Potential recurrence intervals and possible magnitudes of the paleotsunamis that generated the deposits are discussed here.

This chapter examines a range of paleoseismic evidence found in a low-elevation coastal lake (Kakawis Lake) located in west central Vancouver Island, British Columbia. It then relates this evidence in time, space and nature to similar deposits encountered elsewhere on Vancouver Island and the Pacific Northwest. Oral traditions, historic written records and diverse archaeological evidence related to areas surrounding the lakes were also integrated to produce a maximum chrono-correlation.

RESEARCH SITES

The cored site was a freshwater lake located less than 500 m away from coastal waters in the Clayoquot Sound region (Figure 4.3). The lake is surrounded by dense temperate rain forest vegetation typical of the region, with arboreal coniferous varieties such as cedar, hemlock and spruce.

Kakawis Lake is located on the western peninsula of Meares Island (Figure 4.4), that is a rugged and rocky body composed of granitic and metamorphic rocks, metasediments as well as a few volcanic rocks (BCGSB, 2000). Kakawis Lake sits on an intrusive granodioritic body, 4 m above mean sea level (amsl), 4.5 km north of Tofino and 9 km east from the open Pacific Ocean. It has an outlet stream 200 m long that flows SE into Lemmens Inlet, a fjord that penetrates Meares Island. The island is separated from the insular mainland by steep-sided inlets and channels. It is sheltered from the open Pacific Ocean by Vargas Island, Esowista Peninsula and numerous islands and intertidal lows around Tofino. The intertidal marsh and shallow areas of Lemmens Inlet and Browning Passage are carpeted with blocks and rubble with sand and silt derived from the crystalline and metamorphic bedrock (Fulton, 1995) as well as organic debris that surround the area.

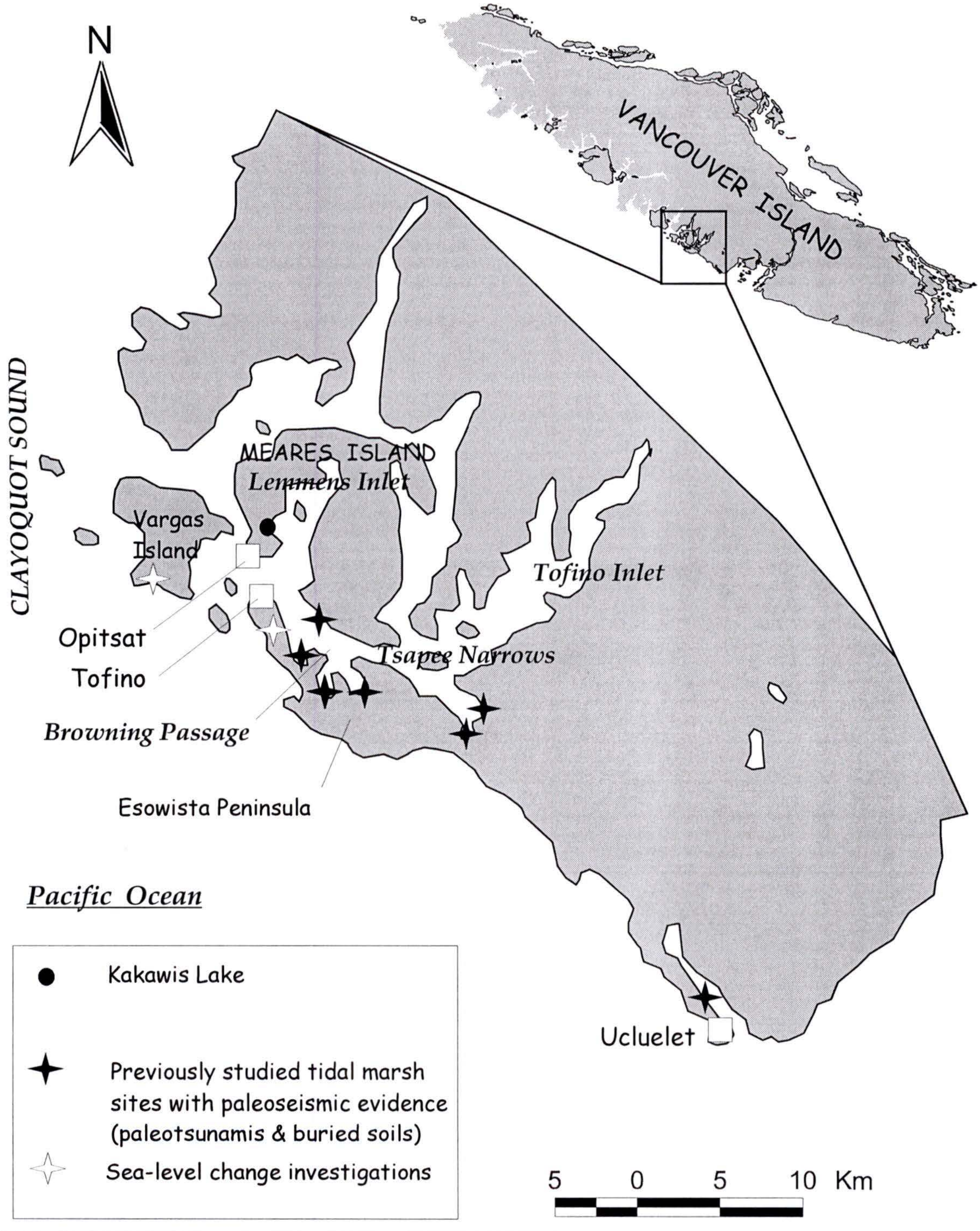


Figure 4.3 Location of Clayoquot Sound region, depicting the principal sites neighboring the study sites of Kakawis Lake. Sources for locations of previously studied tidal marsh paleoseismic sites: Bobrowsky and Clague (1991); Clague and Bobrowsky (1994a, 1994b); Guibault *et al.* (1995, 1996). Sources for locations of sea-level investigations: Friele and Hutchinson (1993).

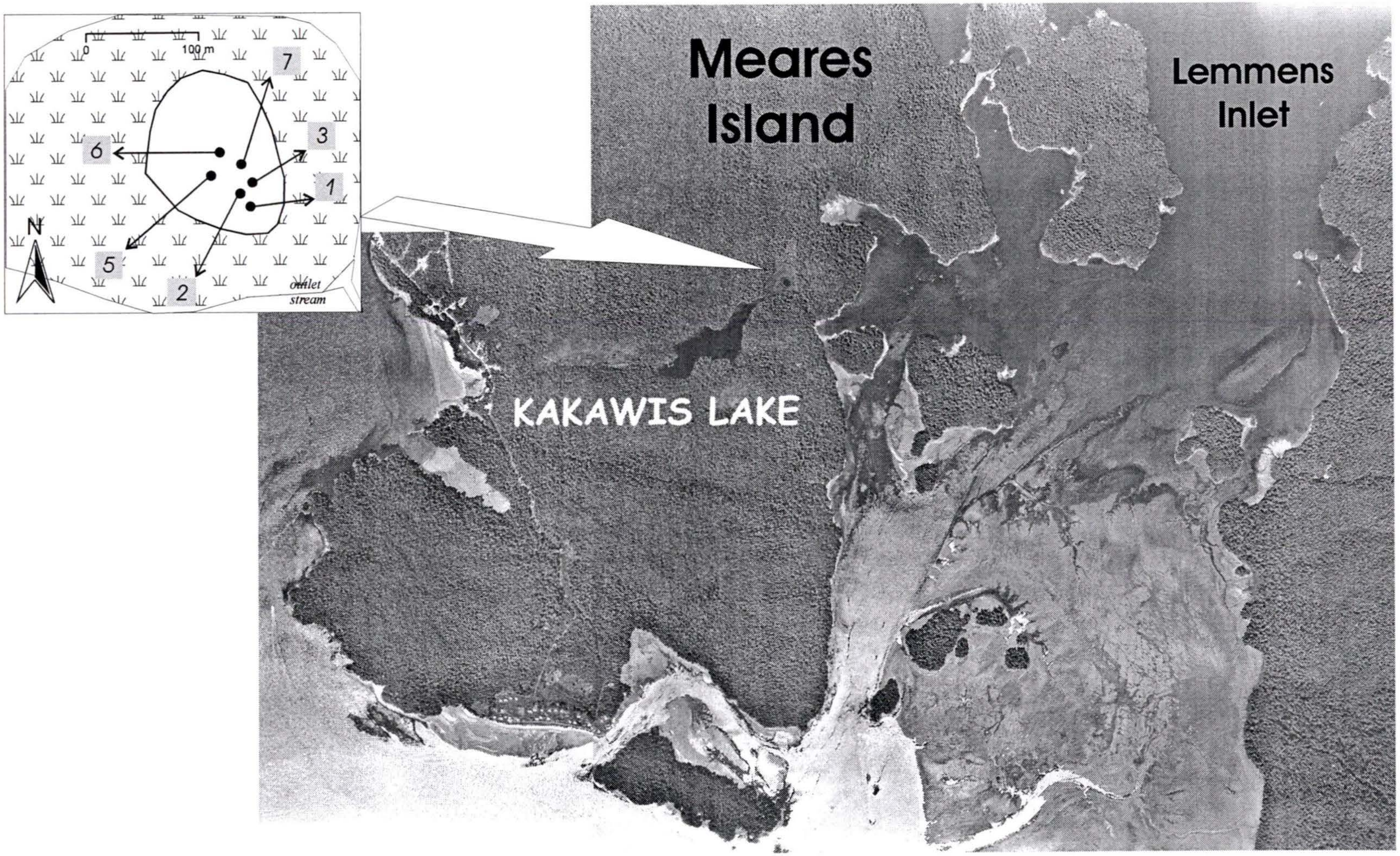


Figure 4.4 Lemmens Inlet entrance and SW peninsula of Meares Island (BC Ministry of Env., Lands & Parks, air-photo C-020-F1-96 / 30BCC9600, org. scale 1:15.000). The core basin is shown by an arrow. The area is protected by numerous islands, passages, shallow waters and vast intertidal mud-flats as seen in this photograph. Very narrow areas are channels deep enough to hold volumes of incoming ocean water.

Kakawis Lake was identified for this investigation because of its low elevation above mean sea level and proximity to previously studied sites (Figure 4.3). In the vicinity of Kakawis Lake, evidence of past tsunamis is preserved mainly as sand sheets in many tidal marshes. South Meares Island and Tofino marshes, located along the sides of Browning Passage, were the focus of paleotsunami investigations that documented subsidence, burial of peat horizons and tsunami inundation associated with great paleoearthquakes (Bobrowsky and Clague, 1991; Clague and Bobrowsky, 1994a, 1994b; Guibault *et al.*, 1995, 1996). In addition, Holocene sea level curves, last Glacial Maximum ice extent and post-glacial rebound interpretations as well as coseismic subsidence rates have been inferred from several investigations cited within the Clayoquot Sound area (Clague *et al.*, 1980, 1982; Bobrowsky and Clague, 1992; Friele and Hutchinson, 1993; Dyke, 1996; Clague, 1996, 1997; Clague and Bobrowsky, 1999; James *et al.*, 2000).

METHODS

To reconstruct the paleotsunami record of Kakawis Lake, six sediment cores (K1, K2, K3, K5, K6 and K7) ranging from 2.72 to 5.43 m were recovered from the east basin, near the single lake outlet stream (Figures 4.4 and 4.5). The cores were obtained using PVC pipes and by modifying the percussion coring system of Reasoner (1993) to operate it from a floating platform.

All cores were described, analysed and sampled in the laboratory, following analytical procedures described in Chapter 2. Procedures included two geophysical methods (magnetic susceptibility and electric resistivity) and a radiographic analysis (x-radiograph imagery of an entire split core). The non-destructive procedures were successful applications in defining anomalously coarse sandy-detrital-shelly layers embedded in lacustrine sediments.

Water content, organic and inorganic carbon content, and calculated physical parameters were obtained for the overall sedimentary sequences. C/N ratios were analysed in two cores, comprising both lacustrine and inferred tsunami layers. Separation and subsequent analyses of the materials (clasts, shells and vegetation detritus) from the

MEARES ISLAND, SW PENINSULA
Topographic Map of the surroundings of Kakawis Lake

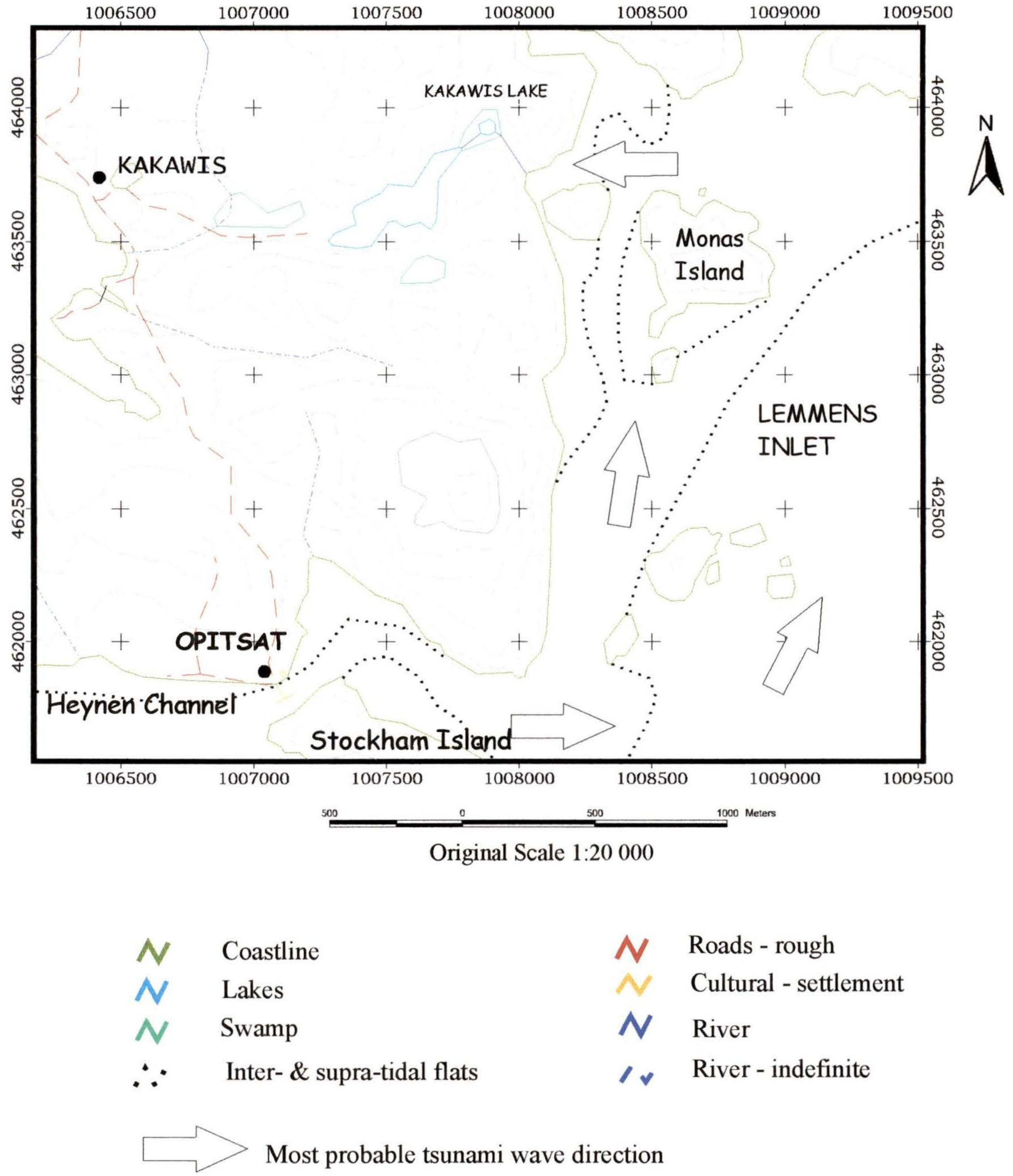


Figure 4.5 Trim Map of areas 92F and 92E, SW peninsula of Meares Island, North of Tofino, on the Clayoquot Sound region. The topographic contours have 20m intervals. Note the low morphology surrounding Kakawis Lake and the extensive tidal flats at the entrance of Lemmens Inlet.

anomalous layers was also carried out on the cores, and percentage contents of carbonate, vegetative (detrital) and terrigenous particles were obtained. Detailed grain size analyses were performed in the anomalous layers inferred to be tsunamigenic in origin. Shell fragments, > 1 mm, were used in species identification. Individual terrigenous cobbles and sand-size particles were closely analysed. No microfossil assemblages were evaluated.

Samples of wood, bark, twig, conifer needles and cone bracts from below, within and above the anomalous layers were radiocarbon dated at Isotrace Laboratory (University of Toronto). Shell fragments from the bottom glaciomarine unit of core K5 (the longest core recovered from Kakawis Lake) were also dated by the same laboratory. Radiocarbon ages cited in this study are reported as calibrated age ranges (datum = AD 1950 and 68.3% confidence interval) unless specified, and were determined by using INTCAL 98 and CALIB 4.3 (Stuiver and Pearson, 1993; Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). Sedimentation rates were calculated from ^{14}C dates obtained stratigraphically below inferred tsunami deposits and were constrained by modern accumulation rates obtained from ^{137}Cs activity analysis. The ^{137}Cs analysis of the top 30 cm of sub-bottom lacustrine sediments from Kakawis Lake was also used to test for tsunami evidence of the AD 1964 Alaska tsunami event in the lake. This tsunami event is known to have deposited anomalous sheets of sand in marshes around Tofino, Esowista Peninsula and Meares Island (Bobrowsky and Clague, 1991; Clague and Bobrowsky, 1994a, 1994b) (Figure 4.3).

THE CASCADIA SUBDUCTION ZONE REGION

The present tectonic regime of south-western British Columbia, Washington, Oregon and northern California is controlled by the motions of a young (~10 Ma) (Heaton and Hartzell, 1987) oceanic crust colliding with the North American (NA) continental plate. The Juan de Fuca (JdF) plate, a remnant of the Farallon plate, underthrusts NA at the Cascadia Subduction Zone (CSZ), a 1000 km long tectonic lineament, at a rate between 33 and 50 mm/a (Keen and Hyndman, 1979; DeMets *et al.*, 1990; Savage *et al.*, 1991; Hyndman and Wang, 1993, 1995; Dragert *et al.*, 1994, 2001; Flück *et al.*, 1997). In British Columbia the collision takes place off-shore of Vancouver Island (Figure 4.1), the southernmost exposed part of a 100 Ma old Insular Supraterrane, with rocks from Wrangellia and smaller Pacific Rim and Crescent terranes (Muller, 1977; Gabrielse and Yorath, 1992; Yorath and Nasmith, 1995).

Over the past decade, diverse geophysical, thermal regime and sea-level fluctuation models have indicated that Cascadia has great potential of generating disruptive events (Clague *et al.*, 1982; Savage, 1983; Rogers, 1988; Friele and Hutchinson, 1993; Hyndman and Wang, 1993; Flück *et al.*, 1997). Cascadia presents most of the features related to an active subduction zone, but its' locked behaviour makes it different from other active subduction zones of the world that have produced great earthquakes since AD 1900 (e.g. Alaska, Colombia, Peru-Chile, Japan) (Heaton and Hartzell, 1986; Whitmore, 1993). The seismic theory categorizing Cascadia as an active but cyclic subduction zone (Hyndman and Wang, 1993), with long inter-seismic periods and short, greatly disruptive seismic events, is today widely accepted (Dragert *et al.*, 1994, 2001; Hyndman and Wang, 1995). Despite the locked regime of the shallower subducting portion of Cascadia (all the above), western B.C. is the most seismically active region in Canada (Anglin *et al.*, 1990). The accumulating inter-seismic strain (elastic) is deforming, compressing and bulging the western continental crust of Vancouver Island, leading to an uplift of 1-4 mm/a (Hyndman and Wang, 1995) as well as a continuous accumulation of energy (Savage *et al.*, 1991).

RECONSTRUCTION OF THE SEDIMENTARY RECORD FROM KAKAWIS LAKE

Figure 4.6 shows the different units observed at Kakawis Lake longest core (K5).

SUB-BOTTOM SEDIMENTARY SEQUENCE FROM KAKAWIS LAKE

Kakawis Lake sedimentary sequences were divided into three main units based on distinct lithological differences. From bottom to top, the units are summarized as follows

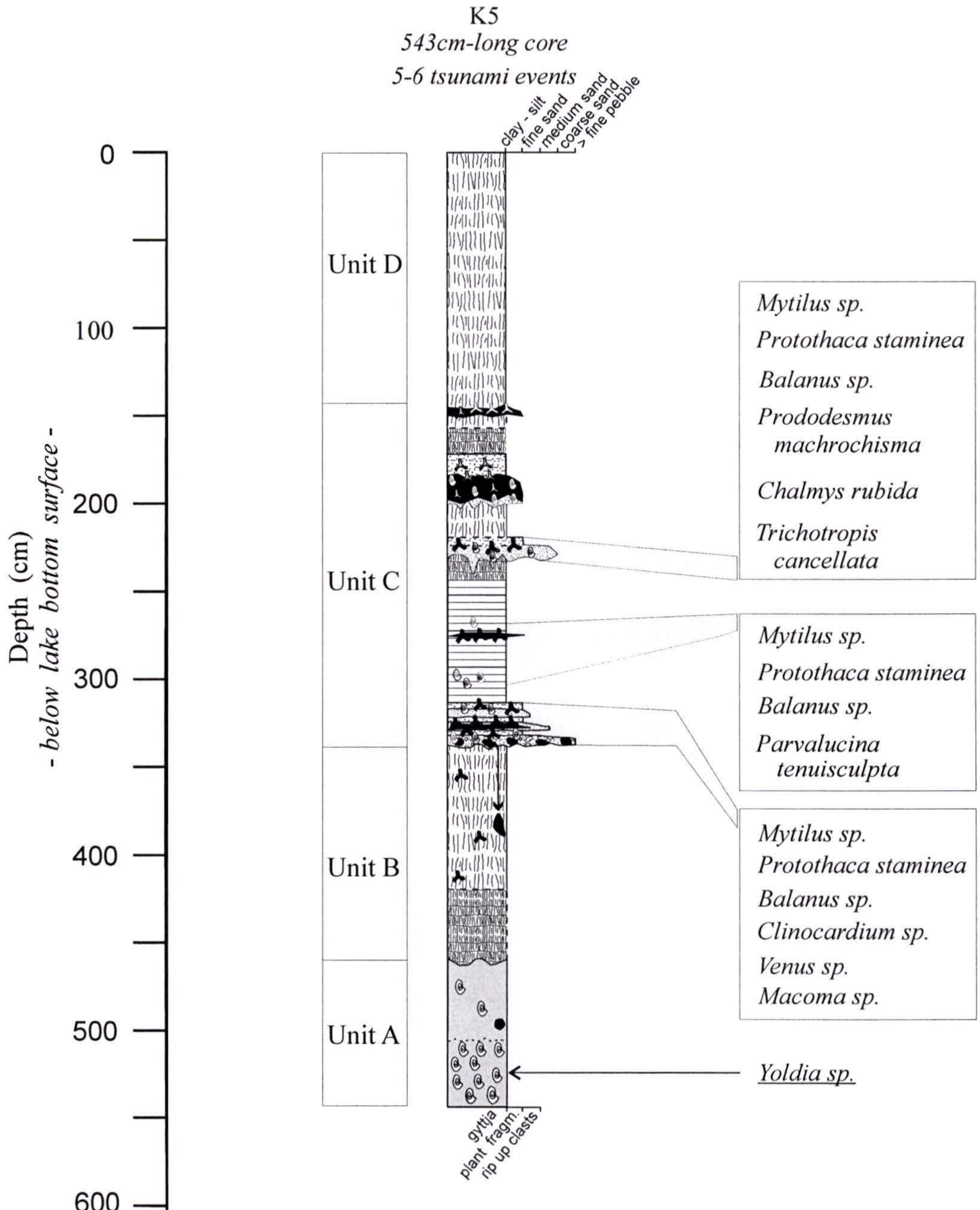


Figure 4.6 Graphic log showing lithology of core K5. Different tsunami deposits at Kakawis Lake have similar marine shell species associated with the anomalously coarse layers. The abundance of these intertidal molluscs, crustaceans and minor gastropods fossils is associated with different pre-historic tsunami events that may have inundated Kakawis Lake at different times. Lithological units are shown.

(Figure 4.6). Unit A is composed of greyish massive glaciomarine sandy silty clay associated with deep water marine shell species (*Yoldia sp.*) showing sporadic granitic pebble-size clasts glacially shaped. Unit A was only recovered from core K5. Late Wisconsinan age ranges between 15,329-15,734 cal yrs BP (bottom) and 14,154-14,394 cal yrs BP (middle) were obtained for this unit. The peak of the Late Wisconsin glaciation around Tofino may have not been much earlier than 16,700± 150 ^{14}C yr BP (date from Clague *et al.*, 1980; Blaise *et al.*, 1990). Based on the glacial and postglacial rebound history of central to south Vancouver Island (Mathews *et al.*, 1970; Clague *et al.*, 1982; Dyke, 1996; James *et al.*, 2000) the maximum extent of the Cordilleran Ice Sheet over the central-western margin of Vancouver Island occurred around 14,500 to 14,000 cal years BP, when it reached the continental shelf. Sea level on central western Vancouver Island then oscillated around 30 m above present datum (Clague *et al.*, 1982). Ice retreat in isostatically depressed coastal areas was rapid. Subsequent marine regression was caused by isostatic rebound, and submerged coastal lowlands rapidly rose between 13,000 to ~10,000 cal yrs BP (Clague *et al.*, 1982). Unit A may represent distal marine facies associated with initial decay of the Cordilleran Ice Sheet in the western peripheral margin of central Vancouver Island (c.f. Clague, 1983, 1989b; Roberts, 1991; Dyke, 1996).

Unit B corresponds to the very dark brown massive to discontinuously horizontal fine sediments enriched in organic matter associated with lacustrine deposition within Kakawis Lake (Figure 4.6). A pre-Holocene radiocarbon age range of 13,614-13,814 cal yrs BP dates the beginning of this organic-rich accumulation in the lake and is associated with the ice-free conditions of parts of marginal coastal lowlands of SW Vancouver Island (c.f. Blaise *et al.*, 1990; Mathewes, 1991; Roberts, 1991; Hebda, 1995; Dyke, 1996; Clague *et al.*, 1997). The age was obtained from a wood fragment just 3 cm above the sharply wavy contact with Unit A. A crude sedimentation rate of 0.02 cm/a is estimated for Unit B (pre-Unit C) based on radiocarbon dates. Lacustrine sedimentation re-starts after Unit C deposition (Unit D) extending in time until today and defines the modern fresh water gyttja accumulating at the floor of the lake.

Unit C represents the numerous anomalous layers embedded within massive to finely laminated gyttja (Figures 4.6 and 4.7). The layers are inferred to be deposited by tsunamis either of distant or local provenance, but most likely tectonic origin. Although efforts have been made to distinguish tsunami layers from other marine-induced extreme waves, it is very difficult to unequivocally differentiate one from the other based only on lithological characteristics (Sato *et al.*, 1995). However, in the case of Kakawis Lake anomalous layers, the evidence strongly suggests the depositional mechanism to be tsunamis. A collage of information including stratigraphical, macro-biological, radiocarbon data as well as spatial distribution, grain size analyses and variation of lithofacies, may help identify tsunami deposits from other extreme ocean waves with confidence (c.f. Nishimura and Miyaji, 1995; Shi *et al.*, 1995; Nanayama *et al.*, 2000). Terrestrial and fluvial origins are discarded (c.f. Figures 4.4 and 4.5). Details of such analyses are expanded in Chapter 3.

Unit C has an erosional basal contact with Unit B. Six possible tsunami events are suggested, averaging 1.5 m of anomalous accumulation (Figure 4.7). These deposits were emplaced in the lake during middle to late Holocene, between 8169-8344 cal yrs BP and 2334-2358 cal yrs BP.

TSUNAMI DEPOSITS AT KAKAWIS LAKE

It is thought that Kakawis Lake may have experienced six inferred tsunami events during the middle to late Holocene (Figure 4.7). Terrigenous material ranging from mud to cobble size particles, carbonate material comprising diverse shell species exclusively marine (up to 4 cm long), and terrestrial plant detritus of various types and sizes (up to 9 mm long) represent the materials forming the anomalous layers. All materials are from local intertidal, shoreface, backshore and terrestrial environments found in the immediate vicinity of Kakawis Lake.

The anomalous layers were classified into distinct facies to enhance the identification and correlation between the different tsunami events found in all six cores recovered from Kakawis Lake. In Chapter 3, these facies are used to establish a model of

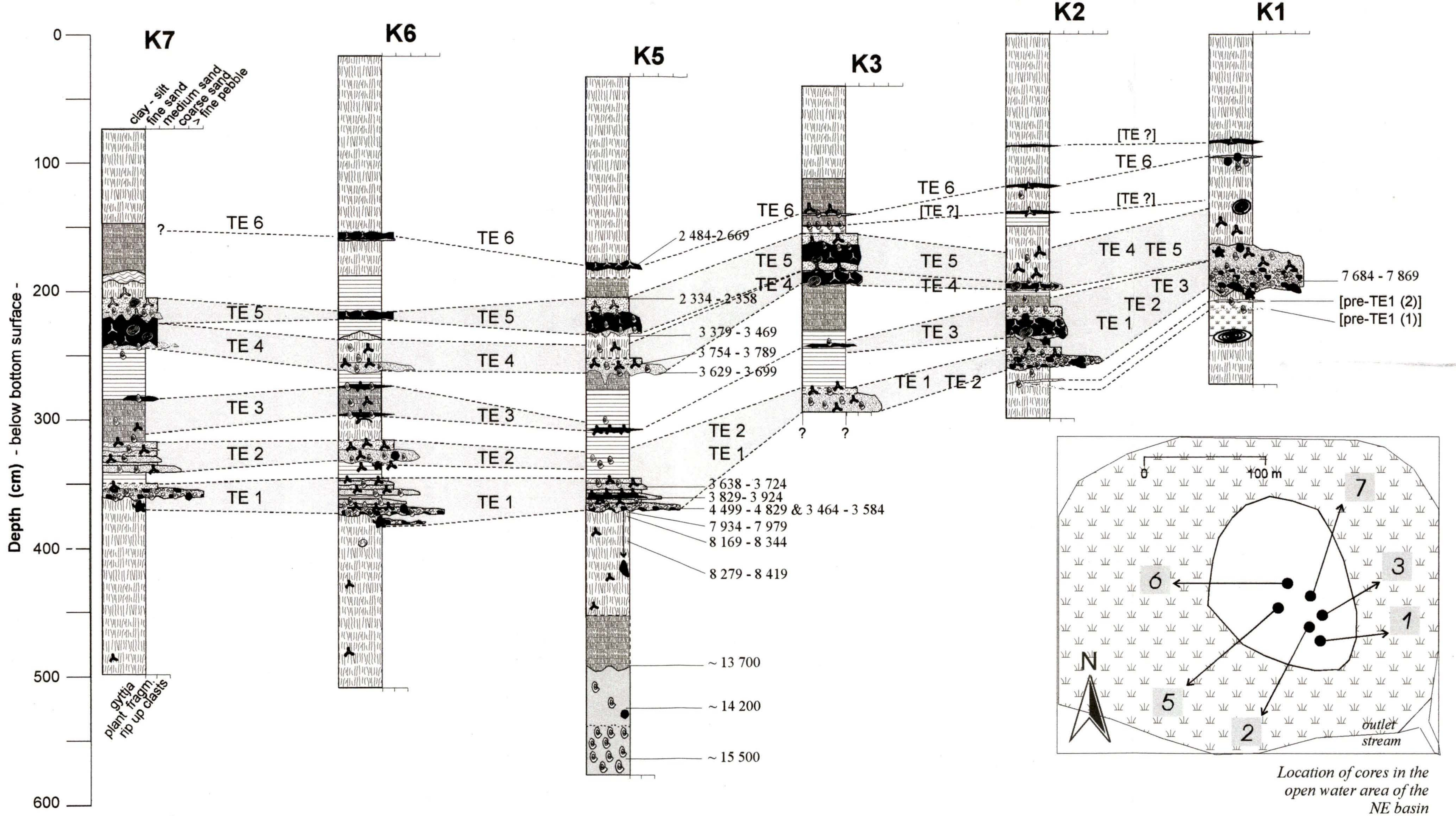


Figure 4.7 Graphic logs of sediment cores recovered from Kakawis Lake. The cores are organized from northwest (left) to southeast (right). The lake is deeper near cores K5, K6 and K7. Based on thickness of tsunami layers, core K1 is the closest to the tsunami run-up source. Tsunami deposits farther away (northwest) from the outlet stream contain less gravel- size particles and also grain-sizes generally decrease. However, tsunami beds (pulses) are better defined towards the central part of the lake where organic detritus caps are generally thicker. This is most probably due to differences between settlement velocities of suspended particles at the time of tsunami inundation. Radiocarbon ages are shown in age ranges 14C calibrated years BP (datum = AD 1950). Tsunami events are designated by numbers (1 for the oldest and 6 for the youngest). Finer anomalous layers are designated by a question mark.

tsunami deposition. Each facies was inferred to represent different stages associated with pulses (influx/flood) or inter-pulses (outflow/ebb) of a given tsunami wave train. Four facies were recognized based on compositional as well as geophysical and biochemical characteristics defined from the various analyses undertaken: a) massive gravel facies; b) massive sand facies; c) chaotic organic conglomerate; and d) organic detritus cap. A group of facies constitute a tsunami event, but not all events presented all four facies. Table 4.1 summarizes the characteristics of each facies at core sites K1 and K7. K1 is the closest core to the outlet stream and K7 is the farthest one (Figures 4.5 and 4.7). To better establish textural differences or similarities between tsunami deposits emplaced in lakes from those found in tidal marshes, a sample from the AD 1700 tsunami sand layer at Port Alberni marsh was also collected and analysed following the same procedures used for samples from Kakawis Lake.

GEOCHRONOLOGY OF TSUNAMI EVENTS

The timing of the inferred marine inundations at Kakawis Lake is bracketed by 14 radiocarbon ages (Figure 4.7). All radiocarbon ages were obtained from terrestrial plant detritus. Ages of tsunami events comprise the 68.3% confidence interval range and are referred as calibrated ages before AD 1950 (cal yrs BP) to allow consistency with previously published paleo-tsunami chronologies. Most of the plant material used for age determination was collected from core K5 in the centre of the lake. Some radiocarbon ages were obtained from core K1, the closest to the outlet stream. The plant fragments are reworked material from nearby forest floors present at the time of the tsunami inundations. It is known that dates obtained from plant detritus accumulated along the peat-mud contact of coseismically buried tidal marsh soils provide the approximate age of the tectonic event that produced the subsidence (Atwater *et al.*, 1995; Nelson *et al.*, 1995, 1996b).

For massive tsunami deposits found in lacustrine basins, the lowest radiocarbon values obtained from within the deposit may provide the approximate maximum date of deposition, hence a possible age of the inundation event. However, it is suggested that when a broad range of radiocarbon dates is obtained from different organic material from

Table 4.1 Variations between geophysical, biochemical and sedimentological characteristics of different tsunamigenic facie from cores K2 and K6/K7 from Kakawis Lake. For comparison purposes, values were also obtained from a sample for the AD 1700 tsunami sand from Port Alberni marsh.

Facies #	**7**				**8**				**9**				**10**				*Port Alberni*
Facies Name	Massive gravel				Massive sand				Chaotic organic conglomerate				Organic detritus cap				*Tsunami sand AD 1700 event*
Facies description	pebbly-shelly-detrital sand with cobbles				shelly-detrital sand with sporadic gravel				coarse plant detritus with shells and minor sand				shelly-sandy fine plant detritus				*detrital sand*
CORES	KA6/K7		K2		K6/K7		K2		K6/K7		K2		K6/K7		K2		*marsh*
Analyses	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	*min-max*
Electrical Res. (mV)	42	138	n/a	n/a	35	102	n/a	n/a	35	270	n/a	n/a	33	75	n/a	n/a	*n/a*
Mag. Susc. (x10e6 SI/vol)	260	760	n/a	n/a	80	260	n/a	n/a	0	300	n/a	n/a	0	240	n/a	n/a	*n/a*
C/N	21	35	n/a	n/a	17	29	n/a	n/a	16.5	17	n/a	n/a	15	32	n/a	n/a	*13.1*
TOC (%)	12	25	5	20	25	40	25	30	15	60	28	60	15	58	15	43	*2.3*
Max grain size (phi)		-4		-7		-2.5		-2.5		-2		-2.5		0.5		0.5	*-0.5*
Mean grain sizes (phi)	0	-6	-1.5	-6	4	-0.5	0	-1	6	1.5	6	0	6	0.5			*1.6*
Particle sorting	VPS	PS	PS	PS	MS	WS	PS	PS	MS	MS	PS	PS	VPS	PS	PS	PS	*MWS-WS*
Number of modes		6		4		4		5		3		2		3		3	*2*
Terrigenous composition:																	
% Gravel	10	46	44	94	0	22	12	36	0	0	0	28	0	20	0	30	*0*
% Sand	40	80	8	44	65	100	34	85	35	100	0	80	0	100	0	100	*0-100*
% Mud	1	1	0	14	1	1	2	54	0	35	0	48	0	50	0	4	*0-10*
Elemental composition:																	
% Carbonate material	30	50	10	35	10	55	45	52	0	40	0	52	15	50	20	52	*<1*
% Vegetative fraction	1	10	0	35	42	60	28	48	55	100	32	100	45	85	15	55	*0-11*
% Terrigenous fraction	13	60	0	88	2	35	2	20	0	5	1	21	0	31	0	22	*0-100*
Max of macro-plant detritus (cm)		4		4		2		2		9		9		2		2	*1*
Max of macro-shell fragments (cm)		4		4		3		3		2		2		1		1	*n/a*
Internal structure	chaotic				massive				chaotic				massive				*massive*
Tsunami Event more commonly associated with this facies	TE1		TE1 & TE2		TE2, TE4, TE5 & TE6		TE3, TE4 & TE6		TE3, TE5 & TE6		TE3, TE4 & TE5		TE1, TE2 & TE5		TE1, TE2 & TE3		*exclusively AD 1700*

the same stratigraphical layer, such diversity may show the erosive/cannibalistic behaviour of tsunamis. Due to their great energy, tsunamis may destroy previously deposited layers (even older tsunami deposits if present) and mix the older material with their actual load. In paleo-deposits, it is very difficult to establish the thickness of sediment eroded during a tsunami event (i.e. unconformities as bottom contacts).

In core K5, a twig 7934-7979 cal yrs BP obtained directly below the contact with the underlying gyttja from Unit B pre-dates any tsunami deposition at Kakawis Lake (Figures 4.6 and 4.7). Based on the recovered stratigraphic sequences, the first tsunami event to surge into the lake is reported as event TE1 and may have had at least three to four pulses. Twig remains from the bottom of TE1 yielded ages of 3464-3584 cal yrs BP (associated with the first pulse). A much older age (4499-4829 cal yrs BP) was obtained from another twig from the same layer. An age range of 3638-3724 cal yrs BP was established from the top of TE1 (last pulse). An age range of 7684-7869 cal yrs BP was derived from a twig within the coarsest facies (massive gravel) of event TE1 in core K1. In this same layer and core, two older age ranges were derived from a cone bract and a wood fragment. The ranges are 8589-8769 cal yrs BP and 11,084-11,179 cal yrs BP respectively. Event TE1 showed the most diverse pattern of radiocarbon ages among all the six inferred tsunami events (Figure 4.8). Such broad range of dates probably suggests the existence of previously deposited anomalous layers that were truncated, eroded and/or destroyed during the emplacement of TE1. Such possibility may explain the presence of older organic material mixed with comparatively newer plant detritus within TE1, suggesting a "cannibalistic" behaviour for tsunamis during inundation.

Event TE2 may have been emplaced shortly after TE1 because there is little laminated gyttja separating the two deposits. TE2 may have been generated by at least two wave pulses that dispersed material unevenly across the Kakawis water basin. Event TE3 follows TE2.

A twig from the bottom contact of TE4 yielded ages of 3629-3699 cal yrs BP, and bark remains from the top of the same event provided an age of 3754-3789 cal yrs BP (Figure 4.8). TE4 marks a return of anomalously coarse material deposition after a calm period of lacustrine sedimentation. TE4 was probably deposited by a major wave pulse.

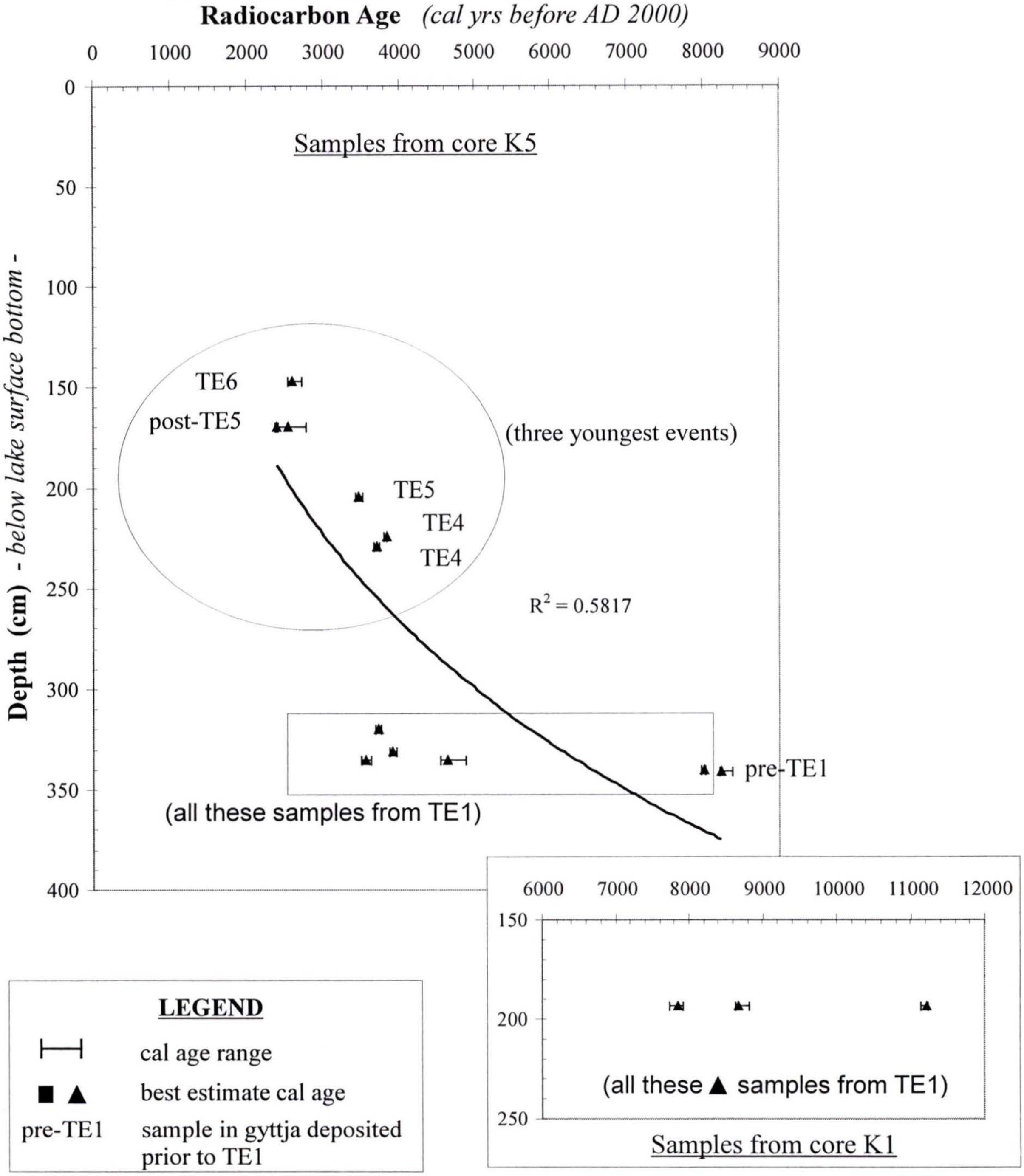


Figure 4.8: Radiocarbon ages from organic samples collected within, above or below different inferred tsunami deposits from two cores (K1 & K5) from Kakawis Lake. All ages are in calendric years before AD 200 and the confidence interval used is 1 sigma (68.3% confidence interval -c.i.-). No ages were obtained from tsunami events TE2 and TE3. Note the different radiocarbon ages obtained for the first tsunami event TE1 (oldest event at Kakawis Lake). Such diversity may suggest material re-working and/or previously deposited organic debris from older anomalous events which were eroded, mixed and/or re-worked by TE1.

Shortly after TE4 deposition, TE5 entered Kakawis Lake. An age range of 3379-3469 cal yrs BP from a cone bract marks the beginning of TE5 (Figure 4.8). Two more age ranges obtained from coniferous needles and twigs are associated with the section directly above the top contact of the event (2349-2739 and 2334-2358 cal yrs BP). TE5 is defined by one or two wave pulses.

TE6 is the youngest tsunami event to be recorded at Kakawis Lake. An older age (2484-2669 cal yrs BP) was established on twigs collected from the top section of the event (Figure 4.8). TE6 is also the thinnest event and disappears towards the centre of the lake.

By correlating the radiocarbon ages obtained for all the above inferred tsunami deposits with the Atwater – Hemphill-Haley chronology of large subduction earthquakes and accompanying tsunamis estimated for the Cascadia region (Atwater and Hemphill-Haley, 1997), it is possible that Kakawis may have experienced the three oldest events inferred for this North American region (Figure 4.9 and Table 4.2). The chronology identifiers named N (BC 400-800), L (BC 800-1300) and J (BC 1400-1500) may be associated with events TE6, TE5, TE4, respectively. No specific radiocarbon ages were obtained for Kakawis tsunami events TE3 and TE2, however, they are stratigraphically older than TE4 and younger than TE1. TE3, TE2 and TE1 may be associated with events older than identifier J but younger than 7964 cal yrs BP, however there is no absolute certainty on the origin of the possible tsunamis that inundated the lake to produced TE3, TE2 and TE1.

EMPLACEMENT OF TSUNAMI DEPOSITS AT KAKAWIS LAKE

TE1 was the most energetic tsunami event found within Unit C. Large clasts (up to -6.5 Φ), marine shells (up to 4 cm), and plant detritus (up to 5 cm) characterise all the facies associated with TE1. The diversity and abundance of marine shell species (shell fragments in pristine condition) and preserved acorn barnacle walls attached to the largest granitic clasts may indicate short transport. Tsunami waves are known to be turbulent flows. Assuming TE1 was deposited by a tsunami, the quality and sizes of the different components suggest forces sufficiently powerful to relocate medium-sized cobbles but

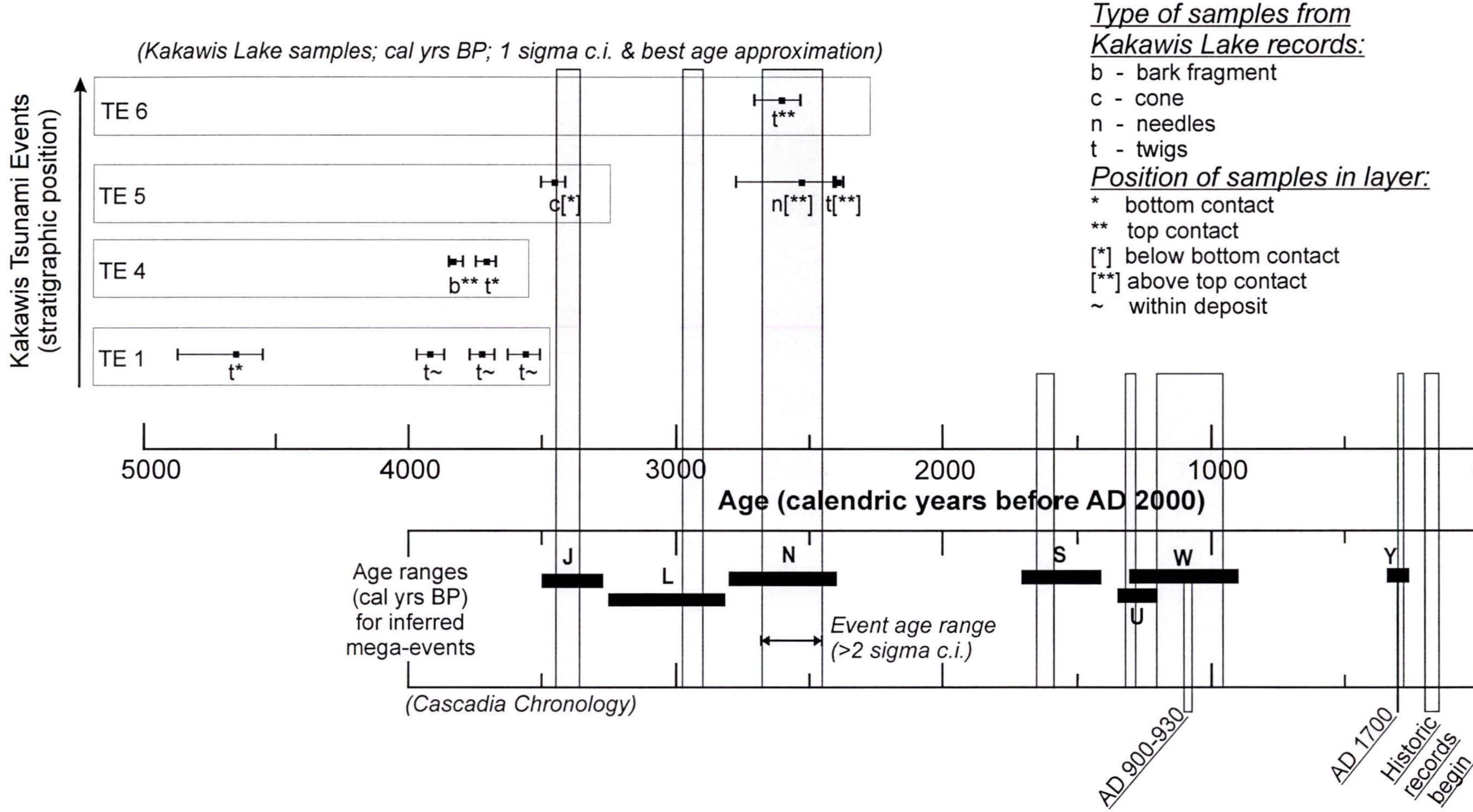


Figure 4.9: Calibrated radiocarbon age ranges of organic samples collected from Kakawis Lake inferred tsunami deposits. Type of organic sample and its position in the record are specified. The tsunami events (TE) to which the samples correspond (also stratigraphically) are marked. TE4, TE5 and TE6 may overlap large earthquakes defined as identifiers N, L and J which are based on radiocarbon ages (Cascadia Chronology modified from Atwater and Hemphill-Haley, 1997 and Atwater, 2002 - *personal communication* -).

Table 4.2: Chronology of Palaeo-tsunamigenic evidence on coastal lakes from western Vancouver Island (British Columbia, Canada).

A — **Mega-thrust Earthquake Chronology - Ages of earthquakes at Cascadia and nearby subduction zones -**

B — **Geological Evidences on Vancouver Island**

C — **Cored lakes on the West Coast of Vancouver Island** *('x' indicates presence of tsunamigenic deposit according to age shown in Table A)*

	Kakawis	Kanim	Deserted	Catala
elevation (m)	~4	6	3	~3
outlet stream (m)	200	700	500	500
depth (m)	3	~2	20	1

Identifier	Age BP *(before AD2000)*	Estimated Age Range	Calendar Age *(AD or BC)*	Marshes	Lakes	Kakawis	Kanim	Deserted	Catala
Al	36	36	*AD 1964*	x					
Y	300	300	*AD 1700*	x	x			x	x
Al? CSZ?	800	800 (?)	*AD 1200 (?)*	x					x?
W	1100	900-1300	*AD 1100-700*	x?	x				x
U	1300	1200-1300	*AD 900-700*						x?
S	1600	1400-1700	*AD 600-300*		x			x	
N	2600	2400-2800	*BC 400-800*		x	x	x	x	
L	3000	2800-3300	*BC 800-1300*		x	x?			
J	3400	3300-3500	*BC 1300-1500*		x	x			
					x	*3 older events <6015 cal yrs BC*			

Letters correspond to event identifiers for Cascadia Subduction Zone earthquakes, based on buried soils present in marshes at Willapa Bay (WA coast, USA)

Datum for lake elevation is mean sea level

Outlet stream length is the approximate distance of lake from closest seashore

Source Table A:
Atwater and Hemphill-Halley, 1997.

Al: Alaska
CSZ: Cascadia Subduction Zone

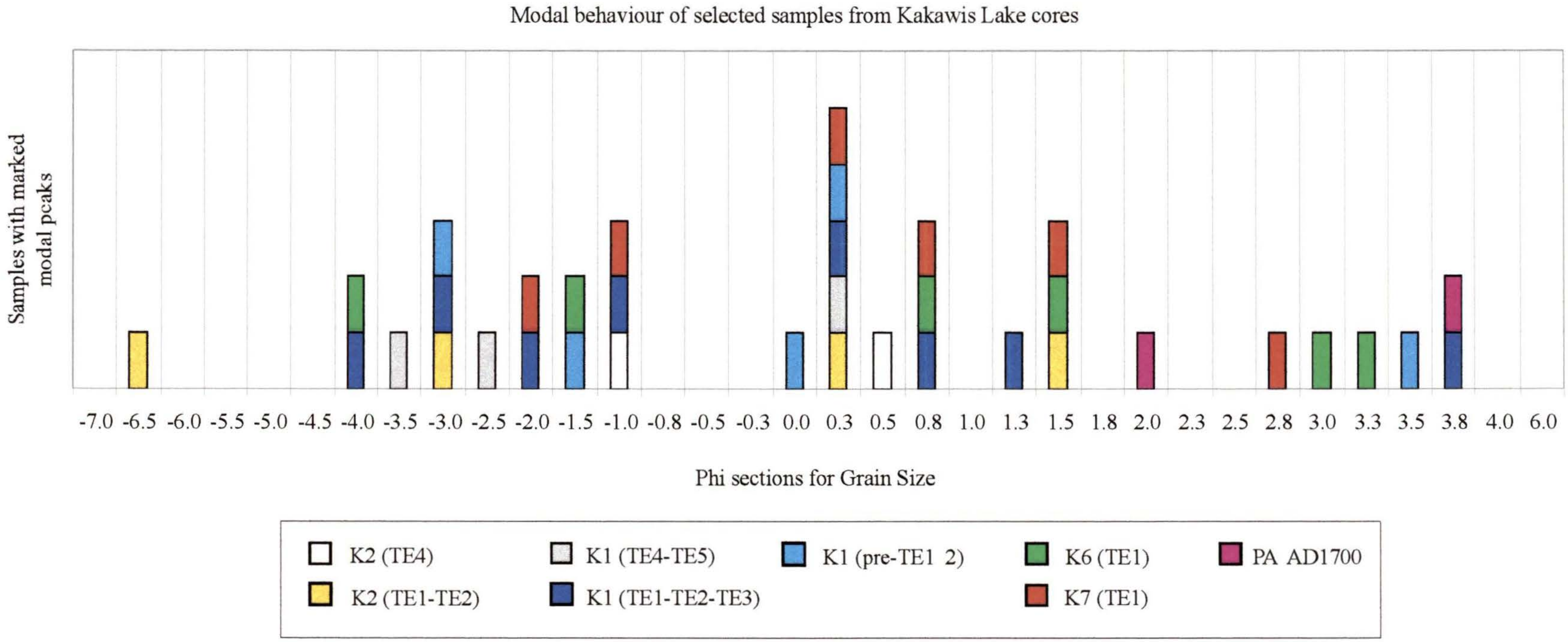
Source Tables B & C:
Clague et al, 1994, 1998, 1999; Hutchinson et al, 1997, 2000; Clague and Bobrowsky, 1994a, 1994b, 1999; Benson et al, 1997. (except for Kakawis Lake ; -current research-)

also rapid enough to preserve long fragments of *Protothaca staminea, Clinocardium sp.*, and *Venus sp.* shells and abundant fragile *Mytilus trossulus* shell fragments. The largest marine shells were found in core K1, suggesting an easier reach of the tsunami to this side of Kakawis basin (closest to the outlet stream) (Figure 4.10). Such characteristics imply that Kakawis Lake may have been at or just below sea level at the time of TE1 (Figures 4.11 and 4.12).

Between TE1 and TE3 a normal gradation seems to occur. Clast sizes diminish from cobble to very fine sand. Large macro-plant detritus diminishes in size by 50% at TE3. Marine shell fragments also diminish in size by almost 50% and the diversity of species diminishes by 75%. This gradational pattern may imply the presence of an obstacle between Lemmens Inlet and Kakawis Lake that impeded major clastic input at the time of TE3 deposition (Figure 4.5). Kakawis Lake may have been continuously emerging since the time of event TE1.

A thick accumulation (up to 67 cm) of laminated to horizontally discontinuous gyttja separates TE3 from TE4. This organic matter-rich accumulation suggests a calm period for Kakawis Lake that may be related with a steady isostatic rebound of the region. However, TE4 marks the return of anomalously coarse material deposition. TE4 is composed of thick (6-22 cm) massive, very coarse sand, as well as large marine shells and plant fragments up to 9 cm long. The diversity of marine shell species for TE4 increases by 88% compared to TE3 and the size of the marine shell fragments increases by 30%.

Shortly after TE4, TE5 inundated Kakawis Lake. TE5 is similar to TE4. Massive gravel (up to -4 Φ) and coarse to fine sand is also associated with the event, as well as large marine shell fragments and plant detritus similar to TE4. The size and abundance of the different materials as well as the thickness of events TE4 and TE5 suggest that Kakawis basin may have been again at reach of oceanic waves by the time of both inundations. This implies a possible coseismic subsidence of the lake and/or sufficient tsunami run-up heights and energy to permit deposition of such coarse load in Kakawis Lake.



Legend for abbreviations:

K - Kakawis core (numbers designate core sites)
TE - tsunami event (deposit) and number (1 for earliest and 6 for latest)
pre-TE - layer deposited prior to the latest tsunami deposit
PA AD1700 - AD 1700 tsunami from Port Alberni marsh

Figure 4.10 Modal behaviour of selected tsunami deposits from Kakawis Lake. A sample taken from the AD 1700 tsunami at Port Alberni marsh serves as comparison. The PA AD1700 deposit is a well sorted sand. Number of modal peaks tend to decrease towards the centre of the lake (core K7) and towards the top of the cores (latest tsunami events). However, particle sizes are sparse despite stratigraphical position.

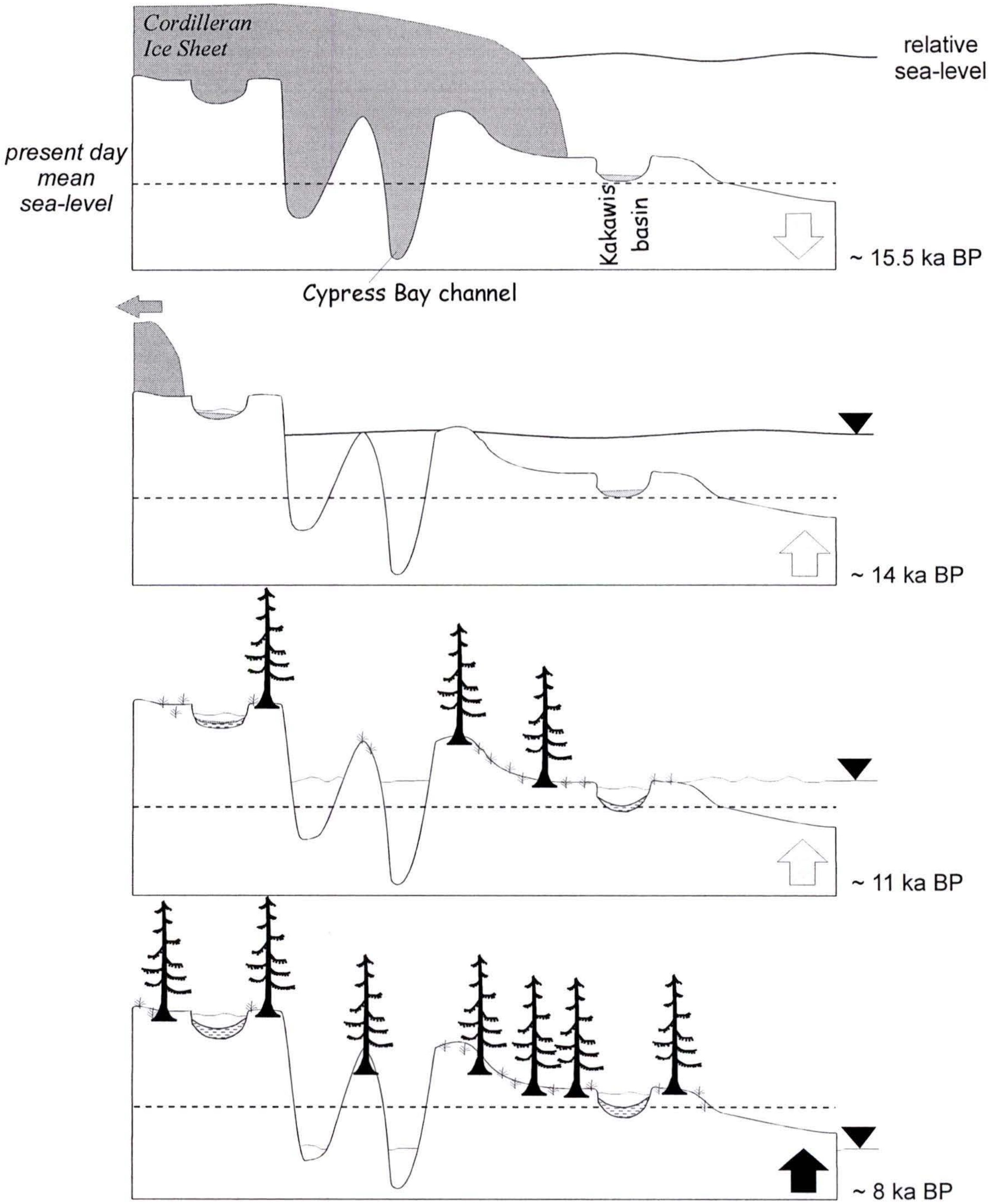


Figure 4.11 Hypothetical late Pleistocene and early Holocene evolution of the coastal low-lands surrounding Kakawis Lake. Relative sea level is assumed based on evidence and radiocarbon dates from this study and previous sea-level investigations for the west coast of Vancouver Island Basal glaciomarine clays were recovered from both lakes. Model for ~11ka BP is based on evidence found only at Darville Lake (glaciolacustrine clay?). Grey arrows indicate glacio-isostatic rebound. Black arrow indicates tectonic uplift (and eustatic changes). Abundance of vegetation is just relative (based on sedimentation rates at both lakes).

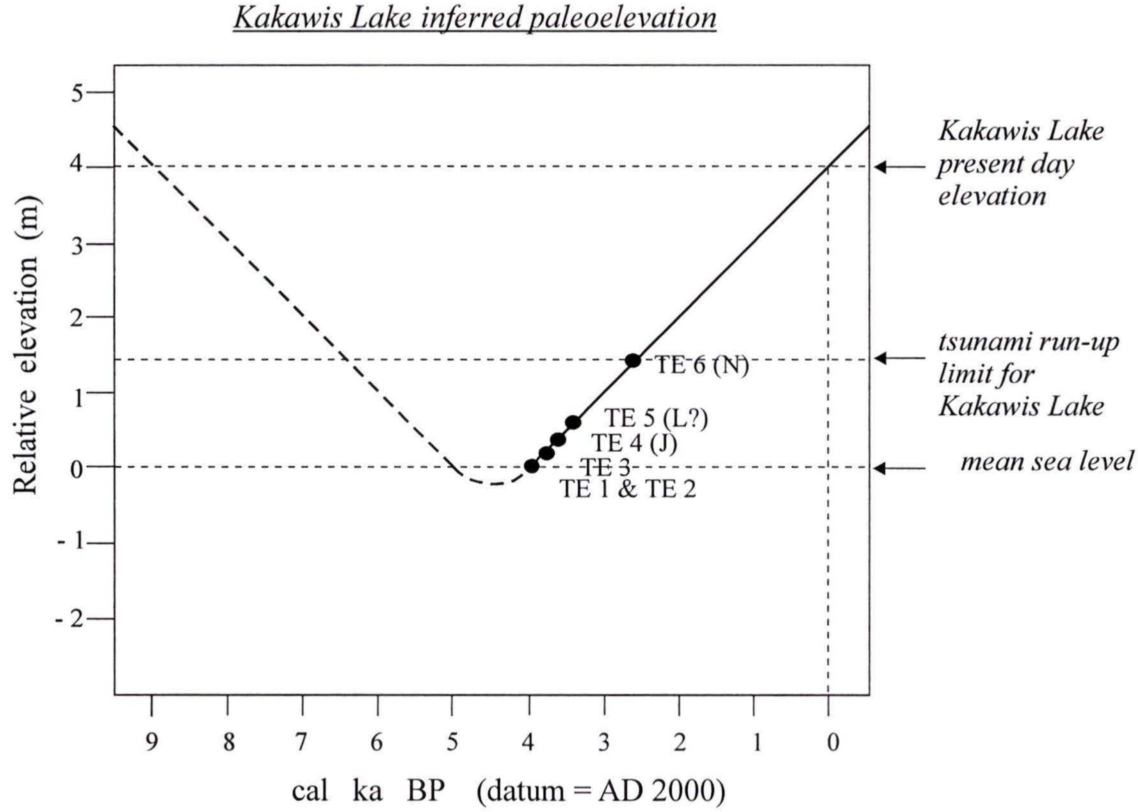


Figure 4.12 Inferred lake paleoelevation at the time of emplacement of the six inferred tsunamis at Kakawis Lake. Black dots correspond to the best calibrated age estimate obtained from radiocarbon ages of individual tsunami events at the lake (TE1 is the oldest event and TE6 the youngest). Paleoelevations are associated with an uplift rate of 1m/1000yrs. Lake paleoelevation prior to 5ka BP are inferred to be higher (dashed line) due to the absence of possible tsunami events between TE1 and the contact with the glaciomarine (~ 13,800 cal yrs BP). Present elevation of Kakawis Lake is 4 m above mean sea level (mean sea level at Tofino is 2.5 m above datum).

TE4 and TE5 are closely spaced in time and space and no apparent normal gradation seems to be associated with these events. TE6 marks a return of anomalous deposition within Kakawis Lake, although it contains much finer material than earlier events and was deposited after a relatively long period (up to 60 cm) of laminated to massive gyttja accumulation. This suggests further passive uplift of the lake before a much smaller tsunami event (TE6). The small areal extent, thickness, size of material and composition of TE6 imply that the lake may have been out of reach of tsunami inundation or that tsunami run-up heights were insufficient to reach Kakawis basin with the same energy as for TE4 and TE5.

Inferring Energy Levels of Tsunami Inundations at Kakawis Lake vs. other extreme ocean waves

Much of the work concerning hydrodynamics of shoaling tsunamis (including transport of clastic materials) has been done as part of coastal geomorphology/erosion studies where emplacement of large cobbles and boulders has also been analysed (Bryant *et al.*, 1992; Dawson, 1994; Bryant and Young, 1996; Hearty, 1997). Detailed sedimentological and depositional studies leading to an understanding of transport mechanisms have been completed for modern deposits undoubtedly emplaced by tsunamis, which may still be visible on several coastal land surfaces (Nishimura and Miyaji, 1995; Sato *et al.*, 1995; Shi *et al.*, 1995; Nanayama *et al.*, 2000). In all cases, tsunami occurrence has better explained the presence of coarse deposits and/or erosive structures both onshore and farther inland (i.e. raised platforms) than wind generated waves such as storm surges. Moreover, the differences in frequency, period and energy between both types of waves are believed to influence particle grain size, sorting and sedimentary facies (Nanayama *et al.*, 2000).

Storm surges are dynamically similar to tsunamis, however, such waves only have one crest, generating a single sediment layer if deposition takes place (Nanayama *et al.*, 2000). Contrary, tsunamis present a train of waves capable of developing couplets of upflow/outflow deposits. Wide, gently-sloping, shallow offshore shelves are effective storm surge generators. The same environment produces shoaling of tsunami waves, maximizing their decrease in energy. However, storm waves normally break in the surf zone in contrast to tsunamis that often reach shore as bores or wave crests with great energy (Morton, 1988; Komar, 1997). To date, 75% of the tsunamis recorded in the Pacific Ocean have not shown wave breaking once reaching shore (Murty, 1977; Pelinovsky *et al.*, 1998; Bryant, 2001). This characteristic implies that tsunamis behave like solitary shallow waves, maintaining their form once near shore and generating motion throughout their entire water column (Murty, 1977; Myles, 1985).

In the nearshore zone, high velocities (>1 m/s) have been recorded during storms, enabling sediment remobilization (Héquette *et al.*, 2001). However, onshore sediment transport by storms may be obstructed by significant offshore transport due to development of strong seaward flows, leading to erosion and dispersal of sediments (Komar, 1997; Héquette *et al.*, 2001). Moreover, storm surges tend to separate fine and coarse materials (Morton, 1988; Witter *et al.*, 2001). Tsunamis may reach velocities of ~10 m/s at shore and are considered constructional waves, able to transport all sediment sizes inland and maintain such transport over long distances (Murty, 1977).

Based on the above factors, a breaking storm surge may not have sufficient energy to travel across the 9 km of intricate waterways between the outer shore and the "entrance" to Kakawis Lake (Figures 4.3 and 4.4). A tsunami may have more energy to reach the same area, even if its velocity decreases and if most of its energy had been already dissipated due to refraction, diffraction and bathymetrical differences across the continental shelf. Given the size of the terrigenous material (up to -6.5 Φ) incorporated within some facies from Kakawis Lake, in addition to the intricate morphology and bathymetry that an extreme ocean water has to face to get to Kakawis Lake, it is believed that the best transport mechanism for such anomalous facies is a tsunami (Figure 4.10; Table 4.1). Moreover, a variety of clasts (< +1 Φ) presented scars on their surfaces, suggesting a turbulent flow as transporting agent, involving collision by saltation rather than suspension.

It is known that friction is a function of the roughness of the bed over which any given wave travels, and it is specified by size, shape and arrangement of grains on the bottom surface (Pettijohn *et al.*, 1973; Middleton and Southard, 1984). Unfortunately, there is a lack of information relative to tsunami particle transport along irregular coastlines (e.g. west coast of Vancouver Island) (Hearty, 1997). To better explain the origin of at least the oldest tsunami deposits at Kakawis Lake, some grain size and shear stress parameters were evaluated, based on simple sediment movement theories (i.e. not including the complexity of tsunami dynamics). It is more important to determine the characteristics of a flow capable of keeping large grains moving rather than a flow capable of initiating movement on such grains.

The following factors were assumed: (a) the sediment source area is in the immediate vicinity of the Kakawis Lake outlet stream (i.e. intertidal flat and shoreface); (b) a poor-sorting and relative protrusion of the particles forming the bottom floor exists; (c) the inferred bed slope is flat (0^o); (d) the surging wave is a turbulent flow; and (e) high boundary Reynolds numbers must be considered, given the size of the sediments (~ -3 Φ). Following principles of sediment movement (Pettijohn *et al.*, 1973; Middleton and Southard, 1984) and according to Everts curves (Pettijohn *et al.*, 1973), it was established that a flow may maintain non-cohesive grains of -1 Φ in diameter (common size value to tsunami facies in Kakawis Lake) moving over a bed of immobile grains ranging between 2 and -1 Φ. The minimum shear stress (β) needed to keep moving -1 Φ grains (over that particular bed) should range between 0.005 and 0.05. However, for more poorly-sorted beds the largest value of β may not be enough to move larger grains. For example, a grain of -3.5 Φ in diameter (i.e. granules) would only be moved if the bed grains are > -1 Φ. It is very difficult to infer the adequate velocity needed to keep such coarse particles moving because the characteristics of the bed (presumably intertidal flat) at the time of the first tsunami event (TE1) are unknown.

However, based on evidence, the mean sizes of the coarsest tsunami facies (polymodal) of Kakawis Lake range between 4 and -6 Φ. Based on the Hjulstrom curve (Pettijohn *et al.*, 1973), the flow velocities required to move such particles should range between 0.2 and 0.6 m/s, almost half to less than half the average tsunami surge velocity at shore (outer shore). Such velocities are concordant with the decrease of tsunami velocity once the wave is in contact with nearshore shallow waters. In addition, such values constrain the assumption made earlier about dissipation of tsunami energy across the shallow intricate waterways leading to Kakawis Lake. A storm surge would not be able to move such coarse particles from TE1 in the vicinity of Kakawis Lake (i.e. Lemmens Inlet). As for the youngest tsunami events at Kakawis Lake, they were emplaced at much higher lake elevations, hence storm surges could not be a viable depositional mechanism.

Inferring Sea Level position for Tsunami Deposits from Kakawis Lake

The Tofino-Ucluelet region has experienced a tectonic uplift ranging between 1 and 1.5 m every 1000 years over the past 3000 to 4000 years (Clague *et al.*, 1982; Friele and Hutchinson, 1993; Clague, 1996). Statistical analyses of foraminifera data recovered from marshes around Browning Passage (Meares Island and eastern Esowista Peninsula marshes) imply coseismic submergence to be between 55 and 71 cm for the Tofino region, at the time of a mega-thrust earthquake (Guibault *et al.*, 1996) (Figure 4.3). The suggested lake elevations are based on modeled sea level curves for the area and the tectonic history of the region.

The submergence-emergence cycle determined by Friele and Hutchinson (1993) for the Tofino-Ucluelet region is characteristic for the entire central west coast of Vancouver Island. According to them, sea level was 10 m below present datum between 10,000 and 8000 years BP (datum = AD 1950), suggesting complete isostatic rebound for this west coast at that time. Eustatic and tectonic sea level changes then became dominant. Around 6000 to 4800 cal yrs ago, mean sea level was ~3 m higher than it is today. Between 4800 and 2700 cal yrs BP, sea level steadily fell (not less than 1 m amsl). From 2700 to 2000 cal yrs BP, sea level stood ~2 m above present sea level. From 2000 cal yrs BP until today, sea level has been gradually falling, leading to a continuous emergence of coastal lowlands (Friele and Hutchinson, 1993). By relating the stratigraphic positions of basal Units A and B from Kakawis Lake, radiocarbon ages of post-glacial marine shells and pre-tsunamigenic plant detritus (Figures 4.6 and 4.7) with the inferred sea level curve for the Tofino-Ucluelet area (Bobrowsky and Clague, 1992; Friele and Hutchinson, 1993), the following pattern relative to sea level is implied.

By the end of deglaciation, the presence of marine shell species *Yoldia sp.* within the glaciomarine clays suggests that the bottom of the lake was most probably submerged at depths >10 m below present sea level (Figure 4.11). During the initial organic-rich deposition (pre-tsunami Unit B), Kakawis Lake was still submerged below sea level possibly implying a brackish (lagoonal/estuarine?) evolution of the basin between 13,614 and 8169 cal yrs BP (minimum values of calibrated age ranges obtained from plant detritus; datum = AD 1950).

Around 7934-7979 cal yrs BP (date obtained from plant fragment just below the oldest tsunami event TE1), sea level may have been <10 m lower than today. However, the existence of a sharp undulating contact, presumably erosional, between pre-tsunami Unit B and TE1 implies a stratigraphic unconformity. Such a contact may suggest that some of the underlying sediments may have been removed during emplacement of TE1, but the thickness of the sediment eroded is unknown. The presence of the unconformity suggests that this first tsunami event is certainly younger than 7934-7979 cal yrs BP. This leads to suggest a sea level position between <10 and 0 m relative to present datum. As such, the Kakawis basin would have been in a vulnerable position for the deposition of material coming from landward directed tsunami surges (Figure 4.12). Moreover, coarse clast sizes would have been easier to transport (depending on availability) because the basin was very much within reach of tsunami waves at this time. Transport may have been easier; hence it may have been possible to relocate fragile material without much re-working (e.g. large and well preserved marine shell fragments from TE1 and TE2).

The first three tsunami events (TE1, TE2 and TE3) at Kakawis Lake span the interval between *ca.* 7934 and 3754 cal yrs BP. By the end of TE3 deposition, prehistoric Kakawis Lake may have been at ~1 m above present day sea level (Figure 4.12). This is concordant with the continually fining and thinning-upward sequence for the three first events, and may indicate that the lake was steadily rising, hence more inaccessible to tsunami surges.

By the time of TE4 deposition (3629 cal yrs BP) sea level was continually falling, increasing the lake's elevation above sea level (~2 m). However, if a coseismic event took place for TE4 deposition, Kakawis Lake would have been sufficiently low to be surged by a tsunami. This is concordant with the re-deposition of coarse material for events TE4 and TE5.

For TE6 deposition (~2500 cal yrs BP), Kakawis Lake must have been at least 2 m above present day sea level, increasing the difficulty for a tsunami wave to surge into the lake. Today, Kakawis Lake is sitting at an elevation of 4 m amsl, out of reach of tsunami waves. According to the uplift model obtained from geodetic surveys and thermal modeling (Hyndman and Wang, 1995), Kakawis Lake has a modeled uplift rate of ~4 mm/a (based on the distance to Cascadia trench) which implies that by 2400-2600 cal yrs BP (TE6 deposition) the lake may have been at least 6 m below present day datum. Such depth is not concordant with the evidence, neither the sea-level history, however the uplift rate implies that Kakawis Lake suffers the effects of coseismic subsidence, but not to the point enabling tsunami run-up (e.g. AD 1700 Cascadia tsunami).

Estimating tsunami run-up heights in Clayoquot Sound

The magnitude, inundation limit and run-up heights of a tsunami depend on the magnitude (hence volume of water displaced) and closeness of the triggering event, the distance to be travelled by the tsunami, any refraction caused by the ocean floor, the bathymetry of the submarine floor near the coastline, the shape of the shoreline as well as the tidal range of the area to be affected. All the above geographical factors may scatter, dissipate and diminish the energy of any tsunami. The tidal range at Tofino is presently ~5 m above datum level (local datum level is 2.1 m below mean sea level) (Canadian Hydrographic Service, 1995). Unfortunately, there is no data showing the stage of the tides at the moment of the inferred tsunami inundations at Kakawis Lake.

Local bottom topography and geometry of the nearshore basin are considered primary characteristics for defining possible propagation patterns of any given tsunami once it reaches shallow waters (Miller, 1964; Pelinovsky *et al.*, 1998; Matsuyama *et al.*, 1999). However, such parameters can be very complex to model numerically in detail (they can lack sufficient accuracy) because of the enormous variety of coastal characteristics and the lack of detailed shallow water surveys (Priest, 2001). In addition, although ocean bottom displacements due to mega-thrust earthquakes can be simulated, they have only been quantitatively measured and recorded from very few earthquakes (e.g. AD 1960 Chilean and AD 1964 Alaskan earthquakes) (Dunbar *et al.*, 1991). Moreover, tsunami modeling can be largely ambiguous due to the uncertainty of earthquake source parameters (Whitmore, 1993), if dealing with a tectonic triggering mechanism.

Deeply indented funnel-like fjords (e.g. Barkley Sound and Port Alberni inlet) amplify tsunami heights (resonance effect). For example, ~7 m tsunami run-up heights were recorded at the head of Port Alberni inlet during the AD 1964 Alaska tsunami (Wigen and White, 1964; White, 1966; Clague and Bobrowsky, 1994a). Heights as much as 16 m have been modeled for the same location for a hypothetical M_w 8.5 Cascadia mega-thrust earthquake (Ng *et al.*, 1990, 1991). However, heights could increase even more according to the stage of the tide, both seasonal and diurnal, at the moment of the tsunami inundation.

Coastal tsunami heights also depend on the distance to the triggering source. British Columbia coastal regions facing the Pacific Ocean are prone to the largest waves associated with distant tsunamis. Simulated sea floor displacements at the Aleutian subduction zone showed capability of generating devastating tsunamis for western Vancouver Island (Dunbar *et al.*, 1991). The Aleutian-Alaskan complex can be categorized as the most threatening distant source of tsunamis for British Columbia based on seismic activity data bases (Soloviev and Go, 1974, 1975; NGDC, 2000). However, the greatest and most destructive Pacific-wide tsunamis (tele-tsunamis or distant-tsunamis) reported since the early 1800's have been triggered by great earthquakes generated along the Nazca Subduction Zone in South America, followed by Sanriku Subduction Zone in Japan, the Kuril-Kamchatka region in the west margin of the Pacific basin and the Aleutian-Alaska complex in the Arctic limit ranking the latter as a low profile subduction zone for the Pacific Ocean (IOC, 1999; UNESCO/IOC, 1999; NGDC, 2000).

On the outer coast of Vancouver Island, tsunami wave heights up to 5 m amsl could be produced by the rupture of CSZ part of an M_w 8 earthquake. Of course such values could be superimposed on the tides affecting this region, which range up to 5 m above datum level (local datum level is 2.1 m below mean sea level) for the Tofino area. Coastal areas of Washington, Oregon and northern California could also be affected with similar tsunami wave heights (Ng *et al.*, 1990, 1991, 1992; Whitmore, 1993; Priest *et al.*, 2000). In washover settings and wetlands openly facing the ocean (< 3-4 m amsl), tsunami inundation and run-up limits could be even higher than those in rugged rocky shores with smaller funnelling geometries than Port Alberni inlet. Model analyses show that those washover settings could be prone to ~2 to 8 m high tsunamis triggered by a Cascadia event (Priest *et al.*, 2000; Priest, 2001).

As an example of tsunami heights generated by a local great tectonic movement, at Tofino (outer coast and the southern tip of Clayoquot Sound) mean tsunami amplitudes ranging between 1.7 and 3.91 m (maximum 5 m above datum) have been modeled for different rupture conditions along CSZ as well as hypothetical earthquake magnitudes (Ng *et al.*, 1990, 1992; Whitmore, 1993). Sea level datum for the Tofino area is 2.1 m below present mean sea level. In historic time, 33 tsunamis (from various origins) have been identified at Tofino from tide records dating from 1906 to 1976 (Wigen, 1979). By relating gauge records with world-wide possible tsunami earthquakes (during 1883-1976 period), Wigen (1979) concluded that Tofino could experience an earthquake-related tsunami wave 6.22 m high every 200 years. A 1.26 m tsunami wave height (trough to crest) was recorded at Tofino as a result of the AD 1960 Chilean earthquake and another wave 2.40 m high was the result of the AD 1964 Alaskan earthquake (Wigen, 1979; Wigen and White, 1964; Thomson, 1981). Both values have been the largest wave heights recorded to date by the Tofino tide gauge.

The presence of inferred tsunami deposits at Kakawis Lake implies that prehistoric tsunamis overflowed the outlet threshold. Such processes may indicate either paleotsunami run-ups were high enough to reach the lake and/or that the lake was sufficiently low (below, at or just above sea level) relative to mean sea level at the time of inundation. Based on the conceptual evolution model shown in Figure 4.11, radiocarbon dates, sea level history, uplift rates as well as neighbouring coastal geography and bathymetry, different elevations for Kakawis Lake are suggested from middle to late Holocene times (Figure 4.12).

The width of the continental shelf off Clayoquot Sound is greater (~100 km) compared to the northern section of Vancouver Island. The width of the continental shelf influences tsunami propagation and energy levels. The potential for bottom friction increases with shelf width, dissipating the energy of any landward-surging tsunami wave. Combined with diffraction, refraction and geometric spreading of the wave, tsunami energies are dispersed and decrease in addition to a reduction of tsunami amplitudes (Murty, 1977; Bryant, 2001). This may be another reason why tsunami deposits seem to be more common in the northern west coast of Vancouver Island than the centre-south coastal region. This only concerns tsunami deposits found in the immediate coastline, and not those located at the heads of inlets, where in contrast, tsunami heights are amplified.

Kakawis Lake is located at 9 km from the outer shore of Vancouver Island, which is directly exposed to the Pacific Ocean. The fjord waters surrounding the natural "entrance" (outlet stream) to Kakawis Lake comprise Lemmens Inlet. The present configuration and bathymetry of Lemmens Inlet show that any landward-surging tsunami wave has to flow over foreshore flats (tidal flats) that cover ~85% of the inlet's entrance and have maximum depths of 2.5 m (below mean water level) (see chart; Canadian Hydrographic Service, 1995). Only a narrow ~200 m wide channel is sufficiently deep (4-14 m) to allow large flows of water. The extensiveness (~18 km^2) of the tidal flats would likely dissipate even more of the energy of a tsunami or any given extreme ocean level wave entering into inlet. Moreover, the bay into which Kakawis Lake outlet streams flows is surrounded by steep rugged bedrock flanks, protected by tidal flats (~1.4 km^2) and sheltered by two small islands located to the south, impeding a direct flow of water from the entrance of Lemmens Inlet to the outlet stream (Figure 4.4).

The present elevation of Kakawis Lake (4 m amsl) gives a maximum value of tsunami run-up limit (at normal high tide) for present-day sheltered rugged rocky areas of the Clayoquot Sound region; and probably for the entire outer coast of Vancouver Island (Figures 4.4 and 4.12). Kakawis Lake did not record the tsunami events of AD 1964

(Alaska), AD 1700 (Cascadia) and ~AD 1200 (Cascadia?), which suggests that: (a) tsunami energies may become sufficiently dissipated over 8 km of intricate shallow waters (from outer coast to Lemmens Inlet; Figure 4.3); (b) tsunami waves may inundate tidal marshes but not reach coastal lands located 4 m amsl (Figure 4.3); (c) wide shallow waters like Clayoquot Sound may not apply as much resonance effect on incoming tsunamis as deeply indented fjords like Alberni Inlet; (d) tsunamis may get reflected by steep rugged rocky flanks that neighbour most of the shallow tidal marshes around the southern channels and inlets of Clayoquot Sound (Figures 4.4 and 4.5); (e) the width of the gently sloping continental shelf off central west Vancouver Island may highly dissipate tsunami energies compared to northern sections of the shelf (Figure 4.1); and (f) neither distant or local tsunamis possibly triggered by mega-thrust earthquakes can reach basins located at 4 m amsl (at normal high tide) on the west coast of Vancouver Island (Figure 4.12).

Tsunamis travelling over long, relatively shallow but wide channels with numerous insular obstacles may loose the required energy to surge onto higher lands. Hence, lakes located far from the outer exposed coast can not be reached by tsunamis. Moreover, their energy may also be highly dissipated due to the length of the continental shelf off the coast of central Vancouver Island, which is wider than in the northern section of the island (Figure 4.1).

HISTORIC AND PREHISTORIC TSUNAMI DEPOSITS ON VANCOUVER ISLAND

LACUSTRINE COUNTERPARTS FOR KAKAWIS LAKE TSUNAMI DEPOSITS

To date, four lakes located on the outer west coast of Vancouver Island provide evidence of tsunami deposits (Figure 4.2). Catala Lake (Clague *et al.*, 1999), Deserted Lake (Hutchinson *et al.*, 2000), Kanim Lake (Hutchinson *et al.*, 1997), and Kakawis Lake (López *et al.*, 1999a, 1999b; López and Bobrowsky, 2000, 2001) have experienced respectively two to four (?), three, one and six tsunami events since the middle to late Holocene.

The thicknesses of individual tsunami deposits emplaced in these lakes vary from a few millimetres to ~40 cm (at Deserted and Kakawis lakes) (Figure 4.13). All tsunami deposits are compositionally similar, containing terrigenous particles, marine carbonate material and terrestrial plant detritus, all allochthonous to the depositional basin. With the exception of Kakawis Lake in which identification has not yet been completed, tsunami deposits were associated with marine diatoms and foraminifera. All shell fragments associated with these deposits have an exclusively marine provenance. Terrestrial plant detritus may be interbedded within a given tsunami deposit and/or capping the deposit. In all lakes, tsunami deposits are coarse textured (note maximum clast size evidenced at Kakawis Lake was -6.5 Φ), and easily distinguishable from underlying and overlying organic-rich lacustrine mud. To date, the most detailed sedimentological analysis on tsunami deposits from Vancouver Island has been undertaken on cores from Kakawis Lake (see Chapters 2 and 3).

The four lakes are located in low-elevation coastal lands, at <6 m amsl and no farther than 700 m from coastal shores (Table 4.2). However, the four lakes show different aged tsunami events. Catala Lake has two tsunami deposits dating ~300 and ~1100 cal yrs BP, in addition to two older ones of unknown ages (see Clague *et al.*, 1999). Deserted Lake has recorded three tsunami events dating 310-520 yrs BP, 1530-1950 yrs BP and 2400-2850 yrs BP (see Hutchinson *et al.*, 2000). Kanim Lake has geologic evidence for only one tsunami event dating ~2800 yrs ago (see Hutchinson *et al.*, 1997), in contrast to Kakawis Lake that has evidence of six tsunami inundations dating ~2400 yrs BP, ~3300 yrs BP, ~3650 yrs BP, and the last three events spanning between ~3754 to <7934 yrs BP.

Catala and Deserted lakes preserve evidence of the last great Cascadia mega-thrust earthquake (AD 1700 = identifier Y). Catala Lake is also inferred to have two of the youngest Cascadia events correlative to the identifiers W (850-1250 cal yrs BP) and U (1150-1250 yrs BP) in the Atwater – Hemphill-Haley chronology from Willapa Bay (Washington). Deserted Lake may have also evidence of Cascadia events S (1350-1650

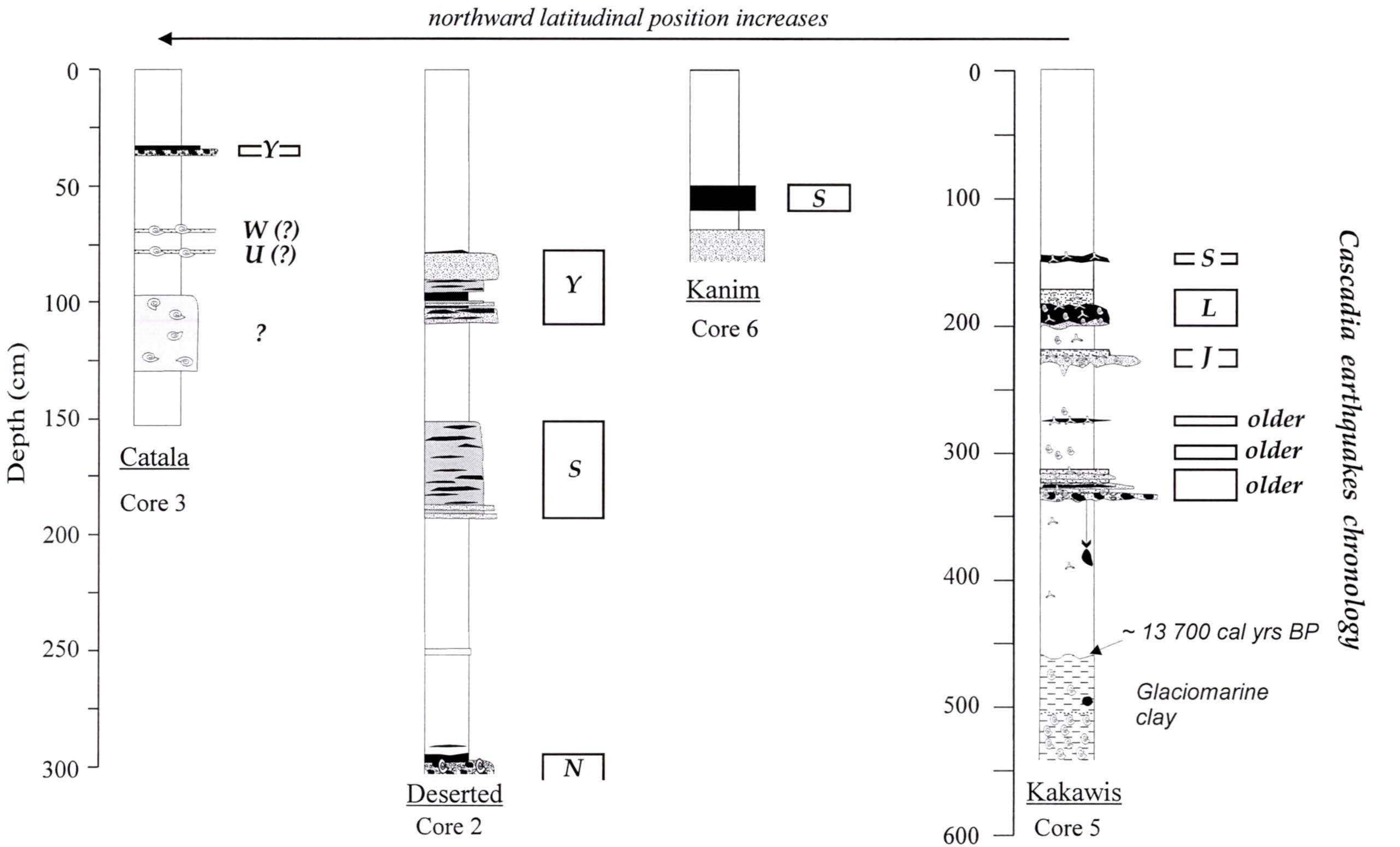


Figure 4.13: Inferred correlation between tsunami deposits from low-elevation lakes of the west coast of Vancouver Island and the Atwater - Hemphill-Haley (1997) chronology from marshes (buried soils) at Willapa Bay (Washington). Sources for Catala, Deserted and Kanim core logs: Clague *et al.* (1999) and Hutchinson *et al.* (1997, 2000)

cal yrs BP) and N (2350-2750 cal yrs BP). Kanim Lake may only have evidence correlative with the N Cascadia event. In Kakawis Lake, tsunami deposits may be associated with events N, L (2750-3250 cal yrs BP), J (3250-3450 cal yrs BP), and possibly older events (>3700 yrs BP) that have not yet been identified in other coastal lakes on Vancouver Island (Table 4.2; Figures 4.12 and 4.13).

The chronological differences evident between the tsunami events recorded at Catala, Kanim, Deserted and Kakawis lakes may be in part due to the width of the continental shelf off Vancouver Island, in addition to their elevation differences (Table 4.2; Figures 4.1 and 4.2). North of Nootka Fault the width of the continental shelf decreases substantially compared to the central and southern areas (Figure 4.1). This difference may influence the dissipation of energy of any given tsunami approaching the outer west coast of Vancouver Island.

Another important factor is that the deformational front of CSZ is associated with the tectonic lineament bracketed by the Nootka Fault to the north (off Vancouver Island at the Nootka Island latitude), and Mendocino Fault to the south (off northern California). According to 2-D and 3-D dislocation models, thermal modelling, GPS surveys and uplift rates determined for the northern section of CSZ, the geometry of both locked and transition zones is wider within the area limited by Barkley Sound to the north (south-central Vancouver Island) and by the Columbia River to the south (Washington-Oregon border) (Dragert *et al.*, 1994, 2001; Hyndman and Wang, 1995; Flück *et al.*, 1997; Priest *et al.*, 2000). This area has been experiencing constant uplift and is associated with the zone of regional coseismic subsidence in the eventuality of a Cascadia mega-thrust earthquake.

Catala Lake is located north of Nootka Fault; Deserted Lake lies directly south of this fault. Kanim and Kakawis are located even farther south of the Nootka fault, but lie north of Barkley Sound (Port Alberni Inlet) (Figures 4.1 and 4.2). The pattern of tsunami deposits in the four Vancouver Island lakes implies that coastal sites located above or at the northern limit of the CSZ deformation front and below 2 m amsl have recorded the youngest events attributed to ruptures of the Cascadia locked zone (Figures 4.1 and 4.13). Paleoseismic analyses at Deserted Lake suggest that coseismic subsidence generated by the AD 1700 was substantially less than the subsidence rate estimated near Tofino (55-71 cm) during the same event, which constrains the northern limit of the CSZ deformation front (Guibault *et al.*, 1995, 1996; Hutchinson *et al.*, 2000). In contrast, lakes located south of Nootka Fault, within the zone of coseismic subsidence, have only recorded tsunami inundations associated with the oldest Cascadia events. This implies prolonged uplift (deformation) of the coastal areas where Kanim and Kakawis lakes are located. Even with coseismic subsidence, the continuous uplift and deformation of the region ensures that the elevation of the lakes relative to sea level increases over time and that they eventually become unreachable to tsunamis. Kanim and Kakawis lakes have not been inundated by tsunamis possibly since Cascadia event S dating back to AD 300-600.

Based on the radiocarbon ages obtained from tsunamigenic plant detritus, tsunamis inundated Kakawis Lake every 285 years on average, with the last tsunami having taken place around BC 400. The recurrence interval for Kakawis tsunami deposits is shorter than the ~500 years interval suggested for the seven large subduction zone earthquakes that have struck Cascadia (Atwater and Hemphill-Haley, 1997). The three youngest tsunami events at Kakawis Lake (TE6, TE5 and TE4) may be equivalent to the Atwater – Hemphill-Haley identifiers N, L and J. If the recurrence interval for Kakawis Lake tsunami deposits is calculated from the estimated age range for these identifiers, the recurrence at Kakawis Lake increases to ~400 years.

The mean recurrence interval estimated from the buried soils at Willapa Bay (Washington) is more than 270 years but less than 550 years because of the long time intervals (700-1300 years) that separate some of the events (between identifiers N and S, and between identifiers W and Y) (Atwater and Hemphill-Haley, 1997). Prehistoric Cascadia mega-thrust events seem to cluster into three major groups. Identifiers J, L and N tend to cluster near BC 1000, whereas identifiers S, U and W seem to cluster near AD 700. To date, identifier Y stands alone at AD 1700. If viewed as broader patterns, the recurrence between the major groups seems to be diminishing with time (1700 years, 1000 years and 300 years for respective intervals). If a broader pattern approach is taken for Kakawis Lake tsunamis, the recurrence seems to be increasing with time (150 years, 900 years and 2400 years), which is concordant with the continuously uplifting pattern observed near this particular area.

The tsunamigenic origin/approach taken to describe the anomalous deposits found in this part of the Northern Hemisphere could be overestimated if other marine-originated deposits related to extreme ocean levels are not accounted for (e.g. storm surges, El Niño events, extreme astronomical tides). The central chrono-stratigraphic controversy is that the initial recurrence interval cited for CSZ mega-thrust earthquakes is between 500 and 550 years (Darienzo *et al.*, 1994; Atwater *et al.*, 1995; Nelson *et al.*, 1995; Atwater and Hemphill-Haley, 1997) but some anomalous layers show smaller intervals that may be better associated with non-seismic extreme ocean levels or distant tsunamis from different sources (Witter *et al.*, 2001). However, the anomalous deposits found at Kakawis Lake are believed to be tsunamigenic because of the long recurrence interval (~1000 years) associated with storm surges for the west coast of Vancouver Island (Hutchinson *et al.*, 1997) and the continuous uplift that the lake has been experiencing. Moreover, the wave heights inferred to be associated with the intervals could not breach Kakawis Lake because they are calculated for outer open coast areas. In addition, storm surges likely dissipate their energy easier than tsunamis along the labyrinth of shallow waters existent between the open ocean and Lemmens Inlet (~8 km).

MARSH COUNTERPARTS FOR KAKAWIS LAKE TSUNAMI DEPOSITS

Widespread occurrence of paleotsunami deposits suggests that coseismic subsidence affected the region. However, in lakes this pattern may be obscured by differential glacio-isostatic rebound and tectonic uplift rates of a given area (e.g. Cascadia region). The long-term uplift of south-central western Vancouver Island (Clague, 1996) may reduce the changes of tsunami deposition in lakes. The uplift pattern also explains why some tidal marshes on Vancouver Island (Table 4.2; Figures 4.3 and 4.14) were only impacted by the youngest tsunamis (local and distant) that hit this region (c.f. Clague *et al.*, 2000). Moreover, tectonic uplift is thought to be responsible for the short lifespan (~1000 to 1500 years) of the tidal marshes (c.f. Friele and Hutchinson, 1993; Clague, 1996).

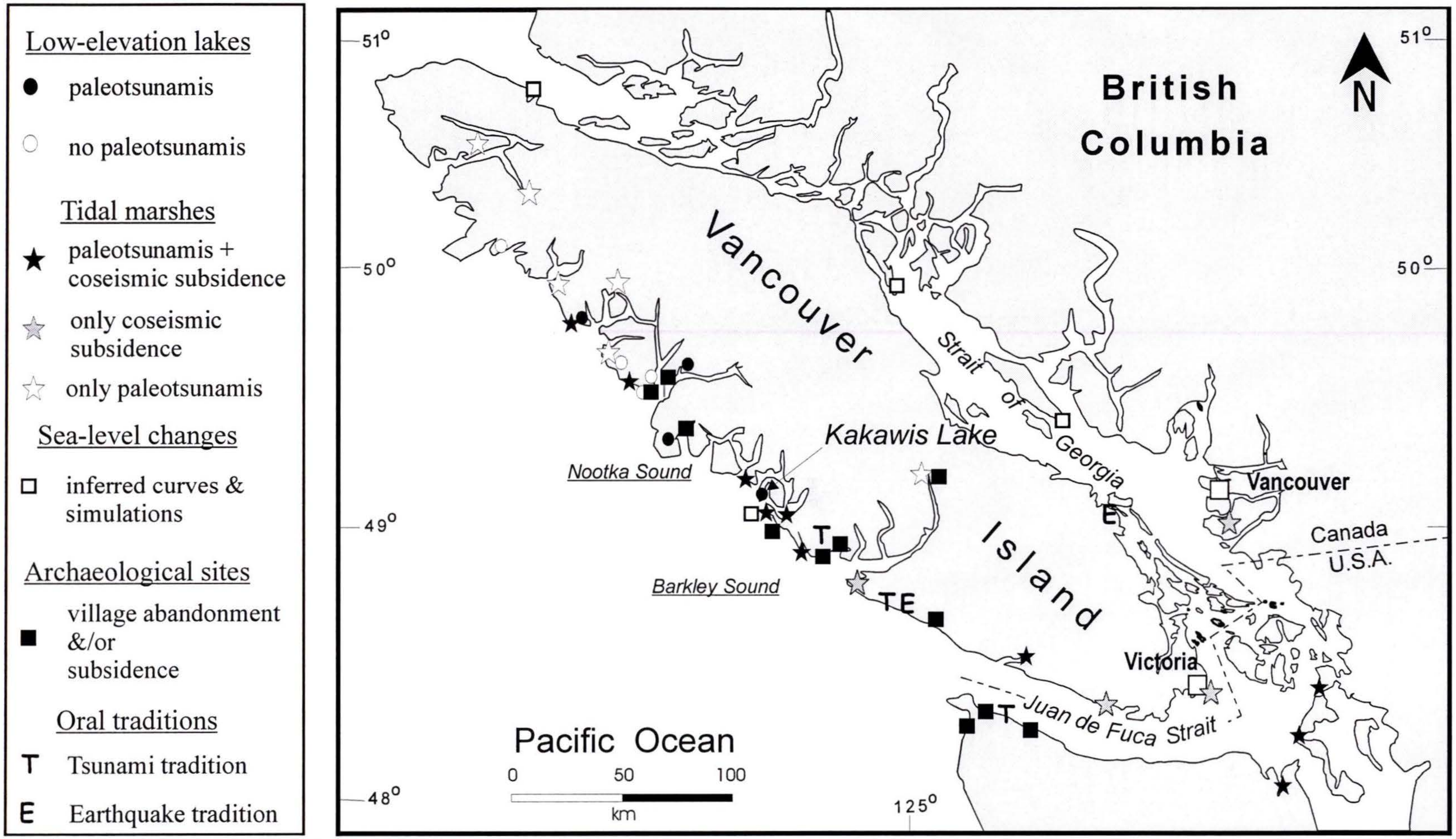


Figure 4.14: Location of sites showing multiple stratigraphical and archaeological evidences of paleoseismicity on the west coast of Vancouver Island. Symbols are explained in the legend. Types of studies done at selected sites are detailed in the legend. Black squares represent the archaeological sites which radiocarbon dates match those obtained for some of the multiple tsunami deposits at Kakawis Lake (Sources of sites other than present research: Clague *et al.*, 2000; Cole *et al.*, 1996; Hutchinson and McMillan, 1997; Minor and Grant, 1996).

The shores of Browning Passage, tidal marshes on south Meares Island and near Tofino were cored as part of earlier paleoseismic studies (Bobrowsky and Clague, 1991; Clague and Bobrowsky, 1994a, 1994b; Guibault *et al.*, 1995, 1996). Several tsunami deposits and buried peat soils were found and dated by both radiocarbon analysis of detrital and growth-position plant fossils and shells, and optical dating of K-feldspars (Huntley and Clague, 1996). Tsunami sand sheets overlying peat and underlying muddy sediments are used as evidence of coseismic subsidence (Clague and Bobrowsky, 1994a, 1994b). Similar couplets have been identified in tidal marshes located on the CSZ deformation front (e.g. along Browning Passage, Meares Island, Tofino and Ucluelet), and are associated with the youngest Cascadia mega-thrust events (identifiers Y and W from the Atwater – Hemphill-Haley chronology, as well as AD 1964 Alaska and ~AD 1200 Cascadia (?) events).

The tsunami sand sheets reported at Meares Island and Tofino marshes correspond to tsunamis triggered by the AD 1964 Alaska, AD 1700 Cascadia, and ~AD 1200 (Cascadia?) earthquakes. No older events were recovered from these environments that could be associated with the tsunami deposits found at Kakawis Lake.

At Port Alberni marshes, eight to nine sand and gravel layers are inferred to be tsunamigenic in origin but they do not have confirmed ages (Clague and Bobrowsky, 1994a; Clague, 1996; Clague *et al.*, 2000). All the layers are thought to be younger than 3500 yrs BP. To date, these sand sheets are the oldest anomalous layers found embedded in tidal marshes of Vancouver Island west coast (Figures 4.3 and 4.14). They do not have counterparts at Tofino nor Ucluelet marshes (Clague, 1996), most probably due to emergence, bioturbation and erosion. Tsunami events from Kakawis Lake could be the lacustrine counterparts of these older tsunamigenic (?) sandy sheets found in the marshes.

Triggering mechanisms such as large submarine landslides were also studied when analysing possible origins of the tsunami deposits from Kakawis Lake. According to Pararas-Cayannis (Murty, 1977), submarine landslides "can produce no large tsunamis that would travel across wide portions of the ocean" because "not more than 2% of the potential energy of a falling or sliding body is converted into wave energy". Although such percentage is great if related to the enormous energy of a tsunami, tsunamis triggered by submarine landslides tend more to affect local and/or regional areas (up to 1000 km from source) but can be highly destructive (e.g. submarine slump near Valdez (Alaska) (Cox and Pararas-Cayannis, 1976); Kitimat Arm (northwestern B.C.) (Murty, 1979; Evans, 2001). Submarine landslides as sources of the three youngest tsunamis that inundated Kakawis Lake were discounted. No such events have been reported in historic times along Lemmens Inlet or Browning Passage basins. Moreover, if Kakawis Lake tsunami deposits can be correlated with the oldest unconfirmed sand sheets at Port Alberni marsh, the responsible event for such deposition may not have been a local large landslide. However, the possibility of distant tsunamis produced by enormous distant landslides is also left open for at least the three oldest (TE1, TE2 and TE3) inferred tsunami events at Kakawis Lake.

ADDITIONAL SUPPORTING DATA

At Kakawis Lake, the most reliable supporting data for time of emplacement of the tsunami deposits are the radiocarbon ages obtained from different vegetation material below, within or above the anomalous sequences. All six tsunami events at Kakawis Lake pre-date historic times, going back as far as middle Holocene. Moreover, all six tsunami events proved to be correlative to the best paleotsunami chronology for the north Pacific coast of North America (Atwater and Hemphill-Haley, 1997). However, additional data may better constrain the time of occurrence of the tsunamis that presumably inundated Kakawis freshwater basin.

Paleoseismology also uses anthropological data as supporting evidence. The west coast of North America has fairly recent written records on earthquake occurrence compared to other regions around the Pacific Ocean (e.g. BC 1830 for China, AD 1530 for Colombia and AD 1562 for Chile) (Ramírez, 1975; Myles, 1985). For example, the AD 1700 Cascadia event may have not been precisely dated if Japanese written records did not exist at that time, even though convincing geological evidence was widespread along the Pacific coastlands of North America (Satake *et al.*, 1996). If for example paleoseismic investigations may be restricted only to local sources of information, geologic evidence in the Pacific coast of North America may be constrained by local aboriginal oral traditions and archaeological evidence, due to the lack of written history.

Northwest Coast aboriginal peoples have oral traditions that describe occurrences of large earthquakes and tsunami inundations. Some of the best examples of tsunami floods narrated by aboriginal peoples of the Cascadia region come from the Makah peoples of Cape Flattery in the northern tip of the Olympic Peninsula (Washington) and the Nuu-chah-nulth peoples of Pachena Bay (just south of Barkley Sound) on western Vancouver Island (Figure 4.13) (Arima *et al.*, 1991; Clague, 2001; Heaton and Snavely, 1985). However, few paleoseismologists have given much credibility to such traditions due to the difficulty that the analysis demands (e.g. chronological factor).

Archaeological evidence of both earthquake-induced burial and unexpected abandonment of aboriginal coastal villages are reported along Cascadia coastal lands (Cole *et al.*, 1996; Minor and Grant, 1996; Hutchinson and McMillan, 1997). These sites are strong evidence for coseismic subsidence in addition to tsunami inundation. Hutchinson and McMillan (1997) obtained numerous radiocarbon dates from 30 native villages located on the outer coast of west central Vancouver Island and the northern tip of Washington, below the potential modeled tsunami run-up limit (~5 m amsl). The sites investigated are located around Nootka Sound, Hesquiat Harbour, the Esowista Peninsula, the shores of the mouth of Barkley Sound and the northern tip of the Olympic Peninsula (Figure 4.14). Some of the radiocarbon ages reported for some of these sites have striking similarities with at least three of the six tsunami events recorded at Kakawis Lake. In the Nootka Sound region, the Yuquot site shows evidence of low cultural activity between 2400-2800 and 3000 cal yrs BP. In the Barkley Sound region, Ch'uumat'a and Shoemaker Bay village sites show an occupational gap ~3000 cal yrs BP. For the same region, one of the Nitinat sites shows low cultural activity between 2300-2700 cal yrs BP. However, this particular site yielded dates going back to 4300 cal yrs BP that may be correlative to the earliest tsunami deposits at Kakawis Lake. As for the Olympic Peninsula region, Hoko River site shows a decline in activity around 3000 cal yrs BP (Hutchinson and McMillan, 1997).

The three regions show substantial reductions in cultural activity associated with the seismic events reported as N and L identifiers in the Atwater – Hemphill-Haley chronology (Figure 4.9) (Atwater and Hemphill-Haley, 1997). Such events, as well as the timing suggesting village abandonment at the archaeological sites, are correlative to the ages of events TE5 and TE6, the youngest tsunami events evidenced at Kakawis Lake. According to Hutchinson and McMillan (1997) estimates, events identified as N and L may have had less impact on site occupation among all three regions if compared to younger events S, U, W and Y. Such implications could suggest that there may have been little tsunami impact on Vancouver Island associated with seismic events N and L, and/or coseismic subsidence was minimal. However, tsunami impact also depends on relative sea level position (by ~3000 cal yrs BP sea level was 2 m higher than present datum (Friele and Hutchinson, 1993). Tsunami deposits corresponding to events TE5 and TE6 at Kakawis Lake showed small tsunami surging if compared to older tsunamigenic events in the same basin. Such evidence in addition to the archaeological implication mentioned above may suggest that the tsunamis that impacted the west coast of Vancouver Island following seismic events N and L were relatively small probably due to minimal coseismic subsidence.

CHARACTERISTICS OF TSUNAMI DEPOSITS IN LAKES: BASED ON KAKAWIS LAKE

Although tsunamis have the ability to both deposit and erode materials along topographically diverse shorelines, in low elevation lakes such as Kakawis Lake the process is depositional rather than erosional. A tsunami wave may deposit large amounts of material minimally disturbing the contemporaneous lake bottom sediments if the lake has sufficient elevation relative to sea level. The inundation process in lakes is different to that impacting flat low-lying beaches, intertidal marshes, wetlands and open shores, settings highly prone to washover. In such environments, tsunami waves surge inland eroding the surface and/or depositing newer and reworked materials backshore. Tsunami inundations in washover settings may be characterised by two types of flows, generating couplets of consecutive layers associated with the influx (swash/flood) and the outflow (backwash/ebb) of the wave (Nishimura and Miyaji, 1995; Sato *et al.*, 1995; Shi *et al.*, 1995; Nanayama *et al.*, 2000). Detailed characterisation of this type of sedimentation has been based on modern tsunami deposits on washover settings.

Some of the earliest eyewitness descriptions of surging tsunamis and the deposition of their carrying sediment come from non-scientific reports (e.g. AD 1604 Peru; AD 1751, Concepción, Chile; AD 1868 Arica, Chile) (Soloviev and Go, 1975; Myles, 1985). Most accounts take place in washover settings, bays and tidal marshes in the vicinity of an inundated community or village. Driftwood and great amounts of vegetative material, as well as sand, gravel and many mollusc shells have been observed transported by strong turbulent landward currents. However, there are no accounts describing tsunami deposition or behaviour in lacustrine settings.

Based on geological evidence recovered for paleotsunamis in addition to observations of modern tsunami deposits, the general characteristics of tsunami deposits emplaced in washover settings are: (a) they thin and fine landward and upward in the sequence; (b) they rise landward and away from shore; (c) they may show graded bedding, reflecting both tsunami landward flow and backwash flow; (d) the complex backwash deposit may show imbrication of large clasts, evidence of a seaward direction of the flow; (e) association of multiple coarse/fine couplets is indicative of deposition by successive waves of a tsunami wave train rather than a storm surge; (f) marine macro and micro-fossils are incorporated, confirming the marine provenance of the material; (g) driftwood and plant detritus are associated with the deposit; (h) sharp undulating basal contacts and rip-up clasts of underlying material (e.g. peat) are indicative of flows with great energy (i.e. turbulent), capable of erosion; (i) the thickness and lithofacies may vary accordingly to the original land surface undulation; (j) stratigraphic position may or may not indicate coseismic subsidence in tectonically emerging coasts, hence origin of the tsunami (c.f. Atwater and Moore, 1992; Clague and Bobrowsky, 1994a, 1994b; Darienzo *et al.*, 1994; Dawson, 1994; Nishimura and Miyaji, 1995; Sato *et al.*, 1995; Shi *et al.*, 1995; Dominey-Howes, 1996; Nelson *et al.*, 1996b; Atwater and Hemphill-Haley, 1997;

Benson *et al.*, 1997; Clague *et al.*, 2000; Dawson and Smith, 2000; Nanayama *et al.*, 2000).

Paleotsunami deposits embedded in unconsolidated lacustrine sub-bottoms are strikingly emphasized within the organic-rich muds. Moreover, in tectonically emerging coastlines like the Cascadia region, paleotsunami deposits are better preserved in lacustrine environments than tidal marshes, because there are no external factors such as re-forestation or erosion due to emergence affecting lakes.

Lacustrine tsunami deposits have most of the general architectural characteristics of tsunami deposition in flat, low-lying coastal settings. However, based on the evidence found at Kakawis Lake some further traits can be established. In lakes, tsunami deposits descend away from shore following the lake's bathymetry, given the general concave geometry of such basins. In lakes, the couplet associations are best described as facies resulting from different stages and periodicity of successive tsunami inundations in addition to differences in the settling velocities of materials brought into the basin (c.f. Minoura and Nakaya, 1991; Bondevik *et al.*, 1997a, 1997b).

Analyses of sediments deposited by tsunami swash (influx/pulse) and backwash flows may provide important information relative to tsunami hydrodynamics and particle transport (Minoura and Nakaya, 1991; Dawson, 1994). In lakes, tsunami surges are evidenced by the deposition of coarser materials (e.g. massive gravel, massive sand, coarse plant detritus). However, lakes may lack the complex backwash deposit common to washover settings. In lakes, such a stage of ebbing of the tsunami wave may be represented by deposition of the fine particles that were left suspended within the lake's water column during a previous tsunami pulse (influx) (c.f. Bondevik *et al.*, 1997a, 1997b). Such deposition corresponds to the "calmer" inter-pulse period in between two successive pulses (Figure 4.15).

At Kakawis Lake, tsunami facies (tsunami pulse and inter-pulse) lacked internal structure. This implies that in lakes, tsunami facies associated with coarse material (<0 Φ) have chaotic structures with no indications of flow directions. X-radiographs of massive gravel facies in core K5 associated with tsunami event TE1 show chaotic structures (Figure 4.15). All other facies with clast sizes <0 Φ are massive. However,

GENERAL LAKE STRATIGRAPHY

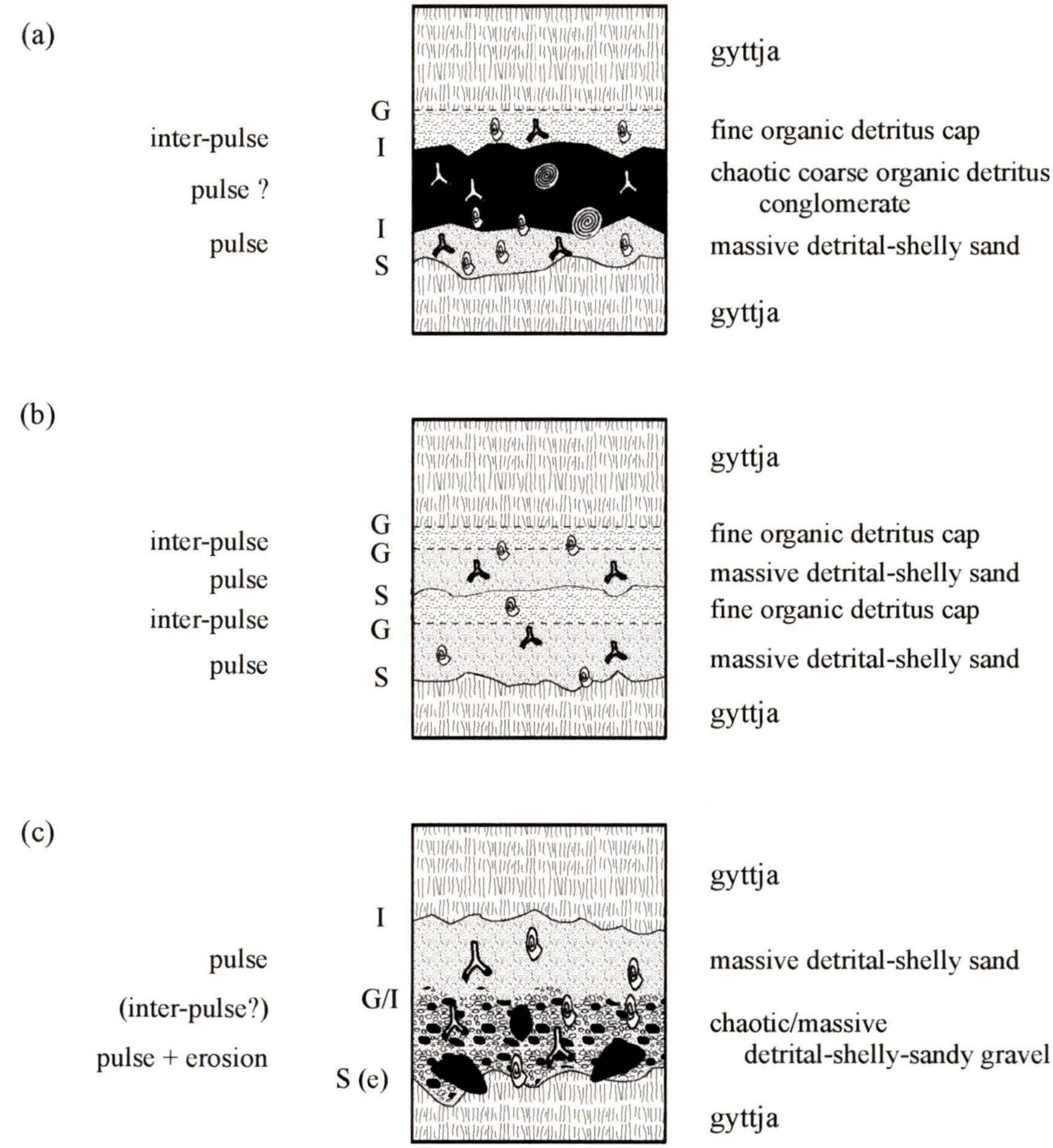


Figure 4.15 Representations of the most common stratigraphy seen in tsunami deposits at Kakawis Lake. The general characteristic is that such deposits are layered between gyttja (lacustrine organic mud). Types of contacts are also given (G - gradational; S - sharp; I - irregular; (e) - erosional). The textural characteristics define the association with the stage of tsunami inundation (pulse and inter-pulse). Macro-plant detritus can be scattered throughout the deposit. The coarsest and less structured deposits (c) lye closer to the outlet stream. More defined and structured deposits (b) are typical of the central area of the lake. Layers with very coarse plant detritus (a) can be found at random within the lake, and depend on the spread of such material throughout the lake at the moment of inundation.

when grouping different facies that define a single tsunami event (coarsest facies at the bottom and finer at the top), lacustrine tsunami events fine upwards.

Compared to the AD 1700 tsunami sand sheet recovered from an intertidal marsh at Port Alberni, tsunami deposits emplaced in Kakawis Lake are generally coarser and more poorly-sorted (Figures 4.10 and 4.16). Differences in grain size between these types of tsunami deposits are very marked (Table 4.1; Figures 4.10 and 4.16) (c.f. Clague and Bobrowsky, 1994a; Clague, 1996 for sedimentological characteristics).

All coarse clastic material found within the tsunami deposits from Kakawis Lake is of local provenance and presently abundant in the nearby vast intertidal areas of Lemmens Inlet. Grain-size distributions in such tsunami deposits range from coarse silt (+6 Φ) to small cobbles (-6.5 Φ). The typical clastic range of tsunami deposits found along the Cascadia coastal region is generally fine to very coarse sand. Tsunami deposits in Kakawis Lake are distinctly polymodal and poorly to very poorly-sorted (Figures 4.10 and 4.16). Such polymodality may suggest different transport processes within a single tsunami surge, enriching the flow with mixed grain sizes and sub-populations. If well-sorted sediment is a synonym for intense re-working and selection of grains over time and space (e.g. removal of finer size fractions due to repeated re-working), poorly-sorted tsunami deposits may imply brief transport over short distances, preventing the sediment from undergoing repeated re-suspension that could increase the sorting. Because of the diversity of grain sizes, modal distributions may be more informative than mean or median size analyses for tsunami sediments.

The sizes of clasts associated with the tsunami deposits generally diminishes away from the outlet stream, with the exception of two events (TE1 and TE5), where cobble-size particles were found throughout the cores (Figures 4.7 and 4.16). Particle sorting increases away from the outlet stream, as well as from oldest (bottom) to youngest (top) tsunami event (Figure 4.16).

Compositionally, carbonate and terrestrial plant detritus are inversely related in lacustrine tsunami deposits (Table 4.2). This relationship may reflect the percentage of vegetation cover at the time of tsunami inundation. For Kakawis Lake, this interval ranges from middle to late Holocene. High values (15 to 35) obtained from C/N ratio

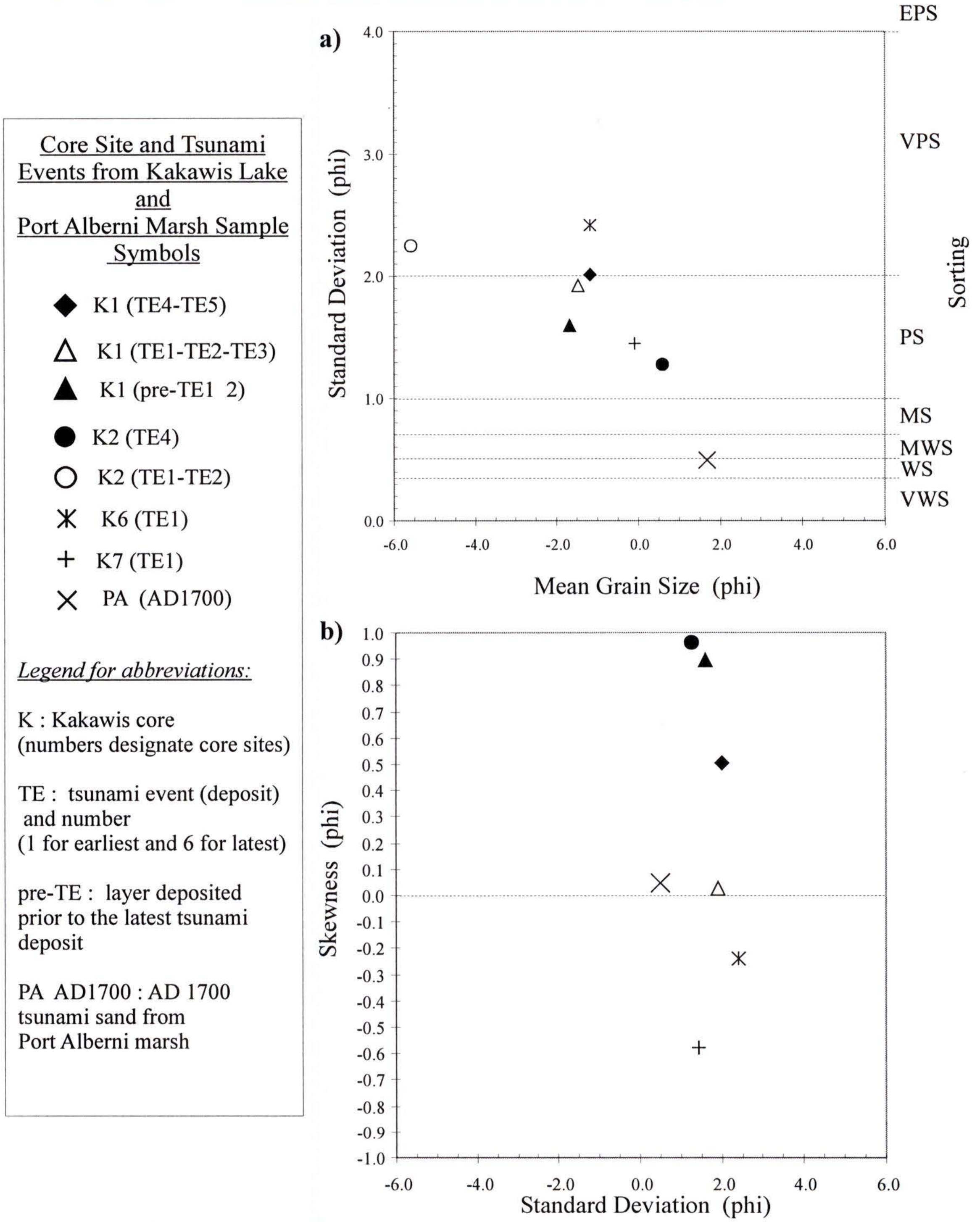


Figure 4.16 Relation between mean size, standard deviation and skewness for selected tsunami deposits from Kakawis Lake. A sample taken from the AD1700 tsunami layer at a marsh in Port Alberni was also analysed for comparison purposes. Folk's (1974) sorting limits are used in graph (a). Graph (b) has to be interpreted with caution due to the polymodal behaviour and maximum particle size values of individual samples. Values of parameters were obtained from moments method statistics.

analyses are consistent with a terrestrial origin for all plant detritus mixed within Kakawis Lake tsunami events (c.f. Chapter 3).

The carbonate material associated with the tsunami events at Kakawis Lake has a marine source. The oldest tsunami events have the highest concentrations of carbonate material. Moreover, the diversity of shell species increased with age of the tsunami deposit (Figure 4.6) (c.f. Chapter 3). No marine diatoms or foraminifera identification have been completed to date on Kakawis cores.

Layers of plant detritus have been seen overlying tsunami deposits emplaced in lakes (Clague *et al.*, 1998, 1999; Hutchinson *et al.*, 1997, 2000). However, at Kakawis Lake, plant detritus may or not cover coarser (gravel or sand) layers depending on the size of the vegetative fragments. Large plant fragments associated with minor sand-sized clastic and shelly particles form thick "stand-alone" layers. Plant detritus can also be overlying and capping clastic-rich layers and the above mentioned coarse plant detritus layers. However, these capping detrital layers have finer grain sizes and are composed of smaller (<1 mm) biologic fractions and very fine sand to mud (Figures 4.7 and 4.15).

Numerous paleoseismic investigations have shown that sand sheets enclosed in peat and muddy layers in tidal marsh on tectonically active coastal environments represent both tsunami deposition and coseismic subsidence (Darienzo *et al.*, 1994; Clague and Bobrowsky, 1994a, 1994b; Atwater *et al.*, 1995; Nelson *et al.*, 1996a). Moreover, it has been suggested that by analysing the thicknesses of these landward-fining tsunami sand sheets the source of the tsunami could be inferred (Carver and McCalpin, 1996). In lakes, it may be very difficult to demonstrate coseismic subsidence because there is no soil to bury. Moreover, depositional processes in lakes differ greatly from those in tidal marshes. However, the thickness of a tsunami deposit in a lake, in addition to the maximum sizes of clastic material deposited, may indicate a possible source for the associated tsunami. All the above being equal, the coarser the material and the thicker the deposit, the closer the tsunami source (i.e. CSZ or distant tsunamis).

SUMMARY AND CONCLUSIONS

Tsunamis have left six recognizable deposits in Kakawis Lake, a coastal low-elevation freshwater basin located on the central coast of west Vancouver Island, British Columbia. The tsunami deposits are an association of four facies recognizable by striking lithological differences. Each facies also depends on differential settling velocities of the input materials, in addition to the periodicity of the tsunami surge (period between successive peaks of a tsunami wave train).

The most poorly structured facies is associated with layers having the coarsest terrigenous material, hence it is the most polymodal (up to 8 modes depending in the closeness to the outlet stream). The largest particle size found in such lacustrine tsunami deposits was -6.5 Φ, broadening the grain size range associated with tsunami deposits found to date on Vancouver Island. Lacustrine tsunami deposits may be much more poorly-sorted than those encountered in tidal marsh environments and washover settings of Vancouver Island. This conclusion may be supported by hydrodynamic differences between landward-flows surging over intertidal marshes and lakes located above mean sea level.

The tsunami deposits found at Kakawis Lake are believed to be remnants of the oldest tsunami events recorded to date on the west coast of Vancouver Island. The deposits may correlate with three of the oldest identifiers from the Atwater – Hemphill-Haley chronology for the west coast of North America, in addition to three other events older than J (the last identifier BC 1400-1500) of unknown origin but presumed tectonic.

Older anomalous deposits of unknown origin are presumed to have existed previous to the time of emplacement of the earliest tsunami event at Kakawis Lake (TE1). Such supposition is based on the wide range of radiocarbon dates obtained from plant detritus throughout TE1. This may suggest a "cannibalistic" behaviour for tsunamis once inundation takes place, besides their erosive and/or depositional characteristics.

Only the youngest Kakawis Lake tsunami deposit has counterparts in two other coastal lakes of Vancouver Island. The oldest tsunami layers reported at Kanim and Deserted lakes may correlate with the youngest event at Kakawis Lake. In the neighbouring tidal marshes around Kakawis Lake, no evidence was found for such tsunami events, dating back middle to late Holocene. Some counterparts may exist embedded within Port Alberni marshes, but the ages of these buried sand layers are to date unknown.

Given the lack of geologic evidence in coastal settings neighbouring Kakawis Lake, in addition to the "old age" of the encountered tsunamigenic events, the use of archaeological evidence to constrain time of emplacement as well as extensiveness of an inferred tsunami inundation is an important addition and contribution. Moreover, given the lack of historic earthquake and tsunami records in the west coast of British Columbia, oral traditions, histories and aboriginal accounts may be very useful if analysed with prudence.

Kakawis Lake apparently did not record the last three major tsunami inundations known to have deposited anomalous layers in numerous low-elevation coastal lakes and tidal marshes along the Pacific Northwest coast. The events known as the AD 1964 Alaska earthquake and tsunami, the AD 1700 Cascadia earthquake and tsunami, and a ~AD 1200 tsunami of unknown source (Cascadia? Alaska?), are not present in Kakawis Lake. The absence of the events, together with an analysis of sea-level changes on the Clayoquot Sound region, implies a new maximum tsunami run-up limit of 4 m above mean sea level (at normal high tide) for the west coast of Vancouver Island.

Lacustrine tsunami deposits have most of the general architectural characteristics of tsunami deposition. They basically differ in two aspects: (a) in lakes, tsunami deposits do not rise landward and away from shore; and (b) plant detritus accumulations are not restricted to the upper limit of the tsunami deposit. Maximum particle sizes, spatial distribution and detailed analysis of lithofacies variation may indicate energy levels of a given tsunami surge as well as elevation of the lake relative to sea level position (at the time of the tsunami event). The latter may also be supported by the existence of erosional contacts (unconformities) at the base of the tsunami deposit, which implies that the basin should have been at reach of the extreme wave (i.e. washover elevation).

Paleoseismic investigations focused on sedimentological characteristics of tsunami deposits may better constrain mathematical models of tsunami inundation as they provide precise geographical locations of tsunami deposit occurrence. Tsunami wave parameters such as horizontal inundation distance, maximum inundation limit, inundation area and run-up heights may be implied from geological evidence left by tsunamis. Moreover, the absence and/or presence of tsunami deposits in diverse but proximal coastal settings may provide valuable information concerning hydrodynamic behaviour of the tsunami wave.

Although the "peat + tsunami sand + mud + peat" association in marshes implies coseismic subsidence in a tectonically active coastal region, such an association can not be used in lacustrine tsunami deposits. If chrono and litho-correlations between tsunami deposits of different coastal lakes can be well established, the widespread character of the lacustrine tsunami deposit may imply a regional (large and wide) effect of the tsunami wave. However, such broad occurrence does not necessarily imply coseismicity.

The integration of diverse data from multiple sources (paleoseismic studies, geological evidence, historic written records, Global earthquake and tsunami databases, archaeological evidence, aboriginal oral traditions, geophysical and geodetic models, sea level studies, tsunami propagation models) may lead to the information we presently need to enhance tsunami behaviour models onshore. Models and simulations are great sources of information, but proper verification of the accuracy of such models is needed. Paleoseismic investigations and field observations may be the link required to verify and constrain such models. Moreover, collective multidisciplinarity may give sufficient information to better elucidate tsunami hazard management and prevention plans.

CHAPTER 5

CONCLUSIONS

When dealing with major natural catastrophic events, such as earthquake-generated tsunamis or tsunamis triggered by any other major mechanism, low-elevation coastal lakes are recognized as ideal targets, given the wealth of information that can be recovered. In tectonically active regions, such information concerns the sedimentological characterisation of the tsunami deposit itself, but it also represents quantitative information of tsunami parameters, from which uplift rates and sea level changes can be inferred.

The sedimentological characterisation of the tsunami deposits from Kakawis Lake was possible given the diversity of techniques and analytical methods applied to all six sediment cores recovered from this unique unconsolidated lacustrine environment using a percussion coring system. New criteria for recognition of tsunami deposits emplaced in lakes was established from methods such as electrical resistivity, magnetic susceptibility, x-radiograph imagery, C/N ratios, and clast and marine shell identification. Such techniques had to cover and depict the various types of materials and tsunami deposits encountered. Given the variety of materials mixed within a single tsunami deposit (terrigenous clasts, marine organisms, terrestrial plant detritus, muddy and sandy matrix), a series of analytical methods were combined, modified and applied to provide a complete analysis of the anomalous sediments.

No single method is proposed as absolute to analyse such unique and complex deposits. However, several of the techniques and methods applied are new to paleoseismic research and especially to the study of paleotsunami deposits. Non-destructive techniques (geophysical and radiographic) yielded remarkable results that highlighted the different tsunami deposits found within the lacustrine sequences of the various cores. However, caution has to be taken especially with magnetic susceptibility and electrical resistivity values, as results depend upon a variety of parameters such as water content, porosity and compaction of the sediment, and not only the generally coarse grain size of the tsunami deposits.

The abundance of organic matter, typical of lacustrine environments, was one of the difficulties assessed during the laboratory analyses. Several standard and unconventional methods were employed to extract organic matter and recover the terrigenous material. It is often not possible to extract one sample and use it in several techniques and there is a limit to the quantity of material that is obtained from the cores (i.e. textural analyses are dependent on the amount of sample). To this end, it is recommended to extract as much information as possible from available sampled material. For example, the identification of biologic detritus was possible because of the selection made for the drying sample procedure. Freeze-drying preserves organic particles in a sample.

Three main units were identified at Kakawis Lake: glaciomarine clays, tsunami deposits and lacustrine gyttja. The tsunami deposits presented a variety of clast sizes, ranging from mud to medium-size cobbles, a diversity of marine shell species mainly comprising molluscs (up to 4 cm long), and terrestrial plant detritus of various types and sizes (up to 9 mm long). All materials are native to the region. Such representative fractions have remarkable sizes for a system presently located 4 m above mean sea level (amsl).

Kakawis Lake experienced six tsunami events during the middle to late Holocene, post-dating 7984 cal yrs BP but pre-dating 2408 cal yrs BP (datum = AD 2000). Each tsunami event was identified based on an initial facies determination, relying on compositional, geophysical and biochemical differences of diverse layers. By recognizing the facies to which each anomalous layer corresponded, a model of deposition was established. Each facies was inferred to represent different stages associated with pulses (influx/flood) or inter-pulses (outflow/ebb) of a given tsunami wave train (Figure 5.1). Four facies were recognized: a) massive gravel facies; b) massive sand facies; c) chaotic organic conglomerate; and d) organic detritus cap. A group of facies constitute a tsunami event, but not all events presented all four facies.

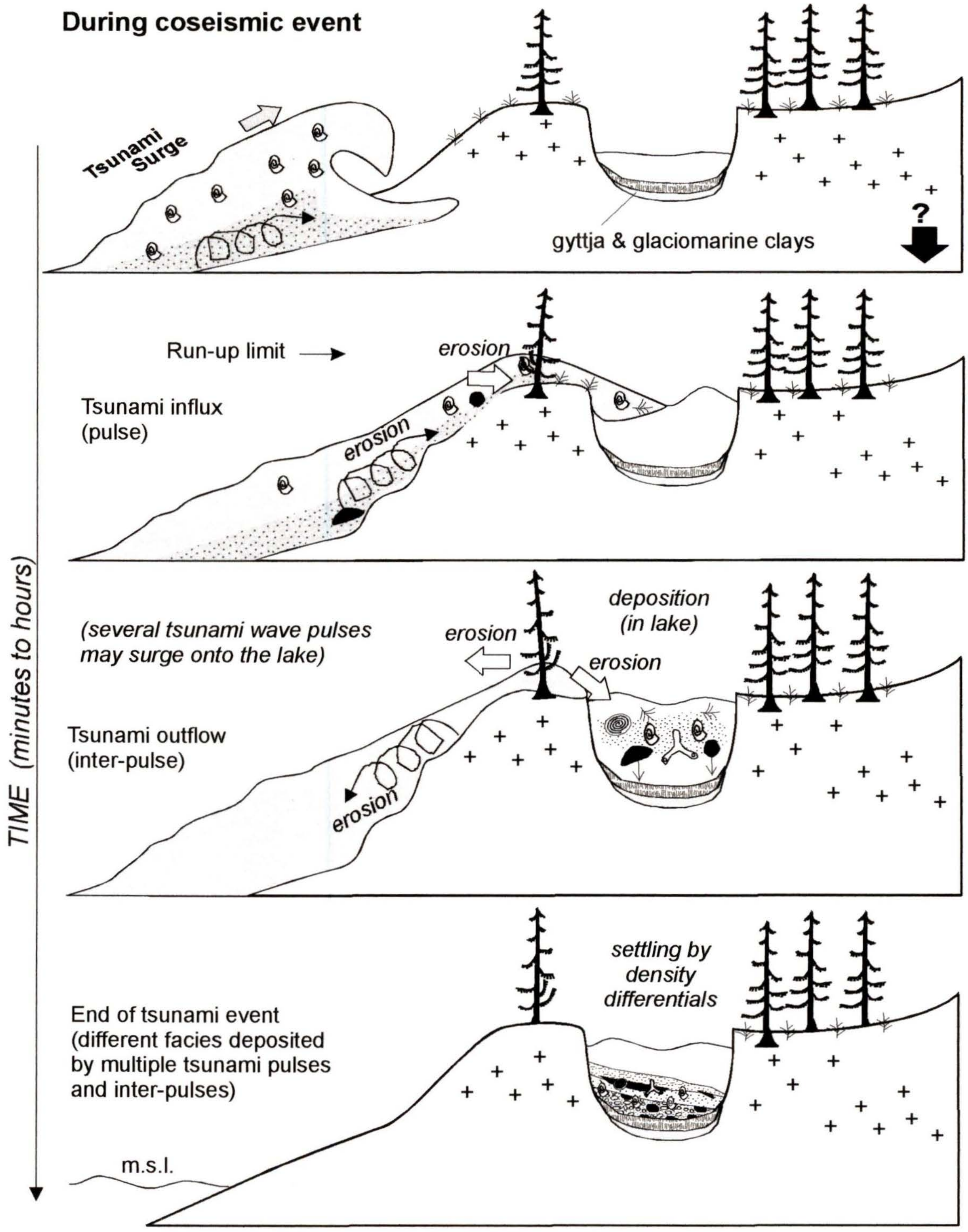


Figure 5.1 Conceptual model of erosion and deposition during tsunami surge in tectonically uplifted rugged, steeped-walled rocky shores like the one surrounding Kakawis Lake. Influx and deposition of coarse material is generated during tsunami pulses. Deposition of suspended fine particles is done during tsunami inter-pulses and after the tsunami. Saline waters may accumulate in the bottom of the lake after tsunami inundation, generating lamination of the bottom sediments.

Such facies association is correlative to the couplets association indicative of deposition by successive waves of a tsunami wave train, rather than a storm surge.

Single tsunami facies can be identified from magnetic susceptibility and electrical resistivity analyses. The coarser the facies, the higher the magnetic and resistivity values. However, caution has to be taken because organic-rich gyttja and layers enriched in macro-plant detritus also show high resistivity values due in part to the size of the detritus and water saturation. The highest values are found in the top sections of the cores where water content is greatest. Textural sorting and gradation trends can also be depicted using these techniques.

X-radiographs showed the internal three-dimensional (3-D) structure of the coarsest tsunami facies, defining a chaotic architecture for coarse tsunami deposits emplaced in lacustrine environments. The lowest values of total organic carbon (TOC) were associated with tsunami deposits, with the exception of tsunami facies enriched in macro-plant detritus. There is a direct relationship between TOC and mineral content coefficients for tsunami layers. Carbonate and plant detritus contents are inversely related in the tsunami deposits. The lowest water content values were also associated with tsunami deposits.

The high C/N values (15-35) obtained from the tsunami deposits suggest that most organic matter and plant detritus incorporated within the tsunami facies are primarily terrestrial, however a minor fraction of the organic matter may also have a marine origin. In turn, the other two components of the tsunami materials (clasts and marine shells) have a marine origin. All shell species identified are restricted to marine intertidal to sub-tidal environments associated with mud-sand to rocky substratum (e.g. *Mytilus sp., Venus sp., Protothaca staminea, Macoma sp.* and *Clinocardium sp.*). The presence of fragile (*Mytilus trossulus*), rare (*Chlamys rubida*) and strong-current immune (*Trichotropis cancellata*) marine shells may imply waves capable of both accessing secluded water areas and transporting material collected from sub-tidal areas, probably only reachable by tsunami waves. The presence of permanently fixed fossil calcified exoskeletons of adult balanomorph barnacles (*Balanus sp.*) to most clasts $> -1\ \Phi$, also indicates marine provenance for the coarsest terrigenous fraction. All materials are from local intertidal, shoreface, backshore and terrestrial environments found in the immediate vicinity of Kakawis Lake.

The weakness in the ^{137}Cs curve could either mean that a) there is constant mixing and mobilization of micro-particles in the upper-most fine organic-rich lake sediments; b) there is downward diffusion in the surface sediments; c) there is very little autochthonous and allochthonous sediment input; d) the width range (every 5 cm) used for each sample analysed was too large to detail any major variations in the ^{137}Cs profile; and/or, e) the last 46 years of watery gyttja were not covered during coring. Moreover, there was no anomalously coarse layer associated with the sediment interval analysed with ^{137}Cs. Such finding suggests that the AD 1964 Alaska tsunami did not reach Kakawis Lake.

Moderately-well to poorly-sorted extra local sands often mixed with marine organisms and a variety of plant detritus are the most common features in any given tsunami layer found in washover settings. Such characteristics are relatively easy to recognize if the enclosing depositional environment lacks such features and its' lithology is significantly different. The general architectural characteristics recognized in tsunami deposits emplaced in washover settings are that they thin and fine landwards, and rise landward and away from shore (indicative of landward surges of water).

Some of the general patterns apply to tsunami deposits found in lacustrine environments; however, a broader range of distinct characteristics were established based on detailed sedimentological analyses and interpretations of the six tsunami deposits found in Kakawis Lake sedimentary sequence. A detailed characterisation of such tsunami deposits is as follows (Figure 5.2):

- Tsunami deposits embedded in unconsolidated lacustrine sub-bottoms are well emphasized within the organic-rich muds.
- The thickness of tsunami deposits in lakes may be greater than those emplaced along washover settings.
- Individual tsunami layers (facies) are massive and to some extent chaotic if the material is coarser than $<0\ \Phi$.
- Lacustrine tsunami facies such as the ones found at Kakawis Lake, lack internal structure, hence there are no indications of paleocurrents.

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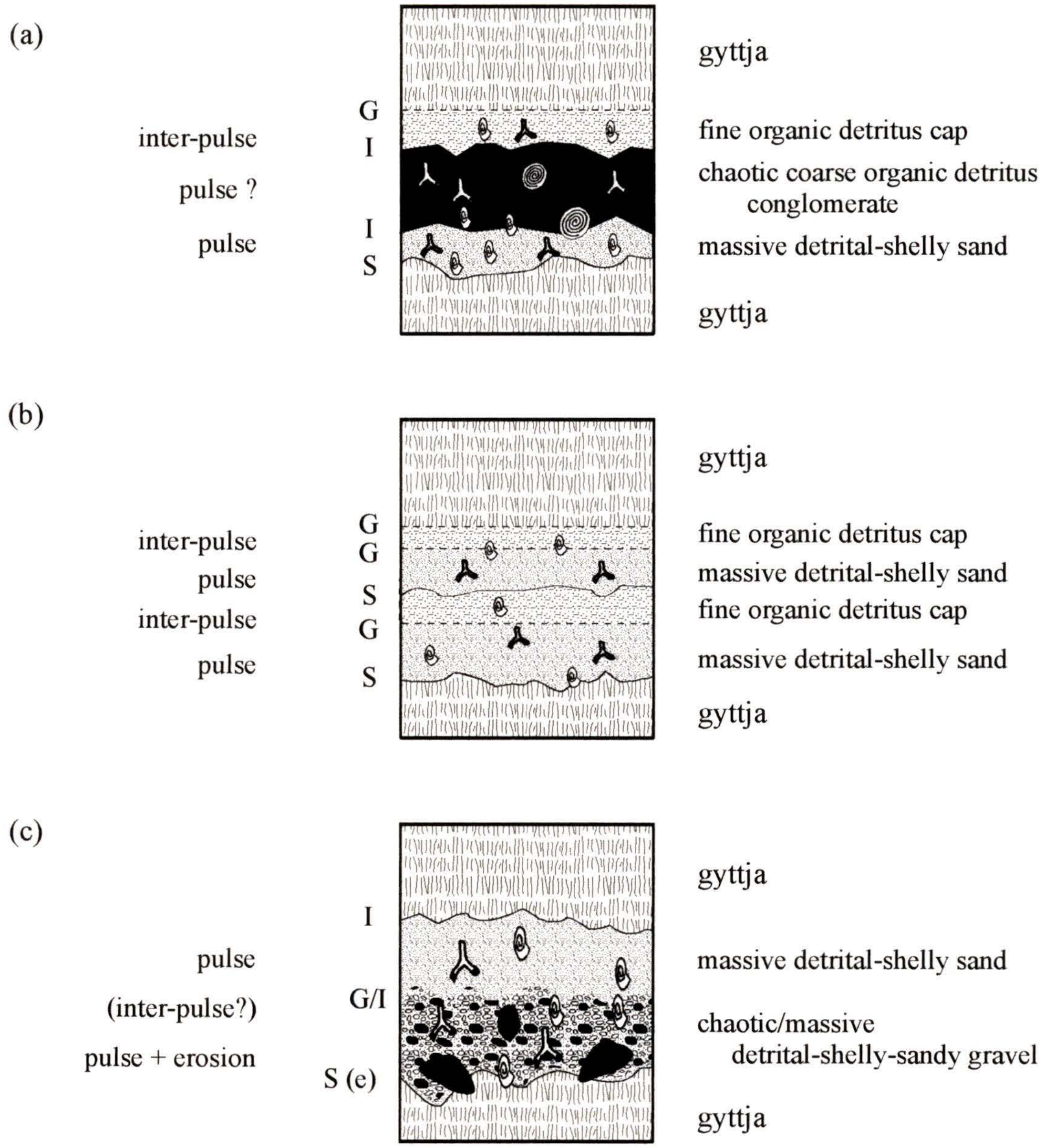

Figure 5.2 Representations of the most common stratigraphy seen in tsunami deposits at Kakawis Lake. The general characteristic is that such deposits are layered between gyttja (lacustrine organic mud). Types of contacts are also given (G - gradational; S - sharp; I - irregular; (e) - erosional). The textural characteristics define the association with the stage of tsunami inundation (pulse and inter-pulse). Macro-plant detritus can be scattered throughout the deposit. The coarsest and less structured deposits (c) lye closer to the outlet stream. More defined and structured deposits (b) are typical of the central area of the lake. Layers with very coarse plant detritus (a) can be found at random within the lake, and depend on the spread of such material throughout the lake at the moment of inundation.

- If a single tsunami event (assemblage of facies) is analysed, a normal gradation can be observed. Moreover, the general succession of tsunami events at Kakawis Lake fines and thins upwards.
- All tsunami events showed sharp, undulating basal contacts, implying erosion which is typical of turbulent flows (i.e. tsunamis). A few rip-up clasts associated with the coarsest layers also indicate erosive and turbulent conditions, suggesting a probable unconformity.
- The contacts between the different facies varied from sharp to gradational.
- The thickest (~40 cm) and most poorly-sorted tsunami deposits are located closer to the outlet stream and may be a combination of several successive tsunami events.
- The coarsest clasts sizes (-6.5 Φ) were found within the oldest tsunami deposits as well as the ones located the closest to the outlet stream. Such deposits contained the highest clast-barnacle association.
- Some of the coarsest plant detritus and shell fragments are found embedded in the tsunami deposits closest to the outlet stream, together with the highest diversity of marine shell species.
- The resolution of individual events as well as tsunami facies is better closer to the centre of the lake. This observation is consistent with settling parameters of lakes.
- Architecturally, all tsunami events decreased in thickness away from the outlet stream. However, they follow the bathymetry (concavity) of the lacustrine basin, resulting in layers that may appear to be descending away from shore.
- In general, particle sorting increases towards the centre of the lake as well as upwards.
- Grain-size distributions for these tsunami deposits ranged from coarse silt (+6 Φ) to medium cobbles (-6.5 Φ).
- Tsunami deposits at Kakawis Lake are distinctly polymodal and poorly to very poorly-sorted.

- Plant detritus may or not cover coarser facies depending on the size of the vegetative fragments.
- Chaotic organic conglomerate facies (large plant fragments associated with minor sand-sized clastic and shelly particles) form thick "stand-alone" layers, opposite to organic detritus cap facies that can overlie both clastic-rich layers and the above mentioned coarse plant detritus layers.
- Although sand layers deposited by tsunamis and extreme storms may be in-distinguishable on the basis of lithological characteristics, the existence of a very coarse fraction ($<-5\ \Phi$) and the geographical position of the lake suggest tsunamis as depositional mechanism.

Low-elevation coastal lakes are more favourable preservation environments because (Figure 5.3): a) they may lie within reach of tsunami run-up; b) oceanic currents and other marine erosive/transport processes are not prevalent; c) they are enclosed low-energy environments; d) the velocity of burial of anomalous marine-sourced layers depends on the lake sedimentation rate; e) successful preservation does not necessarily require coseismic subsidence; f) identification of anomalous layers is easier given the contrast to typical lacustrine sediments; and g) coastal lakes are efficient sediment traps. In general, in tectonically emerging coastlines, tsunami deposits are better preserved in lacustrine environments than tidal marshes.

Tsunami inundation processes in lakes are different from ones impacting flat low-lying beaches, intertidal marshes, wetlands and open shores, which are easier settings to be over-washed by extreme ocean levels. Contrary to tidal marsh and some washover settings on tectonically emerging coasts, coseismic subsidence may be very difficult to be evidenced in lakes because in such environments there is no soil to bury. Nonetheless, the thickness of a tsunami deposit in a lake, in addition to the maximal clast sizes involved may indicate a possible source for the associated tsunami. All the above being equal, the coarser the material and the thicker the deposit, the closer the tsunami source (i.e. CSZ or distant tsunamis).

The chaotic, shelly and anomalously coarse deposits mixed and/or capped with terrestrial organic detritus at Kakawis Lake, are interpreted to be deposits emplaced by

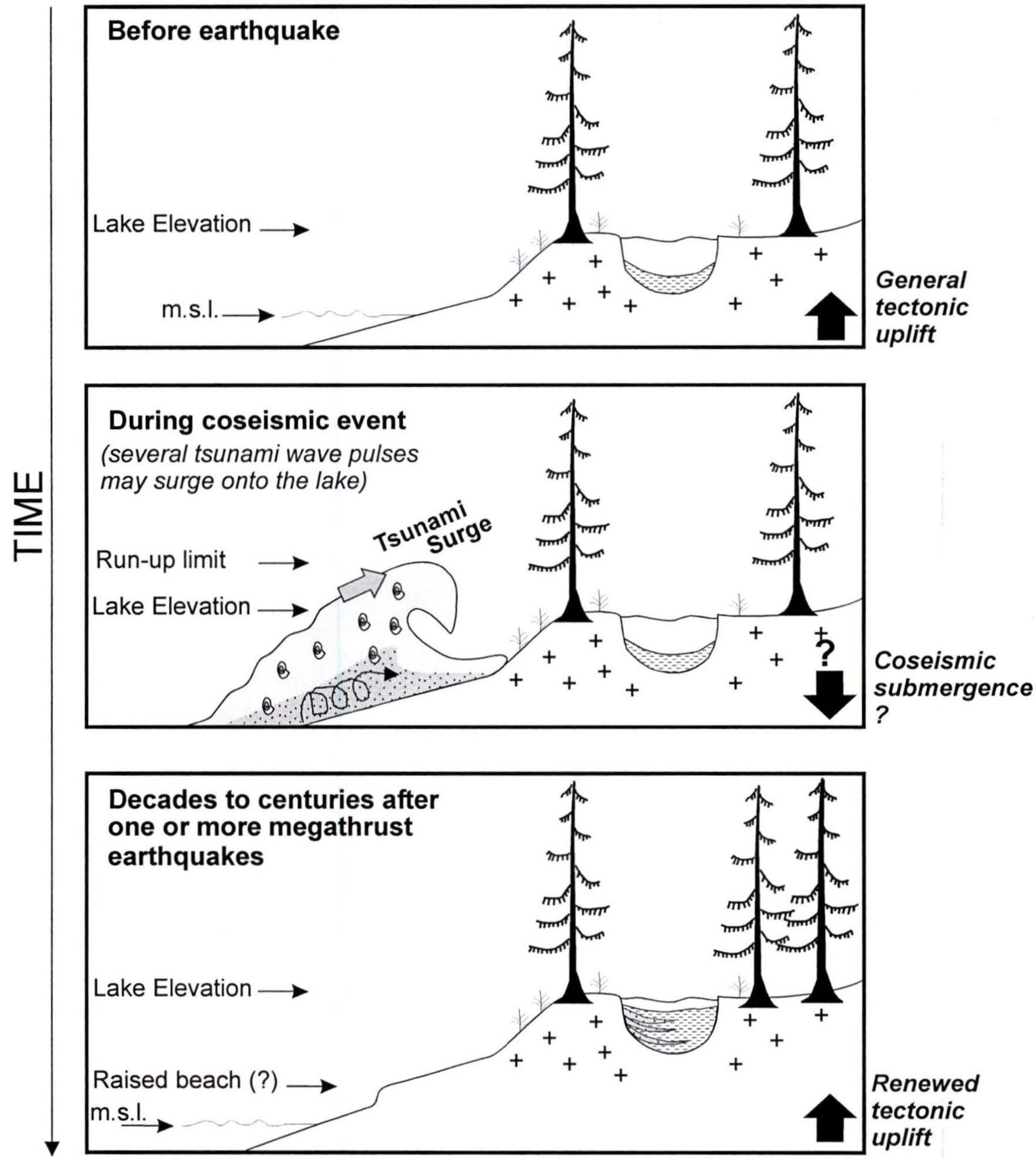

Figure 5.3: Conceptual model for generation of paleotsunamigenic evidence in low-lying coastal lakes on tectonically deforming coasts (i.e. Cascadia Subduction Zone region). The model does not apply for lakes located in flat low-lying coasts, susceptible to washover by extreme ocean water levels. The diagrams are based on paleoseismic evidence found in unconsolidated sedimentary sequences from Kakawis Lake. Given the continuously uplifting coast, tsunami waves may not be able to reach again the once lower-lying coastal lake, setting new maximum tsunami run-up heights for these types of rugged, steep walled and rocky coasts.

tsunamis of distant and/or local provenance. Based on radiocarbon dates, all six tsunami events evident at Kakawis Lake likely define the oldest tsunami deposits found to date on Vancouver Island. By correlating the radiocarbon ages with the Atwater – Hemphill-Haley paleoseismic chronology estimated for the Cascadia region, it is possible that Kakawis may have experienced some of the oldest events inferred for the Pacific coast of North America. The chronology identifiers named N (BC 400-800), L (BC 800-1300) and J (BC 1400-1500) may be associated with three of the youngest tsunami events from Kakawis Lake. It is possible that the three older ones may be associated with events older than identifier J but younger than 7964 cal yrs BP of unknown origin but presumed tectonic based on the assumed recurrence pattern of mega-thrust events in this region.

Only the youngest Kakawis Lake tsunami deposit has counterparts in two other Vancouver Island coastal lakes. The oldest tsunami layers reported at Kanim and Deserted lakes may correlate with the youngest event at Kakawis Lake. In the neighbouring tidal marshes around Kakawis Lake, no evidence was found for tsunami deposits, dated middle to late Holocene. Some counterparts may exist embedded within Port Alberni marshes, but the ages of the buried sand layers are so far unknown.

Archaeological evidence reported along Cascadia coastal lands may be correlative with Kakawis Lake tsunami deposits. Numerous radiocarbon ages reported from ancient cultural sites on the west outer coast of Vancouver Island, match the radiocarbon ages obtained from at least three of the tsunami events recorded at Kakawis Lake. The seismic events reported as N and L identifiers in the Atwater – Hemphill-Haley chronology correlate with both ages, suggesting earthquake-induced burial and unexpected aboriginal village abandonment, as well as with the ages of the youngest tsunami events found at Kakawis Lake.

Based on the radiocarbon ages obtained from tsunami plant detritus, at least six tsunami events surged onto Kakawis Lake every 285 to 400 years, with the last having taken place around BC 400. Kakawis Lake apparently does not record the last three major tsunami inundations known to have deposited anomalous layers in numerous low-elevation coastal lakes and tidal marshes along the Pacific Northwest coast. The events known as the AD 1964 Alaska earthquake and tsunami, the AD 1700 Cascadia earthquake and tsunami, and a ~AD 1200 tsunami of unknown source (Cascadia? Alaska?), are not present in Kakawis Lake. The absence of the events, together with an analysis of sea-level changes on the Clayoquot Sound region, implies a new maximum tsunami run-up limit of 4 m above mean sea level (at normal high tide) for the west coast of Vancouver Island.

The present elevation of Kakawis Lake (4 m amsl) gives a maximum limit value of tsunami run-up for present-day sheltered, rugged rocky areas of the Clayoquot Sound region; and probably for the entire outer coast of Vancouver Island. The absence of the last three major tsunami events at Kakawis Lake suggests that: (a) tsunami energies may become sufficiently dissipated over at least 9 km of intricate shallow waters with numerous obstacles; (b) tsunami waves may inundate tidal marshes but not reach coastal lands located 4 m amsl (at normal high tide); (c) wide shallow waters like Clayoquot Sound may not apply as much resonance effect on incoming tsunamis like deeply indented fjords (i.e. Alberni Inlet); (d) tsunamis may get reflected by steep rugged rocky flanks that neighbour most of the tidal marshes around the southern channels and inlets of Clayoquot Sound; (e) the width of the continental shelf off central west Vancouver Island may highly dissipate tsunami energies compared to northern sections of the shelf (north of Nootka Sound); and (f) neither distant or local tsunamis triggered by mega-thrust earthquakes can reach basins located at >4 m amsl (at normal high tide), on the west coast of Vancouver Island.

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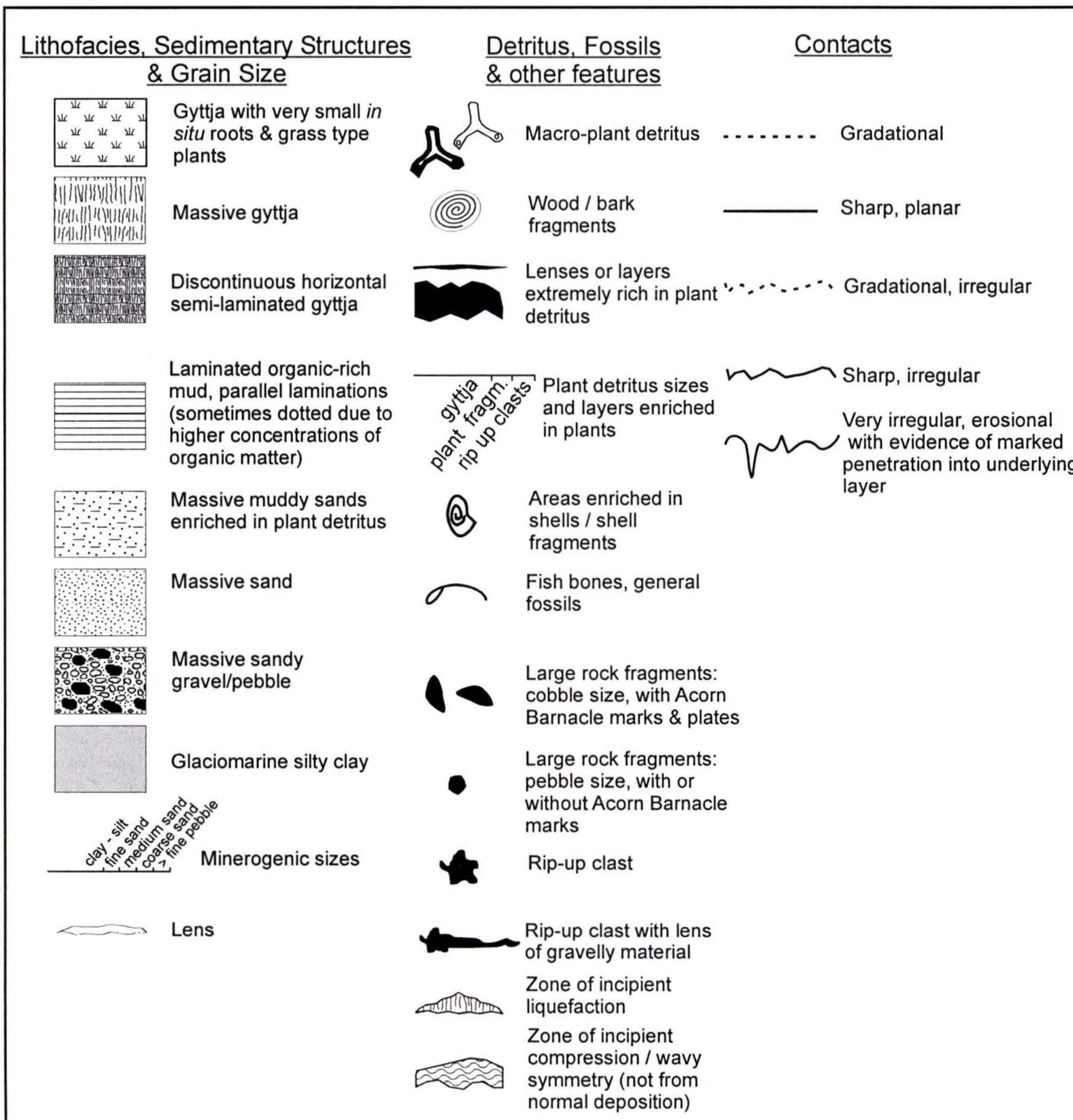
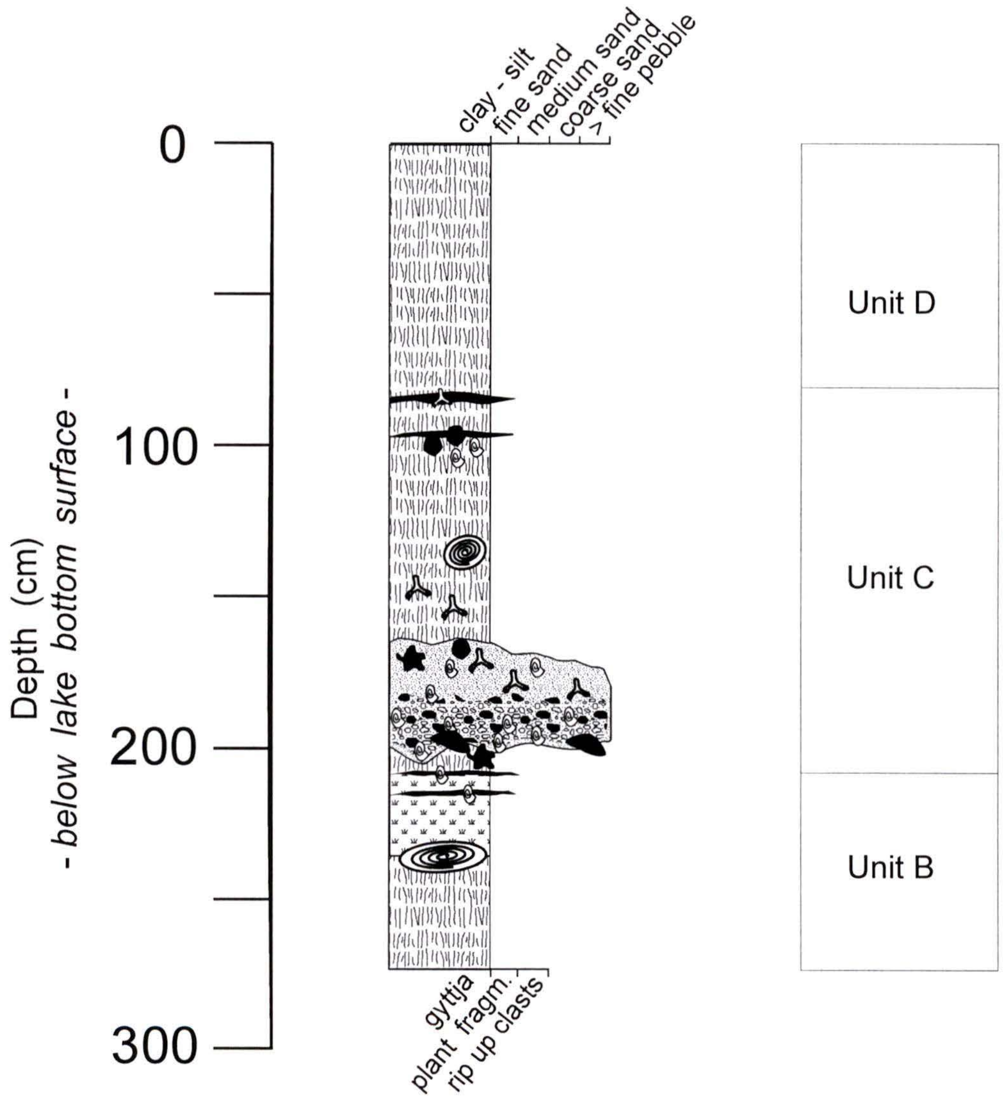
APPENDIX A

Description of unconsolidated sedimentary sequences of cores from Kakawis Lake (K1, K2, K3, K5, K6 and K7)



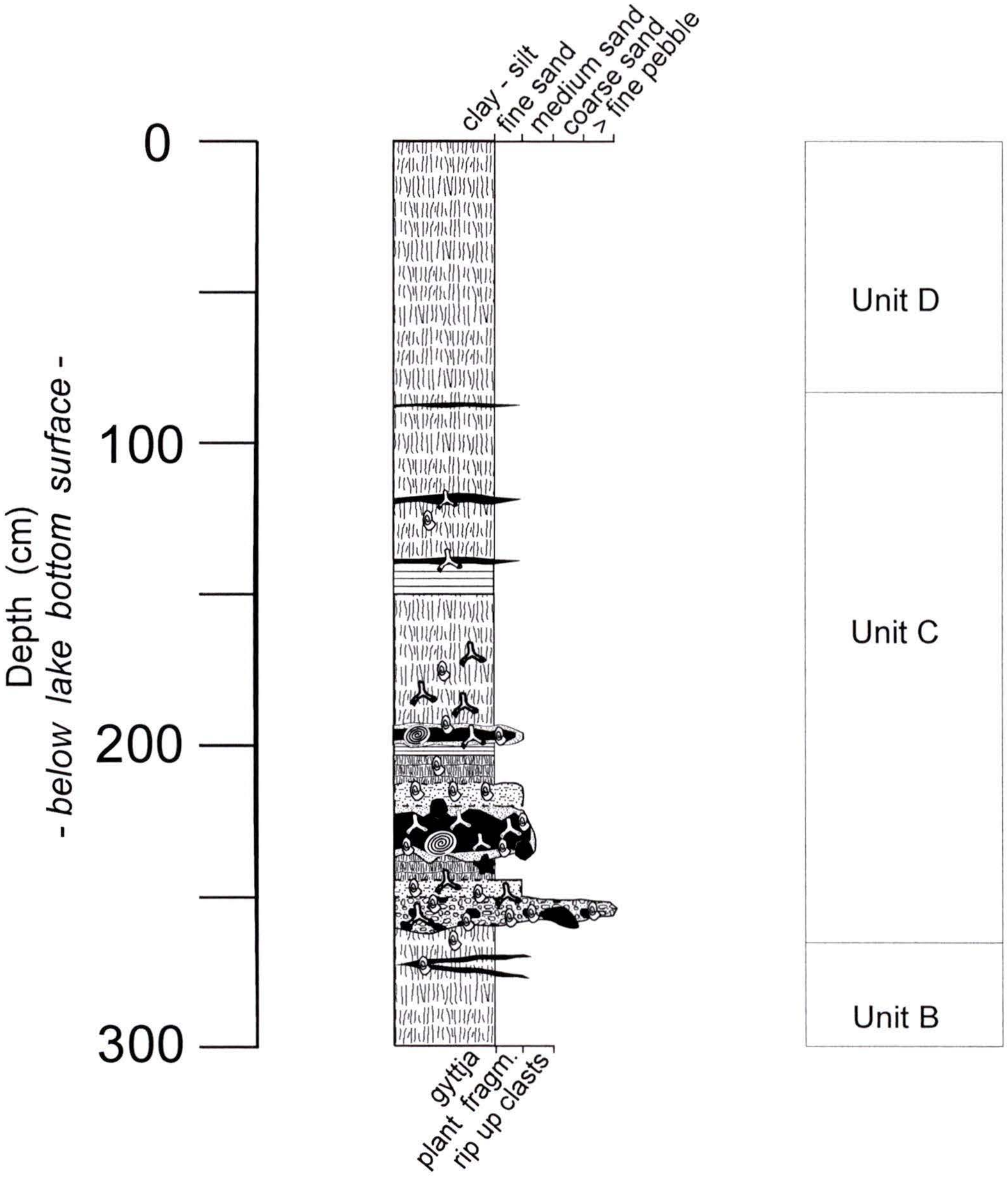
CORE K1 - KAKAWIS LAKE

LITHO-STRATIGRAPHY BASED ON TEXTURAL, BIOLOGICAL, AND GRAIN SIZE ANALYSES



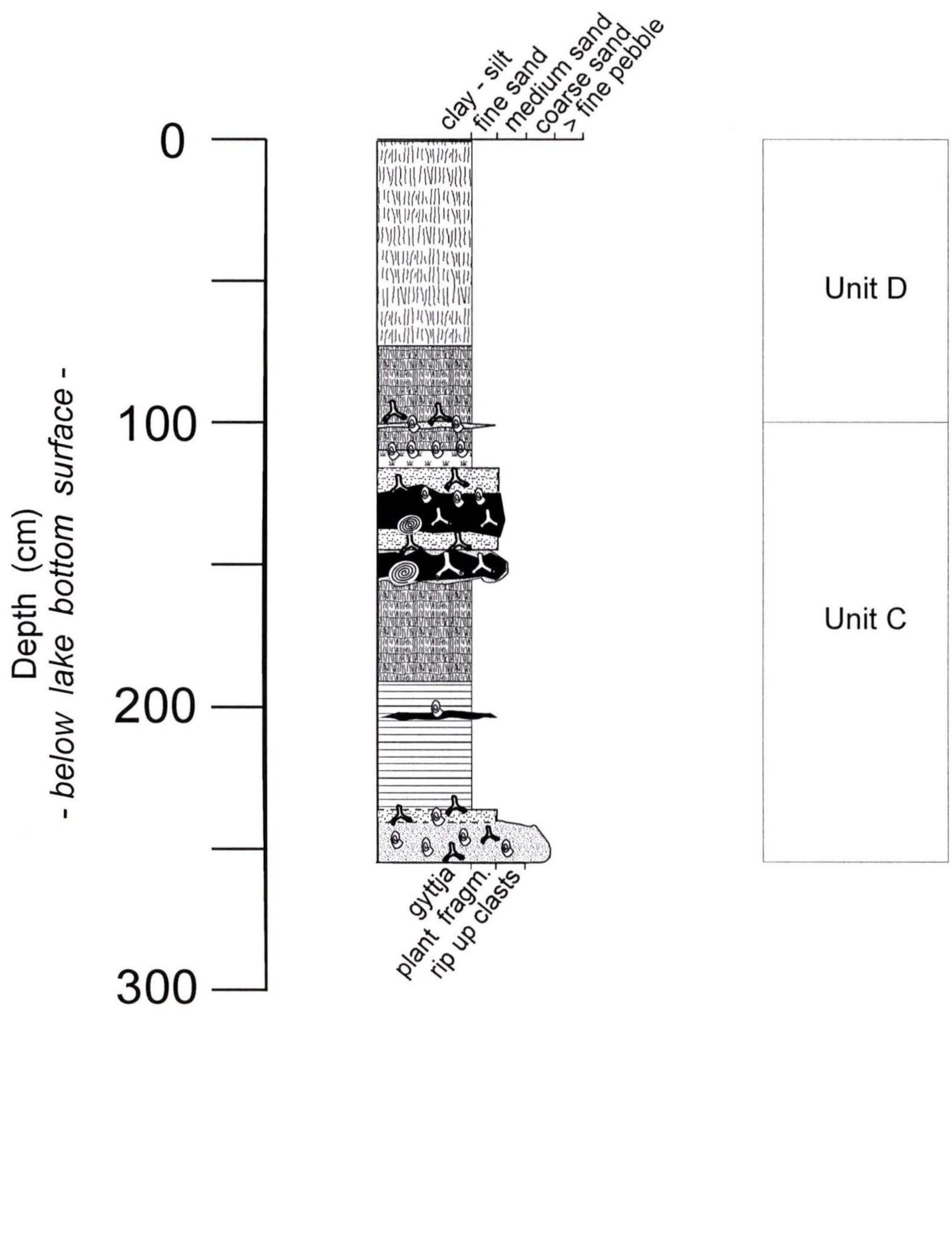
CORE K2 - KAKAWIS LAKE

LITHO-STRATIGRAPHY BASED ON TEXTURAL, BIOLOGICAL, AND GRAIN SIZE ANALYSES



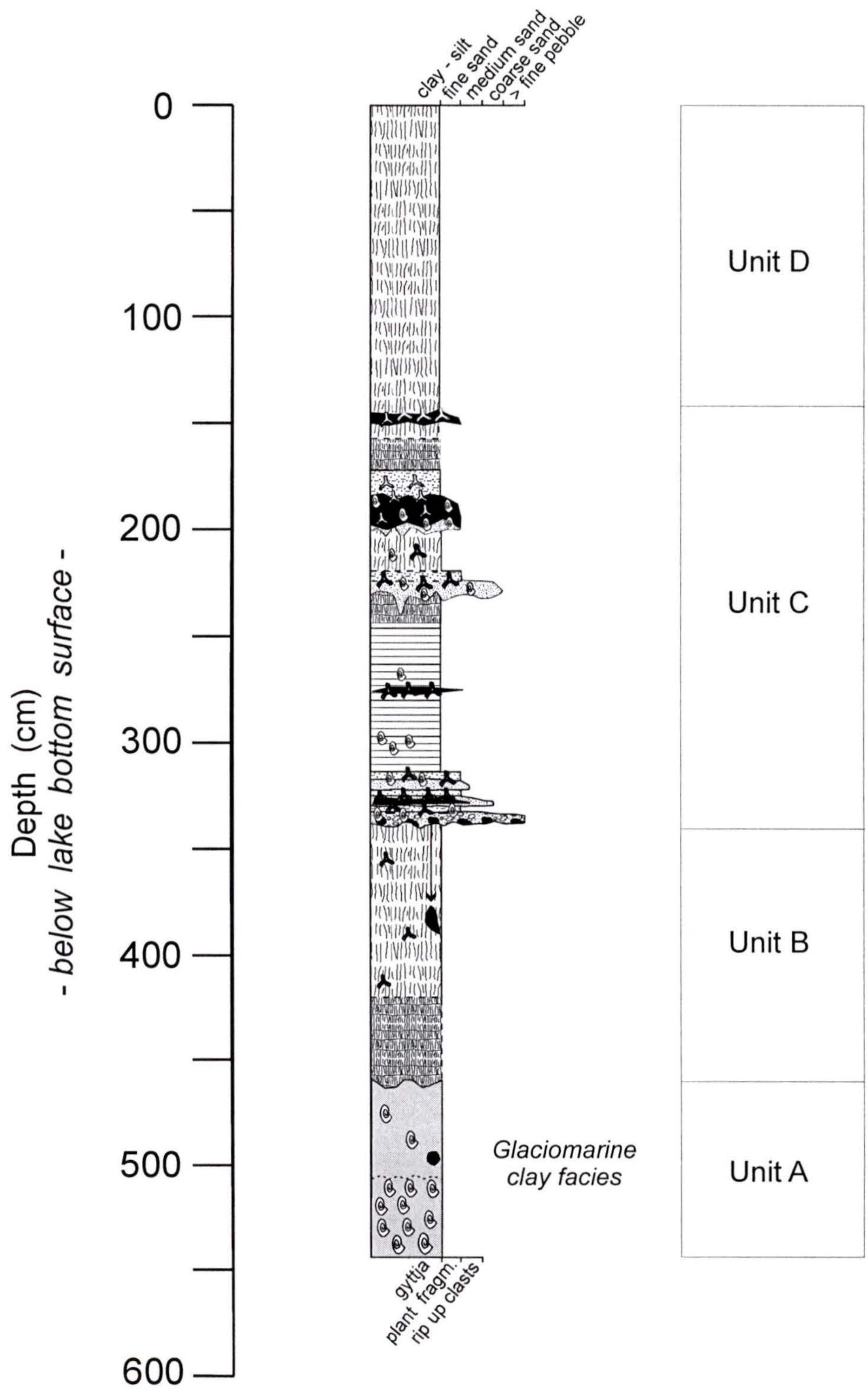
CORE K3 - KAKAWIS LAKE

LITHO-STRATIGRAPHY BASED ON TEXTURAL, BIOLOGICAL, AND GRAIN SIZE ANALYSES



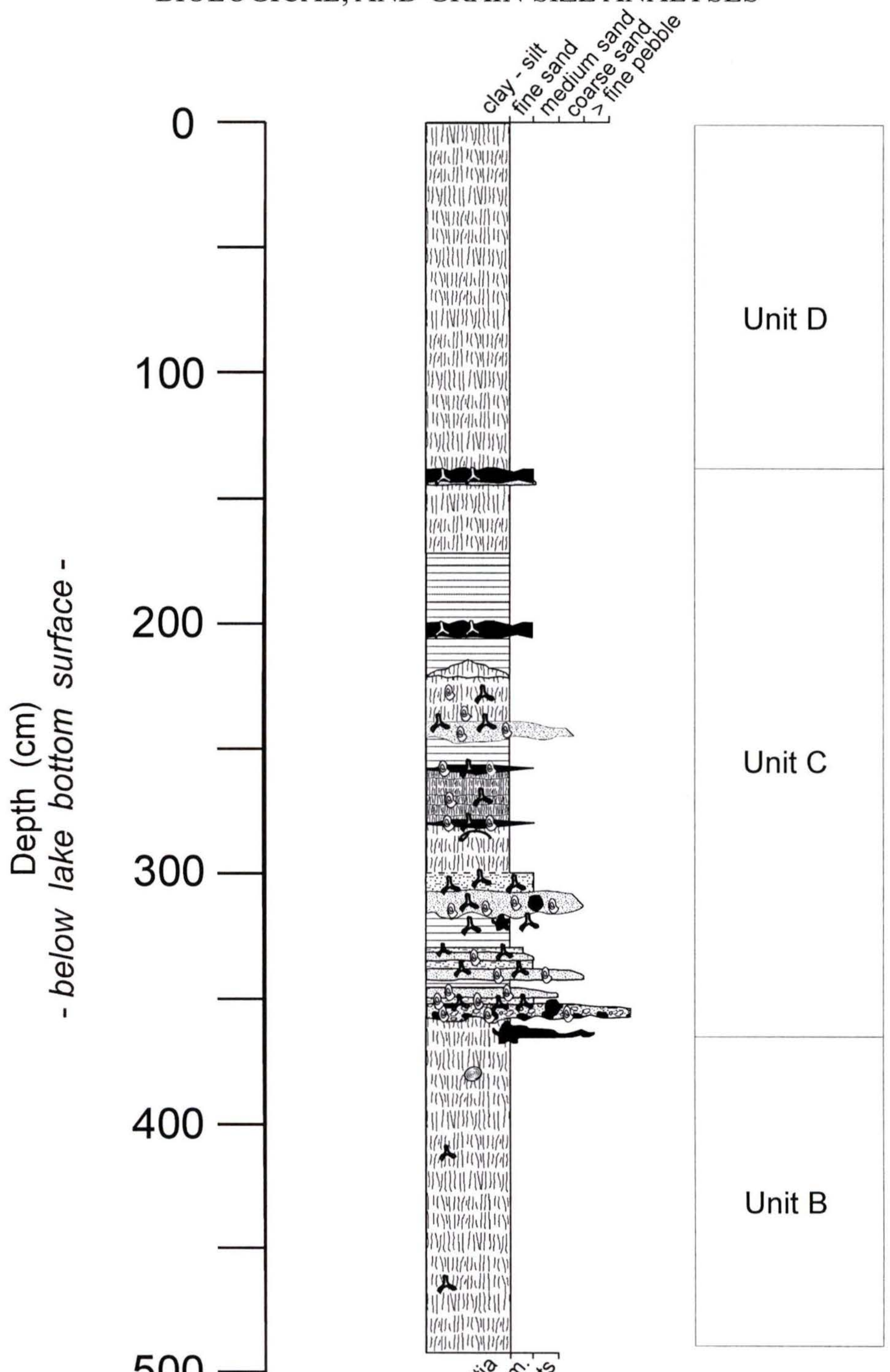
CORE K5 - KAKAWIS LAKE

LITHO-STRATIGRAPHY BASED ON TEXTURAL, BIOLOGICAL, AND GRAIN SIZE ANALYSES



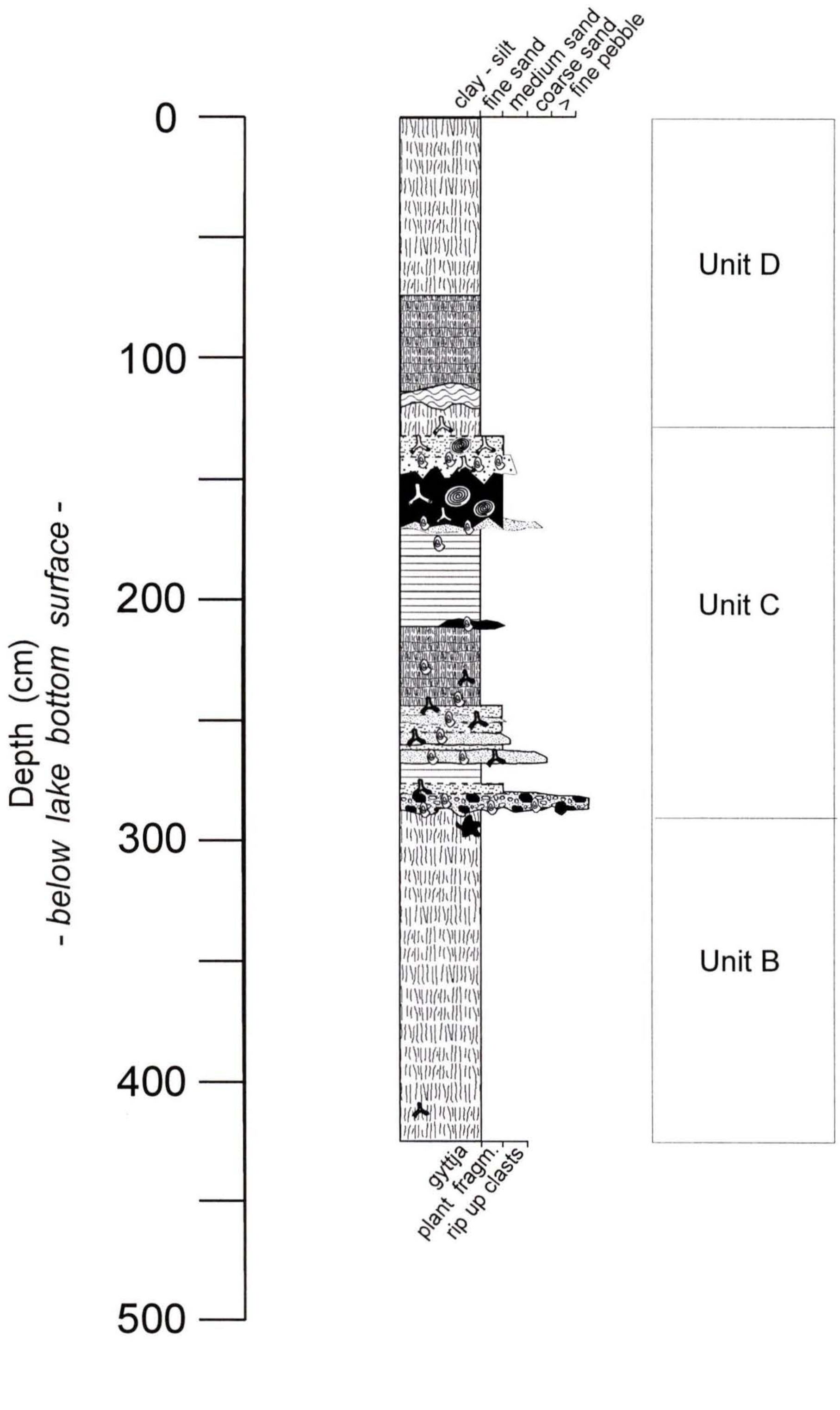
CORE K6 - KAKAWIS LAKE

LITHO-STRATIGRAPHY BASED ON TEXTURAL, BIOLOGICAL, AND GRAIN SIZE ANALYSES



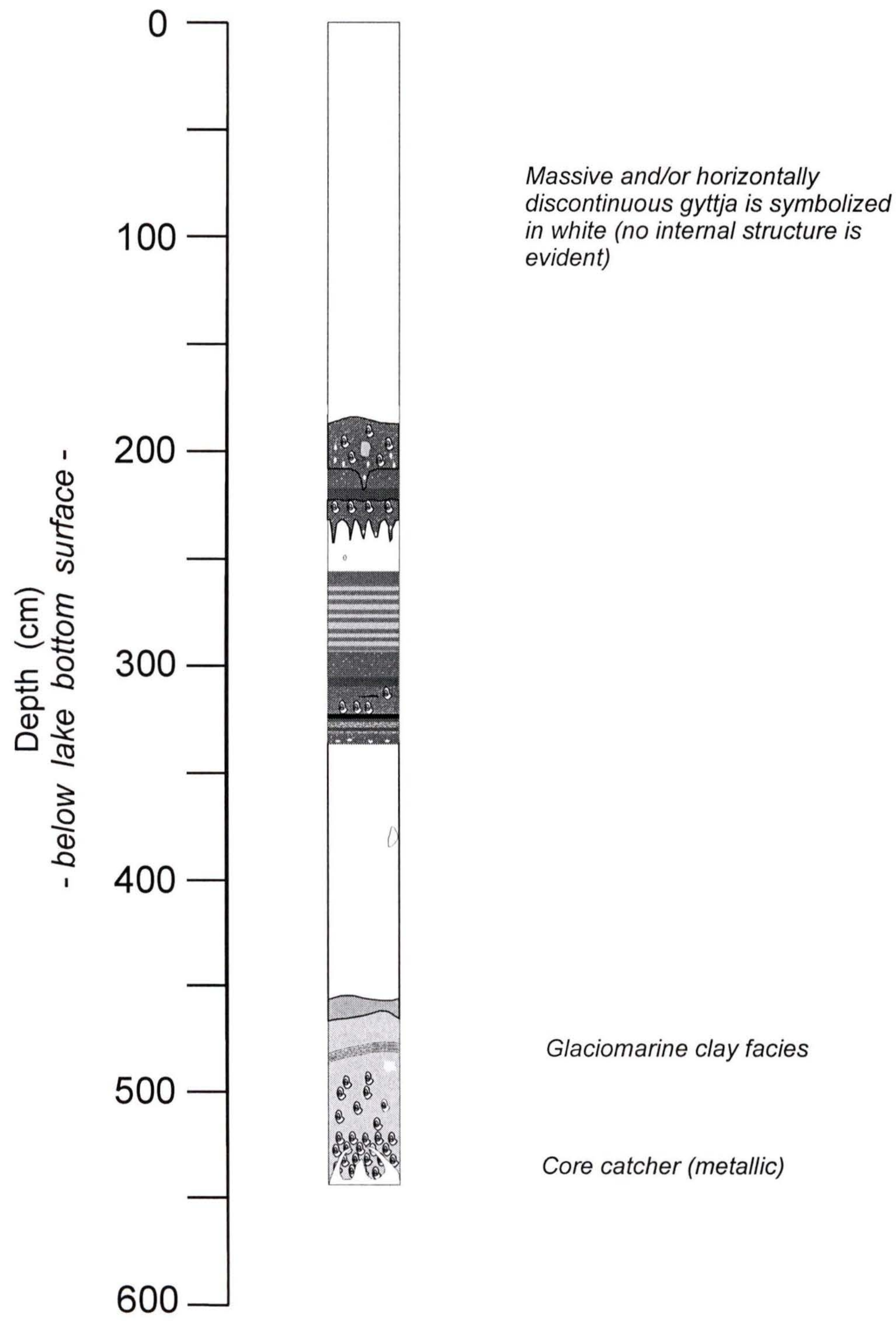
CORE K7 - KAKAWIS LAKE

LITHO-STRATIGRAPHY BASED ON TEXTURAL, BIOLOGICAL, AND GRAIN SIZE ANALYSES



APPENDIX B

Stratigraphic section obtained from X-Radiograph imagery analysis for core K5 (Kakawis Lake)



APPENDIX C

MAGNETIC SUSCEPTIBILITY MEASUREMENTS

Core Name:	**Kakawis # 6**	
No. of Sections:	3	
Total length of the core (cm):	496.5	(cap to cap)
Direction of measurements:	top to bottom	
Stage of core:	un-split	
Technique used:	Magnetic Susceptibility from coil inductance measurements	
Program used:	CORESUSC Version 1.0 based on SUSC15 Core Susceptibility measurements using the Saphire Instruments SI2 susceptibility meter	

Brief observations	True depth in core	Registered depth interval	Measurement (x1000000 SI/vol.)		Value	
	(cm)	(cm)	value	+/- error	+ error	- error
top section 1	1.50	4.00	66.61	0.59	67.20	66.02
	3.50	6.00	289.47	0.59	290.06	288.88
	5.50	8.00	293.08	1.36	294.44	291.72
	7.50	10.00	289.90	0.57	290.47	289.33
	9.50	12.00	288.95	0.96	289.91	287.99
	11.50	14.00	287.42	0.97	288.39	286.45
	13.50	16.00	287.83	0.19	288.02	287.64
	15.50	18.00	187.90	99.09	286.99	88.81
	17.50	20.00	285.91	0.59	286.50	285.32
	19.50	22.00	286.37	0.20	286.57	286.17
	21.50	24.00	286.37	0.57	286.94	285.80
	23.50	26.00	285.66	0.20	285.86	285.46
	25.50	28.00	289.16	0.20	289.36	288.96
	27.50	30.00	288.49	0.20	288.69	288.29
	29.50	32.00	288.80	0.57	289.37	288.23
	31.50	34.00	288.04	0.20	288.24	287.84
	33.50	36.00	286.85	0.19	287.04	286.66
	35.50	38.00	285.07	0.57	285.64	284.50
	37.50	40.00	282.47	0.19	282.66	282.28
	39.50	42.00	279.08	0.96	280.04	278.12
	41.50	44.00	275.37	0.96	276.33	274.41
	43.50	46.00	271.69	0.57	272.26	271.12
	45.50	48.00	269.15	0.19	269.34	268.96
	47.50	50.00	267.13	0.19	267.32	266.94
	49.50	52.00	265.21	0.19	265.40	265.02
	51.50	54.00	263.74	0.57	264.31	263.17
	53.50	56.00	260.90	0.57	261.47	260.33

	55.50	58.00	258.27	0.20	258.47	258.07
	57.50	60.00	179.46	50.02	229.48	129.44
	59.50	62.00	128.63	0.96	129.59	127.67
	61.50	64.00	126.47	0.57	127.04	125.90
	63.50	66.00	124.79	0.96	125.75	123.83
	65.50	68.00	123.70	0.19	123.89	123.51
	67.50	70.00	118.19	0.57	118.76	117.62
	69.50	72.00	114.49	2.12	116.61	112.37
	71.50	74.00	106.80	0.96	107.76	105.84
	73.50	76.00	103.77	0.20	103.97	103.57
	75.50	78.00	104.12	0.97	105.09	103.15
	77.50	80.00	-153.05	0.35	-152.70	-153.40
	79.50	82.00	-142.25	0.74	-141.51	-142.99
	81.50	84.00	-134.89	0.41	-134.48	-135.30
	83.50	86.00	-120.90	1.13	-119.77	-122.03
	85.50	88.00	-113.88	0.74	-113.14	-114.62
	87.50	90.00	-106.10	0.35	-105.75	-106.45
	89.50	92.00	-99.37	0.35	-99.02	-99.72
	91.50	94.00	-97.40	0.03	-97.37	-97.43
	93.50	96.00	-95.33	0.80	-94.53	-96.13
	95.50	98.00	-90.04	0.74	-89.30	-90.78
	97.50	100.00	-84.03	0.04	-83.99	-84.07
	99.50	102.00	-79.23	1.13	-78.10	-80.36
	101.50	104.00	-75.60	1.13	-74.47	-76.73
	103.50	106.00	-71.51	1.13	-70.38	-72.64
	105.50	108.00	-67.53	0.35	-67.18	-67.88
	107.50	110.00	-60.58	0.74	-59.84	-61.32
	109.50	112.00	-54.70	0.74	-53.96	-55.44
	111.50	114.00	-49.80	1.19	-48.61	-50.99
	113.50	116.00	-46.20	0.03	-46.17	-46.23
	115.50	118.00	-40.88	0.03	-40.85	-40.91
	117.50	120.00	-35.09	0.75	-34.34	-35.84
	119.50	122.00	-30.88	0.04	-30.84	-30.92
	121.50	124.00	-26.87	0.42	-26.45	-27.29
	123.50	126.00	-21.66	0.03	-21.63	-21.69
	125.50	128.00	-16.57	0.03	-16.54	-16.60
	127.50	130.00	-14.92	0.35	-14.57	-15.27
	129.50	132.00	-11.11	1.13	-9.98	-12.24
	131.50	134.00	-8.41	0.35	-8.06	-8.76
	133.50	136.00	-4.25	0.80	-3.45	-5.05
	135.50	138.00	-0.35	1.13	0.78	-1.48
	137.50	140.00	3.51	0.36	3.87	3.15
	139.50	142.00	8.31	0.03	8.34	8.28
	141.50	144.00	13.37	0.03	13.40	13.34
	143.50	146.00	23.70	0.03	23.73	23.67
	145.50	148.00	36.61	0.74	37.35	35.87
	147.50	150.00	48.23	0.75	48.98	47.48

	149.50	152.00	48.94	0.03	48.97	48.91
end section 1	151.00	154.00	37.02	0.73	37.75	36.29
top section 2	152.50	155.00	100.10	1.22	101.32	98.88
	154.50	157.00	115.94	1.60	117.54	114.34
	156.50	159.00	114.76	0.45	115.21	114.31
	158.50	161.00	108.77	0.44	109.21	108.33
	160.50	163.00	107.78	1.22	109.00	106.56
	162.50	165.00	108.24	0.32	108.56	107.92
	164.50	167.00	108.54	0.33	108.87	108.21
	166.50	169.00	108.77	0.33	109.10	108.44
	168.50	171.00	108.96	0.33	109.29	108.63
	170.50	173.00	110.61	0.72	111.33	109.89
	172.50	175.00	111.46	0.33	111.79	111.13
	174.50	177.00	118.73	0.06	118.79	118.67
	176.50	179.00	129.08	0.32	129.40	128.76
	178.50	181.00	137.04	0.06	137.10	136.98
	180.50	183.00	148.54	0.45	148.99	148.09
	182.50	185.00	157.90	0.06	157.96	157.84
	184.50	187.00	167.66	0.32	167.98	167.34
	186.50	189.00	189.61	1.22	190.83	188.39
start of s.h.	188.50	191.00	216.95	0.71	217.66	216.24
	190.50	193.00	251.92	0.83	252.75	251.09
	192.50	195.00	274.26	0.33	274.59	273.93
end of s.h.	194.50	197.00	271.95	1.10	273.05	270.85
	196.50	199.00	263.20	0.32	263.52	262.88
	198.50	201.00	249.41	0.83	250.24	248.58
	200.50	203.00	216.11	0.33	216.44	215.78
	202.50	205.00	178.30	0.06	178.36	178.24
	204.50	207.00	165.90	0.32	166.22	165.58
	206.50	209.00	174.83	1.10	175.93	173.73
	208.50	211.00	199.81	0.71	200.52	199.10
	210.50	213.00	227.65	0.06	227.71	227.59
	212.50	215.00	246.92	0.71	247.63	246.21
	214.50	217.00	242.79	0.32	243.11	242.47
	216.50	219.00	210.36	1.10	211.46	209.26
	218.50	221.00	173.50	0.33	173.83	173.17
	220.50	223.00	145.50	1.10	146.60	144.40
	222.50	225.00	125.09	0.33	125.42	124.76
	224.50	227.00	113.09	1.10	114.19	111.99
	226.50	229.00	54.97	0.73	55.70	54.24
	228.50	231.00	60.50	0.34	60.84	60.16
	230.50	233.00	63.20	0.35	63.55	62.85
	232.50	235.00	67.30	0.04	67.34	67.26
	234.50	237.00	72.51	0.34	72.85	72.17
	236.50	239.00	80.21	0.43	80.64	79.78
	238.50	241.00	93.86	0.82	94.68	93.04
	240.50	243.00	122.18	0.81	122.99	121.37

	242.50	245.00	167.38	0.43	167.81	166.95
	244.50	247.00	187.21	0.43	187.64	186.78
	246.50	249.00	171.81	0.43	172.24	171.38
	248.50	251.00	147.46	0.34	147.80	147.12
	250.50	253.00	142.88	0.81	143.69	142.07
	252.50	255.00	150.78	0.34	151.12	150.44
	254.50	257.00	158.48	0.04	158.52	158.44
	256.50	259.00	148.49	0.43	148.92	148.06
	258.50	261.00	121.03	0.34	121.37	120.69
	260.50	263.00	93.79	0.04	93.83	93.75
	262.50	265.00	77.72	0.82	78.54	76.90
	264.50	267.00	72.71	0.43	73.14	72.28
	266.50	269.00	70.92	0.43	71.35	70.49
	268.50	271.00	70.73	0.04	70.77	70.69
	270.50	273.00	64.50	0.04	64.54	64.46
	272.50	275.00	63.17	0.34	63.51	62.83
	274.50	277.00	61.67	0.04	61.71	61.63
	276.50	279.00	59.97	0.04	60.01	59.93
	278.50	281.00	61.25	1.20	62.45	60.05
	280.50	283.00	61.20	0.81	62.01	60.39
	282.50	285.00	61.91	0.04	61.95	61.87
	284.50	287.00	62.65	0.34	62.99	62.31
	286.50	289.00	63.95	0.82	64.77	63.13
	288.50	291.00	68.01	0.34	68.35	67.67
	290.50	293.00	69.79	0.04	69.83	69.75
	292.50	295.00	70.28	0.34	70.62	69.94
	294.50	297.00	73.46	0.04	73.50	73.42
	296.50	299.00	79.48	1.20	80.68	78.28
	298.50	301.00	87.49	0.43	87.92	87.06
	300.50	303.00	-12.48	99.71	87.23	-112.19
end section 2	302.50	305.00	56.23	0.04	56.27	56.19
top section 3	304.50	307.00	136.90	0.96	137.86	135.94
	306.50	309.00	149.00	1.34	150.34	147.66
	308.50	311.00	152.62	2.12	154.74	150.5
	310.50	313.00	161.08	0.57	161.65	160.51
	312.50	315.00	175.19	1.34	176.53	173.85
	314.50	317.00	198.43	0.56	198.99	197.87
	316.50	319.00	223.56	0.95	224.51	222.61
	318.50	321.00	238.38	0.95	239.33	237.43
	320.50	323.00	238.97	1.34	240.31	237.63
	322.50	325.00	233.01	0.18	233.19	232.83
	324.50	327.00	236.88	0.57	237.45	236.31
	326.50	329.00	238.75	0.21	238.96	238.54
	328.50	331.00	238.87	0.59	239.46	238.28
	330.50	333.00	240.01	0.18	240.19	239.83
	332.50	335.00	240.56	0.18	240.74	240.38
	334.50	337.00	241.25	0.57	241.82	240.68

	336.50	339.00	242.19	0.20	242.39	241.99
	338.50	341.00	244.79	0.20	244.99	244.59
	340.50	343.00	247.31	0.21	247.52	247.1
	342.50	345.00	249.36	0.57	249.93	248.79
	344.50	347.00	251.04	0.57	251.61	250.47
	346.50	349.00	258.38	0.59	258.97	257.79
	348.50	351.00	266.01	0.18	266.19	265.83
	350.50	353.00	286.93	0.18	287.11	286.75
	352.50	355.00	288.04	0.57	288.61	287.47
	354.50	357.00	392.05	0.57	392.62	391.48
	356.50	359.00	530.61	0.20	530.81	530.41
	358.50	361.00	649.97	0.18	650.15	649.79
	360.50	363.00	684.48	0.57	685.05	683.91
	362.50	365.00	617.96	0.96	618.92	617
	364.50	367.00	491.35	0.59	491.94	490.76
	366.50	369.00	363.29	0.18	363.47	363.11
	368.50	371.00	1216.44	3.35	1219.79	1213.09
	370.50	373.00	1168.71	2.95	1171.66	1165.76
	372.50	375.00	1139.32	3.34	1142.66	1135.98
	374.50	377.00	1121.21	1.79	1123	1119.42
	376.50	379.00	1108.96	3.35	1112.31	1105.61
	378.50	381.00	735.42	1.80	737.22	733.62
	380.50	383.00	715.66	1.79	717.45	713.87
	382.50	385.00	699.21	2.18	701.39	697.03
	384.50	387.00	673.00	2.56	675.56	670.44
	386.50	389.00	647.62	2.54	650.16	645.08
	388.50	391.00	624.84	1.79	626.63	623.05
	390.50	393.00	617.59	2.18	619.77	615.41
	392.50	395.00	601.81	2.56	604.37	599.25
	394.50	397.00	564.76	1.79	566.55	562.97
	396.50	399.00	532.41	2.56	534.97	529.85
	398.50	401.00	510.91	2.56	513.47	508.35
	400.50	403.00	493.03	2.57	495.6	490.46
	402.50	405.00	454.68	2.95	457.63	451.73
	404.50	407.00	433.64	2.18	435.82	431.46
	406.50	409.00	412.44	2.18	414.62	410.26
	408.50	411.00	394.07	2.18	396.25	391.89
	410.50	413.00	372.06	2.19	374.25	369.87
	412.50	415.00	352.39	2.56	354.95	349.83
	414.50	417.00	330.12	3.35	333.47	326.77
	416.50	419.00	311.38	2.56	313.94	308.82
	418.50	421.00	292.09	1.40	293.49	290.69
	420.50	423.00	273.26	2.95	276.21	270.31
	422.50	425.00	257.24	2.96	260.2	254.28
	424.50	427.00	212.13	2.18	214.31	209.95
	426.50	429.00	182.24	2.18	184.42	180.06
	428.50	431.00	159.91	3.35	163.26	156.56

	53.50	56.00	74.45	0.24	74.69	74.21
	55.50	58.00	70.82	4.10	74.92	66.72
	57.50	60.00	65.16	1.40	66.56	63.76
	59.50	62.00	60.57	0.15	60.72	60.42
	61.50	64.00	55.79	1.40	57.19	54.39
	63.50	66.00	62.52	2.35	64.87	60.17
	65.50	68.00	80.56	0.04	80.60	80.52
	67.50	70.00	89.05	1.19	90.24	87.86
	69.50	72.00	96.63	1.13	97.76	95.50
	71.50	74.00	99.68	1.13	100.81	98.55
	73.50	76.00	105.45	0.74	106.19	104.71
	75.50	78.00	113.90	0.35	114.25	113.55
	77.50	80.00	126.50	0.74	127.24	125.76
	79.50	82.00	137.01	0.35	137.36	136.66
	81.50	84.00	146.09	0.36	146.45	145.73
	83.50	86.00	160.57	0.74	161.31	159.83
	85.50	88.00	186.28	1.90	188.18	184.38
	87.50	90.00	214.55	0.35	214.90	214.20
	89.50	92.00	227.54	1.90	229.44	225.64
	91.50	94.00	230.91	0.35	231.26	230.56
	93.50	96.00	240.24	1.52	241.76	238.72
	95.50	98.00	246.65	1.90	248.55	244.75
	97.50	100.00	239.71	0.42	240.13	239.29
	99.50	102.00	214.95	0.03	214.98	214.92
	101.50	104.00	185.80	0.35	186.15	185.45
	103.50	106.00	164.65	0.03	164.68	164.62
	105.50	108.00	164.40	0.35	164.75	164.05
	107.50	110.00	182.68	1.13	183.81	181.55
	109.50	112.00	211.60	0.03	211.63	211.57
	111.50	114.00	220.06	0.03	220.09	220.03
	113.50	116.00	211.11	0.35	211.46	210.76
	115.50	118.00	187.00	0.04	187.04	186.96
start of s.h.	117.50	120.00	161.16	0.42	161.58	160.74
	119.50	122.00	139.25	0.04	139.29	139.21
	121.50	124.00	118.54	1.51	120.05	117.03
end of s.h.	123.50	126.00	107.02	0.35	107.37	106.67
	125.50	128.00	96.62	0.35	96.97	96.27
end section 1	127.50	130.00	77.48	0.74	78.22	76.74
top section 2	129.50	132.00	134.81	0.04	134.85	134.77
	131.50	134.00	161.10	1.12	162.22	159.98
	133.50	136.00	162.31	2.28	164.59	160.03
	135.50	138.00	160.82	0.73	161.55	160.09
	137.50	140.00	172.38	0.35	172.73	172.03
	139.50	142.00	198.19	0.73	198.92	197.46
	141.50	144.00	224.04	0.82	224.86	223.22
	143.50	146.00	217.44	0.73	218.17	216.71
	145.50	148.00	186.85	0.04	186.89	186.81

	147.50	150.00	171.22	0.73	171.95	170.49
	149.50	152.00	166.88	0.04	166.92	166.84
	151.50	154.00	170.27	0.04	170.31	170.23
	153.50	156.00	174.58	0.35	174.93	174.23
	155.50	158.00	183.40	0.34	183.74	183.06
	157.50	160.00	215.50	0.04	215.54	215.46
	159.50	162.00	278.59	0.82	279.41	277.77
	161.50	164.00	297.05	1.20	298.25	295.85
	163.50	166.00	237.96	0.43	238.39	237.53
	165.50	168.00	194.94	0.73	195.67	194.21
	167.50	170.00	181.70	0.04	181.74	181.66
	169.50	172.00	179.71	0.04	179.75	179.67
	171.50	174.00	177.71	0.35	178.06	177.36
	173.50	176.00	177.31	0.35	177.66	176.96
	175.50	178.00	175.25	0.04	175.29	175.21
	177.50	180.00	175.68	0.82	176.50	174.86
	179.50	182.00	174.09	0.04	174.13	174.05
	181.50	184.00	172.25	0.34	172.59	171.91
	183.50	186.00	171.68	0.34	172.02	171.34
	185.50	188.00	172.63	0.34	172.97	172.29
	187.50	190.00	172.95	0.04	172.99	172.91
	189.50	192.00	172.47	0.81	173.28	171.66
	191.50	194.00	175.07	0.04	175.11	175.03
	193.50	196.00	177.76	0.73	178.49	177.03
	195.50	198.00	183.98	0.43	184.41	183.55
	197.50	200.00	186.99	0.04	187.03	186.95
	199.50	202.00	187.48	0.73	188.21	186.75
	201.50	204.00	183.20	0.82	184.02	182.38
	203.50	206.00	93.33	1.74	95.07	91.59
	205.50	208.00	102.60	0.19	102.79	102.41
	207.50	210.00	111.74	0.20	111.94	111.54
	209.50	212.00	122.27	0.20	122.47	122.07
	211.50	214.00	131.91	0.59	132.50	131.32
	213.50	216.00	138.46	0.96	139.42	137.50
	215.50	218.00	141.04	0.96	142.00	140.08
	217.50	220.00	142.65	1.35	144.00	141.30
	219.50	222.00	140.05	1.73	141.78	138.32
	221.50	224.00	134.45	1.35	135.80	133.10
	223.50	226.00	131.14	1.35	132.49	129.79
	225.50	228.00	128.53	0.19	128.72	128.34
	227.50	230.00	127.48	0.58	128.06	126.90
	229.50	232.00	122.49	0.97	123.46	121.52
	231.50	234.00	121.12	0.96	122.08	120.16
	233.50	236.00	125.30	5.99	131.29	119.31
	235.50	238.00	116.09	0.58	116.67	115.51
	237.50	240.00	116.26	0.19	116.45	116.07
	239.50	242.00	112.80	1.35	114.15	111.45

	241.50	244.00	110.62	0.19	110.81	110.43
	243.50	246.00	109.17	1.35	110.52	107.82
	245.50	248.00	104.55	0.19	104.74	104.36
	247.50	250.00	100.66	0.20	100.86	100.46
	249.50	252.00	99.09	0.20	99.29	98.89
	251.50	254.00	93.08	1.35	94.43	91.73
	253.50	256.00	91.40	0.58	91.98	90.82
	255.50	258.00	91.26	0.97	92.23	90.29
	257.50	260.00	88.74	0.58	89.32	88.16
	259.50	262.00	87.98	0.20	88.18	87.78
	261.50	264.00	86.91	0.58	87.49	86.33
	263.50	266.00	87.28	0.19	87.47	87.09
	265.50	268.00	89.13	0.58	89.71	88.55
	267.50	270.00	92.23	0.19	92.42	92.04
	269.50	272.00	102.09	0.19	102.28	101.90
	271.50	274.00	105.72	0.19	105.91	105.53
	273.50	276.00	94.77	1.35	96.12	93.42
end section 2	275.50	278.00	56.21	0.96	57.17	55.25
top section 3	276.50	279.00	216.41	1.24	217.65	215.17
	278.50	281.00	282.15	0.86	283.01	281.29
	280.50	283.00	469.86	0.09	469.95	469.77
	282.50	285.00	674.70	3.57	678.27	671.13
	284.50	287.00	776.53	0.09	776.62	776.44
	286.50	289.00	743.78	0.86	744.64	742.92
	288.50	291.00	634.95	0.48	635.43	634.47
	290.50	293.00	528.56	0.30	528.86	528.26
	292.50	295.00	440.86	0.68	441.54	440.18
	294.50	297.00	378.01	0.48	378.49	377.53
	296.50	299.00	336.87	1.25	338.12	335.62
	298.50	301.00	323.47	0.86	324.33	322.61
	300.50	303.00	322.58	0.29	322.87	322.29
	302.50	305.00	322.87	0.86	323.73	322.01
	304.50	307.00	321.69	0.29	321.98	321.40
	306.50	309.00	322.92	0.86	323.78	322.06
	308.50	311.00	324.50	1.25	325.75	323.25
	310.50	313.00	325.69	0.09	325.78	325.60
	312.50	315.00	331.14	0.30	331.44	330.84
	314.50	317.00	336.35	1.25	337.60	335.10
	316.50	319.00	340.41	0.48	340.89	339.93
	318.50	321.00	345.79	0.48	346.27	345.31
	320.50	323.00	348.21	0.30	348.51	347.91
	322.50	325.00	352.11	1.25	353.36	350.86
	324.50	327.00	356.20	0.48	356.68	355.72
	326.50	329.00	360.41	0.86	361.27	359.55
	328.50	331.00	364.63	0.09	364.72	364.54
	330.50	333.00	368.25	1.25	369.50	367.00
	332.50	335.00	374.80	0.09	374.89	374.71

	334.50	337.00	382.69	0.48	383.17	382.21
	336.50	339.00	387.45	0.48	387.93	386.97
	338.50	341.00	390.48	0.68	391.16	389.80
	340.50	343.00	397.96	1.63	399.59	396.33
	342.50	345.00	403.55	1.63	405.18	401.92
	344.50	347.00	409.63	0.48	410.11	409.15
	346.50	349.00	416.69	0.29	416.98	416.40
	348.50	351.00	420.98	0.68	421.66	420.30
	350.50	353.00	78.33	1.61	79.94	76.72
	352.50	355.00	98.83	0.07	98.90	98.76
	354.50	357.00	103.98	0.70	104.68	103.28
	356.50	359.00	107.99	0.32	108.31	107.67
	358.50	361.00	113.71	0.32	114.03	113.39
	360.50	363.00	119.30	0.07	119.37	119.23
	362.50	365.00	120.61	0.45	121.06	120.16
	364.50	367.00	127.94	0.71	128.65	127.23
	366.50	369.00	139.07	0.32	139.39	138.75
	368.50	371.00	145.77	0.07	145.84	145.70
	370.50	373.00	143.98	0.07	144.05	143.91
	372.50	375.00	139.23	0.71	139.94	138.52
	374.50	377.00	138.30	0.71	139.01	137.59
	376.50	379.00	141.59	0.32	141.91	141.27
	378.50	381.00	145.50	0.71	146.21	144.79
	380.50	383.00	151.44	1.48	152.92	149.96
	382.50	385.00	162.02	0.32	162.34	161.70
	384.50	387.00	172.47	0.71	173.18	171.76
	386.50	389.00	190.93	1.48	192.41	189.45
-d.u.i. of c.c.-	388.50	391.00	215.75	0.71	216.46	215.04
	390.50	393.00	256.56	1.09	257.65	255.47
	392.50	395.00	314.92	0.45	315.37	314.47
	394.50	397.00	427.58	1.09	428.67	426.49
	396.50	399.00	602.66	1.48	604.14	601.18
	398.50	401.00	856.11	1.48	857.59	854.63
	400.50	403.00	1367.63	0.07	1367.70	1367.56
	402.50	405.00	2347.73	0.32	2348.05	2347.41
	404.50	407.00	4308.05	0.71	4308.76	4307.34
	406.50	409.00	8494.91	1.09	8496.00	8493.82
	408.50	411.00	20100.44	1.23	20101.67	20099.21
	410.50	413.00	47217.62	1.23	47218.85	47216.39
	412.50	415.00	123173.82	3.04	123176.86	123170.78
	414.50	417.00	423230.05	2.07	423232.12	423227.98
c.c. starts	416.50	419.00	997430.32	20.94	997451.26	997409.38
	418.50	421.00	%1799825.78	10.47		
	420.50	423.00	%2725389.99	25.52		
	422.50	425.00	%3275081.99	30.23		
	424.50	427.00	%3128747.55	45.87		
end of core	426.50	429.00	%1465965.92	73.08		

Explanation of notations

start of s.h.	zone of holes due to screws starts
end of s.h.	end of the zone of holes
-d.u.i. of c.c.-	data under influence of core catcher below
c.c. starts	core catcher zone starts

APPENDIX D

ELECTRICAL RESISTIVITY MEASUREMENTS

Core Name: **Kakawis # 5**
No. of Sections: 4
Total length of the core (cm): 543.3
Direction of measurements: top to bottom

Technique used: 4 pin Wenner array & Fluke voltmeter
Program used: LabView Resistivity.vi version 5.0
Cell Constant calibrated with Std Sea Water (ohm-meter reached 0.209 and Formation Factor 1.000)

Notes & remarks	True depth in core (cm)	Potential (mV)	Temperature (C)	Current (mA)	Ohm-Meters	Formation Factor	Cell Constant
		Average Voltage	Average	Average	Average	Average	
top section 1	70.000	134.061	3.810	0.012	6.617	31.659	0.995
	72.000	127.342	3.815	0.012	6.287	30.079	0.995
	74.000	129.887	3.820	0.012	6.414	30.686	0.995
	76.000	124.147	3.815	0.012	6.129	29.324	0.995
	78.000	121.619	3.845	0.012	6.012	28.763	0.995
	80.000	119.903	3.845	0.012	5.927	28.357	0.995
	82.000	119.802	3.850	0.012	5.923	28.339	0.995
	84.000	119.090	3.850	0.012	5.888	28.171	0.995
	86.000	118.569	3.870	0.012	5.867	28.071	0.995
	88.000	115.696	3.870	0.012	5.725	27.391	0.995
	90.000	113.536	3.865	0.012	5.617	26.874	0.995
	92.000	106.245	3.870	0.012	5.257	25.153	0.995
	94.000	107.027	3.870	0.012	5.296	25.338	0.995
	96.000	102.582	3.885	0.012	5.079	24.302	0.995
	98.000	100.798	3.905	0.012	4.995	23.899	0.995
	100.000	98.930	3.890	0.012	4.899	23.441	0.995
	102.000	97.578	3.890	0.012	4.833	23.121	0.995
	104.000	96.215	3.905	0.012	4.768	22.813	0.995
	106.000	97.269	3.900	0.012	4.819	23.057	0.995
	108.000	91.601	3.905	0.012	4.539	21.719	0.995
	110.000	83.177	3.920	0.012	4.125	19.734	0.995
	112.000	82.541	3.935	0.012	4.096	19.595	0.995
	114.000	81.108	3.930	0.012	4.024	19.251	0.995
	116.000	79.686	3.940	0.012	3.955	18.921	0.995
	118.000	74.704	3.930	0.012	3.706	17.731	0.995
	120.000	74.130	3.945	0.012	3.680	17.606	0.995
	122.000	72.992	3.945	0.012	3.623	17.335	0.995

	124.000	72.594	3.955	0.012	3.605	17.248	0.995
	126.000	75.945	3.940	0.012	3.769	18.033	0.995
	128.000	71.738	3.960	0.012	3.563	17.048	0.995
	130.000	67.854	3.940	0.012	3.367	16.111	0.995
	132.000	65.841	3.940	0.012	3.268	15.634	0.995
	134.000	66.878	3.955	0.012	3.321	15.890	0.995
	136.000	65.988	3.985	0.012	3.281	15.698	0.995
	138.000	63.240	3.970	0.012	3.143	15.035	0.995
	140.000	63.148	3.990	0.012	3.140	15.026	0.995
	142.000	62.104	3.990	0.012	3.089	14.777	0.995
	144.000	62.527	4.015	0.012	3.113	14.894	0.995
	146.000	67.868	3.995	0.012	3.376	16.153	0.995
	148.000	65.585	3.985	0.012	3.261	15.602	0.995
end section 1	150.000	66.047	4.015	0.012	3.288	15.732	0.995
top section 2	152.000	47.441	3.695	0.012	2.214	10.589	0.945
	154.000	49.951	3.705	0.012	2.332	11.154	0.945
	156.000	49.274	3.680	0.012	2.297	10.991	0.945
	158.000	45.273	3.705	0.012	2.113	10.110	0.945
	160.000	44.101	3.717	0.012	2.059	9.853	0.945
	162.000	43.401	3.720	0.012	2.027	9.697	0.945
	164.000	44.373	3.720	0.012	2.072	9.915	0.945
	166.000	43.667	3.723	0.012	2.039	9.758	0.945
	168.000	43.545	3.717	0.012	2.033	9.728	0.945
	170.000	44.828	3.720	0.012	2.093	10.016	0.945
	172.000	43.417	3.723	0.012	2.028	9.703	0.945
	174.000	44.524	3.733	0.012	2.080	9.954	0.945
	176.000	44.125	3.747	0.012	2.063	9.870	0.945
	178.000	44.615	3.733	0.012	2.085	9.975	0.945
	180.000	44.376	3.737	0.012	2.074	9.922	0.945
	182.000	42.393	3.777	0.012	1.984	9.495	0.945
	184.000	44.270	3.740	0.012	2.069	9.900	0.945
	186.000	44.773	3.760	0.012	2.094	10.021	0.945
	188.000	63.260	3.757	0.012	2.959	14.157	0.945
	190.000	79.033	3.757	0.012	3.696	17.687	0.945
	192.000	99.446	3.763	0.012	4.652	22.260	0.945
	194.000	47.400	3.770	0.012	2.218	10.613	0.945
	196.000	45.367	3.780	0.012	2.124	10.163	0.945
	198.000	41.192	3.790	0.012	1.929	9.231	0.945
	200.000	45.561	3.813	0.012	2.136	10.220	0.945
	202.000	40.509	3.820	0.012	1.900	9.089	0.945
	204.000	38.656	3.817	0.012	1.813	8.673	0.945
	206.000	39.099	3.803	0.012	1.832	8.767	0.945
	208.000	41.528	3.820	0.012	1.948	9.318	0.945
	210.000	40.350	3.837	0.012	1.894	9.060	0.945
	212.000	39.002	3.830	0.012	1.830	8.755	0.945
	214.000	39.389	3.910	0.012	1.854	8.871	0.945
	216.000	38.420	3.833	0.012	1.803	8.626	0.945

	218.000	38.331	3.840	0.012	1.799	8.608	0.945
	220.000	38.269	3.853	0.012	1.797	8.599	0.945
	222.000	41.948	3.850	0.012	1.970	9.424	0.945
	224.000	43.053	3.843	0.012	2.021	9.670	0.945
	226.000	41.974	3.863	0.012	1.972	9.435	0.945
	228.000	53.076	3.863	0.012	2.493	11.931	0.945
	230.000	37.823	3.877	0.012	1.778	8.507	0.945
	232.000	36.684	3.880	0.012	1.724	8.252	0.945
	234.000	39.943	3.873	0.012	1.877	8.982	0.945
	236.000	37.182	3.913	0.012	1.750	8.376	0.945
	238.000	37.560	3.897	0.012	1.767	8.455	0.945
	240.000	38.213	3.893	0.012	1.797	8.601	0.945
	242.000	41.376	3.907	0.012	1.947	9.318	0.945
	244.000	38.748	3.947	0.012	1.827	8.740	0.945
	246.000	37.501	3.923	0.012	1.766	8.451	0.945
	248.000	37.159	3.957	0.012	1.753	8.386	0.945
	250.000	37.376	3.940	0.012	1.762	8.429	0.945
	252.000	37.436	3.943	0.012	1.764	8.443	0.945
	254.000	36.651	3.957	0.012	1.728	8.271	0.945
	256.000	38.879	4.010	0.012	1.838	8.793	0.945
	258.000	37.693	3.967	0.012	1.778	8.510	0.945
	260.000	38.189	3.973	0.012	1.802	8.624	0.945
	262.000	38.268	3.977	0.012	1.806	8.643	0.945
	264.000	38.720	3.973	0.012	1.827	8.744	0.945
	266.000	40.008	3.970	0.012	1.888	9.034	0.945
	268.000	39.109	3.977	0.012	1.846	8.833	0.945
	270.000	40.983	3.987	0.012	1.935	9.260	0.945
	272.000	40.826	3.377	0.012	1.879	8.988	0.945
	274.000	45.139	3.983	0.012	2.131	10.198	0.945
	276.000	38.669	3.993	0.012	1.827	8.740	0.945
	278.000	38.335	3.967	0.012	1.809	8.654	0.945
	280.000	40.258	4.173	0.012	1.916	9.166	0.945
	282.000	38.737	4.007	0.012	1.831	8.760	0.945
	284.000	37.850	3.990	0.012	1.788	8.553	0.945
	286.000	38.699	3.983	0.012	1.827	8.743	0.945
	288.000	38.811	3.980	0.012	1.832	8.767	0.945
	290.000	40.752	4.007	0.012	1.926	9.215	0.945
	292.000	47.138	4.093	0.012	2.236	10.697	0.945
	294.000	39.357	4.020	0.012	1.861	8.905	0.945
	296.000	41.173	4.007	0.012	1.946	9.311	0.945
	298.000	41.948	3.997	0.012	1.982	9.482	0.945
end section 2	300.000	42.269	4.003	0.012	1.997	9.557	0.945
top section 3	302.000	41.395	0.457	0.012	1.833	8.770	1.039
	304.000	37.176	0.463	0.012	1.647	7.879	1.039
	306.000	41.411	0.460	0.012	1.834	8.775	1.039
	308.000	35.855	0.443	0.012	1.586	7.591	1.039
	310.000	33.619	0.443	0.012	1.488	7.118	1.039

	312.000	34.811	0.440	0.012	1.540	7.369	1.039
	314.000	32.430	0.447	0.012	1.435	6.868	1.039
	316.000	31.572	0.443	0.012	1.397	6.685	1.039
	318.000	50.622	0.440	0.012	2.240	10.716	1.039
	320.000	71.876	0.440	0.012	3.180	15.215	1.039
	322.000	36.909	0.440	0.012	1.633	7.813	1.039
	324.000	39.337	0.437	0.012	1.740	8.326	1.039
	326.000	44.499	0.433	0.012	1.968	9.417	1.039
	328.000	54.442	0.460	0.012	2.411	11.536	1.039
	330.000	38.295	0.457	0.012	1.696	8.113	1.039
	332.000	39.543	0.453	0.012	1.751	8.376	1.039
	334.000	120.915	0.423	0.012	5.346	25.577	1.039
	336.000	52.476	0.433	0.012	2.321	11.105	1.039
	338.000	47.987	0.440	0.012	2.123	10.158	1.039
	340.000	37.458	0.423	0.012	1.656	7.923	1.039
	342.000	37.536	0.437	0.012	1.660	7.945	1.039
	344.000	39.477	0.433	0.012	1.746	8.354	1.039
	346.000	37.561	0.417	0.012	1.660	7.942	1.039
	348.000	37.086	0.420	0.012	1.639	7.843	1.039
	350.000	38.639	0.427	0.012	1.708	8.174	1.039
	352.000	36.135	0.417	0.012	1.597	7.641	1.039
	354.000	36.449	0.417	0.012	1.611	7.707	1.039
	356.000	35.646	0.413	0.012	1.575	7.536	1.039
	358.000	39.441	0.403	0.012	1.742	8.334	1.039
	360.000	38.664	0.403	0.012	1.708	8.170	1.039
	362.000	37.913	0.403	0.012	1.674	8.012	1.039
	364.000	39.161	0.413	0.012	1.730	8.280	1.039
	366.000	38.212	0.387	0.012	1.686	8.068	1.039
	368.000	37.840	0.383	0.012	1.669	7.988	1.039
	370.000	37.069	0.380	0.012	1.635	7.824	1.039
	372.000	38.546	0.383	0.012	1.701	8.137	1.039
	374.000	41.462	0.387	0.012	1.830	8.755	1.039
	376.000	43.028	0.390	0.012	1.899	9.087	1.039
	378.000	40.889	0.377	0.012	1.803	8.629	1.039
	380.000	40.361	0.373	0.012	1.780	8.516	1.039
	382.000	39.788	0.377	0.012	1.755	8.397	1.039
	384.000	40.146	0.370	0.012	1.770	8.470	1.039
	386.000	40.709	0.373	0.012	1.795	8.590	1.039
	388.000	39.363	0.377	0.012	1.736	8.307	1.039
	390.000	39.147	0.367	0.012	1.726	8.257	1.039
	392.000	36.687	0.380	0.012	1.618	7.744	1.039
	394.000	37.371	0.370	0.012	1.648	7.884	1.039
	396.000	39.648	0.370	0.012	1.748	8.364	1.039
	398.000	38.965	0.347	0.012	1.716	8.211	1.039
	400.000	38.951	0.350	0.012	1.716	8.209	1.039
	402.000	39.254	0.343	0.012	1.729	8.271	1.039
	404.000	40.136	0.327	0.012	1.766	8.449	1.039
	406.000	42.519	0.350	0.012	1.873	8.962	1.039

	408.000	40.980	0.320	0.012	1.803	8.624	1.039
	410.000	38.642	0.353	0.012	1.703	8.145	1.039
	412.000	38.912	0.337	0.012	1.713	8.196	1.039
	414.000	37.065	0.340	0.012	1.632	7.808	1.039
	416.000	40.001	0.333	0.012	1.761	8.424	1.039
	418.000	40.418	0.320	0.012	1.778	8.506	1.039
	420.000	39.994	0.327	0.012	1.760	8.419	1.039
end section 3	422.000	39.410	0.347	0.012	1.736	8.305	1.039
top section 4	424.000	35.925	0.030	0.012	1.646	7.876	1.098
	426.000	34.505	0.030	0.012	1.581	7.565	1.098
	428.000	34.087	0.040	0.012	1.563	7.477	1.098
	430.000	35.662	0.040	0.012	1.635	7.822	1.098
	432.000	33.784	0.040	0.012	1.549	7.410	1.098
	434.000	33.934	0.050	0.012	1.556	7.447	1.098
	436.000	34.145	0.040	0.012	1.566	7.489	1.098
	438.000	33.680	0.065	0.012	1.546	7.397	1.098
	440.000	32.004	0.075	0.012	1.470	7.032	1.098
	442.000	33.130	0.085	0.012	1.523	7.283	1.098
	444.000	33.737	0.085	0.012	1.550	7.416	1.098
	446.000	34.451	0.065	0.012	1.581	7.566	1.098
	448.000	31.682	0.085	0.012	1.456	6.965	1.098
	450.000	32.841	0.055	0.012	1.507	7.209	1.098
	452.000	32.080	0.085	0.012	1.474	7.052	1.098
	454.000	32.365	0.085	0.012	1.487	7.115	1.098
	456.000	30.350	0.080	0.012	1.394	6.670	1.098
	458.000	31.137	0.085	0.012	1.431	6.845	1.098
	460.000	30.934	0.067	0.012	1.420	6.794	1.098
	462.000	32.532	0.067	0.012	1.494	7.146	1.098
	464.000	30.658	0.060	0.012	1.407	6.731	1.098
	466.000	29.378	0.053	0.012	1.347	6.448	1.098
	468.000	29.304	0.057	0.012	1.344	6.433	1.098
	470.000	29.564	0.070	0.012	1.357	6.494	1.098
	472.000	30.494	0.063	0.012	1.399	6.696	1.098
	474.000	32.644	0.080	0.012	1.499	7.174	1.098
	476.000	30.218	0.077	0.012	1.388	6.640	1.098
	478.000	29.794	0.063	0.012	1.367	6.543	1.098
	480.000	30.233	0.093	0.012	1.390	6.649	1.098
	482.000	28.716	0.077	0.012	1.319	6.310	1.098
	484.000	29.465	0.083	0.012	1.353	6.477	1.098
	486.000	27.904	0.087	0.012	1.282	6.135	1.098
	488.000	30.076	0.087	0.012	1.382	6.612	1.098
	490.000	30.284	0.073	0.012	1.390	6.654	1.098
	492.000	30.213	0.073	0.012	1.387	6.638	1.098
	494.000	34.172	0.080	0.012	1.569	7.510	1.098
	496.000	36.881	0.093	0.012	1.695	8.111	1.098
	498.000	36.950	0.110	0.012	1.699	8.132	1.098
	500.000	35.095	0.113	0.012	1.615	7.726	1.098

	502.000	39.858	0.110	0.012	1.833	8.773	1.098
	504.000	42.367	0.110	0.012	1.949	9.325	1.098
	506.000	58.079	0.113	0.012	2.672	12.784	1.098
	508.000	47.064	0.060	0.012	2.160	10.333	1.098
	510.000	55.813	0.097	0.012	2.566	12.276	1.098
	512.000	60.617	0.097	0.012	2.787	13.333	1.098
	514.000	40.196	0.090	0.012	1.847	8.838	1.098
	516.000	48.300	0.110	0.012	2.222	10.631	1.098
	518.000	38.108	0.090	0.012	1.752	8.379	1.098
	520.000	45.544	0.093	0.012	2.093	10.016	1.098
	522.000	43.611	0.120	0.012	2.007	9.604	1.098
	524.000	56.642	0.107	0.012	2.605	12.465	1.098
	526.000	68.678	0.130	0.012	3.163	15.132	1.098
	528.000	62.826	0.130	0.012	2.893	13.843	1.098
	530.000	62.930	0.113	0.012	2.895	13.853	1.098
	532.000	62.279	0.107	0.012	2.865	13.707	1.098
	534.000	74.114	0.093	0.012	3.407	16.299	1.098
	536.000	74.862	0.107	0.012	3.443	16.475	1.098
	538.000	76.199	0.090	0.012	3.502	16.755	1.098
end section 4	540.000	80.372	0.103	0.012	3.696	17.684	1.098
end of core							

Notes: First 70cm had too much water (watery gyttja) and too little material to work with, hence no measurements were taken.

APPENDIX D *(continuation)*

ELECTRICAL RESISTIVITY MEASUREMENTS

Core Name: **Kakawis # 6**
No. of Sections: 3
Total length of the core (cm): 492
Direction of measurements: top to bottom

Tecnique used: 4 pin Wenner array & Fluke voltmeter
Program used: LabView Resistivity.vi version 5.0
Cell Constant calibrated with Std Sea Water (ohm-meter reached 0.209 and Formation Factor 1.000)

Notes & remarks	True depth in core (cm)	Potential (mV)	Temperature (C)	Current (mA)	Ohm-Meters	Formation Factor	Cell Constant
		Average Voltage	Average	Average	Average	Average	
top section 1	0.500	149.833	3.435	0.012	6.841	32.733	0.935
	10.500	0.337	3.450	0.012	0.015	0.074	0.935
	20.500	197.954	3.440	0.012	9.039	43.246	0.935
	24.500	0.355	3.440	0.012	0.016	0.078	0.935
	30.500	0.323	3.455	0.012	0.015	0.071	0.935
	34.500	0.340	3.445	0.012	0.016	0.075	0.935
	40.500	0.344	3.445	0.012	0.016	0.075	0.935
	44.500	0.383	3.470	0.012	0.018	0.084	0.935
	50.500	0.369	3.470	0.012	0.017	0.081	0.935
	54.500	0.356	3.455	0.012	0.016	0.078	0.935
	60.500	0.347	3.480	0.012	0.016	0.076	0.935
	64.500	0.348	3.470	0.012	0.016	0.077	0.935
	70.500	0.351	3.470	0.012	0.016	0.077	0.935
	74.500	0.338	3.465	0.012	0.016	0.074	0.935
	80.500	0.325	3.480	0.012	0.015	0.071	0.935
	84.500	0.315	3.475	0.012	0.014	0.069	0.935
	90.500	267.930	3.505	0.012	12.267	58.696	0.935
	92.500	261.578	3.510	0.012	11.979	57.317	0.935
	94.500	259.614	3.515	0.012	11.892	56.898	0.935
	96.500	250.759	3.515	0.012	11.486	54.958	0.935
	98.500	245.725	3.515	0.012	11.256	53.854	0.935
	100.500	252.287	3.525	0.012	11.561	55.316	0.935
	102.500	261.282	3.510	0.012	11.966	57.251	0.935
	104.500	259.014	3.525	0.012	11.869	56.791	0.935
	106.500	254.171	3.545	0.012	11.658	55.776	0.935
	108.500	243.977	3.550	0.012	11.192	53.551	0.935

	110.500	238.956	3.540	0.012	10.957	52.427	0.935
	112.500	239.221	3.545	0.012	10.972	52.496	0.935
	114.500	233.777	3.560	0.012	10.729	51.334	0.935
	116.500	222.377	3.560	0.012	10.206	48.831	0.935
	118.500	212.467	3.580	0.012	9.759	46.694	0.935
	120.500	209.153	3.575	0.012	9.605	45.956	0.935
	122.500	201.022	3.580	0.012	9.234	44.179	0.935
	124.500	194.246	3.585	0.012	8.924	42.698	0.935
	126.500	186.661	3.580	0.012	8.574	41.022	0.935
	128.500	177.570	3.595	0.012	8.162	39.049	0.935
	130.500	172.260	3.625	0.012	7.927	37.930	0.935
	132.500	172.944	3.610	0.012	7.954	38.057	0.935
	134.500	166.858	3.610	0.012	7.674	36.717	0.935
	136.500	167.205	3.610	0.012	7.690	36.793	0.935
	138.500	165.686	3.605	0.012	7.619	36.452	0.935
	140.500	168.605	3.620	0.012	7.758	37.117	0.935
	142.500	161.626	3.630	0.012	7.440	35.596	0.935
	144.500	164.572	3.625	0.012	7.574	36.237	0.935
	146.500	163.478	3.645	0.012	7.530	36.027	0.935
end section 1	148.500	159.201	3.645	0.012	7.333	35.084	0.935
top section 2	150.500	112.663	3.787	0.012	5.388	25.778	0.965
	152.500	108.168	3.810	0.012	5.178	24.774	0.965
	154.500	108.574	3.827	0.012	5.201	24.885	0.965
	156.500	111.019	3.817	0.012	5.316	25.434	0.965
	158.500	102.892	3.823	0.012	4.928	23.579	0.965
	160.500	103.966	3.820	0.012	4.979	23.822	0.965
	162.500	103.319	3.817	0.012	4.947	23.670	0.965
	164.500	97.487	3.810	0.012	4.666	22.328	0.965
	166.500	100.186	3.810	0.012	4.796	22.946	0.965
	168.500	94.735	3.817	0.012	4.536	21.703	0.965
	170.500	97.241	3.810	0.012	4.655	22.272	0.965
	172.500	96.049	3.813	0.012	4.598	22.001	0.965
	174.500	93.494	3.807	0.012	4.475	21.410	0.965
	176.500	95.378	3.827	0.012	4.569	21.860	0.965
	178.500	106.073	3.823	0.012	5.080	24.308	0.965
	180.500	99.999	3.813	0.012	4.788	22.906	0.965
	182.500	94.147	3.827	0.012	4.510	21.578	0.965
	184.500	104.387	3.817	0.012	4.998	23.915	0.965
	186.500	90.149	3.827	0.012	4.318	20.661	0.965
	188.500	85.408	3.813	0.012	4.089	19.564	0.965
	190.500	87.775	3.817	0.012	4.203	20.109	0.965
	192.500	86.085	3.830	0.012	4.124	19.733	0.965
	194.500	79.899	3.817	0.012	3.826	18.305	0.965
	196.500	80.921	3.830	0.012	3.877	18.549	0.965
	198.500	77.356	3.830	0.012	3.706	17.732	0.965
	200.500	77.824	3.837	0.012	3.730	17.845	0.965
	202.500	80.196	3.837	0.012	3.843	18.388	0.965

	204.500	78.738	3.833	0.012	3.773	18.052	0.965
	206.500	75.457	3.817	0.012	3.613	17.287	0.965
	208.500	73.588	3.833	0.012	3.526	16.870	0.965
	210.500	70.993	3.830	0.012	3.401	16.273	0.965
	212.500	70.666	3.837	0.012	3.386	16.203	0.965
	214.500	67.759	3.837	0.012	3.247	15.536	0.965
	216.500	65.170	3.847	0.012	3.124	14.949	0.965
	218.500	63.750	3.843	0.012	3.056	14.621	0.965
	220.500	62.346	3.847	0.012	2.989	14.301	0.965
	222.500	64.770	3.870	0.012	3.108	14.871	0.965
	224.500	61.066	3.867	0.012	2.930	14.020	0.965
	226.500	60.713	3.857	0.012	2.912	13.932	0.965
	228.500	59.058	3.840	0.012	2.831	13.543	0.965
	230.500	57.387	3.847	0.012	2.751	13.164	0.965
	232.500	60.591	3.853	0.012	2.906	13.903	0.965
	234.500	58.438	3.863	0.012	2.803	13.414	0.965
	236.500	58.109	3.897	0.012	2.792	13.358	0.965
	238.500	56.200	3.860	0.012	2.696	12.899	0.965
	240.500	60.028	3.873	0.012	2.881	13.785	0.965
	242.500	71.259	3.887	0.012	3.422	16.374	0.965
	244.500	56.414	3.887	0.012	2.709	12.962	0.965
	246.500	54.261	3.887	0.012	2.606	12.468	0.965
	248.500	55.965	3.877	0.012	2.687	12.854	0.965
	250.500	52.595	3.883	0.012	2.525	12.083	0.965
	252.500	53.205	3.880	0.012	2.554	12.221	0.965
	254.500	51.698	3.877	0.012	2.482	11.874	0.965
	256.500	52.769	3.913	0.012	2.537	12.138	0.965
	258.500	51.179	3.890	0.012	2.458	11.761	0.965
	260.500	50.276	3.893	0.012	2.415	11.555	0.965
	262.500	49.195	3.893	0.012	2.363	11.307	0.965
	264.500	47.628	3.903	0.012	2.289	10.951	0.965
	266.500	48.848	3.893	0.012	2.346	11.227	0.965
	268.500	51.010	3.900	0.012	2.451	11.727	0.965
	270.500	48.923	3.907	0.012	2.351	11.251	0.965
	272.500	49.741	3.900	0.012	2.390	11.436	0.965
	274.500	52.184	3.930	0.012	2.511	12.012	0.965
	276.500	47.241	3.913	0.012	2.271	10.866	0.965
	278.500	51.624	3.897	0.012	2.480	11.866	0.965
	280.500	50.431	3.917	0.012	2.425	11.602	0.965
	282.500	46.914	3.910	0.012	2.255	10.790	0.965
	284.500	45.247	3.907	0.012	2.175	10.405	0.965
	286.500	44.945	3.913	0.012	2.161	10.339	0.965
	288.500	47.060	3.907	0.012	2.262	10.822	0.965
	290.500	51.004	3.900	0.012	2.451	11.726	0.965
	292.500	47.414	3.913	0.012	2.280	10.906	0.965
	294.500	47.740	3.887	0.012	2.293	10.969	0.965
	296.500	47.384	3.903	0.012	2.277	10.895	0.965
	298.500	52.239	3.893	0.012	2.510	12.006	0.965

end section 2	300.500	65.754	3.890	0.012	3.158	15.110	0.965
top section 3	310.500	82.489	3.377	0.012	3.736	17.876	0.930
	312.500	85.160	3.363	0.012	3.855	18.444	0.930
	314.500	98.610	3.380	0.012	4.467	21.375	0.930
	316.500	59.656	3.383	0.012	2.703	12.932	0.930
	318.500	55.204	3.377	0.012	2.500	11.963	0.930
	320.500	56.028	3.383	0.012	2.539	12.145	0.930
	322.500	56.397	3.403	0.012	2.557	12.236	0.930
	324.500	53.472	3.403	0.012	2.425	11.601	0.930
	326.500	55.554	3.413	0.012	2.520	12.058	0.930
	328.500	62.232	3.477	0.012	2.831	13.544	0.930
	330.500	63.925	3.500	0.012	2.911	13.926	0.930
	332.500	84.013	3.477	0.012	3.821	18.284	0.930
	334.500	54.900	3.523	0.012	2.502	11.972	0.930
	336.500	52.801	3.513	0.012	2.406	11.509	0.930
	338.500	86.015	3.523	0.012	3.921	18.759	0.930
	340.500	51.480	3.533	0.012	2.347	11.231	0.930
	342.500	53.551	3.530	0.012	2.441	11.681	0.930
	344.500	68.681	3.533	0.012	3.131	14.983	0.930
	346.500	70.360	3.560	0.012	3.212	15.366	0.930
	348.500	50.286	3.587	0.012	2.298	10.995	0.930
	350.500	49.571	3.570	0.012	2.264	10.832	0.930
	352.500	124.317	3.600	0.012	5.685	27.203	0.930
	354.500	134.681	3.590	0.012	6.156	29.454	0.930
	356.500	52.884	3.587	0.012	2.417	11.563	0.930
	358.500	70.836	3.600	0.012	3.239	15.497	0.930
	360.500	50.585	3.633	0.012	2.316	11.083	0.930
	362.500	49.624	3.610	0.012	2.270	10.861	0.930
	364.500	49.095	3.623	0.012	2.247	10.752	0.930
	366.500	52.254	3.627	0.012	2.392	11.445	0.930
	368.500	50.762	3.640	0.012	2.325	11.124	0.930
	370.500	46.861	3.637	0.012	2.146	10.268	0.930
	372.500	48.577	3.637	0.012	2.225	10.644	0.930
	374.500	50.652	3.660	0.012	2.322	11.110	0.930
	376.500	50.399	3.653	0.012	2.310	11.051	0.930
	378.500	53.624	3.663	0.012	2.458	11.763	0.930
	380.500	57.941	3.670	0.012	2.658	12.714	0.930
	382.500	62.200	3.687	0.012	2.854	13.658	0.930
	384.500	49.727	3.687	0.012	2.282	10.919	0.930
	386.500	48.498	3.673	0.012	2.224	10.643	0.930
	388.500	48.693	3.690	0.012	2.235	10.693	0.930
	390.500	50.035	3.705	0.012	2.298	10.995	0.930
	392.500	50.540	3.710	0.012	2.322	11.109	0.930
	394.500	51.544	3.720	0.012	2.369	11.334	0.930
	396.500	50.567	3.710	0.012	2.323	11.115	0.930
	398.500	49.994	3.715	0.012	2.297	10.991	0.930
	400.500	47.576	3.715	0.012	2.186	10.459	0.930

	402.500	47.703	3.725	0.012	2.193	10.492	0.930
	404.500	48.286	3.730	0.012	2.220	10.622	0.930
	406.500	47.146	3.730	0.012	2.168	10.372	0.930
	408.500	46.420	3.730	0.012	2.135	10.212	0.930
	410.500	46.694	3.765	0.012	2.150	10.287	0.930
	414.500	45.854	3.745	0.012	2.110	10.094	0.930
	420.500	45.612	3.730	0.012	2.097	10.034	0.930
	424.500	46.336	3.740	0.012	2.132	10.198	0.930
	430.500	44.193	3.775	0.012	2.036	9.740	0.930
	434.500	45.046	3.745	0.012	2.072	9.916	0.930
	440.500	41.207	3.745	0.012	1.896	9.071	0.930
	444.500	43.733	3.755	0.012	2.013	9.631	0.930
	450.500	44.206	3.770	0.012	2.036	9.741	0.930
	454.500	44.356	3.780	0.012	2.044	9.778	0.930
	460.500	43.981	3.760	0.012	2.025	9.688	0.930
	464.500	43.328	3.760	0.012	1.995	9.544	0.930
	470.500	43.002	3.765	0.012	1.980	9.474	0.930
	474.500	41.853	3.755	0.012	1.926	9.217	0.930
	480.500	43.021	3.765	0.012	1.981	9.478	0.930
	484.500	43.478	3.765	0.012	2.002	9.579	0.930
	490.500	40.542	3.750	0.012	1.866	8.926	0.930
end section 3	492.000	40.560	3.745	0.012	1.866	8.929	0.930
end of core							

APPENDIX D *(continuation)*

ELECTRICAL RESISTIVITY MEASUREMENTS

Core Name: **Kakawis # 7**
No. of Sections: 3
Total length of the core (cm): 403.5
Direction of measurements: top to bottom

Technique used: 4 pin Wenner array & Fluke voltmeter
Program used: LabView Resistivity.vi version 5.0
Cell Constant calibrated with Std Sea Water (ohm-meter reached 0.209 and Formation Factor 1.000)

Notes & remarks	True depth in core (cm)	Potential (mV)	Temperature (C)	Current (mA)	Ohm-Meters	Formation Factor	Cell Constant
		Average Voltage	Average	Average	Average	Average	
top section 1	0.500	133.100	0.780	0.012	6.425	30.741	1.115
	2.500	133.947	0.795	0.012	6.471	30.959	1.115
	4.500	133.186	0.805	0.012	6.437	30.797	1.115
	6.500	134.337	0.805	0.012	6.492	31.064	1.115
	8.500	135.455	0.800	0.012	6.545	31.314	1.115
	10.500	133.304	0.815	0.012	6.446	30.840	1.115
	12.500	131.217	0.825	0.012	6.348	30.371	1.115
	14.500	126.868	0.820	0.012	6.136	29.358	1.115
	16.500	132.065	0.870	0.012	6.403	30.634	1.115
	18.500	131.183	0.875	0.012	6.361	30.437	1.115
	20.500	131.212	0.875	0.012	6.363	30.443	1.115
	22.500	129.390	0.875	0.012	6.274	30.020	1.115
	24.500	122.204	0.885	0.012	5.929	28.367	1.115
	26.500	118.676	0.905	0.012	5.763	27.574	1.115
	28.500	118.820	0.905	0.012	5.770	27.607	1.115
	30.500	117.366	0.890	0.012	5.695	27.250	1.115
	32.500	113.904	0.885	0.012	5.526	26.440	1.115
	34.500	112.510	0.885	0.012	5.458	26.117	1.115
	36.500	112.791	0.885	0.012	5.472	26.182	1.115
	38.500	105.761	0.890	0.012	5.132	24.556	1.115
	40.500	104.134	0.890	0.012	5.053	24.178	1.115
	42.500	101.821	0.880	0.012	4.939	23.630	1.115
	44.500	100.004	0.895	0.012	4.854	23.225	1.115
	46.500	97.422	0.885	0.012	4.727	22.614	1.115
	48.500	96.942	0.875	0.012	4.701	22.492	1.115
	50.500	93.493	0.880	0.012	4.535	21.697	1.115
	52.500	91.331	0.890	0.012	4.432	21.205	1.115

	54.500	93.559	0.885	0.012	4.539	21.718	1.115
	56.500	83.367	0.885	0.012	4.045	19.352	1.115
	58.500	85.948	0.870	0.012	4.167	19.936	1.115
	60.500	82.129	0.885	0.012	3.985	19.064	1.115
	62.500	80.358	0.880	0.012	3.898	18.649	1.115
	64.500	76.025	0.880	0.012	3.688	17.643	1.115
	66.500	77.674	0.890	0.012	3.770	18.035	1.115
	68.500	75.006	0.895	0.012	3.641	17.419	1.115
	70.500	71.665	0.875	0.012	3.475	16.627	1.115
	72.500	71.889	0.885	0.012	3.488	16.688	1.115
	74.500	68.815	0.900	0.012	3.341	15.986	1.115
	76.500	66.310	0.905	0.012	3.220	15.407	1.115
	78.500	66.864	0.895	0.012	3.245	15.528	1.115
	80.500	71.698	0.900	0.012	3.481	16.655	1.115
	82.500	71.987	0.905	0.012	3.496	16.726	1.115
	84.500	65.061	0.915	0.012	3.161	15.124	1.115
	86.500	62.439	0.905	0.012	3.032	14.507	1.115
	88.500	63.370	0.910	0.012	3.078	14.728	1.115
	90.500	63.509	0.900	0.012	3.084	14.753	1.115
	92.500	62.635	0.890	0.012	3.040	14.543	1.115
	94.500	60.854	0.905	0.012	2.955	14.140	1.115
	96.500	58.998	0.925	0.012	2.868	13.721	1.115
	98.500	59.108	0.890	0.012	2.868	13.724	1.115
	100.500	58.226	0.910	0.012	2.828	13.532	1.115
	102.500	57.872	0.900	0.012	2.810	13.443	1.115
	104.500	57.399	0.890	0.012	2.786	13.327	1.115
end section 1	106.500	59.547	0.890	0.012	2.889	13.826	1.115
top section 2	108.500	49.980	1.270	0.012	2.773	13.267	1.252
	110.500	44.709	1.270	0.012	2.480	11.868	1.252
	112.500	48.832	1.273	0.012	2.710	12.965	1.252
	114.500	47.914	1.267	0.012	2.658	12.717	1.252
	116.500	45.097	1.277	0.012	2.503	11.975	1.252
	118.500	52.470	1.273	0.012	2.912	13.931	1.252
	120.500	52.871	1.297	0.012	2.937	14.052	1.252
	122.500	44.960	1.313	0.012	2.499	11.959	1.252
	124.500	48.313	1.300	0.012	2.684	12.844	1.252
	126.500	44.645	1.303	0.012	2.481	11.870	1.252
	128.500	46.423	1.307	0.012	2.580	12.344	1.252
	130.500	44.220	1.327	0.012	2.460	11.770	1.252
	150.500	38.485	1.367	0.012	2.145	10.263	1.252
	152.500	39.731	1.327	0.012	2.210	10.575	1.252
	154.500	38.069	1.340	0.012	2.119	10.139	1.252
	156.500	39.043	1.313	0.012	2.170	10.385	1.252
	158.500	38.216	1.347	0.012	2.128	10.181	1.252
	160.500	36.940	1.333	0.012	2.055	9.835	1.252
	162.500	37.772	1.353	0.012	2.104	10.066	1.252
	164.500	36.242	1.350	0.012	2.018	9.657	1.252

	166.500	36.789	1.347	0.012	2.048	9.801	1.252
	168.500	36.973	1.347	0.012	2.059	9.850	1.252
	170.500	36.862	1.360	0.012	2.054	9.826	1.252
	172.500	36.367	1.357	0.012	2.026	9.693	1.252
	174.500	37.796	1.340	0.012	2.104	10.066	1.252
	176.500	40.149	1.370	0.012	2.238	10.708	1.252
	178.500	37.946	1.357	0.012	2.114	10.114	1.252
	180.500	37.734	1.367	0.012	2.103	10.062	1.252
	182.500	36.001	1.363	0.012	2.006	9.598	1.252
	184.500	35.820	1.357	0.012	1.995	9.547	1.252
	186.500	39.558	1.350	0.012	2.203	10.540	1.252
	188.500	34.932	1.337	0.012	1.944	9.302	1.252
	190.500	35.051	1.347	0.012	1.952	9.338	1.252
	192.500	35.077	1.333	0.012	1.952	9.339	1.252
	194.500	36.299	1.323	0.012	2.019	9.660	1.252
	196.500	36.090	1.323	0.012	2.007	9.604	1.252
	198.500	33.923	1.323	0.012	1.887	9.027	1.252
	200.500	35.316	1.330	0.012	1.965	9.401	1.252
	202.500	33.969	1.323	0.012	1.889	9.040	1.252
	204.500	37.150	1.320	0.012	2.066	9.885	1.252
	206.500	35.464	1.327	0.012	1.973	9.439	1.252
	208.500	36.587	1.320	0.012	2.035	9.735	1.252
	210.500	36.958	1.323	0.012	2.056	9.835	1.252
	212.500	35.377	1.307	0.012	1.966	9.407	1.252
	214.500	34.875	1.317	0.012	1.939	9.278	1.252
	216.500	35.051	1.320	0.012	1.949	9.326	1.252
	218.500	34.580	1.313	0.012	1.922	9.198	1.252
	220.500	34.599	1.310	0.012	1.923	9.202	1.252
	222.500	34.024	1.313	0.012	1.891	9.050	1.252
	224.500	33.827	1.310	0.012	1.880	8.997	1.252
	226.500	33.264	1.310	0.012	1.849	8.846	1.252
	228.500	35.288	1.310	0.012	1.961	9.385	1.252
	230.500	35.597	1.307	0.012	1.978	9.465	1.252
	232.500	34.410	1.293	0.012	1.911	9.144	1.252
	234.500	33.962	1.303	0.012	1.887	9.029	1.252
	236.500	35.894	1.323	0.012	1.996	9.552	1.252
	238.500	32.148	1.293	0.012	1.786	8.543	1.252
	240.500	35.697	1.283	0.012	1.982	9.482	1.252
	242.500	39.690	1.280	0.012	2.203	10.540	1.252
	244.500	34.409	1.303	0.012	1.912	9.148	1.252
	246.500	39.024	1.297	0.012	2.168	10.372	1.252
	248.500	33.763	1.287	0.012	1.875	8.970	1.252
	250.500	33.546	1.283	0.012	1.862	8.910	1.252
end section 2	252.500	35.074	1.290	0.012	1.948	9.319	1.252
top section 3	255.500	44.549	0.490	0.012	2.130	10.191	1.120
	257.500	40.765	0.477	0.012	1.948	9.319	1.120
	259.500	84.975	0.480	0.012	4.061	19.429	1.120

	261.500	88.185	0.493	0.012	4.218	20.180	1.120
	263.500	68.557	0.497	0.012	3.279	15.688	1.120
	265.500	47.901	0.507	0.012	2.292	10.966	1.120
	267.500	38.670	0.507	0.012	1.851	8.853	1.120
	269.500	37.690	0.523	0.012	1.805	8.636	1.120
	271.500	38.149	0.560	0.012	1.830	8.757	1.120
	273.500	37.559	0.543	0.012	1.800	8.614	1.120
	275.500	40.350	0.557	0.012	1.936	9.260	1.120
	277.500	40.467	0.557	0.012	1.941	9.287	1.120
	279.500	40.358	0.723	0.012	1.951	9.336	1.120
	281.500	39.338	0.563	0.012	1.888	9.031	1.120
	283.500	39.852	0.565	0.012	1.913	9.150	1.120
	285.500	41.034	0.555	0.012	1.968	9.417	1.120
	287.500	39.471	0.565	0.012	1.894	9.063	1.120
	289.500	38.395	0.580	0.012	1.844	8.822	1.120
	291.500	38.583	0.570	0.012	1.852	8.861	1.120
	293.500	37.638	0.580	0.012	1.808	8.648	1.120
	295.500	41.339	0.590	0.012	1.986	9.503	1.120
	297.500	40.486	0.595	0.012	1.946	9.309	1.120
	299.500	40.060	0.575	0.012	1.923	9.202	1.120
	301.500	39.621	0.585	0.012	1.903	9.105	1.120
	303.500	36.932	0.610	0.012	1.777	8.498	1.120
	305.500	36.339	0.610	0.012	1.748	8.362	1.120
	307.500	37.519	0.610	0.012	1.804	8.633	1.120
	309.500	39.931	0.610	0.012	1.920	9.188	1.120
	311.500	40.002	0.615	0.012	1.925	9.207	1.120
	313.500	37.982	0.620	0.012	1.828	8.744	1.120
	315.500	38.326	0.605	0.012	1.843	8.817	1.120
	317.500	37.757	0.620	0.012	1.817	8.692	1.120
	319.500	37.666	0.625	0.012	1.813	8.673	1.120
	321.500	37.157	0.620	0.012	1.788	8.554	1.120
	323.500	36.141	0.645	0.012	1.741	8.330	1.120
	325.500	37.875	0.650	0.012	1.825	8.732	1.120
	327.500	37.048	0.650	0.012	1.785	8.541	1.120
	329.500	37.150	0.650	0.012	1.790	8.565	1.120
	331.500	35.513	0.650	0.012	1.711	8.188	1.120
	333.500	34.267	0.650	0.012	1.651	7.900	1.120
	335.500	35.388	0.655	0.012	1.706	8.161	1.120
	337.500	33.817	0.655	0.012	1.630	7.798	1.120
	339.500	34.750	0.655	0.012	1.675	8.013	1.120
	341.500	34.682	0.660	0.012	1.672	8.000	1.120
	343.500	35.022	0.670	0.012	1.689	8.082	1.120
	345.500	36.260	0.675	0.012	1.749	8.370	1.120
	347.500	35.441	0.670	0.012	1.709	8.179	1.120
	349.500	34.080	0.670	0.012	1.644	7.865	1.120
	351.500	33.381	0.635	0.012	1.607	7.691	1.120
	353.500	33.343	0.670	0.012	1.608	7.694	1.120
	355.500	33.668	0.680	0.012	1.625	7.773	1.120

	357.500	33.110	0.680	0.012	1.598	7.645	1.120
	359.500	32.006	0.675	0.012	1.544	7.388	1.120
	361.500	32.366	0.685	0.012	1.563	7.475	1.120
	363.500	32.229	0.690	0.012	1.556	7.445	1.120
	365.500	32.388	0.685	0.012	1.564	7.480	1.120
	367.500	31.513	0.685	0.012	1.521	7.278	1.120
	369.500	31.674	0.695	0.012	1.530	7.318	1.120
	371.500	30.585	0.695	0.012	1.477	7.067	1.120
	373.500	32.347	0.680	0.012	1.561	7.468	1.120
	375.500	30.486	0.710	0.012	1.473	7.049	1.120
	377.500	30.039	0.705	0.012	1.451	6.944	1.120
	379.500	31.218	0.700	0.012	1.508	7.215	1.120
	381.500	30.046	0.705	0.012	1.452	6.946	1.120
	383.500	30.425	0.710	0.012	1.471	7.035	1.120
	385.500	30.978	0.710	0.012	1.497	7.162	1.120
	387.500	30.388	0.710	0.012	1.469	7.026	1.120
	389.500	31.337	0.710	0.012	1.514	7.246	1.120
	391.500	32.425	0.705	0.012	1.567	7.496	1.120
	393.500	32.820	0.710	0.012	1.586	7.589	1.120
	395.500	33.762	0.710	0.012	1.632	7.806	1.120
	397.500	32.214	0.705	0.012	1.557	7.447	1.120
	399.500	32.510	0.695	0.012	1.570	7.511	1.120
	401.500	32.905	0.755	0.012	1.594	7.625	1.120
end section 3	403.000	33.587	0.730	0.012	1.625	7.773	1.120
end of core							

APPENDIX E

PHYSICAL PARAMETERS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.
CORE NUMBER : Kakawis 1

Protocol: Loss-on-Ignition
Sub-Sampling Principle: Structural
Sub-Sampling Method: Volumetric

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume of sample	Initial Sample	Dry Sample	Volume of water in sample	Bulk Density	Relative *in situ* Grain Density	Relative *in situ* Porosity
			(cc)	(g)	(g)	(cc)	(g/cc)	(g/cc)	(%)
			Initial wet sample	Initial wet sample	Weight dry sample				
			Vs	Wws	Wds	Vw	BD	GD	Po
		GL-K1-98				Wws-Wds	Wws/Vs	Wds/(Vs-Vw)	Vw/Vs*100
1 - 1	84.0	L1 a 84	10	9.287	0.828	8.459	0.929	0.537	84.590
1 - 2	110.0	L2 a 110	10	10.689	1.221	9.468	1.069	2.295	94.680
2 - 3	140.0	L3 a 140	10	10.239	1.796	8.443	1.024	1.154	84.430
2 - 3	160.0	L3 a 160	10	10.601	2.419	8.182	1.060	1.331	81.820
2 - 4	166.0	L4 a 166	10	14.990	10.336	4.654	1.499	1.933	46.540
2 - 4	196.0	L4 a 196	10	10.210	4.320	5.890	1.021	1.051	58.900
2 - 5	201.0	L5 a 201	10	9.317	2.330	6.987	0.932	0.773	69.870
2 - 5	220.0	L5 a 220	10	9.722	2.002	7.720	0.972	0.878	77.200
2 - 6	240.0	L6 a 240	10	8.748	1.511	7.237	0.875	0.547	72.370

For BD, GD and Po calculations, it is assumed that 1 cc of water = 1 g and that the lacustrine freshwater has a constant density of 1 g/cc.

TOTAL CONTENTS OBTAINED AFTER LOSS-ON-IGNITION PROTOCOL

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.

CORE NUMBER : Kakawis 1

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Values after ignition of sample				Total Remaining Content by sample		Type of Material
			(%)	(%)	(%)	(%)	(%)	(g)	
			Total Water	Total Organic Carbon	Total Inorganic Carbon	Total Carbon			
			%ml	TOC	TIC	TC	RT	RT	
		GL-K1-98	wet weight	dry weight	dry weight	dry weight	dry weight	dry weight	
1 - 1	84.0	L1 a 84	91.084	52.536	1.932	54.469	45.531	0.377	plant detritus layer
1 - 2	110.0	L2 a 110	88.577	49.877	3.767	53.645	46.355	0.566	gyttja (massive)
2 - 3	140.0	L3 a 140	82.459	46.269	3.898	50.167	49.833	0.895	gyttja (massive)
2 - 3	160.0	L3 a 160	77.181	27.573	4.093	31.666	68.334	1.653	top tsunami deposit (detrital cap)
2 - 4	166.0	L4 a 166	31.047	3.880	3.212	7.092	92.908	9.603	top tsunami deposit
2 - 4	196.0	L4 a 196	57.689	22.963	4.468	27.431	72.569	3.135	bottom tsunami deposit
2 - 5	201.0	L5 a 201	74.992	47.682	3.305	50.987	49.013	1.142	bottom tsunami deposit
2 - 5	220.0	L5 a 220	79.408	39.910	2.997	42.907	57.093	1.143	organic mud/marsh
2 - 6	240.0	L6 a 240	82.727	53.938	3.839	57.776	42.224	0.638	gyttja (massive)

APPENDIX E *(continuation)*

PHYSICAL PARAMETERS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.
CORE NUMBER : Kakawis 2

Protocol: Loss-on-Ignition
Sub-Sampling Principle: Structural
Sub-Sampling Method: Volumetric

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume of sample	Initial Sample	Dry Sample	Volume of water in sample	Bulk Density	Relative *in situ* Grain Density	Relative *in situ* Porosity
			(cc)	(g)	(g)	(cc)	(g/cc)	(g/cc)	(%)
			Initial wet sample	Initial wet sample	Weight dry sample				
			Vs	Wws	Wds	Vw	BD	GD	Po
		GL-K2-98				Wws-Wds	Wws/Vs	Wds/(Vs-Vw)	Vw/Vs*100
1 - 3	75.0	L3 a 75	10	8.746	0.738	8.008	0.875	0.370	80.080
1 - 3	100.0	L3 a 100	10	10.636	1.341	9.295	1.064	1.902	92.950
1 - 6	123.0	L6 a 123	10	10.867	1.352	9.515	1.087	2.788	95.150
1 - 7	140.0	L7 a 140	10	10.715	1.356	9.359	1.072	2.115	93.590
2 - 8	150.0	L8 a 150	10	10.717	1.518	9.199	1.072	1.895	91.990
2 - 10	183.0	L10 a 183	10	11.112	1.995	9.117	1.111	2.259	91.170
2 - 13	208.0	L13 a 208	10	11.910	1.849	10.061	1.191	-30.311	100.610
2 - 14	214.0	L14 a 214	10	10.046	1.663	8.383	1.005	1.028	83.830
2 - 14	226.0	L14 a 226	10	11.106	2.073	9.033	1.111	2.144	90.330
2 - 16	257.0	L16 a 257	10	12.985	7.947	5.038	1.299	1.602	50.380
2 - 17	265.0	L17 a 265	10	10.756	1.763	8.993	1.076	1.751	89.930

For BD, GD and Po calculations, it is assumed that 1 cc of water = 1 g and that the lacustrine freshwater has a constant density of 1 g/cc.

TOTAL CONTENTS OBTAINED AFTER LOSS-ON-IGNITION PROTOCOL

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.
CORE NUMBER : Kakawis 2

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Values after ignition of sample				Total Remaining Content by sample		Type of Material
			(%)	(%)	(%)	(%)	(%)	(g)	
			Total Water	Total Organic Carbon	Total Inorganic Carbon	Total Carbon			
			%ml	TOC	TIC	TC	RT	RT	
		GL-K2-98	wet weight	dry weight	dry weight	dry weight	dry weight	dry weight	
1 - 3	75.0	L3 a 75	91.562	55.285	2.981	58.266	41.734	0.308	gyttja (massive)
1 - 3	100.0	L3 a 100	87.392	62.491	4.474	66.965	33.035	0.443	gyttja (massive)
1 - 6	123.0	L6 a 123	87.559	52.737	4.808	57.544	42.456	0.574	gyttja (massive)
1 - 7	140.0	L7 a 140	87.345	44.690	4.941	49.631	50.369	0.683	plant detritus layer
2 - 8	150.0	L8 a 150	85.836	33.926	4.677	38.603	61.397	0.932	gyttja (laminated/massive)
2 - 10	183.0	L10 a 183	82.046	24.862	4.311	29.173	70.827	1.413	top tsunami deposit (detrital cap)
2 - 13	208.0	L13 a 208	84.475	28.935	4.651	33.586	66.414	1.228	gyttja (semi-laminated)
2 - 14	214.0	L14 a 214	83.446	37.342	4.029	41.371	58.629	0.975	top tsunami deposit (detrital cap)
2 - 14	226.0	L14 a 226	81.334	37.241	4.149	41.389	58.611	1.215	tsunami deposit
2 - 16	257.0	L16 a 257	38.799	6.040	12.747	18.787	81.213	6.454	bottom tsunami deposit
2 - 17	265.0	L17 a 265	83.609	52.127	4.708	56.835	43.165	0.761	lens below tsunami deposit

APPENDIX E *(continuation)*

PHYSICAL PARAMETERS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.
CORE NUMBER : Kakawis 6

Protocol: Loss-on-Ignition
Sub-Sampling Principle: Structural
Sub-Sampling Method: Volumetric

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume of sample	Initial Sample	Dry Sample	Volume of water in sample	Bulk Density	Relative *in situ* Grain Density	Relative *in situ* Porosity
			(cc)	(g)	(g)	(cc)	(g/cc)	(g/cc)	(%)
			Initial wet sample	Initial wet sample	Weight dry sample				
			Vs	Wws	Wds	Vw	BD	GD	Po
		GL-K6-99				Wws-Wds	Wws/Vs	Wds/(Vs-Vw)	Vw/Vs*100
1 - 1	10.0	L1 a 10	10	31.953	1.702	30.251	3.195	-0.084	302.510
1 - 2	80.0	L2 a 80	10	24.925	1.701	23.224	2.493	-0.129	232.240
1 - 2	140.0	L2 a 140	10	23.630	1.709	21.921	2.363	-0.143	219.210
2 - 2	160.0	L2 a 160	10	22.327	2.235	20.092	2.233	-0.221	200.920
2 - 3	175.0	L3 a 175	10	21.385	2.090	19.295	2.139	-0.225	192.950
2 - 3	198.0	L3 a 198	10	18.968	1.996	16.972	1.897	-0.286	169.720
2 - 4	200.0	L4 a 200	10	19.641	2.413	17.228	1.964	-0.334	172.280
2 - 5	207.0	L5 a 207	10	9.699	1.111	8.588	0.970	0.787	85.880
2 - 5	215.0	L5 a 215	10	10.609	1.144	9.465	1.061	2.138	94.650
2 - 6	220.0	L6 a 220	10	11.503	1.474	10.029	1.150	-50.828	100.290
2 - 6	239.0	L6 a 239	10	10.321	1.710	8.611	1.032	1.231	86.110

2 - 7	248.0	L7 a 248	10	10.881	1.545	9.336	1.088	2.327	93.360
2 - 8	258.0	L8 a 258	10	11.916	1.637	10.279	1.192	-5.867	102.790
2 - 8	279.0	L8 a 279	10	11.748	1.788	9.960	1.175	44.700	99.600
2 - 8	296.0	L8 a 296	10	11.516	1.971	9.545	1.152	4.332	95.450
3 - 9	311.0	L9 a 311	10	10.246	2.341	7.905	1.025	1.117	79.050
3 - 10	318.0	L10 a 318	10	9.910	2.274	7.636	0.991	0.962	76.360
3 - 10	344.0	L10 a 344	10	10.588	2.302	8.286	1.059	1.343	82.860
3 - 12	360.0	L12 a 360	10	10.419	3.439	6.980	1.042	1.139	69.800
3 - 12	410.0	L12 a 410	10	10.169	1.347	8.822	1.017	1.143	88.220
3 - 12	460.0	L12 a 460	10	10.069	1.381	8.688	1.007	1.053	86.880

For BD, GD and Po calculations, it is assumed that 1 cc of water = 1 g and that the lacustrine freshwater has a constant density of 1 g/cc.

TOTAL CONTENTS OBTAINED AFTER LOSS-ON-IGNITION PROTOCOL

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.

CORE NUMBER : Kakawis 6

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Values after ignition of sample				Total Remaining Content by sample		Type of Material
			(%)	(%)	(%)	(%)	(%)	(g)	
			Total Water	Total Organic Carbon	Total Inorganic Carbon	Total Carbon			
			%ml	TOC	TIC	TC	RT	RT	
		GL-K6-99	wet weight	dry weight	dry weight	dry weight	dry weight	dry weight	
1 - 1	10.0	L1 a 10	94.673	57.462	2.056	59.518	40.482	0.689	gyttja (massive)
1 - 2	80.0	L2 a 80	93.176	56.496	1.881	58.377	41.623	0.708	gyttja (massive)
1 - 2	140.0	L2 a 140	92.768	57.812	2.048	59.860	40.140	0.686	tsunami deposit - plant detritus

2 - 2	160.0	L2 a 160	89.990	51.723	2.595	54.318	45.682	1.021	gyttja (massive)
2 - 3	175.0	L3 a 175	90.227	60.000	3.541	63.541	36.459	0.762	gyttja (laminated)
2 - 3	198.0	L3 a 198	89.477	56.613	3.808	60.421	39.579	0.790	plant detritus layer
2 - 4	200.0	L4 a 200	87.714	54.911	3.481	58.392	41.608	1.004	plant detritus layer
2 - 5	207.0	L5 a 207	88.545	54.725	4.230	58.956	41.044	0.456	gyttja (laminated)
2 - 5	215.0	L5 a 215	89.217	55.070	3.759	58.829	41.171	0.471	gyttja (laminated)
2 - 6	220.0	L6 a 220	87.186	38.874	4.274	43.148	56.852	0.838	gyttja (massive)
2 - 6	239.0	L6 a 239	83.432	31.053	4.094	35.146	64.854	1.109	top tsunami deposit
2 - 7	248.0	L7 a 248	85.801	35.663	4.337	40.000	60.000	0.927	bottom contact tsunami/gyttja
2 - 8	258.0	L8 a 258	86.262	30.544	4.215	34.759	65.241	1.068	plant detritus layer
2 - 8	279.0	L8 a 279	84.780	35.459	4.251	39.709	60.291	1.078	plant detritus layer
2 - 8	296.0	L8 a 296	82.885	30.847	3.754	34.602	65.398	1.289	gyttja (massive)
3 - 9	311.0	L9 a 311	77.152	44.682	3.887	48.569	51.431	1.204	tsunami deposit
3 - 10	318.0	L10 a 318	77.053	22.032	3.474	25.506	74.494	1.694	bottom contact tsunami/gyttja
3 - 10	344.0	L10 a 344	78.258	28.367	3.866	32.233	67.767	1.560	gyttja (laminated)
3 - 12	360.0	L12 a 360	66.993	23.728	6.165	29.892	70.108	2.411	tsunami deposit
3 - 12	410.0	L12 a 410	86.754	55.679	3.935	59.614	40.386	0.544	gyttja (massive)
3 - 12	460.0	L12 a 460	86.285	51.050	3.548	54.598	45.402	0.627	gyttja (massive)

APPENDIX E *(continuation)*

PHYSICAL PARAMETERS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.
CORE NUMBER : Kakawis 7

Protocol: Loss-on-Ignition
Sub-Sampling Principle: Structural
Sub-Sampling Method: Volumetric

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume of sample	Initial Sample	Dry Sample	Volume of water in sample	Bulk Density	Relative *in situ* Grain Density	Relative *in situ* Porosity
			(cc)	(g)	(g)	(cc)	(g/cc)	(g/cc)	(%)
			Initial wet sample	Initial wet sample	Weight dry sample				
			Vs	Wws	Wds	Vw	BD	GD	Po
		GL-K7-99				Wws-Wds	Wws/Vs	Wds/(Vs-Vw)	Vw/Vs*100
1 - 2	30.0	L2 a 30	10	11.537	1.158	10.379	1.154	-3.055	103.790
1 - 3	65.0	L3 a 65	10	11.065	1.032	10.033	1.107	-31.273	100.330
1 - 4	76.0	L4 a 76	10	12.223	1.199	11.024	1.222	-1.171	110.240
1 - 4	110.0	L4 a 110	10	12.040	1.400	10.640	1.204	-2.188	106.400
1 - 5	116.0	L5 a 116	10	11.685	1.535	10.150	1.169	-10.233	101.500
2 - 5	130.0	L5 a 130	10	11.646	1.796	9.850	1.165	11.973	98.500
2 - 6	141.0	L6 a 141	10	13.209	4.647	8.562	1.321	3.232	85.620
2 - 7	175.0	L7 a 175	10	11.107	1.639	9.468	1.111	3.081	94.680
2 - 7	200.0	L7 a 200	10	12.100	1.794	10.306	1.210	-5.863	103.060
2 - 7	230.0	L7 a 230	10	12.016	2.066	9.950	1.202	41.320	99.500
2 - 7'	245.0	L7' a 245	10	12.212	2.013	10.199	1.221	-10.116	101.990
2 - 7'	270.0	L7' a 270	10	12.792	2.304	10.488	1.279	-4.721	104.880

2 - 7'	277.0	L7' a 277	10	13.276	3.068	10.208	1.328	-14.750	102.080
2 - 9	290.0	L9 a 290	10	11.176	1.900	9.276	1.118	2.624	92.760
2 - 9	345.0	L9 a 345	10	11.847	1.664	10.183	1.185	-9.093	101.830
2 - 9	420.0	L9 a 420	10	11.719	2.204	9.515	1.172	4.544	95.150

For BD, GD and Po calculations, it is assumed that 1 cc of water = 1 g and that the lacustrine freshwater has a constant density of 1 g/cc.

TOTAL CONTENTS OBTAINED AFTER LOSS-ON-IGNITION PROTOCOL

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.

CORE NUMBER : Kakawis 7

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Values after ignition of sample				Total Remaining Content by sample		Type of Material
			(%)	(%)	(%)	(%)	(%)	(g)	
			Total Water	Total Organic Carbon	Total Inorganic Carbon	Total Carbon			
			%ml	TOC	TIC	TC	RT	RT	
		GL-K7-99	wet weight	dry weight	dry weight	dry weight	dry weight	dry weight	
1 - 2	30.0	L2 a 30	89.963	55.786	1.900	57.686	42.314	0.490	gyttja (massive)
1 - 3	65.0	L3 a 65	90.673	46.802	2.229	49.031	50.969	0.526	gyttja (massive)
1 - 4	76.0	L4 a 76	90.191	57.965	3.670	61.635	38.365	0.460	gyttja (semi-laminated)
1 - 4	110.0	L4 a 110	88.372	55.214	4.071	59.286	40.714	0.570	gyttja (semi-laminated)
1 - 5	116.0	L5 a 116	86.864	34.853	3.648	38.502	61.498	0.944	gyttja (semi-laminated)
2 - 5	130.0	L5 a 130	84.578	33.408	4.065	37.472	62.528	1.123	gyttja (massive)
2 - 6	141.0	L6 a 141	64.819	12.804	3.809	16.613	83.387	3.875	tsunami deposit
2 - 7	175.0	L7 a 175	85.244	32.337	3.905	36.242	63.758	1.045	gyttja (laminated)
2 - 7	200.0	L7 a 200	85.174	30.825	3.512	34.337	65.663	1.178	gyttja (laminated)

2 - 7	230.0	L7 a 230	82.806	21.636	2.807	24.443	75.557	1.561	gyttja (semi-laminated)
2 - 7'	245.0	L7' a 245	83.516	24.640	3.080	27.720	72.280	1.455	top tsunami deposit (detrital cap)
2 - 7'	270.0	L7' a 270	81.989	25.043	3.906	28.950	71.050	1.637	bottom tsunami deposit
2 - 7'	277.0	L7' a 277	76.891	22.262	3.748	26.010	73.990	2.270	top tsunami deposit (detrital cap)
2 - 9	290.0	L9 a 290	82.999	52.421	4.368	56.789	43.211	0.821	bottom tsunami deposit
2 - 9	345.0	L9 a 345	85.954	50.781	4.387	55.168	44.832	0.746	gyttja (massive)
2 - 9	420.0	L9 a 420	81.193	31.851	4.900	36.751	63.249	1.394	gyttja (massive)

APPENDIX E *(continuation)*

PHYSICAL PARAMETERS

Location of Specimen: Port Alberni Marsh (Inlet head) - SW coast Vancouver Island
SAMPLE NUMBER: PA1700 Hand Specimen

Protocol: Loss-on-Ignition
Sub-Sampling Principle: Structural
Sub-Sampling Method: Volumetric

CORE SECTION & LAYER	DEPTH (cm)	SAMPLE #	Volume of sample	Initial Sample	Dry Sample	Volume of water in sample	Bulk Density	Relative *in situ* Grain Density	Relative *in situ* Porosity
			(cc)	(g)	(g)	(cc)	(g/cc)	(g/cc)	(%)
			Initial wet sample	Initial wet sample	Weight dry sample				
			Vs	Wws	Wds	Vw	BD	GD	Po
						Wws-Wds	Wws/Vs	Wds/(Vs-Vw)	Vw/Vs*100
		GL-PA1700-00							
Hand sp.	70.0	a	10	18.666	14.351	8.666	1.867	10.758	86.660

For BD, GD and Po calculations, it is assumed that 1 cc of water = 1 g and that the lacustrine freshwater has a constant density of 1 g/cc.

TOTAL CONTENTS OBTAINED AFTER LOSS-ON-IGNITION PROTOCOL

Location of Specimen: Port Alberni Marsh (Inlet head) - SW coast Vancouver Island

SAMPLE NUMBER: PA1700 Hand Specimen

CORE SECTION & LAYER	DEPTH (cm)	SAMPLE #	Values after ignition of sample				Total Remaining Content by sample	
			(%)	(%)	(%)	(%)	(%)	(g)
			Total Water	Total Organic Carbon	Total Inorganic Carbon	Total Carbon		
			%ml	TOC	TIC	TC	RT	RT
			wet weight	dry weight	dry weight	dry weight	dry weight	dry weight
		GL-PA1700-00						
Hand sp.	70.0	a	23.116897	2.341	1.199	3.540	96.460	13.843

APPENDIX F

CARBON : NITROGEN RATIOS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.
CORE NUMBER : Kakawis 6
Analysis by: B.C. Ministry of Forests - Research Branch
Protocol: NCS element analysis
Pre-treatment: Sub-samples were freeze-dried; results are corrected to an oven-dried basis (moisture factor determination made at 105 degrees C).

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume	Initial Sample	Total Carbon	Total Nitrogen	C:N Ratio	Type of Material
			(cc)	(g)	(%)	(%)		
			Initial wet sample	Freeze-Dried sample				
			Vs	Wds	C	N	C:N	
		GL-K6-99						
3 - 9	311.0	L9 a 311	10	2.238	25.380	0.878	28.907	tsunami deposit
3 - 10	318.0	L10 a 318	10	2.420	13.360	0.744	17.957	bottom contact tsunami/gyttja
3 - 10	344.0	L10 a 344	10	2.225	15.990	0.792	20.189	gyttja (laminated)
3 - 12	360.0	L12 a 360	10	5.706	9.410	0.267	35.243	tsunami deposit
3 - 12	460.0	L12 a 460	10	1.400	30.870	1.537	20.085	gyttja (massive)

APPENDIX F *(continuation)*

CARBON : NITROGEN RATIOS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.
CORE NUMBER : Kakawis 7
Analysis by: B.C. Ministry of Forests - Research Branch
Protocol: NCS element analysis
Pre-treatment: Sub-samples were freeze-dried; results are corrected to an oven-dried basis (moisture factor determination made at 105 degrees C).

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume	Initial Sample	Total Carbon	Total Nitrogen	C:N Ratio	Type of Material
			(cc)	(g)	(%)	(%)		
			Initial wet sample	Freeze-Dried sample				
			Vs	Wds	C	N	C:N	
		GL-K7-99						
1 - 2	30.0	L2 a 30	10	1.235	31.680	2.279	13.901	gyttja (massive)
1 - 3	65.0	L3 a 65	10	1.118	28.000	1.941	14.426	gyttja (massive)
1 - 4	76.0	L4 a 76	10	1.415	35.730	2.138	16.712	gyttja (semi-laminated)
1 - 4	110.0	L4 a 110	10	1.401	34.290	2.170	15.802	gyttja (semi-laminated)
1 - 5	116.0	L5 a 116	10	1.703	19.650	1.314	14.954	gyttja (semi-laminated)
2 - 5	130.0	L5 a 130	10	1.954	18.430	1.277	14.432	gyttja (massive)
2 - 6	141.0	L6 a 141	10	2.901	13.410	0.783	17.126	tsunami deposit
2 - 7	175.0	L7 a 175	10	1.925	18.250	1.104	16.531	gyttja (laminated)

2 - 7	200.0	L7 a 200	10	1.819	16.100	1.004	16.036	gyttja (laminated)
2 - 7	230.0	L7 a 230	10	2.015	13.070	0.770	16.974	gyttja (semi-laminated)
2 - 7'	245.0	L7' a 245	10	2.336	12.990	0.707	18.373	top tsunami deposit (plant coat)
2 - 7'	270.0	L7' a 270	10	2.619	14.730	0.613	24.029	bottom tsunami deposit
2 - 7'	277.0	L7' a 277	10	2.994	12.100	0.657	18.417	top tsunami deposit (plant coat)
2 - 9	290.0	L9 a 290	10	1.863	34.370	1.234	27.853	bottom tsunami deposit
2 - 9	345.0	L9 a 345	10	2.001	30.260	1.721	17.583	gyttja (massive)
2 - 9	420.0	L9 a 420	10	2.429	18.620	1.193	15.608	gyttja (massive)

APPENDIX F *(continuation)*

CARBON : NITROGEN RATIOS

Location of Core: Port Alberni Marsh (Inlet head) - SW coast Vancouver Island

CORE NUMBER : PA1700 Hand Specimen

Analysis by: B.C. Ministry of Forests - Research Branch

Method: NCS element analysis

Pre-treatment: Sub-samples were freeze-dried; results are corrected to an oven-dried basis (moisture factor determination made at 105 degrees C).

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Volume	Initial Sample	Total Carbon	Total Nitrogen	C:N Ratio
			(cc)	(g)	(%)	(%)	
			Initial wet sample	Freeze-Dried sample			
			Vs	Wds	C	N	C:N
		GL-PA1700-00					
Hand sp.	20.0	a	10	12.757	1.050	0.080	13.125

APPENDIX G (1)

CARBONATE, ORGANIC AND TERRIGENOUS TOTAL CONTENTS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 1

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total CaCO3		Total Organic Matter		Total Terrigenous Sediment		*Total material analysed*	
		GL-K1-98	Wd	W(sh)	%	W(p)	%	W(t)	%	W	%
1 - 1	94	L1 b 94	10.022	2.202	21.972	7.011	69.959	0.689	6.870	10.022	100.000
1 - 1	100	L1 b 100	20.376	10.147	49.801	9.814	48.164	0.145	0.713	20.376	100.000
2 - 2	120	L2 b 120	8.560	0.000	0.000	1.588	18.551	0.000	0.000	1.588	18.551
2 - 3	150	L3 b 150	12.974	0.000	0.000	0.687	5.295	0.000	0.000	0.687	5.295
2 - 4	168	L4 b 168	93.772	13.091	13.960	5.787	6.171	74.895	79.869	93.772	100.000
2 - 4	190	L4 b 190	105.580	33.775	31.990	4.644	4.399	67.161	63.611	105.580	100.000
2 - 5	206	L5 b 206	38.239	8.808	23.034	8.559	22.384	20.500	53.610	38.239	100.000
2 - 5	225	L5 b 225	12.064	3.378	28.002	8.276	68.604	0.102	0.849	12.064	100.000

TERRIGENOUS MATERIAL FRACTIONATION

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 1

TSUNAMI EVENT OR LAYER TYPE	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total Terrigenous Sediment		Total Sediment: Coarse Fraction (s>=2mm)		Total Sediment: Sand Fraction (63um<s>2mm)		Total Fines: Mud Fraction (s<63um)	
		GL-K1-98	Wd	W(t)	% (based on Wd)	W(cs)	% (based on W(t))	W(s)	% (based on W(t))	W(f)	% (based on W(t))
TE6	94	L1 b 94	10.022	0.689	6.870	0.148	21.496	0.480	69.781	0.060	8.723
TE6	100	L1 b 100	20.376	0.145	0.713	0.033	22.719	0.045	30.912	0.067	46.368
TE4-TE5	168	L4 b 168	93.772	74.895	79.869	40.720	54.370	32.784	43.773	1.391	1.857
TE1-TE2-TE3	190	L4 b 190	105.580	67.161	63.611	39.253	58.446	27.439	40.856	0.468	0.697
pre-tsunami	206	L5 b 206	38.239	20.500	53.610	14.837	72.376	5.602	27.327	0.061	0.298
pre-tsunami	225	L5 b 225	12.064	0.102	0.849	0.000	0.000	0.041	40.000	0.061	60.000

Only samples containing clastic allochtonous materials are shown in this table.

Here percentages are calculated based on the Total Terrigenous material (W(t)) and not on the whole sample (Wd).

Tsunami Events: TE 1 corresponds to the earliest event and 6 to the latest found within Kakawis Lake.

APPENDIX G (1) *(continuation)*

CARBONATE, ORGANIC AND TERRIGENOUS TOTAL CONTENTS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 2

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total CaCO3		Total Organic Matter		Total Terrigenous Sediment		*Total material analysed*	
		GL-K2-98	Wd	W(sh)	%	W(p)	%	W(t)	%	W	%
1 - 3	80	L3 b 80	0.043	0.000	0.000	0.043	100.000	0.000	0.000	0.043	100.000
1 - 3	110	L3 b 110	0.095	0.000	0.000	0.095	100.000	0.000	0.000	0.095	100.000
1 - 6	130	L6 b 130	0.141	0.000	0.000	0.141	100.000	0.000	0.000	0.141	100.000
1 - 7	144	L7 b 144	0.144	0.000	0.000	0.144	100.000	0.000	0.000	0.144	100.000
2 - 8	162	L8 b 162	10.394	4.486	43.158	5.908	56.842	0.000	0.000	10.394	100.000
2 - 9	170	L9 b 170	14.633	6.494	44.379	8.127	55.539	0.012	0.082	14.633	100.000
2 - 11	194	L11 b 194	24.132	12.500	51.798	6.584	27.281	5.031	20.848	24.132	100.000
2 - 14	218	L14 b 218	23.838	9.164	38.444	13.724	57.573	0.949	3.983	23.838	100.000
2 - 15	237	L15 b 237	17.381	8.276	47.614	8.241	47.417	0.726	4.179	17.381	100.000
2 - 16	250	L16 b 250	298.421	27.002	9.048	6.030	2.021	265.294	88.899	298.421	100.000
2 - 17	267	L17 b 267	18.056	8.153	45.155	8.898	49.280	0.968	5.359	18.056	100.000
2 - 17	280	L17 b 280	0.020	0.000	0.000	0.000	0.000	0.020	100.000	0.020	100.000

TERRIGENOUS MATERIAL FRACTIONATION

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 2

TSUNAMI EVENT OR LAYER TYPE	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total Terrigenous Sediment		Total Sediment: Coarse Fraction (s>=2mm)		Total Sediment: Sand Fraction (63um<s>2mm)		Total Fines: Mud Fraction (s<63um)	
		GL-K2-98	Wd	W(t)	% (based on Wd)	W(cs)	% (based on W(t))	W(s)	% (based on W(t))	W(f)	% (based on W(t))
TE5 (detrital cap)	170	L9 b 170	14.633	0.012	0.082	0.012	100.000	0.000	0.000	0.000	0.000
TE4	194	L11 b 194	24.132	5.031	20.848	0.624	12.403	4.248	84.431	0.159	3.166
TE3	218	L14 b 218	23.838	0.949	3.983	0.338	35.600	0.609	64.193	0.002	0.208
TE3	237	L15 b 237	17.381	0.726	4.179	0.079	10.875	0.255	35.110	0.392	54.015
TE1-TE2	250	L16 b 250	298.421	265.294	88.899	249.504	94.048	15.038	5.668	0.752	0.283
pre-TE1 2	267	L17 b 267	18.056	0.968	5.359	0.063	6.511	0.706	73.006	0.198	20.482
pre-TE1 1	280	L17 b 280	15.353	0.020	0.130	0.020	100.000	0.000	0.000	0.000	0.000

Only samples containing clastic allochtonous materials are shown in this table.
Here percentages are calculated based on the Total Terrigenous material (W(t)) and not on the whole sample (Wd).

Tsunami Events: TE 1 corresponds to the earliest event and 6 to the latest found within Kakawis Lake.

APPENDIX G (1) *(continuation)*

CARBONATE, ORGANIC AND TERRIGENOUS TOTAL CONTENTS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 6

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total CaCO3		Total Organic Matter		Total Terrigenous Sediment		*Total material analysed*	
		GL-K6-99	Wd	W(sh)	%	W(p)	%	W(t)	%	W	%
1 - 2	130	L2 b 130	5.406	0.893	16.516	4.416	81.689	0.080	1.472	5.406	100
2 - 2	165	L2 b 165	0.049	0.000	0.000	0.049	100.000	0.000	0.000	0.049	100
2 - 3	177	L3 b 177	0.067	0.000	0.000	0.067	100.000	0.000	0.000	0.067	100
2 - 3	193	L3 b 193	0.059	0.000	0.000	0.059	100.000	0.000	0.000	0.059	100
2 - 4	200	L4 b 200	0.336	0.000	0.000	0.336	100.000	0.000	0.000	0.336	100
2 - 5	210	L5 b 210	1.156	0.000	0.000	1.156	100.000	0.000	0.000	1.156	100
2 - 6	221	L6 b 221	0.096	0.007	7.292	0.089	92.708	0.000	0.000	0.096	100
2 - 6	230	L6 b 230	12.672	3.190	25.170	8.987	70.922	0.000	0.000	12.672	100
2 - 6	240	L6 b 240	22.952	4.774	20.798	10.146	44.205	7.774	33.871	22.952	100
2 - 7	250	L7 b 250	3.804	0.000	0.000	3.804	100.000	0.000	0.000	3.804	100
2 - 8	259	L8 b 259	13.091	4.269	32.608	8.507	64.982	0.020	0.151	13.091	100
2 - 8	270	L8 b 270	11.723	3.223	27.495	8.405	71.699	0.015	0.128	11.723	100
2 - 8	280	L8 b 280	16.764	6.234	37.186	10.292	61.391	0.019	0.113	16.764	100
2 - 8	295	L8 b 295	0.582	0.052	8.935	0.516	88.660	0.014	2.405	0.582	100
3 - 9	313	L9 b 313	27.289	13.216	48.431	11.350	41.591	2.463	9.026	27.289	100
3 - 10	320	L10 b 320	18.387	4.764	25.909	12.771	69.459	0.176	0.958	18.387	100
3 - 10	339	L10 b 339	23.690	11.437	48.278	11.269	47.569	0.515	2.172	23.690	100

3 - 10	346	L10 b 346	21.376	10.341	48.375	10.461	48.940	0.205	0.959	21.376	100
3 - 10	350	L10 b 350	19.292	9.346	48.447	8.745	45.329	0.089	0.461	19.292	100
3 - 11	354	L11 b 354	90.648	31.470	34.716	8.278	9.132	50.661	55.887	90.648	100
3 - 12	365	L12 b 365	20.933	10.391	49.639	9.976	47.658	0.566	2.703	20.933	100
3 - 12	382	L12 b 382	1.142	0.051	4.466	1.045	91.506	0.046	4.028	1.142	100

TERRIGENOUS MATERIAL FRACTIONATION

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 6

TSUNAMI EVENT OR LAYER TYPE	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total Terrigenous Sediment		Total Sediment: Coarse Fraction (s>=2mm)		Total Sediment: Sand Fraction (63um<s>2mm)		Total Fines: Mud Fraction (s<63um)	
		GL-K6-99	Wd	W(t)	% (based on Wd)	W(cs)	% (based on W(t))	W(s)	% (based on W(t))	W(f)	% (based on W(t))
TE6 t (detrital cap)	130	L2 b 130	5.406	0.080	1.472	0.000	0.000	0.039	48.780	0.041	51.220
TE4	240	L6 b 240	22.952	7.774	33.871	0.081	1.042	7.691	98.932	0.002	0.026
TE3 - plant detritus layer	259	L8 b 259	13.091	0.020	0.151	0.000	0.000	0.020	100.000	0.000	0.000
TE3	270	L8 b 270	11.723	0.015	0.128	0.015	100.000	0.000	0.000	0.000	0.000
TE3 - plant detritus layer	280	L8 b 280	16.764	0.019	0.113	0.019	100.000	0.000	0.000	0.000	0.000
g (m) mid / TE2 t (detrital cap)	295	L8 b 295	14.115	0.014	0.099	0.014	100.000	0.000	0.000	0.000	0.000
TE2	313	L9 b 313	27.289	2.463	9.026	0.305	12.383	2.156	87.535	0.002	0.082
TE2 b	320	L10 b 320	18.387	0.176	0.958	0.037	21.014	0.139	78.986	0.000	0.000
TE1 m	339	L10 b 339	23.690	0.515	2.172	0.000	0.000	0.512	99.602	0.002	0.398
TE1 m	346	L10 b 346	21.376	0.205	0.959	0.000	0.000	0.205	100.000	0.000	0.000

TE1	350	L10 b 350	19.292	0.089	0.461	0.000	0.000	0.089	100.000	0.000	0.000
TE1	354	L11 b 354	90.648	50.661	55.887	22.938	45.278	27.719	54.714	0.004	0.008
TE1 b	365	L12 b 365	20.933	0.566	2.703	0.109	19.263	0.455	80.371	0.002	0.365
pre-TE1	382	L12 b 382	16.449	0.046	0.280	0.046	100.000	0.000	0.000	0.000	0.000

Only samples containing clastic allochtonous materials are shown in this table.
Here percentages are calculated based on the Total Terrigenous material (W(t)) and not on the whole sample (Wd).

Tsunami Events: TE 1 corresponds to the earliest event and 6 to the latest found within Kakawis Lake.

Layer Type:	g (m)	gyttja (massive)	t	top of layer
	g (s-l)	gyttja (semi-laminated)	m	middle of layer
	g (l)	gyttja (laminated	b	bottom of layer
	PD	plant detritus layer		
	T/g	contact between tsunami deposit and underlying gyttja layer		
	top	above unit containing tsunami deposit, towards top section of core		
	mid	between tsunami deposits, in the middle section of the core		
	bot	below unit containing tsunami deposits, towards the bottom section of the core		

APPENDIX G (1) *(continuation)*

CARBONATE, ORGANIC AND TERRIGENOUS TOTAL CONTENTS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 7

CORE SECTION & LAYER	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total CaCO3		Total Organic Matter		Total Terrigenous Sediment		*Total material analysed*	
		GL-K7-99	Wd	W(sh)	%	W(p)	%	W(t)	%	W	%
1 - 2	32	L2 b 32	0.010	0.000	0.000	0.010	100.000	0.000	0.000	0.010	100.000
1 - 2	55	L2 b 55	0.013	0.000	0.000	0.013	100.000	0.000	0.000	0.013	100.000
1 - 4	80	L4 b 80	0.047	0.021	45.319	0.009	18.085	0.017	36.596	0.047	100.000
1 - 4	105	L4 b 105	2.827	0.000	0.000	2.827	100.000	0.000	0.000	2.827	100.000
1 - 5	122	L5 b 122	0.029	0.000	0.000	0.029	100.000	0.000	0.000	0.029	100.000
2 - 6	142	L6 b 142	23.280	7.542	32.397	12.769	54.848	2.967	12.746	23.280	100.000
2 - 6	150	L6 b 150-160	25.026	2.901	11.591	21.860	87.347	0.266	1.061	25.026	100.000
2 - 6	160	L6 b 160	27.743	2.723	9.816	23.683	85.367	1.337	4.818	27.743	100.000
2 - 7	180	L7 b 180	15.208	11.106	73.027	4.102	26.973	0.000	0.000	15.208	100.000
2 - 7	202	L7 b 202	12.744	4.964	38.951	7.700	60.421	0.000	0.000	12.744	100.000
2 - 7	215	L7 b 215	14.203	5.379	37.875	8.824	62.125	0.000	0.000	14.203	100.000
2 - 7	235	L7 b 235	14.291	5.576	39.016	8.715	60.984	0.000	0.000	14.291	100.000
2 - 7'	250	L7' b 250	19.928	11.144	55.920	8.602	43.167	0.180	0.903	19.928	100.000
2 - 7'	264	L7' b 264	25.577	12.618	49.333	12.584	49.202	0.375	1.465	25.577	100.000
3 - 8	280	L8 b 280	87.919	32.550	37.023	3.696	4.204	51.455	58.526	87.915	99.995

3 - 9	296	L9 b 296	0.057	0.057	100.000	0.000	0.000	0.000	0.000	0.057	100.000

TERRIGENOUS MATERIAL FRACTIONATION

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 7

TSUNAMI EVENT OR LAYER TYPE	DEPTH in core (cm)	SAMPLE #	Base material amount (100%)	Total Terrigenous Sediment		Total Sediment: Coarse Fraction (s>=2mm)		Total Sediment: Sand Fraction (63um<s>2mm)		Total Fines: Mud Fraction (s<63um)	
		GL-K7-99	Wd	W(t)	% (based on Wd)	W(cs)	% (based on W(t))	W(s)	% (based on W(t))	W(f)	% (based on W(t))
g (s-l) top (lens TE6?)	80	L4 b 80	0.047	0.017	36.596	0.017	100.000	0.000	0.000	0.000	0.000
TE5	142	L6 b 142	23.280	2.967	12.746	0.659	22.208	2.308	77.792	0.000	0.000
TE4 PD big detrital cap	150	L6 b 150-160	25.026	0.266	1.061	0.000	0.000	0.266	100.000	0.000	0.000
TE4 PD big detrital cap b	160	L6 b 160	27.743	1.337	4.818	0.000	0.000	1.337	100.000	0.000	0.000
TE2	250	L7' b 250	19.928	0.180	0.903	0.000	0.000	0.180	100.000	0.000	0.000
TE2	264	L7' b 264	25.577	0.375	1.465	0.000	0.000	0.375	100.000	0.000	0.000
TE1	280	L8 b 280	87.919	51.455	58.526	16.156	31.398	35.295	68.594	0.004	0.008

Only samples containing clastic allochtonous materials are shown in this table.

Here percentages are calculated based on the Total Terrigenous material (W(t)) and not on the whole sample (Wd).

APPENDIX G (1) *(continuation)*

MATERIAL CONTENT AND TEXTURAL ANALYSES FINAL RESULTS

Location of Core: Port Alberni Marsh - Inlet
CORE NUMBER : AD 1700 Tsunami Sand Layer (hand sample)

CORE SECTION & LAYER	DEPTH (cm)	SAMPLE #	Base material amount (100%)	Total CaCO3		Total Organic Matter		Total Sediment: Coarse Fraction (s>=2mm)		Total Sediment: Sand Fraction (63um<s>2mm)		Total Fines: Mud Fraction (s<63um)		*Material lost in the processes* - Error Calc. -		*Total material analysed*	
			W	W(sh)	%	W(p)	%	W(cs)	%	W(s)	%	W(f)	%	W(e)	%	W	%
		GL-PA1700-00																
Hand sp.	70	b	132.935	0.000	0.000	13.506	10.160	0.000	0.000	119.429	89.840	0.000	0.000	0.000	0.000	132.935	100.000

APPENDIX G (2)

GRAIN SIZE DETERMINATION OF THE SEDIMENT FRACTIONS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 1

CORE SECTION & LAYER			1 - 1	1 - 1	2 - 4	2 - 4	2 - 5
DEPTH in core (cm)			94	100	168	190	206
SAMPLE #	GL-K1-98		L1b94	L2b100	L4b168	L4b190	L5b206
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.148	0.033	40.720	39.253	14.837
Dry Sieving of sediment material - Coarse Sediment Fraction - - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000	0.000	0.000	8.355	0.000
	13.2mm (-3.5 phi)		0.000	0.000	10.311	0.000	0.000
	8.0mm (-3.0 phi)		0.000	0.000	7.265	15.813	5.925
	5.6mm (-2.5 phi)		0.000	0.000	8.330	2.803	3.632
	4.0mm (-2.0 phi)		0.000	0.000	7.299	4.262	1.704
	2.8mm (-1.5 phi)		0.000	0.000	4.393	3.953	2.121
	2mm (-1.0 phi)		0.148	0.033	3.122	4.067	1.455
	Total sieved		0.148	0.033	40.720	39.253	14.837
	Accuracy of method (%)		100.000	100.000	100.000	100.000	100.000

Sand (s) (representative amount used)	63um< s >2mm	W (s)	0.243		12.027	9.505	0.850
Dry Sieving of sediment material - Sand Fraction - - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)		0.022		1.783	1.470	0.152
	1.00mm (0.0 phi)		0.062		2.144	1.427	0.162
	0.707mm (0.5 phi)		0.108		2.240	1.428	0.120
	0.500mm (1.0 phi)		0.033		2.117	1.370	0.110
	0.355mm (1.5 phi)		0.010		1.893	1.433	0.123
	0.250mm (2.0 phi)		0.004		1.110	1.161	0.094
	0.210mm (2.25 phi)		0.004		0.293	0.247	0.033
	0.180mm (2.50 phi)		0.000		0.168	0.302	0.022
	0.150mm (2.75 phi)		0.000		0.153	0.138	0.020
	0.125mm (3.0 phi)		0.000		0.046	0.154	0.007
	0.090mm (3.5 phi)		0.000		0.052	0.202	0.004
	0.075mm (3.75 phi)		0.000		0.012	0.097	0.002
	0.063mm (4.0 phi)		0.000		0.011	0.075	0.001
	Total sieved		0.243	0.000	12.022	9.504	0.850
	Accurracy of method (%)		100.000		99.958	99.989	100.000

Note: *All weights are accurate to 0.001 grams*

APPENDIX G (2) *(continuation)*

GRAIN SIZE DETERMINATION BY DRY-SIEVING

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 2

CORE SECTION & LAYER			2 - 9	2 - 11	2 - 14	2 - 15	2 - 16
DEPTH in core (cm)			170	194	218	237	250
SAMPLE #	GL-K2-98		L9b170	L11b194	L14b218	L15b237	L16b250
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.012	0.624	0.338	0.079	249.476
	96.0mm (-6.5 phi)						202.900
Dry Sieving of sediment material - Coarse Sediment Fraction - - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000	0.000	0.000	0.000	0.000
	13.2mm (-3.5 phi)		0.000	0.000	0.000	0.000	3.892
	8.0mm (-3.0 phi)		0.000	0.000	0.000	0.000	14.958
	5.6mm (-2.5 phi)		0.000	0.000	0.338	0.000	14.641
	4.0mm (-2.0 phi)		0.000	0.000	0.000	0.057	6.412
	2.8mm (-1.5 phi)		0.000	0.299	0.000	0.000	4.237
	2mm (-1.0 phi)		0.012	0.325	0.000	0.022	2.436
	Total sieved		0.012	0.624	0.338	0.079	249.476
	Accuracy of method (%)		100.000	100.000	100.000	100.000	100.000

Sand (s) (representative amount used)	63um< s >2mm	W (s)	0.000	0.147	0.315	0.122	1.990
Dry Sieving of sediment material - Sand Fraction (s) - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)			0.010	0.050	0.006	0.228
	1.00mm (0.0 phi)			0.047	0.020	0.018	0.228
	0.707mm (0.5 phi)			0.037	0.040	0.026	0.251
	0.500mm (1.0 phi)			0.031	0.050	0.020	0.250
	0.355mm (1.5 phi)			0.008	0.060	0.017	0.329
	0.250mm (2.0 phi)			0.008	0.043	0.016	0.307
	0.210mm (2.25 phi)			0.003	0.024	0.008	0.119
	0.180mm (2.50 phi)			0.002	0.018	0.007	0.080
	0.150mm (2.75 phi)			0.001	0.010	0.003	0.088
	0.125mm (3.0 phi)			0.000	0.000	0.001	0.039
	0.090mm (3.5 phi)			0.000	0.000	0.000	0.051
	0.075mm (3.75 phi)			0.000	0.000	0.000	0.015
	0.063mm (4.0 phi)			0.000	0.000	0.000	0.005
	Total sieved		0.000	0.147	0.315	0.122	1.990
	Accurracy of method (%)			100.000	100.000	100.000	100.000

GRAIN SIZE DETERMINATION OF THE SEDIMENT FRACTIONS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 2

CORE SECTION & LAYER			2 - 17	2 - 17
DEPTH in core (cm)			267	280
SAMPLE #	GL-K2-98		L17b267	L17b280
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.063	0.020
Dry Sieving of sediment material - Coarse Sediment Fraction - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000	0.000
	13.2mm (-3.5 phi)		0.000	0.000
	8.0mm (-3.0 phi)		0.000	0.000
	5.6mm (-2.5 phi)		0.000	0.000
	4.0mm (-2.0 phi)		0.000	0.000
	2.8mm (-1.5 phi)		0.000	0.000
	2mm (-1.0 phi)		0.063	0.020
	Total sieved		0.063	0.020
	Accuracy of method (%)		100.000	100.000

Sand (s) (representative amount used)	63um< s >2mm [Wdr2 (s) - Wst (s)]	W (s)	0.343	0.000
Dry Sieving of sediment material - Sand Fraction (s) - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)		0.029	
	1.00mm (0.0 phi)		0.056	
	0.707mm (0.5 phi)		0.037	
	0.500mm (1.0 phi)		0.043	
	0.355mm (1.5 phi)		0.049	
	0.250mm (2.0 phi)		0.054	
	0.210mm (2.25 phi)		0.014	
	0.180mm (2.50 phi)		0.019	
	0.150mm (2.75 phi)		0.011	
	0.125mm (3.0 phi)		0.012	
	0.090mm (3.5 phi)		0.013	
	0.075mm (3.75 phi)		0.005	
	0.063mm (4.0 phi)		0.001	
	Total sieved		0.343	0.000
	Accurracy of method (%)		100.000	

Note: *All weights are accurate to 0.001 grams*

APPENDIX G (2) *(continuation)*

GRAIN SIZE DETERMINATION BY DRY-SIEVING

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 6

CORE SECTION & LAYER			2 - 2	2 - 2	2 - 8	2 - 8	2 - 8
DEPTH in core (cm)			130	240	270	280	295
SAMPLE #	GL-K6-99		L2b130	L2b240	L8b270	L8b280	L8b295
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.000	0.081	0.015	0.019	0.014
Dry Sieving of sediment material - Coarse Sediment Fraction - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)			0.000	0.000	0.000	0.000
	13.2mm (-3.5 phi)			0.000	0.000	0.000	0.000
	8.0mm (-3.0 phi)			0.000	0.000	0.000	0.000
	5.6mm (-2.5 phi)			0.000	0.000	0.000	0.000
	4.0mm (-2.0 phi)			0.000	0.000	0.000	0.000
	2.8mm (-1.5 phi)			0.000	0.000	0.000	0.000
	2mm (-1.0 phi)			0.081	0.015	0.019	0.014
	Total sieved		0.000	0.081	0.015	0.019	0.014
	Accuracy of method (%)			100.000	100.000	100.000	100.000

Sand (s) (representative amount used)	63um< s >2mm	W (s)	0.030	1.832			
Dry Sieving of sediment material - Sand Fraction - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)		0.000	0.051			
	1.00mm (0.0 phi)		0.011	0.127			
	0.707mm (0.5 phi)		0.005	0.281			
	0.500mm (1.0 phi)		0.004	0.402			
	0.355mm (1.5 phi)		0.002	0.514			
	0.250mm (2.0 phi)		0.003	0.308			
	0.210mm (2.25 phi)		0.001	0.059			
	0.180mm (2.50 phi)		0.001	0.050			
	0.150mm (2.75 phi)		0.001	0.020			
	0.125mm (3.0 phi)		0.001	0.012			
	0.090mm (3.5 phi)		0.001	0.003			
	0.075mm (3.75 phi)		0.000	0.003			
	0.063mm (4.0 phi)		0.000	0.002			
	Total sieved		0.030	1.832	0.000	0.000	0.000
	Accurracy of method (%)		100.000	100.000			

Note: *All weights are accurate to 0.001 grams*

GRAIN SIZE DETERMINATION BY DRY-SIEVING

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 6

CORE SECTION & LAYER			3 - 9	3 - 10	3 - 10	3 - 10	3 - 354
DEPTH in core (cm)			313	320	339	346	354
SAMPLE #	GL-K6-99		L9b313	L10b320	L10b339	L10b346	L11b354
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.305	0.037	0.000	0.000	22.938
Dry Sieving of sediment material - Coarse Sediment Fraction - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000	0.000			17.024
	13.2mm (-3.5 phi)		0.000	0.000			0.000
	8.0mm (-3.0 phi)		0.000	0.000			0.734
	5.6mm (-2.5 phi)		0.270	0.000			0.474
	4.0mm (-2.0 phi)		0.000	0.000			1.209
	2.8mm (-1.5 phi)		0.000	0.000			1.755
	2mm (-1.0 phi)		0.035	0.037			1.742
	Total sieved		0.305	0.037	0.000	0.000	22.938
	Accuracy of method (%)		100.000	100.000			100.000

Sand (s) (representative amount used)	63um< s >2mm	W (s)	1.096		0.255	0.128	3.159
Dry Sieving of sediment material - Sand Fraction - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)		0.042		0.012	0.000	0.282
	1.00mm (0.0 phi)		0.095		0.015	0.008	0.360
	0.707mm (0.5 phi)		0.116		0.028	0.008	0.428
	0.500mm (1.0 phi)		0.161		0.027	0.005	0.568
	0.355mm (1.5 phi)		0.226		0.043	0.017	0.699
	0.250mm (2.0 phi)		0.281		0.047	0.034	0.530
	0.210mm (2.25 phi)		0.069		0.025	0.018	0.141
	0.180mm (2.50 phi)		0.066		0.022	0.019	0.069
	0.150mm (2.75 phi)		0.020		0.021	0.008	0.056
	0.125mm (3.0 phi)		0.012		0.006	0.005	0.014
	0.090mm (3.5 phi)		0.006		0.006	0.003	0.009
	0.075mm (3.75 phi)		0.001		0.002	0.002	0.002
	0.063mm (4.0 phi)		0.001		0.001	0.001	0.001
	Total sieved		1.096	0.000	0.255	0.128	3.159
	Accurracy of method (%)		100.000		100.000	100.000	100.000

Note: *All weights are accurate to 0.001 grams*

Special notes: In sample L11b354, the material retained in the first sieve is Bigger than 16.0mm

GRAIN SIZE DETERMINATION OF THE SEDIMENT FRACTIONS

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 6

CORE SECTION & LAYER			3 - 12	3 - 12
DEPTH in core (cm)			365	382
SAMPLE #	GL-K6-99		L12b365	L12b382
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.109	0.046
Dry Sieving of sediment material - Coarse Sediment Fraction - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000	0.000
	13.2mm (-3.5 phi)		0.000	0.000
	8.0mm (-3.0 phi)		0.000	0.000
	5.6mm (-2.5 phi)		0.000	0.000
	4.0mm (-2.0 phi)		0.000	0.000
	2.8mm (-1.5 phi)		0.088	0.000
	2mm (-1.0 phi)		0.021	0.046
	Total sieved		0.109	0.046
	Accuracy of method (%)		100.000	100.000

Sand (s) (representative amount used)	63um< s >2mm	W (s)	0.257	
Dry Sieving of sediment material - Sand Fraction - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)		0.036	
	1.00mm (0.0 phi)		0.032	
	0.707mm (0.5 phi)		0.030	
	0.500mm (1.0 phi)		0.028	
	0.355mm (1.5 phi)		0.044	
	0.250mm (2.0 phi)		0.047	
	0.210mm (2.25 phi)		0.011	
	0.180mm (2.50 phi)		0.015	
	0.150mm (2.75 phi)		0.006	
	0.125mm (3.0 phi)		0.004	
	0.090mm (3.5 phi)		0.003	
	0.075mm (3.75 phi)		0.001	
	0.063mm (4.0 phi)		0.000	
	Total sieved		0.257	0.000
	Accurracy of method (%)		100.000	

Note: *All weights are accurate to 0.001 grams*

APPENDIX G (2) *(continuation)*

GRAIN SIZE DETERMINATION BY DRY-SIEVING

Location of Core: Kakawis Lake - Meares Island - CW coast Vanc.Isl.

CORE NUMBER : Kakawis 7

CORE SECTION & LAYER			4 - 80	6 - 142	6 - 160	8 - 280
DEPTH in core (cm)			80	142	160	280
SAMPLE #	GL-K7-99		L4b80	L6b142	L6b160	L8b280
Coarse Sediment (s) (representative amount used)	s>=2mm	W (cs)	0.017	0.659	0.000	16.156
Dry Sieving of sediment material - Coarse Sediment Fraction - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000	0.000	0.000	0.000
	13.2mm (-3.5 phi)		0.000	0.000	0.000	0.000
	8.0mm (-3.0 phi)		0.000	0.000	0.000	0.869
	5.6mm (-2.5 phi)		0.000	0.000	0.000	3.391
	4.0mm (-2.0 phi)		0.000	0.232	0.000	4.040
	2.8mm (-1.5 phi)		0.000	0.136	0.000	3.914
	2mm (-1.0 phi)		0.017	0.290	0.000	3.943
	Total sieved		0.017	0.659	0.000	16.156
	Accuracy of method (%)		100.000	99.970		100.000

Sand (s) (representative amount used)	63um< s >2mm	W (s)	0.000	1.152	0.652	10.908
Dry Sieving of sediment material - Sand Fraction - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	1.4mm (-0.5 phi)			0.156	0.015	1.111
	1.00mm (0.0 phi)			0.233	0.011	1.110
	0.707mm (0.5 phi)			0.180	0.041	1.239
	0.500mm (1.0 phi)			0.196	0.085	1.585
	0.355mm (1.5 phi)			0.158	0.153	2.419
	0.250mm (2.0 phi)			0.110	0.168	1.979
	0.210mm (2.25 phi)			0.044	0.047	0.534
	0.180mm (2.50 phi)			0.029	0.056	0.312
	0.150mm (2.75 phi)			0.030	0.026	0.294
	0.125mm (3.0 phi)			0.016	0.025	0.104
	0.090mm (3.5 phi)			0.000	0.021	0.144
	0.075mm (3.75 phi)			0.000	0.004	0.045
	0.063mm (4.0 phi)			0.000	0.000	0.032
	Total sieved		0.000	1.152	0.652	10.908
	Accurracy of method (%)			100.000	100.000	100.000

Note: *All weights are accurate to 0.001 grams*

APPENDIX G (2) *(continuation)*

GRAIN SIZE DETERMINATION OF THE SEDIMENT FRACTIONS

Location of Core: Port Alberni Marsh - Inlet
CORE NUMBER : AD 1700 Tsunami Sand Layer (hand sample)

CORE SECTION & LAYER			Hand Sp.
DEPTH (cm)			70
SAMPLE #	GL-PA1700-00		b
Coarse Sediment (s) (representative amount used)	s>2mm	W (cs)	0.000
- Coarse Sediment Fraction - Set of meshes between 16.0mm & 2mm (Ro-Tap for 20')	16.0mm (-4.0 phi)		0.000
	13.2mm (-3.5 phi)		0.000
	8.0mm (-3.0 phi)		0.000
	5.6mm (-2.5 phi)		0.000
	4.0mm (-2.0 phi)		0.000
	2.8mm (-1.5 phi)		0.000
	Total sieved		0.000
	Accuracy of method (%)		

Sand (s) (representative amount used)	63um< s >2mm	W (s)	6.000
Dry Sieving of sediment material - Sand Fraction - *Set of meshes between 63um & 2mm (Ro-Tap for 20')*	2mm (-1.0 phi)		0.000
	1.4mm (-0.5 phi)		0.000
	1.00mm (0.0 phi)		0.044
	0.707mm (0.5 phi)		0.112
	0.500mm (1.0 phi)		0.384
	0.355mm (1.5 phi)		1.341
	0.250mm (2.0 phi)		1.980
	0.210mm (2.25 phi)		0.876
	0.180mm (2.50 phi)		0.400
	0.150mm (2.75 phi)		0.386
	0.125mm (3.0 phi)		0.231
	0.090mm (3.5 phi)		0.182
	0.075mm (3.75 phi)		0.042
	0.063mm (4.0 phi)		0.013
	Total sieved		5.991
	Accurracy of method (%)		99.850

Note: *All weights are accurate to 0.001 grams*

APPENDIX G (3)

GRAIN SIZE ANALYSIS BY MOMENT METHODS

Location of Core: Kakawis Lake - Meares Island and Port Alberni marsh lands - CW coast Vanc. Isl.

CORE NUMBER : Kakawis 1, Kakawis 2, Kakawis 6, Kakawis 7 and Port Alberni 1700 sand sample

Method: Settling Tube

CORE #	DEPTH in core (cm)	SAMPLE #	Gravel Fraction %	Sand Fraction %	Silt Fraction %	Clay Fraction %	Mud %	Sand/Mud Ratio	Mean (phi)	Std. Dev. (phi)	Skewness	Kurtosis
K1	168	L4 b 168	54.3731	43.7709	1.8561	0.0000	1.8561	23.5827	-1.1783	2.0108	0.5057	2.7697
K1	190	L4 b 190	58.4470	40.8532	0.6998	0.0000	0.6998	58.3766	-1.4915	1.9164	0.0241	1.3471
K1	206	L5 b 206	70.5181	29.1968	0.2852	0.0000	0.2852	102.3833	-1.6879	1.5981	0.8939	3.0748
K2	194	L11 b 194	12.4056	84.4135	3.1809	0.0000	3.1809	26.5375	0.5904	1.2816	0.9615	5.8046
K2	250	L16 b 250	94.0390	5.6783	0.2827	0.0000	0.2827	20.0853	-5.5970	2.2464	1.8560	5.6527
K6	240	L6 b 240	1.0425	137.3102	0.0000	0.0000	0.0000	0.0000	1.2468	1.4545	-0.8848	1.9640
K6	354	L11 b 354	45.8172	54.1828	0.0000	0.0000	0.0000	0.0000	-1.1956	2.4182	-0.2420	1.3546
K7	280	L8b 280	31.3972	68.6028	0.0000	0.0000	0.0000	0.0000	-0.1023	1.4456	-0.5805	2.2338
PA 1700			0.0000	100.0000	0.0000	0.0000	0.0000	0.0000	1.6790	0.4966	0.0461	4.1032
Standard 1			0.0000	100.0000	0.0000	0.0000	0.0000	0.0000	1.6790	0.4966	0.0461	4.1032
Standard 2			0.0000	100.0000	0.0000	0.0000	0.0000	0.0000	1.7609	0.5475	0.1169	5.5457

Note: CaCO3 and organic matter content percentages are excluded.

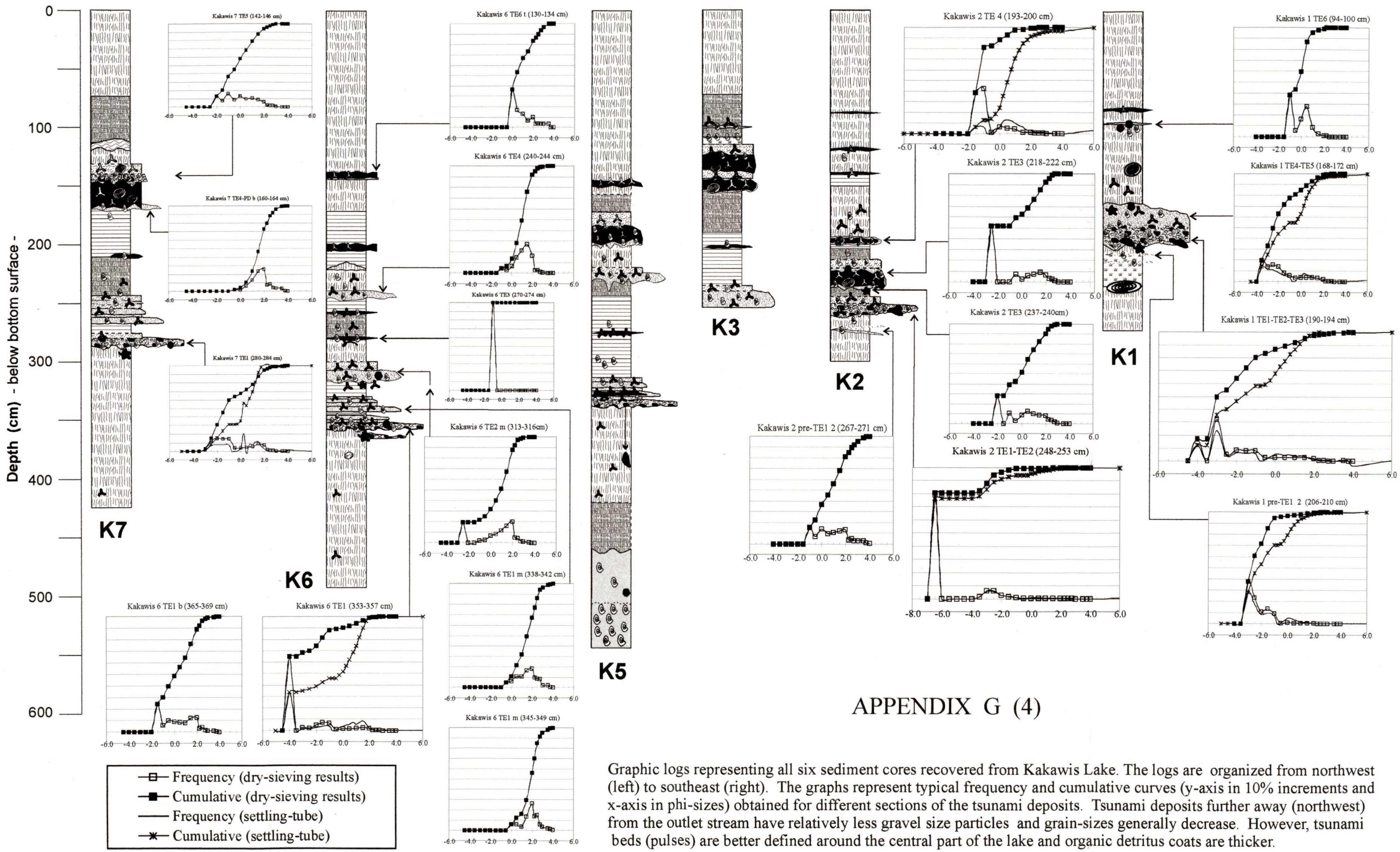
APPENDIX G (3) *(continuation)*

STATISTICAL DATA FROM GRAIN SIZE ANALYSES

Moments Method (from settling tube grain size analysis)					
CORE	Tsunami Event or Layer	Depth in core (cm)	Mean	Standard Deviation	Modes
Kakawis 1	TE4-TE5	168	-1.178	2.011	3
	TE1-TE2-TE3	190	-1.492	1.916	8
	pre-tsunami 2 (pre-TE1 2)	206	-1.688	1.598	5
Kakawis 2	TE4	193	0.590	1.282	2
	TE1-TE2	250	-5.597	2.246	4
Kakawis 6	TE1	354	-1.196	2.418	6
Kakawis 7	TE1	280	-0.102	1.446	8
PA1700	AD 1700 Port Alberni Marsh	70	1.679	0.497	2

Graphical Measures (from dry-sieving grain size analysis)					
CORE	Tsunami Event or Layer	Depth in core (cm)	Mean	Standard Deviation	Modes
Kakawis 1	TE6	94	-0.417	0.831	2
	TE4-TE5	168	-2.083	1.786	3
	TE1-TE2-TE3	190	-2.417	1.987	8
	pre-tsunami 2 (pre-TE1 2)	206	-2.583	0.907	5
Kakawis 2	TE5 (detrital cap)	170	-1.000	0.000	1
	TE4	194	-1.083	0.907	3
	TE3	218	-1.417	1.875	3
	TE3	237	-0.250	1.837	5
	TE1-TE2	250	-5.583	1.786	4
	pre-TE1 2	267	0.680	1.459	5
	pre-TE1 1	280	-1.000	0.000	1
Kakawis 6	TE6 t (detrital cap)	130	0.680	1.182	2

	TE5 - plant detritus layer	200	6.000	2.300	n/a
	TE4 t (detrital cap/gyttja)	230	6.000	2.300	n/a
	TE4	240	1.083	0.947	3
	TE3 - plant detritus layer	259	-1.000	0.000	1
	TE3	270	-1.000	0.000	1
	TE3 - plant detritus layer	280	-1.000	0.000	1
	g (m) mid / TE2 t (detrital cap)	295	-1.000	0.000	1
	TE2 m	313	-0.083	2.038	4
	TE2 b	320	-1.000	0.000	1
	TE1 m	339	1.430	1.120	4
	TE1 m	346	1.597	0.995	4
	TE1	350	1.597	0.995	4
	TE1	354	-3.250	1.737	6
	TE1 b	365	0.083	1.636	5
	pre-TE1	382	-1.000	0.000	1
Kakawis 7	g (s-l) top (lens TE6?)	80	-1.000	0.000	1
	TE5	142	-0.250	1.549	5
	TE4 PD big detrital cap	150	2.000	0.450	2
	TE4 PD big detrital cap b	160	1.597	1.070	3
	TE3 (gyttja)	215	5.000	2.350	n/a
	TE3 (gyttja)	235	5.000	2.350	n/a
	TE2	250	2.000	0.500	2
	TE2	264	2.000	0.700	2
	TE1	280	-0.917	1.951	6



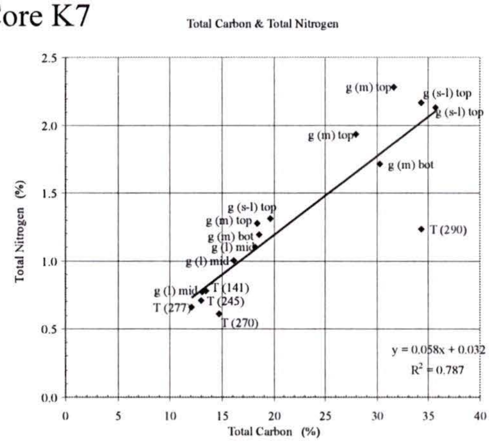
APPENDIX G (4)

Graphic logs representing all six sediment cores recovered from Kakawis Lake. The logs are organized from northwest (left) to southeast (right). The graphs represent typical frequency and cumulative curves (y-axis in 10% increments and x-axis in phi-sizes) obtained for different sections of the tsunami deposits. Tsunami deposits further away (northwest) from the outlet stream have relatively less gravel size particles and grain-sizes generally decrease. However, tsunami beds (pulses) are better defined around the central part of the lake and organic detritus coats are thicker.

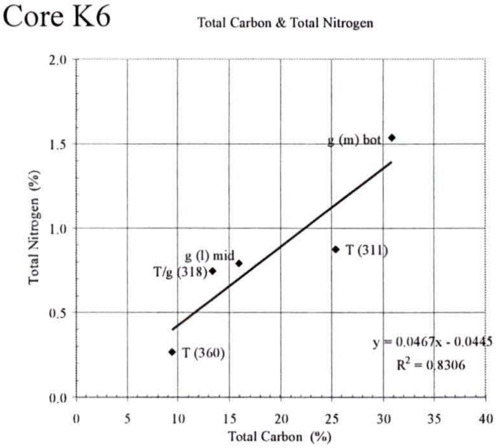
APPENDIX H (1)

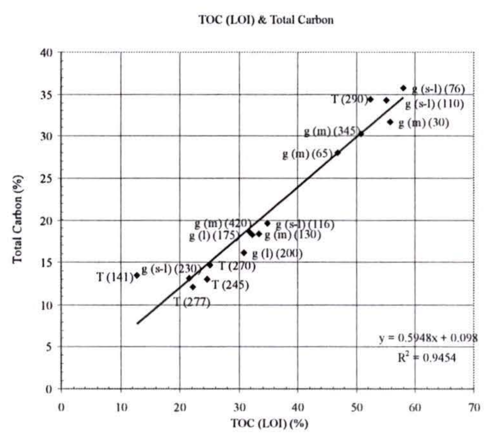
Relation between Total Carbon (by elemental analysis), total Nitrogen (by elemental analysis) and total organic carbon (TOC - by LOI) for cores K6 and K7.

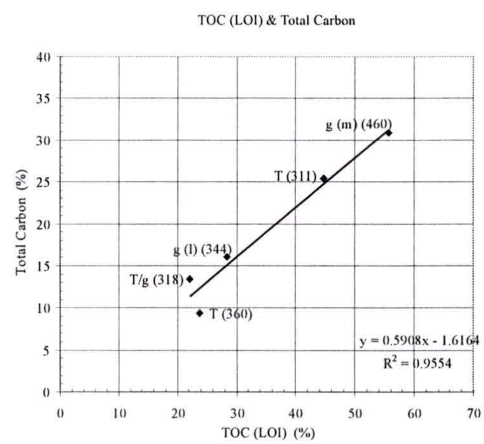
Core K7

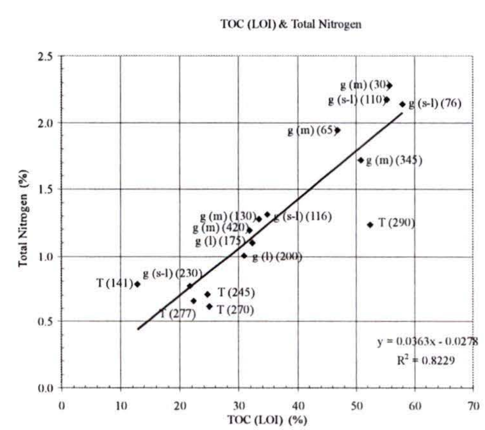


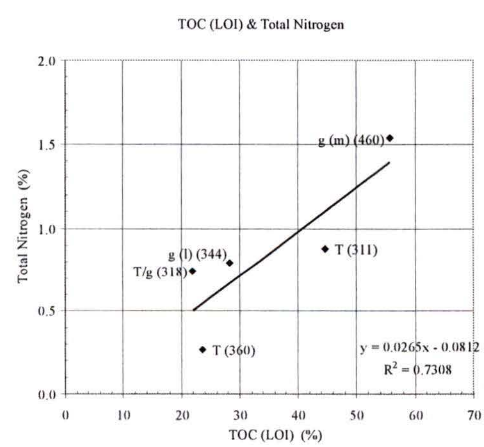
Core K6











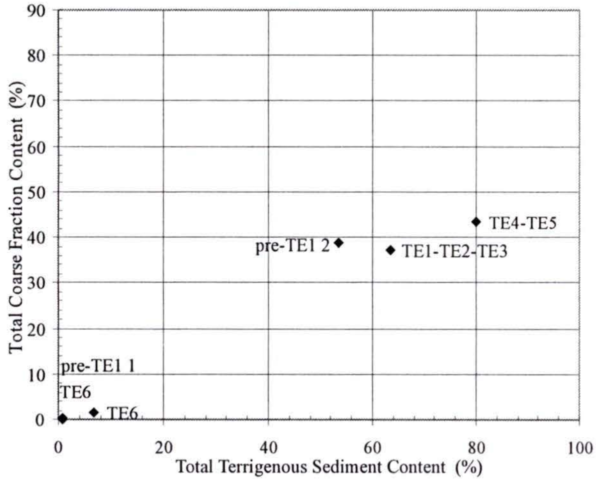
Abbreviations explanation:

g (m) top - gyttja, massive, top of core (post-tsunami deposits)
g (m) bot - gyttja, massive, bottom of core (pre-tsunami deposits)
g (s-l) top - gyttja, semi-laminated, top of core (post-tsunami deposits)
g (l) mid - gyttja, laminated, middle of core (between tsunami deposits)
T/g - contact between tsunami deposit and underlying gyttja
T - tsunami deposit
(123) - depth (in cm) at which sample was taken

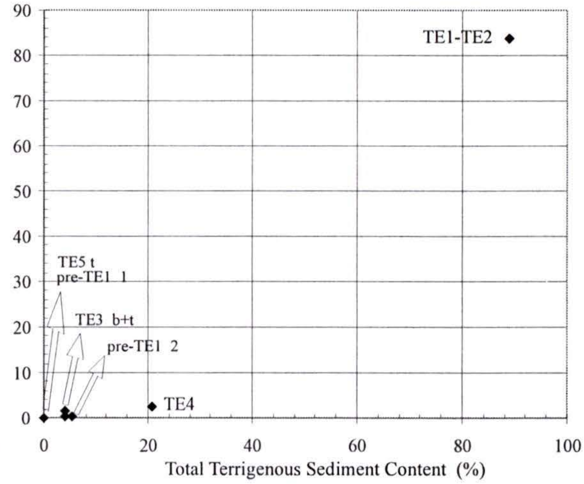
APPENDIX H (2)

Total Terrigenous material per tsunami deposit for selected cores. Relation between percentages of Coarse Fraction and Sand Fraction. Tsunami events (deposits) might be overlapped in areas closer to the outlet stream (e.g. core K1). The proportions of coarse material increase towards the bottom section of any given tsunami deposit.

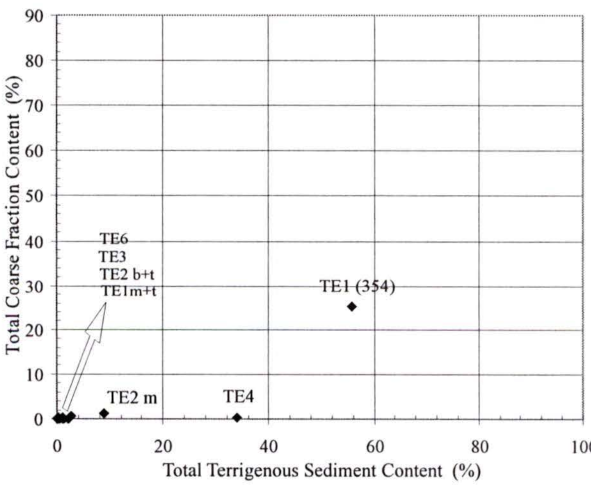
a) Core Kakawis #1



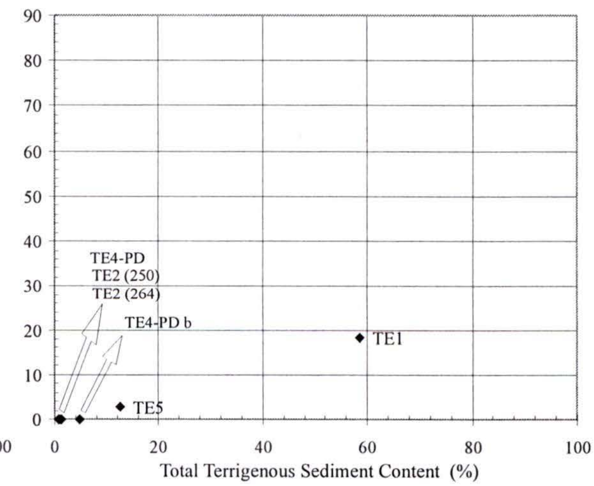
b) Core Kakawis #2



c) Core Kakawis #6



d) Core Kakawis #7

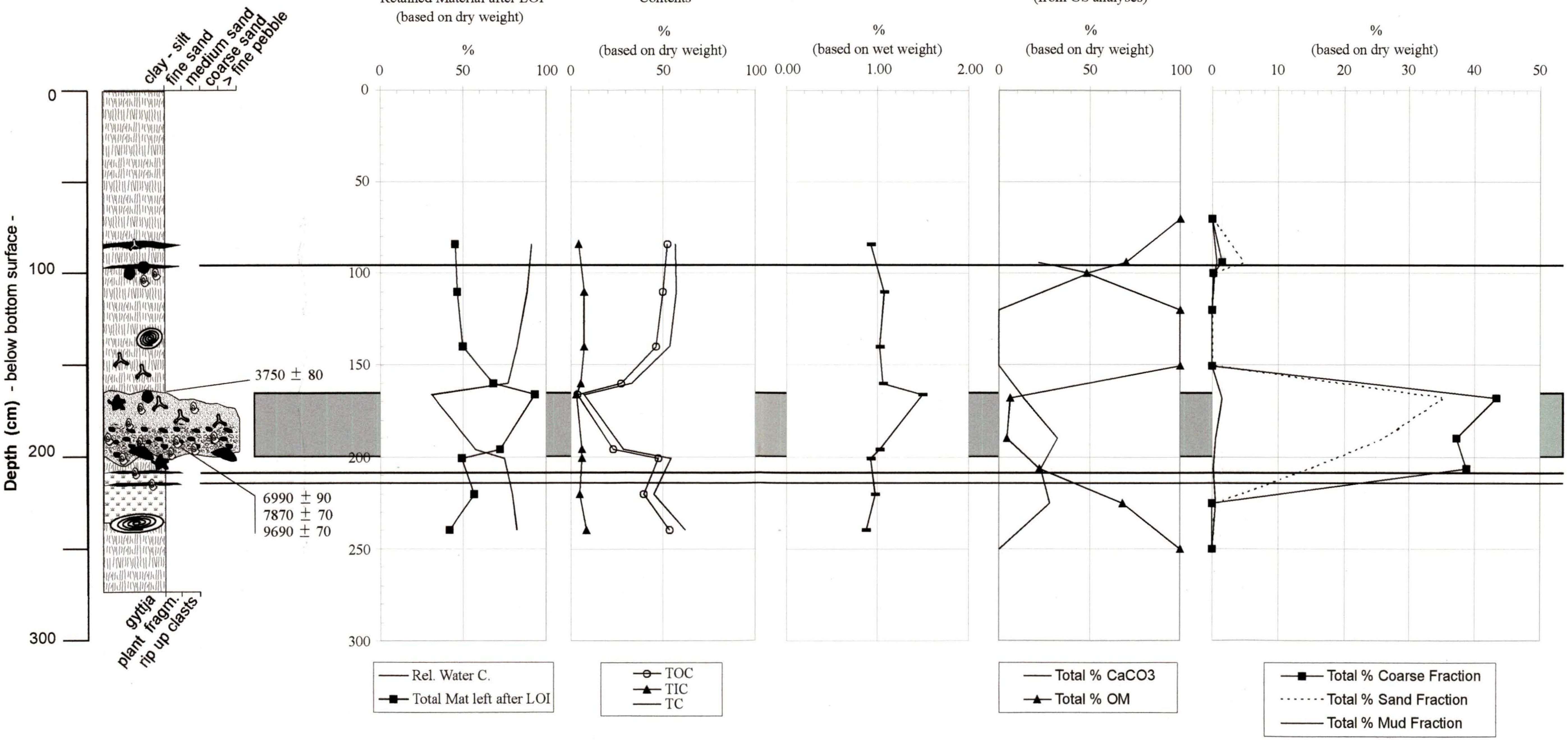


Legend for abbreviations:

TE	- tsunami event (deposit) and number (1 for earliest and 6 for latest)
T/g	- contact between tsunami deposit and underlying gyttja
g/T	- contact between gyttja and underlying tsunami deposit
PD	- plant detritus layer
pre-TE	- layer deposited prior to the latest tsunami deposit
t	- top of the layer in question
m	- middle of the layer in question
b	- bottom of the layer in question
(123)	- depth (in cm) at which sample was taken

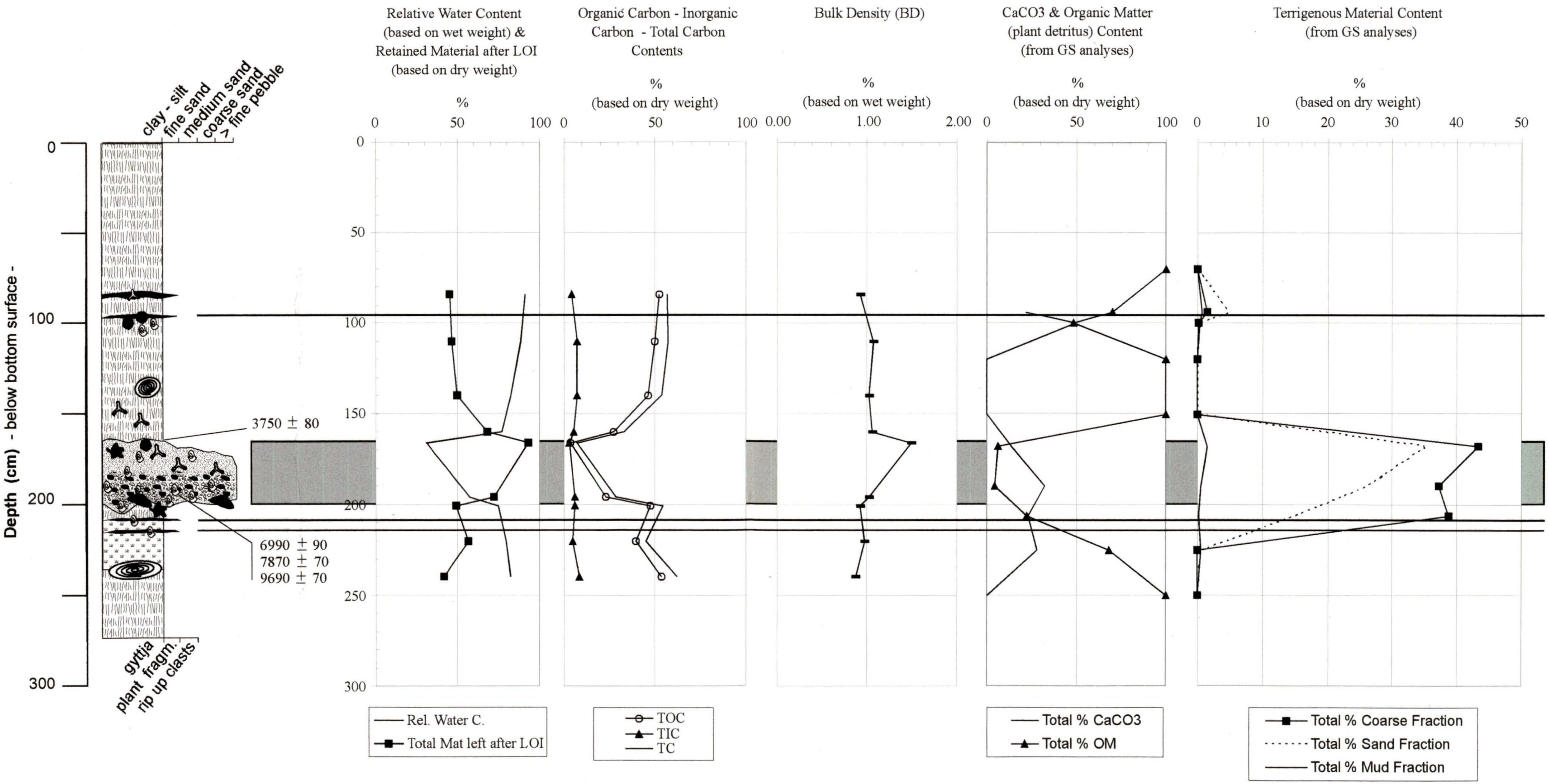
APPENDIX I (1)

Stratigraphic sequence of core K1 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Parameter values are in percentages. Values for Organic Matter content, CaCO3 (shells) content and Terrigenous material (Coarse Fraction, Sand Fraction and Mud Fraction) are proportional to the initial dry weight of the sample. The horizontal axis at the top of the core log represents grain size and clastic facies for the terrigenous material. For organic rich layers the bottom axis indicates sizes of plant fragments and other materials. Radiocarbon ages are shown in 1000 - 14C years BP.



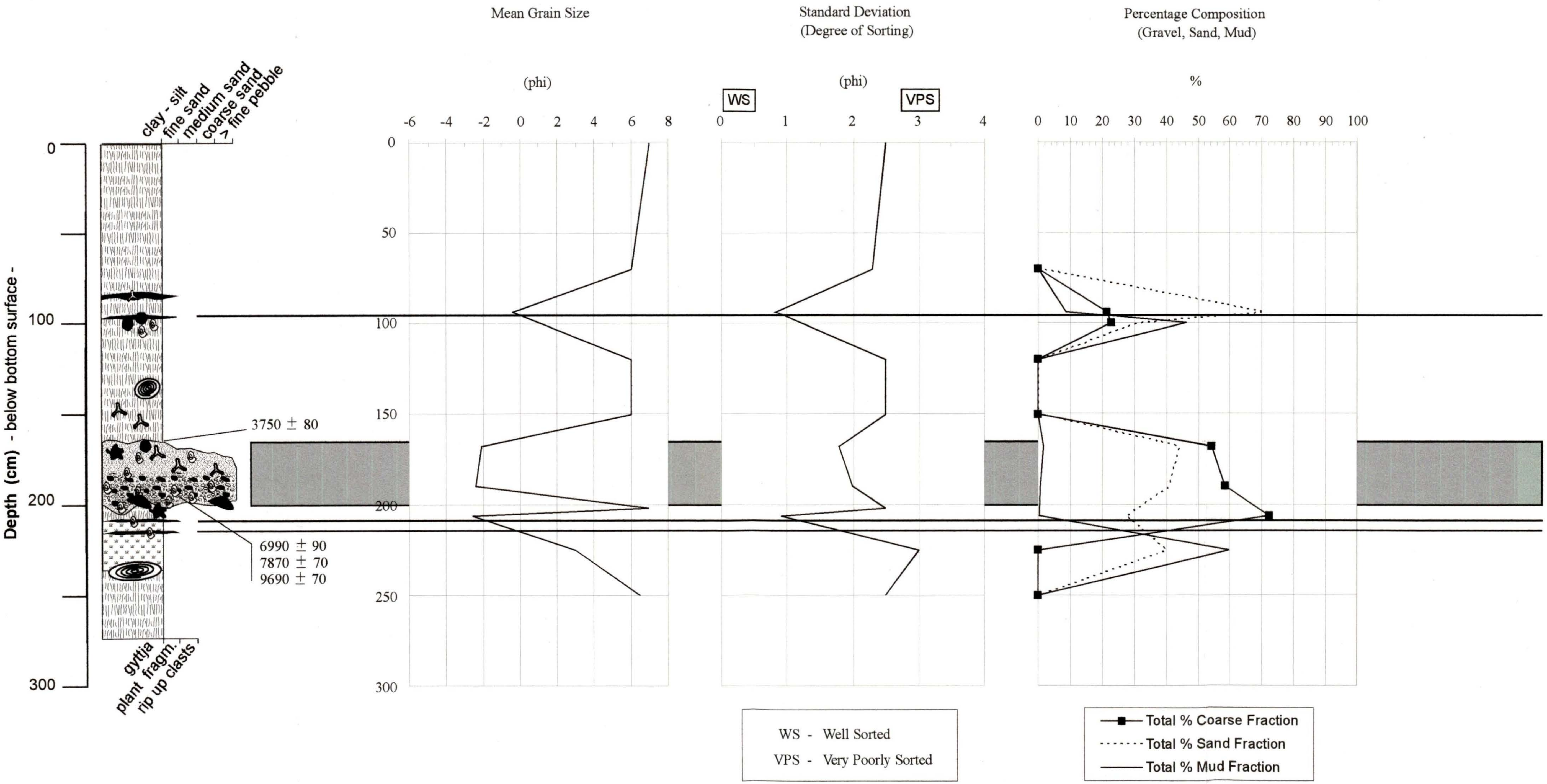
APPENDIX I (1)

Stratigraphic sequence of core K1 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Parameter values are in percentages. Values for Organic Matter content, CaCO3 (shells) content and Terrigenous material (Coarse Fraction, Sand Fraction and Mud Fraction) are proportional to the initial dry weight of the sample. The horizontal axis at the top of the core log represents grain size and clastic facies for the terrigenous material. For organic rich layers the bottom axis indicates sizes of plant fragments and other materials. Radiocarbon ages are shown in 1000 - 14C years BP.



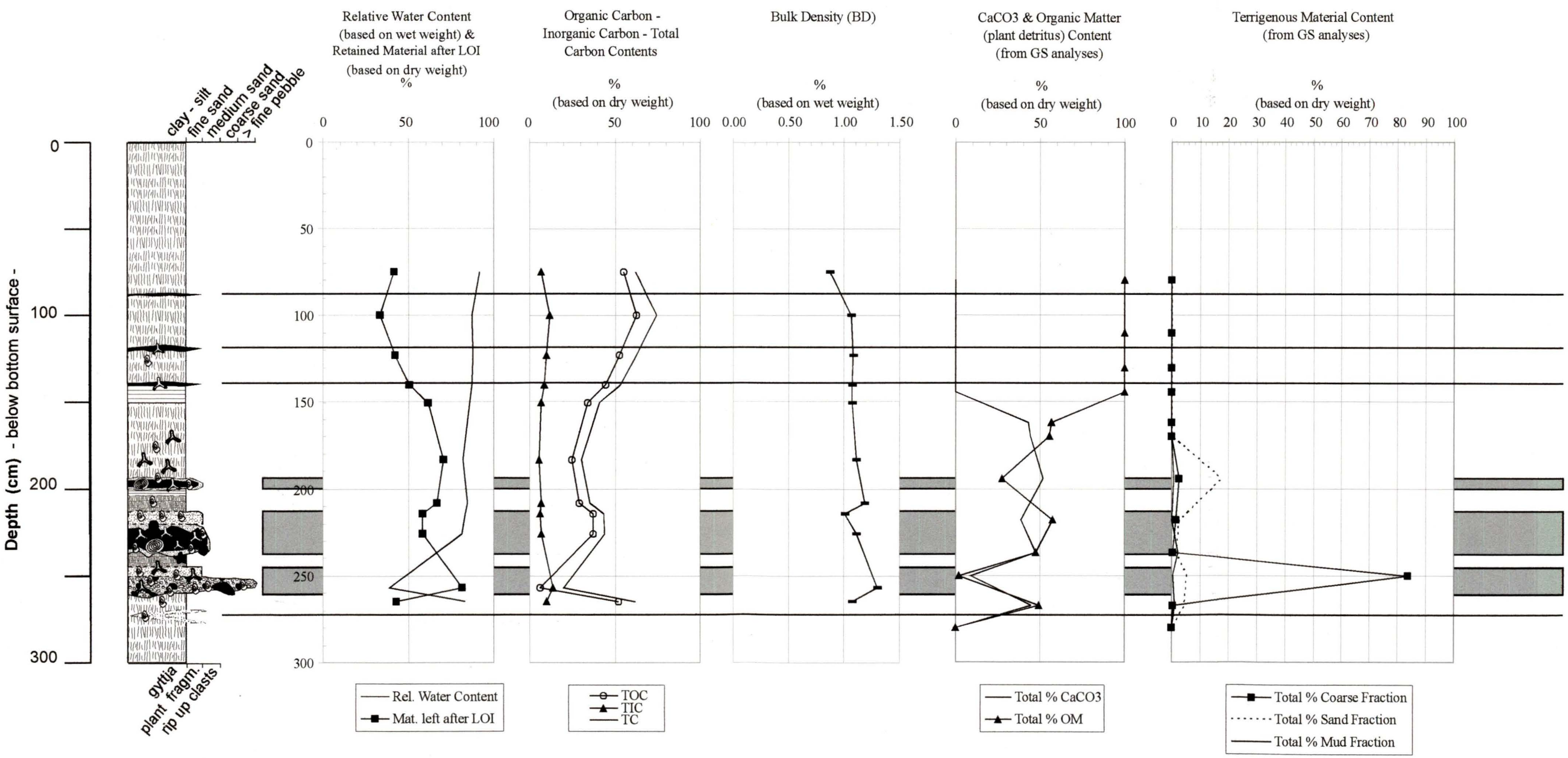
APPENDIX I (1)

Stratigraphic sequence of core K1 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Textural statistics values are in phi. Values for Coarse (Gravel), Sand and Mud fractions are "stand-alone" compositional percentages. Radiocarbon ages are shown in 1000 - 14C years BP.



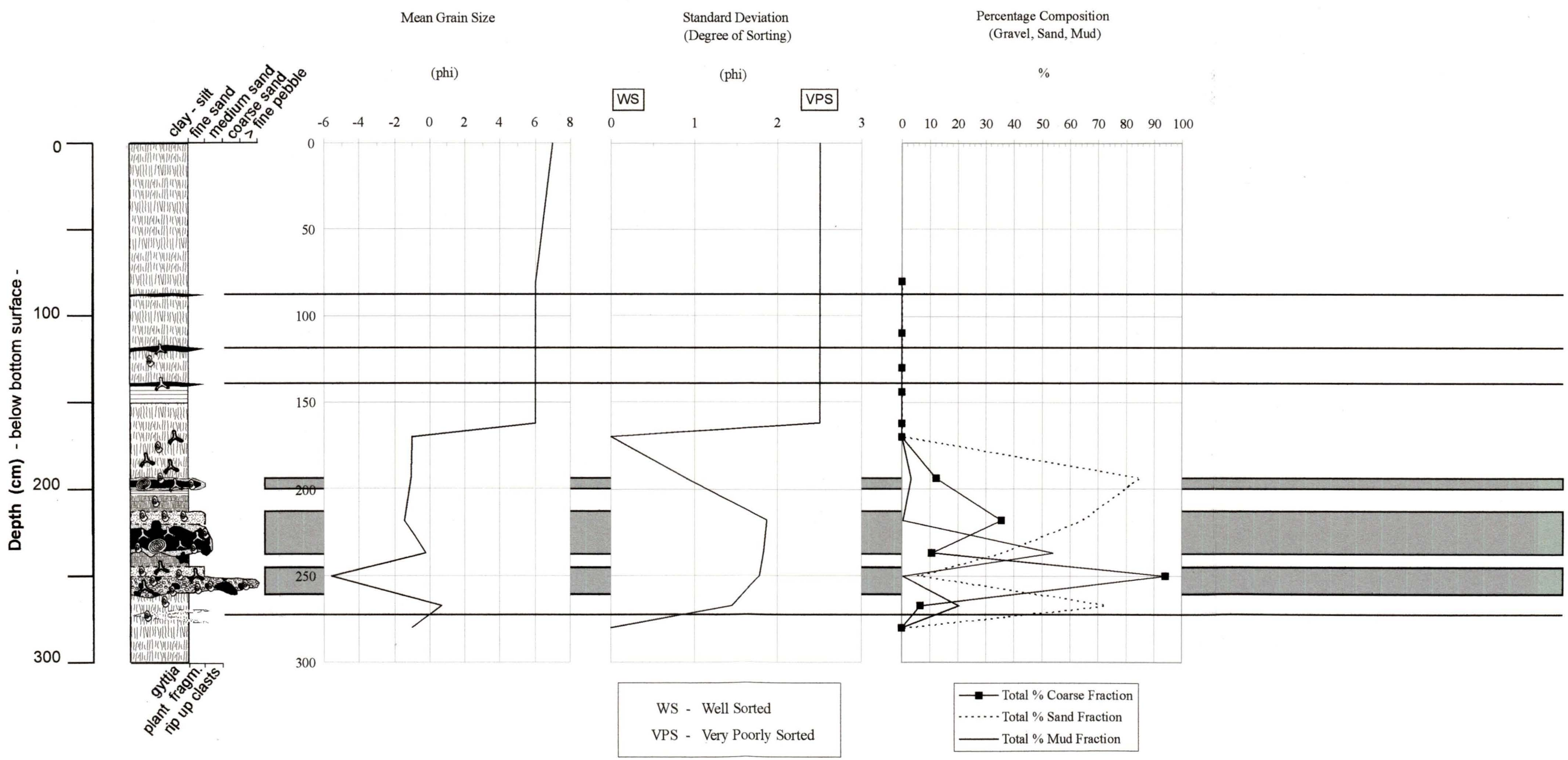
APPENDIX I (2)

Stratigraphic sequence of core K2 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Parameter values are in percentages. Values for Organic Matter content, CaCO3 (shells) content and Terrigenous material (Coarse Fraction, Sand Fraction and Mud Fraction) are proportional to the initial dry weight of the sample. The horizontal axis at the top of the core log represents grain size and clastic facies for the terrigenous material. For organic rich layers the bottom axis indicates sizes of plant fragments and other materials.



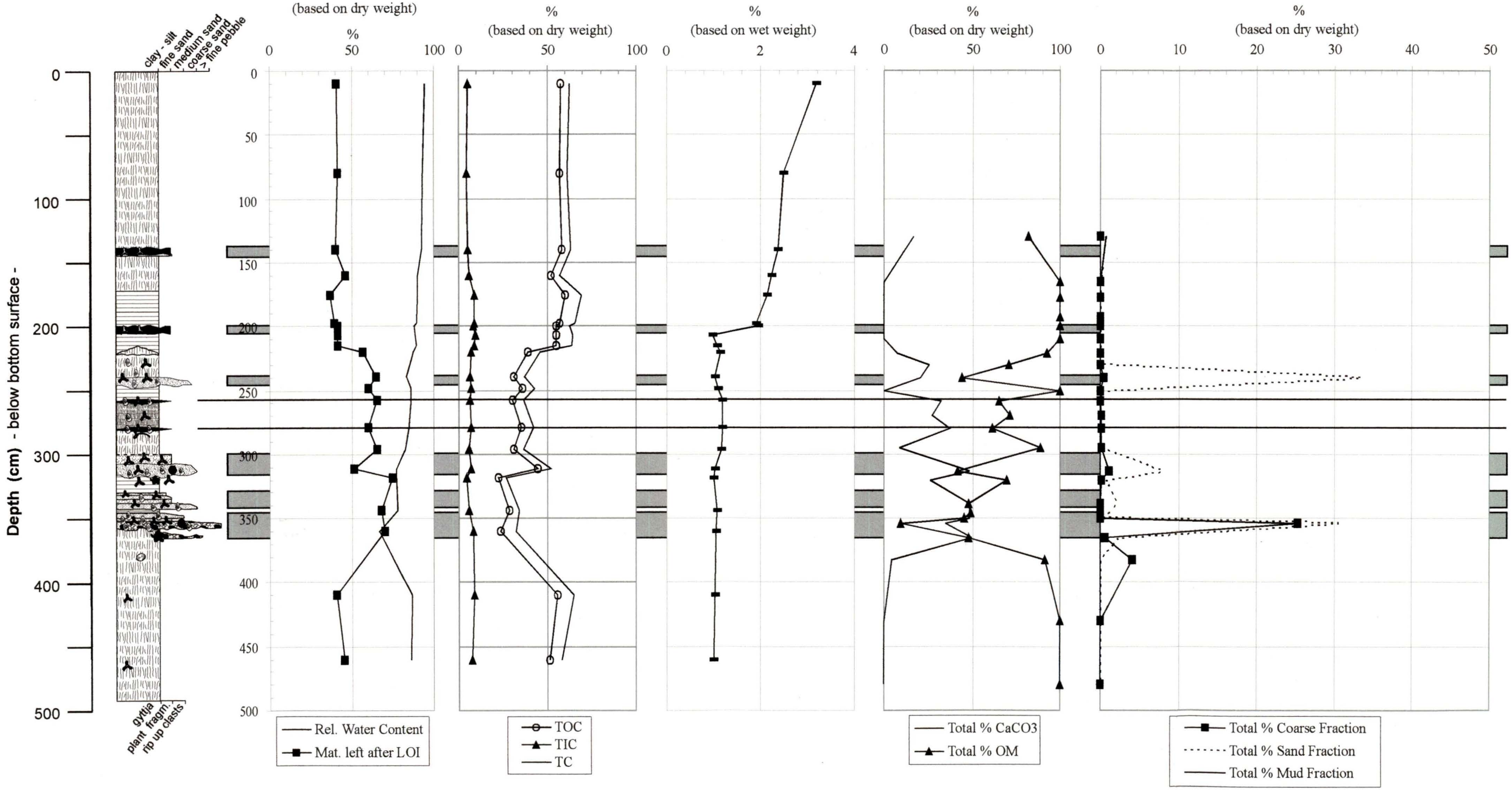
APPENDIX I (2)

Stratigraphic sequence of core K2 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Textural statistics values are in phi. Values for Coarse (Gravel), Sand and Mud fractions are "stand-alone" compositional percentages.



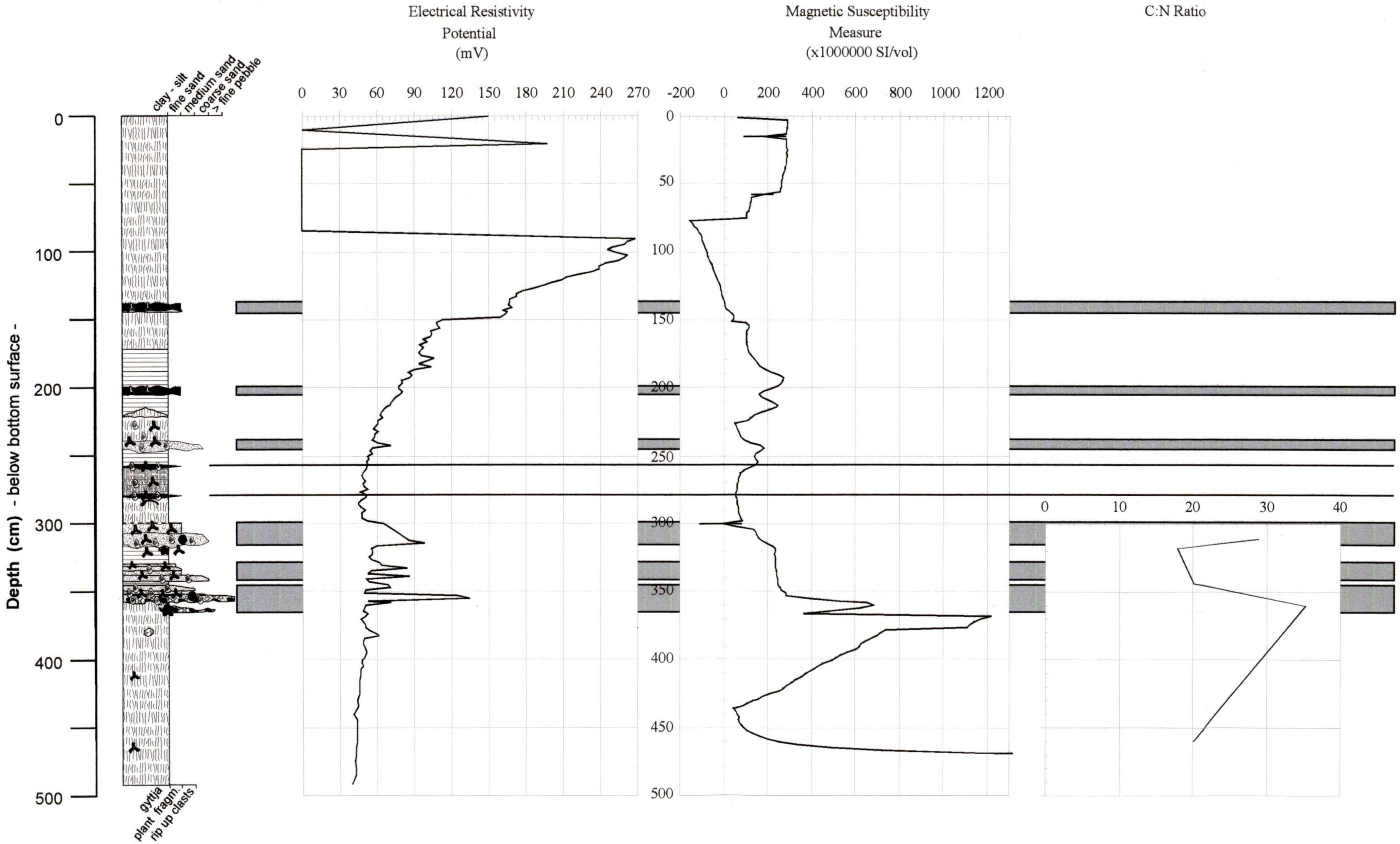
Stratigraphic sequence of core K6 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Parameter values are in percentages. Values for Organic Matter content, CaCO3 (shells) content and Terrigenous material (Coarse Fraction, Sand Fraction and Mud Fraction) are proportional to the initial dry weight of the sample. The horizontal axis at the top of the core log represents grain size and clastic facies for the terrigenous material. For organic rich layers the bottom axis indicates sizes of plant fragments and other materials.

APPENDIX I (3)



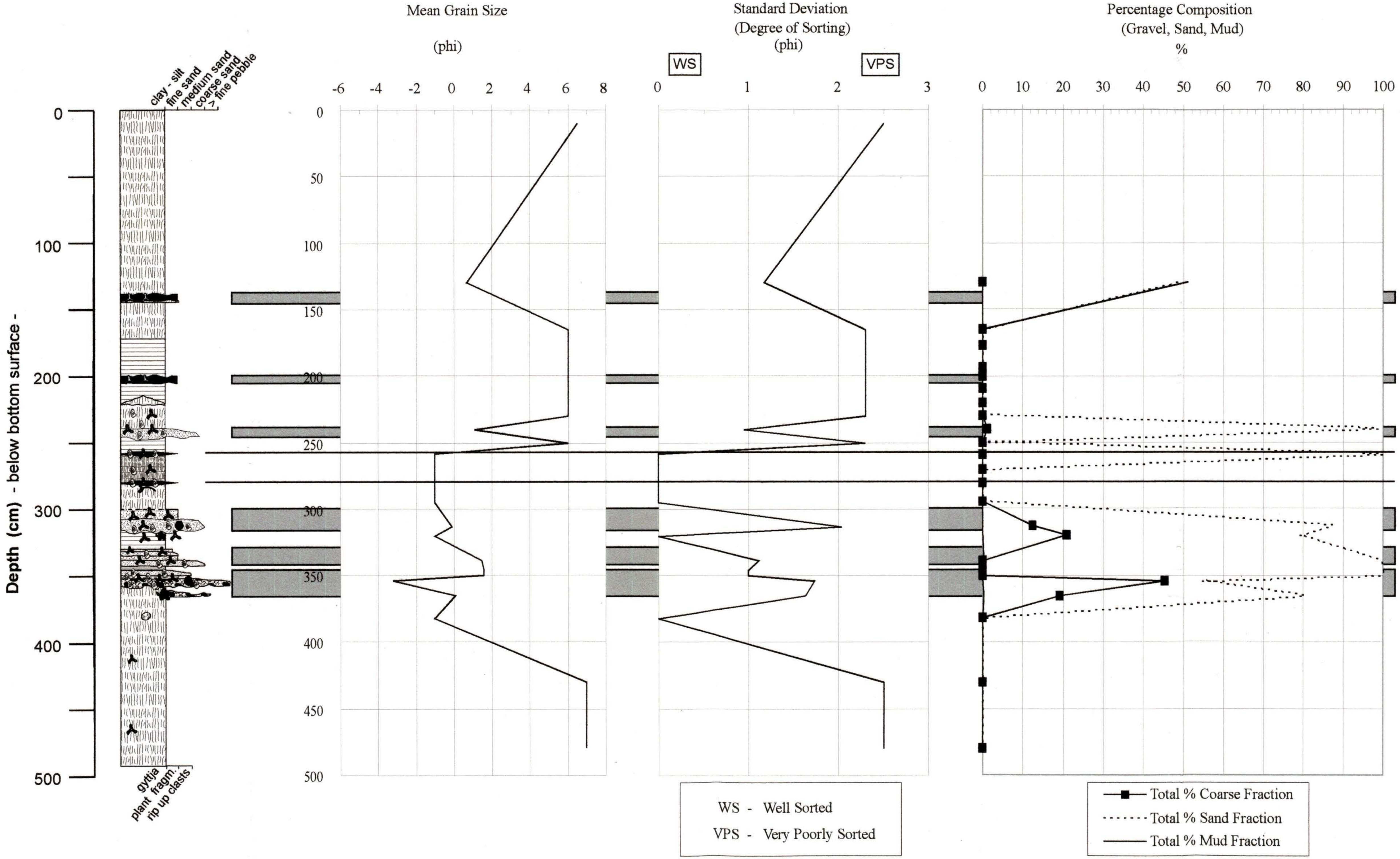
APPENDIX I (3)

Stratigraphic sequence of core K6 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Electrical resistivity and magnetic susceptibility measures were performed on the entire core. C/N analyses were run on selected sections of the sediment for core K6.
The top horizontal axis in the log represents grain size for clastic facies. For organic rich layers and rip-up clasts, the bottom horizontal axis indicates sizes of plant fragments and association with coarse-sized particles. In the electrical resistivity curve, the sudden decrease in values between 25 and 80cm depth is caused by a lack of particles and excess of water. The bottom measures on the magnetic susceptibility curve are highly influenced by the metallic core catcher.



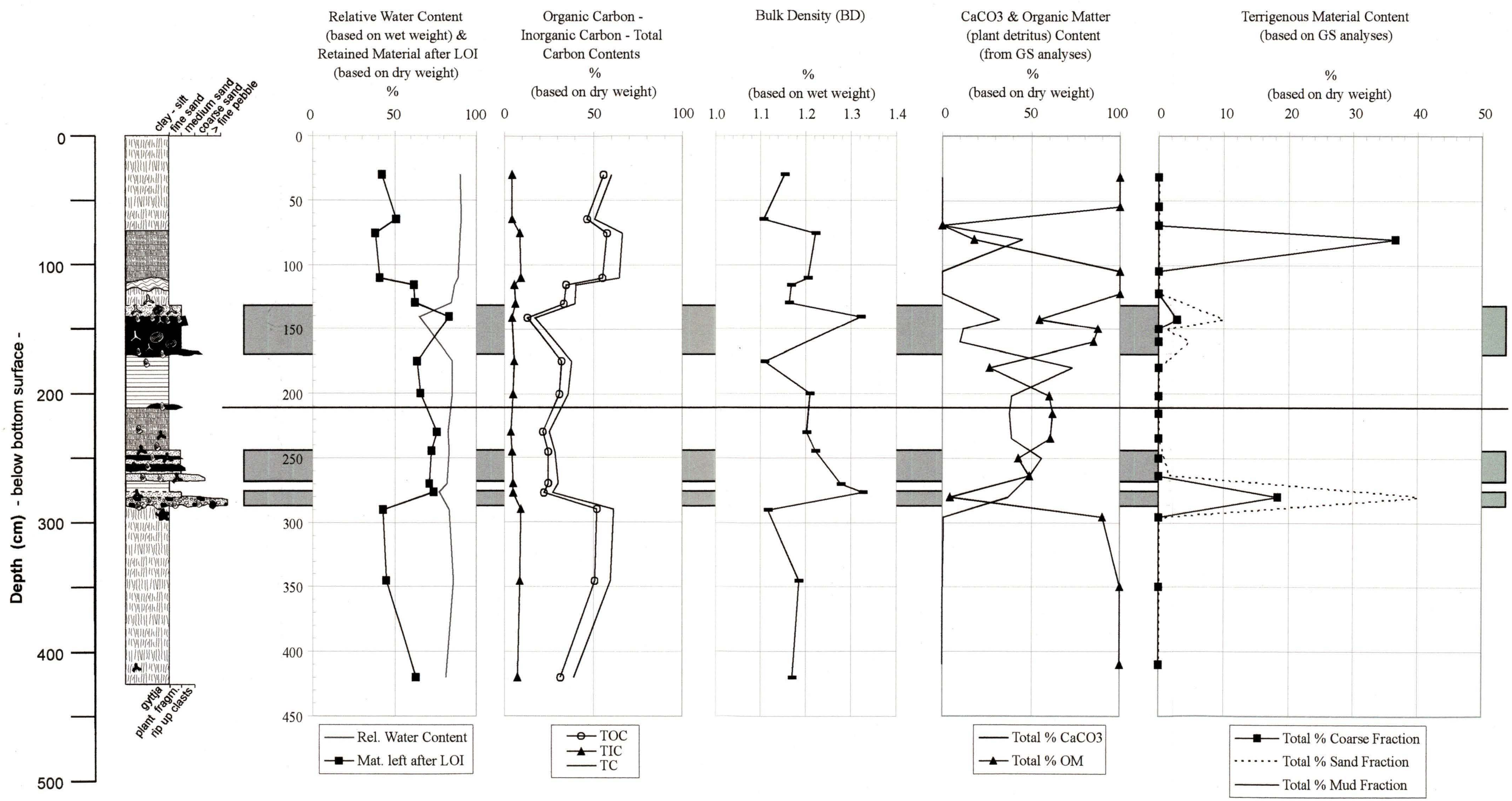
APPENDIX I (3)

Stratigraphic sequence of core K6 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Textural statistics values are in phi. Values for Coarse (Gravel), Sand and Mud fractions are "stand-alone" compositional percentages.



APPENDIX I (4)

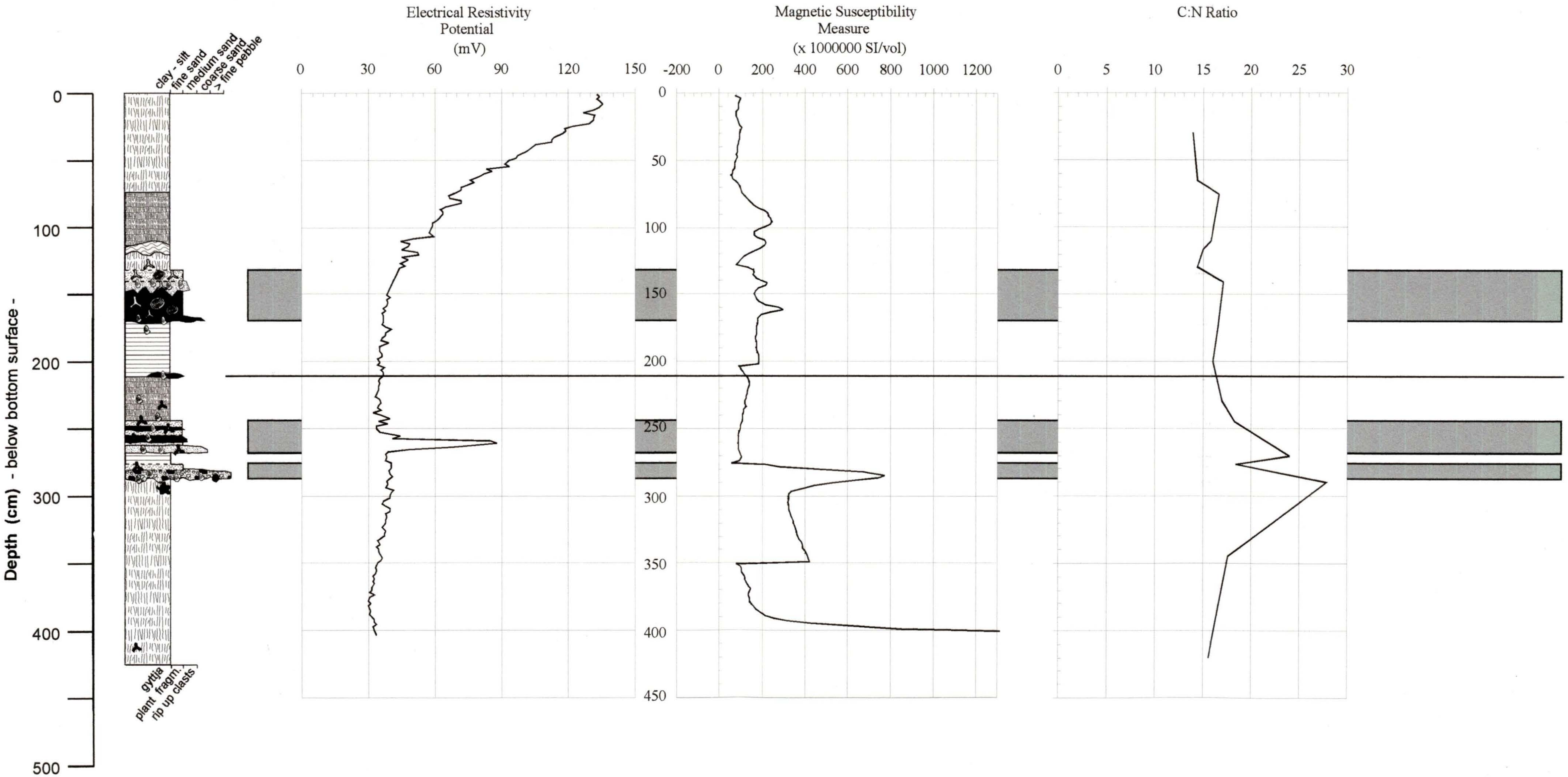
Stratigraphic sequence of core K7 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Parameter values are in percentages. Values for Organic Matter content, CaCO3 (shells) content and Terrigenous material (Coarse Fraction, Sand Fraction and Mud Fraction) are proportional to the initial dry weight of the sample. The horizontal axis at the top of the core log represents grain size and clastic facies for the terrigenous material. For organic rich layers the bottom axis indicates sizes of plant fragments and other materials.



APPENDIX I (4)

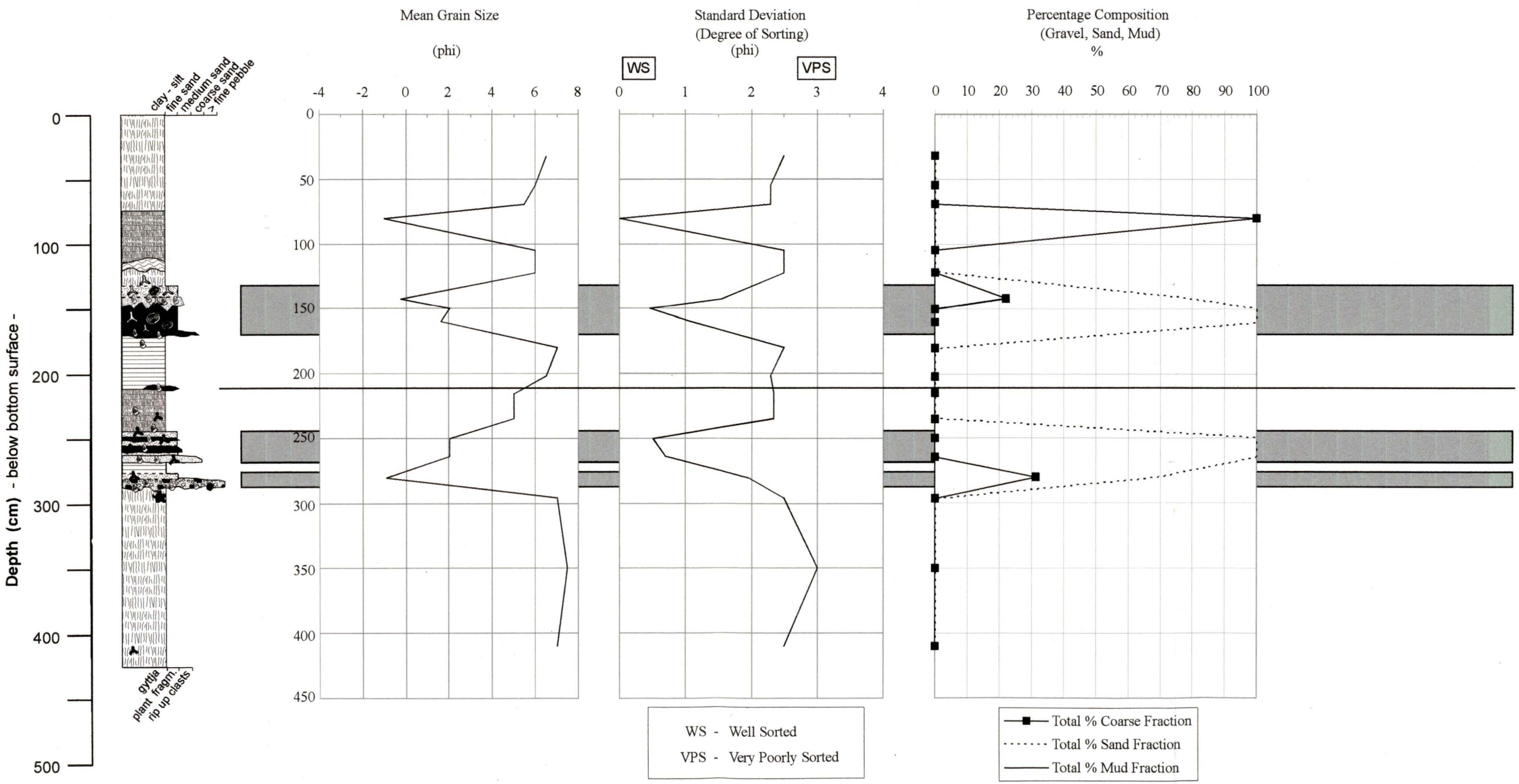
Stratigraphic sequence of core K7 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Electrical resistivity and magnetic susceptibility measures were performed on the entire core. C/N analyses were run on the whole core.

The top horizontal axis in the log represents grain size for clastic facies. For organic rich layers and rip-up clasts, the bottom horizontal axis indicates sizes of plant fragments and association with coarse-sized particles. In the electrical resistivity curve, the continuous increase in values towards the top is caused by a excess of water. The bottom measures on the magnetic susceptibility curve are highly influenced by the metallic core catcher.



APPENDIX I (4)

Stratigraphic sequence of core K7 and graphic representations of some of the different parameters analysed. Tsunami deposits are highlighted by the grey rectangles on the background and black lines crossing the curves. Curves are limited to the most important unit (Unit C) and layers of the core. Textural statistics values are in phi. Values for Coarse (Gravel), Sand and Mud fractions are "stand-alone" compositional percentages.

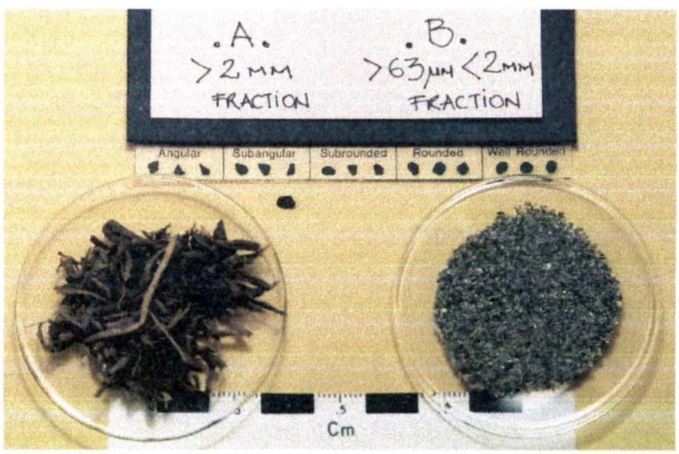


APPENDIX J

Example of materials from event TE2 - TE3 at core K1. Note the angularity of the clasts. This material is associated with tsunamigenic Facies 8.

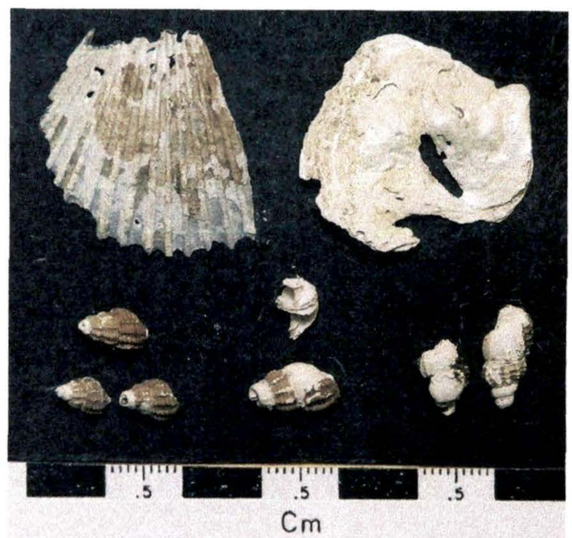
Example of sizes, shape and appearance of the three elemental fractions (clastic material, marine shells and terrestrial plant detritus) from the coarse tsunamigenic Facies 7 at core K6.

Principal elemental fractions from Port Alberni tidal marsh sample taken for comparison purposes. (Tsunami sand identified as AD 1700).



APPENDIX J

Example of size of wood fragments from coarse plant detritus Facies 9. This particular specimen was found in core K3, incorporated in tsunami event TE5.
Note the presence of barnacles (*Balanus sp.*) in the interior wall of the stalk.



Examples of marine shell species incorporated in tsunamigenic Facies 8 and 9 from tsunami event TE4 in core K2. Note the pristine conditions of the small gastropods.

Deep water mollusc species:
Yoldia sp.
from Glaciomarine clays
(Facies 1 and 2) at
Kakawis Lake and Darville Lake

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Universidad EAFIT Annual Research Award	1995

Publications:

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