ISSN 8755-6839

SCIENCE OF TSUNAMI HAZARDS

The International Journal of The Tsunami Society

Volume 23 Number 3 Published Electronically 2005

A POSSIBLE TSUNAMI IN THE LABRADOR SEA RELATED TO THE DRAINAGE OF GLACIAL LAKE AGASSIZ-8400 YEARS B.P. 3
James T. Teller
University of Manitoba, Manitoba, CANADA
Tad Murty
University of Ottawa, Ottawa, CANADA
N. Nirupama
York University, Toronto, CANADA
P. Chittibabu
W. F. Baird and Associates, Ottawa, CANADA

TREND OF MICROMETEOROLOGICAL PARAMETERS DURING TSUNAMI ON THE EAST COAST OF INDIA 17
V. Kanakasabai and M. Rajendran
Annamalai University, Tamilnadu, INDIA

BOULDER DEPOSITS ON THE SOUTHERN SPANISH ATLANTIC COAST: POSSIBLE EVIDENCE FOR THE 1555 AD LISBON TSUNAMI 25
Franziska Whelan
University of Bamberg, Bamberg, GERMANY
Dieter Kelletat
University of Duisburg-Essen, Essen, GERMANY

CONCEPTUAL DIFFERENCES BETWEEN PACIFIC, ATLANTIC, AND ARCTIC TSUNAMI WARNING SYSTEMS FOR CANADA 39
Tad Murty and I. Nistor
University of Ottawa, Ottawa, CANADA
N. Nirupama
York University, Toronto, CANADA
A. D. Rao
Indian Institute of Technology, New Deli, INDIA

COMMENT ON: TSUNAMIS AND TSUNAMI-LIKE WAVES OF THE EASTERN UNITED STATES 52
Alan Ruffman,
Geomarine Associates Ltd., Halifax, CANADA

THE TSUNAMI SOCIETY
2525 Correa Rd., UH/SOEST, Rm 215 HIG
Honolulu, HI 96822, USA

WWW.STHJOURNAL.ORG

OBJECTIVE: **The Tsunami Society** publishes this journal to increase and disseminate knowledge about tsunamis and their hazards.

EDITORIAL STAFF

EDITORIAL BOARD

TSUNAMI SOCIETY OFFICERS

Submit manuscripts of articles, notes or letters to the Editor. If an article is accepted for publication the author(s) must submit a scan ready manuscript, a TeX or a PDF file in the journal format. Issues of the journal are published electronically in PDF format. Recent journal issues are available at

http://www.sthjournal.org.

Tsunami Society members will be advised by e-mail when a new issue is available. There are no page charges or reprints for authors.

Issues of the journal from 1982 thru 2004 are available in PDF format at

http://epubs.lanl.gov/tsunami/

and on a CD-ROM from the Society to Tsunami Society members.

ISSN 8755-6839 **http://www.sthjournal.org**

Published Electronically by The Tsunami Society in Honolulu, Hawaii, USA

A POSSIBLE TSUNAMI IN THE LABRADOR SEA RELATED TO THE DRAINAGE OF GLACIAL LAKE AGASSIZ ~8400 YEARS B.P.

James T. Teller
Dept. of Geological Sciences, University of Manitoba, Winnipeg, MB, Canada
Tad Murty
Dept. of Civil Engineering, University of Ottawa, Ottawa, ON, Canada
N. Nirupama
School of Administrative Studies, York University, Toronto, ON, Canada
P. Chittibabu
W. F. Baird & Associates Coastal Engineers, Ltd., Ottawa, ON, Canada

ABSTRACT

For thousands of years, the thick Laurentide Ice Sheet covered a large part of northern North America, damming northward-draining rivers. As this ice retreated, large lakes formed along its margin. Glacial Lake Agassiz was the largest of these ice-marginal lakes, covering an area of >800,000 km^2 (more than twice the size of the largest lake in the modern world, the Caspian Sea) before it drained catastrophically into the Labrador Sea. Even before that, Lake Agassiz had periodically released large volumes of water into the ocean via the Great Lakes-St. Lawrence and the Athabasca-Mackenzie River systems. The last and largest of these outbursts released >150,000 km^3 through Hudson Bay and Hudson Strait in 6-12 months; the average flux over that period was ~5 Sv (1 Sv = 1×10^6 m^{3}s^{-1}).

When a volume of water this large is discharged into a coastal sea like the Labrador Sea, it may generate a surface flood wave or a tsunami if the water mass is large enough and introduced in a short time. To our knowledge no previous calculations have been made to estimate the potential impact of a flood burst on the generation of solitary waves. Using analogies of tsunamis generated by submarine landslides and ocean earthquakes, the amplitude of a Lake Agassiz generated tsunami is estimated to have been at least 2 m. Directionality considerations, as well as the effect of the Coriolis Force in the Northern Hemisphere, suggest that the resulting tsunami probably traveled 50-100 km along the west coast of the Labrador Sea, south of Hudson Strait where the outburst entered the ocean, before being dissipated. The erosional and depositional affects of historic and prehistoric tsunamis are present in the geological record, and provide guidance in seeking evidence for the Lake Agassiz flood burst and subsequent tsunami. This record may be found along the western coast of the Labrador Sea as well as along the shores of Hudson Strait.

1. INTRODUCTION

There are several sources for tsunami generation: submarine earthquakes which displace segments of the earth's crust, submarine volcanic explosions, submarine landslides, nuclear and large-scale chemical or munition explosions in water such as the Halifax explosion in 1917 (Greenberg et al., 1993, 1994; Ruffman et al., 1995, Mader, 2004; Murty 2003; Murty et al., 2005), cosmic body strikes in the ocean, and decomposition of gas hydrate where crystallized methane and water in ocean sediment may be released when destabilized (Kennett et al., 2003). To this list of triggers, we may also add large-scale abrupt releases of water from the continent that were stored in ice-marginal lakes, although tsunami generation from this source has never been reported in the literature to the best of our knowledge.

It is known that tsunamis generated by asteroid strikes, submarine earthquakes, and volcanic explosions can travel across trans-oceanic distances, whereas those generated by chemical/munition explosions and submarine landslides are dissipated in relatively short travel distances (Murty, 1977, 2003). Our expectation is that a tsunamis generated from a sudden introduction of a large volume of water will be somewhat similar to a tsunamis from a submarine landslide or explosion, at least as far as travel distances and directionality of tsunami energy are concerned. Here, we report and discuss the possibility of tsunami generation ~8400 years ago by the abrupt (catastrophic) drainage of glacial Lake Agassiz in Canada through Hudson Strait into the Labrador Sea.

2. THE SETTING

At the end of the last Ice Age, the Laurentide Ice Sheet (see Figs. 1 and 2), which at one time had a thickness of 3 km over Hudson Bay, disintegrated rapidly. Because the ice sheet had been a barrier to normal northward drainage from a large part of North America, a fringe of ice-marginal lakes formed along the southern side of this continental ice sheet. Lake Agassiz was the largest of these lakes (Fig. 1), expanding north as the ice retreated and growing to a size of 841,000 km^2 by about 8400 years B.P. (Teller et al., 2002); this is twice the size of the Caspian Sea which is the largest lake in the modern world. Overflow from Lake Agassiz during the previous 5000 years of its life had been variously routed south through the Mississippi River to the Gulf of Mexico, east into the Great Lakes and St. Lawrence to the North Atlantic Ocean, and northwest through the Athabasca-Mackenzie rivers to the Arctic Ocean (Fig. 1) (Teller et al., 2002; Teller and Leverington, 2004). These routings of overflow had abruptly shifted from one ocean to another, and were preceded by outbursts due to lake-draw down on more than a dozen occasions (Leverington et al., 2000, 2002; Teller and Leverington, 2004). These draw-downs occurred because as the ice margin retreated it periodically uncovered lower-elevation outlets, which resulted in outbursts of 1600-9500 km^3 that lasted for a few months; this is a short-term flux of 0.05-0.03 Sv ($1 \times \mathrm{Sv} = 1\ 10^6\ \mathrm{m^3 s^{-1}}$) (Teller et al., 2002). By 8400 years B.P., Lake Agassiz had reached a size of 841,000 km^2, with a volume of >150,000 km^3 (Teller et al., 2002; Clarke et al., 2003, 2004). Shortly after this, the glacial barrier across Hudson Bay no longer was able to retain the impounded waters of Lake Agassiz, and it drained through Hudson Bay and Hudson Strait to the Labrador Sea (Fig. 3) (Barber et al., 1999). Teller et al. (2002) estimate that Lake Agassiz drained in less than a year. Based on glaciological modelling, Clarke et al. (2004) calculated that this drainage would have taken only about 6 months. This is a flux of about 5 Sv.

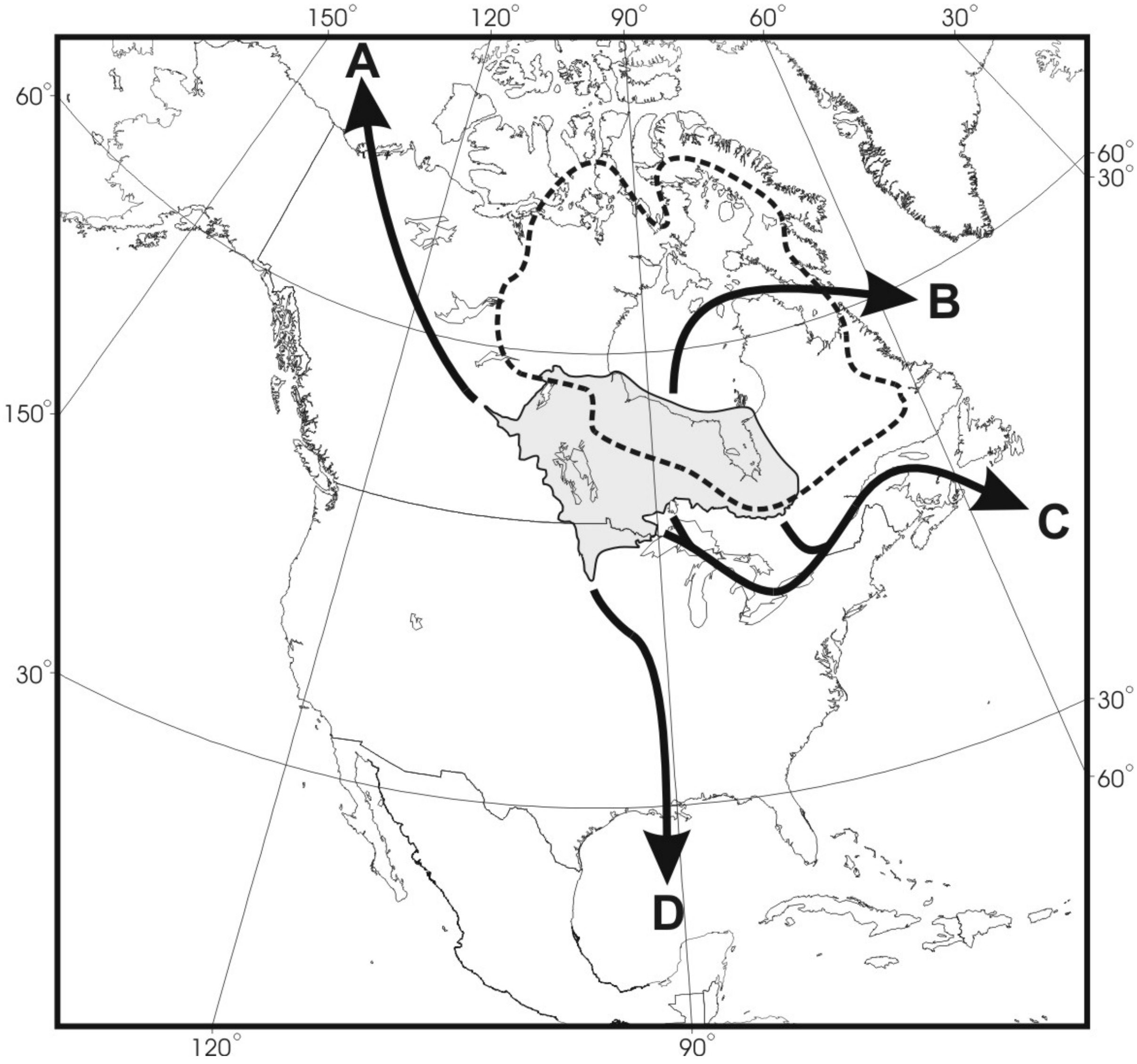


Figure 1: Map showing the total area ever covered by glacial Lake Agassiz (shaded) and the routes of overflow from this lake at various times. A = Mackenzie Valley to Arctic Ocean, B = Hudson Bay to Labrador Sea, C = St. Lawrence Valley to North Atlantic Ocean, D = Mississippi River Valley to Gulf of Mexico. Note that the final drainage of Lake Agassiz occurred along route B at ~8400 yrs B.P. The general outline of the Laurentide Ice Sheet shortly before this at 9000 yrs B.P. is shown by dashed line (Teller et al., 2002, Fig. 1, with permission of Quaternary Science Reviews and Elsevier Ltd.).

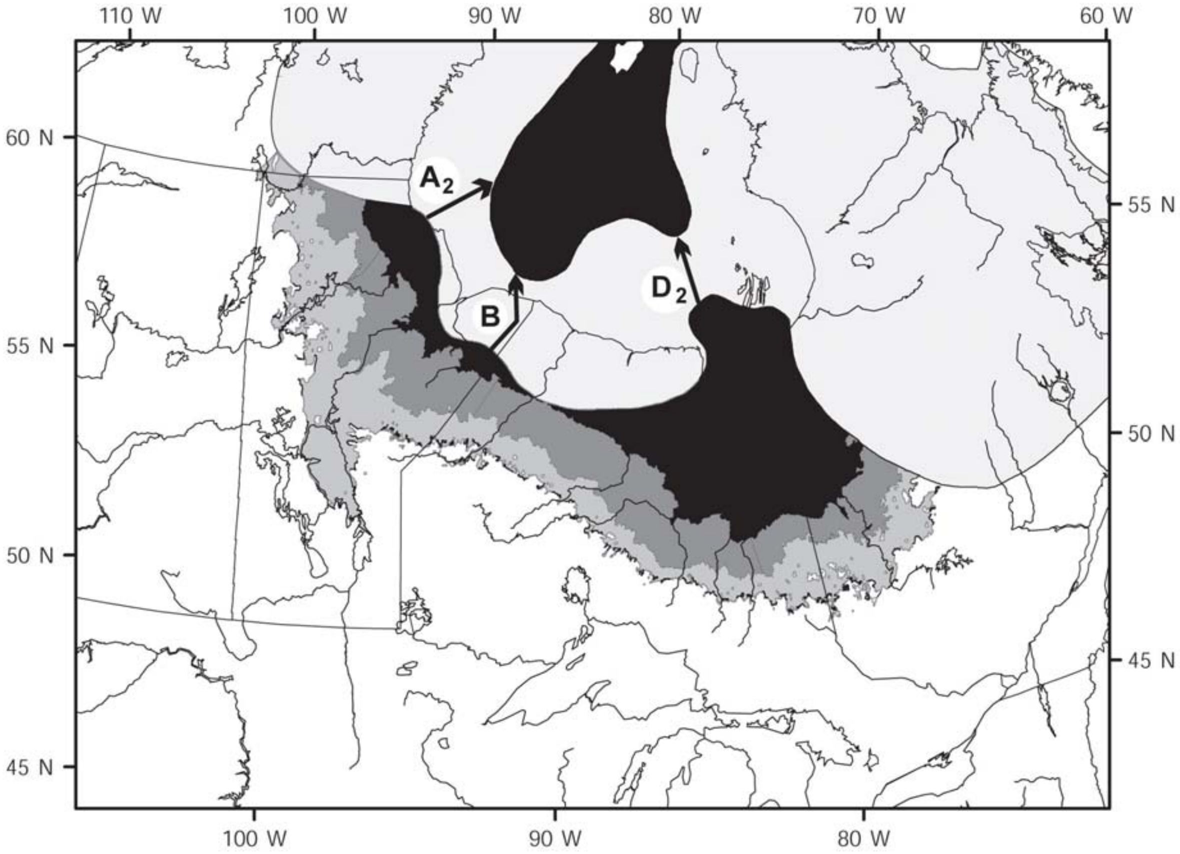


Figure 2. Area covered by Lake Agassiz ~8400 yrs. B.P., showing possible routes into Hudson Bay used by final drainage of lake (A_2, B, D_2), as explained by Clarke et al., (2004). Lightest grey area in northern region is the Laurentide Ice Sheet. Black is the area below sea level (both in Hudson Bay basin and in Lake Agassiz). The two medium grey areas along the southern side of the ice sheet are two areas covered by the lake at two stages during its drainage (Clarke et al., 2004, Fig. 3, with permission of Quaternary Science Reviews and Elsevier Ltd.).

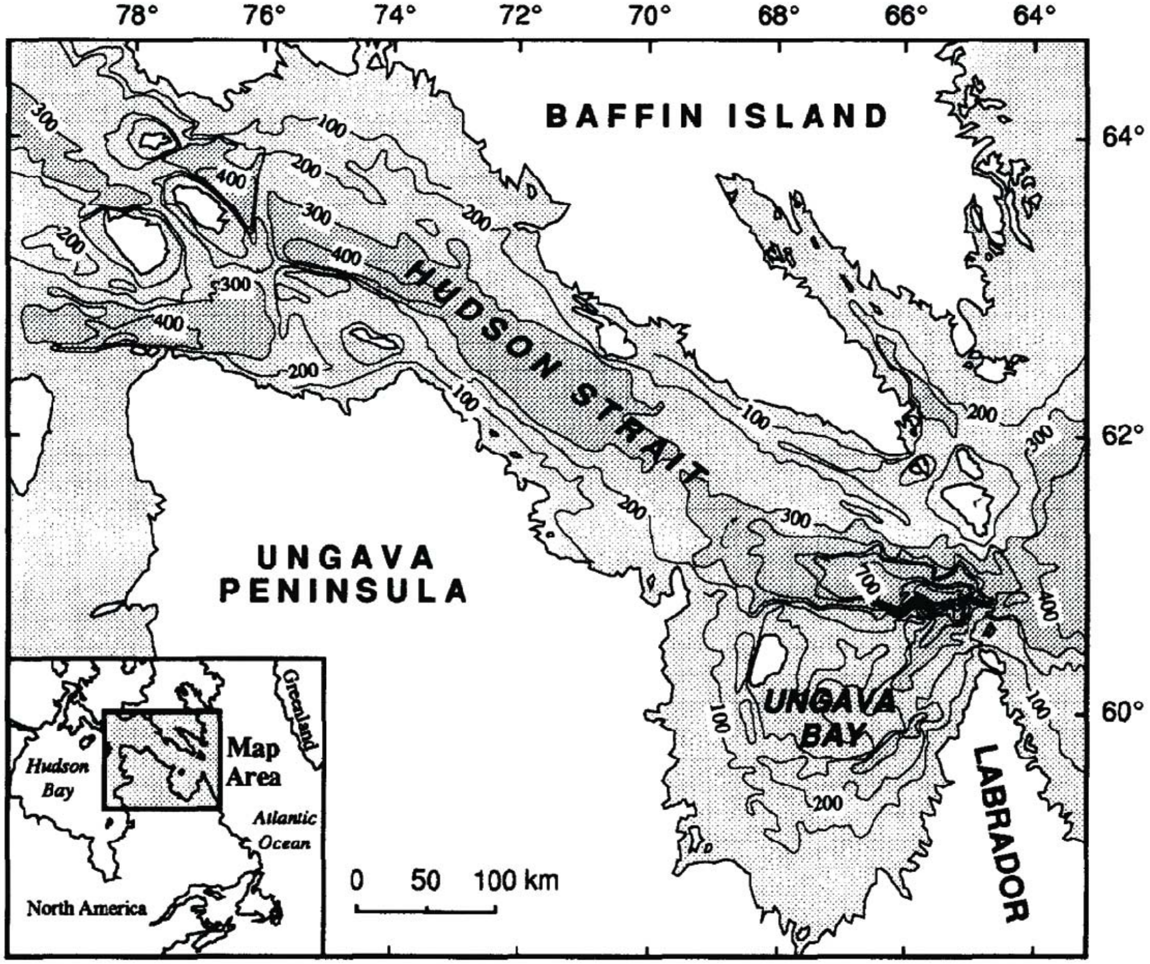


Figure 3. Modern bathymetry of Hudson Strait (Andrews et al., 1995, Fig. 1). Sea level would have been lower, but the land's surface at 8400 yrs. B.P. would have been depressed by isostasy (with permission of Quaternary Science Reviews and Elsevier Ltd.).

3. ESTIMATION OF THE TSUNAMI AMPLITUDE

We used two different methods to estimate the amplitude of a tsunami that could have been generated from the largest outburst (final drainage) from Lake Agassiz, which was about 150,000 km^3. Following Murty (2003), we used the analogy of a submarine landslide as the source for generating a tsunami, where

$$H = 0.3945\ V \qquad (1)$$

H = Amplitude of tsunami in meters
V = Landslide volume that imparts impulsive momentum (millions of cubic meters)

If we take the total volume of water discharged as 150,000 km^3 and take a conservative value of one year duration for the discharge, the rate of discharge works out to be 4.76×10^6 m^3/sec or 4.76 Sv. If we use this value for V in Equation (1) we get,

$H = 1.88$ m

However, submarine landslides usually do not happen in just one second, they take at least 5 to 8 seconds, so V is larger. Because generation of this hyperbolic wave (tsunami) requires an impulsive addition of water, a larger duration will not contribute to this solitary (deep) wave, although it may induce a continuing, shallow, flood wave. For a 5 second duration, we multiply by 5, and H ~ 9.4 m; for an 8 second duration, H ~ 8 x 1.88 = 15 m.

In the second method, we use the analogy for tsunami generation from ocean bottom earthquakes. During the earthquake, a large mound of water instantaneously appears at the ocean surface (above the epicentral area) and this mound of water will then spread, travel, undergo dispersion and scattering (by topography), and ultimately be dissipated.

Using a rough estimate for the cross-sectional area of Hudson Strait and the average depth at its mouth ~8400 years B.P., where the average channel width was ~100 km and the depth was ~0.2 km (Fig. 3), the cross sectional area of a slug of freshwater (A) would have been 2×10^7 m^2. Murty (1979, 2003) designed a formula to estimate the height of a tsunami generated by an earthquake displacing an area of sea floor (A) having a displacive volume of V, where

$$H = \frac{V}{A} \qquad (2)$$

By using this analogy, assuming the triggering duration was 5 seconds, the tsunami amplitude (H) for the 4.76 Sv outburst (V) from Lake Agassiz was:

$V = 4.76$ Sv x 5 seconds $= 23.8 \times 10^6$ m^3, and

from Equation (2) we get

$$H = \frac{23.8 \times 10^6}{2 \times 10^7} = 1.19 \text{ m}$$

If we use an 8 second duration for the earthquake (Agassiz outburst), the tsunami amplitude would be about 3.8 m. If the width of Hudson Strait at its mouth is taken as 50 km instead of 100 km, then the tsunami amplitudes given above would double. If the average depth of freshwater passing through Hudson Strait near its mouth was less than the 200 m used above, then the tsunami amplitude would be greater.

In summary, it is quite likely that the amplitude of the tsunami was not less than 2 m, and could have been 5-10 m or more.

4. DIRECTIONALITY OF THE TSUNAMI ENERGY

Iwasaki (1997) studied the wave forms and the directivity of a tsunami generated by an under-ocean earthquake, as well as by a submarine landslide. He stated that landslide tsunamis show strong directivity as compared to those generated by earthquakes. However, in the quadrant of up to 3π/8 from the axis of Hudson Strait, tsunami directivities are the same whether they are generated by a landslide or an earthquake and, according to the above author, in this quadrant the amplitudes of the first crest and first trough will be about equal in value.

However, for a direction greater than 3π/8, the amplitude of the second crest or trough is somewhere between 1 and 1/5 of the amplitude of the first crest or trough. This means for a direction of 3π/8 (i.e. 67.5°) from the minor axis (perpendicular to the initial major axis of Hudson Strait) the tsunami will dissipate rather quickly and will not travel very far.

The Coriolis Force in the Northern Hemisphere also will give this tsunami a tendency to turn to the right. By doing so, the tsunami will hug the west coast of the Labrador Sea as it travels southward. We estimate that the tsunami will travel southward along the west coast of the Labrador Sea and probably will be dissipated within a distance of about 100 km.

Considering the fact that this tsunami is expected to have an amplitude of at least 2 m, and possibly much greater, and taking into consideration the fact that it hugs the coast as it travels, there is a possibility that tsunami deposits may be found along the coast for up to 100 km.

Figure 4. Location of possible tsunami deposits associated with Lake Agassiz outburst 8400 years ago.

5. GEOLOGICAL RECORDS OF PAST TSUNAMIS

Clearly, a large ocean wave washing up on to the land will impact on the sediment cover along the coast, as well as on life. As shown by the recent tsunami in the Indian Ocean, emanating from Banda Aceh in Indonesia, as well as from other historic tsunamis, erosion and, in turn, deposition are widespread. Fine to coarse debris, at times including boulders, peat masses, trees, uprooted vegetation, and man-made materials, can be moved by the force and runup of a tsunami, and Dawson (1996) summarizes and describes (with photos) some of the changes brought about by tsunamis in historic time, such as those on Hokkaido, Japan (1993), Flores, Indonesia (1992), Lisbon (1775), and Cornwall, England (1755). In the Caribbean, Scheffers (2004) describes extensive rubble ridges, ramparts, and boulder fields deposited up to 12 m above sea level and 400 m inland, which he attributes in part to the historical record of 88 tsunamis in the region since 1489, although some of these deposits probably are related to much older events. Bondevik et al. (2005) describe evidence on the Shetland Islands for three large tsunamis in the North Sea between 8000 and 1500 years ago.

Dawson (1996, 1999), and references therein, elaborates on the nature of tsunami deposits, and Dawson (2000) and Smith et al. (2004) provide particularly informative descriptions of the stratigraphy and extent of paleo-tsunami deposits. Tidal marshes of the west coast of Canada were investigated for evidence of past tsunamis by Clague (1997), Clague et al. (1999), and Clague and Bobrowsky (1994), where the normal sedimentary sequence is interrupted by massive sheets of sand containing marine organisms and vegetal detritus; these deposits are widespread and range from a few millimetres to 0.3 m in thickness. Atwater (1987), Atwater and Moore (1992), and Darienzo and Peterson (1990) find similar sand sheets a kilometre or so inland along the Pacific Northwest of the U.S. that they relate to past tsunamis. Moore and Moore (1984, 1988) describe three sedimentary units – 2, 4, and 2 m thick – deposited during the last interglacial period by successive waves within a tsunami wave train that hit the island of Molokai in Hawaii (see Dawson, 1999). This tsunami is interpreted by Young and Bryant (1992) to have had a 20 m runup and to have eroded large blocks of bedrock as far south as the Australian coast. All these deposits have been attributed to earthquake-generated tsunamis.

In general, the considerable distance inland of coastal sand sheets attributable to paleo-tsunamis distinguishes them from those related to storm surges and hurricanes (Dawson, 1999). In addition, studies of tsunami sheet sand deposits show that they are typically graded upward, from pebbly very coarse sand to finer sand, with an inland decrease in grain size and thickness (e.g. Smith et al., 2004). The discontinuous record of the inland extent of erosion and deposition of past tsunamis make precise estimates of runup uncertain and, in turn, their amplitude imprecise (Dawson, 1999).

In contrast to seismically-induced tsunamis, submarine landslides generate a different type of wave and, therefore, impact somewhat differently on coastal areas. Specifically, tsunamis generated by submarine landslides cannot travel trans-oceanic distances as can earthquake-generated tsunamis, because their wavelengths and periods are much smaller (Murty, 1977). The well-studied Storegga submarine landslide along the Norwegian Sea coast (e.g. Dawson et al., 1988; Dawson et al., 1991; Dawson and Smith, 2000) is estimated to have occurred around 7300 ^{14}C years ago (8150 calendar yrs B.P.) (Bondevik et al., 2003; 2005), although there is a range of dates related to this event between ca. 7800 and 8400 calendar years B.P. (Smith et al., 2004). Deposits left by this tsunami are found at dozens of locations, including 250 borehole sites on the northeastern coast of the U.K., the Shetland Islands, Norway, and Iceland, and Smith et al. (2004) present a summary of the records of the tsunami beds at all these sites. Again, the tsunami deposited widespread sands up to 40 cm thick, in places containing pebbles, cobbles, and boulders as large as 25 cm, and the unit contains marine organisms, eroded peat, vegetation, and clasts ripped-up from coastal sediments; in places, the sand overlies an erosional surface in coastal lowlands and lake basins. The extent of these deposits indicates a wave runup of 10-12 m above sea level in Norway and 20 m on the Shetland Islands (Bondevik et al., 2003, 2005). Henry and Murty (1993) used a two-dimensional finite difference model to simulate the propagation of the tsunami from the Storegga landslide, estimating that the amplitude of the tsunami at the source was 8-12 m, which led to a wave height along the coast of Scotland of 2.4-5.5 m. Harbitz (1992) modelled runup heights of 1-18 m for the northern coast of Scotland, noting that local topographic effects, such as in a narrow embayment, will amplify “open-coast” numbers. Tidal factors are also likely to affect the runup of a tsunami (Smith et al., 2004).

The rough coincidence in time of the Lake Agassiz outburst and the tsunami caused by the Storegga submarine landslide prompts us to ask if that landslide could have been triggered by the Agassiz tsunami – i.e., Lake Agassiz outburst→tsunami→Storegga landslide→tsunami.

6. SUMMARY AND CONCLUSIONS

It is possible that the largest outburst from glacial Lake Agassiz through Hudson Strait into the Labrador Sea ~8400 years B.P. could have generated a tsunami. The total volume of this outburst was >150,000 km^3 and had a flux of ~5 Sv lasting 6-12 months. A field study to locate the possible deposits from this tsunami along the west coast of the Labrador Sea might provide added support for this. While an accurate estimation of the tsunami amplitude is not possible, two different analogies, one based on a submarine landslide and the other on earthquake-displacement of the seafloor, were used to arrive at an approximate value. These analogies suggest that the tsunami amplitude was not less than 2 m and probably was >5 m.

Once the Lake Agassiz outburst flood exited Hudson Strait, we would expect the resultant tsunami to turn south along the Labrador coast due to Coriolis force, just as modern runoff does today (Khatiwala et al., 1999). Although tsunami deposits and erosional features related to this event have not been identified, they are likely to be found for at least 50-100 km south of Hudson Strait, but well above sea level today. The combination of isostatic rebound and the post-glacial rise in sea level mean that the shoreline features along the Labrador coast that formed 8400 years ago now stand 20-50 m above modern sea level; this paleo-shoreline elevation would be closer to +20 m near Hudson Strait (ca. 60° N) and St. John's Newfoundland (ca. 48° N), whereas the ancient shore and its tsunami deposits would lie closer to +50 m in the region between these areas (Dyke, 1996). In addition, the effects of the continuing (6-12 month) outburst of Lake Agassiz (flood wave) along this coast may also be recorded by a scoured zone along the modern inner shelf of the Labrador Sea, or as a residual lag of coarser sediment.

REFERENCES

Andrews, J.T., McLean, B., Kerwin, M., Manley, W., Jennings, A., and Kalls, E. (1995). Final stages of the collapse of the Laurentide Ice Sheet, Hudson Strait, Canada: ^{14}C AMS dates, seismic stratigraphy, and magnetic susceptibility logs. *Quaternary Science Reviews* 14, 983-1004.

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

Atwater, B.F. and Moore, A.L. (1992). A tsunami about 1000 years ago in Puget Sound, Washington: *Science* 258, 1614-1623.

Barber, D.C., A. Dyke, C. Hillaire-Marcel, A.E. Jennings, J.T. Andres, M. W. Kervin, G. Bilodeau, R. McNeely, J. Southen, M.D. Morehead, and J.M. Gagnon (1999). Forcing of the Cold Event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature*, Vol. 400, 344-348.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A., and Lohne, O.(2003). Recordbreaking height for 8000-year-old tsunami in the North Atlantic: EOS, Transactions, *American Geophysical Union*, Vol. 84, No. 31, 289, 293.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A., and Lohne, O. (2005). Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago: *Quaternary Science Reviews* 24, 1757-1775.

Clague, J.J. and Bobrowsky, P.T. (1994). Evidence for a large earthquake and tsunami 100-400 yeas ago on western Vancouver Island, British Columbia. *Quaternary Research* 41, 176-184.

Clague, J.J. (1997): Evidence for large earthquakes at the Cascadia subduction zone: *Rev. Geophysics* 35, 439-460.

Clague, J.J., Hutchinson, I., Mathewes, R.W., and Patterson, R.T. (1999). Evidence for Late Holocene tsunamis at Catala Lake, British Columbia: *Journal of Coastal Research* 15, 45-60.

Clarke, G.K.C., D.W. Leverington, J.T. Teller and A.S. Dyke (2003). Superlakes, megafloods, and abrupt climate change. *Science* 301, 922-923.

Clarke, G.K.C., D.W. Leverington, J.T. Teller, and A.S. Dyke (2004). Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8,200 B.P. cold event, *Quaternary Science Reviews* 213, 289-407.

Darienzo, M.E. and Peterson, C.D. (1990). Episodic tectonic subsidence of Late Holocence salt marches, northern Oregon, central Cascadia margin. *Tectonics* 9, 1-22.

Dawson, A.G., Foster, I.D.L., Shi, S., Smith, D.E., Long, D. (1991). The identification of tsunami deposits in coastal sediment sequences. *Science of Tsunami Hazards*, 9, 73-82.

Dawson, A.G. (1996). The geological significance of tsunamis. *Zeitschrift fur Geomorphologie,* N.F., Suppl. Bd. 102, 199-210.

Dawson, A.G. (1999). Linking tsunami deposits, submarine slides and offshore earthquakes. *Quaternary International* 60, 119-126.

Dawson, S. and Smith, D.E. (2000): The sedimentology of middle Holocene tsunami facies in northern Sutherland, Scotland, UK. *Marine Geology*, 170, 69-79.

Dawson, A.G. (2000). Tsunami deposits. *Pure and Applied Geophysics*, 157, 875-897.

Dyke, A.S. (1996). Preliminary paleogeographic maps of glaciated North America. *Geological Survey of Canada*, Open File 3296.

Greenberg, D.A., T.S. Murty, and A. Ruffman (1993). A numerical model for the Halifax harbour tsunami due to the 1917 explosion, *Marine Geodesy* 16, No. 2, 153-168.

Greenberg, D.A., T.S. Murty, and A. Ruffman (1994). Modelling the tsunami from the 1917 Halifax harbour explosion, *Science of Tsunami hazards* 11, No. 2, 67-80.

Harbiz, C.B. (1992). Model simulatins of tsunamis generated by the Storegga Slides. *Marine Geology* 105, 1-21.

Henry, R.F. and T.S. Murty (1993). Model studies of the effects of the Storegga slide tsunami. *Science of Tsunami Hazards* 10, No. 1, 51-62.

Iwasaki, S.I. (1997). The waveforms and directivity of a tsunami generated by and earthquake and a landslide, *Science of Tsunami Hazards*, 15, No. 1, 23-40.

Kennet, J.P., Cannariato, K.G., Hendy, I.L., Behl, R.J. (2003). Methane hydrates in Quaternary climate change. American Geophysical Union, Washington, 216 p.

Khatiwala, S.P., Fairbanks, R.G., Houghton, R. W. (1999). Freshwater sources to the coastal ocean off northeastern North America: evidence from $H_2{}^{18}O/H_2{}^{16}O$. *Journal Geophysical Research*, 104, C8, 18, 241-18, 255.

Leverington, D.W., Mann, J.D., Teller, J.T. (2000). Changes in the bathymetry and volume of glacial Lake Agassiz between 11,000 and 9300 ^{14}C yr B.P. *Quaternary Research* 54, 174-181.

Leverington, D.W., Mann, J.D., Teller, J.T. (2002). Changes in the bathymetry and volume of glacial Lake Agassiz between 9200 and 7600 ^{14}C yr B.P. *Quaternary Research* 57, 244-252.

Mader, C.L. (2004). Numerical modelling of water waves, second edition, CRC Press, Boca Raton, Florida.

Moore, J.G. and Moore, G.W. (1984). Deposit from a giant wave on the island of Lanai, Hawaii. *Science* 226, 1312-1315.

Moore, G.W., and Moore, J.G., (1988). Large-scale bedforms in boulder gravel produced by giant waves in Hawaii: *In* Sedimentologic Consequences of Convulsive Geologic Events (Clifton, H.E., ed.), *Geological Society of America Special Paper* 229, 101-110.

Murty, T.S., (1977). Seismic Sea waves-Tsunamis, Bulletin number 198, Fisheries Research Board of Canada, Ottawa, 337 Pages

Murty T.S. (1979). Submarine slide-generated water waves in Kitimat Inlet, British Columbia, *Journal of Geophysical Research*, Vol. 84, No. C12, 7777-7779.

Murty, T.S. (2003). Tsunami wave height dependence on landslide volume, *Pure and Applied Geophysics*, 160, 1-7.

Murty T.S., N. Nirupama, I. Nistor and S. Hamdi (2005). Why the Atlantic Generally cannot Generate Trans-Oceanic Tsunamis, Indian Journal of Earthquake Engineering (In Press)

Ruffman, A., D.A. Greenberg and T.S. Murty (1995). The tsunami from the explosion in Halifax harbour. *In* “Ground zero”. 327-344, Ed: A. Ruffman and C.D. Howell, Nimbus Publishing Ltd., Halifax.

Scheffers, A. (2004). Tsunami imprints on the Leeward Netherlands Antilles (Aruba), Curacao, Bonaire) and their relation to other coastal problems: *Quaternary International* 120, 163-172.

Smith, D.E., Shi, S., Cullingford, R., Dawson, A., Dawson, S., Firth, C., Foster, I., Fretwell, P., Haggart, B., Holloway, L., and Long, D. (2004). The Holocene Storegga Slide tsunami in the United Kingdom. *Quaternary Science Reviews* 23, 2291-2321.

Teller, J.T., D.W. Leverington and J.D. Mann (2002). Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation, *Quaternary Science Reviews*, 21, 879-887.

Teller, J.T. and D.W. Leverington (2004). Glacial Lake Agassiz: A 5,000 year history of change and its relationship to the δ^{18}o record of Greenland. *Geological Society of America Bulletin*, 116, 729-742.

Young, R.W., and Bryant, T. (1992). Catastrophic wave erosion on the southeastern coast of Australia: impact of the Lanai tsunami ca. 105 ka? *Geology* 20, 199-202.

TREND OF MICROMETEOROLOGICAL PARAMETERS DURING TSUNAMI ON THE EAST COAST OF INDIA

V.Kanakasabai and M.Rajendran

Department of Civil Engineering, Annamalai University
Annamalainagar-608 002, Tamilnadu, INDIA.
email : vkhdce@yahoo.com, raje69@ yahoo.co.in

ABSTRACT

Tsunami, a large, breaking wave is generated by displacement of seafloor occurring during earthquakes. The Sumatra earthquake of December 26,2004 at 6:28:51 IST generated the deadliest Indian Ocean tsunami causing severe damage along the coast of Indian mainland. The micrometeorological parameters are measured continuously at Portonova on the East coast of India with the help of a 30 m height meteorological tower by the Department of Civil Engineering, Annamalai University. The parameters like wind speed, wind direction, temperature and solar radiation were recorded during the time of Tsunami also, This paper is aimed at processing the data to check whether there are any significant changes in the parameters due to the occurrence of Tsunami. The wind speeds measured at 10m, 17m and 30m heights show a decreasing trend for three days (25th, 26th, 27th December 2004). Likewise the temperature also show a decreasing trend on the day of Tsunami. The solar radiation was steadily increasing without any modulation on that day which was not on the previous day or the next day of Tsunami.

Introduction

Micrometeorology is an intimate study of physical phenomena taking place over limited regions of the surface of the earth and usually within the lowest layers of the atmosphere(Sutton.O.G). Motion of air in the Atmospheric Boundary Layer (ABL) mainly depends on some surface layer parameters like frictional velocity, surface roughness, surface heatflux, Monin-obukov length, etc. These parameters are derived from micrometeorological measurements of wind speed and temperature at different levels; solar radiation; etc. the Department of Civil Engineering, Annamalai University is routinely carrying out such measurements in the coastal town, Portonova, on the East coast of Tamilnadu State, India with a 30m high tower. The data pertaining to these parameters on the day of Tsunami as well as prior and after Tsunami are processed to check whether there are any significant changes in them due to the occurrence of Tsunami.

Study Area

Portonova is situated in Cuddalore district on the East coast of India in 11^{0}30’ N Latitude and 79^{0}45’ E Longitude. The Centre for Advanced Studies in Marine Biology of Annamalai University is located in this place. The coastal line is running straight from NNE to SSW direction. The 30m high meteorological tower is erected at about 750 m from the coast line of Bay of Bengal as depicted in Fig 1.

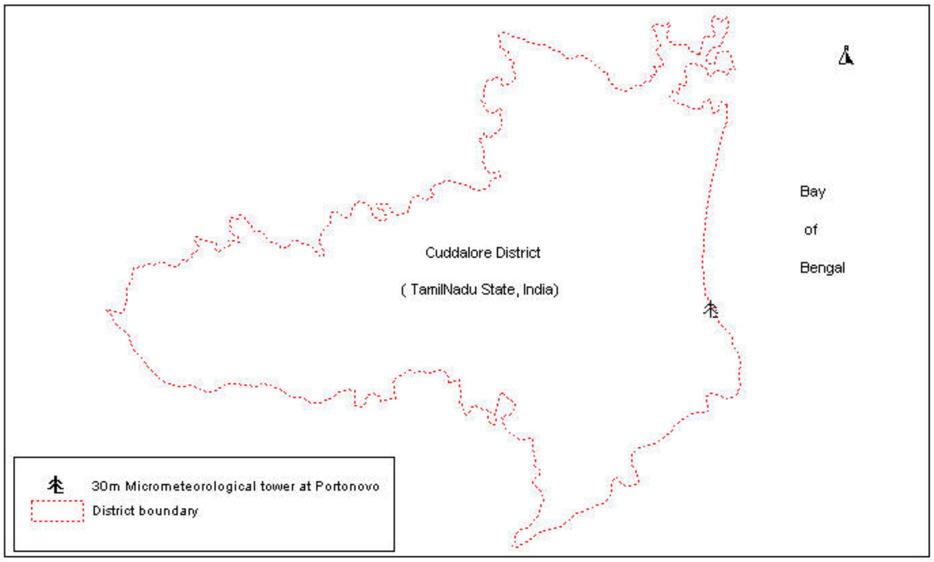


Fig.1 Study Area

Materials and Methods

A 30 m high tower (NRG make, USA) had been erected in the study area for recording micrometeorological parameters to study about ABL near the coast line. The tower was fitted with sensors to measure the mean wind speed and direction at heights of 10 m, 17 m and 30 m above the ground level. Two more sensors measuring temperature and solar radiation were also mounted at 2m height as per the guideline (WMO 1983). The data were continuously logged, retrieved and processed periodically. Wind speed sensors fitted in the tower are 3-cup type anemometers (NRG make #40 type) with measuring range of 1 m/sec to 96 m/sec and accuracy of 0.1 m/sec. Wind direction sensors (#200 series NRG make) used in the experimental system are wind vanes with 1^0 accuracy of measurement . Temperature sensor used in the system is RTD type (NRG make #110s type) with 0.1^0 C accuracy of measurement . For incoming solar radiation measurement (Li-cor # L1-200 SA type) pyronometer is used with the range of measurement as 0 to 3000 W/m^2.

Data logging from these sensors has been carried out by 12 channel data logger (Symphonic type NRG make). This data logger is capable of taking samples at 2 seconds interval and averaging them into 10 minutes. A maximum, minimum and standard deviation are also worked out from this set of readings.

The experimentation for ABL study was initiated during the withdrawal of North East monsoon, that is in December 2004. While continuous measurement was in progress, Tsunami struck the East coast on the morning of 26th December 2004. 5 to 10 m high waves were striking the coast and in fact the tower was surrounded by water for a height of 0.75 m. After two days, the data recorded were transferred for investigation. The data pertaining to wind speed, temperature and solar radiation were given in Tables 1 to 5.

Table 1. Average Wind Speed at 10m height in m/sec.

Time	**24-12-2004**	**25-12-2004**	**26-12-2004**	**27-12-2004**	**28-12-2004**
8:30	5.8	3.0	4.6	3.2	7.8
8:40	5.7	4.8	4.8	3.0	7.6
8:50	6.3	4.2	4.1	3.1	8.0
9:00	5.8	4.5	3.8	3.0	7.9
9:10	7.4	5.6	4.6	3.3	7.5
9:20	7.5	5.9	4.7	3.3	7.9
9:30	6.5	5.9	5.9	4.5	8.0
9:40	7.1	4.5	4.9	5.4	7.3
9:50	7.4	5.3	5.9	4.8	8.0
10:00	7.6	5.2	5.8	4.6	7.2
10:10	7.1	5.6	6.0	4.2	7.2
10:20	7.0	6.7	5.9	3.9	7.5
10:30	7.7	6.5	5.3	3.4	7.6

Table 2. Average Wind Speed at 17m height in m/sec.

Time	24-12-2004	25-12-2004	26-12-2004	27-12-2004	28-12-2004
8:30	6.2	3.0	5.0	3.3	8.9
8:40	6.1	5.1	5.0	3.0	9.0
8:50	6.6	4.4	4.2	3.2	9.1
9:00	6.2	5.0	3.9	3.0	9.1
9:10	8.0	6.1	4.7	3.4	8.5
9:20	8.0	6.3	4.9	3.3	9.0
9:30	7.1	6.5	6.2	4.6	9.2
9:40	7.6	4.8	5.3	5.5	8.3
9:50	7.7	5.6	6.2	5.0	9.0
10:00	8.0	5.6	6.0	4.8	8.2
10:10	7.6	6.1	6.3	4.2	8.2
10:20	7.5	7.1	6.2	3.8	8.3
10:30	8.1	7.2	5.5	3.0	8.3

Table 3. Average Wind Speed at 30m height in m/sec.

Time	24-12-2004	25-12-2004	26-12-2004	27-12-2004	28-12-2004
8:30	6.7	3.6	5.6	3.9	9.4
8:40	6.5	5.4	5.4	3.6	9.4
8:50	7.0	4.8	4.6	3.8	9.7
9:00	6.7	5.4	4.5	3.8	9.5
9:10	8.4	6.6	5.1	3.8	8.7
9:20	8.4	6.8	5.3	3.9	9.4
9:30	7.3	6.9	6.5	5.1	9.5
9:40	8.0	5.4	5.7	5.9	8.6
9:50	8.0	6.1	6.5	5.5	9.3
10:00	8.4	6.0	6.4	5.4	8.6
10:10	7.8	6.4	6.7	4.9	8.6
10:20	7.7	7.7	6.6	4.4	8.6
10:30	8.4	7.6	5.9	3.7	8.8

Table 4. Temperature at 2m height in degree Celsius.

Time	25-12-2004	26-12-2004	27-12-2004
8:30	27.2	26.6	26.0
8:40	28.3	26.9	26.0
8:50	28.4	27.4	26.1
9:00	28.8	27.6	26.3
9:10	29.0	27.5	26.6
9:20	28.5	27.7	26.6
9:30	28.2	27.7	26.9
9:40	28.3	27.8	26.9
9:50	29.2	27.8	26.4
10:00	29.9	27.8	26.0
10:10	29.8	27.8	25.8
10:20	29.6	27.8	25.7
10:30	29.9	28.0	25.6

Table 5. Solar Radiation at 2m height in W/m^2.

Time	25-12-2004	26-12-2004	27-12-2004
8:30	505.2	501.1	132.3
8:40	617.2	531.8	169.9
8:50	581.9	565.2	187.9
9:00	589.1	597.1	231.5
9:10	549.4	626.9	211.1
9:20	249.7	656.5	207.0
9:30	247.2	680.9	243.4
9:40	374.3	705.8	207.6
9:50	777.5	728.6	168.7
10:00	746.0	751.6	142.3
10:10	637.6	770.7	163.6
10:20	744.0	787.6	194.1
10:30	813.0	799.4	161.0

Conclusions

After carefully analyzing the micrometeorological data recorded during Tsunami on the East coast of India, the following conclusions were arrived:

1. The wind speeds measured between 8.30 am and 10.00 am at 10m height were in the range of 5.8 to7.9 m/sec, two days before and after Tsunami. But the wind speed show a decreasing trend of 3.0 to 6.7 m/sec for three days namely the day before Tsunami(25th December 2004) the day of Tsunami (26th December 2004) and the next day after Tsunami(27th December 2004).
2. The same trend was also seen for wind speed measured at 17m and 30m height. The trends depicted in Fig. 2, 3 and 4.
3. The temperature was decreased by one to three degrees on 26th and 27th December 2004. This can be better seen from Fig 5.
4. The solar radiation on 25th and 27th were with variations but on 26th December, it was steadily increasing, indicating that there was no cloud cover on that particular day(Fig 6.).

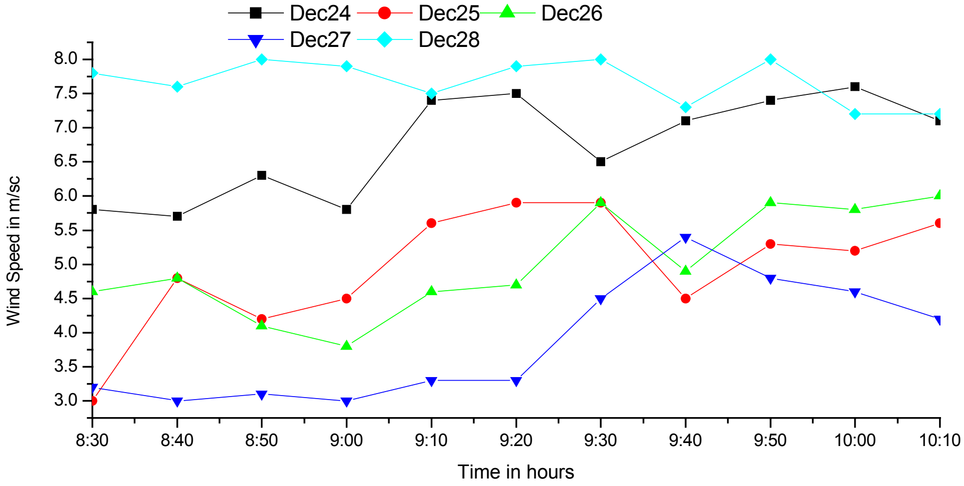


Fig.2 Ten meter Wind Speed Trend

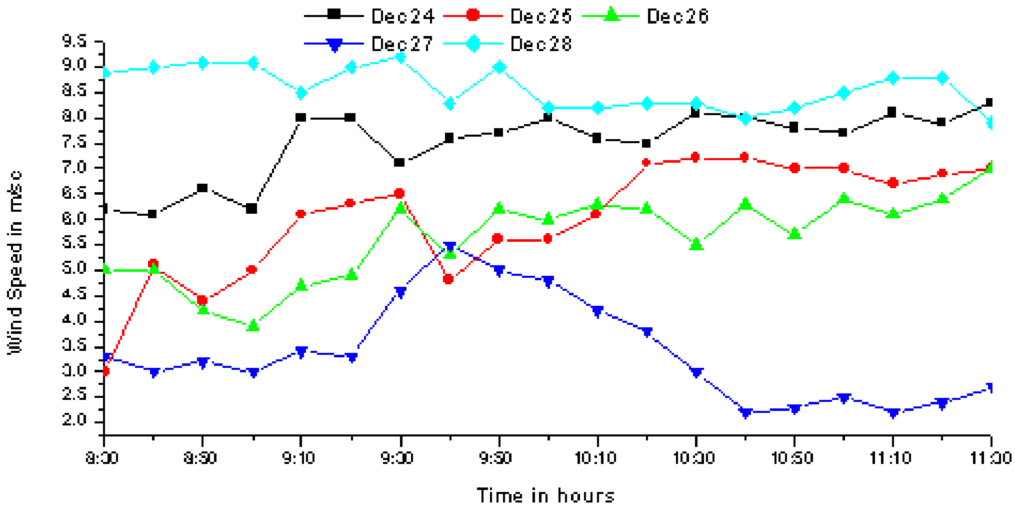


Fig .3 Seventeen metre wind speed Trend

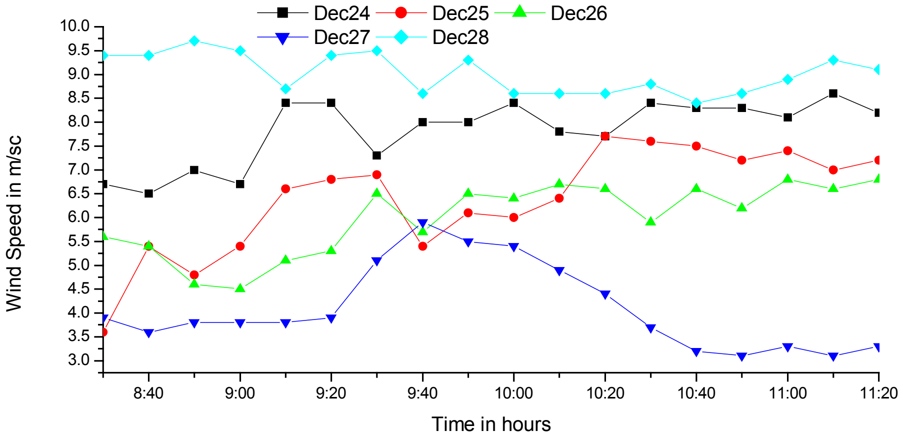


Fig.4 Thirty meter Wind Speed Trend

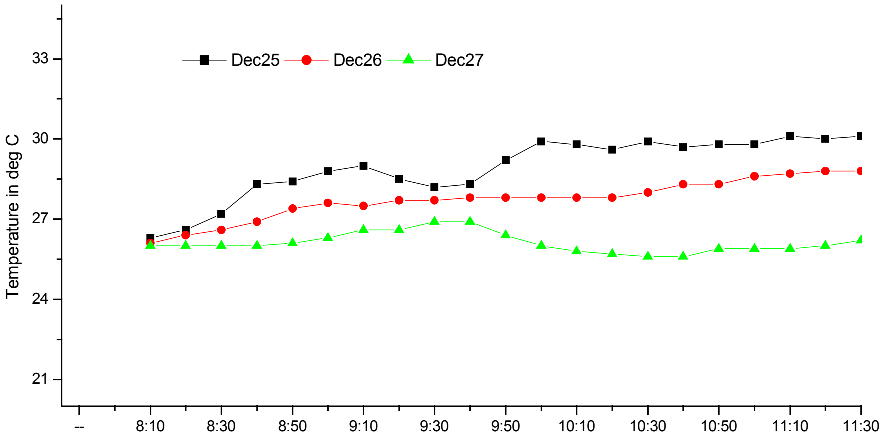


Fig.5 Temperature trend at 2m level

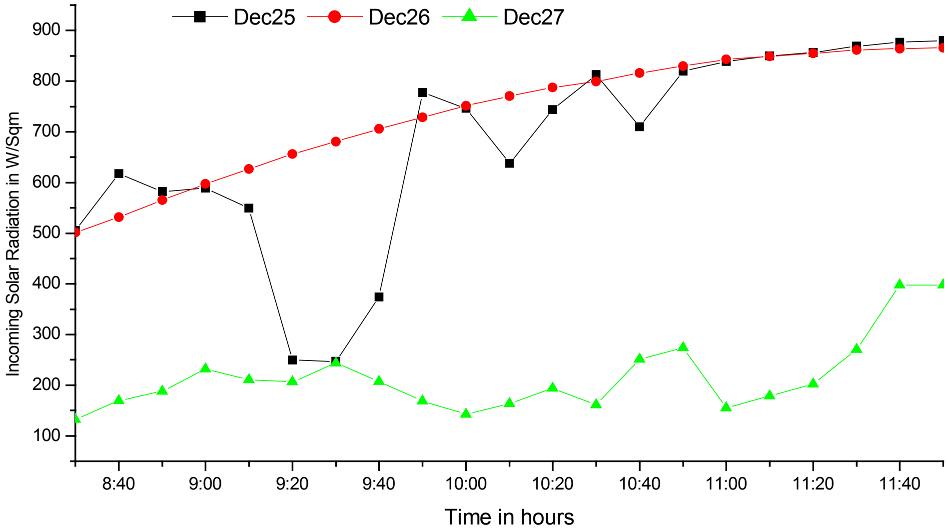


Fig.6 Solar Radiation Trend

Acknowledgements

The authors gratefully thank the University Grants Commission, New Delhi, India for funding the major research project to the Department of Civil Engineering, Annamalai University to carry out the micrometeorological measurement at Portonovo.

References

Sutton O.G. (1953) Micrometeorology. McGraw-Hill Book Company, Inc.
WMO,1983. Guide to Meteorological Instruments and Methods of Observation (Fifth Edition) WMO No.8., Secretariat of the World Meteorological Organization, Geneva, Switzerland.

Boulder Deposits on the Southern Spanish Atlantic Coast: Possible Evidence for the 1755 AD Lisbon Tsunami?

Franziska Whelan [1)]
Dieter Kelletat [2)]

[1)] Department of Physical Geography and Landscape Studies
University of Bamberg
Am Kranen 1, P.O. Box 15 49
D-96045 Bamberg, Germany

e-mail: geowhelan@aol.com

[2)] Department of Geography – Geomorphology and Quaternary Research
University of Duisburg-Essen
Universitätsstr. 15
D-45141 Essen, Germany

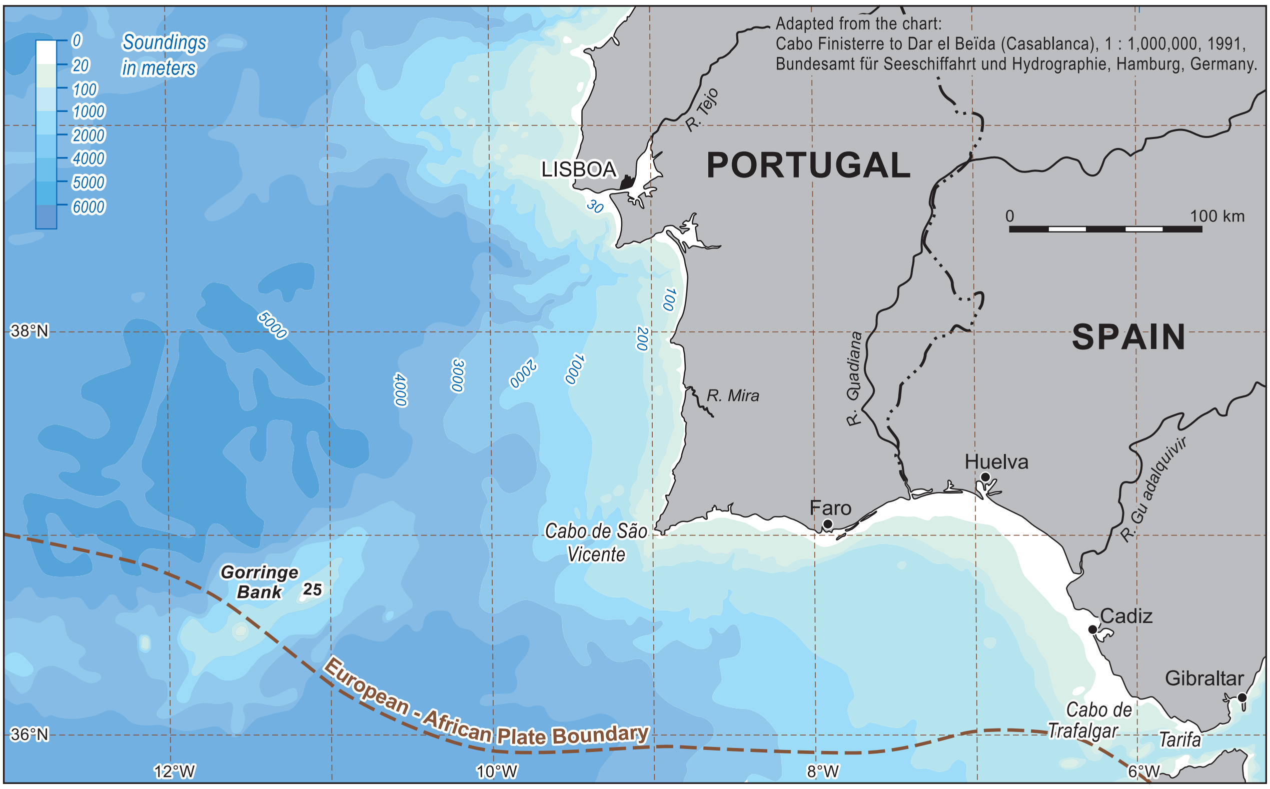
e-mail: dieter.kelletat@uni-essen.de

Abstract

Field evidence of visible tsunami impacts in Europe is scarce. This research focused on an analysis of large littoral debris and accompanying geomorphic features and their relationship to a tsunami event at Cabo de Trafalgar, located on the southern Spanish Atlantic coast. Relative dating of weathering features as well as minor bioconstructive forms in the littoral zone suggest the Lisbon tsunami of 1755 AD as the event responsible for the large deposits described. This tsunami had run up heights of more than 19 m and was generated at the Gorringe Bank, located 500 km west off the Cape. Tsunami deposits at Cabo de Trafalgar are the first boulder deposits identified on the southern Spanish Atlantic coast and are located approximately 250 km southeast of the Algarve coast (Portugal), where other geomorphic evidence for the Lisbon tsunami has been reported.

1. INTRODUCTION

Literature on tsunami deposits along European coastlines is scarce and mostly restricted to individual locations. The few publications on tsunami deposits include the findings of fine sediments in coastal marshes and lakes in Scotland and western Norway deposited by the Storegga tsunami approximately 7200 BP (Dawson *et al.*, 1988; Long *et al.*, 1989; Bondevik *et al.*, 1997; Dawson and Smith, 2000); reports on rounded gravel and sand on the coastlines of the Aegean Sea deposited by the Amorgos tsunami of 1956 (Dominey-Howes, 1996; Dominey-Howes *et al.*, 2000); documentations on sand and cobble deposits at the Algarve coast (Campos, 1991; Andrade, 1992; Dawson *et al.*, 1995; Hindson *et al.*, 1996); or Banerjee *et al.*'s (2001) publication on sand and cobble on the Scilly islands, most likely originating from the Lisbon tsunami in 1755 AD. Heck (1947) and Mastronuzzi and Sanso (2000) described tsunami deposited boulders at the southern Italian coast. Extended boulder ridges, boulder assemblages, and filled bays were observed in western and southwestern Cyprus (Kelletat and Schellmann, 2001, 2002; Whelan and Kelletat, 2002). From Bartel and Kelletat (2003) tsunami boulders from Mallorca island (Spain) have been reported and dated by AMS to about 460 BP and 1400 BP. Kelletat (2005) observed large tsunami boulders broken from beachrock at the southern coast of Turkey, and Scheffers and Kelletat (2005) described and dated tsunami deposits and associated landforms west of Lisbon. This study focuses on newly detected tsunami-deposited boulders at Cabo de Trafalgar, located on the southern Spanish Atlantic coast.



Adapted from the chart:
Cabo Finisterre to Dar el Beïda (Casablanca), 1 : 1,000,000, 1991,
Bundesamt für Seeschiffahrt und Hydrographie, Hamburg, Germany.

Fig. 1 The position of Cabo de Trafalgar in relation to the Gorringe Bank.

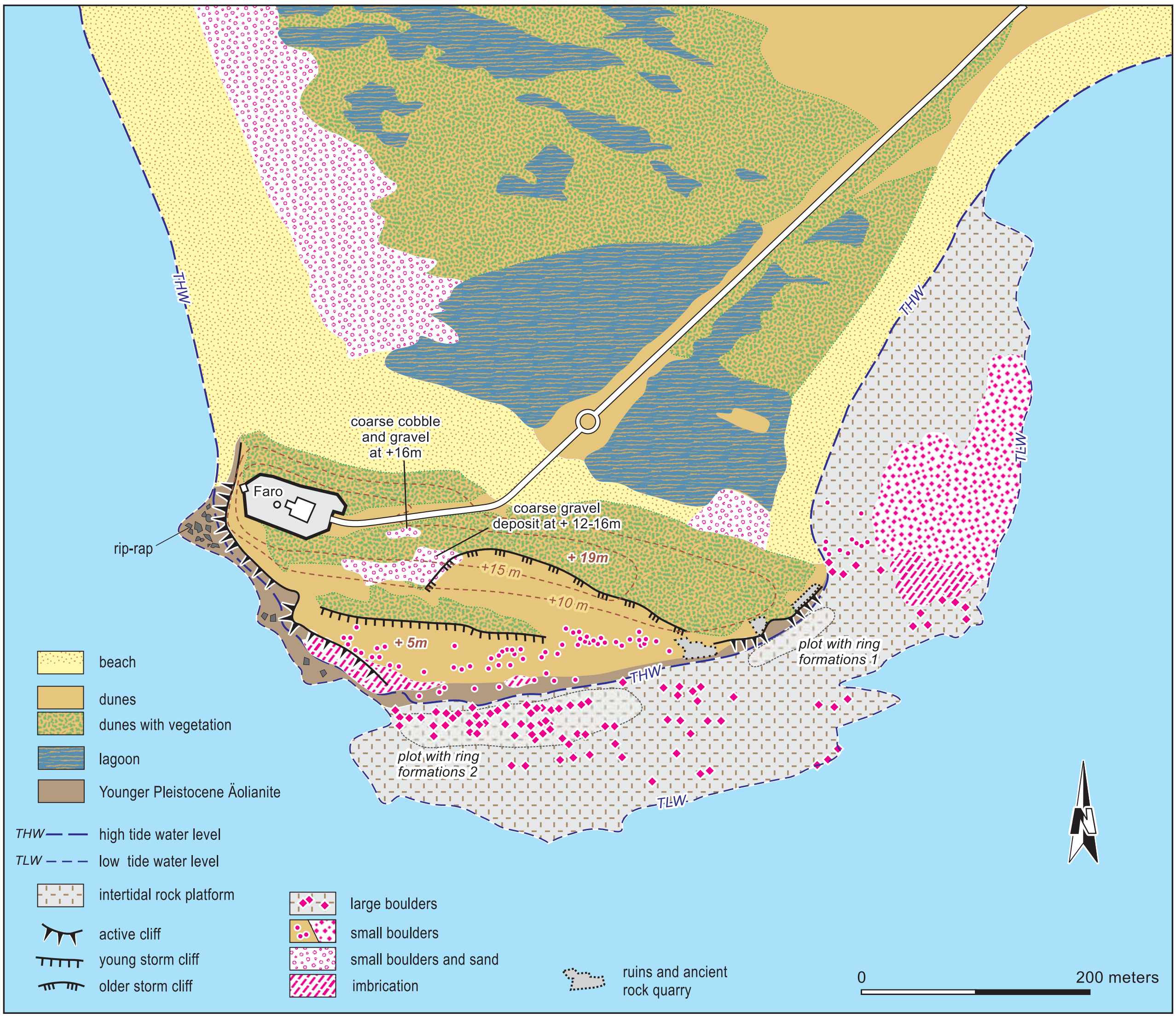


Fig. 2 Sketch of the geomorphologic units of Cabo de Trafalgar.

2. STUDY AREA

Cabo de Trafalgar (Figs. 1 and 2) is a small headland located 36°10´N and 6° W. The centre of Cabo de Trafalgar used to be an elongated (E to W) and isolated island in earlier Holocene times, later connected in the north (Playa de las Plumas) and east (Playa de Mari Sucia) by two beach tombolos, closing a wide and shallow lagoon. This former island was about 500 m long and 200 m wide and nearly 20 m high. Partly mobile dunes cover its relative flat top. The cape is exposed to Atlantic swell and storms, but shallow water extends seaward for several kilometers. Tidal range is about 2.1 m. The former island consists mostly of Young Pleistocene eolianite, resting on a conglomerate (older beach-) platform (Fig. 2). Rather steep cliffs surround the headland, in particular at its exposed western flank. Numerous smaller and very large boulders decorate the coastline in the south and are resting on the intertidal platform, which marks the area of interest.

3. PURPOSE AND METHODS

This study was conducted to analyze the unusually large boulder deposits at Cabo de Trafalgar, their distribution patterns, and the mechanisms likely to be responsible for their transport and deposition. Imbricated boulders with lengths greater than 1 m were analyzed for their kind of setting. All boulders larger than 2 m^3 were mapped using a Global Positioning System (GPS) and were surveyed using supplemental field methods. Measured parameters included length, width, and depth. The orientation of the longest axes, likely transport distances, degree of weathering and encrustations were also analyzed. Potential wave heights for storm or tsunami waves responsible for the boulder transport according to Nott (2003) were calculated. Additionally the spatial pattern of cobble deposits and their characteristic shapes were recorded. Vegetation and soil development as well as anthropogenic features at Cabo de Trafalgar were also observed. All mapping was based on use of a GPS, a 1:5,000 scale topographic map (Instituto de Cartografía de Andalucía, 1997), and a 1:20,000 scale true color aerial photograph (Instituto de Cartografía de Andalucía, 2001).

4. FIELD OBSERVATIONS: MARINE-DEPOSITED DEBRIS

4.1 Spatial patterns of deposits

The large boulders preserved at Cabo de Trafalgar are the only possible proofs for a tsunami event along an approximately 100 km stretch of coastline between the mouth of the Guadalquivir and Punta Camarinal halfway between Barbate and Tarifa. Reasons why geomorphic tsunami evidence or visible deposits have not been preserved along this coastline include extended active beaches and fore dune development, steep and high active cliffs, extended marsh areas, and artificially altered coastlines. Cabo de Trafalgar seems to be the only place susceptible to the preservation of any older geomorphic features along this 100 km long coastal section.

4.2 Large boulders located on the intertidal platform

More than half of the cape is surrounded by a rock platform located to the south and east. This platform is in an intertidal position, and represents the border between the Younger Pleistocene eolianite and a conglomeratic beach deposit at its base (Fig. 2). It is located approximately 1.1 m below mean high tide water level and slightly declines to the south (seaward). The platform extends approximately 80 to 100 m in this direction and ends with a vertical wall, which provides a breaking point for waves during low tide. There is no debris on this platform, with the exception of about 80 large boulders with weights exceeding 10 tons (Fig. 3). Apart from these boulders and some (artificial) ring formations, bioconstructive forms generated by barnacles and vermetids predominate the platform. The barnacles form elongated rims that surround flat water pools (Fig. 4).

Fig. 3 Overview of the boulders on the intertidal platform south of Cabo de Trafalgar during low tide. See person for scale.

Fig. 4 Barnacle rims on the intertidal platform of Cabo de Trafalgar.

Evidently the large boulders have not been moved for a long time. They are not rounded, relatively flat (deriving from the conglomeratic strata) and of irregular shape (Fig. 5). Recent movement can be excluded because of thick incrustations by barnacles and vermetids, which connect the boulders with their basement. No fresh boulders or those without thick barnacle coatings could be found on the platform, even if they do not weigh more than 5 tons. The boulders have been broken off the seaward border of the intertidal platform, which represents a Pleistocene beach layer of limited thickness. This layer is underlain by less resistant rock, which is visible at several notches. Boulder dimensions, volumes and weights (density calculated was 2.5) are listed in Table 1.

Fig. 5
One of the large boulders on the intertidal platform with a weight of approx. 50 tons

The origin of the large boulders from the border of the intertidal platform and their distance moved (20 to more than 200 meters) on this platform is evident. The boulders seem to be moved during the same event, because there is no difference in barnacle coating, bioerosion or other features. Astonishingly no smaller boulders have been thrown on this platform in recent times. Theoretically, they should be stopped in their movement across the platform by the barrier of the large boulders, but this did not occur. The main question is which kind of power has moved boulders of this size: storm waves or tsunami. Evidently during the last decades or even longer no movement has taken place, which excludes storms as an important factor for boulder movement at this site. We used the formulas of Nott (2003) for the physics of boulder movement, in particular equations for the joint bound scenario (because the boulders have been broken off a hard conglomerate stratum) to calculate wave heights. To move 20 ton boulders joint bounded, Nott (2003) has calculated storm wave heights from about 16 m for a cube to more than 40 m for a platy fragment, and to move a boulder of 67 tons (i.e. a cube of 3 m of edge length, with density 2.5) the cubic fragment will require a storm wave height of about 24 m and the platy one close to 50 m, which all can be excluded for any coastline of the world. In contrast, tsunami wave heights values of 4 to 10 m for the 20 ton fragment and up to 12 m for the 67 ton fragment are required. These values, however, are calculated with respect to overturn a boulder, but the Trafalgar boulders have been dragged for 20 to more than 200 m over a rough surface, and some boulders seem to be transported by a swash of water and smashed down, breaking into several pieces. Because of the dense cover of algae and barnacles on the intertidal platform no scratch marks or other features could be found demonstrating a certain kind of boulder movement, but – of course – their existence cannot be excluded. All in all, tsunami run up or wave heights for the Cabo de Trafalgar boulders of 14-16 m are conservative values.

Table 1 Dimensions of the 40 largest boulders from Cabo de Trafalgar.

Length of axes [cm]			**Volume**	**Weight***
a	b	c	[m]	[t]
700	450	150	47.3	118.1
600	500	120	36	90
600	500	100	30	75
600	500	80	24	60
500	430	110	23.7	69.1
500	380	120	22.8	57
450	380	120	20.5	51.3
400	350	120	16.8	42
410	300	115	14.1	35.4
320	260	160	13.3	33.3
400	300	110	13.2	33
450	350	80	12.6	31.5
400	300	100	12	30
400	300	100	12	30
460	360	65	10.8	26.9
450	350	70	10.1	25.2
400	280	90	10.1	25.2
400	250	100	10	25
530	240	75	9.5	23.9
300	300	100	9	22.5
600	200	70	8.4	21
380	360	60	8.2	20.5
400	250	80	8	20
350	200	110	7.7	19.3
300	300	80	7.2	18
350	270	70	6.6	16.5
400	150	100	6	15
400	150	90	5.4	13.5
300	200	90	5.4	13.5
350	220	70	5.4	13.5
280	210	85	5	12.5
280	220	80	4.9	12.3
300	200	80	4.8	12.0
320	200	70	4.5	11.2
250	250	70	4.4	10.9
350	250	50	4.4	10.9
300	200	70	4.2	10.5
350	170	70	4.2	10.5
300	300	45	4.1	10.1
250	200	80	4	10

* density 2.5

The majority of the long axes of the broken-off boulders (N-S) seem to be directed perpendicular to the direction of transport (W-E), however, deviations occur and could be explained by different waves, wave refraction along the platform edges, or transport in suspension rather than rolling over the ground.

4.3 Imbricated boulders

Approximately 280 imbricated boulders weighing between 1 and 10 tons were observed between high tide water level and 5 m above in a coastal stretch of 100 long directly south of the headland. Another approximately 100 imbricated boulders can be found more eastward. Most of these boulders are partially covered with sand (Fig. 6). About 90% are well rounded. Imbrication axes in both areas are determined using the Poser and Hövermann (1952) methodology, showing, that approximately 62% to 72% of all imbricated boulders were aligned perpendicular to the direction of transport (Fig. 7). Another site of well imbricated boulder can be seen on the eastern part of the intertidal platform between high and low water level.

Fig. 6
Imbricated boulders of 1 to 10 tons of weight south of the Trafalgar headland.

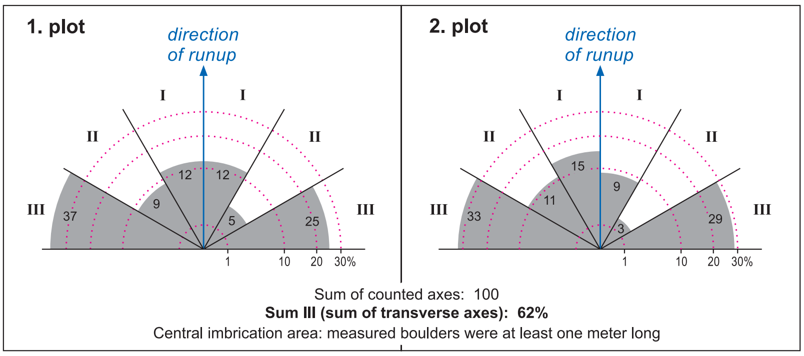


Fig. 7
Direction of axes of two sites with imbricated boulders.

4.4 Cobble deposits on top of the cape

An abundance of well rounded cobbles with diameters exceeding 15 cm were observed near the lighthouse road at ca.15 m asl and close to the roman ruins between 12 and 16 m asl (Fig. 8 and 9). These cobbles are made of Tertiary sandstone and harder strata of the eolianite. On a test plot of 1000 m² at the top of the headland, 51 of 108 cobbles were broken. The percentage of broken cobbles east of the headland at the leeward side of storm or tsunami waves from the west is around 12%. It is important to note that at heights of at least 16 m asl cobbles and even well rounded boulders up to several 100 kg are incorporated in the sand. This forms prove that on top of Cabo de Trafalgar not only dune sand has been deposited but also bimodal sediments with floating boulders and cobbles in the sand were found. As some of the largest floating boulders can be found at the northern (leeward) slope of Cabo Trafalgar, waves at least 19 m high (i.e. the maximum height of Cabo de Trafalgar) would be required for the transport of these boulders.

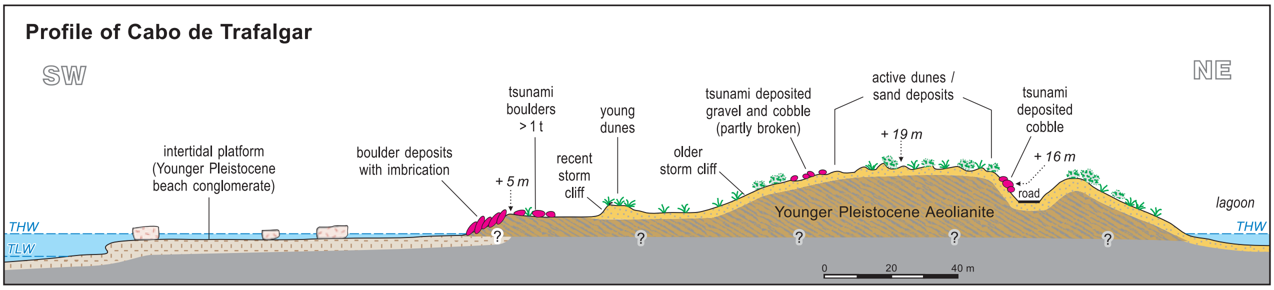


Fig. 8 Distribution of cobbles and large boulders on a profile across Cabo de Trafalgar.

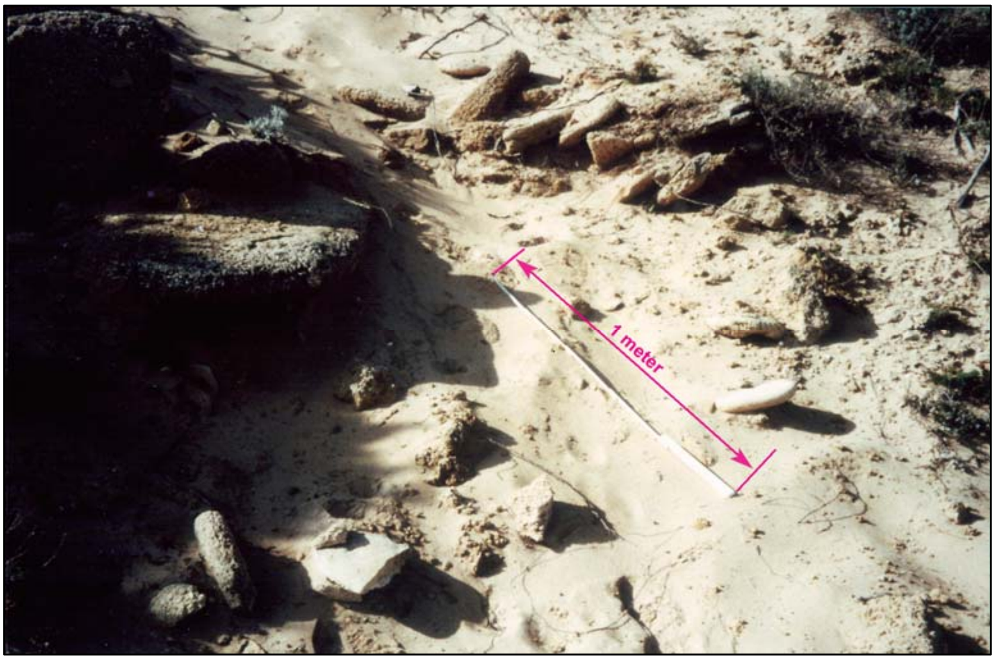


Fig. 9
Well rounded boulders floating in sand on top of Cabo de Trafalgar at 16 m asl.

4.5 Storm versus tsunami deposits

The lighthouse keeper's wife mentioned that a boulder of approximately 50 tons, which appears fresh compared to the intertidal boulders, was deposited in the west in 1989 and broke off a part of the old lighthouse structure. It has been mapped in the rip rap zone in Fig. 2. She was not sure whether extreme storms deposit fresh boulders on the intertidal platform, although waves cross the beaches and lagoonal area north of Cabo de Trafalgar, so that the lighthouse is isolated for some days during winter storms. On the platform, however, there is no evidence for younger boulder deposition or boulder movement: all boulders show the same intensity of barnacle incrustations, no small boulders are piled up against the very large ones, and the boulder assemblage seems to be deposited simultaneously. Fresh boulders with white calcareous algae or *Lithophaga* borings at the landward side of the platform at about high water level may reach weights of not more than 500 kg. These boulders verify that winter storms in this region only have limited capability to transport boulders, most probably because of the shallow water far out into the sea. Even boulders of less than 10 tons will not be moved by storms on the intertidal platform. There are, however, at least two storm marks at the southern slope of the Trafalgar headland (Fig. 2): the higher and older one may reach up to 10 m asl and has cut into older vegetation including some low bushes, and the younger one has only cut a narrow platform in the fore dune, which is scarcely vegetated, at approximately 5 to 5.5 m asl. Both have not rearranged any boulders significantly.

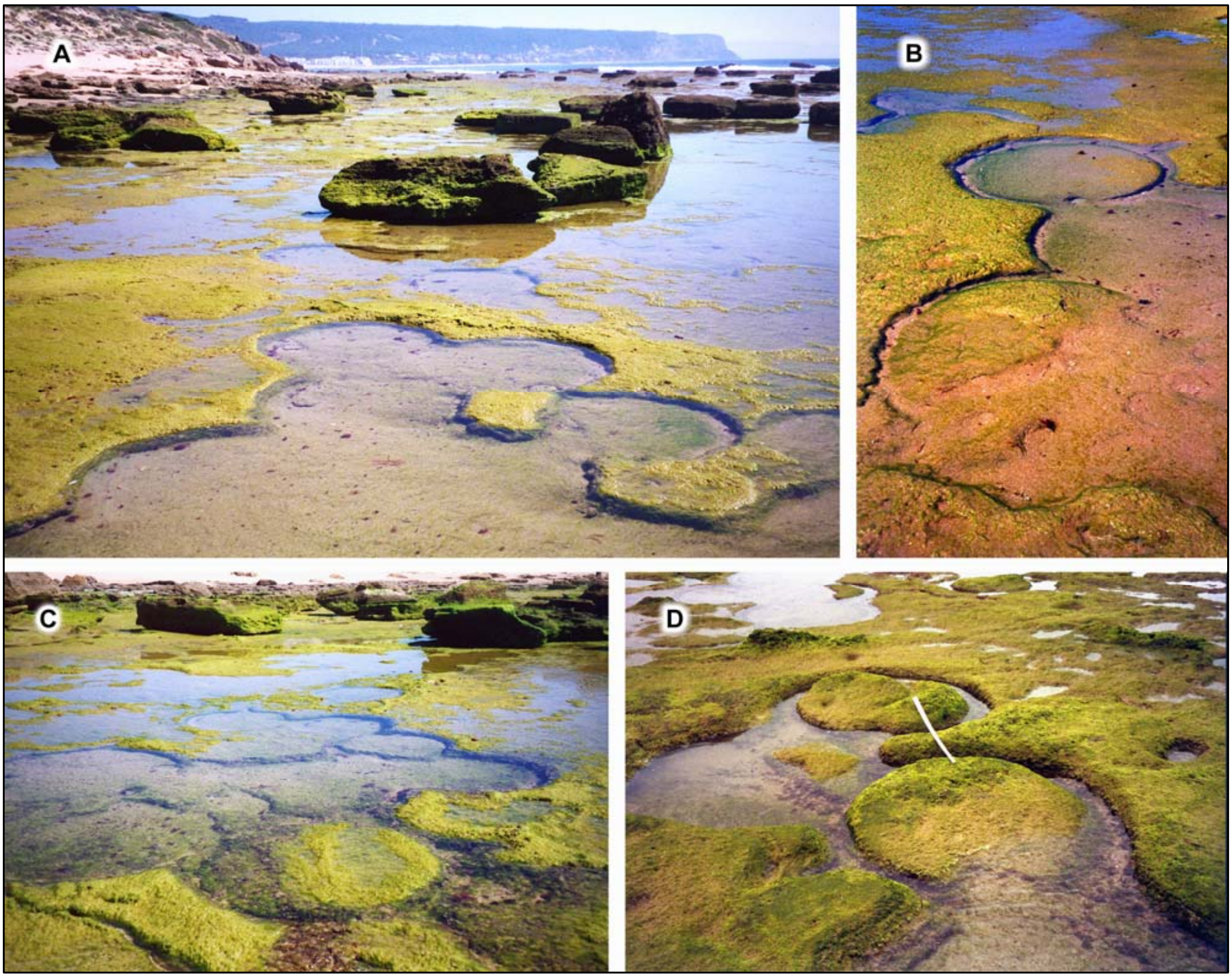


Fig. 10 Ringlike carvings in the conglomerates of the intertidal platform at Cabo de Trafalgar as signs for antique quarrying of column sections.

At the southeastern side of the headland, Roman ruins at about 10 m asl and some low lying quarries can be observed in the eolianite. Without a cross section at the ruined site it is difficult to predict how much this place has been affected by (tsunami) waves in former times. The intertidal platform gives some more evidence of a limited abrasive power of the waves in this region: hundreds of ringlike features (Fig. 10) document, that the hard conglomerate of the intertidal platform was used in antique times as a quarry for column sections, looking like millstones and with diameters of mostly 1.15 m, with a minority of diameters of 0.74 m. The abrasion – although sand, cobbles and boulders are present all along the landward section of the intertidal platform – evidently was not more than some centimeters since antique times.

5. CONCLUSIONS: RELATIVE DATING AND POSSIBLE LINKING WITH THE LISBON EARTHQUAKE AND TSUNAMI IN 1755 AD

Age indicators for the deposition of the boulders are barnacle incrustations (with some vermetids) of many centimeters of thickness, a few signs of bioerosion by gastropods on the limestone parts of the large boulders, a limited soil and vegetation cover on the bimodal sediments with floating boulders on top of the Trafalgar headland, and a deposition of a broad sandy beach in front of the cobble ridge along the beach north of Cabo de Trafalgar (see Fig. 2). At cliffs in eolianite only a few tafoni have been developed by salt weathering. Broken cobbles in the east of the headland as well as on its top show a slight smoothing of former sharp edges by wind abrasion. The well developed and extended barnacle rims on the intertidal platform (Fig. 4) may have developed within many decades or even centuries. These rims have not changed within the last 30 years (*pers. obs.*).

Due to these relative indicators, a correlation of the boulder deposits and the bimodal sediments with floating boulders on the headland as well as the deposition of the cobble ridge in the northern beach to the 1755 AD Lisbon tsunami is a possible conclusion. The epicenter of the earthquake that generated this tsunami was located near the Gorringe Bank, approximately 500 km west of Cabo de Trafalgar (Fig. 1). According to Johnson (1996), a crustal block of 180 to 280 km in length was displaced 10 to 14 m affecting a total area of 800,000 km^2 (Chester, 2001). Based on Moreira (1988), the strongest tectonically induced tsunami in Europe originated from the Gorringe Bank, which is located approximately 200 km to the west of Cabo Sao Vicente (southwestern corner of Portugal). The Gorringe Bank is situated at the Azores-Gibraltar fault zone (Fig. 1), which is the plate boundary between Europe and Africa. Multiple tsunami have been generated in this area, including those in 218/216 BC, 210 BC, 209 BC, 60 BC, 382 AD, 881 AD, 1731 AD, 1755 AD, 1769 AD, and 1969 AD (Moreira, 1988, 1993; Campos, 1991). The 1755 AD earthquake ranked 8.75 to 9.0 on the Richter scale (Campos, 1991; Mader, 2001) and was one of the strongest in human history. The earthquake was felt in Hamburg (Germany), southern England, and North Africa. It generated ripples in lakes all the way up to Finland (Reid, 1914).

Without doubt, the Lisbon earthquake triggered a tsunami of extreme height. However, different run ups have been reported in the literature (Table 2).

Sedimentologic and geomorphologic evidence of the 1755 AD Lisbon tsunami includes sand, pebbles, and cobbles on the Scilly islands and in southern England (Banerjee *et al.*, 2001), and on the Algarve coast in southern Portugal (Hindson *et al.*, 1996; Dawson *et al.*, 1991; Dawson *et al.*, 1995). Andrade (1992) reported the transformation of barrier islands on the Algarve coast, e.g. overwash and channels, generated by the 1755 AD tsunami.

However, there are no sources reporting boulder deposits (>1 t) along the southern Portuguese or Spanish coastline, whereas new investigations found a lot of them west of Lisbon, as well as signatures of run up up to 50 m asl in vegetation scars and datings of older tsunami there (about 2400 BP and 6000 BP(?), see Scheffers and Kelletat, 2005). At Cabo de Trafalgar we could not identify any field evidence of tsunami older than a few centuries. Comparing the run up heights reported for the south coast of the Iberian Peninsula in Table 2, the run up height of a minimum of 19 m asl (i.e. the maximum altitude of Cabo de Trafalgar, which was overrun by waves documented by the large floating boulders) for the Trafalgar area points to an extreme tsunami impact, which may well agree with the tsunami catastrophe of the Lisbon tsunami in 1755.

Table 2 Run up heights of the 1755 AD Lisbon tsunami as reported in the literature

Greater Area	Region	Run up [m]	Source
Portugal	Porto	2	Moreira, 1993
	Lisbon	20	Mader, 2001
		6	Baptista et al., 1999a Kozak &James, 2001 Moreira, 1993
		5-12	Reid, 1914
	Cabo Sao Vicente	30	Moreira, 1988 Kozak &James, 2001
		15	Baptista et al., 1999 a
	Boca do Rio	11-13	Dawson et al., 1995
	Ria de Formosa	12	Moreira, 1993
		9	Andrade, 1992
Spain	Cadiz	11-20	Andrade, 1992
		18-20	Campos, 1991
		>10	Baptista et al., 1999a
		4	Moreira, 1993
	Tarifa	11	Campos, 1991
	Gibraltar	2	Kozak & James, 2001
Morocco	Tanger	10	Baptista et al., 1999b
Madeira		5	Reid, 1914
S-England		3	Reid, 1914
Antillean Islands		>2	Lander & Whiteside, 1997

REFERENCES

Andrade, C., 1992. Tsunami Generated Forms in the Algarve Barrier Islands (South Portugal). Science of Tsunami Hazards, 10 (1), 21-34.

Banerjee, D., Murray, A.S., Foster, J.L.D., 2001. Scilly islands, UK: optical dating of a possible tsunami deposit from the 1755 Lisbon earthquake. Quaternary Science Reviews, 20 (5-9), 715-718.

Baptista, M.A., Heitor, S., Miranda, J.M., Miranda, P., Victor, L.M., 1999a. The 1755 Lisbon tsunami: Evaluation of the tsunami parameters. Journal of Geodynamics, 25 (1-2), 143-157.

Baptista, M.A., Miranda, P.M.A., Miranda, J.M., Victor, L.M., 1999b. Constraints on the source of the 1755 Lisbon tsunami inferred from numerical modelling of historical data on the source of the 1755 Lisbon tsunami. Journal of Geodynamics, 25 (1-2), 159-174.

Bartel, P., Kelletat, D., 2003. Erster Nachweis holozäner Tsunamis im westlichen Mittelmeergebiet (Mallorca, Spanien) mit einem Vergleich von Tsunami- und Sturmwellenwirkung auf Festgesteinsküsten. Berichte Forschungs- und Technologiezentrum Westküste der Universität Kiel, Büsum, 28, 93-107.

Bondevik, S., Svendson, J.I., Johnsen, G., Mangerud, J., Kaland, P.E., 1997. The Storegga tsunami along the Norwegian coast, its age and run up. Boreas, 26 (1), 29-53.

Campos, M.L., 1991. Tsunami hazard on the Spanish coast of the Iberian Peninsula. Science of Tsunami Hazards, 9 (1), 83-90.

Chester, D.K., 2001. The 1755 Lisbon earthquake. Progress in Physical Geography, 25 (3), 363-383.

Dawson, A.G., Long, D., Smith, D.E., 1988. The Storegga Slide: evidence from eastern Scotland for a possible tsunami. Marine Geology, 82: 271-276.

Dawson, A.G., Smith, D.E., 2000. The sedimentology of Middle Holocene tsunami facies in northern Sutherland, Scotland, UK. Marine Geology, 170: 69-79.

Dawson, A.G., Foster, I.D.L., Shi, S., Smith, D.E., Long, D., 1991. The identification of tsunami deposits in coastal sediment sequences. Science of Tsunami Hazards, 9 (1), 73-82.

Dawson, A-G., Hindson, R.A., Andrade, C., Freitas, C., Parish, R., Bateman, M., 1995. Tsunami sedimentation associated with the Lisbon earthquake of 1 November AD 1755: Boca del Rio, Algarve, Portugal. The Holocene, 5 (2), 209-215.

Dominey-Howes, D.T.M., 1996. The Geomorphology and Sedimentology of Five Tsunamis in the Aegean Sea Region, Greece. Thesis, University of Coventry, UK, 272 pp.

Dominey-Howes, D., Cundry, A., Crudace, I., 2000. High energy flood deposits on Astypalaea Island, Greece: possible evidence for the AD 1956 southern Aegean tsunami. Marine Geology, 163: 303-315.

Heck, N.H., 1947. List of Seismic Sea Waves. Bulletin of the Seismological Society of America, 37 (4), 269-286.

Hindson, R.A., Andrade, C., Dawson, A.G., 1996. Sedimentary Processes Associated with the Tsunami Generated by the 1755 Lisbon Earthquake on the Algarve Coast, Portugal. Physics and Chemistry of the Earth, 21 (12), 57-63.

Istituto de Cartografía de Andalucía, 1997. Mapa topografico de Andalucía 1: 5,000. Menendez Pelayo 42-44, Sevilla, Spain.

Istituto de Cartografía de Andalucía, 2001. 1: 20,000 true color aerial photograph acquired on 2001. Patio de Banderas 14, Sevilla, Spain.

Johnston, A.C., 1996. Seismic moment assessment of earthquakes in stable continental regions. 3. New Madrid 1811-1812, Charleston 1886 and Lisbon 1755. Geophysical Journal International, 126 (2), 314-344.

Kelletat, D., 2005. Neue Beobachtungen zu Paläo-Tsunami im Mittelmeergebiet: Mallorca und Bucht von Alanya, türkische Südküste. AMK 05, Schriften des Arbeitskreises Landes- und Volkskunde (ALV), Koblenz (in press).

Kelletat, D., Schellmann, G., 2001. Sedimentologische und geomorphologische Belege starker Tsunami-Ereignisse jung-historischer Zeitstellung im Westen und Südosten Zyperns. Essener Geographische Arbeiten, 32: 1-74.

Kelletat, D., Schellmann, G., 2002. Tsunamis on Cyprus: Field Evidences and 14C-Dating Results. Zeitschrift für Geomorphologie, NF 46 (1), 19-34.

Kozak, J.T., James, Ch. D., 2001. Historical Depictions of the 1755 Lisbon Earthquake. NISEE National Information Service for earthquake Engineering, University of california, Berkeley, URL: http://nisee.berkeley.edu/lisbon/

Lander, J.F., Whiteside, L.S., 1997. Caribbean Tsunamis: An Initial History. Tsunami Workshop, June 11-13, Mayaguez, Puerto Rico. URL: http://www.cima.uprm.edu/~tsunami/Lander/J_Lander.html.

Long, D., Smith, D.E., Dawson, A.G., 1989. A Holocene tsunami deposit in eastern Scotland. Journal of Quaternary Science, 4, 61-66.

Mader, C.L., 2001. Modelling the 1755 Lisbon tsunami. Science of Tsunami Hazards, 19 (2), 93-98.

Mastronuzzi, G., Sanso, P., 2000. Boulder transport by catastrophic waves along the Ionaian coast of Apulia (southern Italy). Marine Geology, 170: 93-103.

Moreira, V.S., 1988. Historical Tsunamis in the European Area. Science of Tsunami Hazards, 6 : 37-42.

Moreira, V.S., 1993. Historiocal tsunamis in maland Portugal and Azores – Case Histories. in: Tinti, S., ed., Tsunamis in the world. Dordrecht, Kluwer Publishers, 65-73.

Nott, J., 2003. Waves, coastal boulders and the importance of the pre-transport setting. Earth and Planetary Science Letters, 210: 269-276.

Poser, H., Hövermann, J., 1952. Beiträge zur morphometrischen und morphologischen Schotteranalyse. Abhandlungen Braunschweigische Wissenschaftliche Gesellschaft, IV: 12-36.

Reid, H.F., 1914. The Lisbon earthquake of November 1, 1755. Bulletin of the Seismological Society of America, IV (2), 53-80.

Scheffers, A., Kelletat, D., 2005. Tsunami Relics in the Coastal Landscape West of Lisbon, Portugal. Science of Tsunami Hazards, 23 (1), 3-16.

Whelan, F., Kelletat. D., 2002. Geomorphic Evidence and Relative and Absolute Dating Results for Tsunami Events on Cyprus. Science of Tsunami Hazards, 20 (1), 3-18.

CONCEPTUAL DIFFERENCES BETWEEN THE PACIFIC, ATLANTIC AND ARCTIC TSUNAMI WARNING SYSTEMS FOR CANADA

T.S. Murty[1], N. Nirupama[2], I. Nistor[1] and A.D. Rao[3]

[1] Civil Engineering Department, University of Ottawa, Ottawa, Canada
[2] Atkinson Faculty of Liberal & Professional Studies, York University, Toronto, Canada
[3] Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi, India

ABSTRACT

Canada has coastlines on three of the four oceans on the globe, namely, the Pacific, Atlantic and Arctic oceans. The Pacific and Atlantic oceans are connected to the Arctic Ocean in the north, but still they are three distinct oceans, and need three individual tsunami warning systems. Tsunamis in the Arctic Ocean are not as well documented as in the Pacific and Atlantic oceans. From what is known, tsunamis in the Arctic Ocean are rare and probably are small in amplitude. Because of very low population density, around the Canadian Arctic, at present, there is no priority for a tsunami warning system for Arctic Canada. For the Pacific Ocean, a tsunami warning system is in existence since 1948. In at least one sense, the warning aspects of the tsunami warning system for the Pacific coast of Canada, is relatively simple and straight forward, because it involves only the federal government (PSEPC) and the provincial government of British Columbia (PEP). For the Atlantic Ocean, A tsunami warning system is now being established. The warning aspects will be some what more complex for eastern Canada, since it not only involves the federal government, but also five provinces, namely, Newfoundland and Labrador, Nova Scotia, New Brunswick, Prince Edward Island and Quebec. The Alaska tsunami warning center (ATWC) in Palmer, Alaska, provides tsunami warnings for both Pacific and Atlantic Canada.

1. INTRODUCTION

Canada is bordered by three oceans (figure 1), namely the Pacific to its west, the Atlantic to its east, the Arctic to its north and the USA to its south. The Pacific and Atlantic oceans, more or less stretch from the high latitudes of the southern hemisphere to the high latitudes of the northern hemisphere, whereas the Arctic Ocean lies only in the high latitudes of the northern hemisphere.. In principle, Canada needs three separate tsunami warning systems, because, tsunami characteristics are quite different in these three oceans. Moreover, for a tsunami warning system to function effectively in real time, all the nations bordering a given ocean, should share seismic and tsunami data in real time, which calls cooperation through various protocols. The only operational tsunami warning system, at present, namely the Pacific tsunami warning system is in existence since 1948 and is being coordinated since 1965 by the I.O.C. (Inter-governmental Oceanographic Commission) of UNESCO in Paris. It is expected that IOC will also be coordinating the Atlantic Ocean tsunami warning system and the Indian Ocean tsunami warning system, that are being established at present, in addition to some regional tsunami warning systems, such as for the Caribbean and Mediterranean seas.

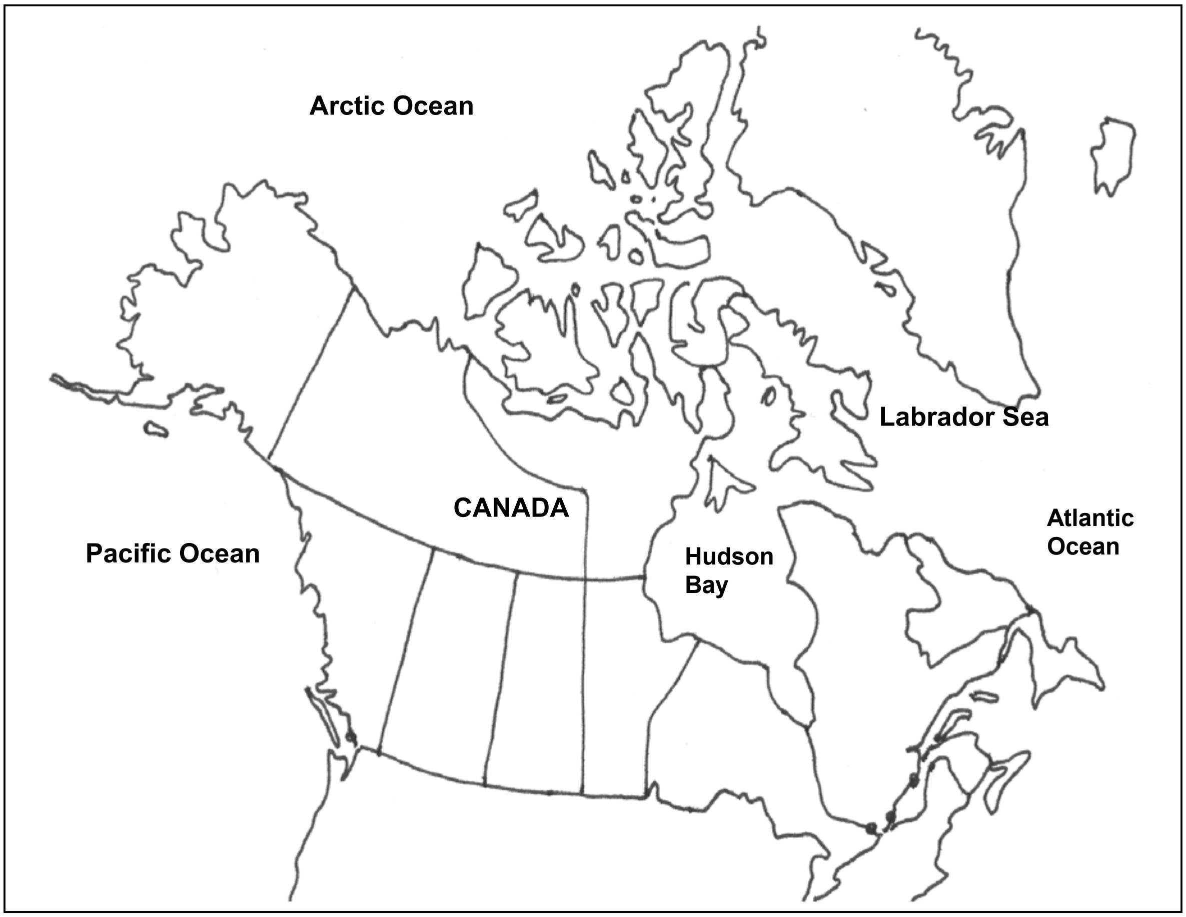


Figure 1: Canada’s coastlines with Pacific, Atlantic, and Arctic oceans

1. TSUNAMI WARNING SYSTEM FOR ARCTIC CANADA

Figure 2 shows the earthquake distribution in Canada. Tsunamis in the Arctic Ocean are poorly documented and there are no reports of major ocean-wide tsunamis in historical time in the Arctic. What little evidence is there, seem to suggest that tsunami amplitudes in the Arctic Ocean probably will be small (Murty, 1977).

The following nations border the Arctic Ocean: Canada, USA (Alaska), Baffin Island, Greenland, Norway, and Russia (Siberia). In principle, all these nations should cooperate under the auspices of the IOC and share seismological and oceanographical data in real time, for an efficient tsunami warning system to function. Since the density of population around the rim of the Arctic Ocean is low at present, there is neither an incentive, nor any priority for an Arctic Ocean tsunami warning system.

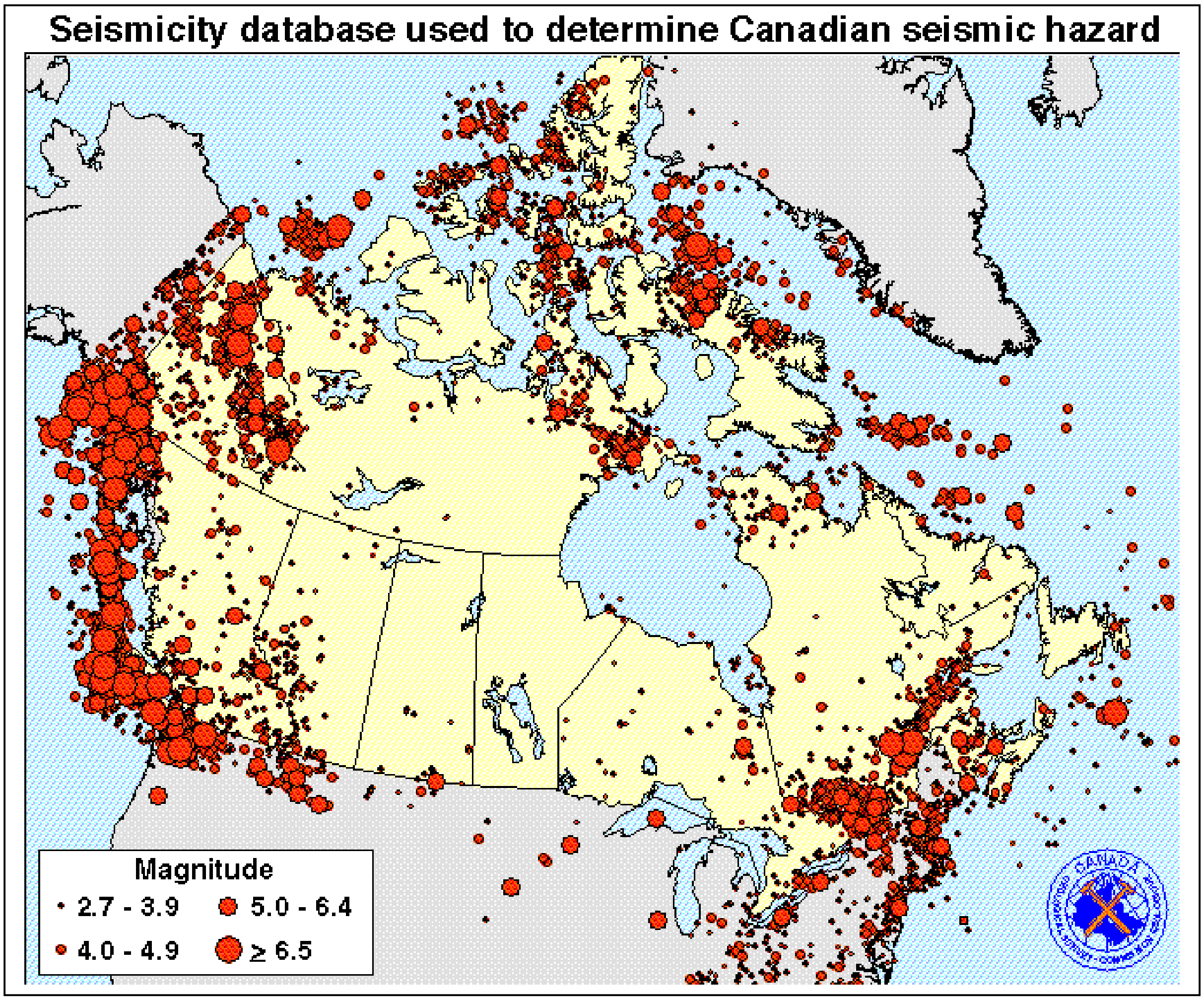


Figure 2: Earthquake distribution in Canada (http://www.civil.bcit.ca/courses/4167/unit1_02.htm#seiz_BC)

2. TSUNAMI WARNING SYSTEM FOR PACIFIC CANADA

Figure 3 shows the major tectonic plates in the world and Figure 4 shows the tectonic faults in western Canada. Following the disastrous Aleutian earthquake tsunami of 1 April 1946, the USA established the Pacific tsunami warning center (PTWC) in Ewa Beach on Oahu Island of Hawaii. In 1965 the IOC started coordinating the activities of the Pacific tsunami warning system for some 26 nations around the rim of the Pacific Ocean, including Canada.

After the disastrous Alaska earthquake tsunami of 28 March 1964, the USA established the Alaska tsunami warning center (ATWC) in Palmer, Alaska, in 1967. The Pacific coast of Canada receives tsunami warning from the Palmer center.

In terms of logistics, the warning aspects of this system for Canada are relatively straightforward, as it involves only the federal government, through the PSEPC (Public Safety & Emergency Preparedness, Canada) and only the provincial government of British Columbia, through the PEP (Provincial Emergency Program).

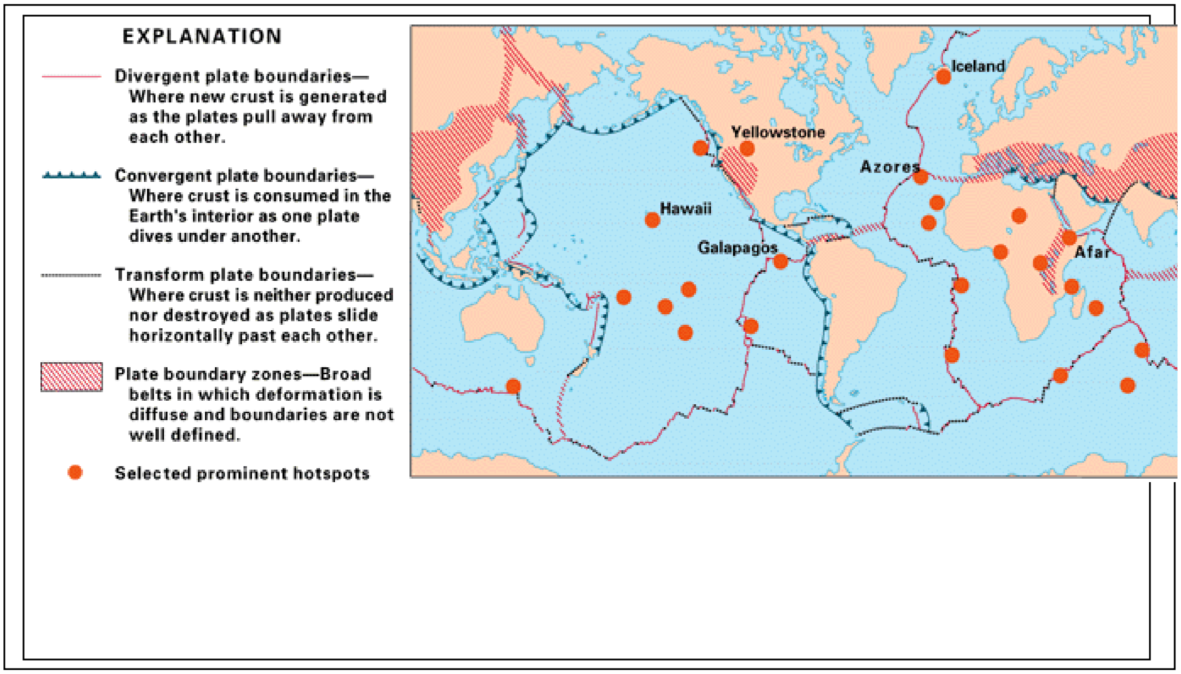


Figure 3: Major tectonic plates on the globe (Source: http://pubs.usgs.gov/publications/text/world_map.html)

In terms of scientific issues, it may be noted that, during the Alaska earthquake tsunami of March 1964, outside of Alaska, the greatest tsunami amplitude occurred, not at the open coast, but at Port Alberni, located at the head of the Alberni inlet, on Vancouver Island. Murty (1977) showed that, the tsunami from the Pacific Ocean, with amplitude of about 0.5 m was amplified to 5.2 m at Port Alberni through quarter wave resonance.

While it is somewhat unlikely that the Alberni inlet can amplify tsunamis coming from the south Pacific (for example, the Chilean earthquake tsunami of 22 May 1960), its geographical orientation and geometry is such that, it can magnify tsunamis from Alaska and the Aleutians.

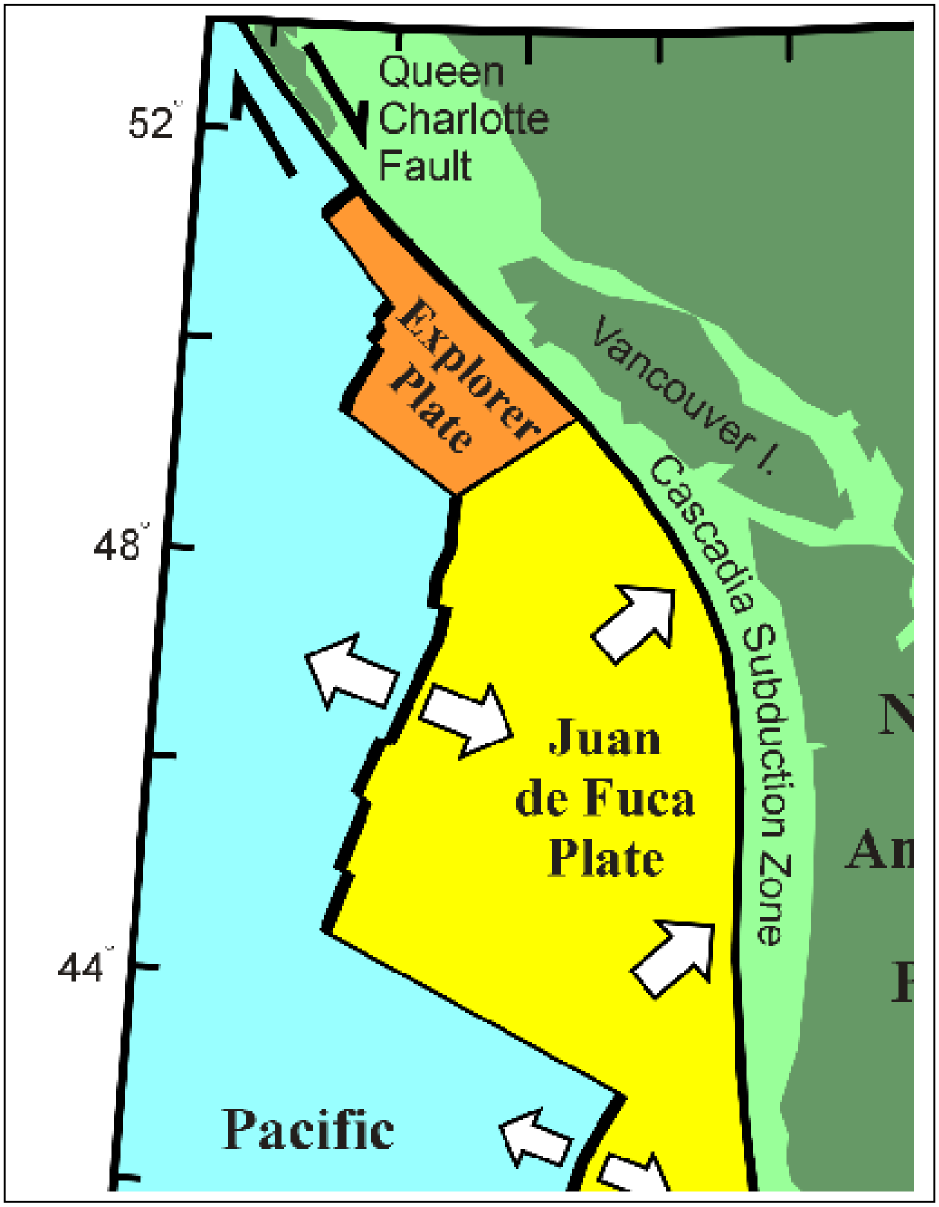


Figure 4: Western Canada tectonic faults in the Pacific Ocean (http://www.civil.bcit.ca/courses/4167/unit1_02.htm#seiz_BC)

3. TSUNAMI WARNING SYSTEM FOR EASTERN CANADA

Figure 5 shows that Atlantic Ocean and the mid-Atlantic ridge, which is a divergent plate boundary, and hence does not give rise to tsunamigenic earthquakes. Usually there are no ocean-wide tsunamis in the Atlantic, and most tsunamis are local, for example, the Caribbean Sea. The Lisbon earthquake tsunami of 1755 was supposed to have had several meters of amplitude in the Caribbean, but was not significant in the western Atlantic.

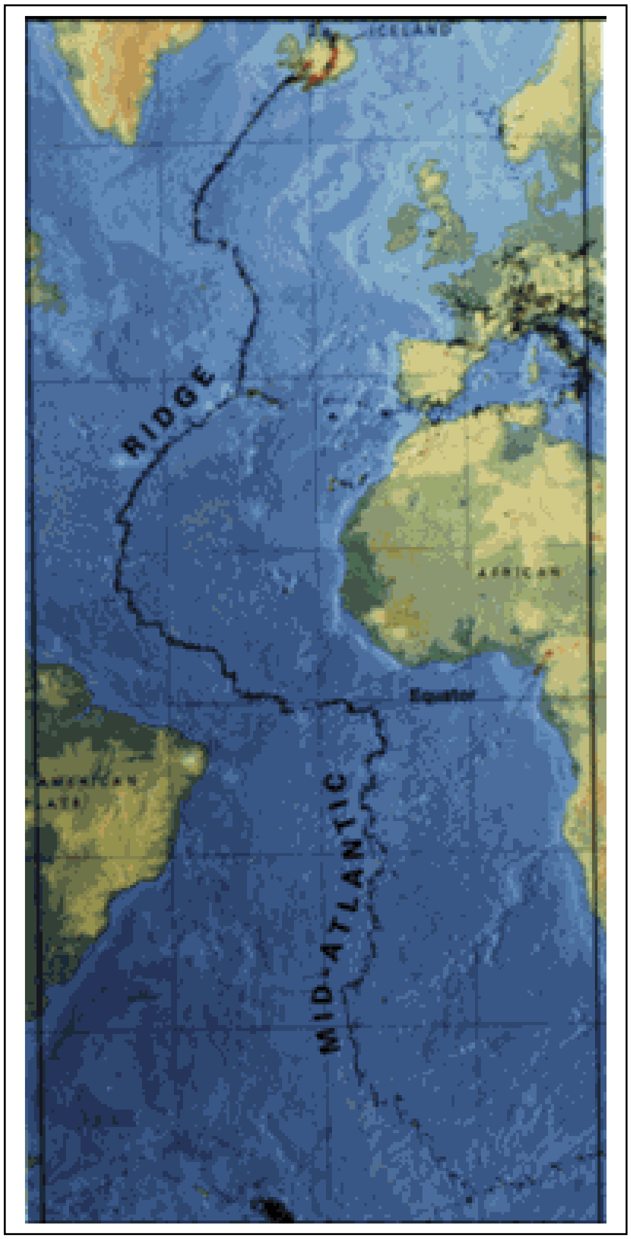


Figure 5: Atlantic Ocean and mid-Atlantic Ridge

We will briefly discuss three tsunamis that were generated in Canada and impacted mostly Canada only. In addition we well briefly mention the tsunami potential in the St. Lawrence estuary. Figure 6 shows the travel time contours of the Grand Banks earthquake tsunami of 18 November 1929 that was reported to have killed 28 people. Quarter wave resonance amplification played a major role in amplifying the tsunami in some of the bays and gulfs on the south coast of Newfoundland. It can be seen from Figure 6 that the tsunami energy could not propagate towards Nova Scotia, mainly because of extensive sand banks in between.

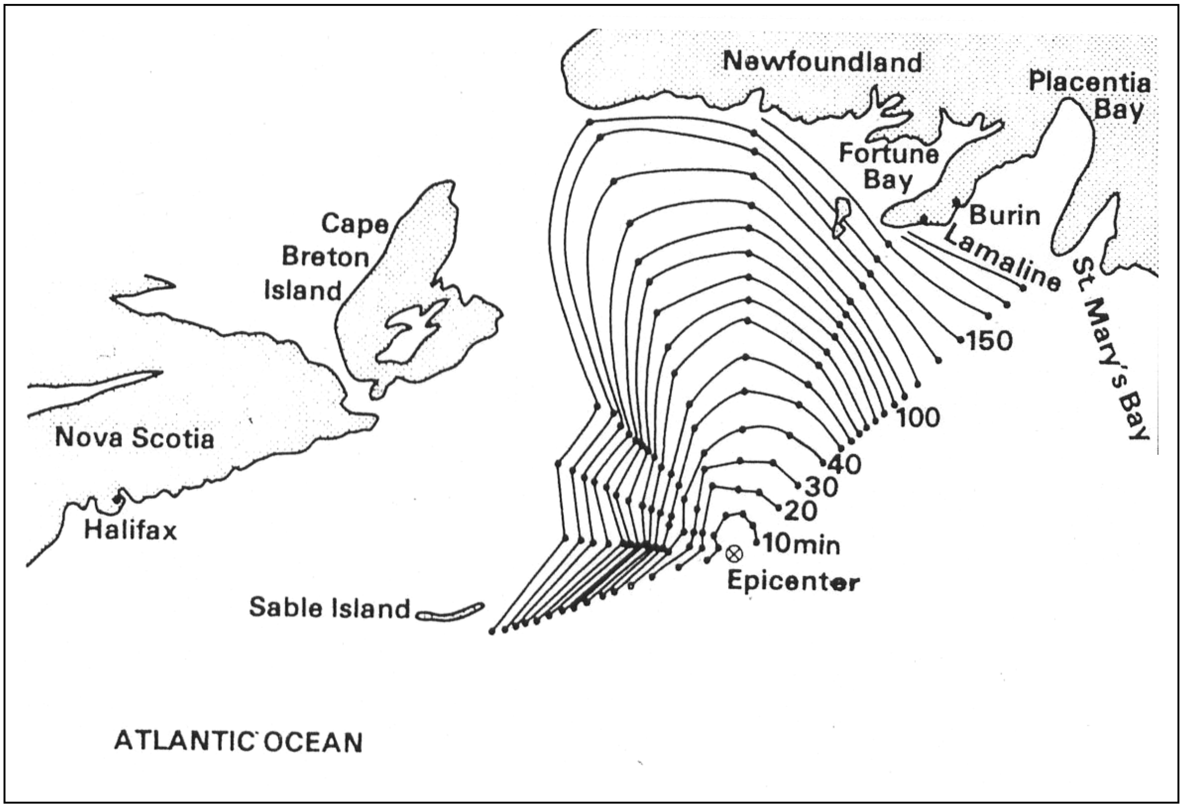


Figure 6: Travel time contours of Grand Banks earthquake tsunami (in minutes)

Greenberg et al. (1993, 1994) and Ruffman et al. (1995) numerically modelled the tsunami in the Halifax harbour, due to a large chemical explosion on 6 December 1917. It is not clear how many people died from the tsunami, as opposed to the explosion itself. Figure 7a shows the tsunami travel times and Figure 7b shows the travel time contours. Figure 8 shoes the tsunami amplitudes. It can be seen that in the Halifax harbour narrows, the tsunami achieved amplitudes of up to 14 m. However, the tsunami quickly dissipated as soon as it entered the Atlantic Ocean.

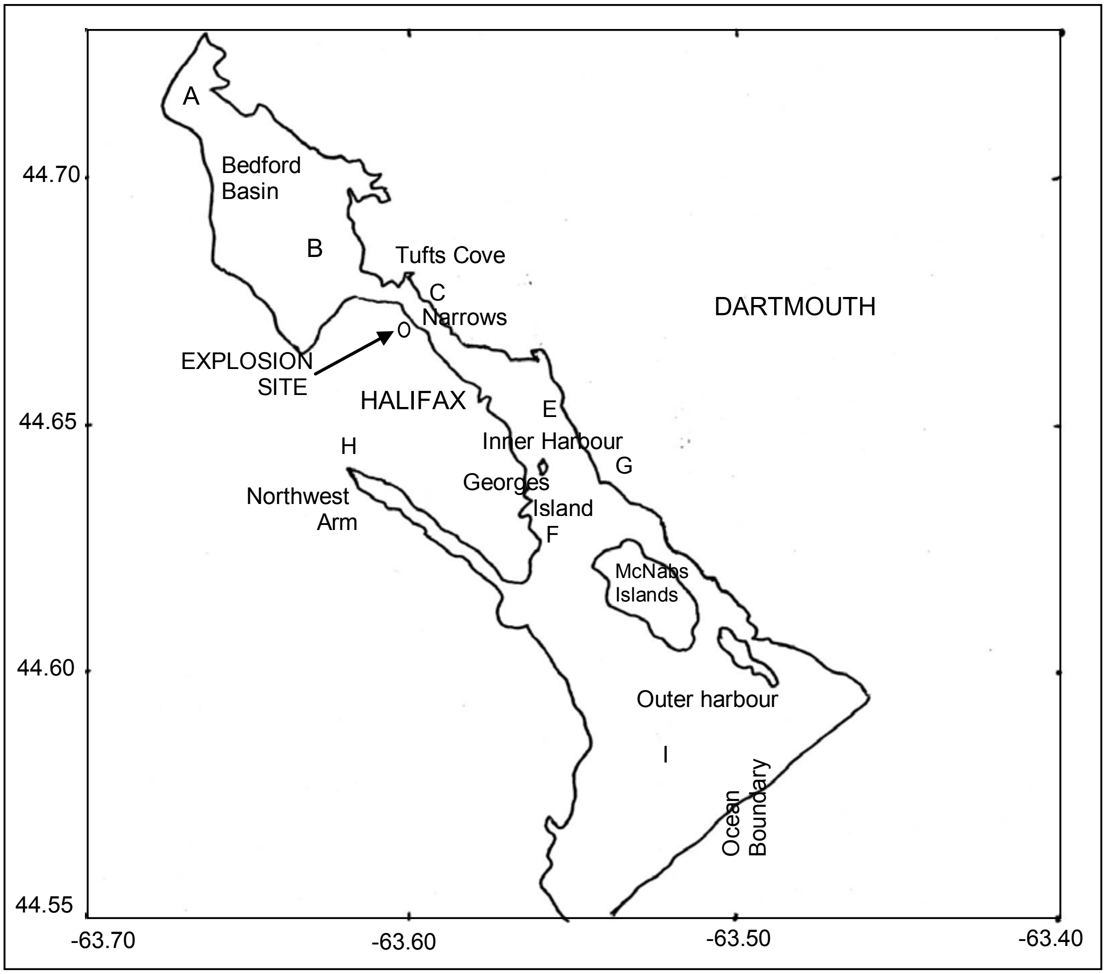


Figure 7a: Halifax Harbour location map. The letters refer to place names where the tsunami amplitude is shown in Figure 8 (Greenberg et al., 1993, 1994)

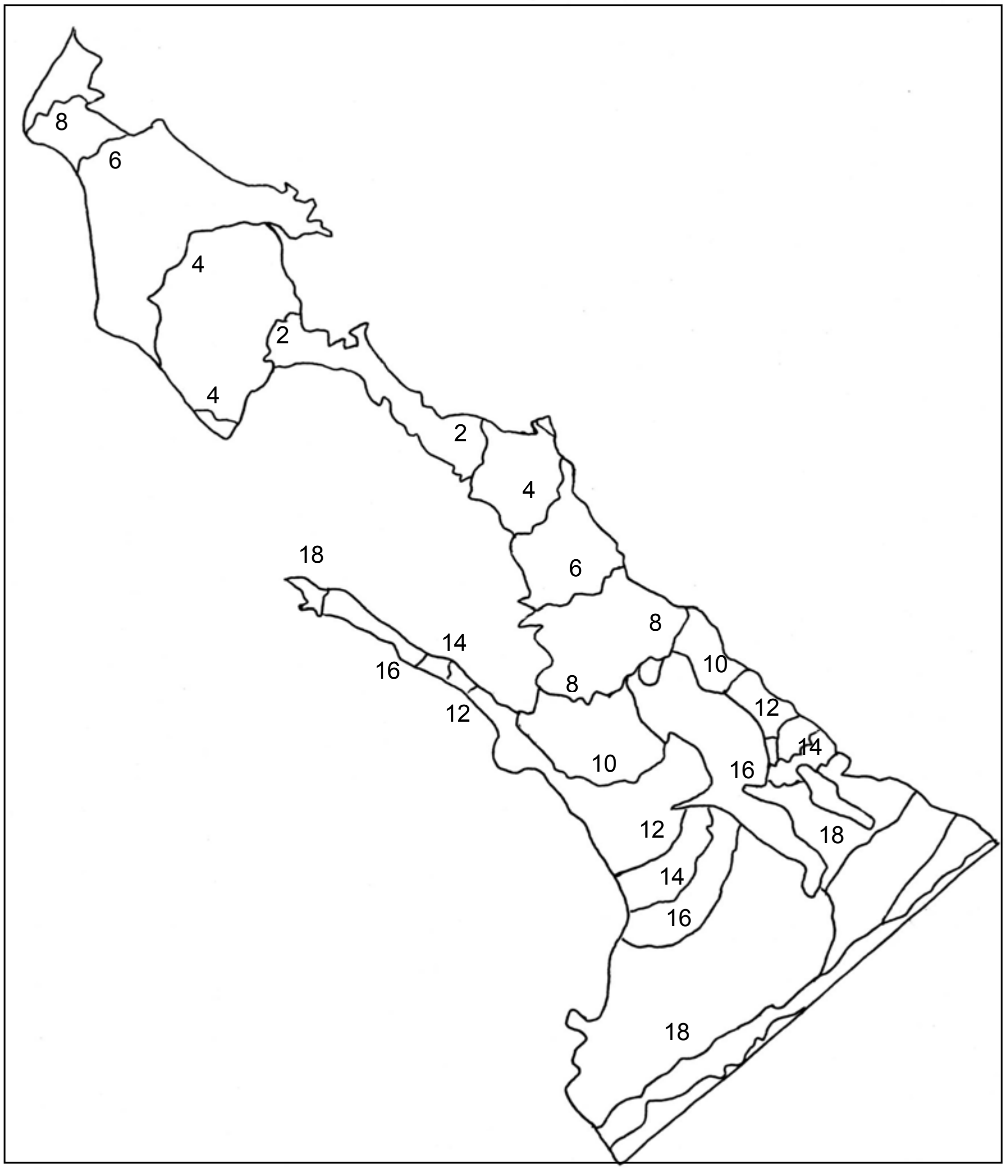


Figure 7b: Travel time contours (in minutes) of the tsunami (from Greenberg et al., 1993, 1994)

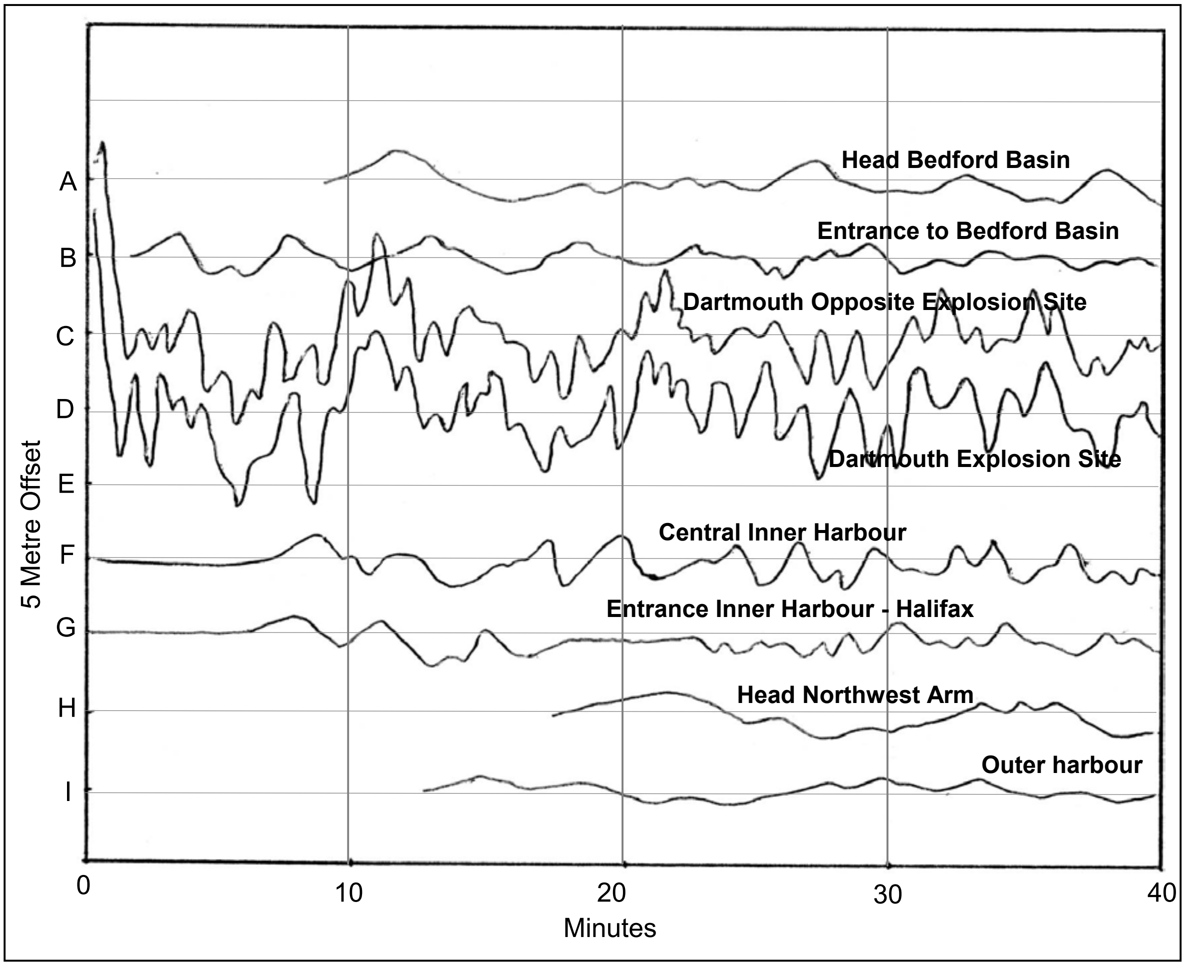


Figure 8: Maximum tsunami amplitudes (in m) at various locations identified in Figure 7a (from Greenberg et al., 1993, 1994)

Figure 9 shows the earthquake distribution in the St. Lawrence estuary. Tsunamis can be generated here from earthquakes and landslides also. Some 8,400 years B.P., at the end of the last glaciation, there was a large discharge of glacial melt water (Teller et al., 2005) from the huge glacial Lake Agassiz into the Labrador Sea through the Hudson Strait. Figure 10 shows the possible location of sand deposits today from this tsunami, which could have achieved amplitudes between 2 to 5 m.

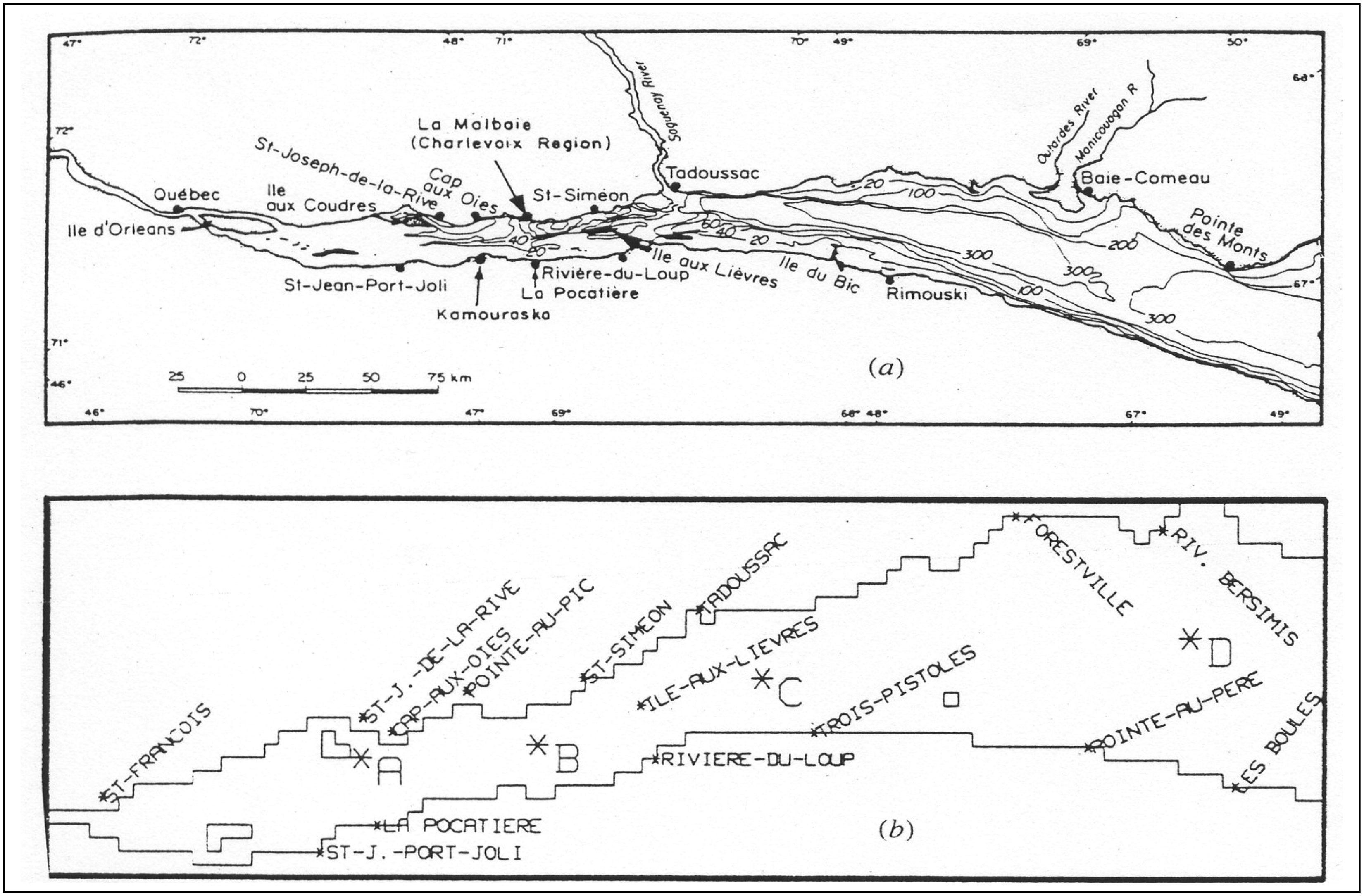


Figure 9: (a) Map of St. Lawrence Estuary in eastern Canada, and (b) The four hypothetical earthquake epicenters used in numerical simulation (from Chasse et al., 1993)

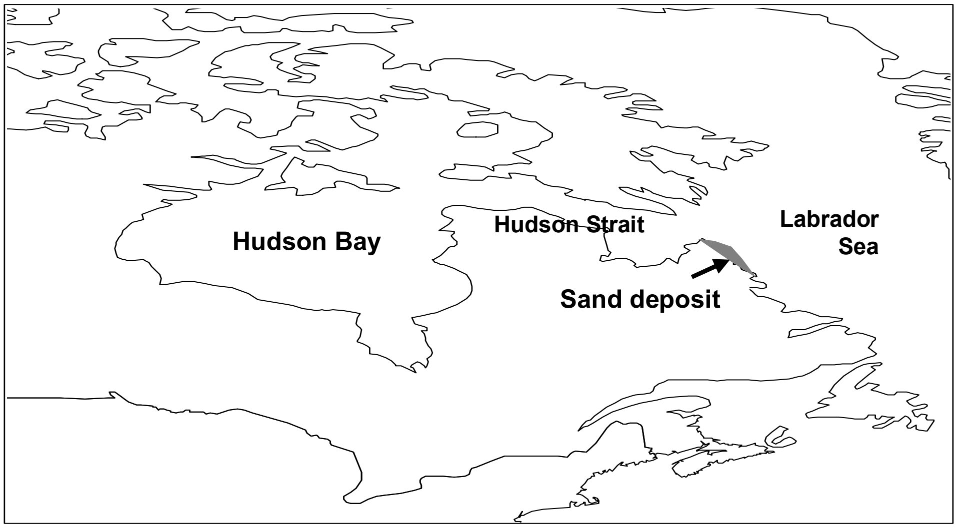


Figure 10: Location of possible sand deposits in the Labrador Sea from a tsunami, some 8,400 years B.P.

4. CONCLUSIONS

Because of low population density, at present, there is no priority for a tsunami warning system for Arctic Canada. The Pacific tsunami warning system is in existence since 1948 and functions reasonably well from a scientific point of view. As for the warning aspects for the Pacific coast of Canada, the logistics are relatively simple, because only the federal government and the province of British Columbia are involved.

For the Atlantic Ocean, a tsunami warning system is now being established the scientific as well as the logistical issues for this system have to be quite different from the Pacific system, for the following reasons. Since tsunamis that impact eastern Canada are of local origin, we cannot count on other countries to provide a tsunami warning to Canada. We have to rely more on our own efforts and systems. Second, for eastern Canada, even the logistics have to be more complicated because, not only the federal government, but five provinces (Newfoundland and Labrador, Nova Scotia, New Brunswick, and Quebec) need to be involved

References

Chasse, J., T.S. Murty and M.I. El-Sabh (1993): A numerical model of water level oscillations in the St. Lawrence Estuary, Canada, Part II: Tsunamis, *Marine Geodesy*, Vol. 16, No. 2, 125-148.

Greenberg, D.A., T.S. Murty and A. Ruffman (1994): Modelling the tsunami from the 1917 Halifax harbour explosion, *Science of Tsunami hazards*, Vol. 11, No. 2, 67-80.

Greenberg, D.A., T.S. Murty and A. Ruffman (1993): A numerical model for the Halifax harbour tsunami due to the 1917 explosion, Marine Geodesy, Vol. 16, No. 2, 153-168.

Murty, T.S. (1977): Seismic Sea Waves – Tsunamis, Canadian Bulletin of Fisheries and Aquatic Sciences, No. 198 Ottawa, Canada, 337 Pages.

Ruffman, A., D.A. Greenberg and T.S. Murty (1995): The tsunami from the explosion in Halifax harbour. *In* "Ground zero". 327-344, Ed: A. Ruffman and C.D. Howell, Nimbus Publishing Ltd., Halifax.

Teller, J.T., T.S. Murty, N. Nirupama, and P. Chittibabu (2005): A possible tsunami in the western part of the Labrador Sea about 8,400 years B.P., Science of Tsunami Hazards (Submitted).

COMMENT ON: *TSUNAMIS AND TSUNAMI-LIKE WAVES OF THE EASTERN UNITED STATES* BY PATRICIA A. LOCKRIDGE, LOWELL S. WHITESIDE AND JAMES F. LANDER WITH RESPECT TO THE NOVEMBER 18, 1929 EARTHQUAKE AND ITS TSUNAMI

Alan Ruffman
Geomarine Associates Ltd.
P.O. Box 41, Station M
Halifax, Nova Scotia
Canada B3J 2L4

This most valuable compilation by Patricia Lockridge *et al.* (2002) covers a wide range of tsunamis and tsunami-like events ranging from marine tectonic, volcanic, and landslide tsunamis to possible meteorologic tsunami-like events. Lockridge *et al.*'s (2002) massive text table (pp. 124-141) entitled "Description of Events" covers events from 1668 to 1992. The 2002 paper in *Science of Tsunami Hazards* was clearly intended to be an update of, an extension to, and a sequel to, the first east coast and Caribbean tsunami compilations contained in Lander and Lockridge's 1989 National Geophysical Data Center volume *United States Tsunamis (including United States Possessions) 1690-1988*.

The Lockridge *et al.* (2002) compilation contains a small error with respect to the 1929 "Grand Banks" Earthquake and Tsunami of which I may be cause in part. In addition the tsunami histories of oceans without a tsunami warning system will be now receiving much closer attention, including historic events in the Atlantic Ocean given the events of December 26, 2004 and March 18, 2005 in the Indian Ocean; both the Atlantic and the Indian Oceans have no tsunami warning system and have an incomplete tsunami history.

THE "GRAND BANKS" EARTHQUAKE AND TSUNAMI

The November 18, 1929 tsunami was created by an M_s 7.2, M_W 7.1, m_B 7.1 earthquake at 2032 UT that occurred 18 km below the 2-km-deep upper continental slope at the mouth of the Laurentian Channel (Bent, 1994; 1995) some 265 km south of the Burin Peninsula on the south coast of Newfoundland at 44.691°N, 56.006°W (Dewey and Gordon, 1984). The earthquake shook loose and mobilized about 200 km^3 of material on the continental slope and rise in what was the first identified and first defined 'turbidity current' (or underwater landslide). Lockridge *et al.* (2002) cited the key 1929-1930 period references, but did not cite W.W. Doxsee's most important review of the event published in 1948, or a number of the more recent references. The Doxsee review appears to be what may have spurred the thinking of the Lamont-Doherty Geological Observatory scientists at Columbia University who were finally able to so nicely explain the cause of the November 18, 1929 tsunami four years later - what we would now call a landslide tsunami (Heezen and Ewing, 1952; Kuenen, 1952; Kullenberg, 1954; Shepard, 1954; Heezen *et al.*, 1954; Heezen and Drake, 1964; Fruth, 1965).

I would recommend that students of the November 18, 1929 tsunami that struck southern

Newfoundland and Nova Scotia obtain a copy of the Doxsee 1948 reference. More modern references vis-à-vis this 1929 underwater landslide event would now include Adams and Basham, 1989; Basham and Adams, 1982; Basham *et al.*, 1982; Bent, 1994; 1995; Dewey and Gordon, 1984; Fine *et al.*, 2005; Hughes Clarke, 1986; 1987; 1990; Hughes Clarke *et al.*, 1989; 1990; Mayer *et al.*, 1988; Piper and Normark, 1982; Piper *et al.*, 1985; 1988; 1999; Ruffman, 1991; 1993; 1995; 1996; Shor *et al.*, 1990; and Tuttle *et al.*, 2004.

1929 TSUNAMI'S HEIGHT AND RUNUP HEIGHT

Lockridge *et al.* (2002) stated that the November 18, 1929 tsunami "surged up several inlets to a height of 15 m" (p. 131). My studies of this event have documented a tsunami wave height of 4 m above sea level on a rising 'spring', or perigean, tide in Great St. Lawrence Harbour (Ruffman, 1996) and 7 m above sea level in Taylor's Bay (Ruffman, 1993; Tuttle *et al.*, 2004) as the tsunami rolled up the harbour as a breaking wave in both locations. We really have no firm data of the depth to which the sea initially withdrew other than anecdotal observations that people saw the harbour floors exposed under the light of a full moon in places where they had not ever seen the seafloor before.

In the first case, in St. Lawrence Harbour, we documented a runup height of about 13 m and at Taylor's Bay about 10 m; in St. Lawrence mainly from oral history and modern detailed topographic maps (Ruffman, 1995; 1996) and in Taylor's Bay from oral history and detailed levelling (Tuttle *et al.*, 2004). I do not believe that the true runup height of the 1929 tsunami has been determined at any other locations at this point.

This section of Lockridge *et al.* (2002) also noted the November 18, 1929 M_s 7.2 earthquake "generated a local tsunami (perhaps a landslide tsunami) that was recorded at Atlantic City ..." (p. 121). I believe that the authors could have been much more definite. The November 18, 1929 hypocentre was 18 km below the ocean floor at the mouth of the Laurentian Channel where water depths were 2 km. Dewey and Gordon (1984) and Allison Bent (1994, 1995) provided a modern relocation and a fault plane solution respectively. No modern authors have suggested that there was a tectonic break of the ocean floor, but rather that the earthquake's shaking precipitated a significant landslide on the upper continental slope. Modern sidescan sonar and seamarc data as well as submersible observations from ALVIN have confirmed the landslide hypothesis (Piper and Normark, 1982; Piper *et al.*, 1985; 1988; 1999; Hughes Clarke, 1986; 1987; 1990; Hughes Clarke *et al.*, 1989; 1990).

Lockridge *et al.* (2002) need not have qualified their statement on p. 121 -- It ***was*** a landslide tsunami -- not 'perhaps' a landslide tsunami!

1929 TSUNAMI'S DEATH TOLL

Lockridge *et al.* (2002) cite deaths of 28 persons in Newfoundland and one in Nova Scotia (p. 131). In their introductory section on 'Notable Historical Events' they cite "29 deaths along the coast of Newfoundland ... but none of these deaths were in the United States." (p. 121). I am cited as a source, and I am afraid I may be the cause of a slight error, in the number of deaths noted by Lockridge *et al.* (2002). In Ruffman *et al.* (1989), a paper given at the June 22-24, 1989 meeting of the Canadian Nautical Research Society in Halifax, Nova Scotia, I indeed did cite 29 possible deaths, including a death in Nova Scotia -- a Mr. John MacLeod.

However, I've since corrected that with a 1994 article in *Cape Breton's Magazine* and in a 'Comment' in *Geology* (2001) which perhaps was published too late to be included in the Lockridge *et al.* (2002) review article? I have established that John MacLeod, who was reported missing at the time in local newspapers, was in fact having a meal with local people that I've now interviewed, so that he must now be struck from the list of 1929 victims.

On the occasion of the 75th commemoration of the "Grand Banks" Earthquake and Tsunami, a local Newfoundland genealogist and I have prepared a major paper, wherein we seek to correct many large and small errors in the list of the names of the victims of the November 18, 1929 tsunami (Ruffman and Hann *et al.* In Press). In this we put the Nova Scotia reported 1929 tsunami death to bed:

> If any readers are diligent, they may find a couple of documents archived at the Centre for Newfoundland Studies at the Queen Elizabeth II Library of Memorial University of Newfoundland, and in a published abstract of a talk given to the Canadian Nautical Research Society on June 22-24, 1989 that the senior author for a while used a 1929 tsunami death toll of 29 persons. John MacLeod was employed in November 1929 as a night watchperson in a sawmill facility owned by R. Dunphy of Point Tupper, Nova Scotia. The sawmill and the watchperson's shed were on a barge anchored in Lower River Inhabitants in Richmond County, southern Cape Breton Island, Nova Scotia. The barge broke loose as the tsunami ran north up the river, and was smashed into the underside of the new railroad bridge some distance upstream. The barge's topsides were crushed and destroyed.
>
> The Halifax *Herald* newspaper of Monday, December 16, 1929 (p. 3, cols. 7 and 8) reported that MacLeod, a "middle aged man", was missing, and that "interested parties are making inquiries in the vicinity in the hope that something definite will be found out within the next few days." The matter never reappeared in the Nova Scotia newspapers. Eventually Ruffman established that Mr. MacLeod was at a local home sharing a meal when the tsunami destroyed his place of work, and that he did not die in the event so Mr. John MacLeod was removed from the list of the 1929 tsunami victims.

I apologise for any confusion I may have caused with my 1989 abstract.

This small criticism and refinement of the work of Patricia A. Lockridge, Lowell S. Whiteside and James F. Lander should not be construed in any way as a criticism of their important work and that of the U.S. National Geophysical Data Center. Rather I recognise that with the loss of James Lander and Patricia Lockridge to the field of research, through illness and retirement, the tsunami work of the National Geophysical Data Center has gone into a period of quiescence. The horrendous events in the Indian Ocean as a result of the Sumatra subduction zone mega earthquakes will, I hope, spur the tsunami research community to action to insist that the tsunami database of the National Geophysical Data Center be continued and expanded. All of us working in the historical tsunamis and seismicity field will have new data, and refinements to data, to contribute to what I trust will be an ongoing compilation, especially in the Atlantic and Indian Oceans.

REFERENCES

Adams, John and Peter W. Basham. 1989. Seismicity and Seismo-tectonics of Canada's Eastern Margin and Craton. *in* Søren Gregersen and Peter W. Basham, editors, *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*. NATO Scientific Affairs Division, ASI Series, Series C, Mathematical and Physical Sciences, Vol 266, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 355-370.

Basham, Peter W. and John Adams. 1982. Earthquake Hazards to Offshore Development on the Eastern Canadian Continental Shelves. *Proceedings of the Second Canadian Conference on Marine Geotechnical Engineering*, June 8-10, Halifax, Nova Scotia, National Research Council of Canada, Ottawa, Ontario, 6 pp. unpaged.

Basham, P.W., D.H. Weichert, F.M. Anglin and M.J. Berry. 1982. *New Probabilistic Strong Seismic Ground Motion Maps of Canada: A Compilation of Earthquake Source Zones, Methods and Results*. Canada Department of Energy, Mines and Resources, Earth Physics Branch (now the Geological Survey of Canada), Open File No. 82-33, December, 205 pp. including 67 figures.

Bent, Allison L. 1994. *Seismograms for historic Canadian earthquakes: The 18 November 1929 Grand Banks earthquake*. Geological Survey of Canada, Open File Report No. 2563(1994), 36 pp.

Bent, Allison L. 1995. A Complex Double-Couple Source Mechanism for the M_S 7.2 1929 Grand Banks Earthquake. *Bulletin of the Seismological Society of America*, Vol. 85, No. 4, August, pp. 1003-1020.

Dewey, James W. and David W. Gordon. 1984. *Map Showing Recomputed Hypocenters of Earthquakes in the Eastern and Central United States and Adjacent Canada, 1925-*

1980. United States Department of the Interior, U.S. Geological Survey, Miscellaneous Field Studies, Pamphlet, 39 pp., plus Map MF - 1699, approximate scale 1:2,500,000.

Doxsee, W.W. 1948. The Grand Banks Earthquake of November 18, 1929. *Publications of the Dominion Observatory*, Canada Department of Mines and Technical Surveys, Ottawa, Ontario, Vol. 7, No. 7, pp. 323-335.

Fine, I.V., A.B. Rabinovich, B.D. Bornhold, R.E. Thomson and E.A. Kulikov. 2005. The Grand Banks landslide-generated tsunami of November 18, 1929: preliminary analysis and numerical modeling. *Marine Geology*, Vol. 215, Nos. 1&2, pp. 45-57.

Fruth, L.S. 1965. *The 1929 Grand Banks turbidite and the sediments of the Sohm Abyssal Plain*. Unpublished M.Sc. thesis, Columbia University, New York City, New York, 257 pp.

Heezen, B.C. and C.L. Drake. 1964. Grand Banks slump. *Geological Society of America, Bulletin*, Vol. 48, No. 2, pp. 221-225.

Heezen, B.C. and M. Ewing. 1952. Turbidity Currents and Submarine Slumps, and the 1929 Grand Banks Earthquake. *American Journal of Science*, Vol. 250, No. 12, December, pp. 849-873.

Heezen, Bruce C., D.B. Ericson and Maurice Ewing. 1954. Further Evidence for a Turbidity Current Following the 1929 Grand Banks Earthquake. *Deep-Sea Research*, Vol. 1, pp. 193-202.

Hughes Clarke, John Edward. 1986. *The geologic record of the 1929 "Grand Banks" earthquake and its relevance to deep-sea clastic sedimentation*. Unpublished Ph.D. thesis, Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, June, 171 pp.

Hughes Clarke, J.E. 1987. *Surficial morphology of Eastern Valley, Laurentian Fan*. Geological Survey of Canada, Open File Report No. 1425(1987), 46 pp. partially numbered.

Hughes Clarke, John Edward. 1990. Late stage slope failure in the wake of the 1929 Grand Banks earthquake. *Geo-Marine Letters*, Vol. 10, pp. 69-79.

Hughes Clarke, John E., Larry A. Mayer, David J.W. Piper and Alexander N. Shor. 1989. PISCES IV submersible observations in the epicentral region of the Grand Banks earthquake. *in* D.J.W. Piper, Editor, *Submersible observations off the East Coast of Canada*. Geological Survey of Canada, Paper 88-20, pp. 57-69.

Hughes Clarke, John E., Alexander N. Shor, David J.W. Piper and Larry A. Mayer. 1990. Large-scale current-induced erosion and deposition in the path of the 1929 Grand Banks turbidity current. *Sedimentology*, Vol. 37, pp. 613-629.

Kuenen, Ph. H. 1952. Estimated Size of the Grand Banks Turbidity Current. *American Journal of Science*, Vol. 250, December, pp. 874-884.

Kullenberg, B. 1954. Remarks on the Grand Banks Turbidity Current. *Deep-Sea Research*, Vol. 1, pp. 203-210.

Lander, James F. and Patricia A. Lockridge. 1989. *United States Tsunamis (Including United States Possessions) 1690-1988*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data and Information Service, National Geophysical Data Center, Boulder, Colorado, August, 265 pp.

Lockridge, Patricia A., Lowell S. Whiteside and James F. Lander. 2002. Tsunamis and Tsunami-like Waves of the Eastern United States. *Science of Tsunami Hazards*, Vol. 20, No. 3, pp. 120-157.

Mayer, L.A., A.N. Shor, J. Hughes Clarke and D.J.W. Piper. 1988. Dense biological communities at 3850 m on the Laurentian Fan and their relationship to the deposits of the 1929 Grand Banks earthquake. *Deep-Sea Research*, Vol. 35, No. 8, pp. 1235-1246.

Piper, David J.W. and William R. Normark. 1982. Effects of the 1929 Grand Banks Earthquake on the Continental Slope off Eastern Canada. *Current Research, Part B*, Geological Survey of Canada, Paper 82-1B, pp. 147-151.

Piper, D.J., A.N. Shor, J.A. Farre, S. O'Connell and R. Jacobi. 1985. Sediment slides and turbidity currents on the Laurentian Fan: Sidescan Sonar Investigations near the epicenter of the 1929 Grand Banks Earthquake. *Geology*, Vol. 13, pp. 538-541.

Piper, David J.W., Alexander N. Shor and John E. Hughes Clarke. 1988. The 1929 "Grand Banks" earthquake; slump and turbidity current. Geological Society of America, *Special Paper on Catastrophic Events in Geology*, No. 229, pp. 77-92.

Piper, D.J.W., P. Cochonat and M.L. Morrison. 1999. The sequence of events around the epicentre of the 1929 Grand Banks earthquake: Initiation of debris flows and turbidity current inferred from sidescan sonar. *Sedimentology*, Vol. 46, pp. 79-97.

Ruffman, Alan, in association with Clyde Cheeseman, Gordon Cheeseman and Wayne Hollett and with the assistance of Reginald E. Janes and Jessie Drover. 1989. *The November 18, 1929 Tsunami in the Community of Port au Bras, Burin Peninsula, Newfoundland* [Abstract]. Annual Conference, Canadian Nautical Research Society, June 22-24, Halifax, Nova Scotia, 1 p.

Ruffman, Alan. 1991. Notes on the Recurrence Rate of a November 18, 1929-like event in the Laurentian Slope (LSP) Seismic Source Zone or of similar shelf-edge slope events off Eastern Canada. *in* John Adams, compiler, *Proceedings, Geological Survey of*

Canada Workshop on Eastern Seismicity Source Zones for the 1995 Seismic Hazard Maps, March 18-19, Ottawa, Ontario, May 2, Geological Survey of Canada, Open File No. 2437(1991), Part 2, pp. 371-396.

Ruffman, Alan. 1993. *Reconnaissance Search on the South Coast of the Burin Peninsula, Newfoundland, for tsunami-laid sediments deposited by the 'tidal wave' following the November 18, 1929 Laurentian Slope Earthquake, August 17 - September 2, 1993*. Geomarine Associates Ltd., Halifax, Nova Scotia, Project 90-19, Report for Seismology, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, Contract No. NRC-04-92-088, as part of the study, 'Paleoseismicity and Defining Earthquake Hazard in Eastern North America', for the U.S. Nuclear Regulatory Commission, Washington, D.C., NRC Identifier 14-08-0001-G, September 26, 228 pp., revised May 8, 1994, 241 pp.

Ruffman, Alan. 1994. The 1929 Earthquake and the Search for John MacLeod. *Cape Breton's Magazine*, Wreck Cove, Nova Scotia, No. 67, Fall, pp. [56]-[58].

Ruffman, Alan. 1995. *Tsunami Runup Maps as an Emergency Preparedness Planning Tool: The November 18, 1929 tsunami in St. Lawrence, Newfoundland as a case study*. Geomarine Associates Ltd., Halifax, Nova Scotia, Project 94-14, Contract Report for Emergency Preparedness Canada, Evaluation and Analysis, Ottawa, Ontario, Contract No. 94-D025, March 31 (revised August 9, 1995), 399 pp.

Ruffman, Alan. 1996. *Tsunami Runup Mapping as an Emergency Preparedness Planning Tool: The 1929 tsunami in St. Lawrence, Newfoundland*. Geomarine Associates Ltd., Halifax, Nova Scotia, Project 94-14, Report for Emergency Preparedness Canada, Office of the Senior Scientific Advisor, Ottawa, Ontario, Contract No. 94-D025, revised November 7, Volume 1 -- Report, 144 pp.; Volume 2 -- Appendices and Enclosures, 281 pp.; Volume 1 issued in July 1997 as an Emergency Preparedness Canada report under the same English title, produced within the Canadian Framework for the International Decade for Natural Disaster Reduction, 107 pp., Canada Department of Public Works and Government Services, Catalogue No. D82-41/1-1996E, ISBN: 0-662-25859-2; Volume 2 placed in several archival locations in July 1997 as an Emergency Preparedness Canada report under the same title, 281 pp.; Volume 1 issued as a French translation in July 1997 as an Emergency Preparedness Canada report titled: *Cartographie du Jet de Rive des Tsunamis et Guide de Planification des Mesures d'Urgence: le Tsunami de 1929 à St. Lawrence, Terre-Neuve*, 128 pp., Canada Département des Travaux publics et Services gouvernement aux, No. du catalogue D82-41/1-1996F, ISBN: 0-662-82145-9; mounted on website <http://www.ocipep.gc.ca/research/resactivites/natHaz/en_tsunami/1994-D025_e.asp> for english and <http://www.ocipep.gc.ca/research/resactivites/natHaz/en_tsunami/1994-D025_f.asp> for french.

Ruffman, Alan. 2001. Potential for large-scale submarine slope failure and tsunami generation along the U.S. mid-Atlantic coast: Comment. *Geology*, Vol. 29, October, p. 967.

Ruffman, Alan and Violet Hann with the help of many, many residents and former residents of the affected communities. In Press. The Revised Death Toll of the Twenty-eight Lives Lost in the November 18, 1929 Tsunami That Struck Newfoundland and Nova Scotia: Canada's Most Tragic Known Historic Earthquake. *Newfoundland and Labrador Studies*, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, 34 pp. plus photographs.

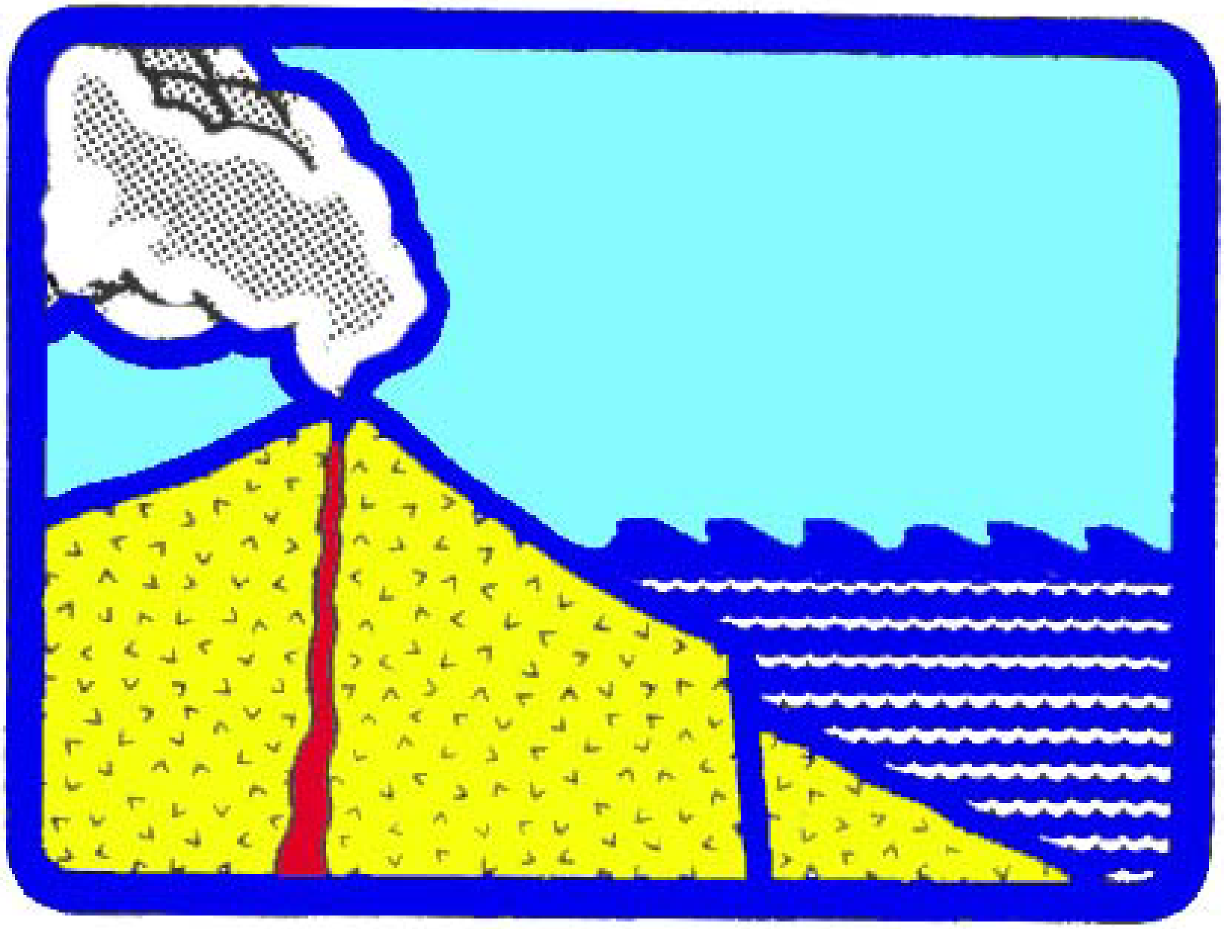
Shepard, F. P. 1954. High-Velocity Turbidity Currents, A Discussion. *in* E.C. Bullard, editor, A Discussion on the Floor of the Atlantic Ocean. February 28, 1953, London, England, *Proceedings of the Royal Society of London*, Series A. Mathematical and Physical Sciences, Vol. 222, No. 1150, March 18, pp. 323-326.

Shor, Alexander N., David J.W. Piper, John E. Hughes Clarke and Larry A. Mayer. 1990. Giant flute-like scour and other erosional features formed by the 1929 Grand Banks turbidity current. *Sedimentology*, Vol. 37, pp. 631-645.

Tuttle, Martitia P., Alan Ruffman, Thane Anderson and Hewitt Jeter. 2004. Distinguishing Tsunami from Storm Deposits in eastern North America: The 1929 Grand Banks Tsunami versus the 1991 Halloween Storm. *Seismological Research Letters*, Vol. 75, No. 1, January/February, cover photo, pp. 117-131.

REQUEST FROM AUTHOR

Alan Ruffman is a marine geophysicist who has done historical seismicity research on the November 18, 1929 Laurentian Slope or "Grand Banks" Earthquake and Tsunami, on the Pre-Confederation Historic Seismicity of Nova Scotia from 1752 to 1967, on a very tragic September 11-12, 1775 Hurricane and storm surge in Newfoundland, on the Saxby Gale, a hurricane of October 4-5, 1869 in Maine and New Brunswick and its record storm surge in the upper reaches of the Bay of Fundy, and on an August 1873 tragic hurricane in Atlantic Canada. He is presently actively searching for primary accounts of the arrival of the November 1, 1755 Lisbon Tsunami along the east coast of North America and in the Caribbean. He has realised that the historic tsunami history will be of greater interest since the Boxing Day tsunami in the Indian Ocean given that the Atlantic Ocean is no better protected than was the Indian Ocean on December 26, 2004 when it comes to a Tsunami Warning System. He has also realised that while many people refer to the Lisbon Tsunami arriving in the eastern Caribbean islands, few - very few - writers cite period, or primary, sources for such data. He would welcome any leads of readers to such coeval, or near-coeval, documentation relevant to the arrival of the November 1, 1755 Lisbon Tsunami along the shores of the western Atlantic, in the Caribbean or along the northeast coast of South America.



2523 Correa Rd, UH/SOEST, Rm 215 HIG
Honolulu, HI 96822, USA

WWW.STHJOURNAL.ORG