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Chapter 3. GEOLOGIC EFFECTS AND RECORDS OF TSUNAMIS

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Contents

1. Introduction

> Nor should we omit to mention the havoc committed on low coasts, during earthquakes, by waves of the sea which roll in upon the land, bearing everything before them, for many miles into the interior throwing down upon the surface great heaps of sand and rock, by which the remains of drowned animals may be overwhelmed.
>
> Charles Lyell, 1832

Those of us working on tsunami traces in the 1980s were commonly doubted because some tsunami scientists argued that tsunamis did not leave deposits, and many geologists were skeptical. However, it is clear from the reports of several pre-1980s surveys that tsunamis eroded and deposited not only sand, but also large boulders and coral debris. Moreover, photographs of tsunamis in progress show turbidity--for example, in a well-known 1957 photo series from Oahu, turbidity clearly develops in the nearshore as the tsunami arrives from the Aleutians. Since the 1990s, and certainly since 2004, there is no doubt that tsunamis erode and deposit sediment (Figure 3.1).

Relative to other aspects of tsunami science, the study of the geologic record of tsunamis is immature. Only since the mid- to late 1980s has extensive work been done, and 1992 is the first year when there were more than 10 papers published (Figure 3.2). The literature expanded rather steadily in the 1990s, largely spurred by a number of damaging tsunamis in the Pacific. The field of tsunami geology continues to expand, especially following the 26 December 2004 Indian Ocean tsunami. Our working bibliography of tsunami geology has over 500 peer-reviewed articles up through 2006, not counting the geology of tsunami sources such as papers discussing what conditions generate "tsunami earthquakes" (e.g., Pelayo and Wiens, 1992; see Chapter 5).

Figure 3.1. Satellite images of Jantang, Aceh (Sumatra, Indonesia) before and after the 26 December 2004 tsunami. Note widening of the river mouth by erosion, stripping of vegetation, and deposition of sand on the coastal plain (light gray color). Images from Digital Globe.

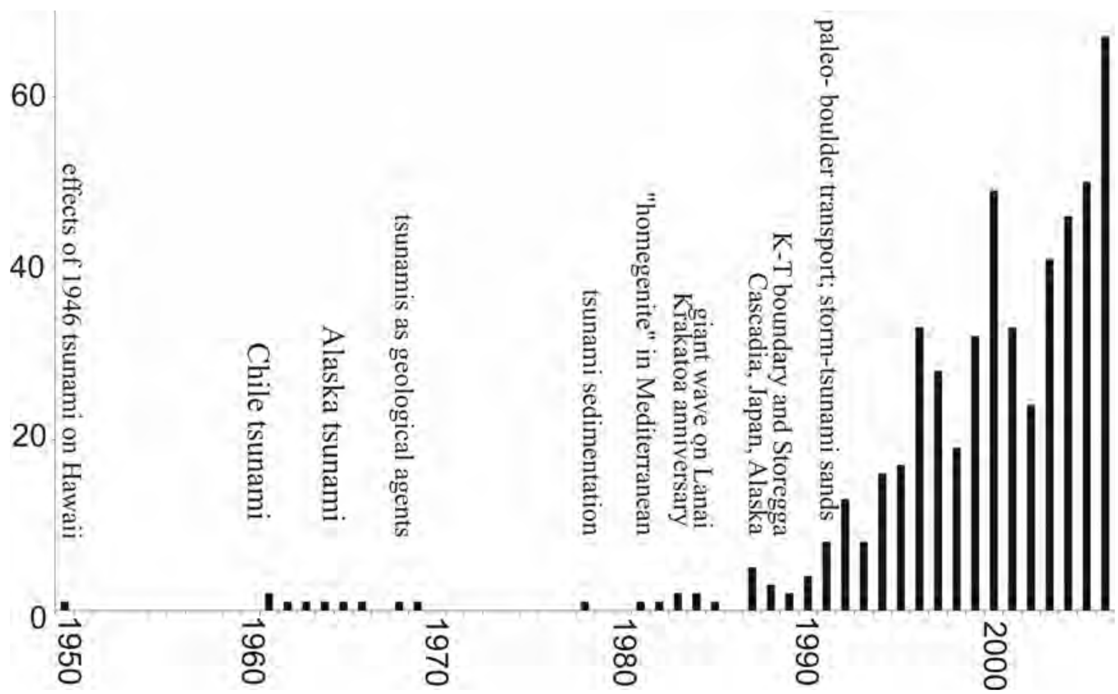

Figure 3.2. History of peer-reviewed articles on tsunami geology (including government publications), based primarily on GeoRef and Web-of-Science databases. Some landmarks (research triggers; pioneer papers) are noted, up through 1991. Non-English-language articles are included but probably underrepresented. Bibliography compiled by Andrew Ritchie, analyzed by the author.

For such an immature field, there have been a remarkable number of review articles on tsunami sedimentology and geomorphology. The earliest of these would be Coleman (1968; also 1978). The majority of reviews have been written by Alastair Dawson--one of the modern pioneers--and co-authors (e.g., Dawson, 1994; Dawson, 1996; Dawson and Shi, 2000; Dawson and Stewart, 2007). Some syntheses (e.g., Bryant, 2001; Kelletat and Scheffers, 2003) include broad and untested speculation, some of which is pointed out in Dominey-Howes et al. (2006; also see Dominey-Howes, 2007), who review the various geological signatures of modern and paleo tsunamis. One review (Shanmugam, 2006) focuses on terminology and on the relationship between tsunamis and turbidity currents. Rhodes et al. (2006) summarize some of the observations and conclusions from a 2005 International Workshop on Tsunami Deposits. Several symposium publications and special volumes have been published with some focus on tsunami geology, the earliest being in *Marine Geology* (Einsele et al., 1996). For example, a publication spike in the year 2000 (Figure 3.2) is largely due to three special volumes that appeared that year.

In general, when there is abundant literature on a subtopic, such as the Cascadia Subduction Zone or the K-T boundary, I will cite the earliest and latest or most comprehensive publications.

2. Historical Review

More than 50% of the tsunami geology literature concerns tsunami deposition on the coastal plain including coastal lakes, from modern and Quaternary seismogenic tsunamis. (In a few cases, the source of the tsunami is disputed or the earthquake also triggered submarine landslides.) This literature is dominated by cases from Japan, Cascadia (northern California to southern British Columbia), and the 2004 Indian Ocean tsunami. Other localities with concentrated studies include New Zealand, the Russian Far East, Alaska, Chile and Peru, the 1929 Grand Banks event, and the 1755 Lisbon earthquake and tsunami. While there are few studies of prehistoric tsunami deposits in low-latitude regions, surveys of recent tsunami effects, in addition to 2004, include Indonesia, Philippines, Papua New Guinea, Hawaii, Peru, Nicaragua, the Caribbean and Mediterranean.

Of the tsunami geology literature identifying tsunami sources other than earthquakes--about 150 articles to date--there is a fairly even split between landslide-generated, volcanogenic, and impact-generated tsunamis, with each category having one or two dominant cases. The landslide-generated tsunami-geology literature is dominated by the Storegga landslide and Hawaii cases, the latter currently disputed. The volcanogenic tsunami-geology literature is dominated by Santorini, with a few articles on Krakatoa. The literature concerning tsunami geology related to asteroid impacts is dominated by the Cretaceous-Tertiary (K-T) boundary case. (A recent change in the formal geologic time scale now means that this boundary is called the Cretaceous-Paleogene boundary.)

2.1. Surveys of tsunami effects

> Besides chairs, tables, bookshelves, etc. . . there were several roofs of cottages, which had been transported almost whole. . . . During my walk around the island, I observed that numerous fragments of rock, which, from the marine productions adhering to them, must recently have been lying in deep water, had been cast up high on the beach; one of these was six feet long, three broad, and two thick.
>
> Charles Darwin, 1835 (in *The Voyage of the Beagle*)

The earliest publications documenting observed effects of tsunamis are summaries from post-tsunami surveys (e.g., Verbeek, 1886; Simons, 1888; Yamana, 1896 compiled by Unohana and Oota, 1988; Platania, 1908; Earthquake Research Institute, 1934; Shepard et al., 1950; Eaton et al., 1961; Konno et al., 1961). The earliest known survey in Russia of the effects of a tsunami, the one produced by the great 1952 Kamchatka earthquake, was kept a military secret and is only recently being uncovered. My review of surveyed geologic effects of modern tsunamis begins with Shepard et al. (1950); Kajiura (1983) and Abe (2005) contain bibliographies of many Japanese tsunami surveys before that time (see also Verbeek, 1886). Zayakin and Luchinina (1987) summarize findings of Russian surveys.

Following the destructive 1 April 1946 tsunami on Hawaii, three geologically trained scientists conducted a post-tsunami survey (Shepard et al., 1950). Francis Parker Shepard, a pioneering marine geologist, was on vacation in Hawaii when the 1 April 1946 Aleutian tsunami struck. Volcanologist Gordon A. MacDonald of the U.S. Geological Survey was mapping the geology of Hawaii in this period. Geologist and hydrologist Doak Cox, born and raised in Hawaii, had just taken a job with the Hawaiian Sugar Planters' Association. Their report includes 33 photographic plates, many showing tsunami erosion and sedimentation. Text sections in the report on damage and erosion describe not only erosional but also depositional phenomena:

> Many fishpond walls of loose rock . . . were damaged or destroyed, and some of the ponds were partly filled with silt, sand, and rocks from the walls . . . . (p. 459)
>
> Where the waves rose over a high beach on a barrier of dunes and flooded lower lands behind, they eroded deep channels through the sand . . . .
>
> At many places sand excavated by the waves must have been carried seaward. Elsewhere, however, much of it was carried inland. At Haena, on northern Kauai, the highway was buried under 4 feet of sand. Thinner layers of sand covered [other] roads . . . on Kauai, Oahu and Maui. Many taro patches in Waipio Valley [on the big island] were completely covered by sand. (p. 462)
>
> . . . A great many coral heads, ranging in size up to 12 feet across, were torn loose and thrown up on the beaches. . . .
>
> At many places the near-shore water became muddy as a result of the tsunami. At most places the water cleared again within a few days. The muddiness . . . may be attributable partly to the stirring up of fine terrigenous sediment on the shallow ocean bottom, but more largely to the result of washing away of soil cover on the temporarily inundated land areas. (p. 463)

Following the great 1960 Chile tsunami, several groups documented geological effects including tsunami erosion and sedimentation around the Pacific. On the south-central coast of Chile, Wright and Mella (1963) described sand covering the soil at several localities; more recent studies in Chile (e.g., Cisternas et al., 2000) describe internal characteristics of this deposit (e.g., Figure 3.3). Eaton's team in Hawaii (Eaton et al., 1961) was present during the tsunami, which arrived in the dark. Their report focuses on details of the tsunami waves and on destruction, but mentions the transport of large boulders and makes a rough calculation of the bore necessary to move them. Reports from Japan (Konno et al., 1961) include the first detailed sedimentological description of a tsunami deposit. Konno's team published cross-sections through the 1960 tsunami deposits on the coastal lowland of northeastern Japan; they documented and described thin sheets of sand and silt thickening into swales, thinning landward, and including graded layers (A. Moore, 2003).

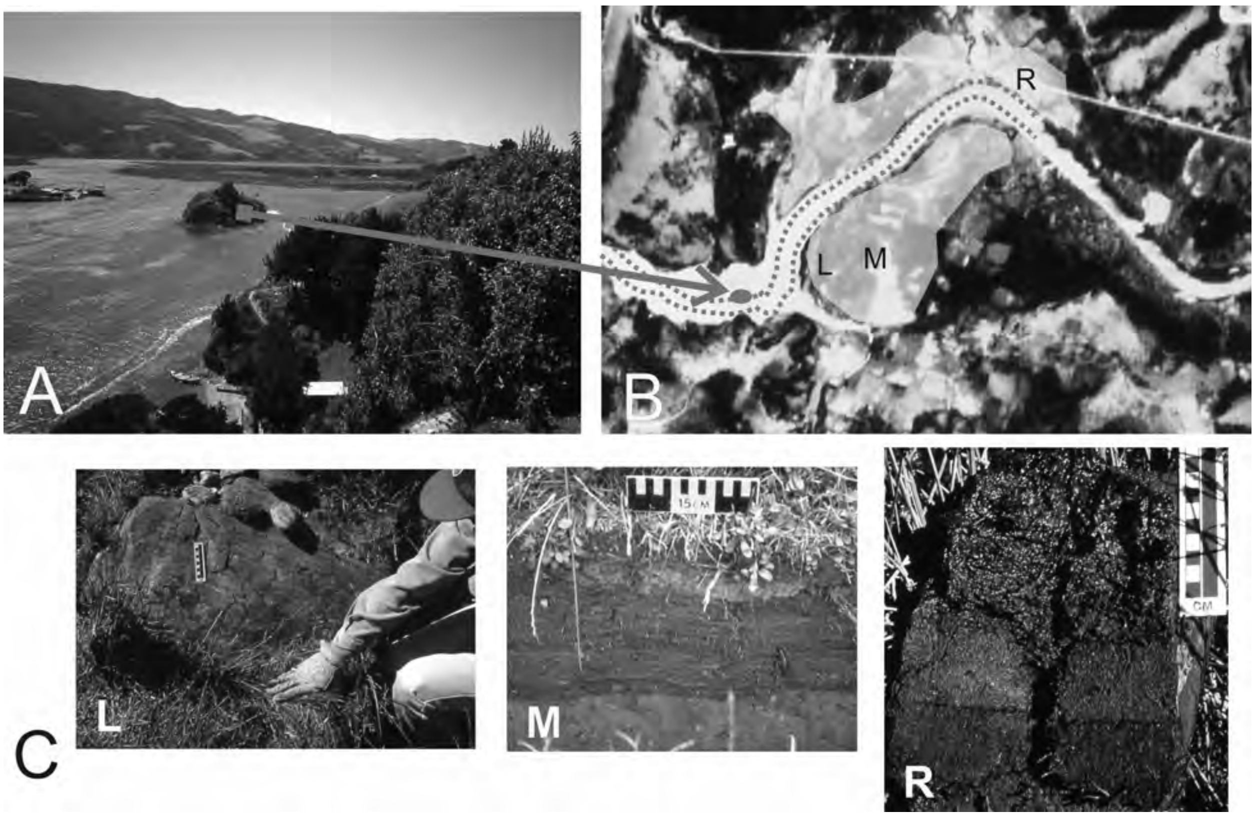

Figure 3.3. Geological effects of the 1960 tsunami at Rio Lingue, central Chile. A: View from south bank near river mouth (left side of air photo); photo in 1989. B: Air photo taken of Rio Lingue in 1960 following the May earthquake, with interpretation. Dotted lines--former river channel banks before tsunami erosion. Shaded area--approximate distribution of preserved tsunami deposits as of 1989. C: Deposits of the 1960 tsunami observed in 1989. Left: proximal tsunami deposits of schist boulders (schist crops out on south bank and large rock in channel). Middle: tsunami deposit of laminated coarse sand, including intraclasts, about 1 km directly inland of the river mouth. Right: tsunami deposit of fine sand ~3 km upstream; tsunami deposit (in middle) overlies formerly farmed soil and is overlain by intertidal muds.

Other early articles that describe geological effects of tsunamis include reports on the 1953 Suva earthquake and tsunami (Houtz, 1962), the Lituya Bay landslide-generated tsunami (Miller, 1960), and the 1964 Alaska earthquake and tsunami (Reimnitz and Marshall, 1965; Plafker and Katchadoorian, 1966). Visiting the Copper River delta in Alaska shortly after the 1964 earthquake and tsunami, Reimnitz and Marshall described "extreme erosion" of tidal flats, which they attributed to "tsunami and seiches" without differentiating the two processes. They postulated that this eroded material would have been deposited in delta channel fills and would likely resemble turbidity-current deposits. The actual deposit of the 1964 tsunami was described first on Vancouver Island in British Columbia (Clague et al., 1994).

In the 1990s, post-tsunami surveys began regularly to include observations of tsunami deposits and other geologic effects of tsunamis (e.g., Abe et al., 1993; Sato et al., 1995; Shi et al., 1995; Dawson et al., 1996; Minoura et al., 1997; Bourgeois et al., 1999; Matsutami et al., 2001; Gelfenbaum and Jaffe, 2003; Rothaus et al., 2004). Already there is voluminous literature on geologic effects of the 26 December 2004 tsunami (Satake et al., 2007), and a whole new community of geoscientists has become engaged in studying the geologic effects of tsunamis. By late 2007, there were more than 35 refereed publications with a major focus on surficial physical aspects of the Indian Ocean tsunami and its aftermath (e.g., Ramasamy et al., 2006).

The December 2004 tsunami has generated a new wave of geological and related studies, many using techniques not available in the times of prior great tsunamis (Alaska, 1964, Chile, 1960, Kamchatka, 1952), and addressing questions that have arisen since then. Moreover, this tsunami affected many low-latitude coastlines, whereas the previous three great tsunamis affected primarily mid- to high-latitude coastlines. Also, because population densities were high on many coastlines affected by the 2004 Indian Ocean tsunami, environmental effects have received more attention.

Of particular interest are the first studies of tsunami effects focused on satellite imagery (e.g., Figure 3.1). Ramakrishnan et al. (2005; India and Sri Lanka) and Borrero (2005; Banda Aceh) were the first to publish analyses of post-tsunami satellite imagery; Borrero also made on-the-ground observations. Yang et al. (2007) used a new satellite dataset, FORMOSAT-2, to identify hard-hit regions of Banda Aceh and Thailand and discuss how this technology may aid future post-disaster responses. Umitsu et al. (2007) combined on-the-ground observations with interpretation of satellite images to examine local topographic effects on tsunami flow, erosion and deposition on the coastlines of Banda Aceh, Sumatra, and Nam Khem, Thailand. The larger inundation, runup and backflow in Banda Aceh (also see McAdoo et al., 2007) showed less geomorphic control than the studied case in Thailand, where typical runup was 4-5 m. Satellite imagery was also used in India, for example, to assess tsunami damage (Kumar et al., 2007); certainly other studies are to come.

Other field surveys that outline geological and geomorphic effects of the 2004 great tsunami include Szczucinski et al.'s studies (2005, 2007) of the environmental and geological impacts of the tsunami on the Thailand coast. Kurian et al. (2006) describe inundation and geomorphological impacts of the tsunami on the SW coast of India, documenting before-and-after beach profiles and quantifying erosion and deposition by the tsunami. Kench et al. (2006) describe geological effects of the tsunami on the Maldives, a set of low-lying, mid-ocean coral islands, where deposition dominated erosion. Lavigne et al. (2007) summarize field observations in Java, and Obura (2006) outlines impacts of the tsunami on the coast of Africa.

Whereas the onshore effects of tsunamis have received much attention, the offshore marine record of historical tsunamis has rarely been documented (e.g., van den Bergh et al., 2003), aside from speculation such as that by Shepard et al. (1950) and Reimnitz and Marshall (1965). In a number of historical cases, on the coastal plain, seaward-directed flow and evidence of seaward flow such as flopped-over plants have been observed. The drawdown phase of the tsunami is typically slower than the uprush, however, and outflow tends to be concentrated in topographic lows such as channels. Terrestrial debris from tsunami outflow has been observed and photographed in the nearshore region in many historical cases. It is likely that on the shelf, a tsunami deposit looks like and might be confused with a deposit from a flooding river mouth (e.g., Wheatcroft and Borgeld, 2000), or a storm-surge return flow (e.g., Aigner and Reineck, 1982).

2.2. Tsunamis, turbidity currents, and submarine canyons

An interesting early paper by geologists E.B. Bailey and J. Weir (1932) attributes aspects of Jurassic-age (Kimmeridgian) conglomerates along the Great Glen fault in Scotland to the action of tsunamis ("tunamis" in their spelling). Bailey was interested in sedimentation and tectonics, had mapped major faults in Scotland, and had previously described what he interpreted as submarine landslide deposits in Paleozoic rocks in Quebec. It is clear the authors had been influenced by reports from the great 1923 Kanto earthquake and tsunami in Japan. In that case, the earthquake and following firestorms generated horrific casualties; the tsunami had a runup of more than 10 m and killed hundreds of people.

Bailey and Weir's interpretation illustrates a fundamental geologic question existing around this time: What was the origin of coarse-grained sediments deposited, apparently, in quiet or deep water? (Walker, 1973; Dott, 1978). In the Kimmeridgian case, Bailey and Weir described boulder-bearing conglomerates, containing shallow-marine fossils and exhibiting some degree of grain-size sorting, interbedded with ammonite-bearing shales. The latter they interpreted to represent quiet water, offshore deposition, and they interpreted that the boulders beds were emplaced by earthquake-triggered landslides, with the observed sorting accomplished by attendant tsunamis.

About 20 years later, in the 1950s, many coarse-grained beds (especially graded beds) interbedded with marine shales (indicating quiet water deposition) were reinterpreted as the deposits of turbidity currents. Turbidity currents themselves had been described by the late 1880s (though not by name) where rivers entered lakes or reservoirs; however, the genetic connection of these sediment-laden density currents with graded beds in the geologic record was first made around 1950 (Kuenen and Migliorini, 1950). Such beds came to be called turbidites. However, the Kimmeridgian boulder beds of Bailey and Weir (1932) were reinterpreted not as turbidites but as submarine debris-flow deposits by Pickering et al. (1984).

Early studies of and speculation about the origin of submarine canyons linked turbidity currents and tsunamis. In 1936, R.A. Daly proposed that sediment-laden undersea currents (later called density currents and turbidity currents) were responsible for the generation of submarine canyons by erosion. However, while agreeing with the basic erosional nature of submarine canyons, Bucher (1940) attributed their origin to erosion by tsunamis, arguing that the return flow would be stronger because of gravitational forces. Bucher cited effects of the 1929 Grand Banks earthquake and tsunami (speculating, as others had and would, about the cause of the timing of submarine cable breaks); he also mentioned the 1933 Sanriku coast tsunami in Japan. Other than Bucher's mention, little attention was paid at the time to the tsunami associated with the 1929 Grand Banks earthquake, partly because it occurred during a storm surge (Piper et al., 1988).

Coleman (1968; also 1978), following Bucher (1940), speculated that the sediment-charged return flow from tsunamis might be responsible for triggering turbidity currents and by this means eroding submarine canyons. He also suggested that erosional geomorphic features associated with deltas and barrier reefs, and apparently not explainable by storms, might be attributed to tsunami action. He guessed that other unusual deposits in the geological record might be from tsunamis. In his articles, he did not consider onshore tsunami erosion or deposition.

Tsunami-triggered return (offshore) flow into deep water was invoked by Kastens and Cita (1981) for a "homogenite" in the Mediterranean Sea they attribute to the tsunami triggered by the Santorini caldera collapse c. 3500 B.P. (Cita and Aloisi, 2000). The 1981 paper was the first description since Bailey and Weir of a specific ancient deposit attributed to tsunami action. However, as noted by Shanmugam (2006), this "homogenite" as interpreted is actually a "turbidite" not a "tsunamite." (Terminology for many deposits related to earthquakes [e.g., "seismites" for liquefied beds] and tsunamis is a morass [Shanmugan, 2006]; I will use "tsunami deposit" and "tsunami-related deposit" in this article.)

The connection of earthquakes, tsunamis and turbidites also includes literature on turbidites (triggered by land failures) triggered by earthquakes, sometimes known as "seismoturbidites" (Mutti et al., 1984). In addition to the Grand Banks case (Piper et al., 1988), such deposits have been described by Adams (1990) from cores in the Cascadia deep-sea channel off the Washington and Oregon coastline and interpreted as evidence for up to 13 prehistoric earthquakes since ~7000 B.P. Nakajima and Kanai (2000) described submarine land failures triggered by the 1983 Japan Sea earthquake as well as prehistoric cases where turbidites are inferred to be proxies for earthquakes (see also Doig, 1990; Inouchi et al., 1996; Goldfinger et al., 2003; Gutscher, 2005; McHugh et al., 2006). All the historic cases considered were also tsunamigenic, and submarine landslides produce tsunamis, but a direct genitive link between tsunamis and turbidity currents is difficult to document.

3. Tsunami Deposits

Tsunami deposits fall into the category geologists refer to as "event deposits," that is, episodic deposits of short-duration, unusual or high-energy processes relative to deposits of everyday or normal conditions, the latter sediments commonly called "background deposits" (Einsele and Seilacher, 1982; Dott, 1983; Clifton, 1988; Einsele et al., 1991). There is no precise definition of "event," and relegation of a process to that category depends partly on temporal and spatial perspective. In the marine realm, the most common such physical events are storms, turbidity currents, underwater landslides, and tsunamis. Rarer and more convulsive events with associated tsunamis would include caldera collapses such as Krakatoa 1883 (Simkin and Fiske, 1983; Carey et al., 2001) and island-sector collapses such as the prehistoric Alika 2 slide on Hawaii (J.G. Moore and G.W. Moore, 1984; J.G. Moore et al., 1994). Catastrophic tsunamigenic events would include oceanic asteroid impacts (Bourgeois et al., 1988; Dypvik and Jansa, 2003).

Tsunamis of geologic significance, that is, ones that leave a geologic record, include those produced by large earthquakes, large landslides, volcanic eruptions, and asteroid impacts. The most common of these, of more than local extent, are tsunamis from earthquakes. Tsunamis from large earthquakes (Mw 7-7.9) will produce regional effects, and tsunamis from great earthquakes (Mw >8, and especially >9) can produce ocean-wide effects.

Thus far, the documented geologic record of recent (Holocene) seismogenic and landslide-generated tsunamis is almost entirely from terrestrial settings, including lakes. There are at least two reasons for the lack of a documented offshore record. First, little work has been done to look for offshore records of tsunamis – in part because of expense, but also in part due to the youthfulness of the field. Second, however, we can expect that most tsunamis will not have as great an effect on the sea floor as storms on the continental shelf (e.g., Bourgeois et al., 1988; Weiss and Bahlburg, 2006) and would thus be reworked. Even on the shoreface, where tsunami effects may be large, their record is likely to be reworked or erased by storm waves. In deeper water, excepting the case of tsunami-triggered turbidity currents, the record is likely to be miniscule and obscure (Pickering et al., 1991).

The literature on pre-Quaternary deposits interpreted to be from tsunami action is almost exclusively about marine deposits of shelf depths and deeper; there are at least three reasons why the onshore record is scarce in older rocks. First, long-term terrestrial erosion removes non-marine strata wholesale. Second, the deposits of recent tsunamis as described in most onshore coastal sites are subtle; moreover, in the geologic record, these deposits may have been interpreted as storm deposits (e.g., see Pratt, 2002). Interpretations of shoreface and shallow-marine facies as tsunami deposits (e.g., Massari and D'Alessandro, 2000; Pratt, 2002) should be viewed with skepticism because storms waves are very effective in this regime. Finally, some of the literature on ancient tsunami deposits is quite speculative and probably wrong.

3.1. Tsunami deposits in the pre-Quaternary Record

Almost all published literature on pre-Quaternary tsunami deposits is associated with asteroid-impact-generated megatsunamis, and about half of these articles are about the Cretaceous-Tertiary (K-T) boundary. Deposits related to postulated megatsunamis also have been associated geologically to several other known impact structures (Gersonde et al., 2002; Dypvik and Jansa, 2003). Most of the remainder of the literature describing ancient tsunami deposits correlates the deposits with geologic evidence for earthquakes; deposits associated with earthquakes are commonly called "seismites."

Pre-Phanerozoic tsunami deposits have been described on a number of continents. The geologically oldest tsunami deposits described in the literature are from Australia and are early Archaean in age, almost 3.5 billion years old (Glikson, 2004). Other Archaean deposits from Australia have been described by Hassler et al. (2000; Hassler and Simonson, 2001) and from South Africa by Byerly et al. (2002). All of these deposits are tied to evidence of asteroid impacts, such as impact spherules; impacts were more frequent in early Earth history than later. Proterozoic deposits from India (Bhattacharya and Bandyopadhyay, 1998), North America (Pratt, 2001) and China (Du et al., 2001) have been tied to evidence for earthquake activity such as deformed beds. Pratt attributes certain layers in the Belt Supergroup to tsunami backwash. Du et al. discuss multiple hypotheses to explain what they call "earthquake event deposits" in Mesoproterozoic strata.

Literature on Paleozoic tsunami deposits is also dominated by impact cases, but includes deposits associated with evidence for earthquakes. Impact-associated cases include Devonian-aged breccias and other coarse-grained deposits known as the Alamo Breccia (Warme and Sandberg, 1995) and the Devonian Narva Breccia correlated with the Middle Devonian Kaluga impact crater (Masaitis, 2002). Speculative earthquake-associated cases include Cambrian and Ordovician strata from North America (Pratt, 2002; Pope et al., 1997).

The Mesozoic tsunami-deposit literature is dominated by K-T boundary articles, but includes a number of Triassic and Jurassic cases, including postulated landslide-generated tsunami deposits (Brookfield et al., 2006). A well-documented impact-related tsunami deposit is associated with the Jurassic Mjolnir crater (Dypvik et al., 2004). There are also several deposits of Cretaceous age attributed to impact-generated or other tsunamis (e.g., Steiner and Shoemaker, 1996; Rossetti et al., 2000; Bievre and Quesne, 2004; Fujino et al., 2006; Weber and Watkins, 2007). Studying upper Cretaceous offshore deposits in Nebraska and South Dakota, USA, Weber and Watkins (2007) used redeposited nannofossils to demonstrate a resuspension event they correlate with the Manson, Iowa, impact ~74 million years ago. Several articles about Mesozoic tsunami geology invoke more than one kind of possible tsunami source (e.g., Bussert and Aberhan, 2004; Schnyder et al., 2005; Simms, 2007). Of course, impacts typically would generate earthquakes and landslides, as can volcanoes, so multiple kinds of tsunami sources would be associated with mega-events.

With regard to the K-T tsunami deposit and associated sediments, the consensus view is that an impact of a ~10-km bolide on the edge of the (paleo-) Yucatan Peninsula generated coarse-grained deposits including tsunami deposits around the Gulf of Mexico and Caribbean (Bourgeois et al., 1988; Smit et al., 1996; Lawton et al., 2005), although there is some literature disputing a tsunami interpretation (e.g., Stinnesbeck and Keller, 1996). K-T deposits related to the impact have also been described in platform carbonates in Brazil (Albertão and Martins, 1996) and in deep-sea sediments of the North Atlantic (Norris et al., 2000). Norris et al. ascribe most observed K-T deposits from deep-sea cores to slope failure and associated turbidity currents; however, they suggest a tsunami may have generated erosional features on the submarine Blake Plateau and elsewhere.

Three Eocene impact structures have been identified in the subsurface record of the continental margin of eastern North America: Chesapeake Bay--35.7 Ma, Toms Canyon--35.7 Ma, Montagnais--51 Ma (Poag et al., 2002), with tsunami deposits described from the Chesapeake Bay structure (e.g., Poag et al., 1992; Poag, 1997). Other pre-Quaternary Cenozoic tsunami deposits include Miocene deposits in Japan (Shiki and Teiji, 1996) and Chile (Cantalamessa and Di Celma, 2005) and scour-and-drape features in Pliocene carbonates in Italy (De Martini et al., 2003). Some work has suggested a relationship between possible tsunami deposits and the Pliocene Eltanin impact structure (Hartley et al., 2001; also see Paskoff, 1991).

3.2. Quaternary deposits attributed to landslide-generated tsunamis

The best-documented deposits from a prehistoric landslide-generated tsunami are from early Holocene Storegga submarine landslides in the North Sea. One of the earliest papers on tsunami deposits was the description by Dawson et al. (1988) of an unusual deposit on the eastern coast of Scotland, which they speculated was produced by tsunami runup from a Storegga event. The correlative deposit was found in Norway, best preserved in coastal lakes (Bondevik et al., 1997; Figure 3.4). Later, a combined group documented multiple landslide-generated tsunamis in this area (Bondevik et al., 2005a; also see Smith et al., 2004).

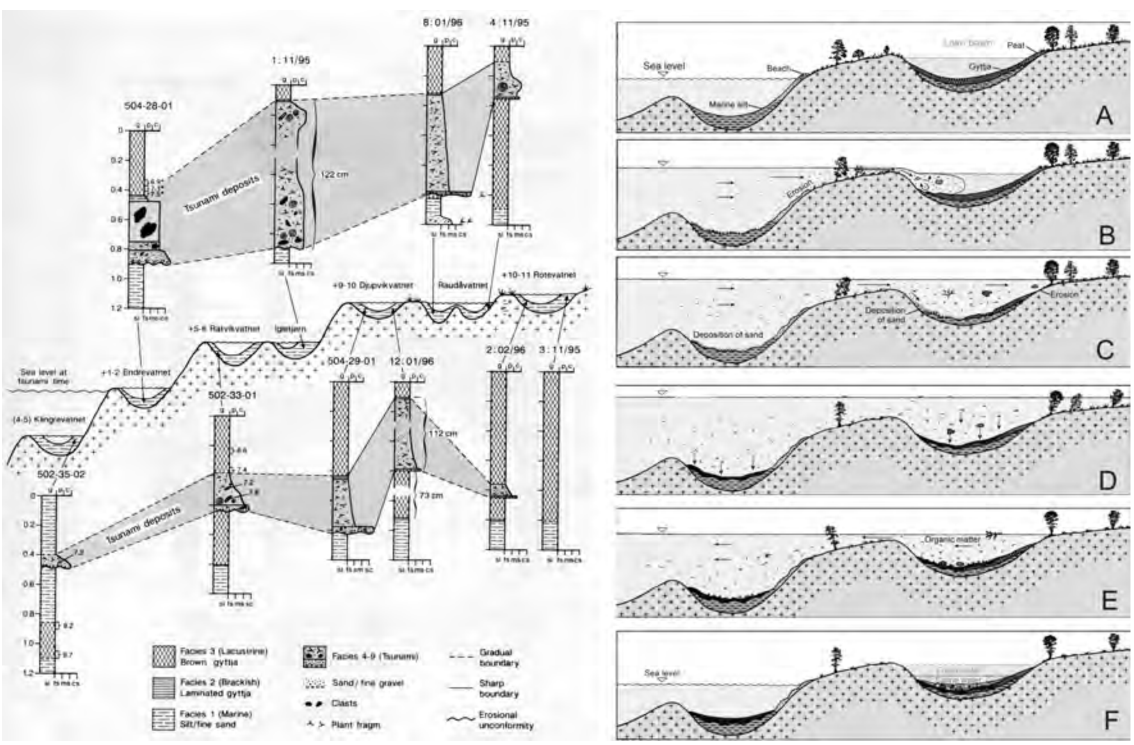

Figure 3.4. Left: Mapped and correlated tsunami deposit in Norwegian coastal lake deposits, from sediment cores. Right: Interpretation of the sequence of events by which this deposit was emplaced by the Storegga-slide-triggered tsunami (Bondevik et al., several publications).

Other tsunami deposits tied to earthquake-triggered landslides include one associated with the North Anatolian fault (Minoura et al., 2005), another with the 1929 Grand Banks tsunami, and another case of sublacustrine gravel ridges attributed to a prehistoric landslide-generated tsunami in Lake Tahoe, U.S. (J. G. Moore et al., 2006). Also, large coral blocks were moved by the 1771 Meiwa tsunami, interpreted by some to be landslide-enhanced but the landslide interpretation disputed by others (see Nakamura, 2006, for review). The Grand Banks tsunami, while understudied around the time of its origin, has recently been reinvestigated. Deposits from the tsunami have been described by Tuttle et al. (2004), who contrast it with an interpreted storm deposit, and A. Moore et al. (2007), who conducted detailed grain-size analysis of the deposit and describe landward fining.

Other Quaternary deposits attributed to submarine landslides are primarily cases associated with volcanic processes. Those landslides not associated directly with eruptive processes include sector collapse of volcanic edifices, of which the most studied are those in Hawaii (J.G. Moore et al., 1994). J.G. Moore and G.W. Moore (1984) mapped, described and named the Hulopoe Gravel on the island of Lanai and suggested it was deposited by a giant tsunami generated by flank collapse of a Hawaiian island. These and similar deposits on other islands had previously been interpreted as uplifted shoreline deposits (reviewed by Grigg and Jones, 1997), and their reinterpretation has remained contentious for more than 20 years. On the tsunami side, A. Moore (2000) made a quantitative argument for tsunami deposition of a similar deposit on Molokai, and McMurtry et al. (2004) described a deposit on the island of Hawaii that they interpret as the deposit of a megatsunami from a flank collapse of Mauna Loa. Most recently arguing on the other side, Felton et al. (2006), in a series of papers, make a detailed paleoecological case against the tsunami interpretation of the Hulopoe Gravel (also see Rubin et al., 2000). On the Canary Islands, Perez Torrado et al. (2006) have described a coarse-grained deposit they also attribute to deposition from a flank-collapse, landslide-generated tsunami.

3.3 Historic and Quaternary geologic records of volcanogenic tsunamis

Explosive island volcanoes are likely to produce sudden sea-floor displacements, such as the 1883 eruption and collapse of Krakatoa, which generated a large tsunami (Simkin and Fiske, 1983; Latter, 1982). Deposits from the Krakatoa tsunamis are used by Carey et al. (2001) in a discussion of tsunami deposits from explosive volcanic eruptions. Van den Bergh et al. (2003) describe an offshore deposit they attribute to the Krakatoa tsunami.

Other historically documented examples of volcanogenic tsunamis and associated deposits include Stromboli in Italy (Tanner and Calvari, 2004), Karimsky Lake on Kamchatka (Beloussov and Beloussova, 2001), and Vesuvius from A.D. 79 (Sacchi et al., 2005). Dominey-Howes et al. (2000) describe historical and geological evidence for historical eruption of Thera (Santorini). Nishimura et al. (1999) review historic tsunami deposits in Japan from volcanogenic sources.

The most studied prehistoric volcanogenic tsunami is one generated by the Santorini caldera collapse about 3500 B.P. (Antonopoulos, 1992; McCoy and Heiken, 2000). Most of these articles describe deposits in the deeper Mediterranean, variously interpreted through the years as more and less directly related to a tsunami (Cita and Aloisi, 2000, and this group's earlier papers; Hieke and Werner, 2000). More recently, Santorini deposits from shallow water and onshore settings have been discovered and described (Minoura et al., 2000; Bruins et al., 2008). At Palaikastro in northeastern Crete, Bruins et al. (2008) reported the discovery of extensive “geoarchaeological tsunami deposits” characterized by a mixture of geological materials, including volcanic Santorini ash, and archaeological settlement debris. Identified tsunami signatures included an erosional lower contact, intraclasts and reworked building stone material in the lower part of the deposit, marine fauna, and imbrication of rounded beach pebbles, settlement debris, ceramic sherds and even bones.

Numbers of other cases of volcanogenic tsunamis have been described, in a few cases including geologic evidence of resulting deposits. In prehistoric cases, there commonly is discussion about what kind of volcanogenic process generated the tsunami—hot pyroclastic flow, cold debris flow, or flank collapse, for example. There are both historic and prehistoric examples of volcanogenic tsunamis from Augustine volcano in Alaska (Waythomas and Neal, 1998; Waythomas et al., 2006); in a prehistoric case, a pumice-bearing tsunami deposit overlies airfall ash, leading to a reconstruction of wave travel time across Bristol Bay. Lowe and de Lange (2000) correlate tsunami deposits on New Zealand to the Taupo (c. 200 A.D.) caldera-forming eruption.

3.4. Holocene seismogenic tsunami deposits

By far the most literature on tsunami geology deals with Holocene tsunami sands deposited on coastal lowlands along seismically active continental margins. This work began in the mid-1980s, the first publications being by Atwater (1987) on Cascadia and Minoura et al. (1987) on Japan. Although there had been some descriptions of historic tsunami sediments by this time (as noted above), this work was scant, and actual tsunamis had been and would be few in the 1970s and 1980s.

Whereas Japan clearly had a historic record of locally generated seismogenic tsunamis, Cascadia did not, and Atwater's described evidence for great earthquakes on the Washington coast spurred research up and down the coast from Canada to California (e.g., Darienzo and Peterson, 1990; Clague and Bobrowsky, 1994; Atwater, 1996; Nelson et al., 1996 as early examples; comprehensive reviews by Clague et al., 2000; Atwater et al., 2005; Nelson et al., 2006; Peters et al., 2007). Moreover, tsunami deposits have been described in the interior seaway between Seattle and Vancouver, BC (Atwater and Moore, 1992; Bourgeois and Johnson, 2001; Williams et al., 2005); some of these are related to local crustal faults.

There have been many studies of Holocene tsunami deposits (and older) in Japan, the most focused of which have been on the island of Hokkaido, which has a relatively short historical record (Minoura et al., 1994; Nishimura and Miyagi, 1995). Thus research there is helping to elucidate tsunami recurrence, and also documenting that prehistoric tsunamis have been larger than historic ones (Nanayama et al., 2003, 2007; Figure 3.5; also see Minoura and Nakata, 1994). Minoura and Nakaya (1991) described sediment effects of the 1983 Japan Sea tsunami and then used that information to interpret paleotsunami deposits on northern Honshu.

Kumagai (1999) documented tsunami deposits from large earthquakes along the Nankai trough in central Japan. On a beach plain in northern Japan, Yagishita (2001) described a layer of coarse gravel most probably deposited by the 1896 Meiji-Sanriku tsunami. Some of the only documented examples of recent tsunami deposits and effects found in marine and estuarine environments come from Japan (e.g., Fujiwara et al., 2000; Noda et al., 2007). However, some deposits attributed to tsunamis in Pleistocene valley fills (Takashimizu and Masuda, 2000) are probably not tsunami deposits but tidally mediated estuarine sands with associated liquefaction structures.

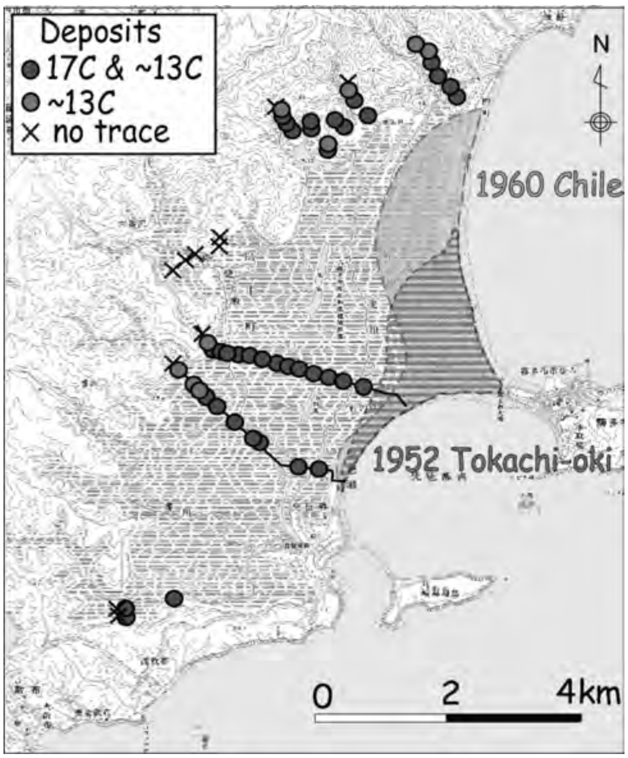

Figure 3.5. Historical tsunamis have inundated the Hokkaido coastline less than 2 km. However, this region has a short written history (unlike other parts of Japan), and paleotsunami deposits some centuries old have been found up to 4 km inland. Based on Nanayama et al., 2003.

There are several other regions where seismogenic paleotsunami deposits have been documented. Such deposits were first described in the Russian Far East by Melekestsev et al. (1995), work continued in particular by Pinegina (e.g., Pinegina et al., 2003). A number of studies have been done in New Zealand (e.g., Goff, 1997; Goff et al., 2001, Cochran et al., 2006; deLange and Moon, 2007), where there has been particular attention paid to the coincidence of archaeological sites with tsunami deposits (McFadgen and Goff, 2007). There is also quite a bit of work in the Mediterranean (e.g., Pirazzoli et al., 1999; Dominey-Howes, 2002; Luque et al., 2002; DeMartini et al., 2003; Reinhardt et al., 2006). Other localities with seismogenic paleotsunami studies not previously mentioned include southern California (Kuhn, 2005), Chile (Cisternas et al., 2006), and Australia (Dominey-Howes, 2007). In India, spurred by studies of the 2004 tsunami deposit, Rajendran et al. (2006) excavated evidence of two possibly comparable paleotsunami deposits, about 1000 and 1500 years old, in archaeological sites.

Because in any one region large tsunamigenic earthquakes have typical recurrence intervals of hundreds of years, few coastlines have long enough historic records to produce statistically significant recurrence probabilities (see Chapter 2). The geologic record of co-seismic deformation has been used in a number of localities to reconstruct these earthquakes (e.g., Atwater and Hemphill-Haley, 1997). Studies of long-term records of seismogenic (paleo)tsunami deposits (e.g., Minoura et al., 1994; Pinegina and Bourgeois, 2001; Kelsey et al., 2002; Nelson et al., 2004; Cisternas et al., 2005; Nanayama et al., 2007) (Figure 3.6) are becoming important to probabilistic hazard analysis not only of tsunamis but also of their parent earthquakes.

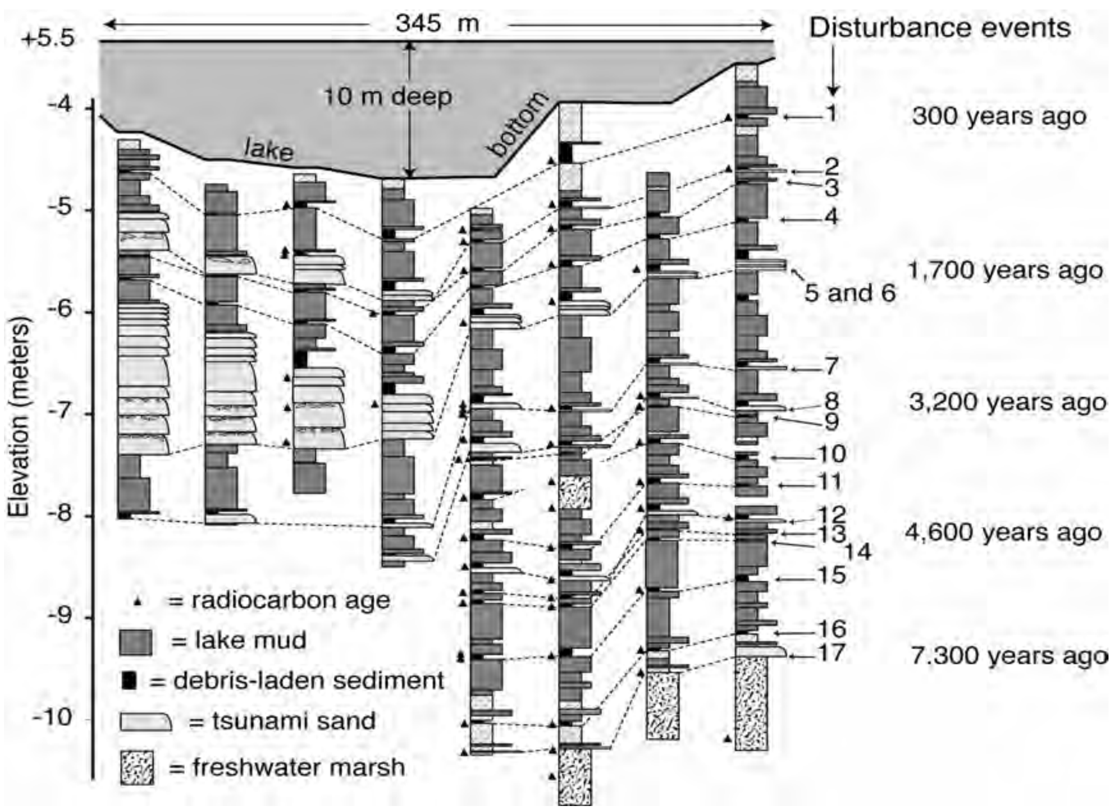

Figure 3.6. An example of long-term records of tsunami deposits interpreted to be from the Cascadia Subduction Zone; from Bradley Lake on the coast of southern Oregon (based on Kelsey et al., 2005).

There is at least one historical case of an inland seismogenic tsunami generated under a lakebed, with a later-studied deposit attributed to the tsunami. That event is the 1872 Owens Valley earthquake, which offset the valley by about one meter, and produced a tsunami that appears to have generated a pebbly sand deposit (Smoot et al., 2000).

3.5. Tsunami-deposit dating and correlation

Numerical age dating of tsunamis has recently been accomplished using optical luminescence dating of quartz grains (Prescott and Robertson, 1997). These grains are reset when exposed to the sun, so that wave-worked nearshore sands are typically zeroed out. Therefore, if these sands are eroded by a tsunami and rapidly buried, the age of their burial can be determined (e.g., Huntley and Clague, 1996; Banerjee et al., 2001; Ollerhead et al., 2001). Murari et al. (2007) tested this technique on the 2004 tsunami deposit in India and with their analysis concluded that most of the tsunami sediment came from near the sediment-water interface, and that a paleotsunami deposit could probably be dated to within about 50 years.

More commonly, tsunami deposits are dated by associated datable material, particularly plant material for radiocarbon dating, which works only for about the last 50,000 years. Radiocarbon dating of shell material is more complicated as local marine reservoirs of carbon must be considered, whereas plants take their carbon from the air. The association of tsunami deposits with marker tephra--that is, well-dated tephra layers (usually by radiocarbon)--has proved very useful in some cases, as illustrated by aforementioned work on Kamchatka and Hokkaido.

Other techniques that have been used to date tsunami deposits are varied. Corals included in deposits have been dated by techniques including electron-spin resonance, radiocarbon and U-series dating. Whether the coral died at the time of the tsunami or was already dead obviously affects these results. Recent tsunami deposits have been dated using included anthropogenic tracers such as PCBs and ^{137}Cs (Barra et al., 2004). Clearly archaeological context can also help date deposits (e.g., Bruins et al., 2008).

Correlation of tsunami deposits is difficult because deposits rarely have intrinsically correlative characteristics. Volcanogenic tsunamis may have associated fresh volcanic materials that aid in correlation (e.g., Waythomas and Neal, 1998; Bruins et al., 2008). On Kamchatka, while individual deposits are rarely correlated, deposits between marker tephra can be counted and thus statistical tsunami recurrence rates estimated (e.g., Pinegina et al., 2003; Bourgeois et al., 2006; Figure 3.7). Nelson et al. (2006) have attempted to correlate tsunami deposits along the Cascadia margin and thus to infer paleo-rupture lengths of the subduction zone. Switzer et al. (2006) used ground-penetrating radar to map deposit continuity in the subsurface.

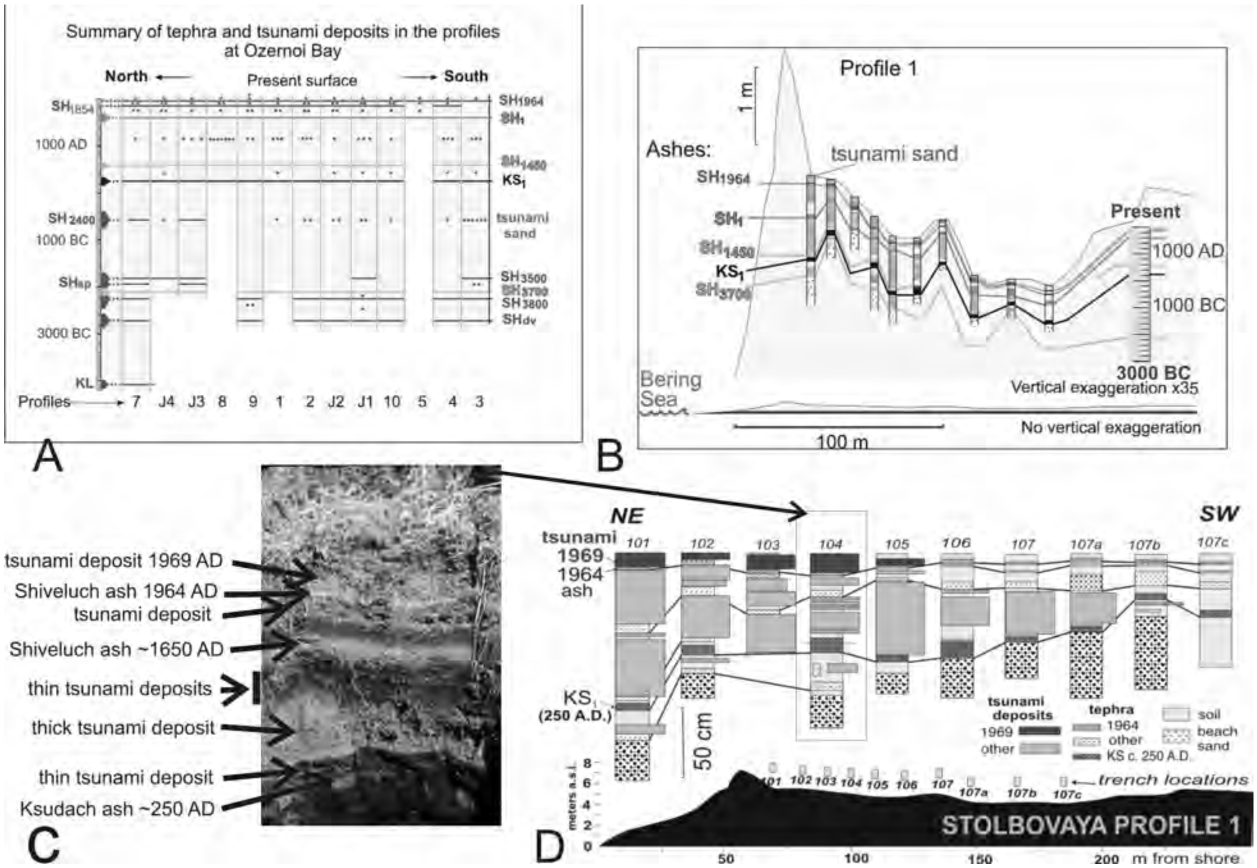

Figure 3.7. A: Summary of tsunami frequency at one locality on Kamchatka, using dated volcanic ash layers for correlation; lines are tephra, dots are tsunami sands. B: Profile 1 (see A) and excavation records, plotted according to true depth in profile. C: Excavation 104 in Profile 1. D: Profile 1 plotted according to field notes; note 1969 tsunami deposit (see Figure 10) (based on Bourgeois et al., 2006).

4. Other Themes in Tsunami Geology

Of themes that emerge in a literature review of tsunami geology, two that bridge disciplines are tsunami geomorphology and geoarchaeology. Many papers also consider aspects of hazard analysis using tsunami deposits (e.g., Fiedorowicz and Peterson, 2002; Szczuciński et al., 2006; Kumar et al., 2007). A few focus on field and lab methodology.

4.1. Tsunami geomorphology and tsunami erosion

Where there is tsunami deposition, there must have been erosion, but erosion and other geomorphic aspects of tsunamis are explicitly considered in less than 5% of prehistoric cases. Historical surveys and photographs, however, clearly show that tsunamis are geomorphic agents, if only temporarily. Dawson (1994) wrote a brief review of known and speculated geomorphic effects of tsunamis, including boulder deposits; Scheffers and Kelletat (2003) wrote another review, including their own speculations about chevrons, to be discussed below. Well-documented, preserved geomorphic features of tsunamis include scoured depressions through beach ridges and associated lobate accumulations landward. Vegetation and soil stripping are also common, especially in the proximal zone. Using both satellite images and on-the-ground surveys, erosion from the 2004 Indian Ocean tsunami has recently been documented in a number of cases (e.g., Srinivasalu et al., 2007 and previously cited papers; also see Fig. 3.1).

There is a very speculative literature on bedrock sculpting by tsunamis (e.g., Bryant and Young, 1996; Aalto et al., 1999), not based on observed examples. There is no fundamental basis for the argument that tsunamis are more powerful sculptors than storm waves. Bryant (2001 and earlier papers) has gone further and argued that tsunamis are important coastal geomorphic agents in Australia and elsewhere, on coastlines where tsunamis are historically rare. These interpretations have been disputed (e.g., Felton and Crook, 2003; Dawson, 2003; Dominey-Howes et al., 2006). For example, Dawson (2003) said "Such explanations are in contradiction with everything that is written and known about the Quaternary of Scotland and the author [Bryant] appears blissfully unaware that features he describes have been affected by a complex glacial and sea-level-change history. Unfortunately, there are many pages of text here that students would be well advised to avoid at all costs."

Another area of unfounded speculation, almost certainly mistaken, is the argument that along many semi-arid coastlines, certain large Holocene parabolic sand dunes, called "chevrons" by some authors, are the product of mega-tsunamis, possibly generated by asteroid impacts (e.g., Bryant, 2001; Scheffers and Kelletat, 2003). Others have interpreted these bed forms as eolian; some cases on carbonate platforms may be due to storm waves. Examples of problems with the "chevron" megatsunami speculation include the facts that very similar bed forms are present in the interiors of continents; that the bed forms do not show evidence of bathymetric and topographic steering as expected from tsunamis and not from wind; and that the bed forms are peculiar to certain climatic conditions. Moreover, the construction of large sandy bed forms requires low shear stresses (bed load transport conditions) over extended time periods (days or more); neither would be the case for impact-generated (or other) tsunamis. The chevrons are constructed principally of sand, though larger clasts have been found nearby (e.g., Kelletat and Scheffers, 2003). If those large clasts were transported at the same time as the "chevron" sand, the bed load condition for the sand would almost certainly be violated.

Let's consider just the bed load transport argument. When sediment is transported at bed load (relatively low boundary shear stress, τ_b), there will be bed forms (ripples, dunes) on the bed, leaving behind cross-stratification. When sediment is transported as suspended load (higher shear stresses), bed forms wash out, called the plane bed condition; typical deposits will be planar laminated, or massive to normally graded if deposited rapidly. Thus already, without reference to chevrons, we can infer for recent tsunami deposits that these historical sediments were transported principally as suspended load, based on their characteristic graded, planar-laminated or massive bedding (summaries in Dawson and Shi, 2000; Dominey-Howes et al., 2006). The transition from bed load to suspended load is dependent on a relationship between boundary shear stress τ_b (typically expressed as "shear velocity" = $[\tau_b/\rho]^{1/2}$) and grain settling velocity W_s, this relationship commonly referred to as the Rouse criterion (e.g., Vanoni, 1975).

For bed load transport to take place, U_* should be less than W_s (Abbott and Francis, 1977). For sand, with a *maximum* W_s in water of about 0.1 m/sec (very coarse sand), the skin friction component of U_* should be less than 0.1 m/sec in order for bed forms to be stable on the bed.

Now let's take a *minimum conservative condition* during postulated megatsunami flow over the chevrons. Actively migrating bed forms must be inundated with water at least twice their height, and chevrons are reported to be 8-20 m high and more (and reported to be present at elevations above modern sea level of more than 100 m) (Kelletat and Scheffers, 2003). If we take a very conservative minimum flow depth of 20 m, a Froude number of 1 (a conservative choice—higher Froude numbers will give greater velocities), and a characteristic roughness of 0.5 m, the skin friction portion of U_* would be about 0.4 m/sec, giving a Rouse number of 0.6, well within the condition for suspended load. Greater flow depths, as postulated or required for these "chevrons" if they are indeed megatsunami deposits, would of course increase the shear velocity and decrease the Rouse number.

.4.2. *Paleontology and archaeology of tsunami deposits*

Fossils in tsunami deposits have been used in a number of studies; fossils are also used extensively to document co-seismic deformation, which will not be reviewed here. Presence of marine fossils in a deposit is one piece of evidence for a tsunami origin, rather than fluvial or eolian (non-marine) processes (Hemphill-Haley, 1995; S. Dawson et al., 1996; Hutchinson et al., 1997; Williams and Hutchinson, 2000; Sawai, 2002). There has also been some discussion of the depth of origin of benthic microfossils in tsunami deposits and its possible significance. From the distribution of foraminifera and ostracodes in their samples, Hussain et al. (2006) inferred that the 26 December 2004 tsunamigenic sediments deposited on the coast of the Andaman group of islands were derived from shallow littoral to neritic depths and not from deeper bathyal territories.

A number of other types of tsunami studies have used faunal and floral elements. Hemphill-Haley (1996) showed that the landward extent of marine microfossils exceeded the landward extent of tsunami sand and silt, illustrating that a recognizable siliciclastic deposit is only a limiting minimum for inundation (Hemphill-Haley, 1996). Nanayama and Shigeno (2006) used microfossils to distinguish tsunami inflow deposits from outflow deposits. While most studies have used microfossils, Fujiwara et al. (2003) described and interpreted mixed molluscan assemblages in tsunami deposits. Hughes and Matthewes (2003) describe plant recolonization following a tsunami.

Many ancient as well as historical settlements are located on coastlines, particularly in cases of maritime societies, so it is not surprising that many coastal archaeological sites include evidence for tsunamis. For example, Veski et al. (2005) describe an anomalous deposit in early Holocene archaeological sites in Estonia that they tentatively correlate with either the Storegga-slide tsunami or an asteroid impact (with regional evidence of spherules) (also see Bondevik, 2003). McFadgen and Goff (2007) summarize several geoarchaeological investigations of mostly seismogenic tsunamis in New Zealand. As noted in the section on Santorini, Bruins et al. (2008) have reported the discovery of extensive "geoarchaeological tsunami deposits" in northeastern Crete. A number of other interdisciplinary studies mention tsunami as a possible contributor to the history of archaeological sites (e.g., Luque et al., 2002; Carson, 2004).

5. Recent Directions in Tsunami Geology and Sedimentology

No doubt the 2004 Indian Ocean earthquake and tsunami will have a major impact on our understanding of tsunami geology, and it is difficult yet to synthesize this ongoing work (Razzhigaeva et al., 2006; Hawkes et al., 2007; Hori et al., 2007; Srinivasalu et al., 2007; and others). The level of effort and detail of work are impressive (e.g., Figure 3.8). An example of the importance of this tsunami to our understanding is its complexity--since 1960 Chile and 1964 Alaska, 26 December 2004 the most complex tsunami in terms of number of large waves. Unraveling this complexity via tsunami deposits is a challenge, but abundant videos and still photos, as well as eyewitness accounts, are helping sedimentologists do so in many thorough studies.

Some basics we have learned or re-learned from the Indian Ocean case, relevant to sedimentology, include the observation that the tsunami on land was rather like a river without banks. Major waves commonly had multiple waves superimposed on them, and many localities experienced withdrawals between major waves. Acceleration, deceleration, and wave reflection are shown in video images. Thus the deposits from this tsunami, and presumably others of comparable scale, are commonly complex, though still dominated by suspended load leading to massive, graded or laminated structure.

Prompted by the 2004 tsunami, many new investigators are being trained in tsunami geology. Countries around the Indian Ocean are engaging their scientists in paleotsunami studies (e.g., Rajendran et al., 2006). Another region where such work is still in early phases is the Caribbean (Morton et al., 2006). Moya et al. (2006) review the tsunami history of Puerto Rico and describe cores with both historical and pre-historical sand layers they interpret to be tsunami deposits. The Caribbean is one of the areas where debate about whether storms (hurricanes) or tsunamis are responsible for boulder transport, gravel ridges, and other coastal features (e.g., Scheffers, 2004; Morton et al., 2006).

In a June 2005 workshop on tsunami geology, 80 scientists conferred on recent advances and new directions in the field. For example, as noted below, geologists and tsunami modelers are beginning to work together, and tsunami sedimentology is becoming more quantitative. Tsunami geology is being used for inverse modeling to earthquake sources. The web of possible interactions among tsunami geology and related fields is shown in Figure 3.9.

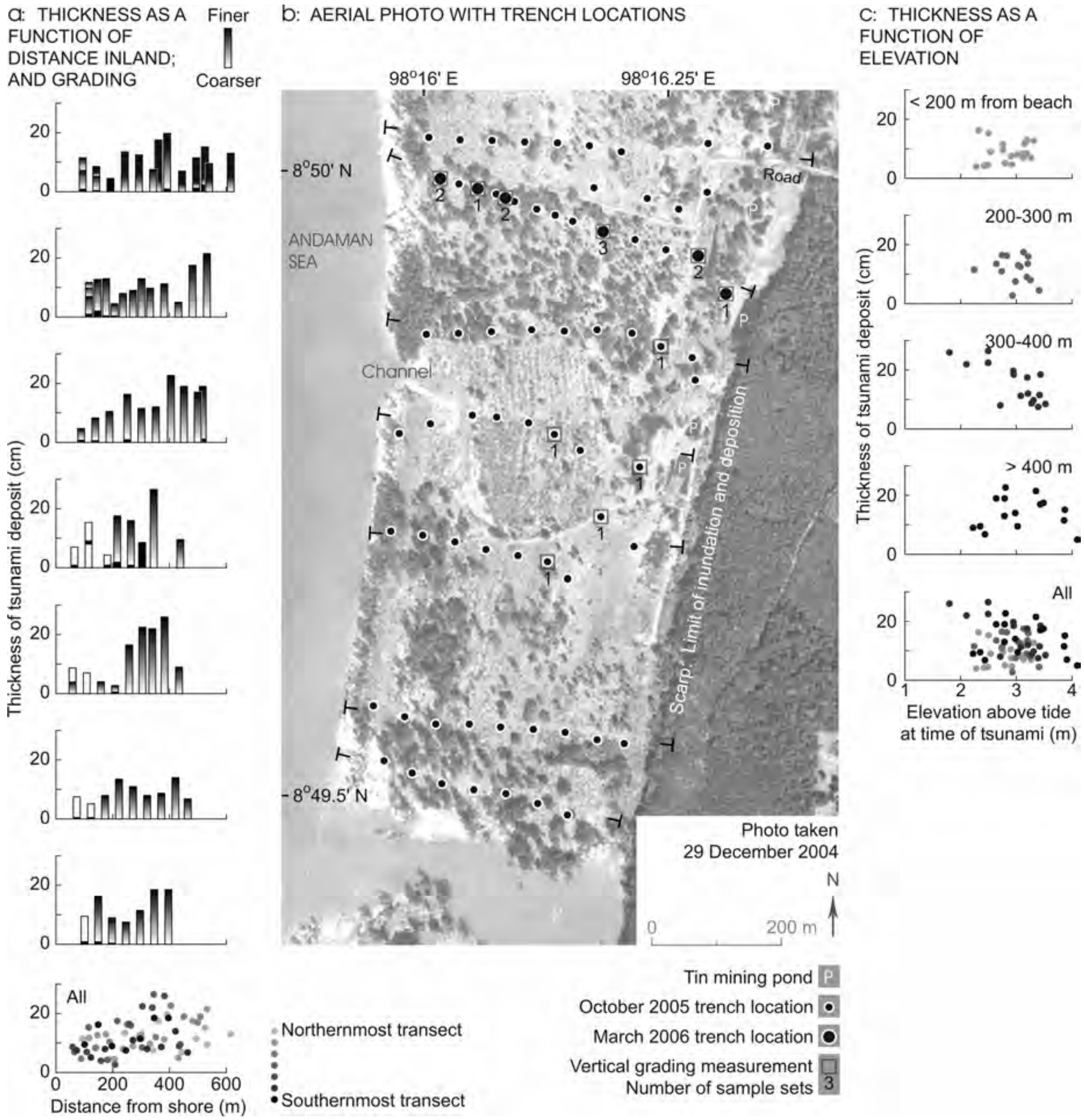

Figure 3.8. Distribution and analysis of the 26 December 2004 tsunami in Kao Lak Thailand (Higman figure from Alam et al., in press); used with permission.

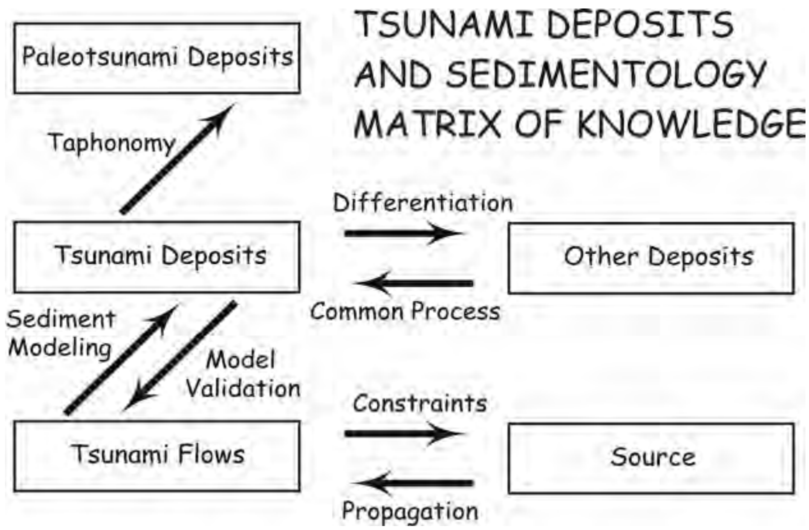

Figure 3.9. A geologist starts with a paleotsunami deposit and works back toward an understanding of the processes by which it was deposited ("tsunami flows"). To arrive there, one must understand how the deposit has been altered since deposition ("taphonomy") and also how tsunamis transport and deposit sediment ("sediment modeling"). One must also determine that the deposit is truly from a tsunami and not from another event such as a storm ("differentiation").

This diagram also emphasizes that other processes and their deposits can help us understand tsunami deposits because many such events--such as dam-break floods, turbidity currents, and tidal bores—share "common processes."

The nature and distribution of tsunami deposits can help validate models of tsunami "flow" – propagation and runup – and that flow's geologic effects – erosion and deposition.

Ultimately, we may want to understand/invert the deposit not only to the tsunami, but also to the tsunami source. What were the rupture parameters of the earthquake? Was the tsunami from an earthquake or from a landslide? A volcanic eruption? An asteroid impact?

Diagram developed by working group during NSF-sponsored Tsunami Deposits Workshop, June, 2005.

5.1. Tsunamis and neotectonics

Mapped tsunami deposits provide minimum runup heights and inundation distances, which in turn are related to earthquake rupture characteristics (see other chapters in this volume). Thus by inverse modeling paleotsunami deposits can help us reconstruct tsunami sources and attendant tectonic character of a region. For example, Satake et al. (2005) used modern and paleotsunami records on Hokkaido to reconstruct earthquake sources on the southern Kuril trench. Bourgeois et al. (2006) reconstructed more than 2000 years of paleotsunami history on the Bering Sea coast of Kamchatka and used this information, as well as an inverse model of the local 1969 tsunami, to estimate the convergence rate on this previously understudied boundary. Nelson et al. (2006) used paleotsunami deposits and other paleoseismological evidence to examine possible segmentation of the Cascadia subduction zone. Martin et al. (2008) distinguished two earthquake sources (1969 and 1971) on Kamchatka by inverting the distribution of deposits back to the source regions (Figure 3.10).

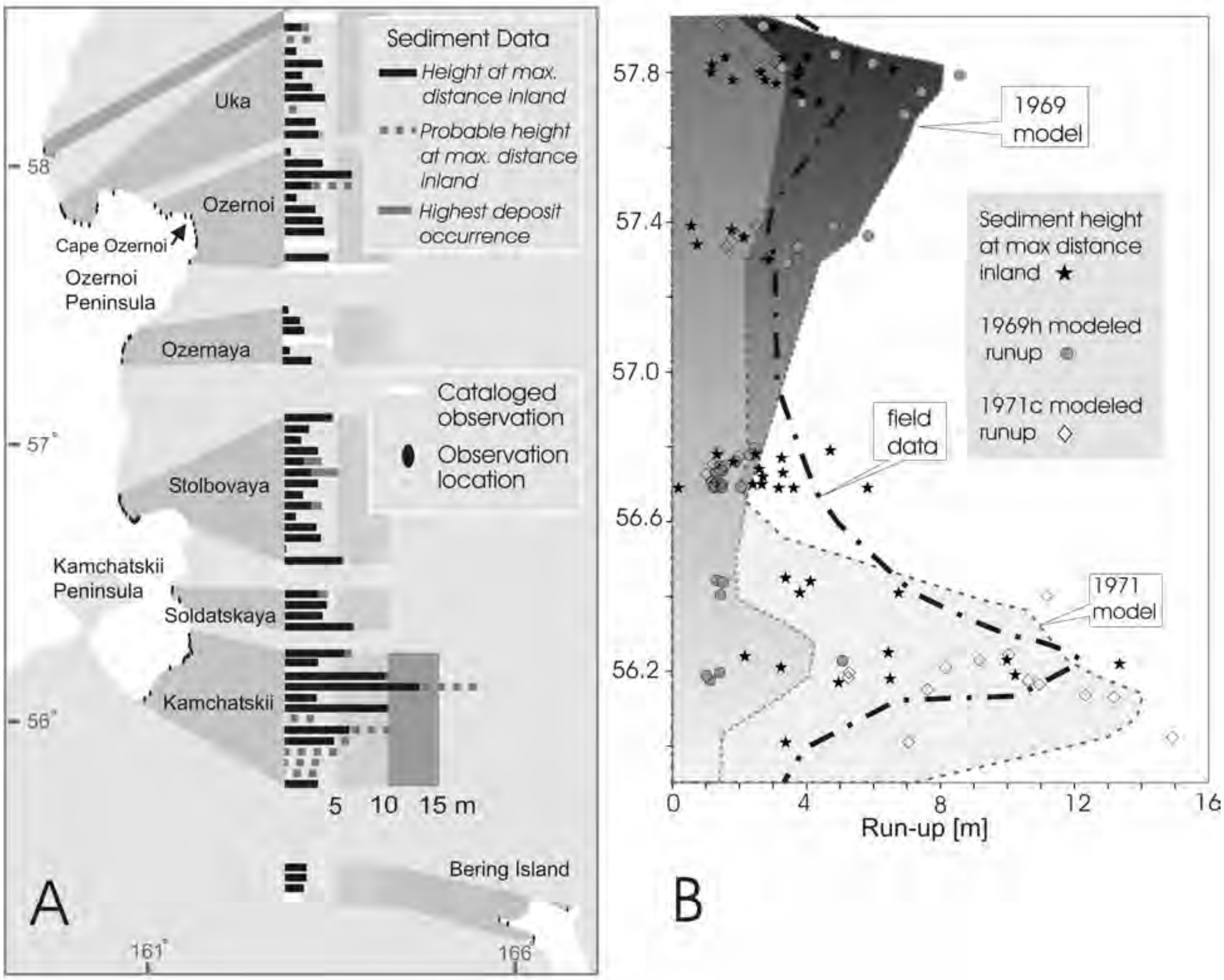

Fig. 3.10. Elevations of recent tsunami deposits along the Bering Sea coast of Kamchatka compared to runup models generated with the Method of Splitting Tsunamis (MOST) (Martin et al., 2008). Right: Distribution of maximum elevations of young tsunami deposits. Tsunami deposits can be taken only as MINIMA for tsunami elevation, runup and inundation because 1) the water must be higher than the highest deposit, but we do not know now much higher; and 2) the tsunami can outrun its deposit. Left: Comparison of runup models and tsunami sediment data. After Martin et al., 2008.

5.2. Storm vs. tsunami and the boulder-transport problem

Since the beginnings of modern studies, the most pressing question has been, How does one distinguish an (onshore) tsunami deposit from an onshore storm deposit? (e.g., Witter et al., 2001). Knowledge of both is rapidly growing, and studies from the 2004 Indian Ocean tsunami and 2005 Katrina hurricane will add significantly to our body of knowledge. Several papers on this topic have taken the approach of comparing historical examples of storm and tsunami deposits (e.g., Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004; Morton et al., 2007). From these studies, as well as from reasoning about the differences between tsunamis and storm surges, a summary contrast is emerging (e.g., Figure 3.11). Offshore, *most* tsunamis will be less effective than storms, and their record in the nearshore may commonly be erased by storm waves (Weiss and Bahlburg, 2006). Onshore, storms are more likely to generate wedge-like, bed-load dominated units, whereas tsunamis are more likely to produce sheet-like, suspended-load dominated deposits (Figure 3.11).

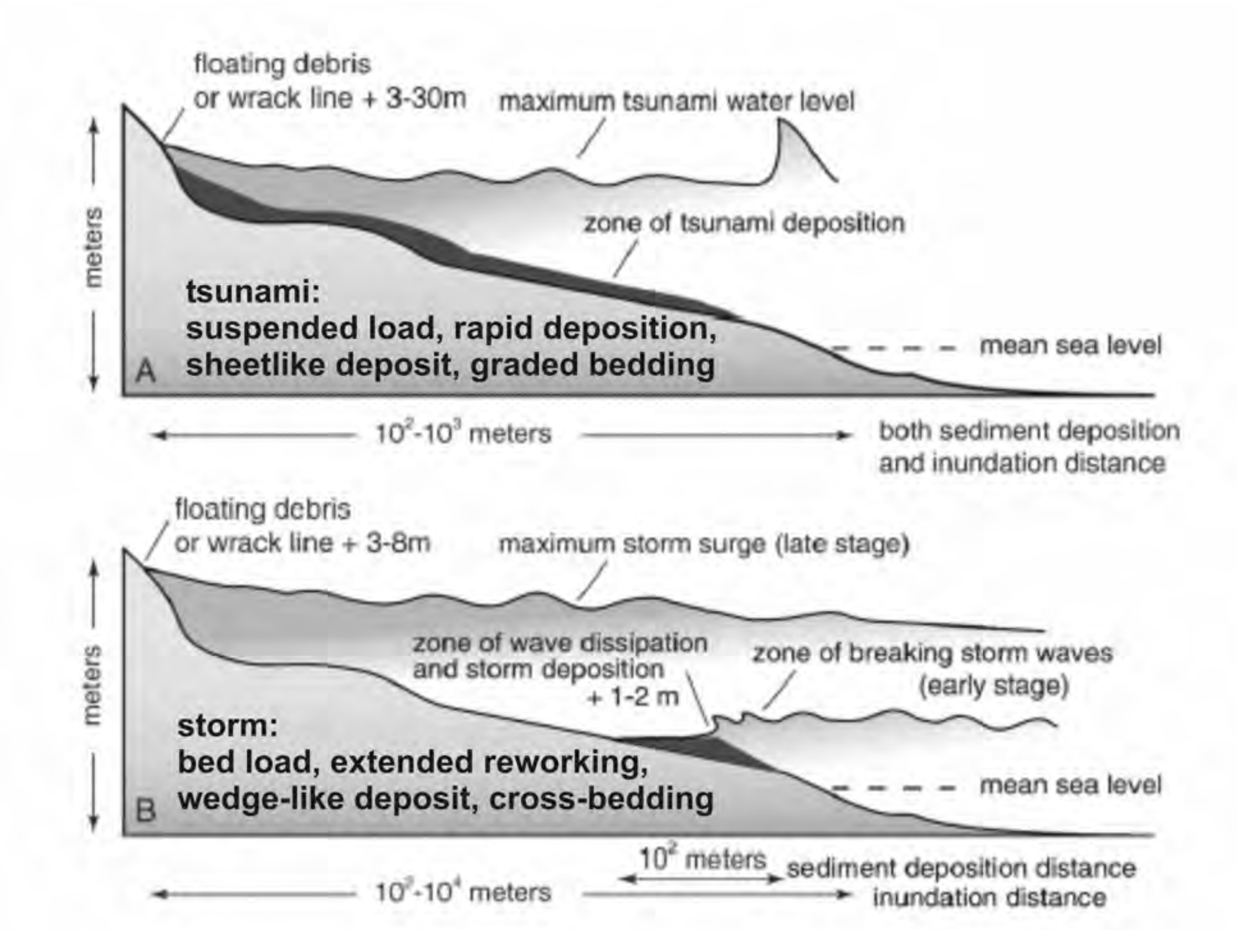

Figure 3.11. Summary comparison of sand deposited by a typical tsunami and a typical storm surge, on a coastal profile. After Morton et al., 2007, courtesy of the authors.

In addition to discussing physical characteristics, some authors have examined whether fauna, flora, or other microscopic characters can help distinguish deposits of storms from tsunamis (e.g., Nigam and Chaturvedi, 2006). Kortekaas and Dawson (2007) found no difference in foraminifera in historical storm and tsunami deposits and concluded that only a combination of characteristics allowed distinction. Bruzzi and Prone (2000) used the surface texture of sand grains as a possible criterion for distinguishing storm and tsunami deposits.

The most controversial field of tsunami geology currently is the interpretation of certain coarse-grained deposits, particularly boulders, transported either by storms or tsunamis (if not some unimagined process). Recent large-clast transport by both storm waves and tsunamis is well documented, but even this literature must be read critically. Our bibliography includes nearly 30 refereed articles, about half favoring tsunamis and half storms. (Of course, both interpretations could be valid in different or even the same cases, such as the Caribbean.) Most of these papers consider boulders and gravel currently on the surface; for this review, pre-Quaternary deposits are excluded.

The earliest paper attributing surficial bouldery deposits to a prehistoric tsunami was the aforementioned work by J.G. Moore and G.W. Moore (1984, 1988) on the Hulopoe Gravel on Lanai. The interpretation of these deposits remains unsettled (Noormets et al., 2004). Other coastal regions where the controversy is active include Australia (Young et al., 1996; Nott, 1997; Saintilan and Rogers, 2005) and the Caribbean (Jones and Hunter, 1992; Scheffers, 2004; Morton et al., 2006). Mastronuzzi and Sanso (2000) conclude that boulders on the coast of southern Italy were tsunami-transported. Williams and Hall (2004) document accumulations of "megaclasts" on the Atlantic coast of Ireland, attribute them to large storms, and caution against the use of large transported boulders as evidence for (mega)tsunamis.

5.3. Quantitative tsunami sedimentology

Only recently have there been many substantive studies on quantitative aspects of tsunami sedimentology (e.g., Jones and Mader, 1996; Minoura et al., 1997; Hindson and Andrade, 1999; Matsutomi et al., 2001; Tonkin et al., 2003; Schlichting and Peterson, 2006; Smith et al., 2007; Gelfenbaum et al., 2007). Approaches have varied from experimental to theoretical, from forward to inverse modeling. Studies fall broadly into two categories: studies of tsunami sediment transport, and inversions of map distributions of deposits to runup and source models.

Forward models of tsunami propagation and runup (without sediment) have been benchmarked and tested, though these models are commonly limited by bathymetric and topographic data (see Chapters 8 and 9). (Clearly roughness is another major factor; for example, Minoura et al. (1996) describe how a tsunami over snow will lose less momentum than over vegetation.) Because these forward models predict the distribution of tsunami flow over a coastal area, the distribution of a tsunami deposit over this area can be inverted to a tsunami and its source. This approach has been attempted, for example, in the North Sea Storegga case (Bondevik et al., 2005b), in Japan (Satake et al., 2005), and on Kamchatka (Figure 3.10).

There are still few published quantitative studies of tsunami sediment transport, but the field is growing. In an early attempt, Eaton et al. (1961) made crude calculations of the forces necessary to move large boulders transported by the 1960 Chile tsunami on Hawaii. Bourgeois et al. (1988) calculated the shear stress necessary to move the largest clasts in a deposit at the Cretaceous-Tertiary boundary by calculating lift and drag on the clasts. Then, using Airy wave theory as an approximation, they estimated the size of the wave that could have moved these clasts in >50 m water depth. However, methods for calculating initiation of boulder transport remain unsettled.

There are two published kinds of inverse models for tsunami sediment transport, and both are works in progress, with numbers of assumptions. Also, Matsutomi et al. (2001) review a semi-empirical method of relating tsunami flow to sediment transport. The "advection model" (Soulsby et al., 2007; Moore et al., 2007; and earlier cited work) calculates a depth-velocity product that can transport a given grain size class (in suspension) from high in the flow to its farthest point inland. This model assumes no reentrainment. If neither the depth nor velocity is known, then a second method must be used to solve for these two unknowns. The "Rouse model" (my term) (Jaffe and Gelfenbaum, 2007) assumes that all the sediment at one point on the bed was deposited from the overlying water column at one time and inverts the sediment size and volume distribution of that deposit to a shear stress using the Rouse equation. This approach assumes the flow is quasi-steady and quasi-uniform.

Forward models of tsunami sediment transport have been presented at meetings but have yet to be published, except in meeting proceedings (Gelfenbaum et al., 2007; see Huntington et al., 2007). All studies of tsunami sediment transport remain in alpha testing, and this field is a very promising one for future scientists because of its importance both to evaluating tsunami hazard and to reconstructing geologic history.

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