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Catastrophic Wave Erosion, Bristol Channel, United Kingdom: Impact of Tsunami?

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Abstract

On January 30, 1607, a massive wave from the ocean surged up Bristol Channel in the United Kingdom, flooding more than 500 km2 of lowland along 570 km of coast. It killed 2000 people and is considered Britain's worst natural disaster on land. The wave occurred on a fine day and surprised inhabitants. Contemporary descriptions of the event have many of the characteristics of accounts of recent catastrophic tsunamis. Geomorphic evidence for tsunamis in the channel can be found in the form of transported and imbricated boulders, bedrock sculpturing on coastal platforms and ramps, and, at isolated locations, wholesale erosion of the coastal landscape. Hydrodynamic calculation of the height of the tsunami and flow velocities can be derived from boulder dimensions. Tsunami wave height increased from 4 m in the outer Bristol Channel to more than 6 m within the inner Severn Estuary. Theorized flow velocities range between 11.8 and 18.1 m s1, increasing up the estuary. Under topographic enhancement, these depths and velocities may be sufficient to generate bedrock sculpturing, which is indeed observed at a few locations on rocky headlands in the channel. Interpolation of the amount of cliff retreat at Dunraven Bay indicates that an imbricated boulder train was deposited by tsunami sometime between 1590 AD and 1672 AD, a time span that encompasses the January 30, 1607, event.

Keywords

tsunami, Bristol Channel, 1607

Disciplines

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ARTICLES

Catastrophic Wave Erosion, Bristol Channel, United Kingdom: Impact of Tsunami?

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ABSTRACT

On January 30, 1607, a massive wave from the ocean surged up Bristol Channel in the United Kingdom, flooding more than 500 km^2 of lowland along 570 km of coast. It killed 2000 people and is considered Britain's worst natural disaster on land. The wave occurred on a fine day and surprised inhabitants. Contemporary descriptions of the event have many of the characteristics of accounts of recent catastrophic tsunamis. Geomorphic evidence for tsunamis in the channel can be found in the form of transported and imbricated boulders, bedrock sculpturing on coastal platforms and ramps, and, at isolated locations, wholesale erosion of the coastal landscape. Hydrodynamic calculation of the height of the tsunami and flow velocities can be derived from boulder dimensions. Tsunami wave height increased from 4 m in the outer Bristol Channel to more than 6 m within the inner Severn Estuary. Theorized flow velocities range between 11.8 and 18.1 m s^{-1}, increasing up the estuary. Under topographic enhancement, these depths and velocities may be sufficient to generate bedrock sculpturing, which is indeed observed at a few locations on rocky headlands in the channel. Interpolation of the amount of cliff retreat at Dunraven Bay indicates that an imbricated boulder train was deposited by tsunami sometime between 1590 AD and 1672 AD, a time span that encompasses the January 30, 1607, event.

Introduction

It is now recognized that tsunamis affect the evolution of many coastal landscapes worldwide. In Australia, megatsunamis are responsible for shaping headlands and spreading sediment kilometers inland, in some cases tens of meters in thickness (Bryant et al. 1992, 1996, 1997; Bryant and Young 1996; Bryant and Nott 2001; Nott and Bryant 2003). In the Caribbean, tsunamis are responsible for the deposition of boulder ridges along the coast and the transport of boulders hundreds of meters inland (Scheffers 2002, 2004; Scheffers et al. 2005). In Spain, repeated tsunamis are recorded in mid-Holocene coastal deposits (Ruiz et al. 2005). And in the southern Ryukyu Islands, five large tsunamis have spread inland in the past 3000 yr (Kawana and Nakata 1994). In most cases, the evidence is prehistoric, based on geological indicators, and poorly correlated to specific tsunamis. But sedimentation in New Zealand has been linked to major tsunamis, some of them in the historic record (Goff et al. 1998; Goff and Chagué-Goff 1999). Also, Andrade (1992) showed there was a major reorganization of the barrier islands along the Algarve coast of Portugal by tsunamis after the Lisbon earthquake of November 1, 1755. This article adds to this recent evidence juxtaposing the geological and historic records. On January 30, 1607, major flooding occurred in the lowlands adjacent to Bristol Channel and the Severn Estuary in the United Kingdom. While this flooding has been explained as a storm surge, we showed through an analysis of historic records that the event was likely a tsunami (Bryant and Haslett 2002; Haslett and Bryant 2004). This

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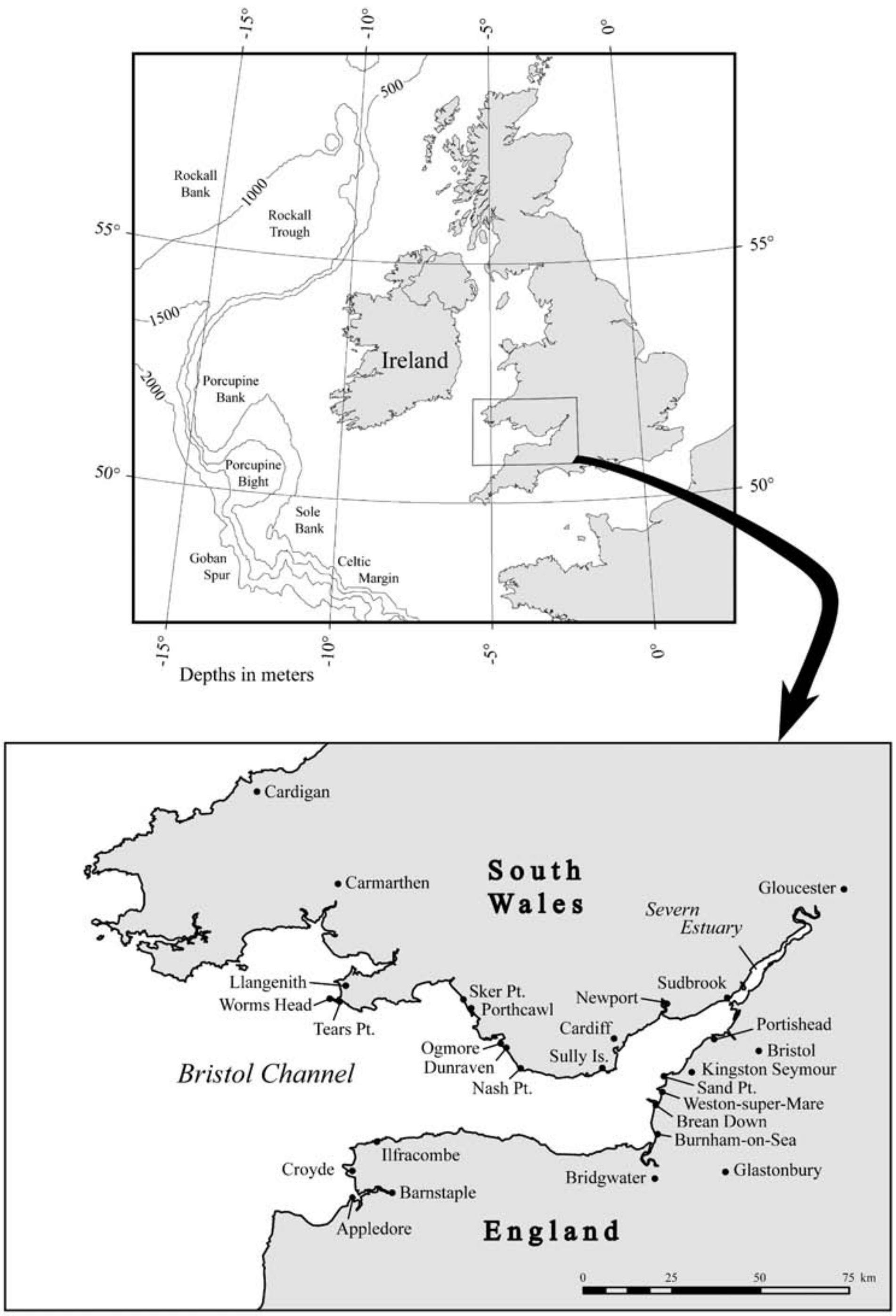

Figure 1. Location map of Bristol Channel.

article outlines the geomorphic evidence for the presence of tsunamis in Bristol Channel (fig. 1) that may relate to this event.

1607 Event

Historic floods in Bristol Channel and the Severn Estuary are reasonably well documented. Two events had the greatest regional impact: a flood related to the surge of the Great Storm of November 26–27, 1703, and a catastrophic flood on January 30, 1607 (January 20, 1606, for a contemporary seventeenth-century English calendar). The 1703 storm, although reported to have had a severe impact on shipping and buildings across southern Britain, had local and minor physical impacts on the coast (Risk Management Solutions 2003). But the 1607 flood appears to have been restricted to the coast and coastal lowlands of Bristol Channel and the Severn Estuary, catastrophically flooding 518 km^2 along 570 km of coastline and causing 2000 recorded deaths and great economic loss. The area affected by the 1607 flood extended from Barnstaple (Devon) and Carmarthenshire coast in Bristol Channel to the head of the Severn Estuary at Gloucester (privately published pamphlet available at St. Thomas the Apostle, Redwick [anonymous, undated]; Morgan 1882; Boon 1980). Most of the documentary evidence refers to Somerset and Monmouthshire. Some local churches record the flooding with commemorative plaques, such as at Kingston Seymour (Bailey 2000), Goldcliff (Boon 1980), St. Brides (Coxe 1904), Redwick (privately published pamphlet [anonymous, undated]), and Peterstone (Haynes 1986). The plaque at Kingston Seymour indicates that floodwaters were 1.5 m deep and remained for 10 d. It therefore appears that the flood was of considerable extent and depth.

Bryant and Haslett (2002) and Haslett and Bryant (2004) reviewed the contemporary accounts describing the 1607 flood event. While some mention stormy conditions, stating that the sea was "very tempestuously moved by the windes" (*Lamentable Newes out of Monmouthshire in Wales*, contemporary pamphlet, quoted in Morgan 1882, p. 4), others make no mention of the weather, stating that the flood occurred without warning. Some portray a tranquil scene:

> [F]or about nine of the morning, the same being most fayrely and brightly spred, many of the inhabitants of these countreys prepared themselves to their affayres then they might see and perceive afar off as it were in the element huge and mighty hilles of water tombling over one another in such sort as if the greatest mountains in the world had overwhelmed the lowe villages or marshy grounds. Sometimes it dazzled many of the spectators that they imagined it had bin some fogge or mist coming with great swiftness towards them and with such a smoke as if mountains were all on fire, and to the view of some it seemed as if myriads of thousands of arrows had been shot forth all at one time. (*God's Warning to his People of England*, contemporary pamphlet, quoted in Mee 1951, p. 131)

These apparently eyewitness accounts have led a number of popular and local history writers to refer to the flood as being caused by a "tidal wave" (Phillips 1951; Haynes 1986). This is not surprising, given the similarity of the descriptions to historic tsunamis, such as the one following the eruption of Krakatau in 1883, where accounts refer to the sea as being hilly. Also, reference to dazzling, fiery mountains and myriads of arrows is similar to accounts of tsunamis on the Burin Peninsula, Newfoundland, in 1929, where the tsunami crest was shining like car headlights, and in Papua New Guinea in 1998, where the tsunami was frothing and sparkling (Bryant 2001).

Based on these inconsistencies and other documentary evidence, Bryant and Haslett (2002) developed the hypothesis that the 1607 flood could have been caused by a tsunami. Other supportive contemporary accounts include that of "one Mistress Van … is vouched before she could get uppe into the higher rooms of her house, having marked the approach of the waters, to have been surprised by them and destroyed, her house being distant above four miles in breadth from the sea" (*Lamentable Newes*, quoted in Morgan 1882, p. 5). This suggests that the flood occurred very rapidly to cover a considerable distance, which is corroborated further by a passage stating that the flood waters are "affirmed to have runne … with a swiftness so incredible, as that no gray-hounde could have escaped by running before them" (*Lamentable Newes*, quoted in Morgan 1882, p. 4). The rapidity with which such extensive flooding was achieved is more likely due to a tsunami than to a storm surge. Furthermore, a fully laden 60-t ship ready to set sail at Appledore in North Devon was transported from the harbor onto marshland by the wave, a situation that is unlikely if storm conditions were prevailing at the time (Haslett and Bryant 2004). Previously published yet enigmatic physical occurrences within the Severn Estuary may also be associated with the 1607 flood (Bryant and Haslett 2002). These include the complete erosion of all salt marsh before the mid-seventeenth century (Allen and Rae 1987) and the erosion down to bedrock of two spurs of alluvial agricultural land in the early seventeenth century (Allen and Fulford 1992).

The Relative Magnitude of Geomorphic Signatures of Tsunamis

Dawson et al. (1991), Goff et al. (1998), Dawson and Shi (2000), and Bryant (2001) have cataloged the geomorphic signatures indicating the presence of tsunamis in coastal landscapes. There are five categories that are applicable to Bristol Channel, with its rocky coastline and extensive tidal flats. These categories are sand layers, imbricated boulder deposits, cavitation features, bedrock sculpturing, and landscape erosion. The first two classes are de-

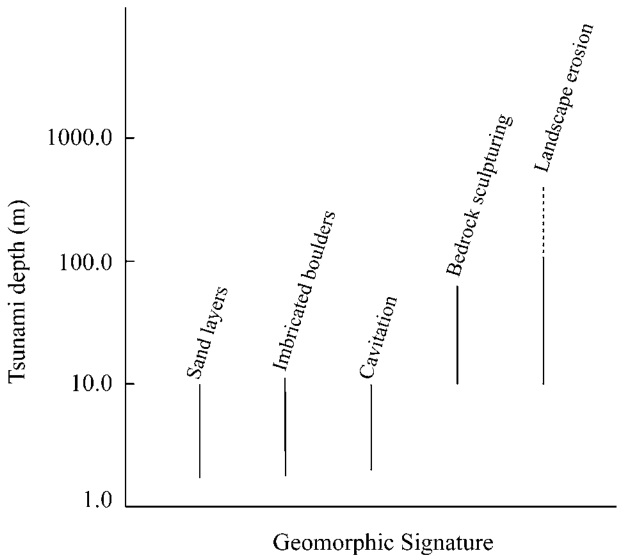

Figure 2. Lower and upper ranges of flow depths associated with various tsunami features.

positional, while the last three are erosional. Figure 2 plots the lower and upper ranges of flow depths associated with each feature in the literature. Note that this literature is not restricted solely to tsunamis but also encompasses catastrophic water flow. In coastal landscapes, the depth of flow equates to the wave height of a tsunami at shore or over land. The classes in figure 2 have been ranked according to increasing flow depths required to produce each feature.

The first category, requiring the lowest tsunami flow depth, dominates the literature as a primary sedimentary signature (Clague and Bobrowsky 1994; Dawson 1994; Pinegina et al. 1996). It consists of sand layers covering or embedded within floodplains and marshes. The thickness of these layers ranges from 1 to 40 cm. There is intense debate whether or not such evidence represents deposition by storm surges or tsunamis. The lowest tsunami heights plotted in figure 2 that can unequivocally generate these deposits are about 1.5 m. This is enough to overwash flat coastlines and marshes and travel far enough inland to lay down spatially coherent layers of sediment both alongshore and inland. The majority of these deposits consist of sand, although silt and even anomalous muds have been noted (Goff and Chagué-Goff 1999). The recent 2004 Indian Ocean tsunami event laid down sand layers in many places along the coasts of Sri Lanka, India, and Thailand only a few centimeters thick despite having flow depths in excess of 3 m. Unfortunately, sand layers in coastal deposits bordering Bristol Channel for the 1607 event do not exist because the salt marshes were eroded away in the early part of the seventeenth century. It is not known whether the January 30, 1607, event triggered this erosion.

Boulders represent the next most identifiable signature attributed to tsunami (Bourrouilh-Le Jan and Talandier 1985; Jones and Hunter 1992; Young et al. 1996; Nott 1997; Bryant and Nott 2001; Scheffers 2002). The recent literature often ignores the full suite of characteristics that helps to distinguish transport by tsunami from storm waves (Noormets et al. 2002, 2004; Felton and Crook 2003; Williams and Hall 2004). Both tsunamis and storm waves occupy a similar regime near the ocean. Young et al. (1996) and Bryant (2001) discussed boulder transport in terms of paleotsunami when (1) the boulders were deposited in groups, (2) the boulder deposits lacked smaller sediment sizes typically associated with storm deposits on cliff tops (Solomon and Forbes 1999), (3) the boulders were imbricated and contact supported, (4) the points of contact support lacked evidence of percussion implicating suspension transport, (5) the boulders showed lateral transport or shifting distinctive from in situ emplacement due to cliff collapse under gravity, (6) the boulders were elevated above the swash limit for storm waves, (7) the boulders were situated away from any shoreline where storm waves impacting on the coast could have simply flicked material onto shore, (8) the evidence of transport by tsunamis rather than storm waves was unequivocal, based on hydrodynamic determinations, (9) the direction of imbrication matched the direction of tsunami approach to the coast regionally, and (10) there were other nearby signatures of tsunamis. Figure 2 presents the range of flow depths where boulders have been linked to tsunamis using hydrodynamic determinations. Note that flow depths have been calculated for submerged boulders based on the equation (Nott 2003)

$$H_t \geq \frac{0.5a(\rho_s - \rho_w)/\rho_w}{C_d(ac/b^2) + C_l}, \quad (1)$$

where a is boulder length (m), b is boulder width (m), c is boulder thickness (m), ρ_s is the density of a boulder (g cm^{-3}), ρ_w is the density of seawater (1.024 g cm^{-3}), C_d is the the coefficient of drag (typically 1.2), and C_l is the coefficient of lift (0.178).

Unless boulder transport lies above the limit of storm waves, it is difficult to separate tsunamis from storm waves when the flow depth is less than 2 m. The maximum theoretical flow depth moving boulders attributable to tsunamis is 11.2 m, cal-

Figure 3. Fluting in bedrock at Ilfracombe, Devon, United Kingdom.

culated from boulders in northern Queensland, Australia (Nott 1997).

Cavitation is a process whereby bubbles with very low internal pressure develop in high-velocity flow. These bubbles are unstable and collapse rapidly, generating impact forces up to 30,000 times greater than normal atmospheric pressure (Barnes 1956). The process has never been identified for storm waves or historical tsunamis but has been identified at sites showing other erosional signatures linked to megatsunamis (Bryant and Young 1996). Cavitation is a known process in engineering. Its presence limits the depth of water allowed to go over spillways and the speed at which propellers can turn on ships (Barnes 1956). It is more dependent on flow velocity than on flow depth and on increasing flow power than on simple flow velocity (Allen 1984). Velocities of 9–10 m s^{-1} with a minimum flow depth of 2 m are required for cavitation (Baker 1978). In field conditions, cavitation is inseparable from corrasion, producing smoothed bedrock erosional features termed s-forms (Hjulström 1935; Dahl 1965; Allen 1984). Cavitation attributable to tsunamis has been identified in the field (Bryant and Young 1996) but appears to be destroyed by corrasion processes where the depth of flow exceeds 8–10 m. Thus, cavitation is shown in figure 2 as operating under tsunami water depths of 2–10 m.

Cavitation operates at the lower threshold for bedrock sculpturing, a process whereby vortices in water flow can erode bedrock into curvilinear features. Bedrock-sculptured features in the noncoastal literature range in size from scalloped forms less than 1 m in diameter (Kor et al. 1991) to pothole features up to 30 m deep (Baker 1978). In the channeled scabland of the western United States, tornadic flows of 77 m s^{-1} more than 140 m deep have been theorized for the formation of potholes and canyons (Craig 1987). Catastrophic discharge from beneath icecaps that has been linked to pothole formation probably occurred at velocities of 5–10 m s^{-1} and water depths of 10 m (Kor et al. 1991). Along the Australian coast, tsunami-carved potholes and stacks rarely exceed 20 m in height (Bryant and Young 1996; Bryant 2001). A minimum flow depth of 12 m has been calculated from associated features (Bryant et al. 1997; Bryant and Nott 2001). Evidence exists for even greater tsunami water depths. Incipient pothole formation at Flagstaff Point, Wollongong, where water cut through a 20-m-high cliff face, implies a flow depth at least as great. At Point Samson, Western Australia, bedrock-sculptured features are associated with megaripples with an amplitude of 5 m and a wavelength of 1000 m (Bryant and Nott 2001). These required theoretical water depths of 60 m (based on Allen 1984). From these observations, bedrock sculpturing by tsunami requires a water depth of 10–60 m.

Landscape erosion has been found historically only under the most extreme conditions. Even the 2004 Boxing Day tsunami, which was the greatest in 120 yr in the Indian Ocean and was matched in recent times only by the 1960 Chilean and 1964 Alaskan tsunamis, did not appreciably erode the bedrock landscape. The April 1, 1946, Alaskan tsunami at Scotch Cap certainly eroded the cliff line at this location, overtopping the headland 30 m above sea level (Bryant 2001). The tsunami had a minimum height of 10 m because it destroyed a lighthouse situated at this level above sea level. The upper documented limit of tsunami run-up that has eroded bedrock is 524 m. This was produced by the July 9, 1958, tsunami in Lituya Bay,

Figure 4. Nash Point rock platform in South Wales looking east. Note formation of cuestas and scarps up to 5 m high cut across the platform.

Figure 5. Shallow vortex pool with central plug at Ogmore, South Wales.

Alaska (Miller 1960). While the wave height never reached this value in the bay, it probably exceeded 100 m in order to generate this high run-up. These values have been used in figure 2 to show the flow depths generated by tsunamis that can erode bedrock into landscape features. Along the New South Wales coastline of Australia, erosion of the rocky coast by megatsunamis at the minimum flow depths shown for this signature in figure 2 has been so significant that the coastline can be considered tsunami generated (Bryant et al. 1996; Bryant 2001).

Evidence of Bedrock Sculpturing in Bristol Channel

Evidence for bedrock sculpturing around Bristol Channel appears at four locations: Ilfracombe, Nash Point, Ogmore, and Worms Head (fig. 1).

Ilfracombe. The cliffed coast at Ilfracombe on the northwest Exmoor coast consists of Devonian Ilfracombe slates (Edmonds et al. 1985). Bedding dips south up to 80° and strikes 270°. Water flow across a promontory west of the harbor has eroded fluted topography that is structurally controlled by this bedding at two scales (fig. 3). At the smaller scale are flutes up to 30 cm high, with a distinct orientation of 275°. These flutes are thus cut into the beds at a low (5°) angle. At the larger scale, these smaller flutes are superimposed on sail-like structures about 5 m high. The sails have the same orientation. The flutes give these sails a cockscomb-like outline that has been attributed at several locations in Australia to erosion by vortices in high-velocity flow under megatsunamis (Bryant 2001). This type of erosion was found only at this one location in Bristol Channel.

Nash Point. Nash Point, on the Glamorgan Heritage Coast, consists of gently dipping interbedded lower Jurassic limestones and Lias shales (Wilson et al. 1990). At sea level, limestone beds 25–40 cm thick dominate, forming topographic high and low points on anticlines and synclines, respectively, over distances of 1–2 km. Bedding dips east-northeast as much as 3° and strikes east-southeast. The latter controls in places the planform of rock platforms that at midtide are up to 100 m wide (fig. 4). This structural control produces a classic, sloping type-A platform (Haslett 2000). But more notable is the formation along bedding planes of cuestas at right angles to the shoreline. On the westward faces of anticlines, erosional faces cut across several bedding planes, producing scarps that are up to 5 m high. Boulders imbricated westward are trapped in the down-dip depression of bed-controlled cuestas but are freely scattered on the lee side of large scarps. Significantly, in long profile, the erosional surfaces on the lee sides of scarps on anticlines are smoothly curvilinear and suggestive of bedrock sculpturing. At a smaller scale, muschelbrüche (scallop-shaped depressions) up to 2 m in length and aligned west-to-east are embedded in this undular surface. Muschelbrüche are a characteristic signature of bedrock sculpturing and are generated by catastrophic flow in both subglacial and tsunami-affected environments (Dahl 1965; Bryant and Young 1996). Those at Nash Point are larger than those observed along the New South Wales coast in Australia, where their presence is associated with a myriad of other signatures of megatsunamis.

Figure 6. Hummocky topography eroded into the platform at Worms Head, South Wales.

Figure 7. Eroded headland on the east side of Sully Island, South Wales. Note the lack of debris on the raised platform surface, compared to surfaces lower down and more exposed to wave action. The bench at the top of the Carboniferous limestone lies above the limit of highest tides. We postulate that its formation was aided by tsunami increasing in height at this point because of rapid narrowing of Bristol Channel.

The juxtaposition of cuestas, scarps, and muschelbrüche are indicative of substantial unidirectional flow from the west. Their age of formation is uncertain, but they are not recent, because the undular surfaces are being actively eroded at their highest points.

Ogmore. The ramplike surfaces at Ogmore are cut into Carboniferous limestone and basal Triassic conglomerates, which are dipping seaward at angles of up to 5° (Wilson et al. 1990). Erosion is cutting through these beds and could be attributed to present-day wave attack but for two facts. First, the backshore is covered in a layer of sand that contains profuse quantities of angular conglomerate cobbles and boulders. This deposit is similar to "dump" deposits linked to paleotsunamis in Australia (Bryant 2001). Second, a shallow vortex pool with a central plug has been cut into the conglomerate (fig. 5). This pool has a less eroded seaward rim. The feature indicates high-velocity, turbulent flow within a vertical vortex that becomes locked into place by the depression being eroded (Bryant and Young 1996). Flow is downward over the plug and upward around the rim. The feature is one of the classic signatures of bedrock sculpturing produced by megatsunamis. Incipient vortex pools in Australia indicate that their formation is rapid, occurring in a matter of minutes. The Ogmore feature supports this hypothesis. Under storm wave attack, the blocky conglomerate along this coast should erode uniformly to a rough, seaward-dipping, planar surface. The pool, with its lack of structural control, its seaward rim, and its central high, indicates that vortices embedded in high-velocity flow have swept over this surface.

Worms Head. Evidence for erosional vortices also exists at Worms Head, an anticlinal headland consisting of Carboniferous limestone that extends 4 km west of the mainland (George 1970). Worms Head occupies one of the most exposed coastlines in Bristol Channel (fig. 1). Here a horizontal platform cuts through limestone beds dipping 80° seaward. The platform terminates landward at a ramped surface that rises 5 m higher over a distance of 30–40 m. This ramped surface is highly dissected, showing evidence that blocks have been plucked from the surface along beds and joints (fig. 6). In places, small depressions no more than 3 m wide and 1 m deep have been scoured out of the surface with minimal evidence of structural control. The pools are concentrated on the west-facing surface of the ramp. Their spatial distribution is random. They cover the ramp surface and occur higher up on a raised bedrock ridge backing this ramp toward Worms Head itself. The pools and plucked bedrock topography are characteristic of hummocky topography linked to tsunami-generated flow on the New South Wales coast of Australia (Bryant and Young 1996). Hummocky topography is produced by a myriad of overlapping vortices under high-velocity flow.

Evidence of Landscape Erosion in Bristol Channel

Evidence that tsunamis may be causing significant coastal erosion occurs at Sully Island and Ball Rock (fig. 1). Here Bristol Channel decreases in width by 30%, from 22 to 14 km. The orientation of the channel also changes by 45° at this point, from east-west to northeast-southwest. Any tsunami traveling up the channel is constricted at this point and forced to increase in height significantly. Sully Is-

Figure 8. Breaching at the back of the promontory at Ball Rock landward of Sully Island, South Wales. This headland is sheltered by Sully Island from storm waves. Similarly shaped promontories with erosion at their landward end have been related to tsunami in New South Wales, Australia.

land and Ball Rock, near Cardiff, show evidence of recent erosion by high-energy waves (fig. 7). The island and adjacent headlands consist of Carboniferous limestone overlain by the Triassic Red Beds (Waters and Lawrence 1987). The limestone is resistant to erosion, compared to the Red Beds. Preferential erosion has occurred at the contact 3–4 m above the high-tide mark. The raised platform surfaces on the headland, less frequently exposed to wave attack, have been swept clean of rocky debris. Yet profuse amounts of dolomitic mudstone boulders eroded from the Triassic now cover the seaward foreshores of the island.

Ball Rock is a small promontory attached to the mainland east of Sully Island and sheltered by Sully Island from storm waves moving up the channel. Here the Triassic mudstones have been stripped away, together with about a 1–2-m layer of the underlying marginal facies in the center of the promontory (fig. 8). In long profile, Ball Rock looks like an inverted toothbrush, and this characteristic shape has been defined as a prominent signature of high-velocity tsunami flow along the New South Wales coast of Australia (Bryant and Young 1996; Bryant 2001). The erosion is markedly enhanced relative to the surrounding coastline. There is little doubt that refraction of waves around Sully Island has focused increased energy onto this section of coast. The debatable point is whether the waves are attributable to storms or to tsunamis.

Table 1. Data for Boulders with the Greatest Resistance to Flow by Tsunamis and Storm Waves at Various Sites around Bristol Channel

Region, site	Distance seaward from tide limit at Gloucester (km)	Lithology	Rock density	a-axis (m)	b-axis (m)	c-axis (m)	Volume (m^3)	Weight (t)	Height of tsunami, H_t (m)	Height of storm wave, H_{storm} (m)
Severn Estuary:										
Sudbrook	45	Sandstone	2.32	4.45	3.60	.70	11.2	25.6	6.1	24.4
Portishead	56	Sandstone	2.32	2.60	2.50	.23	1.5	3.4	5.7	22.7
Inner Bristol Channel:										
Brean Down	81	Limestone	2.61	5.15	4.75	2.10	51.4	132.0	5.3	21.3
Sully Island	85	Sandstone	2.32	2.15	1.57	.26	.9	2.3	3.5	14.2
Dunraven Bay	106	Limestone	2.61	2.94	2.76	.64	5.2	13.3	4.8	19.3
Ogmore	107	Limestone	2.61	4.85	3.10	1.05	15.8	40.6	4.6	18.6
Sker Point	112	Dolomite	2.75	4.40	4.10	.85	15.3	41.5	8.4	33.6
Outer Bristol Channel:										
Tears Point	147	Limestone	2.61	2.14	2.05	.42	1.8	4.7	3.8	15.4
Croyde	162	Slate	2.68	3.01	2.30	.65	4.5	11.8	3.9	15.7

Figure 9. Limestone boulders imbricated up to and above high tide at Tears Point, South Wales.

Analysis of Boulder Deposits in Bristol Channel

Boulders occur sporadically as isolated clasts and commonly as sorted accumulations at various localities throughout Bristol Channel and less frequently in the more sheltered Severn Estuary. Field criteria at nine locations (table 1) indicate that boulders have been transported by waves at or above mean high tide and arranged in imbricated trains. Measurements were made of the *a*- (longest), *b*- (intermediate), and *c*- (shortest) axes. The direction of any imbrication and the position of the boulder relative to tides were recorded. The latter was achieved using lichen zonation (Cremona 1988; Haslett and Curr 1998; Haslett 2000). At each location, a number of large boulders were measured, with 136 boulders measured in total. Table 1 shows details of the largest boulder from each site. From these data, we estimate the wave height required to transport the boulders by tsunami (H_t), using equation (1), or by storm waves (H_{storm}), using the fact that storm waves are four times higher (Nott 2003).

Outer Bristol Channel. We examined two sites along outer Bristol Channel at Croyde on the south shore and at Tears Point on the north shore. At Croyde, many glacial erratics lie on the shore platform (Stephens 1970). But an isolated boulder of local Devonian slate origin was observed that, though not imbricated, had clearly been transported by waves. It required $H_t = 3.9$ m and $H_{storm} = 15.7$ m to transport it. At Tears Point, imbricated limestone boulders have been deposited at the east end of a 2.5-km-long shore platform eastward from Worms Head (fig. 9). These boulder trains extend above high tide on the shore platform. Sizable boulders do not lie elsewhere on this platform. Wave heights required to transport the boulders most resistant to the flow were calculated at $H_t = 3.8$ m and $H_{storm} = 15.4$ m.

Inner Bristol Channel. Five sites were examined along inner Bristol Channel. At Sker Point, boulder trains lie on a shore platform promontory extending above high tide. The boulders are well imbricated and appear to have been transported considerable distances, as there is no source evacuated nearby (fig. 10). The flattest boulder with the greatest resistance to flow required $H_t = 8.4$ m and $H_{storm} = 33.6$ m to transport it. At Ogmore, the boulder most resistant to flow required $H_t = 4.6$ m and $H_{storm} = 18.6$ m to transport it. At Dunraven Bay, 3 km east of Ogmore, wave-transported boulders lie in a train ascending up to high tide below a high cliff of Carboniferous limestone at the east end of the bay (fig. 11). Clearly, past rockfalls put the boulders on the beach, where they have been subsequently transported and imbricated by waves. Two boulders offering the greatest resistance to flow required $H_t = 4.8$ m and $H_{storm} = 19.3$ m to transport them. The significance of many isolated boulders elsewhere in the embayment is discussed below. Farther east at Sully Island, many boulders are associated with cliff collapse. Several distinct and well-imbricated boulder trains occur, often distant from cliff faces (fig. 12). The boulder most resistant to flow required $H_t = 3.5$ m and $H_{storm} = 14.2$ m to transport it. This may be an underestimate, for many larger boulders here cannot unequivocally be associated with wave transport rather than rockfall.

Figure 10. Imbricated boulders at Sker Point near Porthcawl, South Wales (backpack is 0.4 m high).

Figure 11. Imbricated boulder train at the eastern end of Dunraven Bay, South Wales (two people for scale).

At Brean Down on the Somerset coast, large, isolated boulders lie up to 100 m from a cliff at the north end. Although cliff fall cannot be ruled out, this seems unlikely, given such distances along a horizontal beach surface. The cliff, though actively eroding, is a relic of the last interglacial sea level highstand. A wedge of Pleistocene sediments was eroded away from the foot of the cliff during the Holocene marine transgression (Apsimon et al. 1961). It is unlikely that large boulders would have slid downslope over the gently inclined surface of a former extended sediment wedge. Nor is it likely that the boulders originate from the Pleistocene sediments, which contain only sand and gravel. The boulders are unlikely to have been glacially transported, as the closest known erratics are 20 km away. The largest boulder (fig. 13) required $H_t = 5.3$ m and $H_{storm} = 21.3$ m to transport it.

Severn Estuary. At Portishead in Kilkenny Bay, a boulder train about 20 m long extends above the highest limit of tides up to the foot of low, vegetated backing cliffs. The boulder most resistant to flow lies below the highest tide limit and required $H_t = 5.7$ m and $H_{storm} = 22.7$ m to move it. At Sudbrook, many boulders occur at the foot of low cliffs composed of Triassic Sudbrook sandstone that fringe a rocky headland (Welch and Trotter 1961). Most appear to have toppled from the undercut cliff (fig. 14). But a boulder fan on the upstream (east) side of the headland extends about 50 m from the cliff base. The downstream (west) side of the headland is nearly devoid of boulders. It appears that boulders have been removed from the west side and deposited upstream on the east side. A distinct eastward-orientated boulder train now lies below high tide. The boulder most resistant to flow required $H_t = 6.1$ m and $H_{storm} = 24.4$ m to move it.

Discussion

Relevant to our study are the results by Williams and Hall (2004) on boulders on the coast of western Ireland. They describe large boulders that they suggest other authors would take to be evidence of tsunamis. They then go on to demonstrate that the boulders were transported by storm waves and so discount boulders as indicators of tsunamis in this region. But a storm wave origin is entirely understandable for the sites they investigated, where plunging coastlines bring deep water adjacent to the coast. The maximum deep-water wave height with a 50-yr return period here is 35 m (NERC 1991). Some of the largest boulders required storm waves well within this limit. For example, using equation (1), a 250-t boulder found at sea level required an initial $H_{storm} = 16.9$ m, while a 117-t boulder now located 12 m above sea level required a H_{storm} =

Figure 12. Well-imbricated boulders at Sully Island, South Wales (spade is 1.0 m high).

Figure 13. Large isolated boulder on the beach at Brean Down, Somerset (spade is 1.0 m high).

28.9 m. Boulders weighing 2.9 t are now found 50 m above sea level. The 50-yr wave height not only can account for the initial movement of all boulders in the region but also can transport most of them to their final locations.

Bristol Channel and the Severn Estuary have much lower storm wave heights than the Irish Atlantic coast, which makes it more likely that the distribution of boulders we examined has been influenced by tsunamis. Figure 15 plots the maximum H_t and H_{storm} required to move boulders at each of our sites against distance seaward from Gloucester at the limit of tides in the estuary. The H_t increased from 4 m to more than 6 m as the tsunami was constricted moving up the funnel-shaped estuary (fig. 16). An exception occurs at Sker Point in inner Bristol Channel, where large imbricated boulders occur. Figure 16 clearly shows that the anomalously high value at Sker Point is related to a bathymetric high protruding into Bristol Channel that could increase wave height locally by refraction. The low heights required to transport boulders at Sully Island may be underestimated because some larger boulders that possibly could have fallen from the cliffs were excluded.

The trend line opposes the height distribution of storm waves in Bristol Channel and the Severn Estuary (McLaren et al. 1993). Storm wave heights are greatest in the outer channel, where they have been recorded at ≥10 m. Storm wave heights of 4.7 and 3.5 m occur in the inner channel and the Severn Estuary, respectively, both with 50-yr return periods. This pattern is due to decreasing water depths up the estuary. In outer Bristol Channel, boulders require H_{storm} between 15 and 16 m, which is theoretically possible (fig. 15). But in inner Bristol Channel and in the Severn Estuary, the required H_{storm} is significantly greater than observed storm wave heights, by a factor of 7. These data suggest that the transport of large boulders in the upper part of the channel was achieved not by storm waves but by tsunamis. It is important to evaluate the local storm wave environment before concluding whether a boulder has been transported by storm waves or by tsunamis.

An analysis of the relation between shore-normal direction and the mean orientation of the imbricated boulders at each site (table 2; fig. 17) shows a variance of 53°. This suggests that wave refraction is not efficient, a feature of tsunamis more than of storm waves. Furthermore, from these boulder data it is possible to estimate the velocity of run-up (V_r) and inland penetration of the tsunami (Bryant 2001). As these calculations are based on boulder dimensions, the results vary similarly to the wave height results. Run-up velocity and the extent of inland penetration generally increase up-estuary (table 2). Theorized flow velocities ranged between 11.8 and 18.1 m s^{-1} up the estuary. Tsunami inundation in the upper parts of Bristol Channel and the Severn Estuary produced catastrophic results because extensive coastal lowlands—known as "Levels" in both Somerset and Gwent—back the shoreline. Based on equations presented in Bryant (2001) for pastures, the maximum inland penetration possible for the tsunamis across the lowlands of outer and inner Bristol Channel was 2.5 and 6.7 km, respectively. In the Severn Estuary upstream from Sudbrook, the wave could have reached 4.9 km inland.

The suite of characteristics that helps to distin-

Figure 14. Boulder accumulation fanning upstream in the Severn Estuary (toward viewer) along cliffs at Sudbrook, South Wales (standing figure for scale).

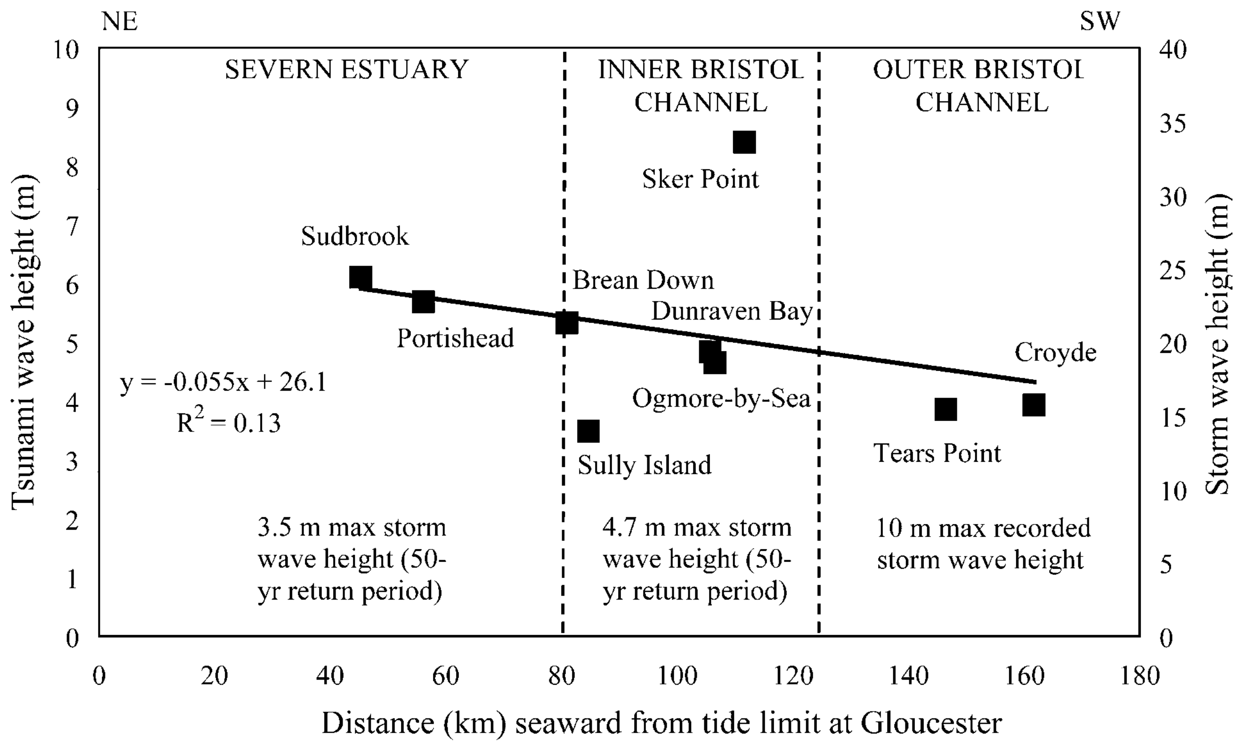

Figure 15. Variation in tsunami and storm wave heights required to transport boulders with the greatest resistance to flow in Bristol Channel and the Severn Estuary, United Kingdom. Sites are plotted against distance (km) seaward from the tide limit at Gloucester (known storm wave heights based on McLaren et al. 1993).

guish boulder transport by tsunamis rather than storm waves (discussed above) is evaluated for Bristol Channel and the Severn Estuary in table 3. Generally, sites where boulders are clearly imbricated or occur in groups have more characteristics favoring tsunami transport (7–9). Lower scores (4–6) are characteristic of sites where boulders lie isolated or scattered. The characteristics that occur most frequently are that the boulders have not been simply flicked ashore by storm waves but occur in groups and that they have an imbrication matching the direction of any tsunami moving up the channel.

The presence around Bristol Channel of bedrock-sculpturing features linked elsewhere to tsunamis (Bryant and Young 1996), together with the discovery of eyewitness descriptions similar to those for tsunamis (Bryant and Haslett 2002), spurred our research into the 1607 flood event within Bristol Channel. Analysis of boulders indicates that the tsunami could have been 8.4 m high at the coast (table 1). There is evidence from the orientation of imbricated boulders that the tsunami impinged on the confining shorelines at a high incident angle. Along a bedrock coast, this is conducive to jetting, high wave velocities, and higher wave heights. The conditions are at the lower limit for the generation of bedrock sculpturing. We believe that the erosional features at Ilfracombe, Ogmore, Nash Point, and Worms Head are evidence that bedrock sculpturing was initiated in Bristol Channel.

The fact that the signatures of tsunami are found in Bristol Channel up to the more sheltered Severn Estuary is surprising because the northwest European coast in general is not considered tsunami prone. Only two major tsunamis have been documented in the region during the Holocene, one related to the prehistoric Storegga submarine slide that propelled a tsunami onto the east coast of Scotland (Bondevik et al. 1997; Dawson et al. 1988) and a second, associated with the Lisbon earthquake of 1755, that affected parts of the south coasts of England, Ireland, and South Wales, with wave heights up to 3 m (McGuire 2005). The features we describe here are not attributable to either of these events.

Dating erosional features is difficult, but we can infer the timing of the event that transported boulders at Dunraven Bay on the coast of South Wales. Figure 18 indicates the position of boulders at the east end of the bay, mainly emplaced through rock-

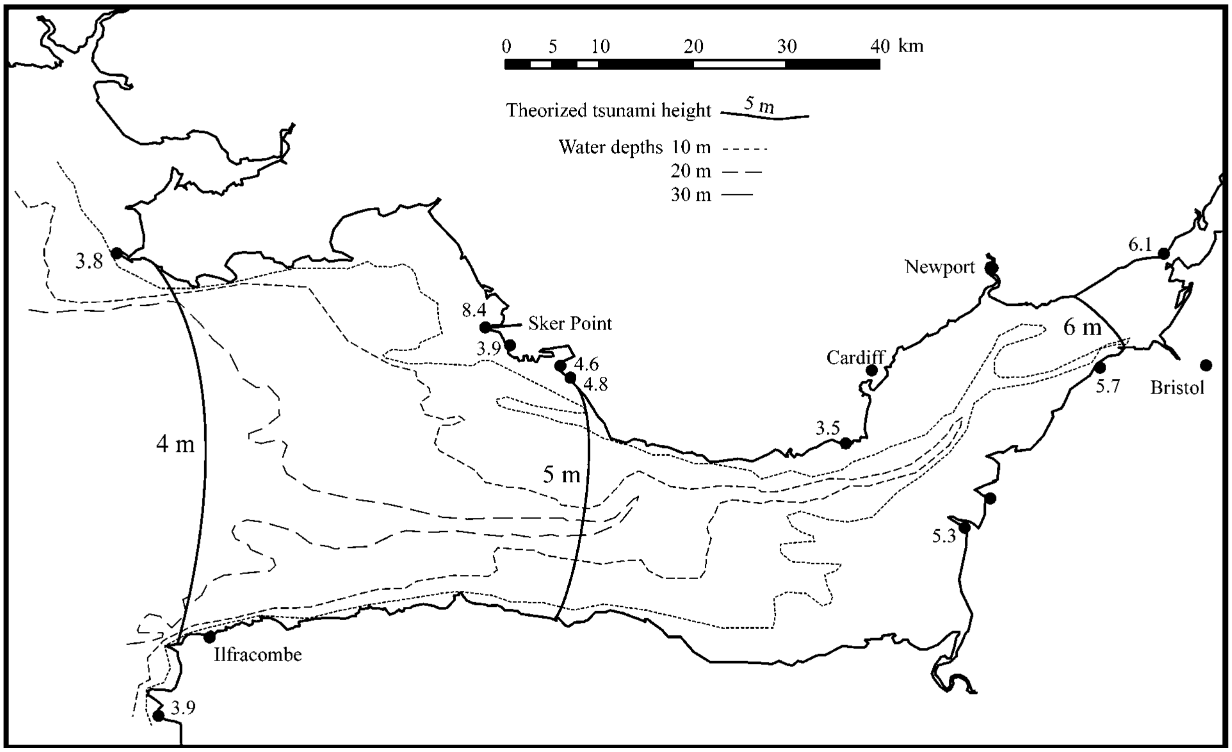

Figure 16. Distribution of tsunami wave heights in Bristol Channel and the Severn Estuary, United Kingdom, indicated by boulders with the greatest resistance to flow.

fall from thickly bedded Carboniferous limestone cliffs. In the center of the bay, retreat of a cliff consisting of Jurassic sedimentary beds has left a boulder lag on the beach. The Jurassic beds are more permeable and as a result more prone to rapid erosion because of freezing and thawing of groundwater (Williams and Davies 1987). The seaward margin of the boulder lag at the eastern end of the beach corresponds to the boundary between seaward imbricated and landward unsorted boulders below the cliff. This relation suggests that the event that transported the imbricated boulders occurred

Table 2. Maximum Velocity, Maximum Distance Inland, and Flow Direction of Tsunamis Inferred from Boulders at Various Sites around Bristol Channel

Region, Site	Distance seaward from tide limit at Gloucester (km)	V_r (m s^{-1})	Penetration inland (km)	Shore orientation: Fetch (°)	Shore orientation: Direction	Mean orientation of imbricated boulders (°)
Severn Estuary:						
Sudbrook	45	16.2	4.9	178	S	208
Portishead	56	14.9	4.0	335	NW	337
Inner Bristol Channel:						
Brean Down	81	14.5	3.7	270	W	217
Sully Island	85	11.8	2.1	217	SSW	247
Dunraven Bay	106	13.8	3.2	250	WSW	237
Ogmore	107	13.5	3.1	263	W	260
Sker Point	112	18.1	6.7	234	SW	282
Outer Bristol Channel:						
Tears Point	147	12.3	2.4	210	SSW	226
Croyde	162	12.4	2.5	317	NW	…

Note. V_r = run-up velocity.

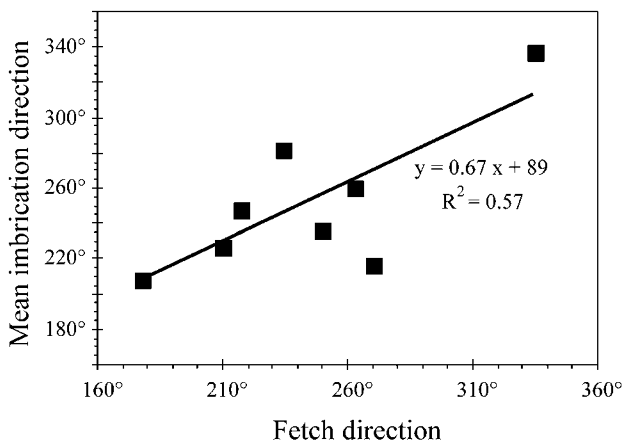

Figure 17. Comparison of boulder imbrication direction and shore-normal (fetch; table 2) direction for sites in Bristol Channel and the Severn Estuary, United Kingdom.

when the cliff at the back of the beach was positioned at the seaward margin of the boulder lag. The event removed any boulder lag that may have existed on the beach beforehand. Maximum rates of cliff retreat along this coast measured from old maps and using fixed-pin markers range from 0.300 to 0.335 m yr^{-1} (Keatch 1965; Davies and Williams 1991). Between 1590 and 1990, the coast generally retreated 120 m. Our field measurements indicate that maximum cliff retreat at Dunraven Bay was 110 m from the seaward margin of the boulder lag. This positions the cliff at this location around 1634–1672 AD. The imbricated boulders seaward of the lag were transported by a high-energy event before then but not earlier than 1590 AD. This reasoning corroborates with archeologically and radiocarbon-dated evidence for the complete erosion of all salt marsh in the Severn Estuary before the mid-seventeenth century (Allen and Rae 1987) and the erosion down to bedrock of two spurs of alluvial agricultural land in the early seventeenth century (Allen and Fulford 1992).

A likely trigger for a tsunami in this region is an earthquake, a submarine slide, or a combination of both. An active fault zone lies offshore of south Ireland, which experienced a 4.5 magnitude earthquake in the 1980s. Roger Musson (head of seismology, British Geological Survey) believes that a higher-magnitude event could have occurred in the historic past. Indeed, Disney (2005) mentions a second-hand report of an earth tremor felt on the morning of January 30, 1607. There are also fault zones within Bristol Channel itself that may be active. The United Kingdom's Department for Environment, Food and Rural Affairs (DEFRA 2005) reports that fault zones in the Sole Bank area of the Celtic Margin pose a credible tsunami threat (fig. 1). Finally, the steep continental slope offshore of Ireland has several locations where large slope failures have occurred, such as along the Celtic Margin, Goban Spur, Sole Bank, Porcupine Bank and Bight, and Rockall Bank and Trough (Kenyon 1987; fig. 1). Large failures have been recently studied in the Rockall Trough (Øvrebø et al. 2005), Porcupine Bight (Huvenne et al. 2002), and elsewhere along the continental slope (Evans et al. 2005), many of

Table 3. Assessment and Scoring of Boulder Occurrences in Bristol Channel and the Severn Estuary, United Kingdom, against a Suite of Characteristics That Help to Distinguish Transport by Tsunami from Transport by Storm Waves

	Sites with boulders suspected of being transported by tsunami									
Characteristic of tsunami-transported boulders	Sudbrook	Portishead	Brean Down	Sully Island	Dunraven	Ogmore	Sker Point	Tears Point	Croyde	Total sites (out of 9)
Deposited in groups	✓	✓	✓	✓	✓	✓	✓	✓	✓	9
Only boulders	✓	✓		✓	✓		✓	✓	✓	7
Imbricated and contact supported				✓	✓		✓	✓		4
Evidence of suspension transport				✓	✓		✓	✓		4
Evidence of lateral transport	✓	✓	✓	✓	✓		✓	✓		7
Above the storm wave limit		✓					✓	✓	✓	4
Not flicked by storm waves	✓	✓	✓	✓	✓	✓	✓	✓	✓	9
Hydrodynamic determinations exclude storms	✓	✓	✓	✓	✓	✓	✓			7
Imbrication matches direction of tsunami approach	✓	✓	✓	✓	✓		✓	✓	✓	8
Other nearby signatures of tsunami				✓	✓	✓		✓		4
Total characteristics (out of 10)	6	7	5	9	9	4	9	9	5	

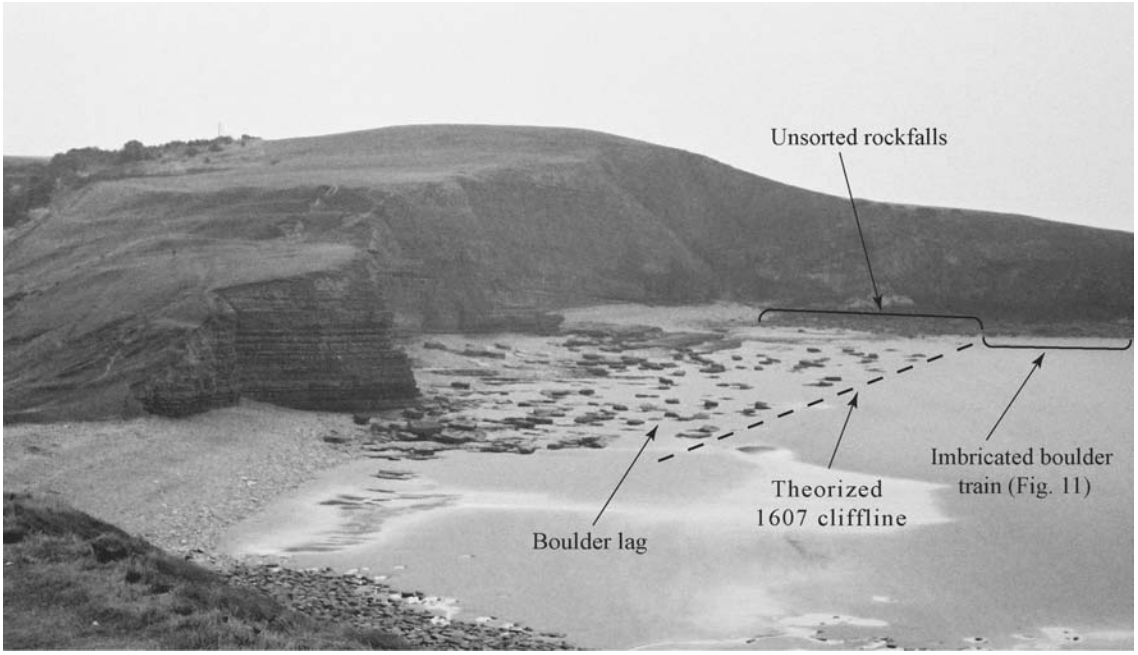

Figure 18. Setting of the imbricated boulder train shown in figure 11 in Dunraven Bay, South Wales. The seaward extent of the boulder lag marks the position of the cliff line in 1607 (see text for discussion).

which may be tsunamigenic, although dating is lacking for most.

Conclusion

Despite the recent Indian Ocean tsunami of 2004, tsunamis along most coastlines are currently viewed as an underrated hazard. But an examination of the prehistoric record along many of these coasts gives conclusive evidence of depositional and erosional impact of tsunamis, in some cases of immense proportions (Bryant 2001). Our purpose here is only to present field evidence showing that Bristol Channel in the United Kingdom has been subject to tsunamis. The channel is an ideal environment to experience this phenomenon because its funnel shape can enhance the height of any tsunami up-channel and because headlands protruding from the coast can locally exacerbate tsunami flow velocities. Descriptions of a flood event on January 30, 1607, resemble those for recent catastrophic tsunamis. These descriptions from Bristol Channel may be related to geomorphic evidence of tsunami erosion in the form of transported and imbricated boulders, bedrock sculpturing on coastal platforms and ramps, and, in spots, wholesale erosion of the coastal landscape. While identification in the geological record is of scientific interest, the extension of such evidence to the historic record presages an immediate concern for devastating tsunamis on our present coastlines. Bristol Channel is now marked as one of these coastlines of concern.

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