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Bedrock-sculpturing by Tsunami, South Coast New South Wales, Australia

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Abstract

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Keywords

tsunami, New South Wales, bedrock-sculpturing

Disciplines

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Bedrock-Sculpturing by Tsunami, South Coast New South Wales, Australia¹

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ABSTRACT

Bedrock-sculpturing resulting in *s-forms* is associated with catastrophic flooding in near- and subglacial environments produced by flow velocities approximating 10 m s^{-1} . These velocities can also be produced by extreme tsunami generated by submarine landslides or comet impacts with oceans. Repetitive tsunami events during the late Holocene have overwashed headlands along the New South Wales south coast and produced two suites of bedrock-sculptured terrain. At the smaller scale, *s-forms* similar to muschelbrüche, v-shaped grooves, and sichelwannen have developed on upslopes while broad potholes, flutes, and transverse troughs have formed on headland crests. Cavitation features consisting of sinuous grooves, impact marks, drill holes, and cavettos appear more ubiquitously. At the larger scale stripped ramps, large potholes, cascade channels and canyon-like features have been generated. Six flow phenomena: Mach-stem waves, jetting, vortex impingement, horseshoe vortices, helical flow, and multiple vortex formation are all involved, either singly or in combination with each other, in the creation of bedrock-sculptured features and terrain. Tsunami-sculptured terrain undoubtedly has a global distribution whose extent requires further investigation.

Introduction

Despite an increased awareness of the significance of tsunami as a geological process (e.g., Coleman 1968; Moore and Moore 1984; Dawson et al. 1988; Young and Bryant 1992a; Bryant et al. 1992; Chen et al. 1995), the range of their effects on coastal geomorphology is still poorly comprehended. We have previously reported evidence of tsunami along the New South Wales coastline at two scales of magnitude. The first scale records the impact of large events characterized at the end of the Last Interglacial by a tsunami generated by the Lanai slide in Hawaii, a local submarine slide in the Tasman Sea or possibly a comet impact into the Tasman Sea (Young and Bryant 1992a, 1992b). The magnitude of this event was so great that it eroded the ends of many headlands and swept the south coast of New South Wales bare of many of its interglacial barrier deposits (Bryant et al. 1996). The second scale records smaller events of a repetitive nature, many of which occurred during the Holocene and appear to have originated from earthquake activity in the southeast Tasman Sea, probably along

the seismically active Macquarie Ridge, an oceanic extension of New Zealand (Bryant et al. 1992; Young et al. 1993b). We use the term tsunami in the broadest sense to refer to any wave generated suddenly and having a period of greater than 1 minute and a height at shore in excess of 2 m, regardless of its origin.

There is both depositional and erosional evidence of tsunami impact along the New South Wales coastline. Boulders up to 49 m^3 in size, weighing as much as 90 tonnes and requiring tractive forces exceeding 100 kg/m^2 were often shifted, imbricated, and stacked (Young et al. 1996). The size and fabric characteristics cannot be readily attributed to swell or storm waves but are analogous to boulder deposits formed by large-scale unidirectional flows in fluvial environments (Johansson 1976; Baker 1984; Kesel and Lowe 1987) or emanating as catastrophic meltwater discharge in front of, or beneath, continental ice-sheets (Williams 1983; Elfström 1987; Maizels 1989). Other depositional evidence of tsunami impact includes highly bimodal mixtures of sand and cobbles, and "dump" deposits of well-sorted coarse debris (Bryant et al. 1992). The erosional evidence

consists of bedrock-sculpturing caused by vortex formation under unidirectional, high-velocity flow (Young and Bryant 1992a). Many of these features are strikingly similar to the bedrock-sculpturing associated with subglacial flow (Ljungner 1930; Dahl 1965; Bernard 1971; Kor et al. 1991; Shaw 1988; Sharpe and Shaw 1989) and with mega-floods caused by glacial outbursts or extreme rainstorms (Baker 1981; Baker and Pickup 1987). Such forms have been labelled *p-forms*, but this term implies plastic rather than turbulent viscous flow. Kor et al. (1991) suggested that the term *s-form*, for sculpted form, was more appropriate.

While *s-forms* were alluded to in an earlier report of tsunami impact (Young and Bryant 1992a), they have been difficult to conceptualize for the coastal environment because there is no other reference to their presence in the coastal literature. In addition, the coastal environment also contains evidence of erosive bedrock features apart from the type of *s-forms* described so far in the literature. This paper presents a description of the widespread spatial organization of catastrophically sculptured-bedrock terrain in the coastal environment and explores the likely mechanisms responsible for its generation. This terrain contains both smoother, small-scale *s-forms* and irregular, larger-scale forms. The features are a product of Last Interglacial and Holocene tsunami events along the New South Wales coastline and are commonly orientated in the same direction as associated tsunami-migenic boulder deposits along the adjacent coast (Young et al. 1996). Such features are so well organized that their recognition along a non-glaciated coastline would be a clear indication that such a coast has been affected significantly by high energy tsunami wave events. The purpose of this paper is thus threefold: (1) to describe more completely the suite of bedrock-sculptured features present along New South Wales south coastline; (2) to present for the first time genetic models classifying tsunami-generated features at two spatial scales; and (3) to outline six types of flow phenomena responsible for the creation of these features.

Regional Setting

Given the similarity of the coastal *s-forms* to those from subglacial environments, it is essential to note that glaciated conditions did not exist along the New South Wales coast during the Pleistocene, and that these features are not the exhumed remnants of Permian glaciation. Pleistocene glaciation in New South Wales was limited to a very small area above 1700 m near Mt. Kosciusko lying 140

km inland (Galloway 1963). Although dropstones scattered through Permian sediments exposed on the modern shoreline seem indicative of ice rafting, there is no evidence of glacial erosion of these sediments, and indeed the best of the sculptured features described here are cut in massive lava flows that postdate the Permian.

The distribution of Tertiary basalts, sediments, and weathering profiles along the coastal lowland, together with the excellent preservation of Quaternary and Tertiary shore platforms, demonstrates the long-term tectonic stability of this coast (Young and McDougall 1982; Bryant 1992; Young and Bryant 1993). Moreover, Late Quaternary sea levels were no higher than 3 to 4 m above present mean sea level (Bryant 1992; Young et al. 1993a). Thus the possible role of tectonic elevation or of higher sea levels in the sculpturing of these features can be ruled out.

Although a narrow continental shelf allows about 95% of wave power to reach the surf zone along this coast (Wright 1976), the wave regime is dominated by swell rather than by storm waves, and mean wave height is only 1.2 m. The 1 in 10 year recurrence interval of deep-water storm waves, based on hindcast data for a 43 year period, is 9 m (Blain Bremner and Williams 1985). Moreover, waves of this height and period break before reaching shoreline. Even during the greatest recorded storm of this century, 25 May 1974, storm waves near Wollongong did not wash over 7 m high platforms sculptured by tsunami. The sculptured features we report here not only are conspicuously rare within the limits of normal wave action, but also extend to more than 10 m above the limits of contemporary storm waves, and must therefore be linked to truly catastrophic events.

Sculptured Bedrock Terrain

In describing tsunami-sculptured forms we have used the terminology of Kor et al. (1991) for *s-forms* sculpted by glacial meltwater. At this stage we have resisted the temptation to introduce a new terminology for coastal features that basically have the same form as glacial ones, even though the flow characteristics of tsunami- and meltwater-generated morphologies differ significantly. First, the flow creating tsunami-generated sculptured features has a free surface. Many *s-forms* described in the literature were produced subglacially by flows that were vertically constrained by ice. In these subglacial environments, high-pressure gradients generated very high velocities near the bed. The *s-forms* formed by tsunami were formed by

vertically unconstrained flow initially produced by oscillatory gravity waves, albeit of very long wavelength. Second, because the New South Wales coastal landscape has not been modified by ice, there is the more significant problem of form inheritance. Form inheritance is influenced by lithology, bedrock structure, the degree of bedrock weathering, and the pre-existing geomorphology of the headland. In some cases, for example at Bass Point-Atcheson Rock (figure 1), tsunami from different directions have eroded headlands so that bedrock terrain controls subsequent tsunami overwashing and erosion. Finally coastal tsunami flow is usually repetitive. Flow repetition is caused by pulses of unidirectional flow as individual waves making up a tsunami wave train pass over a bedrock protuberance. While underwater slides tend to produce only a few individual waves (Harbitz 1992), earthquakes can generate tsunami wave trains consisting of over 100 long waves that impact upon a coastline repetitively over a period of 24 hours or more (Wiegel 1964). While *s-forms* are generally perceived as the product of one event of

several days duration in near-glacial environments, in the coastal environment they can be considered the product of repetitive events recurring over a slightly shorter timespan.

Smooth, Small-Scale Features. Forms similar to the complete suite of *s-forms* described for subglaciated landscapes (Kor et al. 1991) appear on tsunami-swept coastal headlands. *S-forms* develop best on smoothed and polished surfaces, a feature far less common in coastal environments. This polishing appears to be the product of sediment abrasion and is apparently the cause of the enhancement of *s-forms* on very resistant, unweathered bedrock. In the coastal environment, however, the striation and chatter mark features associated with sediment abrasion, especially by large boulders, are generally missing. For this reason the role of high water pressures impinging on bedrock surfaces cannot be ruled out as a mechanism for the polishing. Coastal *s-forms* can be categorized into three groups (figure 2), two of which are restricted topographically either to the stoss upslope or the crest of headlands. The third category consists of

Figure 1. Location of sites along the New South Wales coast.

Figure 2. Classification of *s-forms* for tsunami-sculptured rock coastlines (based on Kor et al. 1991).

cavitation and smaller vortex features. The presence of the last category depends upon the attainment of threshold velocities inducing cavitation or upon the presence of vertical faces.

Upslope morphology consists of features similar in form to muschelbrüche, v-shaped gouges, and sichelwanne. The commonest attribute developing on the steeper stoss side of rock headlands are muschelbrüche, often as a myriad of overlapping features suggestive of continual or repetitive formation. They vary in amplitude from barely discernible forms to features having a relief >15 cm (figure 3). Horizontally their dimensions rarely exceed 1.0–1.5 m. Whereas muschelbrüche appear to form subglacially with convex upflow rims, in the coastal environment these rims develop downflow. This contrast in the relationship of form-to-flow direction is a common difference between most types of subglacial and coastal *s-forms*. The difference may be due to the unconstrained nature of vortex formation in the coastal zone, a characteristic that permits vortices to be more erosive upslope. Coastal muschelbrüche inevitably develop first on steeper slopes and appear to grade upslope into more elongated forms and then flutes.

V-shaped gouges, which grade between muschelbrüche and flutes, are well developed at many sites along this coast. They are generally the same size as muschelbrüche, but have greater relief. Their closest analogue in subglacial environments may be the open spindle flute, but in contrast the "v" in tsunami-swept environments always closes downflow. Very sharp v-shaped gouges with a raised pedestal between the wings of the "v" can also develop (figure 4). Unlike other *s-forms*, v-shaped gouges may form a continuum over a large range of sizes. Smoothed v-shaped features have been found at Bass Point which are approximately 10 m high and over 30 m wide. Lower-amplitude forms are probably the coastal equivalent of subglacial sichelwanne, displaying the characteristic crescentic depression, but again with their orientation reversed to that found under subglacial flow. Both v-shaped gouges and sichelwanne can develop in association with muschelbrüche. All three types of *s-forms* may be partially controlled by jointing in the underlying bedrock because they tend to be aligned parallel to joints where such are prominent.

Crest features consist of broad potholes, flutes,

Figures 3–7. 3. Mussel-shaped *s-forms* or muschel-brüche developed on the upflow side of a platform at Bass Point. Tsunami flow is from right to left such that the steepest rim points downflow. Note the overlapping of the features at different scales. Camera lens for scale on rim of large central feature. 4. "V"-shaped gouges formed in resistant gabbroic diorite on the headland at Tuross Head. Tsunami flow is from right to left. 5. Small dissected potholes on the crest of the headland at Atcheson Rock on the ocean side of the canyon structure shown in figure 15. 6. Flutes on the crest of the ramp 14 m above sea level at Tura Point. Note the cavettos on the sides of the flutes. These features lie at the top of the ramp shown in figure 11. Camera lens for scale. 7. Transverse trough at the top of the headland at Bingie Bingie Point. Tsunami flow is from left to right. Note smoothed, polished bedrock upstream surface covered in a series of smaller transverse troughs and flutes.

and transverse troughs. Potholes are one of the best features replicated at different scales by tsunami overwash. While large-scale forms can be up to 70 m in diameter, their smaller equivalents have dimensions of 4–5 m. The smaller potholes also tend to be broader with a relief of <1 m. the smaller forms can exhibit a central plug, but this is rare (figure 5). Instead the potholes tend to develop as flat-floored, steep-walled rectangular depressions usually within the zone of greatest expected turbulence. While this shape may be controlled by bedrock jointing, their origin as bedrock-sculptured features is unmistakable because the inner walls are inevitably undercut or imprinted with cavettos. In places, potholes have amalgamated where vortices have eroded their connecting walls, creating a chaotic landscape of jutting bedrock with a relief of 1–2 m (figure 5). Because flow is unconstrained, these forms occur where turbulence was greatest, usually on the stoss or crest of steep slopes, or on the seaward portion of headlands. These are zones where high velocity water flow has changed direction suddenly. Broad potholes are best developed at Shelly Point and Atcheson Rock (figure 1). These smaller features appear to have no equivalent in subglacial or channeled scabland landscapes. The forms are not common, which, coupled with the fact that their relief approximates the depth of downcutting on inherited platform surfaces, indicates that such features can be interpreted as embryonic coastal sculpturing features. We are also uncertain whether the steep-sided, rounded deep potholes isolated on intertidal rock platforms, and attributed to mechanical abrasion under normal ocean wave action, are catastrophically sculptured forms or not. Intriguingly many of these latter features also evidence undercutting and cavettos along their walls.

The crest of headlands can also be dominated by fluting features. The term flute, rather than furrow, is preferred to describe long linear forms that develop under unidirectional, high velocity flow in the coastal environment. Fluting was described in an earlier paper for Tura Point (Young and Bryant 1992a). Fluting on coastal headlands is always linear and rarely associated with superimposed *s-forms*. Where other *s-forms* are superimposed they tend to consist of cavettos along the flanks of the flute or, in one case at Stoney Creek, faceting on the upstream end. The faceting consists of depressions with sharp intervening ridges that have the appearance of being chiselled out of the bedrock flutes. Similar features have been noted in rivers and attributed to small stable vortices developing as a skin layer between the main high velocity flow

and the underlying bedrock surface (Maxson 1940). In a few instances flutes taper downstream and are similar in shape to rock drumlins and rat-tails described for subglacial environments (Tinkler and Stenson 1991; Shaw 1994). The features always appear on the seaward crest of rises and are noticeable for their protrusion above, rather than their cutting below bedrock (figure 6). Flutes also tend to grade through a range of sizes from features several meters in length to ones up to 30–50 m long with length being inversely proportional to bedrock slope. The relief of a flute tends to remain constant within a 1–2 m range such that the longer the feature the flatter it becomes. Longer flutes can be difficult to discern in the field because of their low relief. Flutes may be the coastal equivalent of hair-pin marks formed by horseshoe vortices, and unlike other coastal *s-forms* appear to have the same orientation to the flow as subglacial features (Shaw 1994). These vortices are generated by flow separation around a more resistant bedrock obstacle. At Tuross Head the flutes have constrained the deposition of contact-imbricated boulder streamers described elsewhere (Young et al. 1996). In most cases flutes lie upslope of fields of muschelbrüche and disappear rapidly on the gentler slopes at the top of headlands.

Near the crests of headlands, flow can separate from the bedrock surface forming a transverse roller vortex capable of eroding very smooth-sided, low, transverse troughs. In some cases the troughs are difficult to discern because they tend to form where flow was still highly turbulent after passing over the crest of overwashed headlands. In these cases the troughs are embedded into chaotic topography similar in origin to that producing merged potholes. This is especially common on very low angle slopes. Transverse troughs can also form on stoss slopes where the bed flattens or locally slopes downflow. Under these circumstances troughs are usually short, rarely exceeding 5 m in length. The smoothest and largest features develop on broad undulating crests where they can dominate bedrock surfaces. Here troughs can measure over 50 m in length and 10 m in width (figure 7).

Cavitation features are a product of high-velocity flow as great as 10 m s^{-1} (Baker 1978). Such phenomenon have been invoked before to account for *s-forms*. Hjulström (1935) attributed the formation of *sichelwannen* to cavitation under flows of very high velocity, a conclusion which was supported by Dahl (1965) who argued that they develop almost instantaneously. In tsunami environments, cavitation marks may develop parallel, or at right angles to the flow on vertical or horizon-

tal surfaces. Cavitation features are widespread and consist of sinuous grooves, impact marks, drill holes and cavettos.

Sinuous grooves are very prevalent. While they dominate lee slopes, they are not necessarily restricted to them. Sinuous grooves tend to extend no more than 2 m in length and have a width of 5–8 cm at most (figure 8). Depth of cutting can vary from a few millimeters to several centimeters. In some cases the sinuous grooves become highly fragmented longitudinally and are similar to comma marks found in subglacial environments. Often they form en echelon in a chain-like fashion (figure 9). It is tempting to credit their formation to chemical erosion along joints, microfractures, or igneous inclusions. Four facts suggest otherwise. First, while small-scale structures may have a subtle control on the occurrences of sinuous grooves, detailed measurements show that the grooves diverge up to 10° from structural alignments. Second, joints in bedrock are linear over the distances

Figure 8. Sinuous offset grooves cut into tonalite at Bingie Bingie Point. Flow direction is from bottom to top. Note that these features end in drill holes that gouge into the tonalite bedrock surface.

Figure 9. Sinuous grooves on the ramp at Tura Point, downslope of the evacuation zone in figure 11. Flow is from bottom to top. The grooves also end in drill holes. The features are similar to chains of comma marks found in subglacial environments.

which grooves develop. The grooves described here are sinuous. Third, joint spacing on rock surfaces is rarely less than a couple of meters. Sinuous grooves often appear as sets within the space of individual joint blocks. Finally sinuous grooves occur only on polished and rounded surfaces swept by tsunami, and not on the highly weathered surfaces nearby.

Impact marks on vertical faces facing the flow appear as pits with embedded, star-shaped grooves radiating outward (figure 10). It would be simple to suggest that such features represent the impact mark of a rock hurled at high velocity against a vertical rock face, if it were not for the fact that such marks also appear in sheltered positions or along undercuts where such a process is unlikely. Drill holes are found over a range of locations on tsunami-swept headlands. Their distinguishing characteristic is a pit several centimeters in diame-

Figure 10. Star-shaped impact mark facing the tsunami wave on the face of the raised platform at Bass Point. Note the drill holes as well. The sheltered juxtaposition of both forms suggests that the erosion was produced by cavitation rather than by the impact of a rock thrown against the face.

ter bored into resistant bedrock such as tonalite or gabbroic diorite. Drill holes appearing on vertical faces, either face the flow (figure 10), or develop at right angles to it. Such marks also appear on the inner walls of the largest potholes either with horizontal axes up to 10 cm deep or as crescentic pits 20–30 cm in width. However, the most common type of drill mark appears at the end of a linear or sinuous groove and extends downwards at a slight angle for several centimeters into very resistant bedrock (figure 8). In some cases, grooves also narrow with depth to form knife-like slashes a few centimeters deep (figure 8). Sinuous grooves may represent the collapse of one or more cavitation bubbles under very high velocity over a distance of 1.0–1.5 m. If the bubble collapses while in contact with the bed, then a drill hole is produced at the end of the groove. These characteristics make sinuous drill marks useful indicators of the direction of tsunami flow across bedrock surfaces.

The most common, small vortex feature is the cavetto, consisting of curvilinear grooves eroded into steep or vertical faces. While cavetto-like features can form due to chemical weathering in the coastal zone, especially in limestones, their presence on resistant bedrock at higher elevations above the zone of contemporary wave attack is one of the best indicators that tsunamis have swept over a bedrock surface. Cavettos develop on the sides of flutes (figure 6), along the inside walls of larger potholes and on the sides of large-scale can-

yons and cascades. These latter features will be described later. It was the presence of cavettos developed on the sides of flutes at Tura Point at an elevation of 14 m above present sea-level that first drew our attention to the possibility of corrosive high velocity flow over bedrock surfaces by tsunami (Young and Bryant 1992a). In the tsunami-swept environments along the New South Wales coast, cavettos are remarkably similar in appearance to those formed subglacially (Dahl 1965; Sharpe and Shaw 1989; Kor et al. 1991).

Large-Scale Features. Tsunami have also produced bedrock-sculptured *s-forms* at the larger scale on narrow headlands that jut out into the Tasman Sea. With one exception, most of the erosion has been generated by a tsunami from the northeast. A description of this erosion was presented for Tura Point (Young and Bryant 1992a). This tsunami was attributed to a cataclysmic landslide from the island of Hawaii about 105 ka that swamped the adjacent island of Lanai; however it may also have been generated locally within the Tasman Sea. Besides Tura Point, this tsunami caused erosion at Mullimburra Point, Bannisters Head, Bass Point, and Windang Island (figure 1). Erosion on all these headlands was related to the same northeast source deduced for the Tura event. In addition to the Tura event, erosion at Bass Point involved a second, large tsunami that overwashed and eroded the headland from the southeast. This event was responsible for most of the boulder deposits documented in Young et al. (1996) and produced dramatic sculpturing on the south side of Bass Point, especially on Atcheson Rock (figure 1).

One of the most common features of high velocity overwashing from the Tura event is the stripping of joint blocks from ramps (Young and Bryant 1992a). In some cases flow detached from the bedrock surface generating enormous lift forces that plucked joint-controlled rock slabs from the underlying bedrock. This process was inferred for Tura Point and also for Bannisters Head and Bass Point. Generally bedrock plucking removed only two or three beds from a restricted area, leaving a shallow, closed depression on the ramp surface devoid of rubble and unconnected to the open ocean (figure 11).

At Bass Point, scouring was repetitive over a distance of 2 km as the tsunami wave travelled along the lee-side of the headland. This produced a sculptured form similar to potholes described for subglacial landscapes (Kor et al. [1991] and for the channeled scabland of northwestern United States [Baker 1981]). Pothole formation has been attributed to erosion by "kolks" or vortices with near

Figures 11–14. 11. The Tura Point ramp. The tsunami came in from the northeast toward the top right-hand corner of the photograph. Fluting features lie at the top of the cliff 14 m above sea level (figure 6). The wave evacuated the depression in the foreground as it rushed down the ramp. 12. Large, broad erosional pothole formed at Bass Point. Note the central plug, which lies at the center of the vortex eroding the feature. 13. Deep pothole on the south side of Atcheson Rock. The presence of drill holes on vertical faces and of smaller potholes at the bottom indicates the existence of multiple vortices and cavitation, respectively. 14. Series of pool-and-cascade features at Bass Point. Flow was toward the top. The height of the relict platform surface is at least 8 m above present sea level. Flow cascaded off the platform through a series of pools, one of which appears in the foreground. Flow then dropped off the platform, cutting the 3–4 m deep gap lying below this pool in the photo. The pothole in figure 12 lies on the lower platform surface in the background.

vertical axes aided by turbulent bursting (Baker 1978). At Bass Point the potholes are wider than they are deep, and they were formed by large whirlpools 50–70 m in diameter (figure 12). These whirlpools eroded into basalt but left a plug of bedrock protruding 2–3 m vertically upward from the floor of the pit at the quiescent centre of the vortex. Similar plugs are visible in potholes formed under subglacial catastrophic flow regimes (Allen 1984; Kor et al. 1991). The best coastal examples, however, are at Atcheson Rock and Cathedral Rocks 5 km to the south (figure 13). On the south side of Atcheson Rock, flow structures indicate that the vortex pit was eroded by a tsunami from the southeast as flow climbed over a 17 m high ridge. A large vortex, spinning in a counterclockwise direction, produced smaller vortices rotating around its edge on the downflow side against the headland. These flow characteristics are like those produced by multiple suction vortices in tornadoes (Fujita 1971; Grazulis 1993) except that the sub-vortices appear to have remained spatially stable. The overall whirlpool is over 10 m wide and characterized by a central plug of bedrock standing 5 m high. This plug is surrounded by four, 3 m-diameter potholes, one of which bores another 3 m below the floor of the pit into resistant basalt. The counterclockwise rotation of the overall vortex undercut the sides of the pit, producing downward-eroded helical spirals that have also been noted under subglacial flow conditions and high velocity streamflow (Alexander 1932; Dahl 1965; Allen 1984; Kor et al. 1991). Circular or sickle-shaped holes are drilled horizontally into the sides of the pothole and into the wall of the plug. These latter features appear unrelated to subsequent chemical weathering or to intrusions in the basalt. We attribute their formation to cavitation along the outside wall of the vortex.

As flow accelerated under the effects of gravity and jetted down the steeper sides of some headlands, erosive channelization cut into the back of raised platforms. This channelization may also have been produced by the impingement of flow against breaks in slope. Such features take two forms: linear canyons >2 m deep cutting across or along the landward side of platforms, and pools-and-cascades cut into resistant bedrock on the lee-side of steep headlands. These features appear on headlands affected by the Tura event and are most prevalent on platforms raised 7–8 m above modern sea-level (Young and Bryant 1993). The best developed canyon features occur on Windang Island and North Durras (figure 1). Pools-and-cascades are developed best at Bass Point where water flowing off

a 6–8 m high platform surface, again from the northeast, has carved into basalt (figure 14). Smaller cascade structures were formed by a subsequent southeast tsunami wave. All features bear a resemblance to the larger canyon and cascade forms carved in the channeled scabland of western United States (Bretz 1959; Baker 1978).

In some cases it is difficult to determine whether the erosion at the back of headlands represents flow channelization or simply the impact of enormous waves breaking over the headland. For example, Atcheson Rock preserves a canyon running northeast-to-southeast that was subsequently eroded from the south by a later flow event. The channel is cut through basalt that possesses no major structural or lithological variation across a headland which stands up to 15 m above sea level. In profile the canyon structure looks as if it was formed by a breaking wave crashing onto the headland from the east (figure 15). Smaller, more subdued, versions of this feature may also exist, although they have been attributed in the literature to contemporary wave and weathering processes. These more subdued features can take one of three forms: (1) a butte rising several meters in relief and isolated from the present shoreline by a planar platform, (2) a low irregular rampart on the seaward sides of rock platforms, and (3) bombores, which appear as small isolated reefs or islands separated from shore by a submerged bedrock platform or boulder rubble apron. The more prominent of these features in offshore profile look like an inverted toothbrush.

Spatial Hierarchy of Bedrock-Sculptured Features

Subglacial Environments. Bedrock-sculptured features formed in subglacial environments develop a spatial hierarchy depending upon the degree of impingement of vortices upon bedrock and the bedrock slope. These forms also develop at several scales varying from centimeters to tens of kilometers in length (Shaw and Gilbert 1990; Kor et al. 1991; Tinkler and Stenson 1991). Kor et al. (1991) produced a comprehensive model of the spatial distribution of *s-forms* over a bedrock protuberance in subglacial environments. As flow impinges upon the steep face of a rock protuberance, a suite of sickle- and mussel-shaped forms (respectively termed *sichelwannen* and *muschelbrüche*) develop on the stoss face. Both features have rims convex-up flow with either a furrow or basin structure pointing and merging downflow. Where the slope steepens, potholes develop. If vertical faces develop parallel to the flow, usually as eroded flutes, then

Figure 15. Canyon structure (arrow) cut through the 20 m high headland at Atcheson Rock. This canyon has a NE-SW orientation that is not structurally controlled. The alignment parallels that of other canyon structures in the area. Evidence exists in the cutting for subsequent downcutting of 2–4 m by a late Holocene tsunami sweeping along the coast from the southeast. The latter event also draped a chaotically sorted boulder, sand, shell layer 0.5–2 m thick over the headland to the right of the arrow. Thermoluminescence and radiocarbon dating puts the age of this latter event within the last 800–2300 years (Bryant et al. 1996).

curvilinear channels known as cavettos are commonly cut into these faces. Continued erosion may eventually cover the surface of any flute with sinuous troughs and furrows. Toward the top of the protuberance, sichelwannen grade into more simplified and linear forms such as spindle flutes and comma forms. Both muschelbrüche and spindles are inferred to result from low-angle vortex impingement on a bed. The flow angle is slightly greater for muschelbrüche than it is for spindle flutes. If the flow separates from the bed, then a roller vortex with extending vortices develops. Erosion by these vortices forms sichelwanne. On a larger scale and on flatter slopes, roller vortices produce transverse troughs at right angles to the flow. Hence the top of any protuberance may be covered in a succession of parallel troughs lying at right angles to the flow. Where flow rushed over a raised feature, a myriad of smaller forms grade downflow into an undulating surface.

Tsunami-Swept Landscapes. The spatial arrangement of tsunami-generated sculptured terrain is different from that found in glaciated landscapes.

It is possible to classify the tsunami features into two distinct models of sculptured landscape: (1) smooth, small-scale, and (2) irregular, large-scale. These are shown schematically in figures 16 and 17, respectively. The two types are differentiated by the degree of dissection.

The landscape model for smoothed, small-scale bedrock-sculpturing by tsunami is similar to that defined for glaciated landscapes (Kor et al. 1991) and is generally restricted to headlands <7–8 m in relief (figure 16). Smoothed features generally appear on rounded headlands dominated by the formation of *s-forms* and bedrock polishing. The features are very directional, paralleling each other and any associated boulder alignment (Young et al. 1996). The model differs from the glacial one in that many of the forms are reversed 180° with respect to the inferred flow direction. Boulder alignment downdrift on some platforms supports this interpretation. Smoothed models are dominated by fields of overlapping muschelbrüche-like forms, often associated with sichelwannen-like features or v-shaped grooves on the stoss slopes of headlands.

Figure 16. Model for smooth, small-scale, bedrock surfaces sculptured by tsunami, analogous to that proposed by Kor et al. (1991) for subglacial catastrophic flow with the major difference being the reversed orientation of many forms. Inset shows the model for unconfined tsunami flow producing a gradation of muschelbrüch-sichelwanne-*"v"*-shaped forms upslope.

Figure 17. Model for irregular, large-scale, sculptured landscapes carved by tsunami.

Where vortices develop with axes at a high angle to flowlines then broad potholes may form, rarely with preserved central bedrock plugs. Crude transverse troughs develop where the slope levels off on the stoss side of headlands. At the crest of headlands, muschelbrüche-like forms give way to elongated fluting. The flutes taper downflow into undulating surfaces on the lee slope. Sinuous cavitation marks and drill holes develop on this gentler surface wherever flow accelerates, either because of steepening or flow constriction against the bed. On some surfaces, a zone of fluting and cavitation marks may reappear towards the bottom of the lee slope as a result of flow acceleration. Cavettos or drill holes develop wherever vertical faces are present. While cavettos are restricted to surfaces paralleling the flow, cavitation marks form on any vertical wall. Smoothly, sculptured landscapes are usually associated with tsunami deposits in the form of stacked boulders.

Irregular, large-scale landscapes sculptured by tsunami are ones where headlands rise above 7–8 m, where inherited forms are more prevalent, and where repeated events have scoured bedrock surfaces (figure 17). Commonly several tsunamis separated by substantial intervals of time have eroded the coastline. Many facets of the small-scale model can be superimposed on this irregular landscape. The fluting on Tura Point along a 14 m high cliff is an example of this type of superimposition (figure 6). The large-scale model is characterized by canyons forming toothbrush-shaped headlands, by ramps and by enormous potholes. Ramps can extend from modern sea-level to heights of 30 m. Type sites are located at Bass Point, along the cliffs south of the entrance to Jervis Bay, Bannisters Head and Tura Point (figure 1). Ramps evince evacuation zones (figure 11), cascades or canyons (figures 14 and 15). Large potholes up to 10–15 m deep are found primarily on the upflow side of the headlands, although at Atcheson Rock they have also formed on steep downflow slopes. Smaller potholes are also found in these environments. Irregular landscapes preserve a crude indication of the direction of tsunami approach although the imprint of refracted waves may obscure this pattern. Generally canyon features slope downflow; however where the effects of more than one event can be recognized, earlier canyons may have provided conduits across the headland for subsequent tsunami flow.

Flow Dynamics

Any model of the flow dynamics responsible for tsunami-sculptured bedrock terrain must be able

to explain a range of features varying from sinuous cavitation marks several centimeters wide to potholes over 10 m in diameter. One of the controlling variables for the spatial distribution of these features is bed slope. Stoss slopes are $>10^\circ$, whereas lee-side slopes are gentler. Even a slight change in angle appears to have initiated a change in sculptured form. For instance at Tura Point, the lee-side ramp is surprisingly free of erosional features; however, where local slopes steepen by $1\text{--}2^\circ$, sinuous cavitation marks have formed within a very short distance. Similarly at Stoney Creek (figure 1), fluting developed with a slight increase in bed slope. This suggests that new vortex formation or flow disturbance through vortex stretching is required to initiate an organized pattern of flow vortices able to sculpture bedrock. Smooth bedrock-sculpturing features never appear at the upstream edge of a platform or headland. Instead bedrock-sculpturing is separated from the shoreline on platforms <8 m in height by a zone of plucking (figure 18), or on higher headlands and ramps by cliff erosion. These observations suggest that vortices did not exist in the flow before the leading edge of the tsunami wave struck the coastline. Any model of flow dynamics must account for these differences.

Six flow phenomena: Mach-stem waves, jetting, vortex impingement, horseshoe vortices, helical flow, and multiple vortex formation are all involved, either singly or in combination, in the creation of the bedrock-sculptured features described above. At some locations along the coast, such as Jervis Bay and Bass Point, tsunami overran cliffs and hills over 45 m high. These extreme heights were attained only locally along steeply sloping coasts. Several platforms, where sculpturing is most prominent, also lie in these regions. It is unclear if this enhanced tsunami runup and bedrock erosion is caused by convergence resulting from offshore wave refraction. A more likely process is Mach-stem wave formation. This process occurs wherever the angle between the wave crest and a cliff face is $>70^\circ$. The portion of the wave nearest the cliff continues to grow in amplitude even if the cliff line curves back on itself (Wiegel 1970). The Mach-stem wave process is insensitive to irregularities in the cliff face and has been observed to increase ordinary ocean swell along New South Wales cliffs by a factor of 4. Certainly, this type of wave played a major role in generating the high velocities required to initiate cavitation and the large-scale vortices that formed potholes along the New South Wales coast.

Tsunami, because of their long wave length, behave as surging waves as they approach normal to a shoreline (Young and Bryant 1992a). Jetting is

Figure 18. Zone of plucking on the low-angle platform at Shelly Point. Flow was from left to right. The protrusions may form the core of turbulent vortices. Note the similarity in degree of dissection to that in figure 5 and foreground of figure 15.

caused by the sudden interruption of the forward progress of a surging breaker by a platform or headland. The immediate effect is twofold. First, there is a sudden increase in flow velocity as momentum is conserved and vortex formation is initiated. Second, the sudden velocity increase is sufficient for cavitation and creates lift forces which can pluck blocks of bedrock from the bed at the front of the platform. These effects are supported by hydrodynamic estimates. Theoretically, bore velocity in its simplest form is a function of the square root of the runup height, slope and bed friction (Kirkgöz 1983). At Tura Point with a ramp slope of 7° and a runup height of at least 15 m, this relationship yields current velocities of between 17.9 and 18.4 m s^{-1} under flow depths of 2–10 m (Young and Bryant 1992a). These velocities are well in excess of the 10 m s^{-1} threshold required for cavitation (Baker 1978). A third effect may also occur, especially if the flow separates from the bed at the crest of a headland or platform. Somewhere downstream, depending upon the velocity of the jet, water must reattach to the bed. Where it does, flow is turbulent and impingement on the bed is highly erosive. At this point secondary standing waves may develop in the flow which lead to large vertical lift forces under wave crests. The bedrock plucking at the front of platforms and to the lee of crests, the cavitation drill holes on vertical faces on the stoss

side of headlands and the evacuation zones on the lee-side of ramps are a product of this jetting phenomenon.

Many of the smaller *s-forms* are caused by flow separation from the bed occurring at breaks of slope $>4^\circ$ (Allen 1984). On rock platforms overwashed by tsunami changes in slope are $>15^\circ$. Flow separation also occurs up- or downslope regardless of the scale of the vortex. The notable feature of small *s-forms*, as defined so far in the literature, is the fact that they have a steep rim on their upstream side and taper in relief downstream (Allen 1984; Kor et al. 1991). *S-forms* spatially change their shape depending upon the degree of flow impingement and vortex orientation. Narrow longitudinal vortices impinging upon the bed at a low angle produce spindle flutes which become muschelbrüche at higher angles of attack. This causes the vortex to flatten out. As muschelbrüche shape deepens, then flow separation may occur resulting in the development of a roller with vortices that generate sichelwannen. Similarly, where flow separation occurs at crests, roller vortices produce large transverse trough forms. This model was developed for subglacial flow where the flow was confined between a bedrock surface and the overlying ice-sheet. *S-forms* in terrain sculptured by tsunami have their steep rim orientated downstream. In coastal environments, the flow by tsunami over-

washing bedrock surfaces is not confined. The high velocity and sudden impact of the vortex on the bedrock surface causes the vortex to ricochet upwards and the unconfined nature of the flow permits the vortex to lose contact rapidly with the bed. This produces features that begin as shallow depressions, scour downflow, and then terminate suddenly, leaving a form that is gouged into the bedrock surface with the steep rim downstream. Unconfined *s-forms* grade upslope from muschelbrüche to sichelwannen to v-shaped grooves (figure 16).

Horseshoe vortices are formed by bluff obstacles in flow boundary layers (Shaw 1994). As flow impinges upon an obstacle, higher pressures are generated that cause flow deflection and separation from the bed. This generates oppositely rotating vortices that wrap around the obstacle and scour into the bedrock surface downflow. Erosion requires velocities with a high angular component. Because the horseshoe vortices lie within the boundary layer, they are subject to intense shearing by the overlying flow. This shearing fixes the vortices in position and keeps them straight. Horseshoe vortices produce hairpin scours around a remnant ridge left standing above the bedrock surface bounded by a pair of linear, parallel troughs. The plucked and irregular zones at the front of platforms and the formation of fields of small potholes at the crests of headlands provide the initial obstacles to generate horseshoe vortices by tsunami overwashing. Flutes are produced in these zones and are the products of continued erosion by horseshoe vortices. Taylor-Görtler vortices consisting of paired longitudinal cells of oppositely rotating vortices (Shaw 1988) cannot be ruled out where flowlines are concave upward. Thus coastal flutes represent mature bedrock-sculpturing features progressively eroded into the face of platforms and headlands as long as high velocity overwashing is maintained. This is in contrast to subglacial environments where flow tends to broaden the grooves at the side of an obstacle to produce rat-tail bedrock features (Tinkler and Stenson 1991; Shaw 1994). Hairpin vortices have been invoked to account for flutes in a range of geomorphic environments encompassing hairpin grooves, drumlins, bedrock drumlins, and rat-tail bedrock features in subglacial environments, and yardangs under the influence of wind. The flutes found on New South Wales coastal platforms represent an equivalent feature generated by tsunami.

Tinkler and Stenson (1991) pointed out that some subglacial bedrock rat-tails show evidence of helical flows rolling sideways over the form. This

process tends to erode the form along its axis and shift the ridge of the flute laterally several tens of centimeters. Allen (1984) also showed that the lateral movement of streamlines in surfaces of separation over steps could initiate lateral displacement of eroded features. Lateral displacement of flutes and cavitation features are also present on coastal platforms (figure 8). Such evidence is another sign that helical flow or flow separation has occurred on these bedrock surfaces.

Multiple vortex formation occurs at the largest scale and includes kolks and tornadic flow. Kolks are not a phenomenon usually associated with subglacial flow, although they are a critical mechanism explaining the formation of potholes and the massive plucking observed in the channeled scabland (Baker 1978). Kolks are produced by intense energy dissipation in upward vortex action. The steep pressure gradients across the vortex produce enormous but yet unmeasured hydraulic lift forces. Kolks require a steep energy gradient and an irregular rough boundary to generate flow separation. These conditions are met on the steeper stoss sides of some headlands such as Atcheson Rock; however they do not account for the formation of potholes on the lower gradient slope of Bass Point nearby. Kolks may also be formed by macro-turbulence whereby eddies grow within larger rotational flow.

This latter concept has been invoked to account for the formation of tornadoes (Bryant 1991), and models for tornado formation (Fujita 1971; Grazulis 1993) may be more appropriate in explaining the formation of potholes in tsunami-sculptured terrain. Coastal mega-potholes and the broad pothole features that appear on some headlands (figures 12 and 13) require that the vortex remains stationary while scouring out a pit, and that flow at the center of the vortex remains most of the time below the threshold for bedrock erosion in order for a central residual plug to form. Kolks cannot explain the latter phenomenon. The multiple vortex model developed for tornadoes has lowest flow velocities or even a quiet zone in the center of the overall vortex (Grazulis 1993). Multiple vortex mini-tornadoes are produced by vortex breakdown within a tornado with air being pulled downward into the low pressure of the tornado from above. Applied to tsunami-generated potholes (figure 19), water can be pulled down into large vortices if the vortex becomes large enough in diameter that it is unable to lift the weight of water in the middle of the vortex against the effects of gravity. While water is being lifted out of the erosion pit at the edges of the vortex, it is flowing downwards at the center.

Figure 19. Model for multiple vortex formation in bedrock potholes. Based on multiple vortex formation within tornadoes (Grazulis 1993).

The interaction between the two directions of flow produces multiple vortices organized around the circumference of the larger parent vortex. The highest water velocities occur at the outer edge of secondary vortices along the wall of the pit. Here the direction of flow in the mini-vortex and parent vortex are the same and reinforce each other. The presence of what we believe to be cavitation drill holes on the outer wall of the pothole at Atcheson Rock indicates that these flow velocities exceeded 10 m s^{-1} . Toward the center of the vortex system, the direction of water movement in the mini-vortex and parent vortex are opposite and begin to cancel each other out. Here the resultant flow velocity is the rotational velocity of the mini-vortex minus that of the parent vortex. These lower rotation velocities toward the center of the vortex system aid the collapse of water into the center of the vortex, but at velocities too low to erode bedrock for part of the time. This process leaves a plug of bedrock in the middle of the pothole. Once multiple vortices form, the system of flow becomes self-perpetuating as long as there is flow of water to maintain the parent vortex. The fact that the plug height is always lower than the pothole walls suggests that multiple vortices develop in the waning stages of tsunami overwash after the crest of the tsunami has swept past and established the parent vortex.

Critical rotational velocities required to erode resistant bedrock also take time to build up. Flow velocities increase first through convergence of water over bedrock and then through funnelling at

preferred points along the coast. Vortices developing in conjunction with this flow must accelerate with each increase in flow velocity in order to maintain their angular momentum. Once a critical velocity is reached, bedrock erosion commences. The spin-up process causes vortex erosion to develop and terminate quickly, as demonstrated by the fact that some potholes are only partially formed. Whereas mini-vortices in tornadoes can freely circumscribe paths around the wall of the tornado, those in potholes are constrained in location by the bedrock they are eroding. The commonality between our features (figures 12 and 13) and those observed for subglacial flow (Kor et al. 1991; Allen 1983) and the channelled scabland of Washington State (Bretz 1959) suggests that this tornado model has broad applicability for features sculptured in bedrock in any environment where fluid flow can generate sufficiently high velocities and large erosional vortices.

Concluding Remarks

The models presented in this paper are the first time that organized bedrock-sculptured features generated by high velocity, catastrophic flow have been linked to tsunami. The features, upon which the models are based, are part of a continuum of anomalous coastal deposits and geomorphic forms found along the New South Wales coast that categorize an aspect of coastal landscape that is the product of extreme tsunami overwashing. While some of the anomalous deposits can be explained

by exceptional storms, when viewed as a whole, only catastrophic tsunami overwashing adequately accounts for the complete suite of forms. This certainly applies to the presence of large- and small-scale bedrock-sculptured terrain described in this paper. Identical bedrock-sculptured features have been extensively reported in the literature for subglacial and catastrophic river flows. The similarity in bedrock-sculpturing amongst the three types of landscapes is impressive; however, the main difference between small-scale tsunami-sculptured features and subglacial ones is their opposing orientation. This can be attributed to the unconfined nature of tsunami overwashing on coastal headlands. While the literature on subglacial flow supports the arguments presented here, hopefully the fact that such features can form in a non-glaciated coastal region will also lend credence to the spatial models being constructed for significant subglacial flow under Last Glacial icecaps in the northern hemisphere.

It is unusual that most of the bedrock-sculpturing features reported here have not been noted in the coastal literature before. The features

should not be unique to the New South Wales coast because other world coastlines are known to have been affected by large tsunami. The North Sea coastline affected by the Storegga slide in the mid-Holocene, the islands in the Hawaii region affected by mega-slides throughout the Pleistocene, the Sanriku coast and Ryukyu Islands of Japan, and the western North American coastline where tsunami sedimentation has been documented for the Late Holocene should be examined systematically and more broadly for supportive evidence.

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