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Abstract
There are only two volcanic centres in the Grenadine islands of the Lesser Antilles that are known to be potentially active: the submarine volcano Kick ‘em Jenny and the nearby Île de Caille centre, both located in the southern Grenadines. Kick ‘em Jenny has erupted more often in historical time than any other volcano in the Lesser Antilles arc; it has erupted at least 12 times since its presence first became known in 1939. Kick ‘em Jenny has developed within the remnants of a much larger, older volcanic structure, which collapsed at some stage in the past to generate large debris avalanche deposits downslope. Past eruptive activity is characterised by both explosive and effusive eruptions, and it is likely that both types of eruptions can be expected in the future. The hazardous phenomena associated with the volcano at its current depth to the summit of 180 m can be divided into direct and indirect hazards. Direct hazards are those associated with an eruption that only affect the area in the direct vicinity of the volcano. They include ballistic ejecta, water disturbances and degassing. Significant degassing may also occur in periods of quiescence between eruptions. Indirect hazards are not restricted to the area directly above the volcano; rather they affect a much more widespread area. They include volcanic earthquakes, volcanic ash fall and tsunamis. Earthquakes are commonly associated with eruptions at Kick ‘em Jenny, but do not normally cause any damage. At its current depth and configuration, Kick ‘em Jenny is unlikely to produce ash fall or tsunamis; these phenomena are only likely to become a possibility if Kick ‘em Jenny grows much larger. Kick ‘em Jenny lies on the western flank of a bathymetric high manifested at the water surface by a group of small volcanic islands which includes Île de Ronde and Île de Caille. Recently, five more submarine vents were identified between Kick ‘em Jenny and these islands. All these centres may belong to one large volcanic complex, for which Kick ‘em Jenny is the currently active vent. Île de Caille is the youngest island in the entire Lesser Antilles arc. Two age dates of volcanic rocks on nearby Ronde island indicate a Pliocene age, but no dates are available for Caille, whose extremely youthful appearance indicates that it is young (<1,000 years) and may erupt again. Future eruptions from Caille will probably be phreatomagmatic and will affect nearby islands and surrounding waters. Significant ash fall may also occur on more distant islands such as Grenada. Being wholly and partially submarine respectively, the hazards and eruption scenarios for Kick ‘em Jenny and Île de Caille are considerably different to those of onshore volcanoes in the Lesser Antilles. The hazard maps for both these centres take the form of concentric zones around the volcanoes.

Introduction
The information in this contribution is based on a review of data collected by the Seismic Research Unit over the past 50 years, two recent scientific surveys conducted aboard the NOAA ship Ronald H Brown, a thorough literature search and a comparison with submarine volcanoes from other parts of the world.

Geographical setting
Kick ‘em Jenny is a submarine volcano located approximately 8 km north of Grenada (summit 12°18.024’ N; 061°38.388’ W) and is the only submarine volcano in the Lesser Antilles island arc which is known to have erupted in the past 500 years. Île de Caille is a small 1.5 km wide island located about 5 km to the east of Kick ‘em Jenny and is part of a bathymetric high manifested at the water surface by a group of small volcanic islands which also includes Île de Ronde, Diamond Rock and the Sisters. Two recent surveys conducted by the NOAA ship Ronald H Brown (in 2002 and 2003) revealed several other submarine volcanic vents located between Kick ‘em Jenny and the Caille/Ronde region. The discovery of these new vents, together with the fact that Kick ‘em Jenny is located on the western flanks of this bathymetric high, suggests that these features may all belong to one large volcanic complex for which Kick ‘em Jenny is currently the most active vent. Kick ‘em Jenny and the islands mentioned above are located within the southern (Grenada) Grenadines.

Previous work
The first account of activity at Kick ‘em Jenny volcano was made following a series of explosions in 1939 (Devas and MacAdam-Sherwin 1939; Devas 1974). Subsequent eruptions have been described in Molard (1947); Shepherd and Robson (1967); Shepherd (1988); Sigurdsson (1989); McClelland et al. (1989a); McClelland et al. (1990) and Lindsay et al. (2005). The seismic and acoustic signals that characterise submarine eruptions at Kick ‘em Jenny have been described by Shepherd and Robson (1967) and Lindsay et al. (2005). Bathymetric surveys of Kick
'em Jenny have been carried out since the 1960s by a succession of ships. The first four known surveys were by British Royal Navy ships and the results mentioned in Robson and Tomblin (1966) and Sigurdsson and Shepherd (1974). Several more surveys were carried out in the late 1970s and 1980s and reported in Sigurdsson and Sparks (1979), Westercamp et al. (1985a), Bouysse et al. (1988) and Sigurdsson (1989). The most recent surveys were carried out by the NOAA ships Malcolm Baldridge in 1997 (Watlington et al. 2002) and Ronald H Brown in 2002 (Lindsay et al. 2005) and 2003. The first direct observations of the crater were made during a survey in 1989 and reported in Sigurdsson (1989). Detailed examination and sampling of the crater floor was carried out by a Remotely Operated Vehicle (ROV) during the 2003 Ronald H Brown survey. The geology and petrology of the volcano has been discussed by Sigurdsson and Shepherd (1974) and Devine and Sigurdsson (1995). An assessment of the tsunami hazard associated with 'em Jenny is presented in Smith (1994) and Smith and Shepherd (1993, 1995 and 1996).

Very little has been published on Île de Caille and nearby Ronde, although these islands have been included in regional structural and geochemical studies of the Grenadines (Westercamp et al. 1985a,b and Le Guen de Kerneizon 1985, respectively).

Geology
Kick 'em Jenny is a frequently active basaltic submarine volcano located on the western margin of the Lesser Antilles arc. The dominant products of recent activity at the volcano are pyroclastic deposits and pillow lavas of amphibole-rich basalt and basaltic andesite (Sigurdsson and Shepherd 1974). The volcano is located within a horseshoe-shaped structure that has been identified as a collapse scarp in a much older volcanic feature. Debris avalanche deposits located downslope from Kick 'em Jenny indicate that a major collapse must have occurred from this 'proto-Kick 'em Jenny' at some stage in the past.

Île de Caille is a small volcanic island comprising cross-bedded hyaloclastic basaltic tuff rings and basaltic lava flows. Although no age dates are available for Caille, and samples from nearby Île de Ronde have been dated at 3.2 - 4.6 Ma (Westercamp et al. 1985b), the extremely youthful appearance of lava and tuff deposits on this island indicates that activity may have occurred there within the last 1,000 years (Sigurdsson and Sparks 1979) and that it may erupt again. Despite its proximity to Kick em Jenny, the basalts on Caille are quite different both mineralogically (Le Guen de Kerneizon et al. 1985) and isotopically (White and Patchett 1984).

Bathymetric observations in the vicinity of Kick 'em Jenny crater show that it lies on the western edge of a field of domes and craters (at least three craters and two domes), one of which (‘Kick 'em Jack’) is at least as big as Kick 'em Jenny. The centres appear to be older than Kick 'em Jenny and no longer active. The close association of these recently-discovered submarine centres with Kick 'em Jenny, Caille and Ronde suggests that these all may belong to one large volcanic complex, possibly fed from the same magma chamber, which also includes the original, now-collapsed, proto-Kick 'em Jenny volcano.

There is some minor fumarolic activity on the small island of Petit Martinique to the north of Carriacou (Stasiuk 1999) and some active submarine hot springs in the Tobago Cays, but these...
Simplified geological map (A) and shaded relief map (B) of Kick ‘em Jenny and nearby features.
ISLAND GROWTH IN THE LESSER ANTILLES

The group of volcanic vents that includes Kick ‘em Jenny, ‘Kick ‘em Jack’, Caille, Ronde and the small unnamed vents to the southeast of Kick ‘em Jenny are an excellent modern-day example of how all the other volcanic islands in the Lesser Antilles were formed. All the volcanic islands in the Lesser Antilles once started out as submarine volcanoes. Then, after countless eruptions over millions of years, the volcanoes grew to reach the surface of the sea, join with nearby islands and eventually form the islands we know today. The same thing will probably happen with the southern Grenada Grenadines sometime in the future: eventually Kick ‘em Jenny will break the sea surface and form an island. With continuing eruptive activity over a long time period (millions of years) it may grow big enough to join with the nearby islands of the Sisters, Diamond Rock, Caille and Ronde to form one large island.

Volcanic monitoring

Volcanic and seismic activity at Kick ‘em Jenny and the southern Grenadines is monitored by the Seismic Research Unit of the University of the West Indies, St. Augustine, Trinidad. Between 1952 and 1975 the nearest station to Kick ‘em Jenny was in southern Grenada about 30 km from the vent. In 1975 this station was moved to the location GRW (Mt. St. Catherine), 15 km from the volcano. Improvements to the monitoring system completed in July 2001 make Kick ‘em Jenny probably the most closely and intensively monitored submarine volcano in the world (Lindsay et al. 2005). The system currently consists of a five-station seismograph network, tide gauges, tiltmeters, hydrophones and GPS stations all located on nearby islands (The Sisters, Île de Caille, Île de Ronde, Carriacou and northern Grenada) as well as a small observatory in Sauteurs, northern Grenada. The five seismographs in the network, which include a three-component broadband station at Sauteurs (GRHS), allow earthquakes associated with the volcano to be accurately located. From the Sauteurs Observatory data are transmitted via the internet to the Seismic Research Unit in Trinidad. At times of increased activity the observatory is manned by scientists from Trinidad; at all other times it is operated remotely from Trinidad. Eruptions

SeaBeam image of Kick ‘em Jenny and the newly discovered ‘Kick em Jack’ and nearby unnamed domes (D1, D2) and craters (C1, C2). View from SW

Kick ‘em Jenny Monitoring Centre in Sauteurs; Diamond Rock and Île de Ronde in background

islands, also located in the southern Grenadines, are nevertheless considered old (Eocene-Oligocene) and unlikely to erupt again.
at Kick 'em Jenny produce characteristic acoustic signals called ‘T-phase’ which travel great distances through the ocean and which are detected by seismographs throughout the Caribbean, including that on Saba, about 600 km north of the volcano.

**Potentially active volcanic centres**

**Kick 'em Jenny**

**Historical activity**

Throughout historical time Kick 'em Jenny has been the most frequently active volcano in the Lesser Antilles. It has erupted at least 12 times since it was first discovered in 1939, and it must have been active many times before then, although there are no written records of eruptions earlier than this. The presence of the volcano was in fact first revealed by an eruption consisting of a sequence of vertical explosions spread out over two days from July 23 to July 24, 1939. The eruptions ejected several ash-laden columns to heights of up to 300 m above the surface of the sea and generated water turbulence and numerous small earthquakes (Devas and MacAdam-Sherwin 1939; Devas 1974).

Some small waves were generated during the eruption (Devas and MacAdam-Sherwin 1939; Devas 1974). Based on eye witness descriptions, these were short wavelength waves more closely resembling heavy surf than a tsunami. The two seismograph stations that were in operation in the eastern Caribbean at the time (in Martinique and Montserrat) recorded strong signals with a dominant frequency of about 1 Hz (Lindsay et al. 2005). Shepherd and Robson (1967) showed that similar signals in 1965 were propagated through the ocean as low-frequency acoustic waves and referred to them as “T phase” by analogy with similar signals generated by tectonic earthquakes. Since 1939 such T-phase signals have been recorded in 11 episodes, and these are all thought to represent eruptions of the volcano (Lindsay et al. 2005). Visible surface phenomena during eruptions at Kick 'em Jenny have been observed only twice since 1939: in 1974 and 1988 material was ejected into the air, and the sea bubbled turbulently. The most recent eruption occurred in December 2001. Kick ‘em Jenny has displayed both explosive and effusive
behaviour in the past, although the exact nature of this activity is difficult to determine. Bathymetric surveys in the 70s and 80s revealed that the 1977 eruption led to the formation of a dome in the crater of the volcano, which subsequently collapsed during the 1988 eruption (Lindsay et al. 2005).

The December 2001 eruption
The most recent period of elevated activity at Kick ‘em Jenny occurred between December 4 and December 6, 2001 and has been described in detail by Lindsay et al. (2005). The eruption was relatively small, with no manifestation at the sea surface. Interestingly, it was the first active episode at Kick ‘em Jenny to be preceded and accompanied by a volcanic earthquake swarm since seismograph networks were established in the Eastern Caribbean in 1952. The first premonitory earthquake occurred on September 24 2001, and earthquake activity continued sporadically until the morning of December 4, when the numbers began to escalate rapidly. Most of these events plot in a wide band to the west of the volcano, and some of the larger magnitude earthquakes generated small T-phase. Several of these events were felt in northern Grenada. Beginning at 1918 hours on the evening of December 4, several bursts of free T-phase were recorded, which were interpreted as volcanic explosions (Lindsay et al. 2005).

Despite the intensive precursory seismic activity, the amplitudes of the free T-phase signals produced in 2001 were only about one half of those recorded during the 1990 eruption at the same seismograph stations, indicating that the more recent eruption may have been smaller. A bathymetric survey of the volcano carried out in March 2002 did not reveal any major changes in

References: 1 = Devas (1974); 2 = Shepherd and Robson (1967); 3 = McClelland et al. (1990); 4 = Sigurdsson (1989); 5 = McClelland et al. (1989a); 6 = Molard (1947); 7 = Shepherd (1988); 8 = Seismic Research Unit, unpublished data; 9 = Lindsay et al. (2005).
Epicentres of the larger earthquakes (>M=2.2), 2001 eruption. The size of the stars gives an indication of relative magnitude. Orange triangles are seismic stations.

The 2001 eruption provided an excellent opportunity to test the recently upgraded monitoring and warning system at the volcano. The reinforced seismic network allowed precursory earthquakes to be quickly recognised and located, providing the authorities in Grenada with sufficient time to respond by increasing the diameter of the exclusion zone around the volcano prior to the onset of actual eruptive events (Lindsay et al. 2005).

**Morphology**

Kick ‘em Jenny is a conical shaped volcano that rises 1300 m from the sea floor. It is asymmetric, as it abuts the Grenadines shelf to the east. It has a summit crater, and at least once in its recent history a dome has grown (and subsequently collapsed) within this crater. Information on the morphology of the volcano has been obtained since the 1960s via a number of bathymetric surveys. Up to 1974 Grenada was a British-dependent territory, and the first four known surveys were by the Royal Navy ships HMS Vidal (1962), HMS Lynx (1966), HMS Hecla (1972) and HMS Tartar (1974). Robson and Tomblin (1966) reported that the Vidal survey detected a distinct conical peak close to the location indicated by Devas and MacAdam-Sherwin (1939) and Devas (1974) as the source of the eruption column in 1939. The depth to the highest point on the volcano was measured as 236 metres, although Lindsay et al. (2005) suggest that this figure actually represents the depth to a point on the western flank of the volcano rather than the depth to summit. The next survey was made by HMS Lynx in 1966 and was less elaborate than the previous one; the Lynx simply swept the area of the cone located by the Vidal searching for the highest point, which it found at a depth of 190 metres. The 1972 HMS Hecla survey provided the first details on the morphology of the volcano, revealing a 1300 m high conical structure with a summit crater. The volcano was found to be asymmetrical in an east-west direction because of abutment of the Grenadines shelf (Sigurdsson and Shepherd 1974), and the north-south and east-west diameters of the cone were reported as 6 and 4 km respectively. A distinct circular crater 180 m in diameter and at least 15 m in depth was identified (Sigurdsson and Shepherd 1974). Depth to the highest point on the crater rim was 190 metres. There was no evidence for a breach in the crater rim, and the bathymetry around the crater was smooth. Two distinctive fault scarps were recognised directly east of the volcano. Both these scarps were thought to represent north-trending normal faults each with 70 - 150 m downthrow to the west. The first samples of the eruptive products of the volcano were collected on this cruise (Sigurdsson and Shepherd 1974). A reconnaissance survey by HMS Tartar in December 1974 once again located the crater, which was essentially unchanged since the Hecla survey. Once again, the measured depth to the highest point was 190 metres. A further survey by the RV Gillis in 1976 increased the level of detail, but the gross morphology of the summit of the volcano was unchanged. The crater was still present, and the depth to the crater rim was again 190 metres.
By the time of the next cruise by the RV Endeavor in 1978 the morphology of the crater had changed significantly. Although the crater rim was still discernible, and the highest point was still at a depth of about 190 metres, the crater itself was now partially filled by a dome-shaped mass of rock whose highest point was at a depth of 160 metres below the surface. This depth remained constant through subsequent surveys in 1981 and 1985, until the dome was destroyed, probably during the 1988 eruption. During the 1989 survey, the first direct observations of the crater were made from the manned submersible Johnson Sealink II operated from the RV Seward Johnson. The crater was described as breached, and remnants of a dome within the crater were observed (McClelland et al. 1989b; Sigurdsson 1989).

In July 1996 a survey conducted by the NOAA ship Malcolm Baldridge resulted in the first three-dimensional view of the volcano. The volcano’s summit, located on the western rim of the crater, was reported to be 178 m below sea level (Watlington et al. 2002). The lowest point on the crater rim was measured on the eastern side at 248 m below sea level, and the maximum depth of the distinguishable crater was found to be 278 m, 100 m lower than the summit. There was no evidence for a dome within the crater, which was estimated to be 590 m wide at the 255 m depth contour (Watlington et al. 2002).

A further survey was carried out from the NOAA ship Ronald H Brown in March 2002 (Lindsay et al. 2005). A detailed multibeam survey of the volcano revealed a symmetrical cone with a summit crater approximately 300 m in diameter. The depth to the highest point on the crater rim was 185 m, and the depth to the lowest point inside the crater was 264 m. The crater varied in diameter; distances measured from diametrically-opposite highest points range from 300 to 370 m, and it was breached to the northeast. There was no dome present within the crater, but there was an interior crater in the northwestern part of the main crater. This survey revealed that Kick ‘em Jenny lies within a major horseshoe-shaped feature, closed to the east, where it dips at an angle of about 20º under the summit region, and open to the west, where inward-dipping scarps extend a considerable distance downslope. This arcuate feature probably represents the collapse scarp produced during a major sector collapse of a larger, proto-Kick ‘em Jenny volcano. The bathymetric map produced following this survey revealed several areas of minor, more-recent slumping along this scarp.

The most recent survey was carried out in March 2003, again aboard the NOAA ship Ronald H Brown. This survey is the most detailed carried out to date and involved SeaBeam bathymetric surveys, seismic reflection profiles and video footage and sampling within the crater from a remotely operated submarine. The images from within the crater confirm that no dome or dome remnants are present, in fact the crater floor is essentially featureless, with the exception of the inner crater located in the northwestern quadrant of the main crater. This inner crater is elliptical in shape and is approximately 100 m long by 50 m wide and up to 50 m deep. The depth to the summit of the volcano (western crater rim) was measured at 180 m, and the lowest point in the crater was 267 metres.

Debris avalanche deposits
During the 2003 NOAA survey, a hummocky mound of material representing the remnants of a major collapse from the present site of Kick ‘em Jenny was located between 6 and 16.5 km to the WNW of the Kick ‘em Jenny crater on the downslope.

Results of bathymetric surveys conducted at Kick ‘em Jenny

<table>
<thead>
<tr>
<th>Date</th>
<th>Vessel</th>
<th>Depth (summit)</th>
<th>Ref</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966 June</td>
<td>HMS Lynx 192 m</td>
<td>Robson and Tomblin (1966)</td>
<td></td>
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</tr>
<tr>
<td>1972 May</td>
<td>HMS Hecla 190 m</td>
<td>Sigurdsson and Shepherd (1974)</td>
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<tr>
<td>1974</td>
<td>HMS Tartar 190 m</td>
<td>Data in Seismic Research Unit</td>
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<tr>
<td>1976 May</td>
<td>RV Gillis 190 m</td>
<td>Sigurdsson and Sparks (1979)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978 April</td>
<td>RV Endeavor 160 m</td>
<td>Sigurdsson and Sparks (1979)</td>
<td>Depth reflects dome in crater</td>
<td></td>
</tr>
<tr>
<td>1985 April</td>
<td>RV Conrad 160 m</td>
<td>Bouysse et al. (1988)</td>
<td>Depth reflects dome in crater</td>
<td></td>
</tr>
<tr>
<td>1997 May</td>
<td>RV Malcolm Baldridge 178 m</td>
<td>Watlington et al. (2002)</td>
<td>Depth to crater floor: 278 m</td>
<td></td>
</tr>
<tr>
<td>2002 March</td>
<td>RV Ronald H. Brown 185 m</td>
<td>Lindsay et al. (2005)</td>
<td>Depth to crater floor: 264 m</td>
<td></td>
</tr>
<tr>
<td>2003 March</td>
<td>RV Ronald H. Brown 180 m</td>
<td>Shepherd and Wilson, unpub. data.</td>
<td>Depth to crater floor: 267 m</td>
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</tr>
</tbody>
</table>
into the Grenada trough. By interpolating the underlying surface on either side of the deposits and generating a series of cross sections across the slumped material it is possible to measure the dimensions of the deposit. The deposit covers an area of about 67 km$^2$, with a mean thickness of 151 m and a maximum thickness of 300 m. The total volume is 10±0.5 km$^3$.

The presence of this large deposit, together with the collapse scarp to the east of Kick ‘em Jenny, implies that, at some time in the past, there was a much bigger volcano (a “proto” Kick ‘em Jenny) on the site of Kick ‘em Jenny which collapsed into the Grenada trough, generating debris avalanche deposits and leaving the collapse feature through which the present-day Kick ‘em Jenny has emerged.

If the debris avalanche was derived from the collapse of a volcanic cone with a slope of 45°, then the proto-Kick ‘em Jenny volcano was 2.1 km from base to top and 4.2 km above the sea floor. Such a volcano would have probably formed an island similar in size to the existing nearby Île de Caille or Île de...
Ronde. The collapse of $10 \pm 0.5 \text{ km}^3$ of material from this proto-volcano into the Grenada trough probably generated a significant tsunami. Smith and Shepherd (1996) discussed the problem of tsunami generation by large submarine landslides at Kick ‘em Jenny and concluded that the main factors controlling the size of tsunami waves generated in this way are the dimensions of the body that collapses and the vertical distance it travels. Based on a range of scenarios they estimated possible initial heights for landslide-derived tsunamis from Kick ‘em Jenny of 5 – 70 m. Inserting actual parameters from the recently-discovered debris avalanche deposit, the collapse scarp and the reconstructed proto-volcano into the equations used by Smith and Shepherd (1996) indicates a tsunami wave amplitude at source of as much as 50 m. This is comparable with the size of tsunamis generated by Santorini volcano in the Aegean in about 1638 (Antonopoulos 1992), Unzen in Japan in 1792 (Simkin and Siebert 1994) and Krakatau volcano in Indonesia in 1880 (Latter 1982), but is much less than that predicted for the Cumbre Vieja volcano in La Palma, Canary Islands, where Ward and Day (2001) suggest that catastrophic failure of the volcano’s western flank may drop up to 500 km$^3$ of material into the sea generating a tsunami with an initial amplitude of 900 m.

Age determinations
No age determinations have been carried out on Kick ‘em Jenny rocks.

Seismicity
In general, eruptions from Kick ‘em Jenny produce characteristic T-phase signals that are detected by seismographs throughout the Caribbean. On most occasions, the eruptions are not preceded by any unusual seismicity (e.g. volcanic earthquakes). There are, however, two exceptions to this. Prior to the 1990 eruption of Kick ‘em Jenny the nearest seismograph station (GRW, 15 km to the south) recorded several hours of harmonic tremor, with a predominant period of about 1.5 seconds. Then in 2001, for the first time, discrete volcanic earthquakes were recorded prior to an eruption. Several earthquakes occurred in the months preceding this eruption, on September 24 (1 event), October 27 (2 events), November 25 (1 event), December 1 (2 events) and December 3 (1 event). Then on the morning of December 4 the number of shallow earthquakes began to escalate rapidly, and between December 4 and 5 over 800 shallow volcanic earthquakes were recorded on the seismic station in Sainters (approx. 8 km south of the summit). The number of events recorded at the Sisters station, 3 km east of the summit, is estimated to be about 5 times larger. Lindsay et al. (2005) speculate that the differences in seismicity between 1990 and 2001 may indicate eruption through open and closed vents, respectively. The epicentres of the larger earthquakes (magnitude greater than 2.2) that preceded the December 4 eruption plot mainly to the north and northwest of the crater, and there appears to be a correlation between the earthquake epicentres and the northern arm of the collapse scarp within which the volcano sits, suggesting an alternative explanation for the premonitory volcanic earthquakes of the recent eruption, namely that they may in fact have been related to shallow movement along this scarp rather than actual eruptive activity at the volcano (Lindsay et al. 2005). In this alternative scenario, the free T-phase generated towards the end of the seismic swarm could reflect landsliding off the collapse scarp or the flanks of the volcano into the Grenada trough (Shepherd et al. 2004).

Geothermal activity
Most frequently active volcanoes are associated with some degree of geothermal activity, and Kick ‘em Jenny is no exception. Until recently scientists had only speculated about the possibility of hydrothermal venting in the crater of the volcano. The presence of hydrothermal venting was strongly suggested during an incident in 1989 in which the Johnson Sea Link manned research submersible experienced a problem during its first dive on Kick ‘em Jenny. As the submersible passed over the crater rim and into the open crater, it entered a zone of sudden updraft and the craft was rapidly lifted towards the surface. The pilot claimed he thought they had encountered a pool or column of warmer water and that the updraft carried them towards the surface.
Direct hazards

The most immediate hazards at Kick 'em Jenny whilst it remains submarine are those that directly relate to activity within the crater, such as ballistic ejecta and water disturbances. Hot rocks thrown from Kick 'em Jenny would pose a great danger to nearby ships or boats; any ship which happened to be over the vent of the volcano during the 1939 eruption would certainly have been destroyed. Magma degassing is also considered a potential threat, as this may lead to lowered water density and thus a decrease in buoyancy of boats above the volcano (this phenomenon is well-known in areas of methane escape, see for example Marchant 2000 and Henderson 2000, and a similar phenomena has recently been described by May and Monaghan 2003). These direct hazards only pose a threat to boating in the direct vicinity of the volcano, and are the reason why there has been a permanent restricted-access zone in place around the volcano since the Seismic Research Unit upgraded the monitoring and warning system in 2001.

Indirect hazards

Indirect hazards are not restricted to the area directly above the volcano, rather affect a more widespread area. At Kick 'em Jenny, the main indirect hazards are earthquakes, ash fall and tsunamis.

More recently in March 2003 scientists observed, for the first time, active degassing from within the crater of Kick ‘em Jenny. Numerous fumaroles, emitting a constant stream of gas bubbles, were observed in the inner crater, over an area approx. 100 m x 50 m in size. Measurements of actual water temperatures above the fumaroles reached 70 °C. Much higher temperatures (few hundred degrees) were, however, present within 10-20 cm of the surface, as indicated by the melting of a hard plastic tube upon insertion into the floor of the inner crater at a depth of 260 m.

Future eruptions

Kick ‘em Jenny has erupted 12 times since 1939, on average that is about once every 5 years. Over the last 60 years the longest gap between eruptions has been 12 years, and the most recent eruption occurred on December 4, 2001. Based on this past activity, it is highly likely that Kick ‘em Jenny will erupt again within the next 10 years. Past activity has been both explosive and effusive, and both types of activity are possible in the future.

Hazards of Kick ‘em Jenny

The hazards associated with submarine volcanoes such as Kick ‘em Jenny are quite different from those associated with terrestrial volcanoes.
On September 24, 1952 a Japanese research ship was passing over the active Myojinsho volcano of the Izu-Bonin arc in the Pacific Ocean south of Japan when that volcano erupted ripping the hull apart. The boat sank, resulting in the loss of all 31 people on board. Myojinsho has erupted with a similar frequency to Kick ‘em Jenny during historical time, and both volcanoes are the most active submarine centres of their respective arcs. Myojinsho was in eruption at the time the boat sank, and it is believed that one of the small explosions sank the ship, with hot bombs from the volcano puncturing the hull from below and blasting the right side of the ship apart. It was estimated that the small rock fragments found embedded in debris from the boat were travelling at velocities of 200-300 m/sec prior to impact (Morimoto 1960). As a result of this tragedy the Japanese Maritime Safety Agency (JMSA) established a restricted area with a radius of 10 km around Myojinsho that is closed to shipping. This example illustrates the real dangers that ships face in the vicinity of an erupting volcano.

Submarine volcanoes can also be dangerous even when not currently erupting. In fact, one of Grenada’s worst maritime tragedies may have resulted from degassing at Kick ‘em Jenny during a period of relative quiet at the volcano. On August 5, 1944, the wooden schooner Island Queen, with over 60 people on board, disappeared between St. Georges in Grenada and St. Vincent. The one available account of the disaster was written by Cosmo St. Bernard, one of the passengers on the Providence Mark, a boat sailing behind the Island Queen at the time. He claims that the mast light of the Island Queen was last sighted when the Providence Mark was passing Duquesne Bay. This places the Island Queen between 4 - 8 nautical miles north of Duquesne Bay when it was last seen, i.e. in the vicinity of Kick ‘em Jenny. The Island Queen was never seen again, and nothing at all was ever recovered. The prevailing theory regarding the boat’s disappearance is that it was torpedoed by a German or Allied submarine. This theory does not, however, explain the total lack of debris following the boat’s disappearance, as a torpedoed boat would probably result in at least some wreckage floating on the sea surface. On the other hand, if the Island Queen suddenly sank over Kick ‘em Jenny because the water was not dense enough to hold it afloat, then you would not expect to see any debris floating on the surface. Reports of known cases where boats have sunk over gas seeps (e.g. in the North Sea) indicate that everything on board, including people that had jumped clear of the boat, would have had insufficient buoyancy to stay afloat, and would have sunk through the low-density waters (e.g. Marchant 2000). There are no descriptions of an eruption at Kick ‘em Jenny in that year, but there was an eruption the year before, in 1943. It is therefore likely that the volcano was actively degassing in 1944, without any signs at the sea surface of such activity. Perhaps we will never know whether or not the Island Queen sank over Kick ‘em Jenny. Whatever the case, the dangers to shipping of lowered water density should not be underestimated.
Volcanic Hazard Atlas of the Lesser Antilles

Eruption Scenarios

Scenario 1:
The most likely scenario for an eruption at Kick ‘em Jenny at its current depth to crater floor of 267 m is a mild, short-lived (hours to days) explosive phreatomagmatic eruption similar to most of the eruptions that have occurred at this volcano since 1939. Such an eruption may or may not be preceded by precursory seismic activity, the style of which may depend in part on the time lapsed since the last eruption. If the time gap is small, harmonic tremor may occur, and if the time gap is large, discrete volcanic earthquakes may occur, these variations reflecting a relatively open and closed vent, respectively. Any precursory earthquakes may be felt strongly on nearby islands, including the north of Grenada, but these are unlikely to cause significant damage. The eruption itself is likely to be entirely submarine and is unlikely to be witnessed. T-phase signals recorded on seismic stations near the volcano will indicate that an eruption has taken place, and these T-phase events themselves may be strongly felt as earthquakes on nearby islands. The water surface above the volcano may bubble turbulently and become murky, and extensive degassing may lower the water density above the vent. Some small waves may be produced, but it is very unlikely that a tsunami would be generated. Should some extremely energetic explosions occur during the eruption it is possible that some ballistic ejecta may break the sea surface. The hazard map for this scenario takes the form of concentric zones around the volcano’s summit indicating the areas on the sea surface likely to be affected.

Scenario 2:
If the magma supply during an eruption at Kick ‘em Jenny is large, it is possible that the eruption discussed in scenario one above may not be short lived, but rather continue in a sustained manner. This could cause the volcano to grow closer to the surface, probably through the growth of a dome or series of domes within the crater. The best-studied example of underwater dome growth in the West Indies occurred at the Soufrière volcano in St. Vincent in 1971. On that occasion a dome began to grow at the bottom of the 175 m deep crater lake in early September 1971 and reached the surface in late October of the same year. By analogy with this episode we would expect a period of at least one to two months of steady eruption before Kick ‘em Jenny grows to be within 130 m of the surface, i.e. within the range of depths at which violently explosive eruptions are possible at the volcano (Smith 1994). If such a prolonged eruption occurs at Kick ‘em Jenny, it is possible that the volcano may even breach the sea surface and develop a small island, as was the case in Surtsey, Iceland, in 1963. Until the vent region of the volcano reaches 130 m below sea level, the hazards for this scenario will be similar to those discussed above for scenario one. However, once the volcano enters shallow depths, the behaviour of the volcano will change. Eruptions from a shallow vent are likely to be very explosive, generating explosion columns that may reach several hundred of metres above the sea surface. Ash fall may occur on nearby islands downwind of the volcano, and submarine plumes of pumice and ash may emanate from the volcano in the direction determined by prevailing currents. If eruption columns collapse, then small submarine pyroclastic flows down the sides of the volcano.

Very explosive eruptions at Kick ‘em Jenny are likely to occur when the vent region is less than 130 m deep.

The major arcuate collapse scarp surrounding the volcano and associated down-slope debris avalanche deposit discovered during the March 2002 and 2003 multi-beam surveys indicate that at least one large sector collapse has occurred from a proto-Kick ‘em Jenny volcano in the past. The dimensions of the deposit and the scarp indicate that this collapse may have generated a tsunami with an amplitude at source of as much as 50 m. Since this collapse, approximately 1 km³ of material has been erupted to bring the volcano to its present configuration. The current Kick ‘em Jenny has remained stable in approximately the same configuration for at least 40 years, and probably for much longer than that, and the probability that the volcano will collapse from this current configuration is considered extremely small. Should the volcano grow closer to the surface, however, this probability will have to be reevaluated.

A sustained eruption at Kick ‘em Jenny might lead to the formation of a small island, like this one, which formed at Surtsey in Iceland in 1963 (photograph taken on November 21, 1963).
Volcanic hazard map for Kick ‘em Jenny, Scenario 1: short-lived phreatomagmatic eruption at the current depth to vent of 267m

Volcano may be generated. The sea above and surrounding the volcano would be extremely turbulent. As the volcano grows bigger, it is possible that a dome within the crater or even the entire summit area of the volcano may become unstable and collapse, generating a pyroclastic flow or debris avalanche down the side of the volcano. Such a collapse might generate a tsunami, the size of which will depend largely on the volume of material that collapses. In a worst case scenario, if the volcano grows to the same size as it was before the previous major collapse (10 times bigger than the present day Kick ‘em Jenny), and the entire summit region (10 km$^2$) collapses, a tsunami with initial amplitude of up to 50 m may be generated. The probability of growth and subsequent collapse of this magnitude in the near future (i.e. within the next few decades) is negligible. Since the first bathymetric survey of the volcano in 1962 the volcano as a whole has not grown by any detectable amount. The collapse of a dome from within the crater in the late 1980s did not generate a tsunami. Gradual growth of the volcano from its current shape to an unstable pre-collapse shape would certainly be preceded by a long sequence of eruptions and minor collapses, during which the hazards at the volcano, including the probability of tsunamis, will be constantly reassessed.

A hazard map for this scenario has been generated for the stage of the eruption at which the volcano vent is < 130 m deep, but has yet to develop a large, unstable cone. As with the first scenario, the hazard map takes the form of concentric zones around the volcano’s summit indicating the areas on the sea surface likely to be affected.
**Île de Caille**

**Past eruptive activity**

Caille is a well-preserved basaltic volcano formed by Surtseyan volcanic activity, and represents the youngest island in the Lesser Antilles. Early eruptive phases were submarine and produced hyaloclastites. As the volcano grew and the vent became subaerial, eruptions became less explosive and activity was more strombolian in nature (Westercamp et al 1985a). The age of Caille is not known, but its youthful appearance and lack of vegetation have led previous workers to suggest that it is younger than 1000 years BP (Sigurdsson and Shepherd 1974). Archaeologists claim to have found ceramic artifacts dating from the Calivigny culture (approx. 800-1200 AD) embedded in lava flows near the centre of Île de Caille (L. Sutty, pers. comm. 2000), further confirming a young age for the island.

**Historical activity**

There have been no reports of historical eruptions at Île de Caille.
Seismicity
There has been considerable historical seismicity in the area of the southern Grenadines. Although most of this is thought to be primarily associated with Kick ‘em Jenny, precise epicentral locations have only been possible since the monitoring network was upgraded in 2001, and it is therefore possible that some of the historical seismicity may have been associated with Île de Caille, or one of the recently discovered submarine centres adjacent to Kick ‘em Jenny.

Geothermal Activity
There is no known geothermal activity associated with Île de Caille.

Future eruptions
The close association of all the subaerial and submarine vents in the southern Grenadines indicates that these may all belong to one large volcanic complex for which Kick ‘em Jenny is the currently active vent. More work is needed to determine whether or not activity has in fact migrated westwards with time, i.e. from the Caille/Ronde area to Kick ‘em Jenny. However, given the close proximity of the youthful Caille to Kick ‘em Jenny, it must be assumed that it may erupt again in the future. Past eruptions at Caille indicate that future activity will take the form of a moderate basaltic eruption and will be at least partially if not completely phreatomagmatic, depending on the vent location. There is likely to be considerable precursory seismicity and phreatic activity. There may be some extrusion of lava, especially if the vent is not submerged and magma cannot mix with water. Ash fall and ballistic ejecta would affect nearby islands, and material entering the sea will generate significant water disturbances. As the volcano grows it may become unstable, and a portion of it may collapse into the sea, generating a minor tsunami. An eruption at Caille would probably be very similar to that which occurred at Surtsey in Iceland in 1963.

Conclusion
Kick ‘em Jenny and Île de Caille in the southern Grenadines are both live volcanoes that are likely to erupt again in the future. An eruption from Kick ‘em Jenny is much more likely than one from Caille and will probably occur within the next ten years. The hazards that would accompany an eruption from either of these centres are different to those expected at onshore volcanoes, due to the influence of seawater. At its current depth to crater floor of 267 m, future activity at Kick ‘em Jenny is likely to take the form of a small, short-lived, wholly submarine basaltic eruption, generating water disturbances and possibly ballistic ejecta close to the vent. No tsunamis are expected in this most-likely scenario. In a less-likely scenario of prolonged activity the volcano may grow closer to the surface and the eruption may become more explosive. In this scenario activity may breach the sea surface, with explosion columns reaching several hundred of metres above sea level. The sea above and surrounding the volcano would be extremely turbulent, and a small island may even form. Ash fall, submarine plumes of pumice and ash, small submarine pyroclastic flows and debris avalanches may all accompany such an eruption. A future eruption at Caille is likely to display similar phenomena. Any sustained eruption at Kick ‘em Jenny will have to continue for a long time in order to develop a large unstable edifice capable of tsunamigenic collapse. Hazard associated with future eruptions in the southern Grenadines is depicted in the form of concentric zones about the possible vent areas (Kick ‘em Jenny and Caille). It is important to note that the constant degassing at Kick ‘em Jenny may present some danger to shipping even when the volcano is not in active eruption, and the restricted access zones recommended by the Government of Grenada for different levels of activity should be adhered to at all times.
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