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Hay una fuerza motriz más poderosa que el vapor, la electricidad y la energía atómica: la voluntad.

Albert Einstein

Kick 'em Jenny:

Potential hazard for the eastern Caribbean islands and eastern Venezuelan coast

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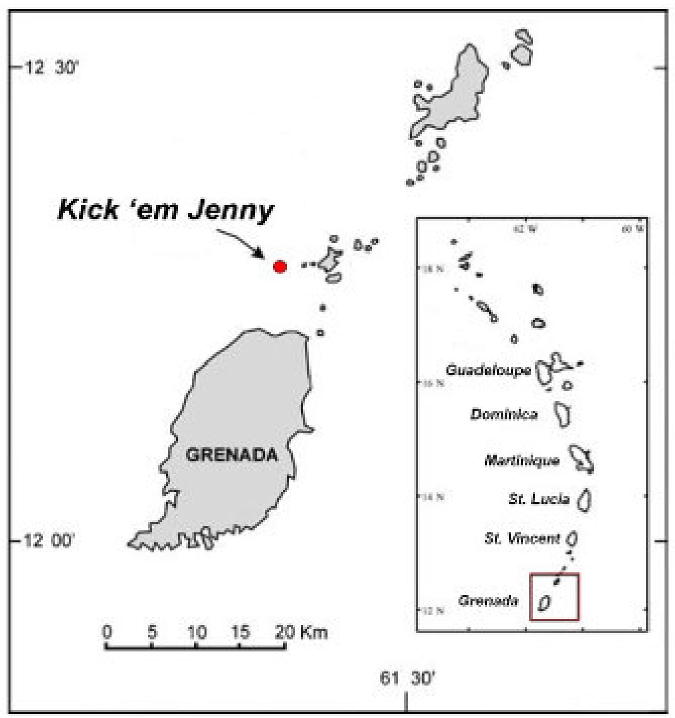
WHAT IS KICK 'EM JENNY ?

Kick 'em Jenny is a submarine volcano located 8 Km north of Grenada. The volcano is about 1300 m high, and consists of an asymmetric circular cone with a central crater measuring approximately 300 m in diameter. The peak height of the rim, (currently at 197 m below the surface of the sea), has remained fairly constant through time, besides a period of dome building in the 1970s/1980s when it was observed as shallow as 160 m bsl. Kick 'em Jenny is the only active submarine volcano in the Eastern Caribbean. It is also the most frequently active volcano in the region, erupting at least 13 times since it was discovered in 1939 (Allen et al. 2018). Over this limited monitoring period, the volcano is known to produce small explosive and effusive eruptions. It also supports a large number of hydrothermal vents that produce hot water and gas. Lavas produced by the volcano are commonly olivine basalts and basaltic andesites, much like the lava flows found on neighboring islands.

Kick 'em Jenny is located on the eastern margin of the Caribbean Plate, where a collision between the Caribbean Plate and the South America Plate to its east, produces a subduction zone that has its surface expression as the Lesser Antilles Trench.

The first record of the volcano was in 1939, although it must have erupted many times before that date. On 23–24 July 1939 an eruption broke the sea surface, sending an ash cloud of steam and debris about 300-400 m into the air (Smith & Shepherd, 1993a; Lindsay & Shepherd, 2005), and generating a series of tsunamis around two meters high when they reached the coastlines of northern Grenada and the southern Grenadines. During that eruption, people on the northern coast of Grenada were able to feel vibrations and see the ash cloud rise above the ocean in the distance. A small tsunami also reached the West coast of nearby Barbados, where a sea-wave suddenly washed over a coastal road.

In 1974 material was ejected into the air and the sea bubbled turbulently, and similar phenomena were observed also in 1988. More recently, an eruption of Kick-'em-Jenny occurred in April 2017, with an instrumentally recorded unrest period in 2018. Another eruption of Kick 'em Jenny occurred in December 4th, 2001, and differed significantly from past eruptions in that it was preceded and accompanied by genuine volcanic earthquakes since seismograph networks (rather than single stations) were established in the eastern Caribbean in 1952 (Lindsay & Shepherd, 2005). In April 2017 seismic episode at Kick 'em Jenny lasted for 4 days from the 29 April until the 2 May, and was again associated with several days of heightened seismicity. In this time-lapse, Allen *et al.* (2018) observations were interpreted as the growth of a small lava dome (25 m high), a clear circular growth in the mouth of the breach in the northern rim of the crater. This eruption also led to the filling of much of the collapse scar created by the landslide in the previous time period by approximately 11 m.



Location map for Kick 'em Jenny volcano, close to Grenada. Boxed inset shows location of map in the Lesser Antilles.

Kick 'em Jenny is an unusual name for a volcano, and many people are curious about its origin. Apparently, the name was once used for Diamond Island, which is a short distance away from the volcano location. That name was given to the island and its surrounding oceanic waters because sometimes there can be extremely rough. After the volcano's first known eruption in 1939, people began referring to it as "Kick 'em Jenny" and the name remained over time.

Kick 'em Jenny is monitored by the Seismic Research Unit of the University of the West Indies. Improvements to the monitoring system were completed in July 2001 make it probably the most closely and intensively monitored submarine volcano in the world (Allen *et al.* 2018).

Kick ém Jenny belongs to a small group of volcanoes of felsic (siliceous) magmas, because siliceous magmas are so viscous, they tend to trap volatiles (gases) that are present, which cause the magma to erupt catastrophically, making this type of volcano more explosive and dangerous.

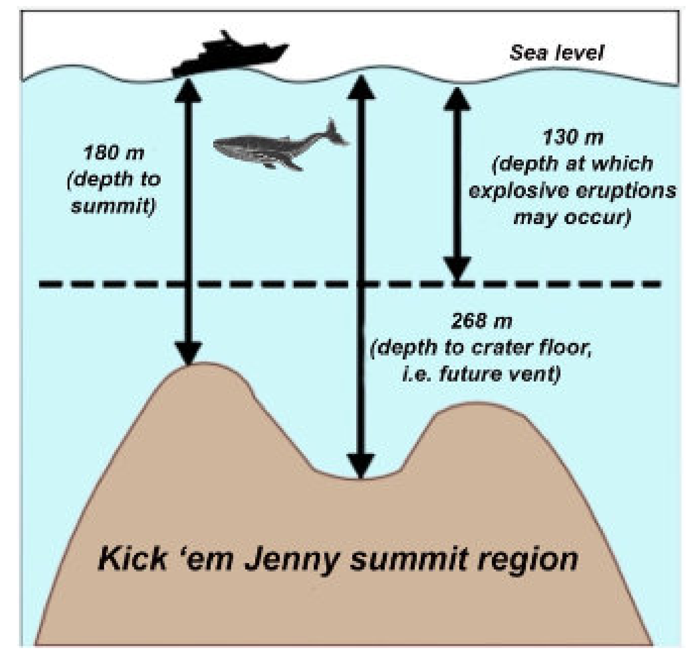
Because scientists can neither see nor hear the volcano, Kick 'em Jenny's lowest alert is always YELLOW and a 1.5 Km exclusion zone around the volcano's summit should be observed by maritime vessels at all times. Kick 'em Jenny is also a modern-day demonstration of how the volcanic islands in this region were formed. With each submarine eruption deposits of volcanic material accumulate around the summit. All of the volcanic islands of the Lesser Antilles began as submarine volcanoes.

HOW DEEP IS KICK 'EM JENNY ?

Between the 1960's and the late 1970's the depth to the summit of the volcano was approximately 180-190 m. In the 1970's and early 1980's the depth to the summit of the volcano decreased to approximately 150 m, reflecting the growth of a dome within the crater. This dome was destroyed during eruptions in the late 1980's and a survey conducted by the U.S.-based National Oceanic and Atmospheric Administration (NOAA) in March, 2002 revealed that the summit was at 180 m below the surface of the sea.

Until recently, it was thought that Kick 'em Jenny had grown 46 m (from 236 m to 190 m below sea level) between the surveys of 1962 and 1966. However, data collected from the two recent cruises (March 2002 and March 2003) and a careful re-examination of data collected on even earlier cruises make it clear that the crater rim of Kick 'em Jenny has remained at the same depth below the surface (180-190 m, within measurement uncertainty) since at least 1966 (Lindsay & Shepherd, 2005). The major sequence of changes over the past forty years has been that a dome grew in the crater between 1976 and 1978. This dome collapsed in either 1988 or 1990 and there is now no trace of it left. The 1988 activity have recorded big submarine explosions. There is in fact a new interior crater about 30 meters deep on the site where the dome used to be so it is more accurate to say that the active vent area of Kick 'em Jenny has in fact become deeper. Kick 'em Jenny has, therefore, not grown closer to the surface between 1962-2003. A submersible survey in 2003 detected a crater with active fumaroles releasing cold and hot gas bubbles.

Kick 'em Jenny volcano has built up through the debris of a large collapse feature (see the Kick 'em Jenny bathymetry model). This collapse feature is large enough suggest that a predecessor volcano, much larger than Kick 'em Jenny, was once tall enough to be an island that rose above the ocean surface. That island is thought to have collapsed about 43,000 years ago (Allen *et al.* 2018).



The volcano is considered to be too deep beneath the surface of the sea to generate an important tsunami. Source: https://uwiseismic.com/volcanoes/kick-em-jenny/

Bathymetric surveys across a 32-year period between 1985 and 2017 indicate that the volcano has added about 7 million cubic meters of material through constructive volcanism. However, during that same time interval, about 35 million cubic meters were lost through submarine landslides. Instead of growing larger and towards the sea surface, the volcano lost about 28 million cubic meters to submarine landslides (Lindsay & Shepherd, 2005).

HOW DANGEROUS IS KICK 'EM JENNY ?

As mentioned before, the 1939 explosive eruption of Kick 'em Jenny generated a series of sea waves which had amplitudes of about 2 meters in northern Grenada and the southern Grenadines, but It is unlikely that the blast of an eruption will produce a major tsunami unless the volcano grows and its summit is at a shallower depth. Future eruptions could build the volcano high enough to become an island. As the volcano grows closer to the surface, the danger from explosive eruptions and tsunami risk will rise.

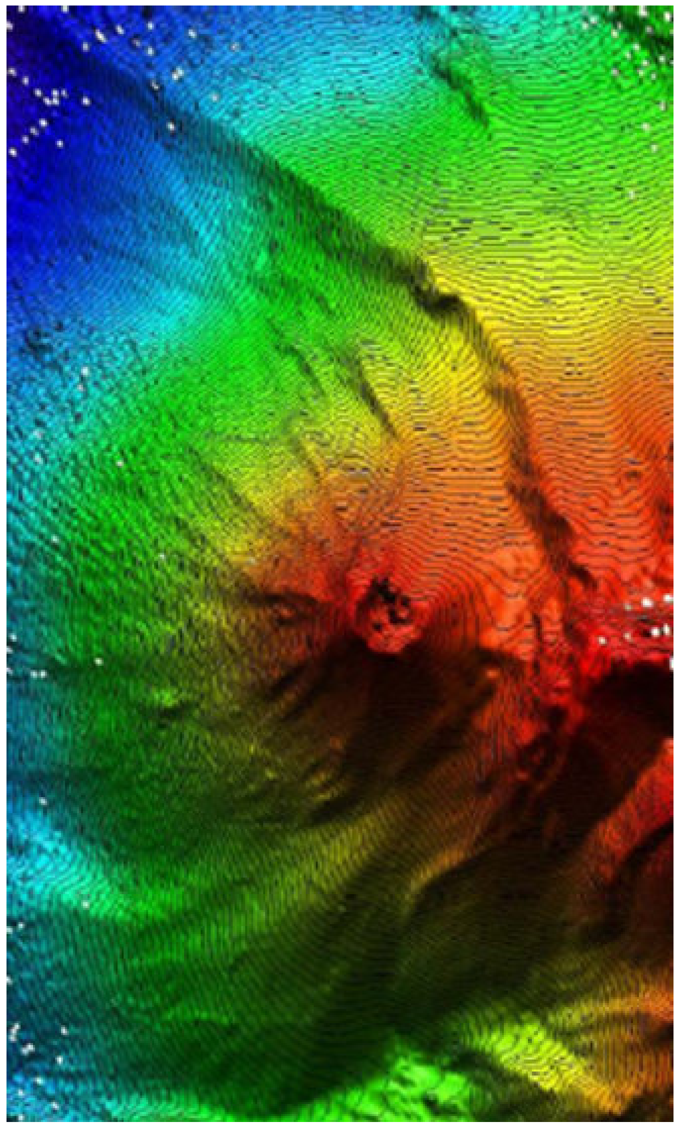
The more likely tsunami threat is from submarine landslides. These tsunamis could be triggered by a dome collapse or a landslide on the flank of the volcano. Either of these events could displace enough water to produce a large wave. These types of events are known to have occurred at Kick 'em Jenny through evidence obtained from sea floor mapping. However, information about any tsunami produced during these events is not available. The sea floor around the volcano shows evidence of historic landslides and debris flows with submarine runouts of several miles (Lindsay & Shepherd, 2005).

A few months after the last eruption (December, 2001), in March 2002, a detailed bathymetric survey (NOAA) was carried out which revealed the presence of a large collapse scarp surrounding Kick 'em Jenny. The earthquakes of the 2001 eruption appear to be closely associated with this scarp, suggesting that it may be still active. If this is the case, the possibility exists for future sector collapse events which may generate debris avalanches and significant tsunamis (Lindsay & Shepherd, 2005).

According to a research from West Indies University of Trinidad and Lancaster University in England, this volcano has an explosive index of 3 to 4 (scale from 0 to 8), which means severe to catastrophic (examples are Nevado del Ruiz, Colombia and Gulunggung, Java). In time when Kick 'em Jenny displaces hydrostatic column, it can have eruptions 5 to 6, meaning Paroxysmal to Colossal, which it can produce big waves (Tsunamis) affecting Caribbean/Venezuelan islands and the Venezuelan coastline (Distance to Paria 175 Km, to Margarita 275 Km and to Puerto La Cruz 400 Km).

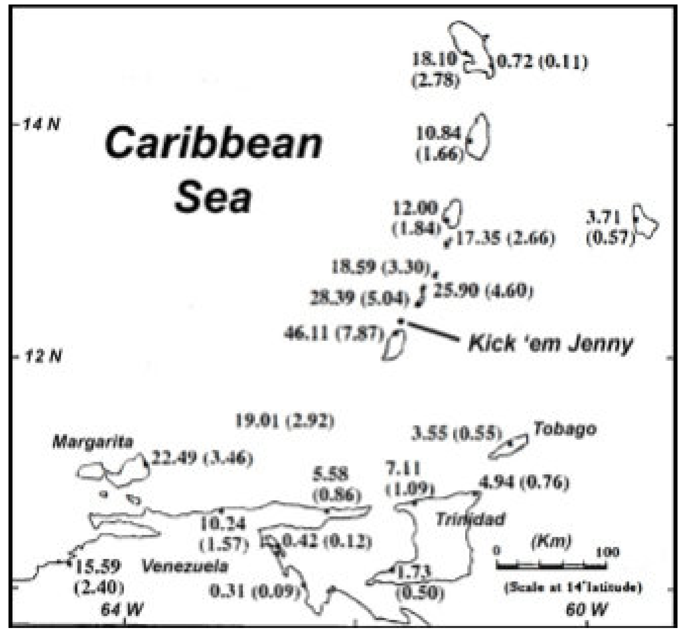
According to mathematic simulations, volcanic analogs, and based upon current monitoring, the speed of the waves at the moment of the explosion can be between

300 and 500 Km/h. A possible realistic scenario has been established by Smith & Shepherd (1993a), where the explosion produced waves between 3 and 4 meters close to Margarita Island and 2 to 3 meters in Puerto La Cruz area; and 5 to 6 meters in the Paria peninsula.



Morphology of Kick 'em Jenny volcano, as revealed by a multi-beam survey by the NOAA Ship Ron Brown in March 2002. The survey shows that the modern cone of the volcano is nested within a larger horseshoe-shaped depression formed by slope failure. Source: https://oceanexplorer.noaa.gov/explorations/03kickem/media/kejsurvey.html

Smith & Shepherd (1993a) calculated scenarios with the average tsunami waves velocity between 500-600 km/h, rising to a maximum of around 800 km/h in deeper water. Within 25 minutes of initiation, the tsunami has reached the whole of the coastline of Grenada, all of the Grenadines and the west coast of St. Vincent. Within one hour it has reached the Leeward islands to the north and the northern coast of Trinidad to the south. Within two hours it has reached all of the islands of the Eastern Caribbean and most of the Venezuelan coast. Smith & Shepherd (1993a) also calculated the average wave height scenario in the surrounding areas, with a Volcanic Explosivity Index (VEI) of 3 (the most realistic scenario) and a VEI of 6 (Krakatau type).



Run-up values in meters for the VEI=6 and VEI=3 scenario events at Kick 'em Jenny (VEI=3 in brackets). Source: Modified from Smith & Shepherd (1993b)

Gisler *et al.* (2006) modeled an explosive eruption of Kick 'em Jenny, where they assumed the extreme (admittedly unlikely) case of an instantaneous explosion near the top of the cone. Because they anticipated that the strongest coupling to the water motion will be through the motion of rock, they do not place the explosion at the summit, but somewhat deep (usually 150 m) below the summit. Gisler *et al.* (2006) used linear theory to calculate initial amplitudes, dispersion, propagation, and shoaling, given a spectrum of potential events and their probability. The worst-case scenario for Gisler *et al.* (2006), included run-ups as high as 37 meters on the northern shore of Grenada for a VEI=5.5 (a Krakatau-like event), considered as likely on a 1000-years scale, or as high as 2.7 meters for a more realistic (VEI=3.7), 100-years scale event.

Gisler *et al.* (2006), also concluded that the efficient production of a tsunami requires a disturbance that covers a substantial distance or lasts a considerable time. Earthquakes or landslides, or more generally a movement of the seafloor or a pressure pulse communicated by the seafloor, produced tsunamis efficiently. Explosions or impacts do not couple to water motion as efficiently as do slower motions of rock. Specifically, the tsunami danger from explosive eruptions of Kick-em Jenny is much less important than the danger that might result from a slope failure at that volcano, similar to that which caused the horseshoe-shape cleft in which the volcano currently nestles.

The repeat time of major eruptions at Kick-em Jenny is likely to be on a longer timescale than previously thought (Allen *et al.* 2018). This is more similar to the behavior of many of the sub-aerial volcanoes in the Caribbean Arc (e.g. La Soufriere, St. Vincent which erupts on a ~50 year cycle) because the regular decadal activity at Kick-em Jenny has contributed little to the construction of the cone. Because of that, Allen *et al.* (2018) concluded that tsunami risk associated with Kick-em Jenny is minimal, but the risk posed to shipping by ejected material and large gas releases during periods of eruption (particularly something on the scale of the 1939 event) should be the key hazard management concern.

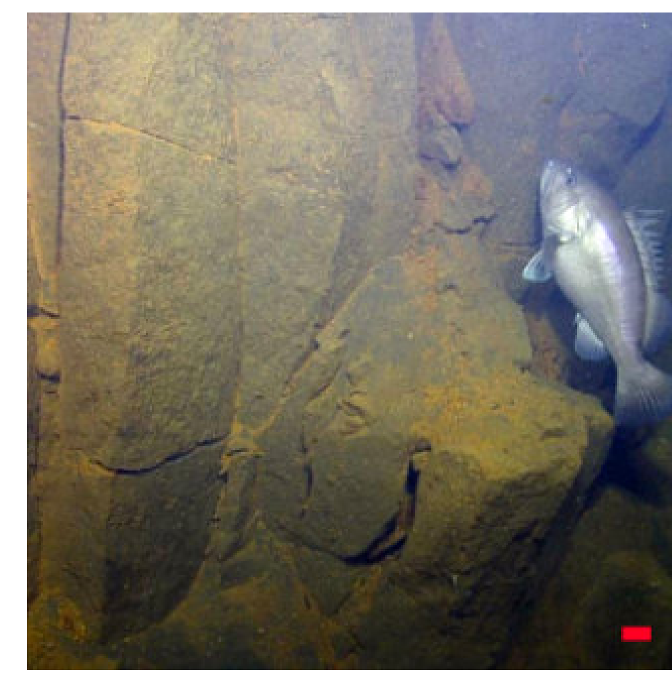
A CLOSE LOOK AT THE VOLCANO

NOAA's Office of Ocean Exploration created in 2002, a mission to investigate and evaluate the evolution of the volcano as well as its relationship to the natural environment surrounding the hydrothermal ventings in the area. The mission began March 9, 2002, with the NOAA research vessel Ronald H. Brown, in port at San Juan, Puerto Rico (Lindsay & Shepherd, 2005).

One of the most spectacular views from the monitors on ship was of the ROV Oceanic Explorer approaching the main crater of Kick'em Jenny and coming up on a wall of gas bubbles. The discovery that Kick'em Jenny was continuously releasing gas bubbles confirms the scientists' previous beliefs that the volcano is actively degassing. It was important to discover just how much degassing was occurring with the volcano because this process can significantly lower the density of the water. This can be a serious danger to shipping or boating that would be occurring in the sorrounding area (Lindsay & Shepherd, 2005).

The magma of Kick'em Jenny is generally an alkali basalt type with a mineral composition that indicates it originates within the lower crust. Sigurdsson (1973) demonstrated that all the volcanoes of the Antilles arc lie above a subduction zone of two lithospheric plates. The activity of these volcanoes is a result of the gradual westward drift of one plate and its thrusting under the adjoining plate. The dominant products of recent activity at the volcano are pyroclastic deposits and pillow lavas of amphibole-rich basalt and basaltic andesite (Devine & Sigurdsson, 1995).

Submersible observations and dredge sampling of the volcano have also revealed two styles of eruption: explosive, tephra-producing eruptions, and non-explosive, dome-forming lava eruptions. Rock samples collected on the flanks of Kick'em Jenny exhibit an increase in gray pumice and lithics, suggesting possible mixture of material from different eruptive events (Devine & Sigurdsson, 1995). The samples are very rich in primary volcanic material and generally lacking in significant amounts of biogenic fragments. This suggests that they are relatively young and have not suffered from significant admixture with non-volcanic sediment. Samples collected near the crater contain the highest proportions of dark basaltic scoria. These represent the products of recent explosive eruptions (Devine & Sigurdsson, 1995).



Columnar-jointed rock in outcrop on the northwestern flank of Kick 'em Jenny outer crater. It is infered that this deposit is related to the mid-1980s lava dome that previously filled the crater and was partially destroyed during the 1988 eruption. A grouper and a red bar of 10 cm as a scale. Photo source: Nautilus Live https://nautiluslive.org/album/2013/11/03/kickem-jenny-dive-two-highlights

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