Is the Pine Island glacier, Antarctica calving triggered by earthquakes and tsunamis?

Iceberg calving event is one of the main processes that removes mass from ice shelves. The large iceberg calving events are a part of the natural cycle, where the frontal portion exceeds beyond its embayment wall and then results into retreat, this process is known as iceberg calving. The calving events are necessary to maintain the mass balance of the ice sheet, which is more frequent in response to atmosphere and ocean warming[1]. Iceberg calving from ice shelves and glacier tongues might be caused by the impact of ocean waves of various types[2]. The isolation of the icebergs will take place when several fractures near the frontal portion penetrate the entire ice shelf thickness[1]. Iceberg calving needs to be monitored as it removes large amounts of mass very quickly. Ice losses by calving exceed ablation through surface melting on the Antarctic and Greenland ice sheets; the fluxes generated from the calving events are strongly influenced by the dynamic change in glacier outlets, while streams have a major effect on ice sheet mass balance and glacial ice velocity[3]. The calving behaviour of glaciers critically depends on their ice velocity. Moreover, ice velocity of glacier (a) determines the rate at which ice delivered to the calving front and it is the primary control on the calving flux and (b) the velocity of down-glacier variations in velocity strongly influences the terminus position and temporal changes in ice thickness by the dynamic thinning[3].

Calving is a frequent process in the Antarctic region, and the Pine Island glacier is largely affected by the calving process. There are many factors responsible for the calving events, as mentioned earlier. Several earthquakes occur at the plate boundaries of the Antarctica Plate. As shown in Figure 1, it is evident that the earthquakes in the northern hemisphere triggered the Antarctic Ice Shelf calving, which was more than ~10,000 km away. The Honshu earthquake which occurred on 11 March 2011, centred 130 km off the east cost of Sendai, Japan, at 32 km (38.32°N, 142.37°E) depth, triggered a tsunami that propagated across the Pacific and Southern Oceans[2]. According to Holdsworth and Glynn[4], iceberg calving from ice shelves and glacier tongues could be due to fatigue associated with repeated flexure caused by the impact of ocean waves of various types. They further proposed that the ocean swelling could significantly stimulate the weightiest mode of coupled gravity wave/elastic flexure that vibrate in the floating ice, which could in turn leads to calving. MacAyeal *et al.*[5] suggested that the arrival of long-period swell from a storm in the North Pacific precipitated the break-up of a large ~800 km^2 iceberg (B15A) in shoaling waters off Cape Adare, Antarctica. Solov'ev and Go[6] reported that the Arica earthquake and tsunami on 13 August 1963 was observed by the Chilean Navy, and a few weeks later an unseasonal abundant, freshly cut iceberg drifted in the Southern Ocean calved from the Antarctica Ice Shelf[2]. Similarly, the earthquake triggered on 19 September 2017 at Mexico city having 51 km depth (18.584°N, 98.399°W) which propagated across the Pacific and Southern Ocean reaching the Antarctica region, has resulted in the calving event that was observed on 23 September 2017. A tsunami wave of 1.75 m was reported in Chiapas where the Pacific Tsunami Warning Centre issued a warning for the entire Pacific coast of Central America, also extending south to Ecuador.

Before the earthquake in Central Mexico on 19 September 2017 of magnitude 7.1 (18.584°N, 98.399°W, 51 km depth); an earthquake of magnitude 8.1 occurred

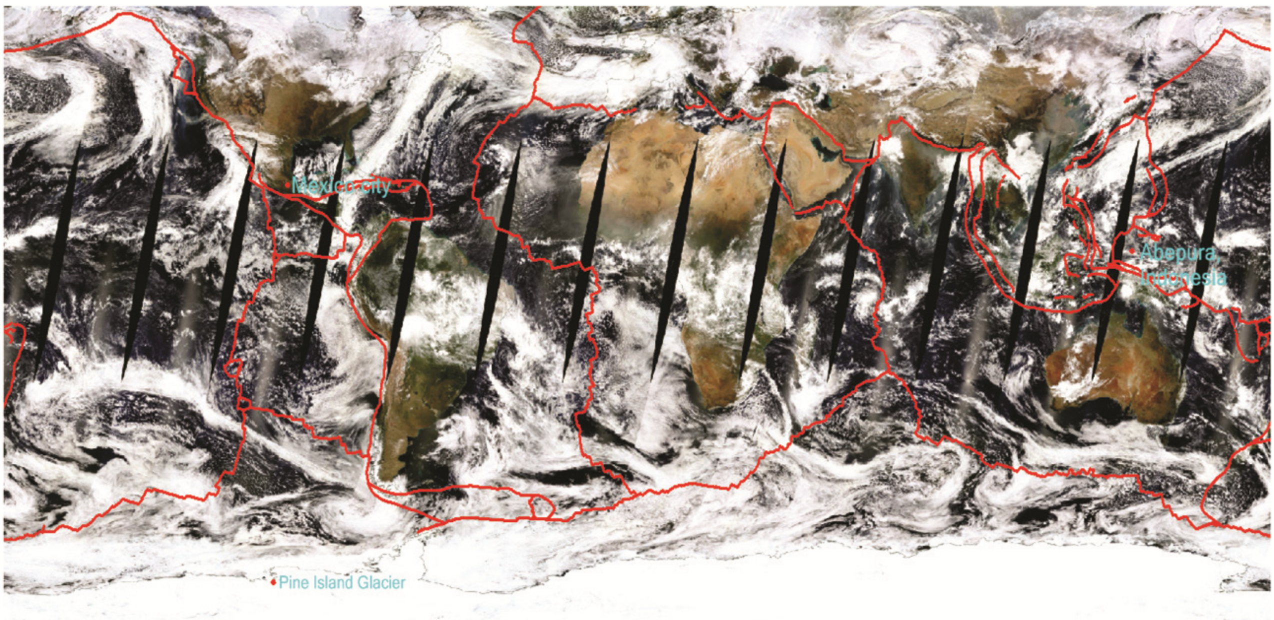

Figure 1. Arrangement of plate boundaries on the world map (Source: MODIS data, plate boundary shape file from ESRI).

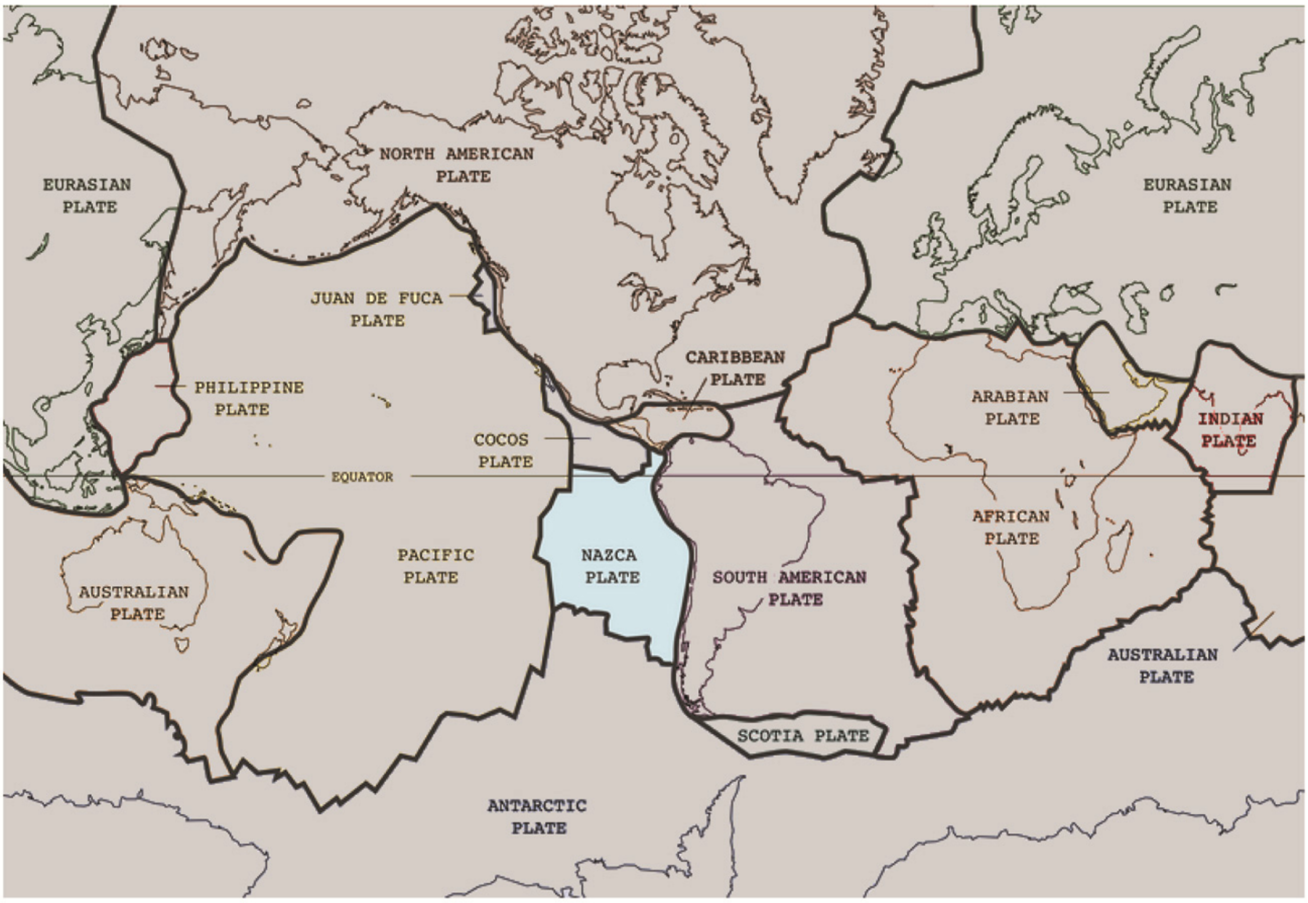

Figure 2. World plates boundaries with emphasis on interconnection of Cocos Plate, Nazca Plate, North American Plate and Antarctica Plate (Image source).

off the Pacific Coast of Mexico around 87 km southwest of Pijijiapan on 7 September 2017; this is known as the Chiapas earthquake (https://en.wikipedia.org/wiki/2017). Mexico is one of the world's most seismically active regions, sitting atop several intersecting tectonic plates. The border between the Cocas Plate and North American Plate, along the Pacific coast of Mexico (Figure 2), creates a subduction zone that generates large seismic events. The rift was already present on the Pine Island glacier, but due to the tsunami wave propagation the rift had widened and eventually gave rise to a large-sized iceberg (~282 km^2). A series of earthquakes occurred during September 2017, starting with the Chiapas earthquake[7]. As on 14 September 2017, the National Seismological Service had recorded at least 1806 aftershocks of magnitude up to 6.1. Dynamic triggering with seismic-wave propagation from one quake affecting other faults may operate at much longer distances, but usually happens within a few days of the triggering quake[8].

The rift was affected by the aftershocks of the earthquake that occurred in Mexico. The time-series data (Figure 3) recorded by Sentinel-1A (https://scihub.copernius.eu/dhus) provide evidence for the breaking of the iceberg of Pine Island glacier. The rift had developed in early 2016, and sustained more than year and a half. Because of iceberg calving, advancement of glacier and rifting is common in this region, but the rift will withstand as long as it is not affected by some major activities like earthquakes, icequakes, ocean swelling, tides and tsunamis.

A ~464 km^2 of iceberg in the Pine Island glacier got detached after a magnitude 7.0 earthquake struck Indonesia, 228 km west of Abepura, Papua (–2°37′44.4″S, 138°31′40.8″E) on 27 July 2015, at depth 48 km, whereas ~100 km^2 of ice mass remained attached to the glacier front. The Indonesian earthquake is listed as one of the strongest earthquakes observed during that month. It occurred as a result of reverse faulting on the fault plane dipping moderately either to the northeast or to the southwest (USGS).

A magnitude 7.1 earthquake on 19 September 2017, close to the boundary between the states of Puebla and Morelos, occurred in the central region of Mexico, at an intermediate depth of 57 km within the Cocos plate with an intraplate normal faulting mechanism characterized by a strike of 112°, 46° dip and –93° rake (National Seismological Service of Mexico). The epicentre was located at 18.40°N and 98.72°W, 12 km southeast of Axochiapan, Morelos, and about 120 km from Mexico city. The closest distance from Mexico city to the rupture zone was approximately 105 km (ref. 9). The large seismic activities were recorded along the Pacific coast of Mexico between the borders of Cocos plate and North American plate. The edges of

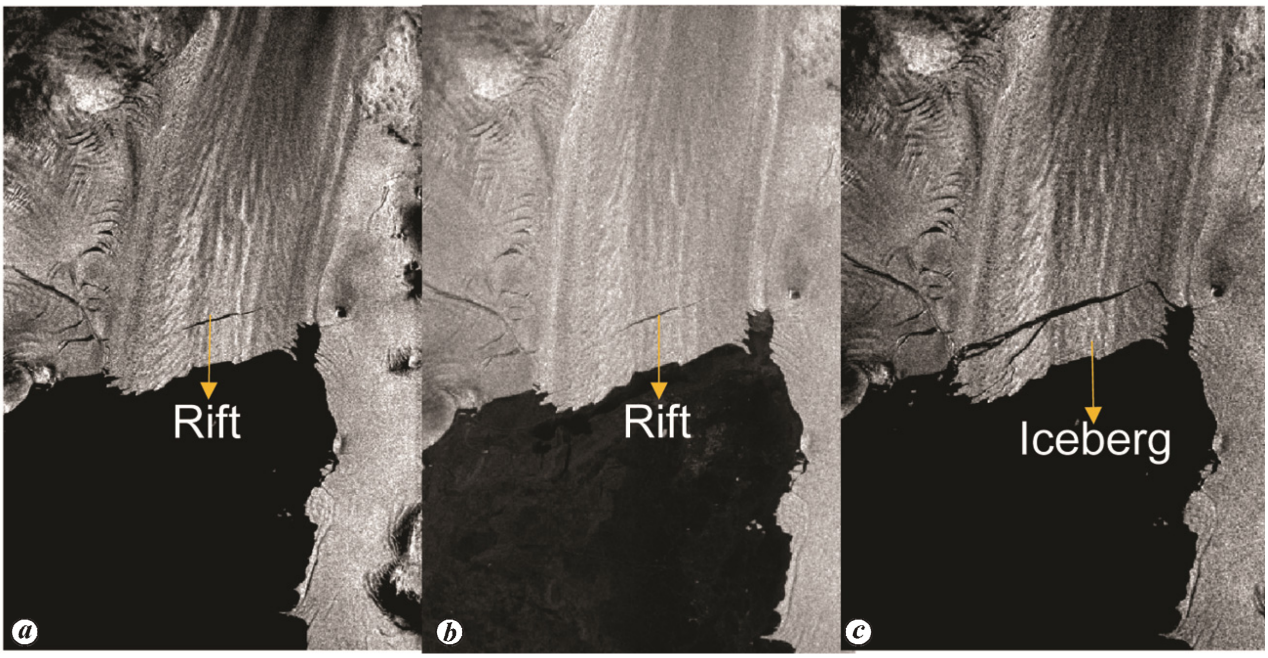

Figure 3. ***a***, Pine Island glacier on 18 September 2017. ***b***, On 21 September 2017, the rift is seen unaffected. ***c***, On 23 September 2017, the rift had reached the edges to form a massive iceberg of ~282 km^2 area, analysed using Sentinel-1A data; breaking of the iceberg took place on 22 September 2017.

the Rivera and Caribbean plates near North American plate boundaries also generate seismic events.

The Indonesian earthquake resulted from reverse fault plane, which occurred in a broad zone of convergence plate between the Pacific and Australia plates. As reported by few authors, the boundary in this region is divided into a series of microplates that shows relative motion between the large plates. The epicentre lies close to the boundaries between the Maoke, Woodlark and Caroline microplates. The Pacific plate moves towards the southwest with respect to Australia, at a rate of approximately 111 mm/yr. To the north of the event, the Caroline plate subducts to the southwest beneath Australia (Maoke and Woodlark) at the New Guinea Trench, where the location and its mechanism of the earthquake on 27 July 2015 are consistent with its occurrence on or near that slab interface at depth. The Pacific plate boundary through Papua New Guinea experiences frequent moderate to large earthquakes. They reflects the complex tectonics of the region, exhibiting reverse faulting mechanisms associated with Pacific subduction, as well as transform, reverse and normal faulting mechanisms associated with the upper plate deformation (USGS). The Pacific plate boundary affects a few regions of Antarctica, as it is interconnected with the Antarctica plate boundary.

This study presents the association of earthquakes and ice-shelf calving. It indicates the linkage between earthquake activity and calving in the Pine Island region of Antarctica. However, there is a need for detailed studies through modelling for establishing the actual pathway of propagation of tsunami waves.

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