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Seismic activity and associated risk in Antarctica

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Information paper submitted by SCAR

Summary

In 2021, ATCM Resolution 7 invited SCAR to provide a report on seismic activity in Antarctica, recognising the risks of seismic and volcanic activity for people and infrastructure, and the need to undertake monitoring and research on seismic activity and the risks associated with a high-magnitude seismic or volcanic event. This paper provides information on the causes and locations of seismic activity in Antarctica, and associated seismic hazard. It also provides an inventory of seismic stations which locate and record seismic activity, and recommends ongoing support for seismic monitoring and research. SCAR will continue to work with The Council of Managers of National Antarctic Programs (COMNAP) towards further assessment of seismic risk near Antarctic stations, noting that priority should be given to the northern Antarctic Peninsula, Bransfield Strait, South Shetland Islands and South Orkney Islands, as well as other regions with seismic clusters such as Victoria Land, Ross Island, Queen Mary Land and Adélie Land.

Background

Antarctica is mostly a seismically quiet continent surrounded by oceans. Compared to other parts of the world, seismic activity in Antarctica is generally low (Kaminuma, 1976; Reading, 2007; Kanao, 2014). The thick ice sheet inhibits most earthquakes on the Antarctic continent (Johnston, 1987), although glacial isostatic adjustment resulting from ice loss favours glacial seismotectonic activity (Muir-Wood, 2000; Turpeinen et al., 2008). Most seismic activity in Antarctica is caused by tectonic movements near plate boundaries located in the Southern Ocean although intraplate activity has also been observed (Lough et al., 2018). Active plate boundaries are found near the Antarctic Peninsula, including the boundaries between the Antarctic, South American, Scotia, and Sandwich plates. Victoria Land also experiences significant seismic activity. The largest earthquake ever recorded in or around Antarctica, with a magnitude of Mw 8.1, occurred in the Southern Ocean near the Balleny Islands in 1998 (Nettles et al., 1999; Himeno et al., 2011). Additionally, seismic activity is related to glacial isostatic adjustment and cryoseismicity, mainly in local areas near coasts. The seismic activity related to volcanoes is local but also significant, such as at Mount Erebus (Kaminuma, 1987; Rowe et al., 1998, 2000; Konstantinou et al., 2019) and Deception Island (Carmona et al., 2012; Jimenez-Morales et al., 2017, 2022; Moreno-Vacas and Almendros, 2021).

Seismic hazard is a function of the magnitude and depth of seismic activity and the geological structure that determines the peak and spectral ground motion parameters in addition to earthquake recurrence. Seismic risk depends on seismic hazard and in addition it is influenced by other factors such as population density, location and infrastructure vulnerability, and other processes associated with seismic events, such as landslides, tsunamis, and liquefaction. It is crucial to assess ground shaking and related geohazards to prepare for worst-case scenarios and take measures to reduce vulnerability to seismic events.

Location of seismic stations in Antarctica

Seismic stations are essential for the location and characterisation of seismic activity in Antarctica. Although stations situated far from the study area around the world can still record significant earthquakes, those located proximally enable a more accurate location and recording of seismic activity, particularly for low-magnitude local earthquakes. The inventory of seismic

stations in Antarctica (Table 1, Figure 1) includes the stations of the International Registry of Seismograph Stations, which are maintained by the International Seismological Centre and the World Data Center for Seismology (http://www.isc.ac.uk/registries/). However, it does not perform continuous control of the stations and may be not be up to date. Permanent stations with real-time records around the world are part of international virtual networks, such as the Global Seismographic Network (GSN), which is part of the IRIS consortium (https://www.iris.edu/hq/programs/gsn). The permanent seismic stations of the IRIS network in Antarctica (e.g. South Pole; Anthony et al., 2021) are shown in Figure 1. These stations cover Antarctica and help quickly identify and locate major earthquakes. Furthermore, several institutions from different countries have deployed seismic stations in areas of high seismicity, such as around the northern part of the Antarctic Peninsula (e.g. Seismographic Argentinian-Italian network, Linares et al., 2021; Spanish network, and other stations, see Annex 1) and in Victoria Land. Other countries are expanding and improving their seismic networks.

In addition, non-permanent networks are important because they allow lower earthquake detection thresholds, better understanding the behaviour of seismicity in a region, and determining the geological structures responsible for earthquake generation. They have been deployed as part of the International Polar Year 2007-08, such as the Polenet/Anet network (Figure 2) (https://polenet.org/sites/), and some of them remain active. Several examples of temporary deployments exist in the Bransfield Strait (Robertson-Maurice et al. 2003; Dziak et al. 2010; Ibanez et al. 2017; Almendros et al. 2020).

It is necessary to update the list of operational seismic stations to determine whether there is sufficient station coverage in areas of seismic hazard interest.

Seismicity distribution in Antarctica and seismic hazard

The USGS Earthquake Catalogue is one of the most comprehensive databases providing information on the location of seismicity in Antarctica (https://earthquake.usgs.gov/earthquakes/search/). Most seismic activity south of 60˚S (Figure 3) is shallow (0-33 km deep), mainly of tectonic origin, and is associated with plate boundaries which in some cases is also linked to volcanic activity (Reading, 2007; Kanao, 2014). Seismicity primarily occurs in oceanic areas, but two continental regions show significant seismic activity due to tectonic deformation: (i) the South Shetland Islands – northern Antarctic Peninsula, and (ii) the Victoria Land – Ross Sea.

The South Shetland continental block, which is separated from the Antarctic Peninsula by a rifted basin in Bransfield Strait, is the area with the highest seismic activity around Antarctica (Kaminuma, 1976; Pelayo and Wiens, 1989; Larter, 2001; Reading, 2007; Kanao, 2014) (Figure 4). Earthquakes with Mw>5 have affected this region because of the tectonic opening of the Bransfield Strait, reaching magnitudes of Mw 7.0 and Mw 6.9 on both extremes of the strait due to ongoing crustal deformation, confirmed by the earthquake focal mechanisms and geodetic GPS measurements. Additionally, seismicity related to volcanic activity and ongoing extension repeatedly occurs in the form of high-rate seismic swarms. For example, in 2014, a seismic swarm with ~9000 earthquakes and maximum magnitude of 4.9 (mb) occurred SE of Livingston Island (Almendros et al. 2018). A recent episode southeast of King George Island has been particularly intense, when a swarm of > 85.000 earthquakes reached magnitudes of up to Mw 5.7 (Olivet et al., 2021; Cesca et al., 2022). Further seismicity unrest has also occurred near Deception Island (Carmona et al., 2012; Moreno-Vacas and Almendros, 2021; Jiménez-Morales et al., 2022). Further east, significant seismicity, including earthquakes reaching Mw 7.7, occurs near the South Orkney Islands, and is related to the slow left-lateral strike-slip motion on the Scotia/Antarctic plate boundary (Ye et al., 2014).

In Victoria Land, seismicity is distributed (Adams, 1969; Reading, 2007; Kanao, 2014) (Figure 3) and reaches up to Mw 6.3, probably related to the reactivation of a major geological boundary that separates East and West Antarctica, limited by the Trans-Antarctic Mountains, or related to glacial processes. Mount Erebus volcano, located in Ross Island, also has related seismicity (Kaminuma, 1987; Rowe et al., 1998).

Sparse seismicity also occurs in other Antarctic areas (Figure 3) with magnitudes lower than Mw 5, probably related to glacial seismotectonic activity associated with glacial isostatic adjustment of Antarctica, which favours seismicity in continental crustal rocks (Kaufmann et al., 2005; Pascal et al., 2010) and cryoseismicity (Nettles et al., 2010) related to ice displacement. Significant clusters of earthquakes reaching up to Mw 5.7 events occur in Queen Mary Land (SE of Casey station), and up to Mw 5.4 in Adélie Land (west of Dumont D'Urville station), but they are relatively far from the nearest Antarctic stations.

The earthquake hazard begins to become significant when the magnitude reaches Mw > 4, which can cause local damage. However, the hazard to infrastructure and the development of landslides and liquefaction increase when the magnitude reaches Mw > 5. Most earthquakes reported in the region are shallow, meaning that they are closer to the surface and thus pose a greater hazard to surface infrastructure in active seismic areas.

There is a limited amount of research on evaluating peak ground motion parameters and Probabilistic Seismic Hazard Analysis (PSHA) in Antarctica, with most studies being recent and focused on local areas such as Palmer station (Feenstra et al., 2019) and Scott Base (Burbidge et al., 2020). These contributions are crucial for determining the seismic hazards in the region.

In addition, there are few studies on seismic-related effects, such as landslides, tsunamis, and liquefaction in Antarctica. The seismic unrest at the Bransfield Strait (Olivet et al., 2021; Cesca et al., 2022) has been interpreted as the result of crustal magmatic intrusions on the base of seismological and geodetic data (Cesca et al., 2022), although it could not be ruled out, so far, if this was accompanied by a submarine eruption. Both shallow seismicity and magmatic-driven seismicity have the potential to trigger tsunamis. Moreover, the Antarctic Peninsula-Scotia Sea region has experienced large submarine landslides that have been linked to seismic activity (Ruano et al., 2014; Pérez et al., 2016). Large submarine landslides have also affected the southern Weddell Sea (Gales et al., 2014). However, no studies have examined the potential for large submarine landslides that could result in significant tsunamis, as observed in the Arctic Ocean (see, e.g., Vanneste et al., 2006; Pedrosa-González et al., 2022).

Vulnerability and seismic risk

The most seismically active and hazardous area of Antarctica, which is relatively populated in comparison to most of Antarctica and with a strong fluctuation of population over different seasons, is the Shetland Islands, the Bransfield Strait coasts, and the northern Antarctic Peninsula. Moving eastward, the South Orkney Islands area is also one where there is a high seismic hazard, but with only two Antarctic stations. The Argentinian Base Orcadas is exposed to tsunami risk being only 4 m above the sea level and close to large earthquakes (e.g, Mw7.7 November 17, 2013 earthquake) (Figure 5). The Victoria Land – Ross Sea area also has several Antarctic stations and seismic activity is moderate.

Antarctic infrastructure is generally well built and designed to withstand strong weather conditions with high horizontal stress. Therefore, in general, constructions should also be relatively sturdy to support earthquake shaking, although they should be tested. However, interior furnishings may be most vulnerable to damage and may pose the highest risk with regards to injuries from falling debris, and should be evaluated accordingly.

The main vulnerability issue for coastal Antarctic stations is their location. This placement increases the vulnerability to tsunamis that may be produced by sharp seabed fault displacement or by the indirect effect of submarine landslides. There is also a potential vulnerability to far-travelled tsunamis resulting from great earthquakes in other parts of the world.

Recommendations and conclusions

1) Seismic monitoring should be supported, particularly in areas of high seismicity and where population is present (South Shetland Islands - northern Antarctic Peninsula; Victoria Land). Monitoring of other regions with seismic clusters should also be improved (e.g.,

Queen Mary Land, SE of Casey station and Adélie Land, west of Dumont D'Urville station).

2) The seismic stations with adequate maintenance generally provide the location of relevant earthquakes (Mw> 4 to 5). An update of the database of operative seismic stations is necessary to identify whether there is adequate station coverage in the areas of interest, and to determine the threshold level of the seismic magnitude captured by the permanent stations. Improved GNSS networks in these regions can also help better identify ground deformations related to seismic hazard.
3) Efficient sharing of records, ideally in real time, is needed to quickly evaluate hazards related to seismic events.
4) Promotion of research related to the determination of ground motion parameters, Probabilistic Seismic Hazard Analysis (PSHA) supported by physics-based numerical simulations and modelling of landslide stability close to Antarctic stations.
5) With respect to tsunami hazards, submarine faults and areas where large landslides have occurred in the Bransfield Strait, South Orkney Islands and Victoria Land should be identified to model their tsunamigenic effects.

SCAR will continue to work with COMNAP towards further assessment of seismic risk near Antarctic stations, noting that priority should be given to the northern Antarctic Peninsula, Bransfield Strait, South Shetland Islands and South Orkney Islands, as well as to other regions with seismic clusters such as Victoria Land, Ross Island, Queen Mary Land and Adélie Land.

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Relevant Contacts:

Almendros, Javier. IAG, University of Granada, Spain, vikingo@ugr.es

Cesca, Simone. GFZ German Research Centre for Geosciences Potsdam, Potsdam, Germany simone.cesca@gfz-potsdam.de

Galindo-Zaldivar, Jesus. IACT, CSIC-University of Granada, Spain, jgalindo@ugr.es

Kanao, Masaki. National Institute of Polar Research, Midori-cho, Tachikawa-shi, Tokyo, Japan, kanao@nipr.ac.jp

Larter, Rob. BAS, UK, rdla@bas.ac.uk

Reading, Anya. University of Tasmania, Australia, anya.reading@utas.edu.au

Vuan, Alessandro. National Institute of Oceanography and Applied Geophysics – OGS, Trieste, Italy, avuan@ogs.it

Wiens, Douglas A. Department of Earth and Planetary Sciences, Washington University, St Louis, MO, USA, doug@wustl.edu

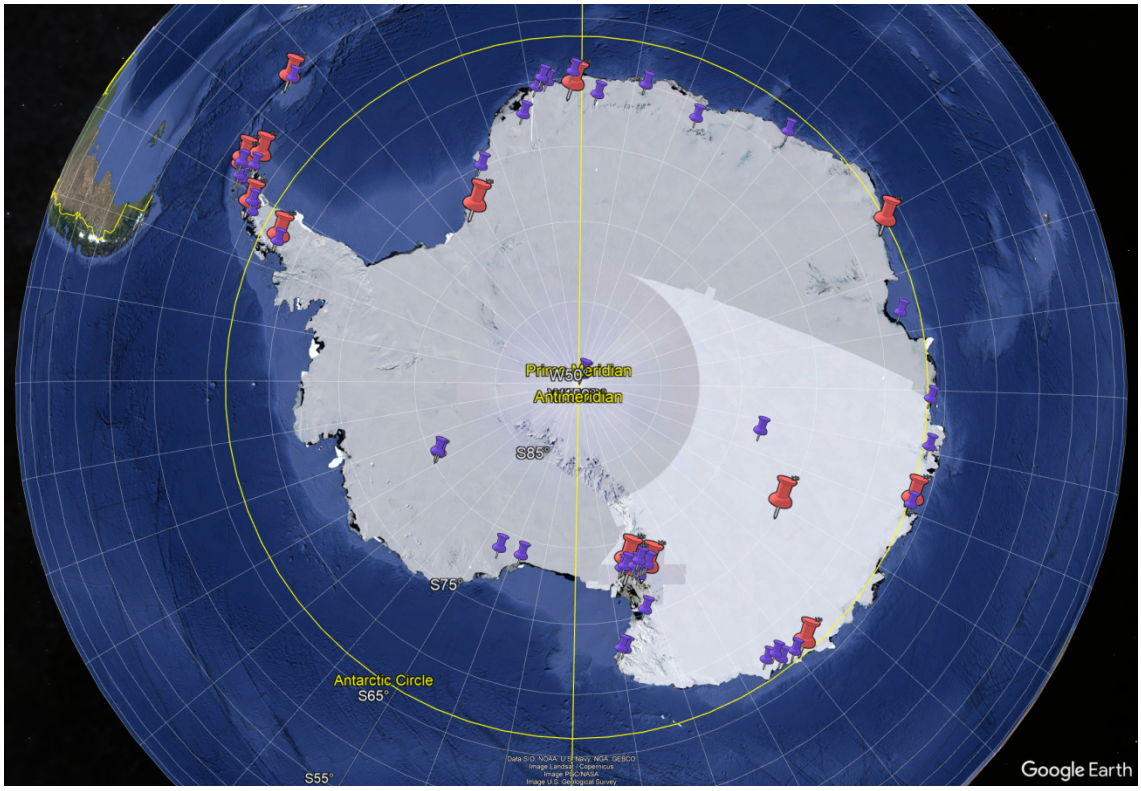

Figure 1 – Seismic stations in Antarctica from the International Registry of Seismograph Stations. In red, permanent stations with real-time reporting on the IRIS network. Blue, other stations. (http://www.isc.ac.uk/registries/).

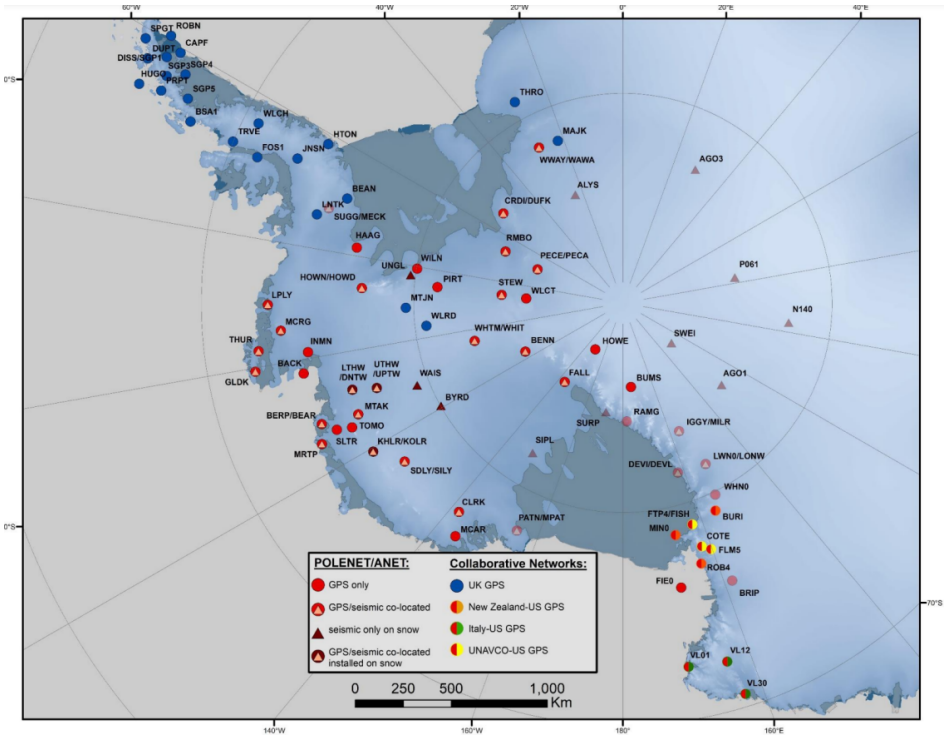

Figure 2 – Polenet/ANET network mainly deployed during the IPY. This network includes seismic and GPS stations (www.polenet.org).

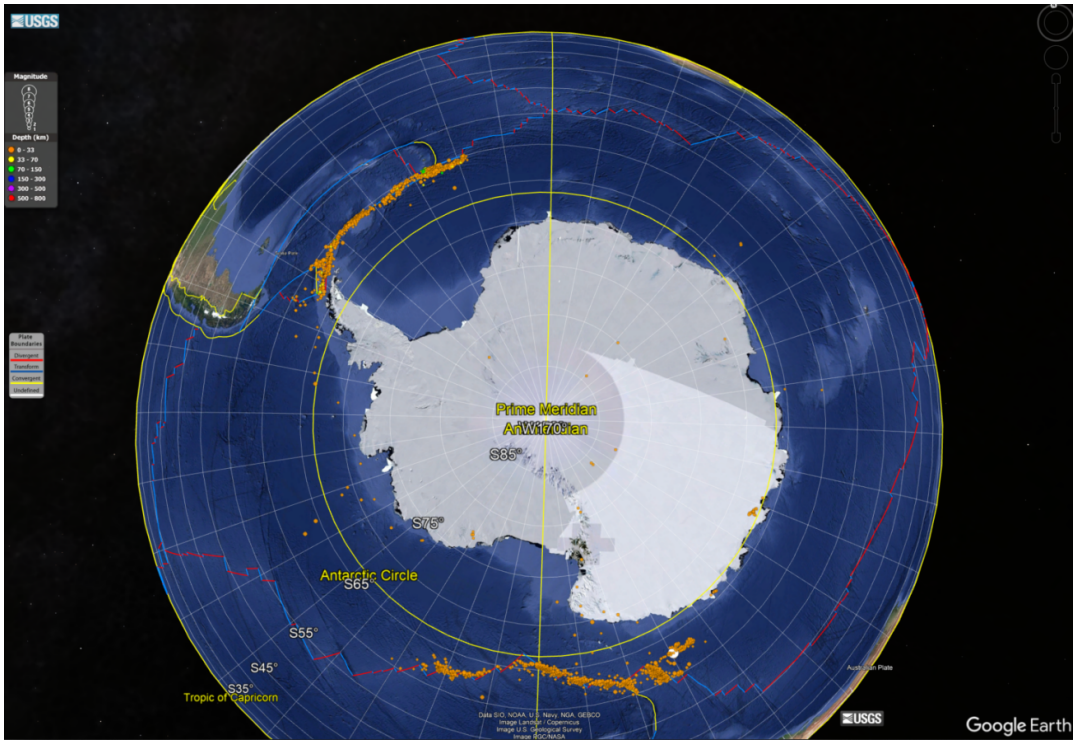

Figure 3 – Seismicity in Antarctica (south of 60ºS) from the USGS Earthquake catalogue (https://earthquake.usgs.gov/earthquakes/search/) (1960 to 2022 period) plotted on Google Earth image (https://earth.google.com/) including plate boundaries. (Rough trace of plate boundaries from USGS (https://earthquake.usgs.gov/learn/plate-boundaries.kmz; mid-ocean ridge spreading segments in red, subduction zones in yellow, transcurrent boundaries and mid-ocean ridge transform faults in blue). Also in yellow Antarctic circle and 0º and 180º meridians.

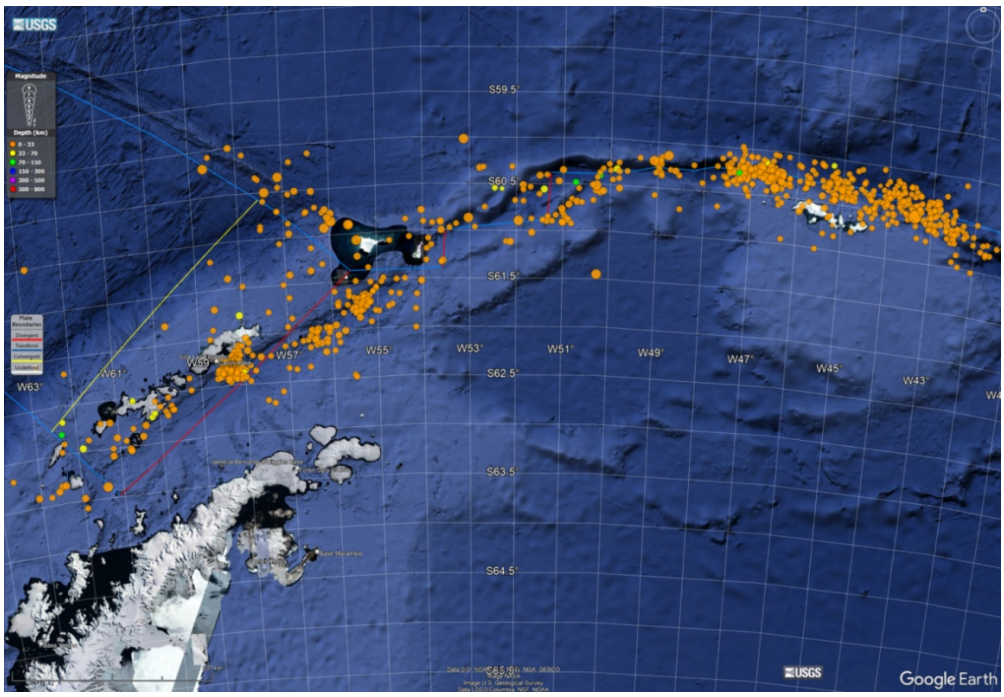

Figure 4 – Seismicity in the Antarctic Peninsula-South Shetland Islands from USGS Earthquake catalogue (https://earthquake.usgs.gov/earthquakes/search/) (1960 to 2022 period) plotted on Google

Earth image (https://earth.google.com/). Rough trace of plate boundaries from USGS (https://earthquake.usgs.gov/learn/plate-boundaries.kmz).

Figure 5 – Base Orcadas (location at Laurie Island) and the effect of the tsunami generated by the 2013 November 17, Mw7.7 earthquake. Dirección Nacional del Antártico (DNA) – Instituto Antártico Argentino (IAA)

Table 1 – Seismic stations in Antarctica as currently recorded in the International Registry of Seismograph Stations (http://www.isc.ac.uk/registries/)

Code	Station name/Region	Latitude	Longitude	Status
AAS	Arctowski Station	-62.16	-58.4625	Closed
	South Shetland Islands			
ABOA	Aboa	-73.05	-13.41667	Open
	Dronning Maud Land			
ADARE	Adare	-72.4167	170.9167	
	Victoria Land			
AIA	Argentine Island	-65.25	-64.26667	Open
	Antarctic Peninsula			
ANC	Marguerite Bay	-68.1944	-67	
	Antarctic Peninsula			
BCAA	Base Cientifica Antartica Artigas	-62.1802	-58.8858	Open
	South Shetland Islands			
BELA	Belgrano 2	-77.875	-34.6269	Open
	Coats Land			
BSA	Byrd (S.R.I.)	-80.0055	-119.043	
	Marie Byrd Land			
BY1	Byrd--Stanford Research Institute	-80.0055	-119.043	
	Marie Byrd Land			
BY2	Byrd--Stanford Research Institute	-80.0773	-119.683	

Code	Station name/Region	Latitude	Longitude	Status
	Marie Byrd Land			
BY3	Byrd--Stanford Research Institute	-79.9456	-119.718	
	Marie Byrd Land			
BYA	Byrd--Stanford Research Institute	-80.0096	-119.481	
	Marie Byrd Land			
BYR	Byrd	-80.0167	-119.517	Closed
	Marie Byrd Land			
CASY	Casey	-66.2791	110.53639	
	Enderby Land			
CCD	Concordia, Antarctica	-75.1065	123.305	Open
	East Antarctica			
CORRE	Terra Adelie	-67.5828	144.275	
	Terre Adelie			
CSY	Casey Station	-66.2894	110.529	Closed
	Wilkes Land			
DEC	Deception Island	-62.9833	-60.7167	Closed
	South Shetland Islands			
DRV	Dumont d'Urville	-66.665	140.009	
	Terre Adelie			
ELIB	Princess Elisabeth base, Queen Maud Land,	-71.947	23.3469	Open
	Antarctica			
ESPZ	Base Esperanza	-63.3980	-56.99639	
	Antarctic Peninsula			
GGV	Gabriel Gonzalez Videla	-64.8199	-62.8633	
	Antarctic Peninsula			
HBA	Halley Bay	-75.5167	-26.6	
	Coats Land			
HLL	Cape Hallett	-72.3139	170.217	Closed
	Victoria Land			
I03AU	Davis Base, Antarctica	-68.5839	78.0685	Open
	Antarctica			
I27DE	GEORG VON NEUMAYER INFRASONIC ARRAY REFER	-70.7011	-8.3029	Open
	Dronning Maud Land			
I55US	WINDLESS BIGHT INFRASONIC ARRAY REFERENCE	-77.7315	167.5874	Open
	Victoria Land			
JUBA	Jubany	-62.2373	-58.66267	
	South Shetland Islands			
LAA	Little America	-78.2	-162.25	
	King Edward VII Land			
LIVV	Livingston, Bulgarian Antarctic Base	-62.6365	-60.3581	Open
	Antarctic Peninsula			
MAIT	Maitri	-70.776	11.736	

Code	Station name/Region	Latitude	Longitude	Status
	Dronning Maud Land			
MAW	Mawson	-67.6039	62.8706	Open
	Mac Robertson Land			
MCM	McMurdo Sound	-77.8333	166.6	
	Victoria Land			
MIR	Mirnyy	-66.5513	93.01667	
	Queen Mary Land			
NVL	N'lazarevskaya	-70.7666	11.83333	
	Dronning Maud Land			
OBA	Oasis-Bungera	-66.1667	100.733	
	Queen Mary Land			
OHC	O'Higgins	-63.3167	-57.9	
	Antarctic Peninsula			
ORCD	Orcadas	-60.7380	-44.73611	
	South Orkney Islands			
PED	Pedro Cerda	-62.9394	-60.585	Closed
	South Shetland Islands			
PIDGE	Terre Adelie	-66.982	143.893	
	Terre Adelie			
PINGU	Terre Adelie	-67.5955	146.077	
	Terre Adelie			
PMSA	Palmer Station	-64.7742	-64.049	Open
	Antarctic Peninsula			
PORMA	Terre Adelie	-66.8184	141.39	
	Terre Adelie			
QSPA	South Pole Quiet Zone Earth Science Obser	-89.9278	145	
	Antarctica			
RMA	Rockefeller Mts	-78.1333	-155.417	Closed
	King Edward VII Land			
SBA	Scott Base	-77.8503	166.756	Open
	Victoria Land			
SEJ	Sejong Station	-62.2208	-58.7528	
	South Shetland Islands			
SGY	Signy Island	-60.7101	-45.5976	Open
	South Orkney Islands			
SMAI	San Martin Antarctic Base	-68.1302	-67.1059	Open
	Antarctic Peninsula			
SNA	Sanae	-70.315	-2.325	
	Dronning Maud Land			
SNAA	Sanae	-71.6706	-2.83789	
	Dronning Maud Land			
SPA	South Pole	-89.9954	115	Closed
	Antarctica			
SYO	Syowa Base	-69.0088	39.5921	
	Dronning Maud Land			
TAA	Terre Adelie	-66.8178	141.395	

Code	Station name/Region	Latitude	Longitude	Status
	Terre Adelie			
TAMA1	TAMSEIS 9900, AN1	-77.2432	166.3725	
	Victoria Land			
TAMA2	TAMSEIS 9900, AN2	-77.0352	163.1808	
	Victoria Land			
TAMA3	TAMSEIS 9900, AN3	-77.115	161.5317	
	Victoria Land			
TAMA4	TAMSEIS 9900, AN4	-77.4371	163.8019	
	Victoria Land			
TAMA5	TAMSEIS 9900, AN5	-77.6986	163.9118	
	Victoria Land			
TAMA6	TAMSEIS 9900, AN6	-77.4536	162.6519	
	Victoria Land			
TAMA7	TAMSEIS 9900, AN7	-77.5296	160.9227	
	Victoria Land			
TAMA8	TAMSEIS 9900, AN8	-77.5494	160.2731	
	Victoria Land			
TAMA9	TAMSEIS 9900, AN9	-77.9553	162.1301	
TNV	Terranova Bay	-74.695	164.124	
	Victoria Land			
TROLL	Troll, Antartica	-72.0082	2.53	Open
	Dronning Maud Land			
VNA	Neumayer	-70.5997	-8.36222	Closed
	Dronning Maud Land			
VNA1	Neumayer--Station	-70.6503	-8.2624	Open
	Dronning Maud Land			
VNA2	Neumayer--Watzmann	-70.9251	-7.39267	
	Dronning Maud Land			
VNA3	Neumayer Olymp	-71.2428	-9.6687	
	Dronning Maud Land			
VND	Vanda	-77.5239	161.672	Closed
	Victoria Land			
VNDA	Vanda	-77.5171	161.85281	Open
	Victoria Land			
VOSTO	Vostok	-78.45	106.8667	
	Vostok Station			
WIL	Wilkes	-66.2592	110.527	Closed
	Wilkes Land			

Annex 1 – Information on existing seismic stations

Information from National Antarctic Programmes on seismic stations in the Antarctic Peninsula and South Shetland Islands (as reported to COMNAP, October 2022)

- Argentina – seismic network comprising 7 permanent stations (AI network). This network is run in conjunction with Italy, through an agreement between the National Institute of Oceanography and Applied Geophysics (OGS) in Trieste and Dirección Nacional del Antártico (DNA)–Instituto Antártico Argentino (IAA). The real-time waveforms from AI network are freely accessible from IRIS and ORFEUS services. It improves the worldwide seismic networks' detection capabilities and contributes to refining regional earthquake locations released by the USGS. Argentina has other instruments on Deception Island for volcanic monitoring and is working to implement new instruments at 4 new monitoring stations.
- Republic of Korea – monitoring system on King George Island; it is an on-going seismic project at initial stage.
- Poland – two working devices transmitting online and the data are available.
- Ukraine – seismic station at Vernadsky Station.
- Uruguay – seismic station on King George Island.

Deception and Livingston islands seismic network

The Spanish National Geographic Institute (IGN) is in charge since September 2020 of the volcanic monitoring of Deception Island. To meet this objective, during the last two campaigns (2021-2022 and 2022-2023), a new volcanic monitoring network has been set up. The new network in Deception Island is formed by 5 permanent broadband seismic stations and 3 GNSS stations for deformation measurements. Each of the stations, consists of a stainless-steel-structure hut that is energetically autonomous, sending both seismic and GNSS data in real time to Spain, via a satellite link installed in the Spanish Gabriel de Castilla Base. Moreover, in order to strengthen the regional monitoring, the IGN has also installed a seismic-GNSS station in the vicinity of the Spanish Juan Carlos I Base, on the Livingston Island.

Table 1.1 – Spanish National Geographic Institute (IGN) Seismic stations in Antarctica.

Code	Station name/Region	Latitude	Longitude	Status
XA.MECO	Gabriel de Castilla Spanish Base. Deception Island	-62.977000	-60.677000	Open
	South Shetland Islands			
XA.BASE	Gabriel de Castilla Spanish Base. Deception Island	-62.976994	-60.682140	Open
	South Shetland Islands			
XA.OBS	Obsidian Hill. Deception Island	-62.940937	-60.690651	Open
	South Shetland Islands			

XA.C70	70´s Crater. Deception Island	-62.918520	-60.652737	Open
	South Shetland Islands			
XA.RON	Ronald Hill. Deception Island	-62.975277	-60.586838	Open
	South Shetland Islands			
XA.LIV	Juan Carlos I Spanish Base. Livingston Island	-62.663727	-60.391020	Open
	South Shetland Islands			