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Investigation of the Mw 7.3 earthquake in Tonga Islands, Pacific Ocean, 11 November 2022

Atınç Pırtı*, Mehmet Ali Yücel, Ramazan Gürsel Hoşbaş

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Abstract. The Mw 7.3 Tonga earthquake occurred on 11 November 2022 at 19°.288 S and 172°.147 W. It was caused by reverse faulting in the outer rise of the Pacific Plate, about 75 km east of the Tonga Trench. We studied the Tonga earthquake on 11 November 2022 in order to detect a violent eruption of the Tonga submarine volcano in the South Pacific. Submarine volcano eruptions can displace seawater in a number of different ways, potentially triggering tsunamis. The Tonga subduction zone has the highest rate of plate convergence on Earth. It is one of the places with the most earthquakes. However, the recorded thrust events that can be placed with certainty on the plate boundary haven't been stronger than M 8.0, and the area's history suggests that there isn't much seismic coupling along the arc. The modelling of this earthquake based on the assumption that the fault plane dips to the west give dimensions of about 50 × 35 km, with most of the distance down-dipping from the hypocenter. In our study, we used the CSRS-PPP software to process TONGA station data using static and kinematic methods. This study shows the horizontal coordinate differences of the TONGA station (static-kinematic), which range from a few millimetres to about 40 centimetres.

Keywords: *GNSS; Tonga earthquake; displacements; deformation*

*Atınç Pırtı** *(atinc@yildiz.edu.tr)*, *https://orcid.org/0000-0001-9197-3411*
Yıldız Technical University, Department of Geomatics Engineering, 34220, Esenler, İstanbul, Türkiye

Mehmet Ali Yücel *(aliyucel@comu.edu.tr)*, *https://orcid.org/0000-0001-6956-5219*
Çanakkale Onsekiz Mart University, Department of Geomatics Engineering, 17100, Çanakkale, Türkiye

Ramazan Gürsel Hoşbaş *(ghosbas@yildiz.edu.tr)*, *https://orcid.org/0000-0002-3189-7696*
Yıldız Technical University, Department of Geomatics Engineering, 34220, Esenler, İstanbul, Türkiye

**Corresponding author*

INTRODUCTION

On 11 November 2022, Friday, a shallow, powerful earthquake of a moment magnitude (Mw) of 7.3 occurred approximately 130 miles from the coastline of Tonga (19°.288 S, 172°.147 W). Tsunami warnings went out across the Pacific Island region. The United States Geological Survey (USGS 2022) was the first to report the quake, which started at 11:48:46 p.m. local time (10:48:46 UTC) at a depth of approximately 37 km. One of the most interesting places on the Earth is the Fiji-Tonga-Kermadec district, which has the most intense deep seismicity in the world (Vavryuk 2004). This is because the Pacific Plate is moving under the Australian Plate at an average rate of 10.5 cm per year (De Mets *et al.* 1990). The slab's shape is complicated, especially in the north, where a sharp bend in the slab can be seen (Giardini 1992; Northard *et al.* 1996). There have also been documents of changes in the slab plunge becoming deeper (Northard *et al.* 1996; Karato *et al.* 2001). According to an anisotropy inversion based on the moment tensors of deep earthquakes, the Tonga subduction zone has orthorhombic geometry and is not a straight line (Vavryuk 2004). The main stress directions in the slab are parallel to the anisotropic symmetry axes. The Fiji-Tonga-Kermadec area was chosen to study pairs and multiples of shallow, transitional, and profound earthquakes because it has many shallow and deep-focus earthquakes. The chosen region stretches from 177°E to 171°W latitude and from 14°S to 33°S longitude (Tibi *et al.* 2003).

Since about two-thirds of the Earth's deep earthquakes happen in the Tonga subduction zone, it is a great place to study intermediate-depth and deep earthquakes (Frohlich 2006). The comparatively young Pacific Plate slides under the older Australian Plate at the fastest rate of convergence of any subduction zone. As a result, the Tonga slab has the coolest and deepest seismic activity. The majority of previous research in this area has focused on how large earthquakes occur and what happens afterward (Fan *et al.* 2019). The Tonga Trench is the area where the Pacific and Australian Plates meet. The motion of these two plates has formed one of the most seismogenic ("earthquake-producing") locations in the world; over 200 earthquakes occur each year near Tonga. Earthquakes with a magnitude greater than 7, which are considered large, happen approximately once every ten years. On the other hand, earthquakes with a magnitude greater than 7.5, which are classified as tremendous, occur once every century. The consequences of these earthquakes may be felt across the globe (Richter 1979; Bevis *et al.* 1995; Cronin 2022; Kilb *et al.* 2006; Warren *et al.* 2007). This investigation evaluated the horizontal and vertical disparities caused by the Tonga earthquake in the region.

DATA AND METHODS

Today, the GNSS satellite technique has an important role in obtaining the millimetre-level accuracy of position determination. The GNSS technique is widely used in studies such as deformation, earthquake and plate movements. In surveys performed with static GNSS, accuracy below centimetre can be obtained as a result of one hour or longer measurements on the point. In kinematic measurements, accuracy is obtained at the centimetre level in instant and then in office processing. Static and kinematic processing methods contribute greatly to studies during and after an earthquake. Especially the graphics of the time series obtained as a result of choosing the GNSS satellite data recording interval as one second are very important.

Study Region

Figures 1a and 1b show the epicentre of Tonga earthquake. Due to the tectonic structure of the Fiji-Tonga region, many earthquakes occur in this region. The Fiji region is compressed by the Pacific and Australian Plates (Fig. 1). The Fiji region, which is between bidirectional compressions, is one of the regions where earthquakes are experienced most frequently and where deep earthquake activity is most concentrated in the world. The zone which subducts the Tonga arc at approximately 45 degrees reaches a depth of almost 700 kilometres. As a result of the displacement caused by friction slip, a large interaction zone is formed between the two plates; this causes seismicity in the subducting plate. The Fiji-Tonga subduction zone is an approach zone where the interaction occurs deep and large along the boundaries. The Fiji plate is a small plate located between the Indo-Australian and Pacific Plate boundaries, between two opposing subduction zones (Fig. 1). For this reason, the historical tectonic development of the region has a very complex structure. As a result of the compression caused by the movements of the plates relative to each other, transform faults were formed in the form of the Fiji fracture zone in the north and the Hunter fault zone in the south. Seafloor spreading occurs as a result of the opening and divergence of the Northern Fiji and Lau Basins. The Fiji area is the region with the largest earthquake activity in the world. The Tonga subduction zone is a natural laboratory where half of the world's deep earthquakes occur and where deep earthquake studies can be done (Figs 1 and 2; Cronin 2022; Bevis *et al.* 1995).

RESULTS

The Tonga earthquake induced a significant deformation, which must be quantified in order to reveal kinematic and, ultimately, comprehend tectonic mechanisms at play. In this scenario, data from the IGS location near the earthquake epicentre Tonga (TONG) is quite useful. The data from Tonga (TONG) stations is downloaded every 30 seconds and adds greatly to the study of crustal deformations. The time series obtained from daily (11.11.2022) solutions were used to estimate and evaluate earthquake-related displacements (Fig. 3). The coordinates and standard

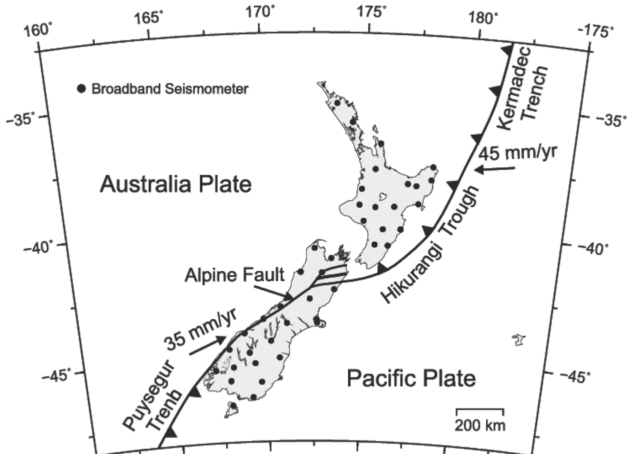

Fig. 1 Australian Plate and Pacific Plate motions (Ristau 2008)

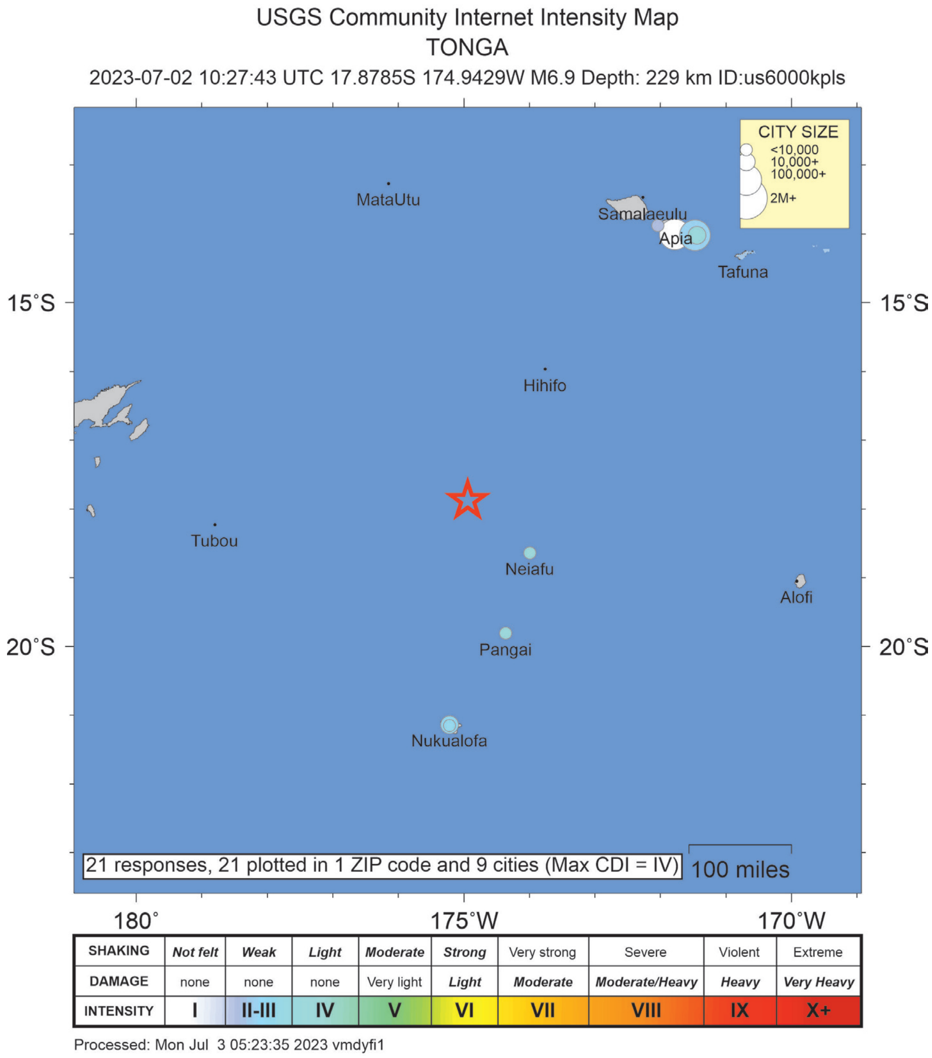

Fig. 2 Epicentre of Tonga earthquake, Mw 7.3, 11 November 2022 (22:48:46 UTC time) (19.288 S, 172.147 W) (USGS 2022)

Table 1 The coordinates and their standard deviations of the station nearby Tonga earthquake region (ITRF14 Epoch 2022.9)

Point	Latitude (φ)	Longitude (λ)	Altitude h (m)	Std (φ) (mm)	Std (λ) (mm)	Std (h) (mm)
TONG	-21°08'40.97061"	-175°10'45.14183"	56.330	2	3	10

deviations of the Tonga (TONG) point are shown in Table 1.

The Tonga IGS station (TONG), which was used in this investigation, is described in the preceding section (Figs 3, 4 and 5). These data were analyzed on 11 November 2022 to study the earthquake impacts (co-seismic displacement) plainly apparent in the time history. For this time period, the IGS server provided a 24-hour RINEX observation file with 30-second intervals (Receiver Independence Exchange). The 24-hour RINEX observation file was provided from the IGS station (Tonga-TONG) and analyzed using the CSRS-PPP programme (static, 24 hours, record interval: 30 seconds) and kinematic technique (00:00:00–23:59:30 UTC, record interval: 30 seconds). During the monitoring period, results of static processing were produced from the solutions (over 24 hours) by computing the ITRF 2014 Epoch with 2022.9 coordinates with an accuracy of 2–3 mm and 10 mm in vertical coordinates (11.11.2022).

When detecting the displacement values, the earthquake's timing is crucial. When the results of kinematic and static processing are compared, these studies indicate the horizontal coordinate discrepancies of the TONGA station (static-kinematic), which vary from a few millimetres to around 42 centimetres (Fig. 3). Additionally, the height component at the TONGA station obtained between the static and kinematic processing approaches a few millimetres to about 42 centimetres, as seen in Fig. 5. Figure 4 displays big values for the latitude (φ) and longitude (λ) components during the earthquake period (22:48:46 UTC Time).

By comparing the coordinates of the TONGA point by using kinematic and static methods before and after the Tonga earthquake (11 November 2022), the co-seismic displacements were obtained. Where Δφcos, Δλcos and Δhcos values are the co-seismic displacements, φpost, λpost and hpost, φpre, λpre and hpre show the average GNSS-based positions estimated from before and after the earthquake. The co-seismic displacement values gained for the IGS station (TONGA-TONG) according to the above procedure are illustrated in Figs 3, 4 and 5. During the time, it was found that the motion at the TONGA station happened in the northand north-west directions, as shown in Fig. 4. The use of GNSS measurements of the three-dimensional displacement directions of the IGS point (TONGA) is illustrated in Figs 5, 6. On 11 11 2022, the earthquake obviously generated a large bias in the horizontal and vertical coordinate findings.

In Fig. 7, ΔS values are the distance differences which were computed between the coordinates of the earthquake centre and coordinates of the TON-

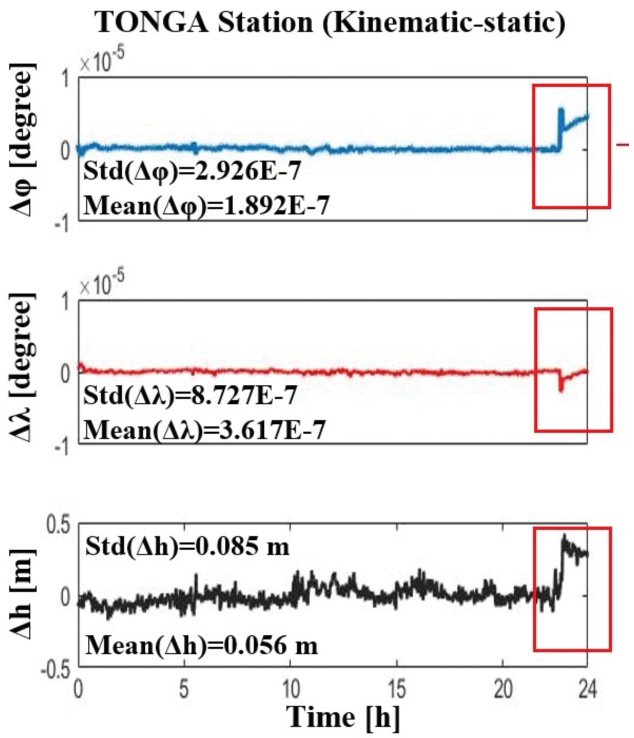

Fig. 3 Geographic coordinate differences (latitude (φ) and longitude (λ) values – 00:00:00–23:59:30 UTC time) time series (kinematic-static method / record interval: 30 seconds) obtained from the station (TONGA-TONG) during the monitoring earthquake period (22:48:46 UTC time)

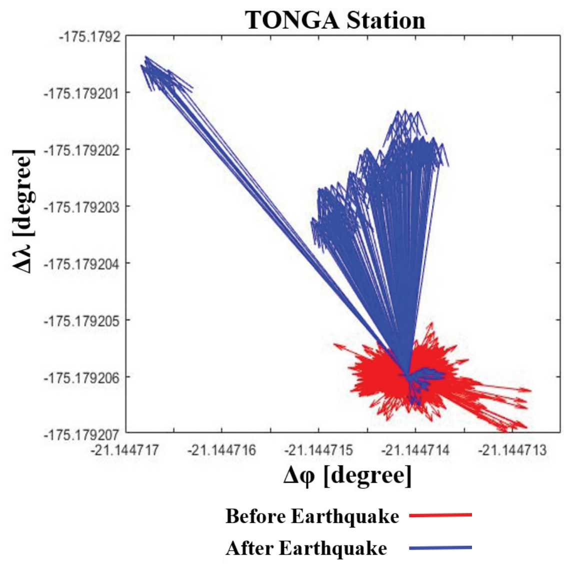

Fig. 4 Earthquake-induced horizontal displacement vectors for the TONGA point on 11 November 2022 (00:00:00–22:48:46 (red line) and 22:48:46–23:59:30 UTC time (blue line))

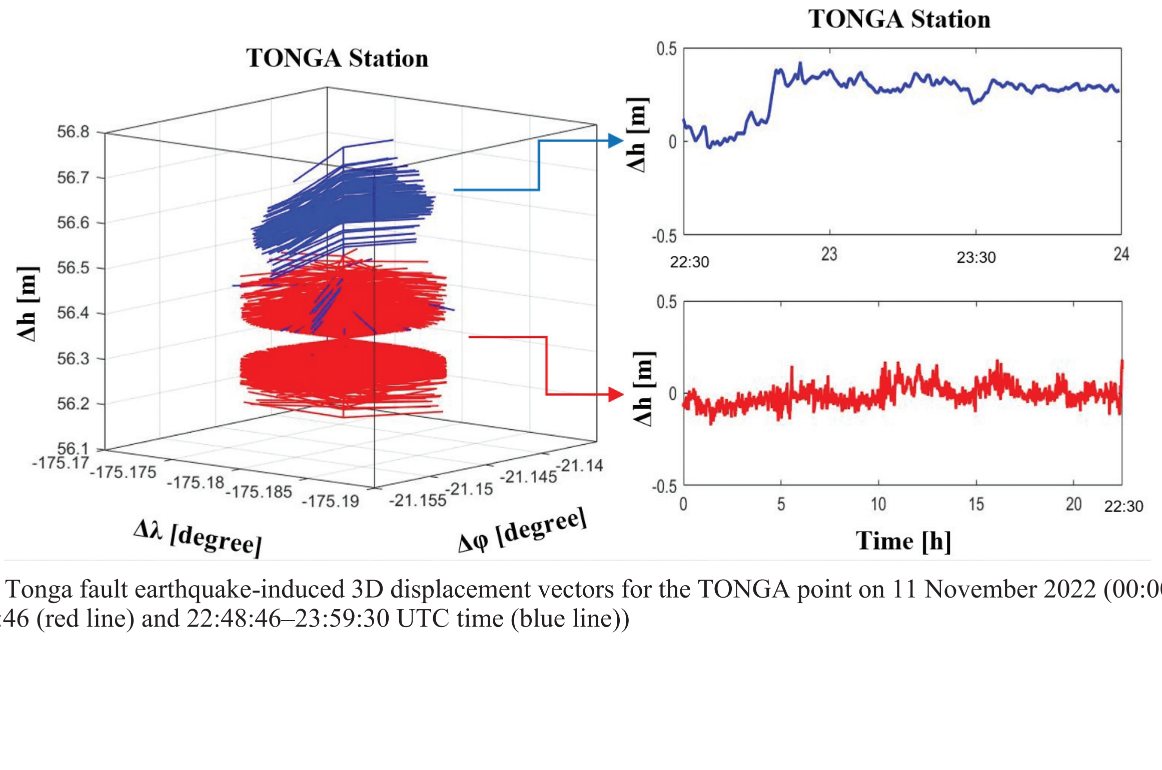

Fig. 5 Tonga fault earthquake-induced 3D displacement vectors for the TONGA point on 11 November 2022 (00:00:00–22:48:46 (red line) and 22:48:46–23:59:30 UTC time (blue line))

GA point obtained from epoch to epoch as a result of kinematic processing. The distance was obtained from the coordinates of the earthquake centre and the coordinates of the TONGA point as a result of static processing. Δh values are the difference between the ellipsoidal heights which were obtained from epoch to epoch as a result of kinematic processing and the ellipsoidal heights of the TONGA point obtained from static processing. In Fig. 7, the standard deviation and mean values of the distance differences (ΔS) before the earthquake were computed as 0.070 m and 0.033 m, respectively. After the earthquake, these values were calculated as 0.068 m and 0.293 m, respectively. The standard deviation and mean values for the height difference (Δh) were obtained as 0.085 m and 0.05 m, respectively, before the earthquake. After the earthquake, these values were calculated as 0.062 m and 0.290 m, respectively. As can be seen from the data obtained, the effect of the earthquake on the horizontal and vertical components was approximately 30 cm.

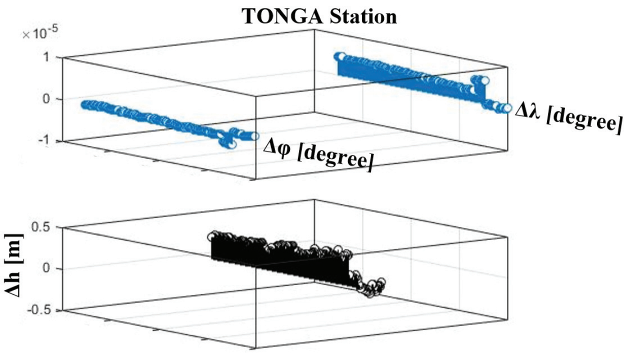

Fig. 6 Comparison of the 3D coordinates of the TONGA station (between static and kinematic processing results)

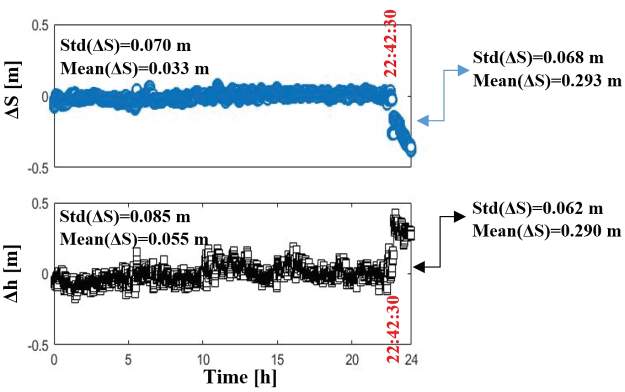

Fig. 7 Comparison of the distance and height differences between the TONG point and the epicentre point of Tonga earthquake (between kinematic processing of coordinate results and epicentre of Tonga earthquake coordinate values)

In Fig. 8, the coordinate values of the epicentre (red star) of the earthquake formed by the Tonga fault and the Tonga IGS point (yellow triangle) are shown. The distance between the epicentre of the earthquake and the TONGA IGS point is approximately 390 km. In addition, when the earthquake occurred at the Tonga fault at 22:48:46 UTC time, it was felt at the TONGA IGS point at 22:42:30 UTC time. In addition, although the Tonga earthquake could be felt at the point of Tonga at 22:42:30 UTC time, it should normally have been felt at 22:36:38.27 UTC time when time difference is taken into account. This time difference due to the effect of the earthquake is computed 5 m 52 s.

DISCUSSION

Tonga is located on the South Pacific Rim, which is one of the world's most active earthquake regions. This means that the country is vulnerable to environmental hazards, such as earthquakes, volcanic eruptions, and tsunamis. Reversal faulting beneath the Pacific Plate's outer rise caused the Mw 7.3 Tonga

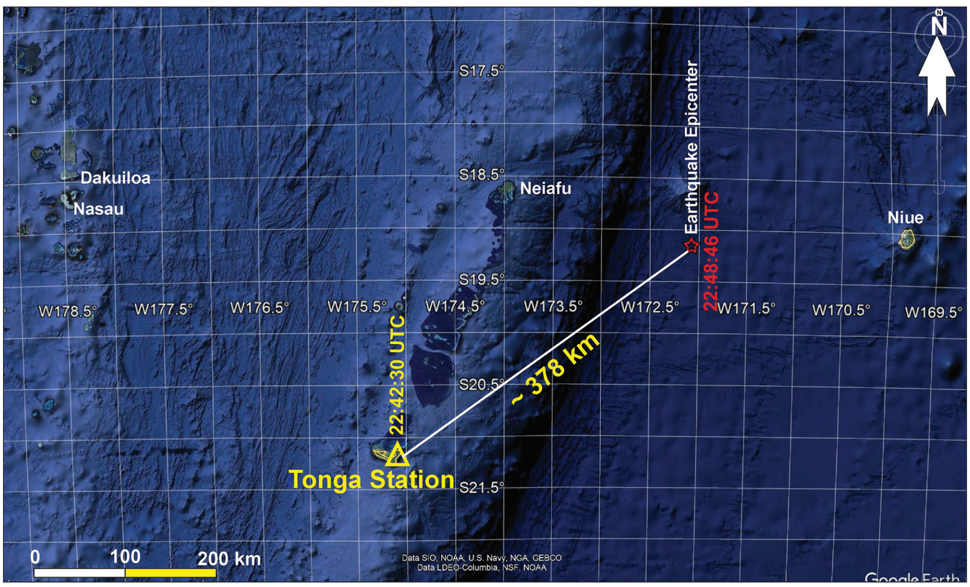

Fig. 8 Epicentre of the earthquake (red star), time and TONGA IGS point (yellow triangle) during the earthquake period

earthquake, which struck on 11 November 2022 about 75 kilometres east of the Tonga Trench. According to the answers for the focal mechanism, the rupture occurred on a reversal fault that slanted somewhat west or east-southeast. To the west of this earthquake, the Pacific Plate subducts under the Australian Plate at a rate of approximately 77 mm/year. While the majority of earthquakes in the outer rise are extensional in nature, this one may have been compressional in nature because it occurred a little bit deeper inside the Pacific Plate in the region where compression is most likely to result from the Pacific Plate bending during subduction. On a large scale, the Australia-Pacific Plate boundary is one of the world's most active plate boundaries. The Australia-Pacific thrust fault border, the Pacific Plate, and the boundaries of the tiny microplates that together make up the Australia Plate's eastern edge are all locations where earthquakes may be found. Large earthquakes are better represented as sliding across a greater fault region, even though they are often depicted as spots on maps. Modelling indicates that this earthquake, primarily a down-dip of the hypocentre, had dimensions of around 50 × 35 km, assuming that the fault line dips west. Frequent big earthquakes occur in the subduction zone around Fiji and Tonga. Over the past 40 years, three other Mw 7 or greater events have occurred within 250 km of the 11 November incident. Within the descending Pacific Plate, the greatest was a M 8.0 earthquake that occurred in May 2006, around 200 km southwest of the events of 11 November (National Earthquake Information Center; Bevis *et al*. 1995; Northard *et al*. 1996; Smith, Price 1996; Wiens, McGuire 2000; Cronin 2022; Tibi *et al*. 2003; Kilb *et al.* 2006; Warren *et al*. 2007; Cronin 2022; Wiens, McGuire 2000). Our results are consistent with the results obtained from articles written by other authors for this earthquake (Cronin 2022).

About 75 kilometres east of the Tonga Trench, reversal faulting beneath the Pacific Plate's outer rise caused the Mw 7.3 Tonga earthquake that struck on 11 November 2022. According to the answers for the focal mechanism, the rupture occurred on a reversal fault that slanted somewhat either west or east-southeast. The Pacific Plate subducts under the Australian Plate at a rate of around 77 mm/year to the west of this earthquake. While the majority of earthquakes in the outer rise are extensional in nature, this one may have been compressional in nature because it occurred a little bit deeper inside the Pacific Plate in the region where compression is most likely to result from the Pacific Plate bending during subduction. Among the most active plate boundaries in the world is the Australia-Pacific Plate boundary on a large scale. The Australia-Pacific thrust fault border, the Pacific Plate, and the boundaries of the tiny microplates that together make up the Australia Plate's eastern edge are all locations where earthquakes may be found. Large earthquakes are better represented as sliding across a greater fault region, even though they are often depicted as spots on maps. According to modelling, this earthquake had dimensions of around 50 × 35 km, mostly down-dip of the hypocentre, assuming that the fault line dips west. Frequent big earthquakes occur in the subduction zone around Fiji and Tonga. Three other Mw7 or greater events have happened within 250 km of the 11 November incident over 40 years before. Within the descending Pacific Plate, the greatest was Mw 8.0 earthquake that occurred in May 2006, around 200 km southwest of the events of 11 November (National Earthquake Information Centre 2022; Bevis *et al.* 1995; Northard *et al.* 1996; Smith, Price 1996; Wiens, McGuire 2000; Tibi *et al.* 2003; Kilb *et al.* 2006; Warren *et al.* 2007; Cronin 2022).

CONCLUSIONS

The horizontal and vertical displacements (coseismic) caused by the 11 November 2022 Tonga earthquake were effectively determined using the relative GNSS analysis technique. For this, the IGS station (Tonga-TONG) close to the epicentre was employed. Using data from the daily coordinate time series, horizontal and vertical displacements with sub-mm accuracy were successfully estimated.

The biggest horizontal displacement value was reported at the TONGA station, which is 390 kilometres from the epicentre and southwest of the Tonga fault. This value was cm in the north and north-west directions. To put it another way, the Tonga fault had an impact on the Tonga point's north and north-west directions. As can be seen from the data obtained, the effect of the earthquake on the horizontal and vertical components was approximately 30 cm.

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