The 2021 M_W 5.9 Woods Point earthquake and associated seismic sequence: Seismogenic fault zone identification from high-precision relocations of aftershocks

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Abstract

The 21st September 2021 M_W 5.9 Woods Point earthquake was the largest historical and instrumentally-recorded seismic event in Victoria. To date, it has triggered more than 1600 recorded aftershocks, the largest being a M_L 4.7 almost 2 years later. We employ a double-difference technique to relocate the earthquake sequence. The events locate within the complex network of faults associated with the Governor Fault Zone – a major geological terrane-bounding basement structure. The locations and rupture kinematics of the earthquake data accord with the geometry of this structure, indicating the likely reactivation of an ancient deformation zone by contemporary crustal stresses across southeast Australia. This event illuminates the need to consider major basement faults in seismic hazard assessments.

Keywords: earthquake; aftershock; Victoria; double difference relocation; seismogenic fault.

1 Introduction & Background

The analyses of mainshock earthquakes and their aftershock sequences can provide information on the characteristics of the source fault. For reliable results, the accuracy of the location and depth of the associated seismic events is crucial. Earthquake hypocentre uncertainties depend on several factors, including the number of seismometers used to locate the earthquake, the distance of these seismometers from the event, their spatial distribution relative to the epicentre, and velocity models used in calculations. Reducing uncertainties to better understand the source fault can in turn more accurately inform seismic hazard models.

The 21st September 2021 M_W 5.9 Woods Point earthquake occurred about 15 km northeast of the Woods Point community, and approximately 130 km east of Melbourne, in a remote part of Taungurung Country, Victoria. Moment tensor inversion by Geoscience Australia (GA) produced a focal mechanism solution showing left-lateral strike-slip displacement on two possible fault plane attitudes (their orientation in 3D i.e., dip and strike); one of these, a near north-south (172°) trending, steeply (83°) west dipping fault accords with the distribution of aftershocks recorded within the first few hours of the mainshock, as located by the Seismology Research Centre (SRC) (Figure 1). The mainshock involved a blind rupture, which was initially inferred to be on a previously unknown fault (Ninis, 2022; Mousavi et al. 2023).

At the time of the M_W 5.9 Woods Point earthquake, the existing regional seismograph network consisted mainly of short-period seismographs (<10 sec. corner frequency) with a few medium-period (10-60 sec.) and broadband instruments. The site nearest to the epicentre was TOT (operated by the SRC) 35.2 km to the south. Additional nearby sites include GLMM (SRC) 56.2 km to the southeast, as well as instruments run by the University of Melbourne (UoM) – CLIF, 58.5 km to the southwest, and BRIG, 64.2 km to the southeast – and TOO (operated by GA) 80.9 km to the west (Figure 1).

Within 36 hours of the mainshock, the first deployed aftershock seismograph - WPM2Y (UoM) was installed 28 km northwest of the epicentre. This was followed, within 79 hours of the mainshock, by an additional nine sites – both broadband and strong motion (UoM - 5 sites; GA - 4 sites) – all located within 23 km from the epicentre (Figure 1). This distribution of seismographs further reduced location uncertainties and improved magnitude completeness range.

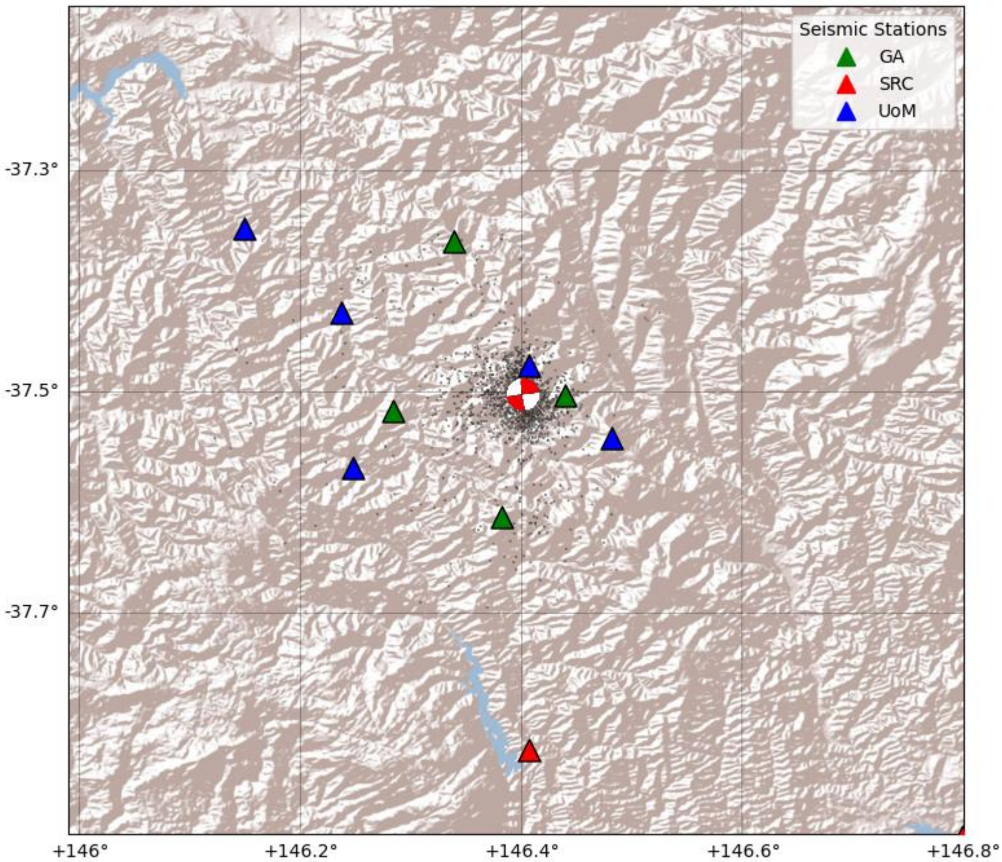

Figure 1. Epicentre location of the mainshock and aftershocks, and the seismic station distribution. Focal mechanism provided by GA.

To date, the aftershock sequence has involved more than 1600 detected events. Most of these (currently >60%) occurred within one month after the mainshock. At the time of writing, seismicity in the area is ongoing, producing on average six earthquakes a month. The sequence has included three earthquakes above M_L 4.0; the first of these – a M_L 4.2 – occurred 19 minutes after the mainshock; the second and largest aftershock – a M_L 4.7 – occurred nearly 2 years later in June 2023, and the third – a M_L 4.1 – occurred almost three years later in August 2024. Focal mechanism solutions provided by GA (https://earthquakes.ga.gov.au/) suggest these three events and the M_W 5.9 mainshock occurred on faults with a similar attitude.

The geology of southeast Australia consists of a series of approximately north-south oriented orogenic belts, terranes and structural constituents which are bound by major (>150 km-long) fault zones. In the Woods Point region, the Governor Fault Zone juxtaposes Selwyn Block crust of continental character to the west, against Cambro-Ordovician Tabberrabbera Zone crust of accretionary character to the east, along a north-northwest-trending interface that extends for more than 300 km across Victoria. Deep seismic refection data (Cayley et al. 2006, 2011) shows the Governor Fault consists of a complex system of anastomosing faults.

The objective of this investigation is to improve the accuracy of the mainshock and aftershock locations of the M_W 5.9 Woods Point earthquake sequence in order to better characterise the fault involved. In this paper we analyse the M_W 5.9 Woods Point earthquake and associated aftershocks and use existing subsurface fault models in an attempt to identify the source fault and regional tectonic context for this earthquake sequence.

2 Data & Analysis

In order to better characterise the fault (or faults) involved in the M_W 5.9 Woods Point earthquake sequence, we undertook steps to improve event location and depth precision for all events within 20 km of the epicentre, a distance approximately twice the fault rupture length.

The original mainshock and aftershocks were located manually as soon as possible after they occurred, using data from the seismometer network available at the time, and the VIC5A velocity model (Wesson, 1988) which was developed specifically for southeast Australia based on data from local earthquakes and blasts. The catalogue includes all recorded events from a minimum of M_L -0.3, from the time of the mainshock until October 2024 – 1665 events in total.

For this study, we first manually revisited P- and S-wave arrivals of all recorded and previously located events above M_L 2.8 (30 events) from the SRC catalogue to ensure accurate picks. For this preliminary analysis, we used M_L 2.8 as an arbitrary cut-off for expediency, as the number of events smaller than this increases exponentially. Moreover, smaller event arrivals become less distinct, particularly at distant sites, and reviewing them didn't necessarily significantly improve their locations.

Following the manual assessment of P- and S-wave arrivals, we used the program HypoDD to implement the double-difference relocation of the events in the aftershock sequence, based on observed (manually picked) catalogue phase arrivals. When the separation between the hypocentres of two events i and j is small compared to the distance between the sources and a common station k, then the ray paths between the two events and the station are similar and the difference in travel times is related to the distance between the two events, reducing the effect of the velocity uncertainties along the path (Waldhauser, 2001). Using the observed travel times obtained from the SRC catalogue (t^{obs}) and the calculated travel times from the velocity model (t^{cal}) using the VIC5A velocity model (Wesson, 1988), the residuals can be obtained using the equation

$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal}$$

This is the double-difference equation which is used to calculate the residuals for event pairs at common stations. The method then minimises the residuals by weighted least squares and the solutions for the relocated hypocentres are found by iteratively tuning the separation vector between hypocentral pairs (Waldhauser and Ellsworth, 2000).

We adjust the weights and parameters used until a stable solution is found. The least squares method used is the conjugate gradients method (LSQR), which is efficient for systems with a large number of events in the order of thousands or more. This method underestimates the errors in the solution, so we used the singular value decomposition method (SVD) on a small subset for all events with M≥2.0 to test the stability of the solution and validate the results.

3 Results & Discussion

A stable solution for the double-difference relocation was achieved after 22 iterations using HypoDD. Not all events from the original SRC catalogue were relocated; some were excluded during various stages of the process due to insufficiently strong association parameters or because their associations were considered weak based on the weights used in the iterations. In total, 1,525 relocated events remained.

The relocated epicentres are compared to manually determined locations in Figure 2. In this figure, the top left and top right maps display the original epicentre locations from the SRC catalogue and the HypoDD relocations respectively. The relocation of the epicentres appears largely consistent with the catalogue epicentres. However, when examining the hypocentres along a west-to-east depth profile (bottom panels of Figure 2), the sequence does not align on a plane, suggesting not one source fault but perhaps a more complex system of fault ruptures involved in the seismic sequence.

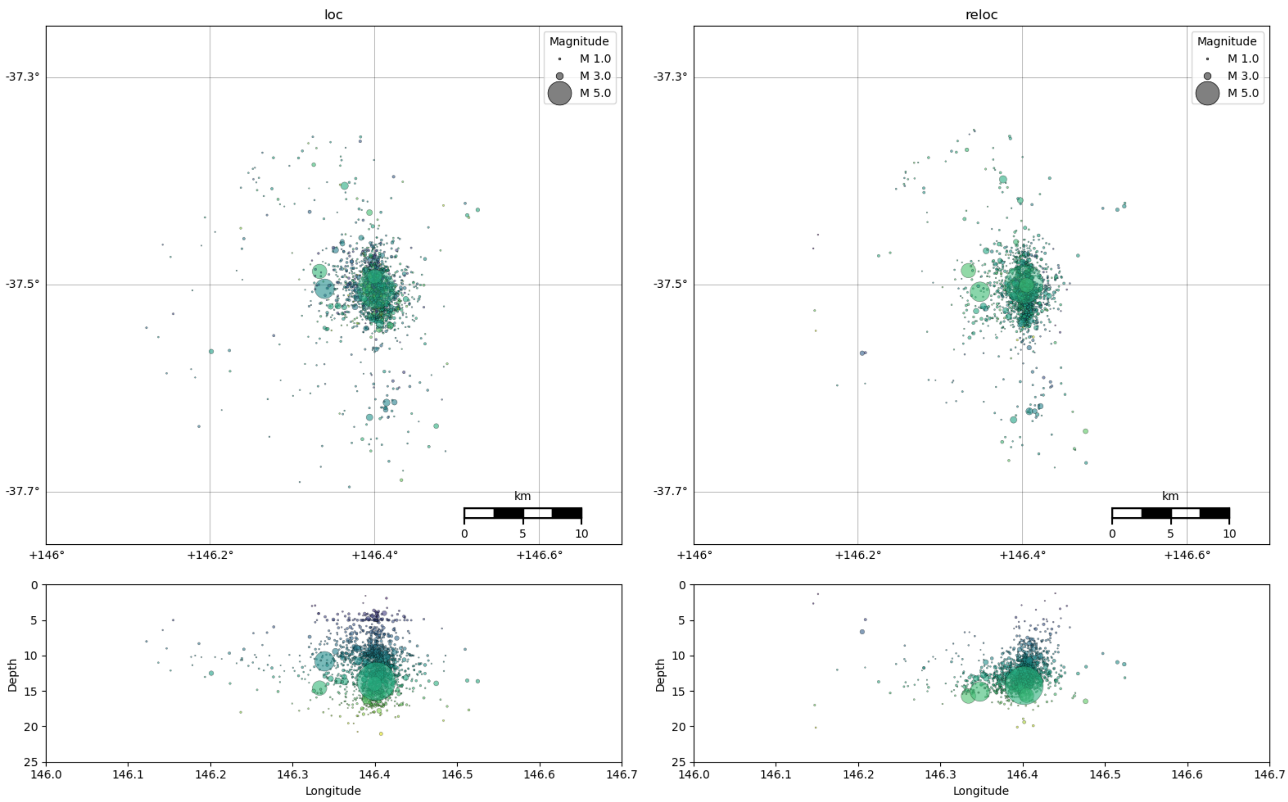

Figure 2. Mw 5.9 Woods Point mainshock and aftershock sequence – original locations (L) and double-difference relocations (R).

Preliminary results suggest that the M_W 5.9 Woods Point earthquake and aftershock sequence occurred on fault structures within the Governor Fault zone, indicating the likely reactivation of an ancient, major terrane-bounding fault structure by contemporary crustal stresses. Further analysis needs to be undertaken to compare the relocated earthquake sequence with 3D subsurface fault data. Together with the 1989 M_W 5.4 Newcastle earthquake (McCue et al. 1990) and indeed other significant historical earthquakes across Australia (e.g., Gordon, 1971; Vogfjörd & Langston, 1987; Crone et al. 1997), the 2021 M_W 5.9 Woods Point earthquake shows that moderate and damaging earthquakes need not occur on previously identified neotectonic faults, and that basement faults with no known evidence for hosting neotectonic activity are also potential sources of earthquake hazard.

4 Conclusions

We used HypoDD to perform a double-difference relocation of the mainshock and aftershocks of the 21st September, 2021 M_W 5.9 Woods Point earthquake to obtain a high-resolution and lower uncertainty solution for their hypocentres. The earthquake sequence locates within the Governor Fault Zone – a major, ancient fault structure not previously considered a source of seismic hazard. Future studies will be focus on better understanding the relationship between the relocated Woods Point seismic sequence and 3D subsurface fault models in the region.

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