Australian Earthquake Engineering Society
2024 National Conference, 21-23 November 2024
Adelaide, South Australia

# Re-evaluation of southeast Australian first-motion focal mechanisms through a semi-automated workflow

Eric C Wang[1], Patrice F Rey[1] and Vasileios Chatzaras[1]

*1. The University of Sydney, School of Geosciences, New South Wales, 2006, Australia*

## Abstract

Focal mechanisms are important for constraining fault source models used in seismic hazard assessment and for mapping present-day maximum horizontal stress ($S_{Hmax}$) orientation. Critically, $S_{Hmax}$ orientation is highly variable across Australia, and its mapping requires in-situ stress orientation indicators such as focal mechanisms. Until recently nodal planes of first-motion P-wave focal mechanisms were manually plotted and are therefore prone to bias. This approach may result in poorly constrained focal mechanisms, negatively impacting on the mapping of the stress field.

To mitigate against human bias, we use two algorithms, FOCMEC and SKHASH, to automate and re-evaluate first-motion focal mechanism solutions. These programs utilise azimuth and take-off angle of seismic rays, and P-wave polarity data to conduct a systematic search of all possible focal mechanisms and output the best-fitting nodal planes. Using these solutions in conjunction with neotectonic features and neighbouring $S_{Hmax}$ orientation indicators (e.g., borehole breakouts, hydraulic fracturing, and overcoring), we reassess published focal mechanisms in the Dalton-Gunning region, the Flinders Ranges, and eastern Victoria.

**Keywords:** First-motion focal mechanism; maximum horizontal stress ($S_{Hmax}$) orientation.

## 1 Introduction

Knowledge of maximum horizontal stress ($S_{Hmax}$) orientation is critical for understanding seismic hazard (Hillis et al., 2008), stability of underground infrastructure (i.e., tunnels and mines) (Kang et al., 2010; Jiang et al., 2023), and exploration of unconventional petroleum resources (Tingay et al., 2009). Australia's $S_{Hmax}$ orientation is highly variable and relies on in-situ $S_{Hmax}$ orientation indicators (Hillis et al., 2008; Rajabi et al., 2017). One such indicator is the focal mechanism, which is usually generated from an earthquake and can indicate how the source fault slipped. Focal mechanisms may be the only stress indicators available in a given region, and are typically the only indicators at depths greater than five kilometres.

Many Australian first-motion focal mechanisms were manually determined, potentially resulting in user error, inconsistency, and bias (i.e., P-wave polarity picking and nodal plane placement). To mitigate these issues, we utilise algorithms to automate and better constrain nodal plane placement of Australian first-motion focal mechanisms. We compare the solutions with known neotectonic features and neighbouring stress indicators to determine the best fitting focal mechanisms.

## 2 Methods

Leonard et al. (2002) provide the most comprehensive catalogue of focal mechanisms in Australia. It consists of 107 fault plane solutions from 84 earthquakes. The 69 focal mechanisms are derived from first-motion analysis. We focus our results and discussion on the Dalton-Gunning region, the Flinders Ranges, and eastern Victoria (Figure 1). These records contain azimuth and take-off angle of seismic rays, and P-wave polarity data. The absence of original waveform datasets prevents utilisation of newer methods for analysis (e.g., automated P-wave picking, new seismic velocity models). Nevertheless, these records allow for best fitting focal mechanism programs to be used. We employ the programs FOCMEC and SKHASH to validate the published focal mechanisms, and ensure the consistency of outputs between the two programs. We also consider neotectonic features and nearby stress orientation indicators to assist in determining the most appropriate solutions.

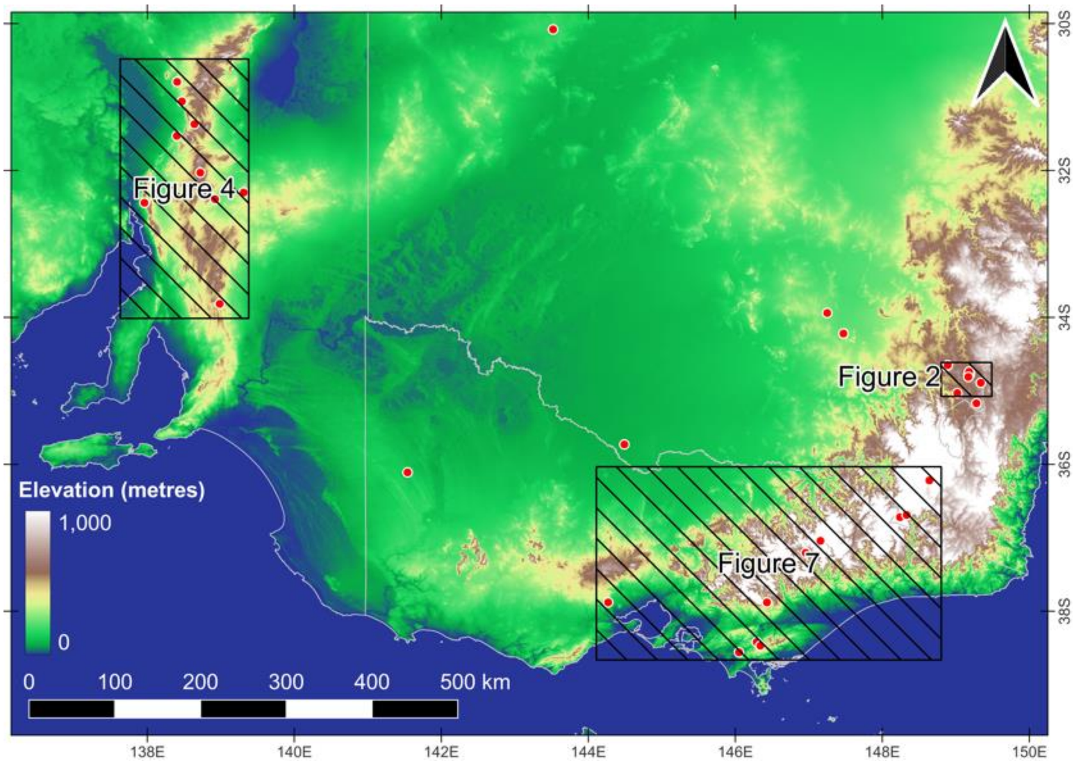


*Figure 1. Southeast Australian earthquakes for which we have first-motion focal mechanism data (from Leonard et al. (2002) and references within).*

FOCMEC is a Fortran 77 program which determines focal mechanisms based on first-motion data (Snoke, 2003). An ideal first-motion focal mechanism separates all compressional and dilatational polarities into their respective quadrants. However, misinterpretation of P-wave first arrivals may result in incorrect polarities, leading to imperfect placement of nodal planes. We use the relative-weighted polarity error criteria, which assign a value between 0 and 1 based on the distance of a misfit polarity from the nodal plane (Snoke, 2003). The sum of these values gives each focal mechanism a relative weight, where lower values indicate better fitting solutions. This technique minimises the error of any misfit polarities. We highlight the top 100 focal mechanisms with grey nodal planes and the five best fitting in red.

SKHASH is a Python package for computing focal mechanisms that is largely based on the legacy HASH Fortran algorithm (Hardebeck & Shearer, 2002; Hardebeck & Shearer, 2003; Skoumal et al., 2024). SKHASH allows for a percentage of polarities deemed incorrect, to which the default value of 10% is applied. Instead of outputting all acceptable focal mechanisms under a weighted threshold like FOCMEC, SKHASH returns the most likely solutions with an associated quality ranking where “A” is the highest and “D” is the lowest. The quality ranking is determined by how well constrained the nodal planes are, with respect to the polarities’ position on the stereonet.

# 3 Results

## 3.1 Dalton-Gunning Region

We assess nine earthquakes with first-motion data in the Dalton-Gunning region (Figure 2). The two 1977 Bowning and the 1971 Dalton earthquakes maintain their published focal mechanisms (or a similar derivative from SKHASH and/or FOCMEC; Figure 3) due to overall agreement between the published, SKHASH, and FOCMEC solutions. Two published focal mechanisms of reverse and oblique-reverse motion exist for the 1984 Oolong earthquake. Both solutions are depicted in the SKHASH results, but only the reverse solution is present in the FOCMEC results. As such, we favour the reverse solution.

The 1975 Gunning earthquake showcases similar results with the published solution. However, an alternative reverse solution with a north-south nodal plane may fit better with the surrounding 1971 Dalton and 1984 Oolong solutions that indicate east-west compression. Similarly, the focal mechanism solutions of the 1977 Dalton and 1974 Gunning earthquakes vary between the published, SKHASH, and FOCMEC solutions. With consideration of the adjacent earthquakes, we suggest the reverse solution from FOCMEC for the 1977 Dalton earthquake, and the published solution for the 1974 Gunning earthquake.

We revise the 1973 Gunning earthquake from strike-slip to reverse due to the SKHASH and FOCMEC solutions, and its proximity to the reverse slip neotectonic fault (Figure 2). The published, SKHASH, and FOCMEC solutions of the 1974 Murrumbateman earthquake are dissimilar to each other. Assuming a similar east-west $S_{Hmax}$ orientation as indicated by the other solutions, then either the published or SKHASH solutions are possible.

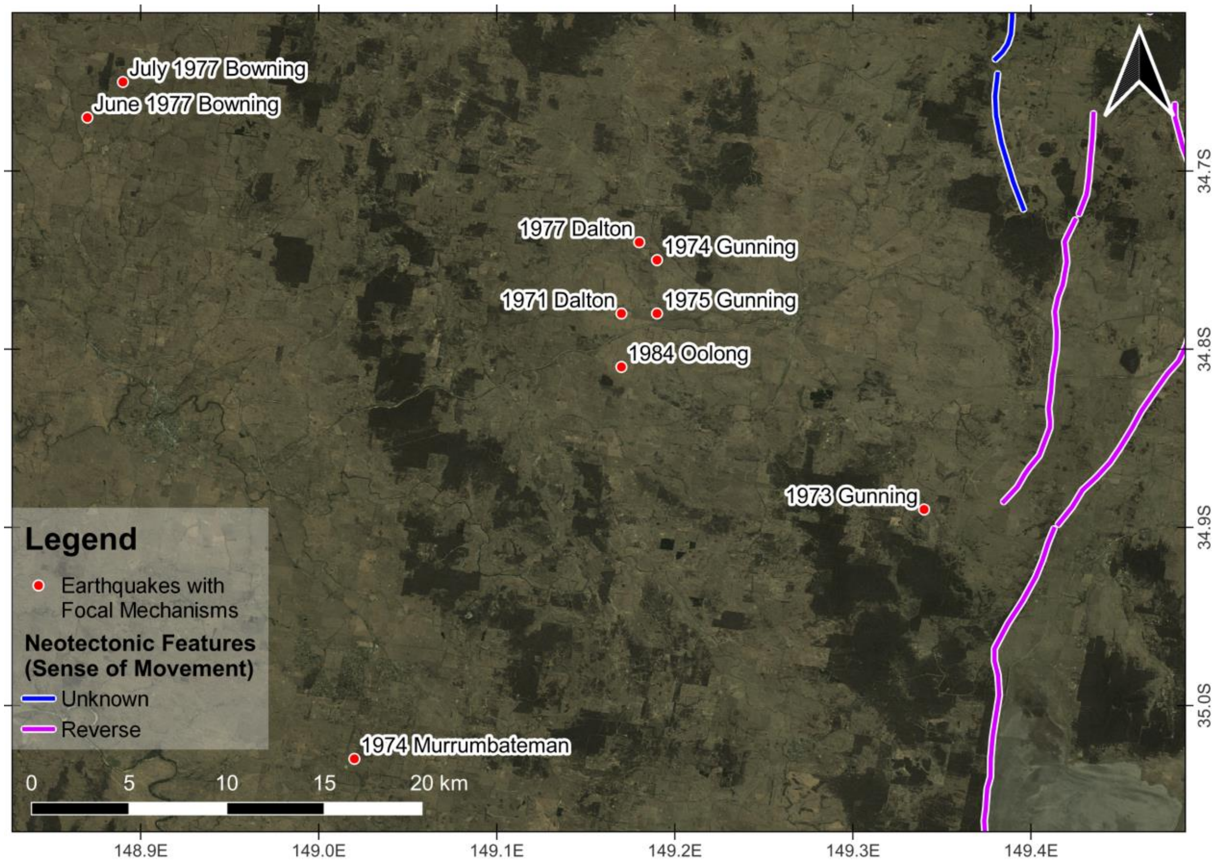


*Figure 2. Locations of analysed earthquakes with their associated event ID around the Dalton-Gunning region (see Table 1). Earthquake locations from Leonard et al. (2002) and references within; neotectonic features from Clark & McPherson (2024).*

*Table 1. List of earthquakes with first motion polarity data in the Dalton-Gunning region (New South Wales. Data sourced from Leonard et al. (2002) and Geoscience Australia (2024).*

| Event ID | Location | Date | Magnitude (ML) | No. of Polarities |
|---|---|---|---|---|
| June 1977 Bowning | Bowning | 30/06/1977 | 4.2 | 22 |
| July 1977 Bowning | Bowning | 4/07/1977 | 4.8 | 33 |
| 1971 Dalton | Dalton | 3/11/1971 | 4.2 | 12 |
| 1984 Oolong | Oolong | 9/08/1984 | 4.3 | 18 |
| 1975 Gunning | Gunning | 4/08/1975 | 3.8 | 11 |
| 1977 Dalton | Dalton | 5/04/1977 | 3.2 | 14 |
| 1974 Gunning | Gunning | 22/03/1974 | 3.0 | 8 |
| 1973 Gunning | Gunning | 8/01/1973 | 2.5 | 13 |
| 1974 Murrumbateman | Murrumbateman | 6/05/1974 | 3.8 | 14 |

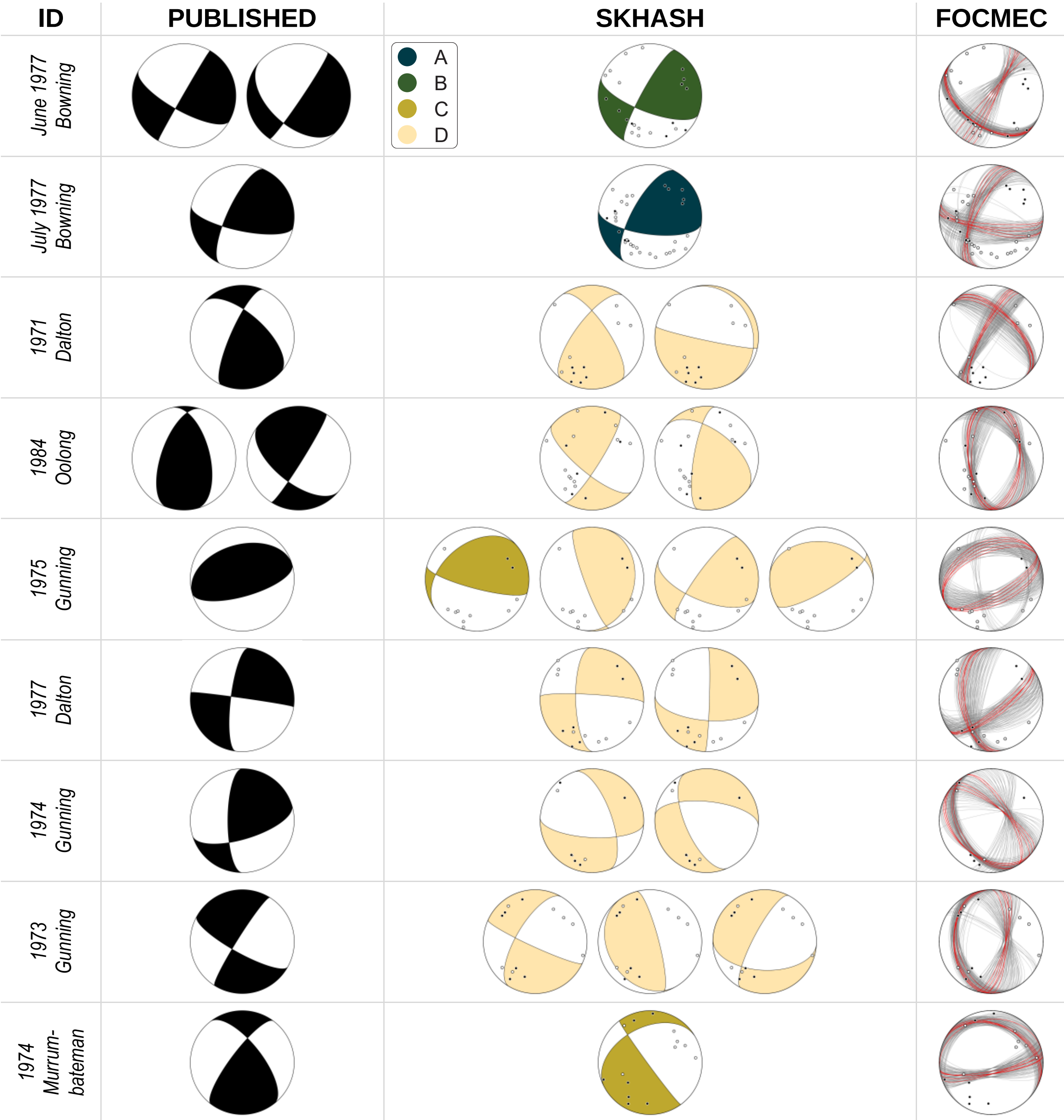


*Figure 3. The Dalton-Gunning region published focal mechanisms with their associated event ID (see Table 1) compared to SKHASH and FOCMEC solutions. Compressional and dilatational polarities are represented by closed and open circles, respectively.*

## *3.2 The Flinders Ranges*

We reassess nine earthquakes with first-motion datasets in the Flinders Ranges (Figure 4). The 1983 Beltana, 1978 Carrieton, and 1977 Quorn earthquakes, as well as the 1992 Moralana swarm, maintain their published focal mechanisms (or a similar derivative from SKHASH and/or FOCMEC; Figure 5) due to agreement with at least one of the three criteria: (1) both SKHASH and FOCMEC results, (2) the prevailing east-west $S_{Hmax}$ orientation from nearby stress indicators (Balfour et al., 2015; Rajabi et al., 2017; Rajabi et al., 2018), and (3) the north striking planes of the reverse neotectonic faults (Figure 4). In contrast, the 1977 Blinman, 1980 Hawker, and 1977 Melton earthquakes are reconsidered due to deviation of the published focal mechanisms from the above-mentioned criteria. In all three earthquakes, we favour the alternative reverse solutions shown in both SKHASH and FOCMEC.

The 1997 Burra earthquake has two first-motion datasets from McCue et al. (2001) and Mountford et al. (1997) (hereafter McCue and Mountford, respectively). Both published focal mechanisms show similar reverse motion, in line with $S_{Hmax}$ orientation and nearby faults. Our results from the McCue polarity dataset do not match with its the published focal mechanism. SKHASH depicts a dominantly strike-slip focal mechanism with an alternative normal solution, while FOCMEC displays a normal solution. Our results for the first motion mechanisms of Mountford showcase similar reverse solutions, but SKHASH ranks an oblique-normal solution higher. Given that both McCue and Mountford datasets are from the same earthquake, we expect similar focal mechanisms. The reverse focal mechanism is the most likely solution given that it appears in both FOCMEC and SKHASH outputs, matching the published solutions.

The 1981 Wilpena earthquake results are highly variable due to the low number of polarities (eight). The published, SKHASH, and FOCMEC focal mechanisms are dissimilar to each other. The surrounding earthquake focal mechanisms, stress indicators, and reverse faults, point to the reverse solutions. The variable results from SKHASH and FOCMEC prevent us from proposing a definitive solution.

*Table 2. List of earthquakes with first motion polarity data in the Flinders Ranges (South Australia). Data sourced from Leonard et al. (2002) and Geoscience Australia (2024). ^Has two polarity datasets from McCue et al. (2001) and Mountford et al. (1997). These are referred to as MC and MO, respectively, under the "No. of Polarities" column. *A swarm event and therefore a composite solution.*

| Event ID | Location | Date | Magnitude (ML) | No. of Polarities |
|---|---|---|---|---|
| 1983 Beltana | Beltana | 29/12/1983 | 4.4 | 34 |
| 1978 Carrieton | Carrieton | 26/03/1978 | 4.1 | 10 |
| 1977 Quorn | Quorn | 16/04/1977 | 3.8 | 13 |
| 1992 Moralana* | Moralana | 12/1992 | 0.7-3.5 | 64 |
| 1977 Blinman | Blinman | 30/08/1977 | 4.2 | 12 |
| 1980 Hawker | Hawker | 22/04/1980 | 3.7 | 9 |
| 1977 Melton | Melton | 28/09/1977 | 4.0 | 16 |
| 1997 Burra^ | Burra | 5/03/1997 | 5.1 | 24 (MC)/26 (MO) |
| 1981 Wilpena | Wilpena | 15/07/1981 | 3.7 | 8 |

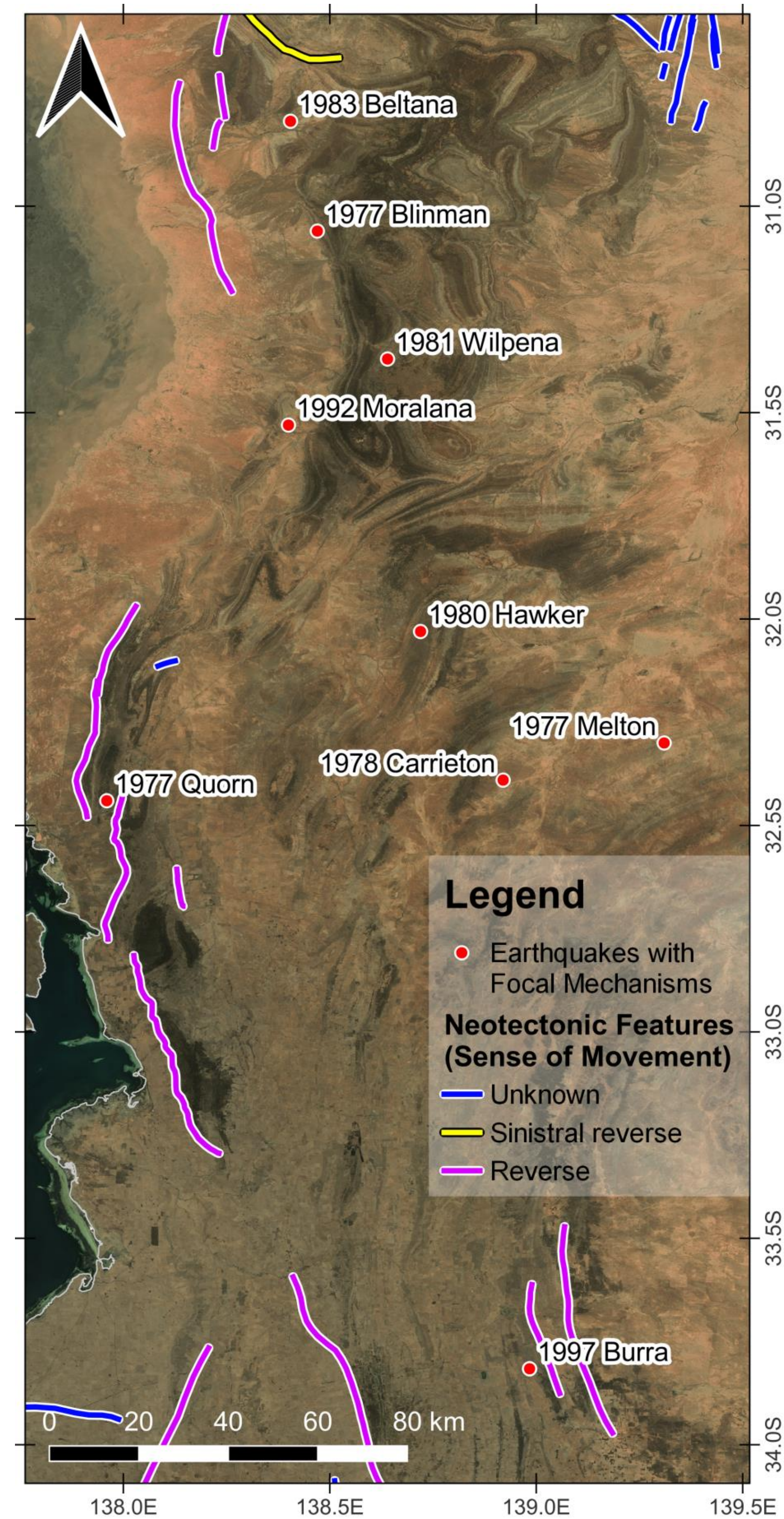


*Figure 4. Locations of analysed earthquakes with their associated event ID around the Flinders Ranges (see Table 2). Earthquake locations from Leonard et al. (2002) and references within; neotectonic features from Clark & McPherson (2024);*

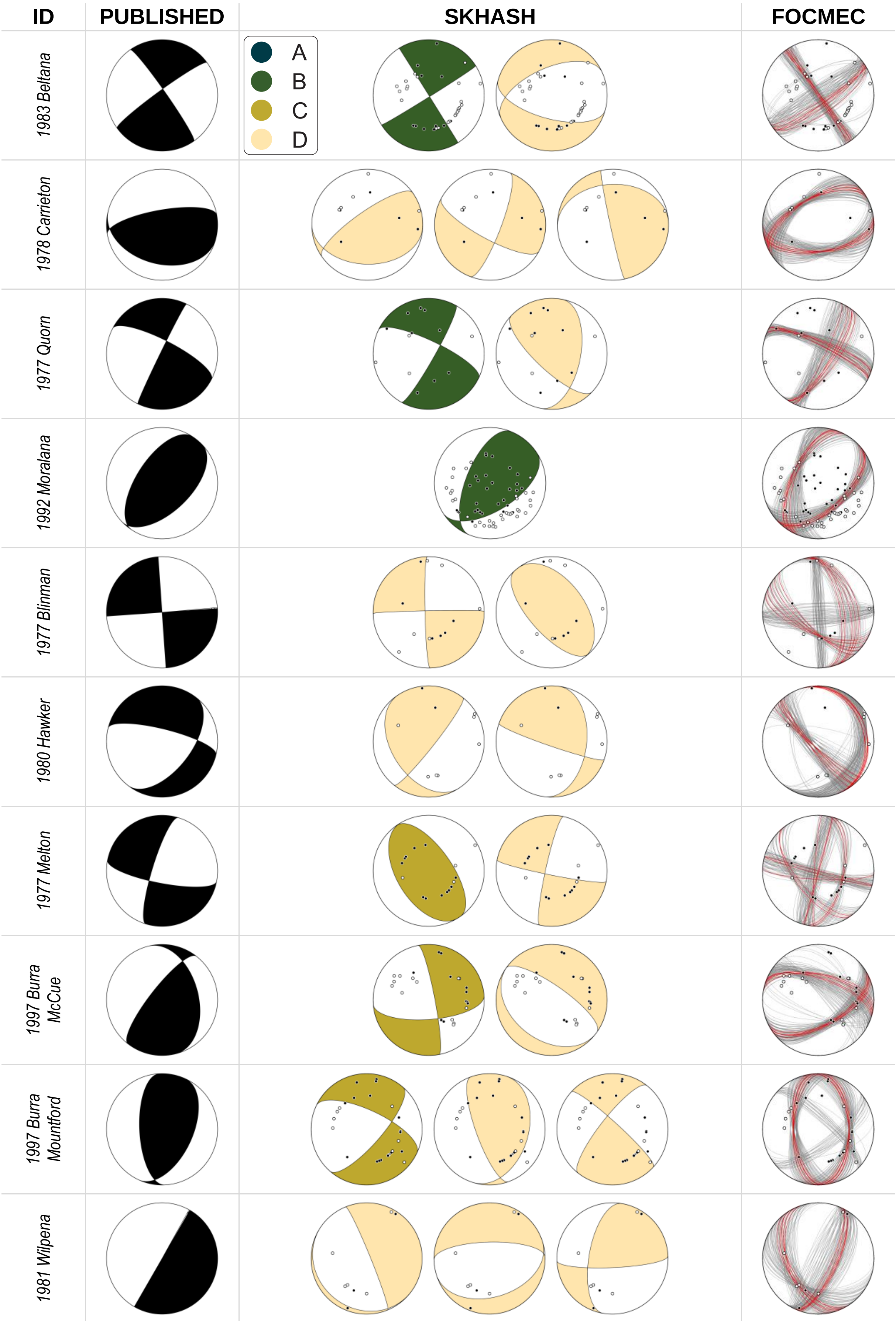


*Figure 5. The Flinders Ranges published focal mechanisms with their associated event ID (see Table 2) compared to SKHASH and FOCMEC solutions. Compressional and dilatational polarities are represented by closed and open circles, respectively.*

## 3.3 Eastern Victoria

We assess ten earthquakes with first-motion data in eastern Victoria (Figure 7). The 1959 Berridale, 2000 and 2001 Boolarra South, 2000 Dumbalk, and 1982 Wonnangatta earthquakes maintain their published solutions (or a similar derivative from SKHASH and/or FOCMEC; Figure 6) due to agreement with at least one of the three criteria: (1) both SKHASH and FOCMEC results, (2) the prevailing northwest-southeast compressive $S_{Hmax}$ orientation from nearby stress indicators (Rajabi et al., 2017), and/or (3) the northeast trending reverse neotectonic faults (Figure 7).

Two published focal mechanisms, a reverse and oblique-normal solution, are associated with the 1977 Balliang earthquake. SKHASH generates both focal mechanisms but ranks the reverse solution higher. Additionally, FOCMEC only produces reverse solutions. As such, we propose that the reverse solutions are more likely.

For the 1976 Pilot Wilderness earthquake, both SKHASH and FOCMEC show reverse solutions with some variation from the published focal mechanism. The 1981 Suggan Buggan earthquake displays dissimilar focal mechanisms across the published, SKHASH, and FOCMEC solutions. Given their proximity, if we consider both the 1976 Pilot Wilderness and 1981 Suggan Buggan earthquake solutions together, the FOCMEC solutions for both earthquakes are somewhat similar. Overall, however, we do not favour a solution due to disagreement across the published, SKHASH, and FOCMEC results.

Both methods for the 1966 Mt Hotham earthquake produce similar normal focal mechanisms comparable to the published solution, which is inconsistent with the compressive northwest-southeast horizontal stress field. A few north-south trending nodal planes in the FOCMEC results produce an alternative oblique focal mechanism. This solution would better fit with the stress field but is in opposition with the dominant normal solutions. The nearby west-dipping Kiewa Fault could be the source fault but has reverse left-lateral slip, as opposed to the normal right-lateral slip of the oblique focal mechanism (assuming the northwest trending nodal plane is the fault plane). Nevertheless, we favour the normal solution due to strong agreement across SKHASH and FOCMEC results, but note the oblique FOCMEC results as a potential alternative.

The SKHASH and FOCMEC results exhibit similar strike-slip solutions for the 1996 Thomson Dam earthquake, which aligns with the northwest-southeast $S_{Hmax}$ orientation. However, Allen et al. (2000) suggests that the earthquake originated from the moderately northwest dipping, reverse slip Yallourn Fault, implying that the published focal mechanism is more suitable. Upon closer inspection, it is evident that the published focal mechanism more effectively constrains misfit polarities near the nodal planes. Consequently, our analysis favours the published solution.

*Table 3. List of earthquakes with first motion polarity data in eastern Victoria. All locations are in New South Wales. Data sourced from Leonard et al. (2002) and Geoscience Australia (2024).*

| Event ID | Location | Date | Magnitude (ML) | No. of Polarities |
|---|---|---|---|---|
| 1959 Berridale | Berridale, NSW | 18/05/1959 | 5.2 | 8 |
| 2000 Boolarra South | Boolarra South, VIC | 29/08/2000 | 5.0 | 15 |
| 2001 Boolarra South | Boolarra South, VIC | 4/07/2001 | 3.4 | 8 |
| 2000 Dumbalk | Dumbalk, VIC | 30/10/2000 | 3.2 | 17 |
| 1982 Wonnangatta | Wonnangatta, VIC | 21/11/1982 | 5.4 | 34 |
| 1977 Balliang | Balliang, VIC | 2/12/1977 | 4.2 | 30 |
| 1976 Pilot Wilderness | Pilot Wilderness, NSW | 8/09/1976 | 3.8 | 13 |
| 1981 Suggan Buggan | Suggan Buggan, NSW | 30/01/1981 | 3.7 | 16 |
| 1966 Mt Hotham | Mt Hotham, VIC | 3/05/1966 | 5.5 | 15 |
| 1996 Thomson Dam | Thomson Dam, VIC | 25/09/1996 | 5.0 | 30 |

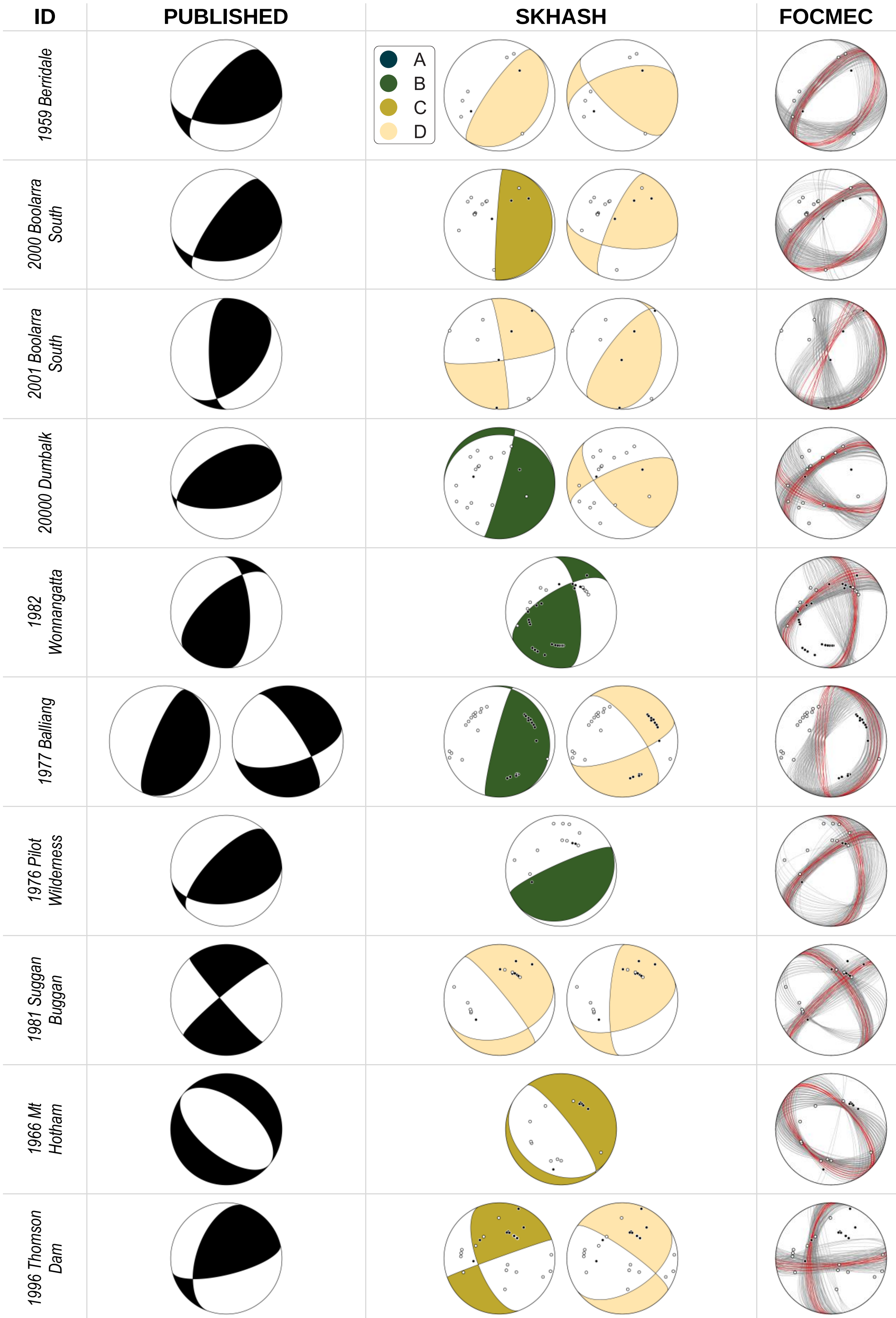


*Figure 6. Eastern Victoria published focal mechanisms with their associated event ID (see Table 3) compared to SKHASH and FOCMEC solutions. Compressional and dilatational polarities are represented by closed and open circles, respectively.*

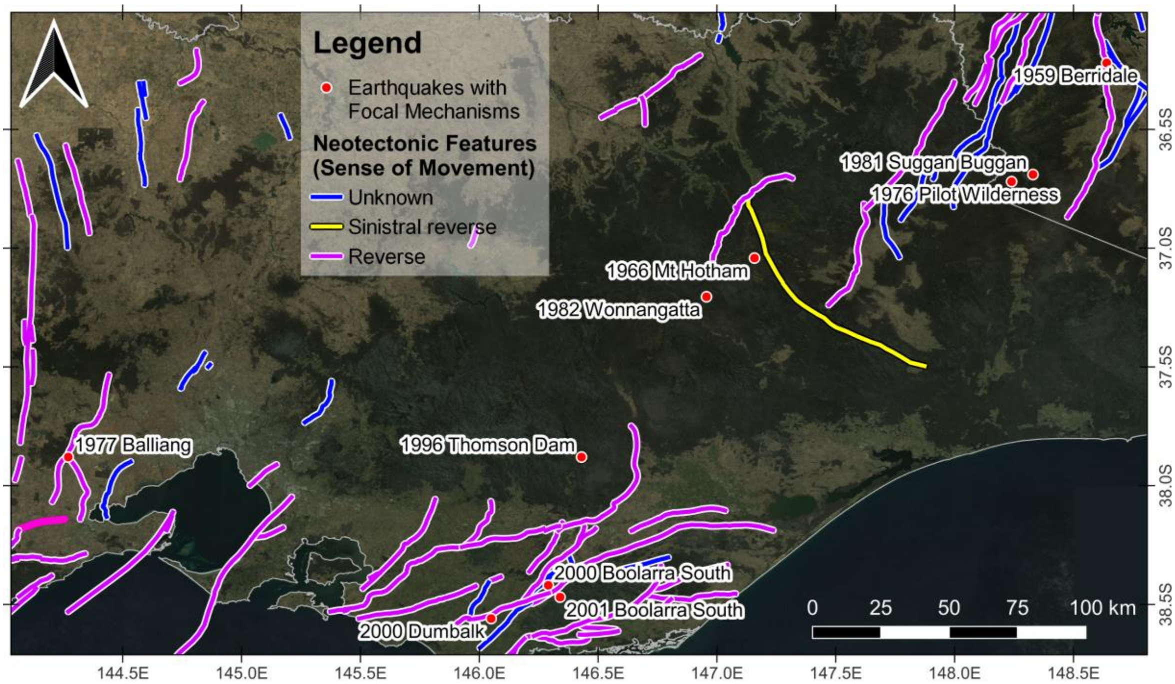


*Figure 7. Locations of analysed earthquakes with their associated event ID around eastern Victoria (see Table 3). Earthquakes locations from Leonard et al. (2002) and references within; neotectonic features from Clark & McPherson (2024).*

## 4 Discussion

The reassessment of Australian first-motion focal mechanisms using SKHASH and FOCMEC, in conjunction with known neotectonic features and $S_{Hmax}$ orientation indicators, has yielded better constrained focal mechanisms. Additionally, other nearby earthquakes with focal mechanisms helped clarify some uncertain solutions. A few events, such as the 1974 Murrumbateman and 1981 Wilpena earthquake, remain ambiguous largely due to differences in the published, SKHASH, and FOCMEC solutions.

SKHASH provides a simple overview of potential solution/s with an associated quality ranking. This enables easy interpretation and selection of the preferred solution by the user. However, as each solution is an average of a set of acceptable solutions, the nodal planes are typically fit poorly, particularly for low polarity datasets. This is exacerbated in datasets with few compressional or dilatational polarities. Additionally, most solutions have a quality ranking of D, which limits the interpretability of earthquakes with multiple acceptable solutions. Without the original waveform, or author's insight, we cannot establish emergent or uncertain polarities.

Conversely, FOCMEC is superior at constraining polarities near the nodal planes resulting in more accurate focal mechanisms. However, the number of solutions provided can overwhelm the user, particularly for low polarity datasets, hence the focus on the top 100 best fitting focal mechanisms. Together, SKHASH and FOCMEC complement each other by providing a comparison to better ascertain the best fitting solution.

## 5 Conclusion

SKHASH and FOCMEC have allowed for the re-evaluation of manually plotted focal mechanisms in a more consistent and less biased manner. This is important in regions with a sparse seismograph network, and lower earthquake magnitude and frequency such as in Australia. In these regions, polarity datasets may deliver multiple possible solutions. Some of the revised focal mechanisms have also provided better constraints on contemporary maximum horizontal stress ($S_{Hmax}$) orientations. Overall, these improved solutions confirm the $S_{Hmax}$ orientations in the Dalton-Gunning region (northwest-southeast), the Flinders Ranges (east-west), and eastern Victoria (northwest-southeast).

# 6 References


Allen, T., Gibson, G. & Hill, C. (2000). The Thomson Reservoir Triggered Earthquakes. *In:* JENSEN, V. H. & BUTLER, B. (eds.) *Dams, Fault Scarps and Earthquakes.* Hobart, Tasmania: Australian Earthquake Engineering Society.

Balfour, N. J., Cummins, P. R., Pilia, S. & Love, D. (2015). Localization of intraplate deformation through fluid-assisted faulting in the lower-crust: The Flinders Ranges, South Australia. Tectonophysics, 655**,** 97-106.

Clark, D. & Mcpherson, A. (2024). *Neotectonic Features Database* [Online]. Geoscience Australia. Available: https://neotectonics.ga.gov.au/ [Accessed].

Geoscience Australia. (2024). *Earthquakes@GA* [Online]. Available: https://earthquakes.ga.gov.au/ [Accessed 1 June 2023].

Hardebeck, J. L. & Shearer, P. M. (2002). A New Method for Determining First-Motion Focal Mechanisms. Bulletin of the Seismological Society of America, 92**,** 6, 2264-2276.

Hardebeck, J. L. & Shearer, P. M. (2003). Using S/P Amplitude Ratios to Constrain the Focal Mechanisms of Small Earthquakes. Bulletin of the Seismological Society of America, 93**,** 6, 2434-2444.

Hillis, R. R., Sandiford, M., Reynolds, S. D. & Quigley, M. C. (2008). Present-day stresses, seismicity and Neogene-to-Recent tectonics of Australia's 'passive' margins: intraplate deformation controlled by plate boundary forces. Geological Society, London, Special Publications, 306**,** 1, 71-90.

Jiang, B., Xin, Z., Zhang, X., Deng, Y., Wang, M., Li, S. & Ren, W. (2023). Mechanical properties and influence mechanism of confined concrete arches in high-stress tunnels. International Journal of Mining Science and Technology, 33**,** 7, 829-841.

Kang, H., Zhang, X., Si, L., Wu, Y. & Gao, F. (2010). In-situ stress measurements and stress distribution characteristics in underground coal mines in China. Engineering Geology, 116**,** 3, 333-345.

Leonard, M., Ripper, I. D. & Yue, L. (2002). Australian earthquake fault plane solutions. Geoscience Australia, Record 2002/19.

Mccue, K., Gregson, P. J., Sinadinovski, C. & Hodgson, L. (2001). Australian Seismological Report, 1997. Australian Geological Survey Organisation - Geoscience Australia, Record 2001/28.

Mountford, H., Love, D. & Sinadinovski, C. (1997). The Burra ML5.1 Earthquake. *In:* CUTHBERTSON, R. J., BOYCE, W., LYNAM, C., JAUME, S. & BUTLER, B. (eds.) *Earthquakes in Australian Cities - Can we ignore the risks?* University of Queensland, Brisbane: Australian Earthquake Engineering Society.

Rajabi, M., Tingay, M., Heidbach, O., Belton, D., Balfour, N. & Bendall, B. (2018). New constraints on the neotectonic stress pattern of the Flinders and Mount Lofty Ranges, South Australia. Exploration Geophysics, 49**,** 1, 125-125.

Rajabi, M., Tingay, M., Heidbach, O., Hillis, R. & Reynolds, S. (2017). The present-day stress field of Australia. Earth-Science Reviews, 168**,** 165-189.

Skoumal, R. J., Hardebeck, J. L. & Shearer, P. M. (2024). SKHASH: A Python Package for Computing Earthquake Focal Mechanisms. Seismological Research Letters, 95**,** 4, 2519-2526.

Snoke, J. A. (2003). FOCMEC: FOCal MEChanism Determinations. *In:* LEE, W. H. K., KANAMORI, H., JENNINGS, P. C. & KISSLINGER, C. (eds.) *International Geophysics.* Academic Press.

Tingay, M. R. P., Hillis, R. R., Morley, C. K., King, R. C., Swarbrick, R. E. & Damit, A. R. (2009). Present-day stress and neotectonics of Brunei: Implications for petroleum exploration and production. AAPG Bulletin, 93, 1, 75-100.

# 7 Supplementary

Table for nodal plane (strike, dip, and rake) and principal axes (P, T, and N axes azimuth and plunge) values from the SKHASH and FOCMEC results can be found at https://github.com/ewan3294/2024-AEES-Supplementary. Alternatively, please contact the author at eric.wang1@sydney.edu.au for this information.