

Surface Expression of Deformation in the South West Seismic Zone: Is There Evidence of it and Strategies for its Detection Using Satellite Geodetic Techniques

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Summary

It is currently unclear whether a surface expression of deformation is associated with earthquake activity in the South West Seismic Zone (SWSZ). In other parts of the world, geodetic monitoring of surface deformation is being used for tectonic studies. After the 1968 Meckering earthquake, the Department of Land Administration undertook a program of geodetic monitoring in the SWSZ. However, changes in funding and advances in technology have dictated that this monitoring scheme now relies upon satellite geodetic techniques. As such, there is a disparity between the time series of terrestrial- and satellite-geodetic measurements across the SWSZ. Moreover, these time series cannot reliably resolve surface motion, due to measurement errors in the different geodetic techniques. Given this, and subject to funding, it is intended to establish a permanent array of geodetic Global Positioning System (GPS) receivers to estimate any surface deformation.

1. INTRODUCTION

Intraplate earthquakes⁽¹⁴⁾ account for only a few percent of global seismic activity. However, when such events do occur they can be very large and destructive. For example, the 1811-12 earthquakes in the Mississippi Valley are the largest seismic events experienced in the conterminous USA since their records began. However, the comparatively low levels of contemporary earthquake activity, which is indicative of significantly less deformation, hinder an understanding of intraplate seismicity and the associated seismic hazard.

The geodetic measurement of strain rates in the seismically active regions at plate boundaries is now well established⁽²⁾. However, only recently have studies been published that describe the investigation of strain rates in regions of current intraplate seismicity^(7,9,11). These have used episodic surveys to monitor deformation in the New Madrid Seismic Zone (NMSZ), Mississippi Valley. Recent work in the South West Seismic Zone (SWSZ) of Western Australia suggests parallels may be drawn between these two areas⁽⁴⁾. The SWSZ extends from near Moora, south east to Albany, and is one of the most seismically active area in Australia. As such, it presents a significant earthquake hazard to the ~1.2 million population of Perth region.

Knowledge of strain rates is one important aspect in the understanding the earthquake activity in the SWSZ. However, surprisingly little is known of the magnitude and orientation of these strain rates, and how these are related to the geographical distribution of earthquake epicentres within the SWSZ. Basically, all that is presently known is that the western half of Australia is currently subject to a east-west-directed compressional stress regime. In addition, the distribution of epicentres is non-uniform and tends to concentrate in specific regions⁽⁴⁾. It is probable that an understanding of the nature and distribution of the regional deformation, and relating this to the geological structures which appear to be controlling the locations of the earthquakes, may hold the key to understanding the SWSZ.

The most effective means of determining strain rates and crustal deformation over large areas is through repeat geodetic measurements of position and/or distance. This short paper describes a *very* preliminary analysis of episodic geodetic data collected in the SWSZ by the Western Australian Department of Land Administration (DOLA). It concludes with a proposal to establish an array of permanent Global Positioning System (GPS) receivers in the SWSZ.

2. SPACE-BASED MONITORING OF TECTONIC DEFORMATION

In a deforming environment, the strain rate can be quantified using repeat measurements of position and/or distance. Historically, this was achieved using terrestrial geodetic measurements, but now relies upon space geodetic techniques, which are more precise over large regions. These techniques comprise Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and, more recently, Global Positioning System (GPS) interferometry. However, VLBI and SLR are cumbersome and expensive techniques, and are thus mainly used for global tectonic investigations. Conversely, GPS is easy to use and considerably less expensive, and has thus established itself as a more convenient technique for geodetic monitoring of contemporary crustal

deformation, both at regional and continental scales. A review of these space-based geodetic techniques is given in, for example, Bilham⁽¹⁾ and Dixon⁽⁵⁾.

However, the majority of tectonic deformation studies that use GPS have concentrated on plate boundaries⁽²⁾, and GPS has rarely been used to study intraplate deformation. This is due to a combination of the small amount of contemporary earthquake activity and the relatively small amount of associated surface deformation in these regions. An example of where GPS has been used to attempt to monitor intraplate deformation is in the NMSZ in the Mississippi Valley⁽¹¹⁾. Importantly, the geometry of the NMSZ presents a striking similarity to the geometry of the SWSZ⁽⁴⁾.

3. GEODETIC INVESTIGATIONS OF THE SWSZ

3.1 The Wellman studies

Wellman⁽¹²⁾ gave a preliminary analysis of surface deformation in Australia based on coordinate data derived from re-adjustments of geodetic measurements. From these data, he concluded that there was a surface expression of deformation in south-east and south-west Australia. However, given that common geodetic measurements had been included in the least-squares adjustments between epochs, it has been shown⁽³⁾ that the perceived motion is insignificant when the measurement errors and re-adjustments using the same data are considered. This also raises question as to the approach used⁽¹³⁾ to analyse repeat levelling and gravity in the SWSZ, especially when the height and gravity anomaly changes could be interpreted simply as levelling errors. Clearly, it is uncertain whether these geodetic determinations of surface motion are real or are simply an artefact of survey measurement errors and re-adjusted coordinates.

3.2 The DOLA geodetic surveys

Soon after the 1968 Meckering earthquake, the Western Australian Department of Lands and Surveys (now DOLA) undertook a program of episodic geodetic monitoring in the SWSZ. This included the establishment of nine horizontal geodetic monitoring cells over seismically active parts of the SWSZ. However, changes in funding and advances in geodetic technology have dictated that this monitoring now relies upon satellite geodetic techniques, usually conducted by contractors. Accordingly, there is a disparity in the quality and time series of terrestrial- and satellite-geodetic measurements⁽⁸⁾ across the SWSZ, especially when considering the small amount of motion (probably less than 5mm per annum) expected in the SWSZ.

Nevertheless, a *very* preliminary assessment of geodetically derived strain rates over the SWSZ is made based on these data⁽¹⁰⁾. The measured distances between ground monuments are compared for seven of the horizontal monitoring cells. This approach is used since these are the primary geodetic measurements that are not subject to the effects of a least-squares adjustment. The strain rates (in mm per year) have been calculated separately for the terrestrial and GPS geodetic data in order to show the disparity between these techniques. As the SWSZ is subject to east-west-directed compressional stress, the east-west component of the geodetic strain rate is used as this is expected to show the largest signal. The statistics of these east-west strain rates for each cell and for all observations in the SWSZ are summarised in Table 1.

cell	<i>Terrestrial geodetic surveys</i>					<i>GPS geodetic surveys</i>				
	#	Max	Min	Mean	Std	#	Max	Min	Mean	Std
1	6	6.8	-1.4	1.9	2.7	10	3.1	-6.6	-1.0	2.7
2	4	0.3	-0.4	-0.1	0.3	12	3.0	-3.8	0.0	1.6
3	0	-	-	-	-	16	0.0	-6.6	-2.0	2.7
4	13	4.6	-5.3	0.4	2.5	1	1.3	1.3	1.3	-
5	8	5.1	-0.1	2.3	2.1	0	-	-	-	-
6	7	5.0	-6.0	0.3	3.7	0	-	-	-	-
7	11	6.4	-2.7	0.8	2.8	1	0.0	0.0	0.0	-
all	49	6.8	-6.0	0.9	2.5	40	3.1	-6.6	0.0	2.2

Table 1. Statistics of the east-west component of strain rates (mm/yr) estimated from repeat terrestrial and GPS surveys in the SWSZ.

From Table 1, it is clear that there is:

- a large amount of variability among the estimates of strain rates in each cell;
- a small disparity between the terrestrially and GPS-derived strain rates;
- an indication of extension (ie. positive strain rates) in a compressional regime; and
- the apparent surface motions, if indeed real, are quite small (<7mm/yr).

However, the results summarised in Table 1 have neglected measurement errors. Some of the terrestrial measurements were made in the late 1960s over long baselines (usually greater than 10km) and are subject to scale errors⁽⁸⁾, whereas modern geodetic GPS surveys are more precise over long baselines⁽⁶⁾. In addition, there is an error associated with centring the instruments over the ground marks (typically a few millimetres), which combines additively over each baseline. Indeed, most of the calculated strain rates could be attributed to these centring errors alone. Therefore, it is difficult to determine whether this geodetic time-series indicates actual surface motion or is simply an artefact of errors associated with the different geodetic techniques. Of course, it is also possible that there has been no surface motion in the SWSZ over the last 30 years.

4. PROPOSED SATELLITE-GEODETIC MONITORING OF THE SWSZ

Given the small disparity in the geodetic time series and the centring error budget, it is proposed to establish a permanent array of GPS monitoring stations in the SWSZ^(1,10,11). This will mitigate instrument set-up errors and thus allow a more precise determination of any surface expression of deformation associated with the earthquake activity in the SWSZ. The survey monuments should consist of concrete pillars, fitted with forced centring apparatus, and permanently mounted on bedrock (~\$4,000 each). This infrastructure will allow for GPS (or other satellite-based) surveys to be conducted over a number of years. Ideally, a permanent GPS antenna (~\$5,000 each) will be left on each pillar to eliminate centring errors, together with a permanent dual-frequency GPS receiver (~\$35,000 each) connected to a modem. If a lack of funding prevents the use of permanent GPS receivers, at the very least the same GPS antennae should be used at each station when episodic GPS campaigns are repeated.

The geodetic network will comprise at least four fixed monitoring stations in a braced quadrilateral configuration, which covers the most seismically active part of the SWSZ.

The positions of these stations will be chosen to coincide with the areas of maximum likely deformation, based on the distribution of earthquake epicentres and the geological structures thought to be controlling these earthquakes⁽⁴⁾. The additional use of permanent GPS tracking stations at Gngangara and Yaragadee will allow the SWSZ GPS network to be oriented with respect to a global reference frame and thus estimate any absolute, as well as relative, motions. It is estimated that such long-term monitoring of the motion of these stations will enable a more reliable determination of the strain rates and associated crustal deformation in the SWSZ.

REFERENCES

1. Bilham, R. (1991). "Earthquakes and Sea Level: Space and Terrestrial Metrology on a Changing Planet" *Reviews of Geophysics*, Vol 29, No 1, pp 1-19.
2. Billiris, H., Paradissis, D., Veis, G., England, P., Featherstone, W., Parsons, B., Cross, P., Rands, P., Rayson, M., Sellers, P., Ashkenazi, V., Davison, M., Jackson, J. and Ambraseys, N. (1991). "Geodetic Determination of Tectonic Deformation in Central Greece from 1900 to 1988" *Nature*, Vol. 350, pp 124-129.
3. Coleman, R. and Lambeck, K. (1983). "Crustal Motion in South Eastern Australia: Is There Evidence for it?" *Aust J. Geod. Photogram. & Surv.*, No 39, pp 1-26.
4. Dentith, M.C., Featherstone, W.E., Hickey, R.W. and Portle, K. (1998). "Towards an Understanding of the Controls on Seismicity in the South West of Western Australia" this volume.
5. Dixon, T.H. (1991). "An Introduction to the Global Positioning System and Some Geological Applications" *Reviews of Geophysics*, Vol 29, No 2, pp 249-276.
6. Larson, K.M. and Agnew, D.C. (1991). "Application of the Global Positioning System to Crustal Deformation Measurement 1: Precision and Accuracy" *J. Geophys. Res.*, Vol 96, No B5, pp 16547-16565.
7. Liu, L., Zobak, M.D. and Segall, P. (1992). "Rapid Intraplate Strain Accumulation in the New Madrid Seismic Zone" *Science*, Vol 257, pp 1666-1669.
8. Savage, J.C., Lisowsky, M. and Prescott, W.H. (1996). "Observed Discrepancy Between Geodolite and GPS Distance Measurements" *J. Geophys. Res.*, Vol 101, No B11, pp 25547-25552.
9. Snay, R.A., Ni, J.F. and Neugebauer, H.C. (1994). "Geodetically Derived Strain Across the Northern New Madrid Seismic Zone" *US Geological Survey Professional Paper 1538-F*, Washington.
10. van Mierlo, J. (1979). "Statistical Analysis of Geodetic Measurements for the Investigation of Crustal Movements" *Tectonophysics*, Vol 52, pp 457-467.
11. Weber, J., Stein, S. and Engeln, J. (1998). "Estimation of Intraplate Strain Accumulation in the New Madrid Seismic Zone from Repeat GPS Surveys" *Tectonics*, Vol 17, No 2, pp 250-266.
12. Wellman, P. (1981). "Crustal Movement Determined from Repeat Surveying - Results from South Eastern and South Western Australia" *J. Geol. Soc. Aust.*, Vol 28, pp 311-321.
13. Wellman, P. (1987). "South West Seismic Zone of Western Australia: Measurement of Vertical Ground Movements by Repeat Levelling and Gravity Surveys" *BMR J. of Geol. & Geophys.*, Vol 10, pp 225-232.
14. Wdowinski, S. (1998). "A Theory of Intraplate Tectonics" *J. Geophys. Res.*, Vol 103, No B3, pp 5037-5059.