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Interseismic and coseismic motions in GPS series related to the Ms 7.3 July 13, 1994, Malekula earthquake, central New Hebrides subduction zone

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Abstract. On July 13, 1994, an earthquake $M_S = 7.3$ occurred at Malekula, in the New Hebrides archipelago. The GPS data collected across the New Hebrides trench between 1990 and 1996 were processed in order to separate the interseismic and coseismic motions from the drifts related to the convergence with the Australian plate. The GPS-derived coseismic displacements at the GPS site in Malekula are 49 ± 15 mm southward, 230 ± 30 mm westward and 170 ± 37 mm downward, when the CMT-derived displacements are 50 mm southward, 210 mm westward and 150 mm downward. Taking into account the interseismic strain accumulation (25 mm/yr at the source established from historical seismicity, 7.5 mm/yr at the GPS site), the strain-free convergence rate at Malekula is 49 ± 3 mm/yr. Other GPS-derived convergence rates are 95 ± 1 mm/yr at Efate and 37 ± 2 mm/yr at Santo. These rates imply a regional right-lateral motion between the Efate and the Santo-Malekula segments. In contrast, the focal mechanism of the earthquake mostly indicates a left-lateral motion. Therefore, we hypothesize that the earthquake is related to variations in the interplate coupling along the converging boundary of the Santo-Malekula segment.

Introduction

The New-Hebrides subduction zone is part of the tectonic system which accommodates the convergence between the Australian and Pacific plates (Figure 1). Along this trench, the Australian plate subducts eastward beneath the New Hebrides archipelago which borders the North Fiji Basin. Facing the New Hebrides archipelago, the Autralian plate bears the Loyalty and New Caledonia ridges, which offers an opportunity for collecting GPS observations across a subduction zone for baselines less than 500 km long. In the present paper, we discuss the results from GPS series at Santo (SNTO), Malekula (MLKL) and Efate (EFAT), central New Hebrides (Figure 1) in relationship with the Malekula earthquake.

The GPS data

Since 1990, GPS campaigns measuring baselines crossing the New Hebrides subduction zone have been conducted between the New Caledonia - Loyalty island group and the Vanuatu (New Hebrides) islands. Successively Trimble 4000 SST (1990 and 1992), Ashtech LX II (1992 and 1993), Leica SR299 (from 1993 to early 1996) and Ashtech Z12 (since mid-1996) dual frequency receivers have been used. Nevertheless, each campaign was conducted using only one type of receiver. Night-time observations were performed in 1990 and 1992 during 8 day campaigns [*Bevis et al.*, 1995; *Taylor et al.*, 1995]. Since 1993, campaigns of 5 days of 24 hour observations have been conducted. Data were processed using version 3.4 of the Bernese GPS software [*Rothacher et al.*, 1993] and the IGS precise ephemerides distributed by CODE. Details on the observing and processing procedures can be found in *Calmant et al.* [1995]. The series are presented relative to a fixed Australian plate for which a reference net was made up of sites at Lifou and Maré Islands on the Loyalty Ridge, and sites at Nouméa and Koumac on the New

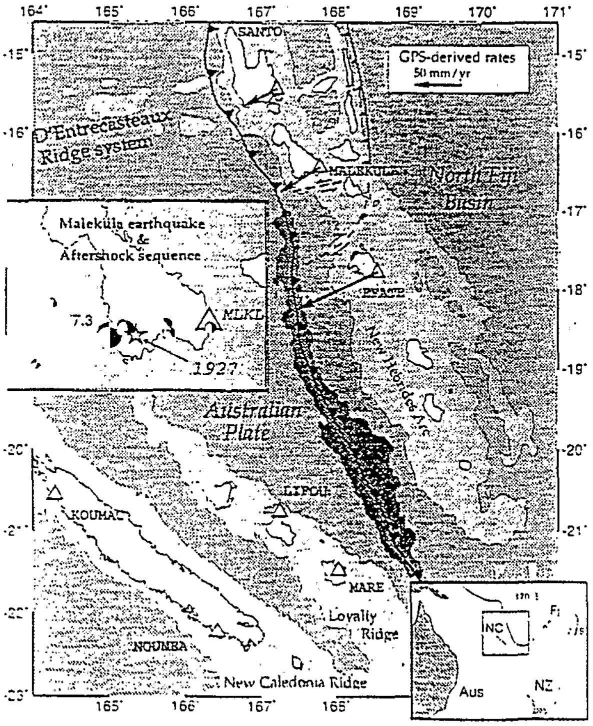

Figure 1. Situation map displaying the main bathymetric features in the study area. Open triangles represent the location of the GPS sites. Vectors represent the GPS-derived convergence rates. The westward dipping back-arc thrust zone is tentatively (dash line) prolonged southwestward as the dextral boundary between the Santo-Malekula and Efate segments.
Left inset: Focal mechanisms of the main events of the seimic sequence are given (lower hemisphere). Star indicates the location of the 1927 earthquake reported by *Isacks et al.* [1981].
Lower right inset : Regional setting of the study area. *Aus* stands for Australia, *NZ* for New Zealand, *FJ* for Fiji and *NC* for New Caledonia. Inner box outlines the area of the main map.

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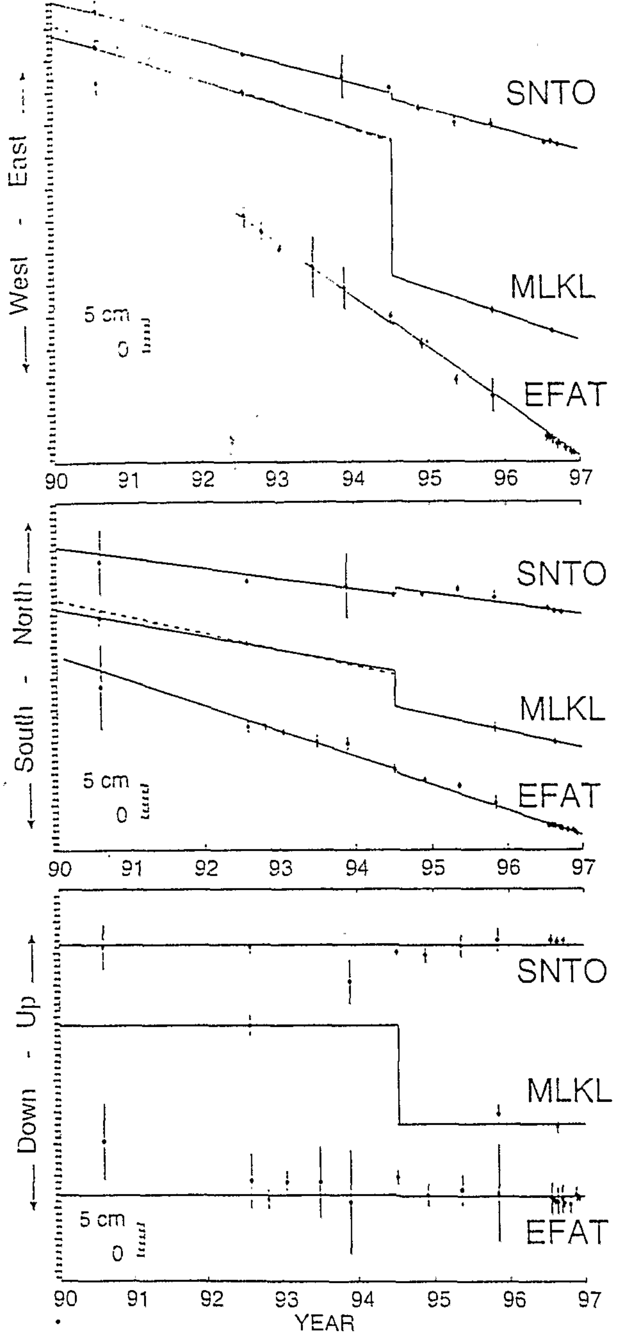

Figure 2. GPS series and best-fitting models. Bars represent projected 1σ 3D repeatability. At SNTO and EFAT, the drifts are derived with offsets set at the CMT-derived values. At MLKL, the drift is, assuming that strain accumulated at 25 mm/yr, lower by 7.5 mm/yr before the coseismic offset than it is after. The dash line stands for the modelled trajectory if the strain accumulation was not accounted for.

Caledonia Ridge (Figure 1). *Calmant et al.* [1995] and *Bevis et al.* [1995] showed that these sites form a geodetic net rigid to within the uncertainties. Therefore, drifts in the GPS series give the convergence rates relative to the Australian plate. The GPS data are presented in Figure 2 as least square weighted averages per epoch of several daily observations. Standard deviations were computed by generalized 3D repeatability of the daily solutions around the weighted averages. It is worthwhile noting that the scatter between daily solutions greatly varies from one epoch to the other. The large scatters occur at strongly perturbed meteorological conditions such as cyclones passing through during the campaigns of November-December 1993 and December 1995. Lastly, data uncertainty in Figure 2 and the uncertainties in the values of the drifts and offsets used to fit the series were also re-scaled by the reduced χ^2 factor between the time series of GPS data and the modelled trajectories.

The Malekula Earthquake

On July 13, 1994, an earthquake of M_s = 7.3 occurred at Malekula. It activated an east-west trending fault dipping northward with a mostly left-lateral strike-slip motion. It is worthwhile noting that the fault has a very small dip angle, namely 42°, unusual for a strike-slip fault. In fact, the slip very likely took place on a pre-existing structure inherited from the early history of the island [*B. Pelletier*, field notes].

We derived coseismic surface displacements based on the elastic half-space hypothesis [*Okada*, 1985 ; *Savage*, 1980]. The fault geometry (63 x 21 km) and slip (163 cm) were derived empirically using the hypocenter coordinates (167.35°E, 16.5°S, 25 km fixed depth), focal mechanism parameters and seismic moment (M_o = 6.6 10^{19}Nm) provided with the Harvard CMT solution. The ambiguity in the actually activated plane was resolved by looking at the aftershock sequence (inset in Figure 1). A limited change in the depth of the source relative to the one fixed for the CMT solution was applied since it improved noticeably the agreement between the CMT-derived displacements and the GPS-derived ones. We chose to use a depth is 18 km rather than the 25 km given by the CMT solution. The coseismic displacements modelled using this modifed CMT are displayed in Figure 3.

We also derived the evolution of the deformation at the location of the GPS sites during the time that strain was accumulating at the source (Figure 4), using the same algorithm as was used to compute the coseismic displacements but varying M_o from 0 to 6.6 10^{19} Nm (M_o of the Malekula earthquake). To illustrate this, note that the interseismsic deformation that occured at the GPS sites is related to that accumulated at the source. Furthermore, the time derivative of the interseismic deformation that occurred at the GPS sites is also related to the rate of that accumulated at the source. At the rupture point, the deformation at the sites equals the coseismic displacement when the deformation accumulated at the source equals the seismic slip. If we divide both axes in Figure 4 by a constant rate, that of the deformation at the source, the slope of the curve becomes the ratio between the current deformation rate at each site and the deformation rate at the source. At the time of rupture, this ratio is 1.3 at MLKL and almost nil at SNTO and EFAT. To determine the deformation rate at the source, we established the time period between the 1994 event and the last event which ruptured this same area from historical seismicity. The event which occurred in 1927 appears to be the most likely preceding event [*Isacks et al.*, 1981; *Louat et al.*, 1988; *Taylor et al.*, 1987, 1990]. Although the actual focal mechanism and depth of this event are unknown, it was located in roughly the same area (167.5°E, 16.5°S) as the 1994 event, and exhibited a similar magnitude (6.8-7.2, *Isacks et al.*, [1981]) and a similar seismic moment (5.6 10^{19} Nm, *Taylor et al.*, [1990]). Thus, the 163 cm released in July 1994 by seismic slip at the source might then presumably have accumulated for 67 years. Consequently, the average rate of strain accumulation would be 25 mm/yr and the deformation rate prior to the

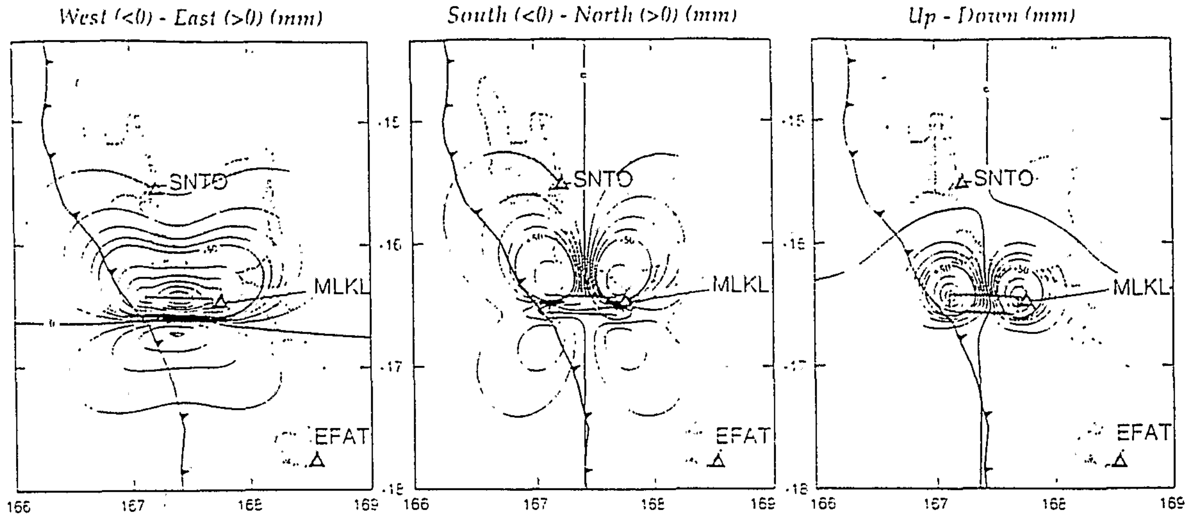

Figure 3. CMT-derived coseismic displacements relative to the July 13, 1994 Malekula event. The shaded rectangle indicates the ruptured area (projected onto the surface). Only selected isolines are given. They are, in mm: 0 (thick), ± 10, ± 20, ± 30, ± 40, ± 50 (thick), ± 100, ± 150, ± 200, ± 250, ± 300.

earthquake would then be about 7.5 mm/yr at MLKL, and negligible at SNTO and EFAT.

Discussion

The GPS series at the MLKL site was modelled by least square inversion with both an offset at the date of the Malekula earthquake, July 13, 1994, and a drift with the constraint that it was reduced by 7.5 mm/yr prior to that date because of the strain accumulation. The strain-free convergence rate so derived is 49 ± 3 mm/yr oriented N240° ± 3°. This result is consistent with the convergence rate of 41 ± 4 mm/yr published by *Taylor et al.* [1995] using the data collected in 1990 and 1992 only, i.e. while the strain was still accumulating. The corresponding offset, standing for the GPS-derived coseismic displacement, is 49 ± 15 mm southward, 230 ± 30 mm westward and 170 ± 37 mm downward. These values compare well with the CMT-derived coseismic displacements: namely 50 mm southward, 210 mm westward and 150 mm downward (Table 1).

At SNTO and EFAT, the CMT-derived estimates of the coseismic displacements are small and the rate of strain accumulation can be neglected. Results of the drift-and-offset inversions at SNTO and EFAT are reported in Table 1. The CMT-derived and GPS-derived coseismic displacements only agree at the 2σ level. Thus, a reverse procedure was applied to determine the convergence rates for these sites, i.e. the value of the coseismic offset used in the GPS inversion was set equal to the CMT-derived estimates. The corresponding convergence rates are 37 ± 2 mm/yr oriented N244° ± 1° at SNTO and 95 ± 1 mm/yr oriented N246° ± 0.5° at EFAT.

Malekula and Santo are considered a piece of inner wall uplifted by the d'Entrecasteaux Ridge (Figure 1) which underthrusts the New Hebrides margin from North Malekula to Santo [*Isacks et al.*, 1981; *Collot et al.*, 1985; *Taylor et al.*, 1987 and 1990]. From the analysis of the historical seismicity along the New Hebrides trench, *Isacks et al.* [1981] noted that the strong interplate coupling which characterizes the subduction at the Santo-Malekula segment might be weaker at South Malekula than

Table 1. Convergence rates and co-seismic offsets deduced from the GPS series and the CMT solution of the July 13, 1994 event.

			SNTO	MLKL	EFAT
GPS-derived[a]	V (mm/yr)		37 ± 2 N244° ± 2°	49 ± 3 N240° ± 3°	95 ± 1 N246° ± 0.5°
	Offset (mm)	E	*-24 ± 5*	-230 ± 30	*-26 ± 9*
		N	*9 ± 6*	-49 ± 15	*4 ± 5*
		U	*15 ± 7*	-170 ± 37	*-27 ± 6*
CMT-derived[b]	Offset (mm)	E	-10	-210	5
		N	10	-50	-5
		U	0	-150	-2

Offset values are given positive toward East (E), North (N) and Up (U).

[a] At MLKL, the convergence rate and geodetic offset were resolved jointly. The strain-free, post-event value is reported for the convergence rate. At EFAT and SNTO, the convergence rates are the result of the drift-only model with the coseismic offset fixed at the CMT-derived estimates. The geodetic offsets, in italics, were determined from drift-and- offset models and are only reported for reference.

[b] Modeled coseismic offsets using the Harvard CMT solution hypocenter, depth set at 18 km.

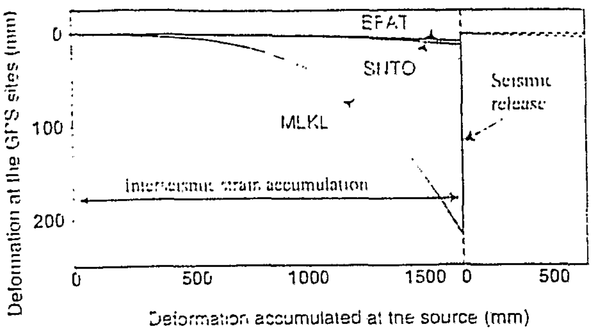

Figure 4. Deformation accumulated at the GPS sites with respect to that accumulated at the source. At the time of the seismic rupture, the slope was 0.3 at MLKL. At SNTO and EFAT, very little deformation was accumulated and the rate of deformation remained negligible, on account of remoteness from the event. After the strain was released seismically, both the deformation and rate of deformation were reset to zero. The grey area stands for the time when the GPS surveys were performed, based on a rate of strain accumulation of 25 mm/yr at the source.

elsewhere along this segment. Considering the Quaternary vertical motions at Santo and Malekula, *Taylor et al.* [1987 and 1990] also concluded a locally weaker interplate coupling at South Malekula. These pieces of evidence, taken together with the sinistral motion of the Malekula event and the larger convergence rate at Efate compared to that at Malekula (which indicates right-lateral motion between Malekula and Efate) imply that (1) the fault activated by the 1994 earthquake is not the northern boundary of the Efate segment, consequently, there exists a small block south of the fault which belongs to the Santo-Malekula segment, (2) the convergence rate of this small block with respect to the Australian plate is less than the 41 mm/yr found at Malekula prior to the 1994 event, consistent with the lower convergence rate evidenced in the northern part of the segment, i.e., 37 mm/yr at site SNTO, and (3) the Malekula earthquake occurred presumably because the interplate thrust zone along the west coast of South Malekula is less strongly locked locally than it is along the rest of the Santo-Malekula both to the north and to the south.

Conclusion

The GPS series collected between 1990 and 1996 at site MLKL, close to the epicenter of the July 13, 1994, South Malekula earthquake, clearly recorded the coseismic displacements and interseismic strain accumulation related to this event. This result emphasizes that variations of motion related to strain accumulation could be detected before the seismic release occurs. The record is less clear for the more distant sites, SNTO and EFAT. The Malekula earthquake provides evidence for differences in interplate coupling along the margin of the Santo-Malekula segment.

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