GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 19, PAGES 3627-3630, OCTOBER 1, 1998

Present-day crustal motion in the Solomon Islands from GPS observations

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Abstract. Site velocities in the Solomon Islands from Global Positioning System measurements spanning two years provide direct evidence of active deformation between the Pacific Plate and the Solomon Arc block. Convergence is occurring at the San Cristobal Trench at a rate of ~52±4 mm/yr, with no apparent local deformation occurring in the Australian Plate at a distance of ~100 km from the trench. The islands of Guadalcanal and Makira are in a first approximation moving with the Pacific Plate although there is evidence of small but significant decoupling from the Pacific Plate of 14-23 mm/yr in a direction of 75-85°.

Introduction

The Solomon Arc is a double island-arc located between the Pacific and Australian Plates (Figure 1). It has been formed in three major tectonic events: subduction of the Pacific Plate, arc-subduction reversal and subsequent subduction of the Australian Plate, and the obduction of the Ontong Java Plateau (OJP). Global Positioning System (GPS) observations made at Honiara and Kira Kira on the Solomon Arc block and at Bellona on the Australian Plate in 1995 and 1997 have been analysed using the GAMIT and GLOBK software [*King and Bock*, 1997; *Herring*, 1997]. We present the analysis of these data and compare the estimated site velocities to motions predicted by the Euler vectors of *Tregoning et al.* [1998] and No-Net-Rotation NUVEL-1A (NNR1A) [*DeMets et al.*, 1994] for the Australian and Pacific Plates. The results support the conclusion that relative motion is occurring between the Solomon Arc and the Pacific Plate.

Tectonic Setting

The Solomon Arc is a double chain of islands located between the Vitiaz trench system to the northeast and the South Solomon trench system to the south and west, encompassing the New Britain and San Cristobal Trenches (Figure 1). Southwestward subduction of the Pacific Plate and related volcanics in the Eocene-Early Miocene created the North Solomon Island Arc [*Kroenke*, 1984]. The Ontong Java Plateau (OJP) collided with the Solomon Arc, probably ~20 to 25 Ma [e.g. *Coleman and Kroenke*, 1981; *Kroenke*, 1984; *Yan and Kroenke*, 1993]. Since that time it is thought that subduction of the Pacific Plate ceased during the Early Miocene but it may have recommenced in the Mid-Miocene. About 10 Ma polarity reversal occurred and the Australian Plate began subducting to the northeast at the New Britain and San Cristobal Trenches, thus creating the southern islands of the New Georgia group, Bougainville and Buka Island [*Vedder and Bruns*, 1989]. Active shallow seismicity occurs along the full extent of the San Cristobal Trench and the small amount of deep seismicity is related to the subduction of the Australian Plate; however, there appears to be a Wadati-Benioff zone associated with the subducted Pacific slab [*Mann et al.*, 1996 and see Figure 2].

Geophysical and geological evidence points to the occurrence of active motion between the Pacific Plate and the Solomon Arc. *Auzende et al.* [1996] stated as indications of current activity northeast of Malaita that faults extend upwards to the seafloor, that absorption of continued crustal shortening can be seen in the outer wall of the North Solomon Trench and that the deformation front has moved eastward into the OJP. One of the deformation ridges northeast of Malaita is constructed of deformed sediments with the deformation evident from the deepest layer to the surface, indicating a continuous process of convergence. *Cooper et al.* [1986] showed seismic evidence of a SW dipping Wadati-Benioff zone along the North Solomon Trench, representing either a resurgence of motion, settling of the old subducted slab or the subducted Australian slab pushing against the relic slab; however, as a result of the low incidence of thrusting earthquakes, they concluded that it probably represents a previously subducted segment of the Pacific Plate rather than active subduction. Thrust and normal shallow earthquakes have occurred along and north of the Kia-Korigole-Kaipito fault system (KKK) which may be related to convergence of the Pacific Plate and the Solomon Arc (Figure 3). *Petterson et al.* [1997] showed from recent swath mapping of the ocean floor between Makira and Santa Cruz that there are numerous volcanic edifices oriented along three linear to arc-shaped chains. They claimed that the northern arc relates to subduction of the Australian Plate, the southern one relates to southward subduction of the Pacific Plate and the central one relates to rifting. In addition, present-day seismicity and faulting and deformation

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Paper number 98GL98GL52761.
0094-8534/98/98GL-52761$05.00

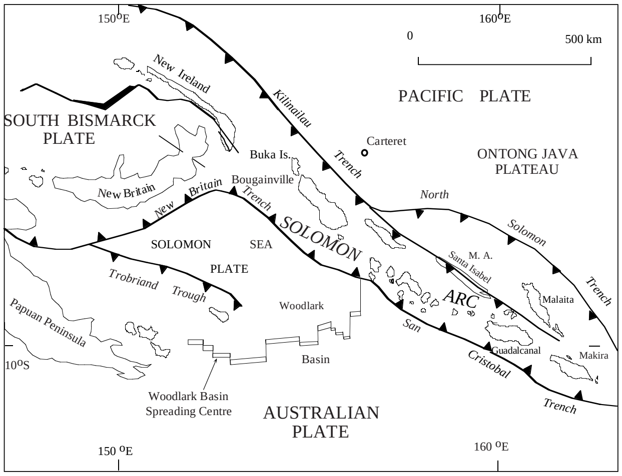

Figure 1. Map displaying the major tectonic features of the region. MA: Malaita Anticlinorium.

of sediments in the Malaita Anticlinorium (MA) indicate that convergence between the Pacific Plate and the Solomon Arc is currently occurring [*Auzende et al.*, 1996; *Petterson et al.*, 1997].

Bruns et al. [1989] claimed that active back-arc thrusting is occurring on the Kilinailau Trench as a result of closure between the Pacific Plate and the island-arc system of Bougainville and the western Solomon Islands. They showed from multichannel seismic reflection data that the trench structures are young and deformed, with both young and underlying rocks being subducted.

The motion of the Solomon Arc is thought to be similar to the motion of the Pacific Plate; however, the decoupling which the geological evidence suggests may be occurring on the northern side of the arc would result in a small amount of relative motion between it and the Pacific Plate. *Tregoning et al.* [1998] showed that the motion of Carteret (located on Kilinailau Island east of the Kilinailau Trench) (Figure 1) is not significantly different to the expected motion of the Pacific Plate. Thus, if decoupling of the Solomon Arc from the Pacific Plate is currently occurring, it must happen between Carteret and Bougainville.

GPS Data and Analysis

Three sites were observed simultaneously using Trimble 4000 SSE receivers in 1995 (days-of-year 262-264) and 1997 (days-of-year 265-268) in 24 hour sessions. The sites on the Solomon Arc are Honiara (Guadalcanal) and Kira Kira (Makira) whilst Bellona Island lies on the Australian Plate side of the San Cristobal Trench. An additional three sites on the Solomon Arc were occupied in 1997 at Gizo (Western Province), Buala (Santa Isabel) and Auki (Malaita), with the latter two sites being situated north of the KKK fault system (Figure 3). We analysed these data, nearby regional sites and up to 60 global sites from the International GPS Service (IGS) network [*Mueller and Beutler*, 1992] using the GAMIT/GLOBK software in a two step method following, for example *Feigl et al.* [1993]. In the first step we used carrier phase measurements to estimate 15 orbital parameters per satellite, three site coordinates and residual tropospheric delay parameters, phase ambiguities and earth orientation parameters. In the second step we combined in a deterministic manner the full variance-covariance matrix of all parameters of each daily solution. We estimated satellite orbital elements, earth orientation parameters and site positions and velocities in GLOBK (Table 1). Vertical velocities were estimated but will not be discussed here because of unresolved modelling problems (e.g. antenna phase centre variations).

We combined all the daily solutions and produced from the filtering process a single free network estimate of a polyhedron of GPS sites that is only loosely oriented to any terrestrial reference frame. This free network includes estimates of station coordinates and velocities. We then aligned this network with the International Terrestrial Reference Frame 94 (ITRF94) [*Boucher et al.*, 1996] by computing 7 parameter Helmert transformations on the coordinates and velocities of the 13 core IGS sites in ITRF94.

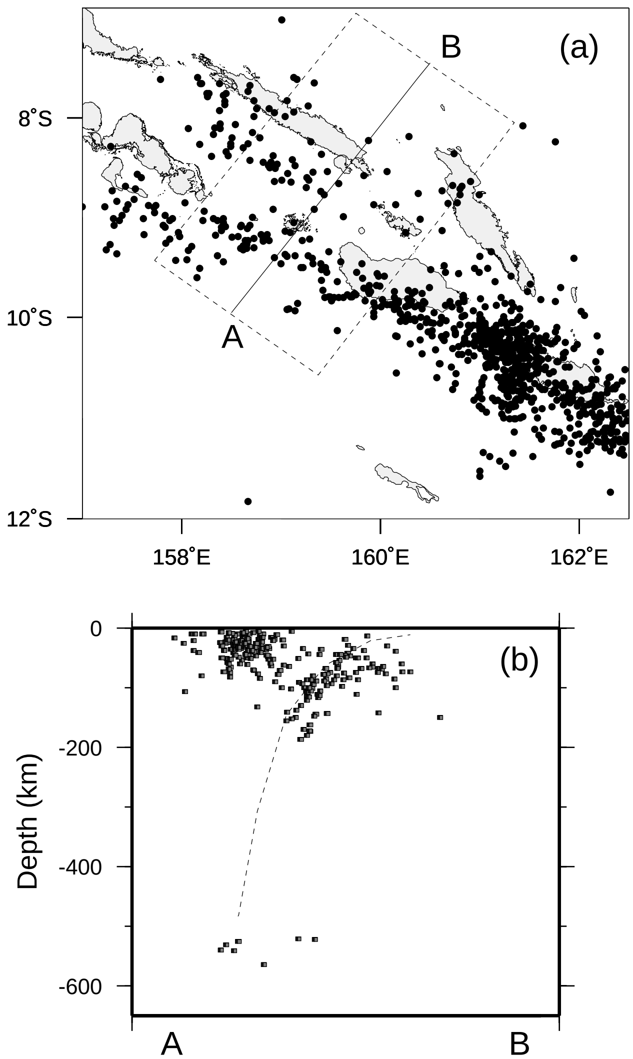

Figure 2. Seismicity of the region from 1973 to 1997 [National Earthquake Information Catalogue]; (a) 0-650 km depth; (b) Projection of earthquakes in dashed box in (a) onto line AB. The dashed line represents a possible top of the subducting Pacific Plate.

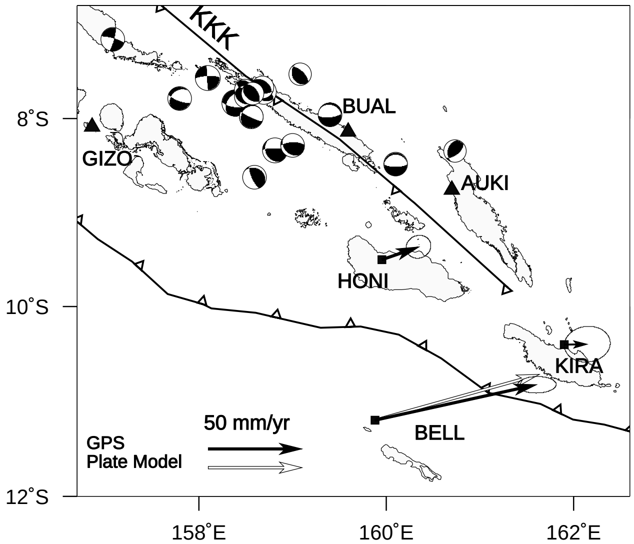

Figure 3. Predicted plate motion velocities (open arrows) and estimated GPS site velocities relative to the Pacific Plate for HONI, KIRA and BELL (black arrows) with associated 95% error ellipses. The available Harvard CMT fault plane solutions for shallow events associated with the subducted Pacific Plate are plotted. GPS sites which were first observed in 1997 are plotted as triangles. KKK: Kia-Korigole-Kaipito fault system.

We computed the mean precision of daily coordinates of each Solomon Islands site in a back-filter solution with stochastic estimation. The precisions of the velocity estimates were then approximated by the uncertainty in the slope of a linear regression through the mean coordinate estimates for each site (with the associated weighted uncertainty of a single observation) (Table 1). Figure 3 shows the ITRF94 velocities of HONI, KIRA and BELL with respect to a fixed Pacific Plate. We compared the GPS-derived velocities to predicted motions from the geologically-derived plate motion model of NNR1A [*DeMets et al.*, 1994] and from Euler vectors for the Pacific and Australian Plates estimated from GPS velocities [*Tregoning et al.*, 1998] (Table 1). There is a slight difference in the reference frames of these two models and *Tregoning et al.* [1998] showed that estimated GPS velocities agreed more closely with ITRF94 velocities than with NNR1A velocities. The predicted plate motions from these two models differ by less than 2 mm/yr in this region and we compare below with the motions of both models; however, motions predicted by the Euler vectors of *Tregoning et al.* [1998], which represent motion in the ITRF94 reference frame, provide comparisons in a consistent reference frame and we used this definition of the motion of the Pacific Plate for computing the relative velocities shown in Figure 3.

The GPS velocity estimate of the site located on the Australian Plate (BELL) is not significantly different to the predicted motion of the Australian Plate computed using either the Euler vector of the Australian Plate of *Tregoning et al.* [1998] (31.6°N, 41.3°E, 0.62°/Myr) or the NNR1A pole, at the 95% confidence level. The Australian Plate appears to behave in a rigid manner at least to within 100 km of the San Cristobal Trench. We computed the component of the relative velocities of BELL-HONI and BELL-KIRA normal to the trench axis (assuming the trench has a bearing of 125°at 159°E) and estimated a convergence of 47-56 mm/yr.

The two sites located on the Solomon Arc show significant clockwise rotations and ~20% reduction in magnitude compared to the predicted Pacific Plate motion using the Euler vector of *Tregoning et al.* [1998] (61.4°S, 105.0°E, 0.63°/Myr), indicating that there is relative motion occuring between the Solomon Arc and the rigid Pacific Plate. It appears that the islands of Guadalcanal and Makira are converging on the Pacific Plate at a rate of 13-23 mm/yr in a direction of 75-85°.

An alternate hypothesis is that there is no Solomon Block; rather that the San Cristobal Trench is partially or fully locked and that elastic deformation is occurring in the Pacific Plate to the north of the trench. In this case, the residual motion at HONI and KIRA would represent interseismic deformation of the Pacific Plate. The direction of deformation estimated by GPS velocities is in good agreement with the overall direction of convergence of the Australian and Pacific Plates, suggesting that north of the trench the relative motion is retarded by ~20 mm/yr; however, the San Cristobal Trench is seismically active along the entire length of the trench, with frequent small earthquakes occurring. This suggests that the trench is not locked, rather that subduction is actively occuring; hence, we conclude that the measured residual velocity with respect to the Pacific Plate represents active deformation between the Solomon Block and the Pacific Plate. This convergence must be accommodated on either the North Solomon Trench or the KKK fault system.

Table 1. Site Names, Site Codes, GPS Derived ITRF94 Velocities and Associated (one sigma) Uncertainties, and Predicted Velocities Using Plate Models of *Tregoning et al.* [1998] and NNR1A.

Site	Code	Latitude	Longitude	GPS Velocities				Tregoning		NNR1A	
				V_n	σ_n	V_e	σ_e	V_n	V_e	V_n	V_e
Bellona	BELL	S11°18.2′	E159°48.0′	46.6	1.8	29.6	4.2	51.9	30.2	48.3	32.5
Honiara	HONI	S9°25.7′	E160°03.2′	34.6	2.5	-38.2	2.7	27.7	-57.9	25.7	-59.5
Kira Kira	KIRA	S10°27.1′	E161°54.2′	28.6	3.9	-45.2	5.0	28.3	-57.5	26.4	-59.1

Units in mm/yr

Conclusions

Convergence is occurring across the San Cristobal Trench at 159°E at a rate of ~52±4 mm/yr in a direction of 34°. This essentially represents the motion of the Australian Plate, since the Australian Plate is moving orthogonally to the plate boundary under which it is subducting. To a first order approximation, the Solomon Islands are moving as part of the Pacific Plate; however, we have estimated significant relative motion of ~20 mm/yr between the islands of Guadalcanal and Makira with respect to the motion of the Pacific Plate. This supports the conclusion that there is convergence between a Solomon Arc block and the Pacific Plate as is indicated by the geophysical data. The current information is too limited to determine the motion of the whole Solomon Arc block but a reoccupation of the sites first observed in 1997 will provide further information on the rate of convergence which may be occurring between the Pacific Plate and the Solomon Arc, as well as possible deformation on the KKK fault system.

Acknowledgments. We are grateful to Mr. J. Vaikota (Surveyor General), Mr. S. Riumana (Ministry of Agriculture and Fisheries), Mr. G. Satu (Department of Civil Aviation Authority) and Mr H. Pike (Customs and Excise Division) of the Solomon Islands Government for their assistance in the fieldwork of this project. This work was funded by a University of South Australia Research and Development Grant and an Australian National University Research Collaboration Scheme grant. We thank J. Beavan and an anonymous reviewer for helpful review comments.

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(Received May 5, 1998; revised Aug 4, 1998;
accepted Aug 14, 1998.)