direction during periods of low field intensity. This clearly emphasizes the importance of anisotropy measurements before any interpretation of transitional directions in terms of geomagnetic field behaviour can be carried out. ☐

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Geodetic observations of very rapid convergence and back-arc extension at the Tonga arc

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THE Earth's most active zone of mantle seismicity arises from the subduction of the Pacific plate at the Tonga trench[1]. It is not known why this slab generates so many more earthquakes than other subducting slabs worldwide. Above the subduction zone the active Tofua (Tonga) volcanic arc is separated by the V-shaped Lau basin from a remnant arc, the Lau ridge, located at the eastern edge of the Australian plate[2]. The irregular and discontinuous magnetic lineations within the basin have proven difficult to interpret[3,4], and so the regional kinematic framework has been obscure. We report geodetic measurements of crustal motion within the Tonga–Lau system, which reveal the fastest crustal motions yet observed. The Lau basin is opening at a rate which increases northwards to a maximum of $\sim$160 mm yr^{-1}. No straining is observed within the northern Tonga ridge, suggesting that it comprises part of a rigid microplate. Convergence rates across the Tonga trench increase northwards to a maximum of $\sim$240 mm yr^{-1}. The extraordinary seismic activity of the subducting slab is probably related to this unusually rapid subduction.

It is widely believed that the Lau basin opened as the Tonga ridge rifted and drifted away from the Lau ridge (Fig. 1), but no consensus exists as to how the crust of the Lau basin was formed. For more than twenty years, geologists and geophysicists have debated the relative importance of localized sea-floor spreading (and microplate tectonics) versus distributed deformation within the Lau and North Fiji basins[4,5]. Recent drilling and marine geophysical surveys within the Tonga–Lau system have prompted a hybrid model in which the Lau basin began opening $\sim$6 Myr ago by diffuse Basin-and-Range style rifting, after which organized sea-floor spreading initiated in the north $\geqslant$4 Myr ago and continues to propagate southwards[3]. But Hamburger and Isacks[5] have argued that the contemporary seismicity of the Lau and North Fiji basins is quite unlike that of spreading centres at mid-ocean ridge systems, and instead implies that these interarc regions are now opening by a diffuse and shear-dominated system of deformation. It is possible that diffuse deformation and localized sea-floor spreading may now coexist within the basin[3].

The Global Positioning System[6] (GPS) was used to measure the relative geometry of a network of monuments during eight-day observation sessions that took place in July 1990 and July 1992. During each session we occupied nine stations (Fig. 1, Table 1) with dual-frequency geodetic GPS receivers for 6–8 consecutive days, except station LLAU which we occupied for 3 days in 1990 and 4 days in 1992. The GPS data were analysed using TEXGAP software[7], and the daily geodetic solutions were combined to estimate instantaneous network geometries for each field campaign. These epoch geometries were compared to estimate station velocities (Table 1, Fig. 1) in a reference frame which minimizes the motions of the three sites in the Pacific plate. Because the GPS measurement accuracies improved between 1990 and 1992, about three-quarters of the uncertainty in the velocity solutions derives from measurement errors in the 1990 campaign.

The GPS station velocities in this Pacific-fixed frame (Fig. 1, Table 1) fall into three groups. (1) The Pacific-plate sites (RARO, NIUE, WSAM) have no significant motion. There is no significant relative motion of these sites in any reference frame. (2) The Fiji–Lau sites (VITI, VANU, LLAU) are moving at $\sim$80 mm yr^{-1} (bearing $\sim$N91°E), which is very similar to the Australia–Pacific convergence rates predicted by the global plate motion model NUVEL-1A[8] (Table 2), implying little or no motion of Fiji relative to the Australian plate. We cannot resolve whether these stations lie within the rigid core of the Australian plate, or within a marginal zone of (Australian) intraplate deformation associated with the North Fiji fracture zone. (3) The velocities of the three Tongan sites (TGPU, VAVA, NTPT) increase northwards from 164 to 240 mm yr^{-1}, with azimuths $\sim$N106°E which do not differ significantly from the mean slip

TABLE 1 GPS site velocities in a Pacific-fixed reference frame

"Fixed" station	Station code	Horizontal velocity (mm yr^{-1})	"Moving" station	Station code	Horizontal velocity (mm yr^{-1})	Velocity azimuth (N°E)
Rarotonga	RARO	5 ± 12	Niuatoputapu	NTPT	240 ± 11	104 ± 1
Upolu (W. Samoa)	WSAM	1 ± 8	Vava'u	VAVA	205 ± 10	108 ± 1
Niue	NIUE	5 ± 16	Tongatapu	TGPU	164 ± 5	105 ± 2
			Vanua Levu	VANU	79 ± 15	92 ± 2
			Viti Levu	VITI	86 ± 14	94 ± 2
			Lakeba (Lau)	LLAU	78 ± 11	89 ± 2

Velocities of nine GPS stations (part of the southwest Pacific GPS network) in a reference frame which minimizes the horizontal motions of the three stations within the Pacific plate (1990–92). Uncertainies stated are standard errors. Note that there is no significant motion of the three stations (RARO, WSAM, NIUE) that lie within the Pacific plate, indicating that this reference frame can be considered Pacific-fixed.

vector azimuths associated with shallow underthrusting earthquakes near the Tongan stations[9]. The GPS site velocities in Tonga (Table 1) differ substantially in magnitude and azimuth from the Australia–Pacific convergence vectors (Table 2). No large earthquakes occurred near the Tonga trench between 1990 and 1992. Unless interseismic convergence across a subduction zone can be very unsteady, we must conclude that the velocities of the GPS sites in Tonga represent the geological subduction rate. The rates of convergence across the trench at the latitudes of Vava'u and Niuatoputapu represent the highest secular plate velocities ever observed. Given the very low seismic coupling of this region[10] (that is, very low ratios of seismic to tectonic slip) it is likely that most if not all of the convergence observed using GPS was achieved by aseismic creep.

The subduction rates in Tonga result from a combination of Australian–Pacific plate convergence and the opening of the Lau basin (Australia–Tonga divergence). We can isolate this second component by using NUVEL-1A to switch to an Australia-fixed frame of reference. (At each station, one subtracts the motion of Australia relative to the Pacific according to NUVEL-1A from the GPS velocities already described). In this Australia-fixed frame (Fig. 2) the stations in Fiji and northern Lau have little or no significant motion, and the velocities of the Tongan stations (Table 3) characterize the motion of the Tonga ridge relative to the Lau ridge due to extension within the intervening Lau basin. These velocities increase northwards from 91 to 159 mm yr^{-1}. It has been proposed that the central Lau basin has converted from diffuse rifting to sea-floor spreading at the Eastern Lau and Central Lau spreading centres (Fig. 2), but the suggested rates of spreading[3,11,12] in this area (55–99 mm yr^{-1}) fall well short of the GPS velocities (91–130 mm yr^{-1}). This suggests that either (1) spreading rates have substantially increased in the recent geological past and this change cannot be resolved in existing magnetic data, (2) the magnetic lineations have been misinterpreted, or (3) diffuse Basin-and-Range style deformation contributes significantly to the net basin extension rate, and localized sea-floor spreading supplements rather than replaces this older mode of extension. The last interpretation is supported by diffuse shallow seismicity within the Lau basin, including several events with focal mechanisms indicative of shear faulting[5].

Despite the evidence for diffuse deformation within the Lau basin, our GPS results indicate no significant longitudinal extension of the arc between stations TGPU and NTPT. We suggest that the Tonga ridge (north of TGPU and probably north of 24° S) is behaving like a rigid windscreen wiper as it rotates to accommodate widening of the Lau basin.

The intense mantle seismicity beneath Tonga–Lau[13,14] may arise because this area has the highest subduction and back-arc extension rates on Earth. Rapid subduction could enhance

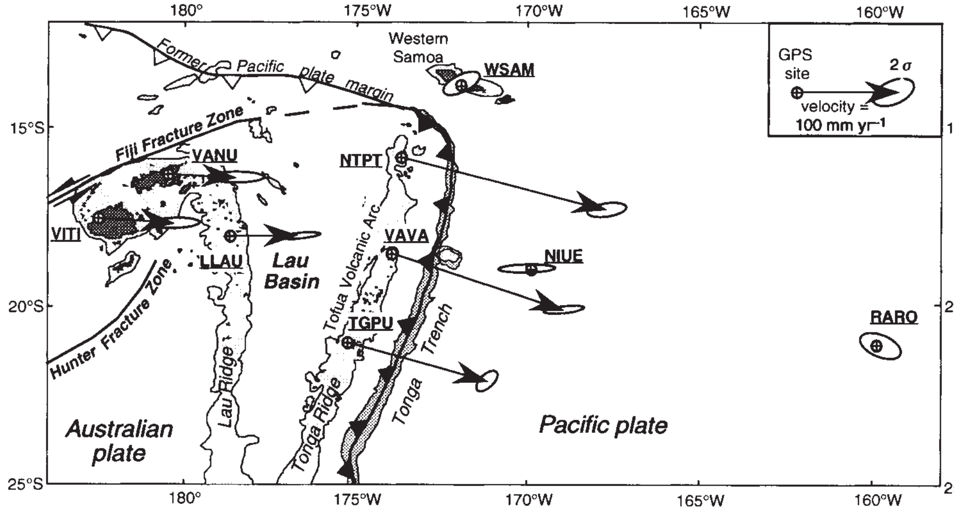

FIG. 1 Crustal velocities in a Pacific-fixed reference frame derived from GPS measurements made in July 1990 and July 1992 at nine geodetic stations within the Tonga–Lau system. The velocity vectors are indicated by arrows; a 100 mm yr^{-1} vector is shown in the inset (top-right corner). The Tonga and Lau ridges are represented using the 1,500-m isobath, and the Tonga trench using the 6,000-m isobath. The Pacific plate subducts westward at the Tonga trench and sinks into the mantle beneath the Tonga ridge and the V-shaped Lau basin. The active Tofua volcanic arc lies at the western edge of the Tonga ridge between about 18° and 22° S. The Lau ridge is a remnant arc that lies at the eastern edge of the Australian plate. North of this ridge the relative motion of the Pacific and Australian plates is accommodated mainly along the seismically active Fiji fracture zone. The Hunter fracture zone between about 174° and 178° E appears to be seismically inactive, suggesting that the Fiji platform, which includes stations VITI and VANU, is stationary or moves very slowly relative to the Australian plate. The GPS velocities (Table 1) are presented in a frame of reference which minimizes motions of the three stations (RARO, WSAM, NIUE) located within the Pacific plate. The uncertainty in each velocity vector is represented by a 2σ (~86% confidence) error ellipse. The aspect ratio and orientation of these ellipses mainly reflects the fact that GPS satellite orbital errors are larger across-track than along-track. The velocities of the Tongan stations, which range from 164 ± 5 mm yr^{-1} at Tongatapu (TGPU) to 240 ± 11 mm yr^{-1} at Niuatoputapu (NTPT), manifest the rate at which the Pacific plate is subducting.

TABLE 2 Australia–Pacific convergence rates according to NUVEL-1A

Station code	Horizontal velocity (mm yr^{-1})	Velocity azimuth (N°E)
NTPT	84 ± 1	93 ± 1
VAVA	79 ± 1	93 ± 1
TGPU	75 ± 1	92 ± 1
VANU	83 ± 1	88 ± 1
VITI	81 ± 1	87 ± 1
LLAU	80 ± 1	90 ± 1

Velocity of the Australian plate in a Pacific-fixed reference frame, predicted by the model NUVEL-1A, as evaluated at the GPS stations in Fiji and Tonga. Uncertainties stated are standard errors.

TABLE 3 Velocities of the Tongan GPS stations in an Australia-fixed reference frame

Station code	Horizontal velocity (mm yr^{-1})	Velocity azimuth (N°E)
NTPT	159 ± 10	110 ± 2
VAVA	130 ± 10	117 ± 3
TGPU	91 ± 05	115 ± 4

These velocities are obtained by subtracting Australian–Pacific plate convergence rates predicted by the global plate model NUVEL-1A from the Pacific-fixed GPS velocities (Table 1). Uncertainties stated are standard errors.

seismicity in several (possibly interrelated) ways. The Pacific plate entering the Tonga subduction zone is 100–140 Myr old, and therefore relatively cool, and as the plate is sinking into the mantle unusually rapidly it follows that it will be cooler, at a given depth, than other slabs worldwide, and therefore better able to store the elastic energy that is released in earthquakes[15]. The rate of seismic energy release depends on strain rate as well as seismogenic volume and temperature[16]. The migration and change in shape of the Tonga trench may account for the contorted nature of the subducting slab[17,14]. Rapid changes in the curvature of a subducting slab imply high rates of bending[18] (or unbending[19]) and membrane[20] strain. Rapid subduction towards a barrier (near 680 km depth) that resists or prevents slab penetration[21] might also lead to higher-than-normal strain rates and seismic activity. If mantle earthquakes are caused by transformational faulting[22], rapid subduction might enhance mantle seismicity by way of the high volumetric flux of material undergoing transformation.

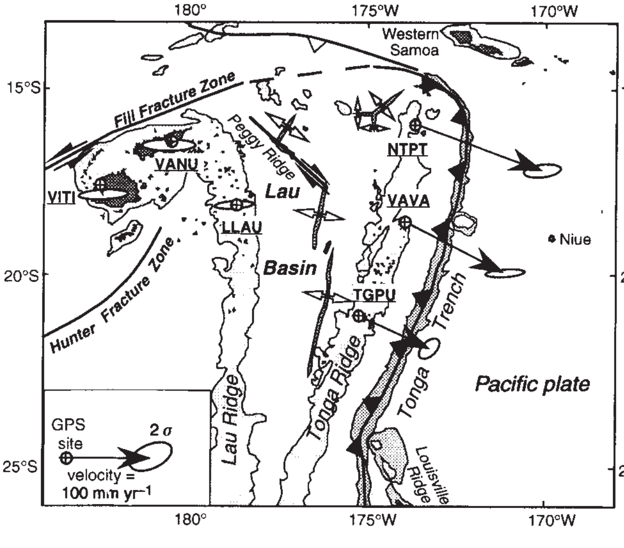

FIG. 2 Crustal velocities in an Australian-fixed reference frame realized by combining the GPS results and the Australian-Pacific plate motion predicted by model NUVEL-1A (see also Table 3). Also shown[3] are the Eastern Lau spreading centre (west of station TGPU), the Central Lau spreading centre (between stations VAVA and LLAU), the Northwest Lau spreading centre (northeast of and adjacent to the Peggy ridge) and the Mangatolu triple junction (just west of station NTPT). The V-shaped Lau basin terminates just south of 24° S, near where the Louisville ridge intersects the Tonga trench. In this Australia-fixed frame the stations VITI, VANU and LLAU have little or no significant motion, while the velocities of the Tongan stations increase northwards from 91 ± 4 mm yr^{-1} at TGPU to 159 ± 10 mm yr^{-1} at NTPT. The Tonga ridge is rotating clockwise at ~7° Myr^{-1} about a pole located close to the southern termination of the Lau basin, in order to accommodate widening of the basin achieved by localized sea-floor spreading and/or diffuse extension.

The rates of crustal motion revealed by GPS in the Tonga–Lau system are so high that it is natural to question the credibility of results derived from just two GPS field campaigns. We offer the following reassurances. (1) The formal errors associated with each GPS campaign solution are based on repeatability, but analyses of the 1990 and 1992 observations included external comparisons with very-long-baseline interferometry and satellite laser ranging measurements (made outside the southwest Pacific), and these comparisons indicate horizontal accuracies comparable to the formal error estimates[7]. (2) Some GPS site velocities can be tested against previous expectations. Most significantly, the GPS results indicate no significant relative motion of the three stations located within the Pacific plate, as one would expect. In no way is this null result built into the solution. Additionally, our solutions indicate little or no motion of the Fiji platform relative to Australia, as expected[23]. (3) Four of the stations (RARO, WSAM, TGPU and VAVA) were observed in a small GPS campaign mounted in July 1988, and for this subset of stations it is possible to assess the consistency of the 1988 measurements with those made in 1990 and 1992. Although the experimental uncertainties in 1988 were much larger than those in 1990 and 1992, so that the 1988 measurements are now of marginal utility, they are statistically consistent with the trends established by the 1990 and 1992 observations. ☐

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