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A comparison of GPS solutions for strain and SKS fast directions: implications for modes of shear in the mantle of a plate boundary zone

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Abstract

The strain rate and vertical velocity fields for New Zealand are computed using GPS data from GEONET (NZ) collected during the past decade. Two domains for shear in the mantle are inferred by comparing the principal shortening direction with the fast direction of shear wave splitting. Beneath the central-southern part of the South Island the strains are low and it's unclear if irrotational strain is taking place or if the splitting here is dominated by anisotropy in the asthenosphere. In contrast, data for the central and northern South Island suggest simple shear is dominant and distributed over a zone 200 km wide. An analysis of the major strike-slip faults confirms that the strike of the major South Island fault systems makes a 60 ± 15 degree angle with the shortening direction. A map of the vertical component of GEONET GPS velocities shows regions of surface uplift $> 5\text{mm/y}$

in both the central South and North Islands. While the pattern of uplift in central South Island is consistent with known geology, the rate of uplift in the central North Island is an order of magnitude higher than the geological rate estimated on a my time scale.

1 Introduction

How and where strain is accommodated in the continental mantle lithosphere remains unclear. In particular, how is strain distributed in the mantle beneath transform faults? And if is distributed, how does the crust and mantle deform together [1]? Central New Zealand is a favourable locality to examine these questions as it straddles the plate boundary between the Pacific and Australian plates, and the boundary is characterized by a ~ 200 km-wide zone of seismicity, faulting and shear wave splitting [2,3,4].

In the past two decades shear wave splitting has become an important, albeit controversial, tool to examine deformation in the lithosphere and asthenosphere [5,6,7]. There is debate about the role of fluid-filled cracks versus aligned minerals as the cause of anisotropy in the crust, but within the mantle lattice preferred orientation (LPO) is a widely accepted cause of anisotropy[8,9]. One aspect that can be difficult to resolve is the relative role of flow in the asthenosphere versus strain in the overlying lithosphere in SKS splitting[4]. Shear wave splitting is manifest in two ways: the amplitude of the difference in shear waves travelling through the earth (dt) with different polarisations

18 (transverse and radial components), and the azimuth of the ray paths that give
19 the largest split, which is interpreted as the direction of the mantle extension.
20 This azimuth is called the fast direction. Interpretation of mantle anisotropy
21 is complex but dt can be related to the thickness of the mantle layer that is
22 deformed and the intrinsic anisotropy of minerals that make up mantle rocks.
23 Traditionally, the interpretation of the extension (fast) direction was that it
24 was parallel or sub parallel to the direction of shear in the lithosphere or flow
25 in the asthenosphere [6]. In practice the fast direction can be influenced by a
26 range of factors including the magnitude of finite strain, the shear strain rate
27 and the amount and pressure of water [10].

28 In New Zealand analysis of SKS splitting has stimulated interpretations in
29 terms of both asthenospheric flow and shear in the lithospheric mantle[11,3,12].
30 Pn anisotropy, which samples only the top of the mantle lid, is also observed
31 and is consistent with the SKS splitting results if most of the anisotropy
32 is confined to a lid of mantle lithosphere some 150 km thick that is being
33 sheared [13,14]. However, the consistency of SKS splitting amplitudes and
34 fast directions throughout New Zealand hints at the possibility that some of
35 the anisotropy may be created in the asthenosphere rather than all being due
36 to shearing of the mantle lid [15].

37 Because New Zealand is a continental region surrounded by oceans the plate
38 tectonic history is well known and the total amount of offset on its major faults
39 can be estimated [16]. There is, therefore, an opportunity to calibrate total

offset due to shear with the width of the sheared region and with the direction and amplitude of shear wave splitting. Previous attempts to understand strain in the mantle beneath the South Island have examined the relationship of the orientation of the fast S-wave polarization from SKS splitting to the direction of the major crustal faults, assuming that the strike of the faults is a proxy for direction of shear strain in the mantle [3,14,4]. Here we take a different approach by considering the maximal strain rate component ($\dot{\epsilon}_1$) direction, from GPS data, as a proxy for the direction of shear strain in the mantle. An underlying assumption is that a sample of 10 y of GPS data provides strain and strain rates that are also applicable to the My time scale.

In New Zealand, shear-wave splitting results show a consistent pattern of splitting amplitudes and directions[17,4]. In addition, a continuous GPS network has been set up (GEONET) which has now given a decade of data from which reliable strain rate components can be mapped on a continent-wide scale [18]. In this paper, we use a new epoch of data (1999-2009) from the GEONET GPS array to examine both horizontal and vertical motion rates. Uncertainties for the vertical velocities are $\pm 50\%$ and we only present a map (fig.2) with minimal discussion. Horizontal velocities (fig. 3) are better resolved ($\pm 5\%$), and we map the relationship of principal geodetic compression axis to SKS splitting directions.

60 2 Datasets

61 With an average spacing larger than 40 km, the GEONET (NZ) network is
62 similar in design to other GPS networks such as Plate Boundary Observatory
63 (PBO)[19,20], PANGA[21], BARD [22,23,24] or EUropean REference Frame
64 (EUREF, [25]) networks. GEONET and the other networks listed above are
65 designed to describe continental scale deformation but cannot describe the
66 sharp velocity gradients related to shallow fault systems or upper crust defor-
67 mation.

68 We processed the 30 s sampling rate data collected by GEONET using the
69 GPS processing package GAMIT 10.4 [26]. The daily solutions were combined
70 with GPS solutions for North America spanning a longer period (1994-2009)
71 [24]. Solutions computed for New Zealand include sites already processed in the
72 International Terrestrial Reference Frame 2000 (ITRF2000) [27]) by including
73 5 IGS sites: AUCK, DUND, GOLD and YSSK and GUAM. The network so-
74 lutions are then referenced in the ITRF without increasing the computational
75 time. This approach, already used for networks far (>500 km) from long-
76 established GPS permanent sites [28], allowed the solutions to be anchored
77 in the global network. The adjustment of daily solutions has been completed
78 with the package GLOBK/GLORG [26]. All the ITRF velocities are displayed
79 in Table 1. For convenience, we plot the velocity field with respect to the site
80 New Plymouth (NPLY) on Figure 1.

81 The geodetic (ground-based geodetic surveys) dataset has been collected from
82 1875 to 1970s using optical instrumentation [29,2]. This dataset was used to
83 provide shear strain values and orientations of the compression axis. By using
84 uncertainties of shear strain rate components (γ_1 and γ_2), we estimate that the
85 shear strain rate (γ) uncertainties for the geodetic dataset are high (50%(or
86 10^{-7} strain) or more). The uncertainties for the orientations of the strain rate,
87 however, are more accurate (usually uncertainties on angles are less than 10
88 degrees [2]).

89 We compute (Figure 3) the strain rate components (compressional, rotational
90 and shear) for the GPS velocity field using the SSPX package [30]. The strain
91 rate maps have been inverted on a grid using a nearest-neighbor interpola-
92 tion (6 neighbors, maximal distance 200km and a grid size of 50 km). The
93 insignificant strain values (where the strain rates computed are smaller than
94 their uncertainty) have been computed following this same method [31]. As
95 the site GUNR had only been installed for 9 months at the time of the analy-
96 sis, it was removed from all the strain rate computations. All the components
97 of strain rate are computed and plotted on Figure 4.

98 The amplitudes of the geodetic shear strain rates reported by [2] based on a
99 time line of 100 yrs are larger (2 to 4 $10^{-7}/yr$) than that for the GPS data
100 that span 10 years. Although the uncertainties on the geodetic measurements
101 are large (50% or more for strain rate amplitudes), we explain the high shear
102 strain rates from the 100 yr span geodetic network by the fact that strain rate

might be distributed along shorter baselines. i.e. 2-10 km base lines rather than 40 km baselines for the GPS data. The survey would then be able to better localize strain rate than a GPS permanent network. A similar effect has been discussed in northern California where gradients of velocities larger than expected could be interpreted in terms of larger local values of shear strain rates[24].

We compare this dataset of surface velocities with the shear wave splitting collected over the past 15 years in New Zealand. Data on SKS splitting shows a consistent pattern of roughly trench parallel fast directions over most of the country [32,11,33,34,35,36,4].

3 Analysis

3.1 GPS vs Geodetic

The GPS data solutions show that across the central South Island, at least 20 mm/yr of differential lateral motion (N225) must be accommodated. If such a strain were accommodated across the whole width (160 km) of the island, the maximum shear strain rate value would be $1.25 \cdot 10^{-7} yr^{-1}$. This is a similar shear strain rate to that proposed by [37] in the Marlborough area or by [38] for the whole of New Zealand. However, the strain rate values proposed by [2] range from 3.1 to $6.8 \cdot 10^{-7} yr^{-1}$. Therefore, if we honour both Walcott's finding

122 and the GPS data, then most of the strain is accommodated across a zone
123 some 30 to 70 km wide. This width for distributed strain is consistent with
124 that predicted by a model based on GPS data in the central South Island [12]
125 geological observations [39] and previous analyses of campaign GPS data [40].

126 3.2 *GPS solution for Vertical motion*

127 A solution for vertical GPS displacements over the past 10 years (fig. 2) shows
128 broad scale vertical movements of New Zealand. These GEONET data are
129 supplemented by a line of GPS receivers across the mid South Island that were
130 put in for the purpose of measuring the rate of vertical surface uplift across the
131 Alpine Fault [41,42]. Smoothing is done by bi-cubic interpolation [43] with a
132 point every ~ 0.5 degree so wavelengths less than 100 km will not be faithfully
133 displayed (Figure 2). We reference the absolute level of this surface uplift map
134 by adopting a finding from recent micro-paleontological studies in the northern
135 Marlborough Sounds that show a 0.8 ± 0.25 mm/y rate of subsidence in the
136 past 4 kyr [44]. We adjusted all stations to honour this data point as it's based
137 on a short time interval and it's from a part of the coast where it's obvious
138 since the earliest geological studies that present day subsidence is occurring
139 [45]. Rates of surface vertical movement of up to 5-8 mm/y are predicted for
140 the Central Volcanic Region of the North Island and the central Southern Alps.
141 The latter Southern Alps observation correlates well with the isostatic vertical
142 strain rate field we can compute from horizontal strain rate components and

143 (Figure 4). A caveat on this map is that the errors are $\pm 2\text{mm/y}$, meaning
 144 that much of the signal does not rise above the uncertainty. Furthermore, the
 145 spacing of stations is such that many areas of the country, or processes, are
 146 aliased and not reliably sampled. For example, the narrow ($\sim 50\text{ km}$) axial
 147 ranges of the North Island are not sampled and rates of uplift here are $\sim$
 148 1-3 mm/y [46]. Nevertheless, the results are broadly consistent with what is
 149 known from other local geological observations. For example, the central North
 150 Island shows a broad uplift rate of about 5 mm/y, based largely on stations
 151 Tauranga and Taupo which show values of 3.7 and 6.8 mm/y respectively
 152 (Figure 3). The uplift pattern of the central North Island is consistent with
 153 the longer (5 My) term rock uplift pattern from mudstone porosity data and
 154 based on samples points just outside the CVR [47]. However, the short-term
 155 rate from vertical GPS is about 10 times greater than the long-term, geological
 156 uplift rate. This difference could be explained by the different space and time
 157 sampling frequency, or the present day uplift could be a temporary phenomena
 158 similar to one of the uplift events observed at Yellowstone caldera in the
 159 past 100 yrs [48]. If the latter, then the vertical uplift velocities for this part
 160 of the country should be closely monitored. Positive uplift rates down the
 161 south-western coast of North Island are consistent with offshore islands just
 162 north of Wellington with wave-cut platforms now at 40 m above sea level [49]
 163 and recent uplift in the Wellington city region [50]. In the South Island the
 164 most extensive area of uplift is the Southern Alps with the rapidly uplifting
 165 Kaikoura Mountains [51] not showing up on this map because there are no

GPS stations near by. Surface uplift on and east of the Alpine fault is shown clearly as this anomaly is well defined by the focussed data from a profile of 14 GPS stations across the Alps [42]. Note that the area of uplift is shown to extend across the western side of the Alpine Fault. This is likely to be an artefact of the smoothing used to present the sparsely and unevenly distributed data.

We compare the observed uplift map with the uplift computed from the combination of the vertical strain rate map assuming that the crust is incompressible (Figure 5):

$$\dot{\epsilon}_3 = -(\dot{\epsilon}_2 + \dot{\epsilon}_1) \quad (1)$$

Assuming the sum of the uplift rate V and motion of the root V_r are related to the compression of New Zealand crust, we compute the motion of the base of the crust of constant thickness $D = 40km$ (Figure 5).

$$(V - V_r) = \dot{\epsilon}_3 D \quad (2)$$

We compute the uplift rate (V_{up}) expected if New Zealand crust is close to the isostatic equilibrium. We assume the crust is of constant thickness D and the ratio $\frac{(\rho_m - \rho_c)}{\rho_m} = 1/6.6$, where ρ_m and ρ_c are respectively the mantle and crustal densities):

$$V_{up} = \dot{\epsilon}_3 D \frac{(\rho_m - \rho_c)}{\rho_m} \quad (3)$$

185 We show the distribution of V_{up} on Figure 5. We conclude that except in the
186 area of the Alpine fault and in the Central Volcanic region of North Island,
187 the crust is close to the isostatic equilibrium (Figure 5).

188 3.3 *Vertical motion and mantle dynamics*

189 Although the central North and South islands have similar uplift rates over
190 similar areas (Figure 2), the processes responsible for uplift are distinctly dif-
191 ferent. In the central South Island crustal thickening has occurred for at least
192 7 My [2,52] and it's of the order of 60% compared to that at the coasts [13].
193 Uplift here can be explained by simple crustal thickening, although uniform
194 thickening of the mantle beneath the Southern Alps [53] has probably served
195 to slow the surface uplift. In stark contrast the central North Island has been
196 subjected to extension and crustal thinning for the past 5 My [54,55]. Seismo-
197 logical evidence [56,57] shows anomalous slow seismic wave-speeds and high
198 attenuation in the upper mantle of the central North Island. Heat output via
199 the active geothermal systems is at a rate about 12 times greater than normal
200 for continental regions [58,59]. Thus while uplift of the central South Island
201 is largely mechanical, uplift of central North island is seen to be more of a
202 thermal process linked to both back-arc spreading, loss of mantle lithosphere
203 and enhanced buoyancy of the asthenosphere [47].

205 For the case of simple shear, deformation in the mantle is a function of the
 206 angle θ that is the angle between the SKS fast direction and the direction of
 207 shear [3]. In previous studies in the South Island the strike azimuth of the
 208 Alpine Fault has been taken as the shear direction in the mantle. Here we re-
 209 define θ to be the angle between the perpendicular of the compression axis as
 210 defined by the GPS solutions and the fast direction for SKS splitting (Figure
 211 6). On this basis there are 3 distinct zones of different θ within New Zealand
 212 (Figure 8). Zone 1 in central and northern North Island shows little organi-
 213 sation because here SKS splitting and mantle flow is influenced by magmatic
 214 processes linked to complexities of back-arc spreading [17]. In the southern
 215 and central South Island there is a zone 3 where $\theta \sim 3 \pm 11$ degree and which
 216 is characterised by low strain values. Finally, there is the central zone 2 from
 217 mid south Island to the south of the North Island where θ increases on average
 218 up to 28 ± 9 degrees (with a highest value close to 50 degrees) (Figure 10).

219 As [7] did for California, we argue that the similarity directions of the GPS
 220 derived axes of compression and extension through the mantle and indicate a
 221 close coupling between strain in the mantle and in the crust. This inference is
 222 largely based on the observation that the GPS strain directions vary smoothly
 223 over 100 km or more. A similar conclusion about a coupling between crust and
 224 mantle, for at least the Marlborough faults region, was reached on the basis

225 of GPS and fault slip data[60]. Thus, instead of taking the strike directions
 226 of major faults as being indicative of the shear direction in the mantle, we
 227 propose that the GPS axis of extension is a better proxy for the orientation of
 228 mantle shear. Moreover, we assume that the present-day direction pertains to
 229 the past 5 my or so when at least half the strike-slip motion and shortening
 230 occurred [12]. At this stage we consider just two end-member models for strain
 231 in the mantle; simple shear and pure shear. Each mode carries with it impli-
 232 cations for the relationship between strain direction and the fast direction of
 233 SKS splitting (Figure 8). For pure shear the direction of principal extension
 234 does not rotate with increasing finite strain and is expected to define the fast
 235 axis polarization direction for SKS splitting. In contrast, for simple shear the
 236 relationship between the angle of the principal extension direction (θ), the
 237 total displacement (d) and the width of the deforming zone (w) is given by
 238 [3]:

$$239 \quad \tan(2\theta) = 2w/d \quad (4)$$

240 The 28 ± 9 degree angle between the SKS fast direction and the GPS axis of
 241 extension in zone 2 implies a finite amount of simple shear. From equation 1,
 242 as shear, or displacement d increases to infinite amounts, θ approaches zero.
 243 Taking $\theta = 28$ degrees, the value of $d = 850$ km [16] then w is predicted to be $\sim$
 244 200 km, which is about the width of the northern South Island. Interpretation
 245 of zone 3 is not straightforward as there are several ways to interpret the low

246 angle of θ . Either the strain here is much higher than further north, which
 247 seems unlikely, or there is a different dominant mode of strain. For example,
 248 with pure shear the θ angle remains close to zero (Figure 9). If there is some
 249 combination of pure and simple shear the angle can also be close to zero [61]. A
 250 third possibility is that as the strain rates are low here, and anisotropy due to
 251 shear in the asthenosphere dominates [62]. This result is based on an analysis of
 252 local splitting events showing that the dominant SKS splitting must be from
 253 depths > 100 km deep.

254 3.5 *Fault strike vs GPS*

255 Our above analysis of geodetic extension directions versus fast polarization
 256 directions for S-waves has provided insight to mantle processes. If, on the
 257 other hand, we want to learn about stress and strain in the crust we need to
 258 examine the relationship between shortening directions and strike directions
 259 of major strike-slip geological faults. In this regard, we measure the angle (al-
 260 pha) between the strike of the faults and the principal shortening axes of the
 261 geodetic strain field (Figure 8). The angle alpha shows values of 60-80 degrees
 262 for most of strike slip faults of the Marlborough and the central Alpine Fault,
 263 30 degrees for faults elsewhere in the South Island and 18-30 degrees in the
 264 Wellington region (Figure 8). The high alpha angles of ~ 60 degrees for Marl-
 265 borough faults and the Alpine fault of compression are compatible with the
 266 analysis of past geodetic surveys (shortening axis) [2] and recent seismologi-

cal studies of maximum compressive stress (σ_H) completed in the area of the central and northern South Island [63,64,65]. Thus stress and strain axes are aligned suggesting the material is isotropic. A 60 degree angle for alpha is also similar to the situation on San Andreas fault in northern California[66] who argue that optimal orientation for σ_H for fault that is strong as its surrounding rock is 30 degrees, and that a 80 degree angle is appropriate for a weak fault embedded in strong rock. Our interpretation of the 60 degree alpha angle for the Marlborough and Alpine faults is that friction has been reduced because of enhanced fluid pressure as inferred from geophysical surveys [67,68].

4 Discussion

In this study we have presented GPS vertical and horizontal solutions for the New Zealand land mass based on 10 years of data. The horizontal data gives us a strain field similar to that published elsewhere [18]. The vertical solution for the whole country has not been computed before and the map we produce is the first such attempt. In 10 years time a better solution will be achievable. Nevertheless, the results of the surface uplift map are consistent with what we know from geological observations. We do, however, highlight the surprisingly high rate of uplift in the central North Island which, if real, should be closely monitored. We present an analysis of the angle between GPS-derived compression axes directions with SKS directions (θ). This analysis

287 gives us new insight into mantle deformation in the sense that this definition
 288 of θ allows us to partition New Zealand into 3 domains. The most southern
 289 domain shows $\theta \sim 0$ and is interpreted as zone of both simple and pure shear
 290 with perhaps the dominant of the latter in the past 5 my. Strain rates are,
 291 however, low here and other interpretations of a low θ value are possible.
 292 The middle of New Zealand, including the Marlborough faults region, has
 293 $\theta \sim 28$ degrees and here we suggest a mode of simple shear over a zone $\sim$
 294 200 km wide. This interpretation differs slightly from previous ones [69,14]
 295 in that the interpretations of the southern and middle domains, in terms of
 296 simple and pure shear, were reversed. The different point of view comes about
 297 by hypothesising that the GPS derived extension direction is a proxy for the
 298 present day shear in the mantle lithosphere. Finally, we compare the strikes of
 299 faults versus the orientations of compression axis and conclude that because
 300 of the dominant high angles, most of the strike slip faults of central New
 301 Zealand, including the Alpine fault, are of low friction possibly due to high
 302 fluid pressures.

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Fig. 1. GEONET network velocity field with respect to the site New Plymouth (NPLY). Note the relative lack of activity in western South and North Islands. The station GUNR is a new station introduced in 2009 and has limited data base. We did not use data from this station in creating the uplift or strain maps.

Fig. 2. a) Surface uplift rate map of New Zealand. Here we have extrapolated between stations onto a ~ 50 km grid with bicubic splines then contoured with GMT [43]. Two main areas can be distinguished where there is uplift higher than uncertainties. See text for discussion.

Fig. 3. Same as Figure 2 without interpolation.

Fig. 4. Strain rate components computed from the GEONET velocity field.

Fig. 5. a) Theoretical vertical strain rate computed from the principal strain rate components ($\dot{\epsilon}_1$ and $\dot{\epsilon}_2$) assuming the material is incompressible. b) Expected rate of the base of the crust V . When V is negative the crust is thickened. c) Expected uplift deduced of the theoretical strain rate map. The peak-to-peak amplitude of the ground motion does not exceed 2 mm/yr. We detail in the text the assumptions to reach this result.

Fig. 6. Left: Comparison of the orientations of the axis of shortening from GPS (red) with the fast axis of shear wave splitting (blue) and with the compression axis from geodetic survey ([2], black). We explain in detail the implications of these observations in the text. We find that while the geodetic and present day shortening directions agree, some transient deformation related to the 1931 Napier earthquake [70], is visible along the east coast of North Island. Right: Comparison of the orientations of the planes of maximum shear from GPS (green) with the fast axis of shear wave splitting (blue).

Fig. 7. Same as Figure 5.a for GPS campaigns published by [71].

Fig. 8. Left: θ angle values between orientations of the axis of compression from GPS and the SKS orientations and with the compression axis from geodetic survey (black). Right: Angles between the GPS compression strain rate axis and the strike of the faults. We subtracted the strike of the fault to the shortening directions. More details in the text. The values have been interpolated using splines [43] on a 0.5×0.5 grid of points.

Fig. 9. Cartoon showing how an original spherical reference body can be deformed by simple and pure shear. For simple shear there is numerical relationship between the width of shear zone, the amount of offset across the zone and the angle (θ) between the maximum extension and the direction of shear. In pure shear the angle θ is $=0$. Combinations of pure and simple shear can produce variable SKS directions as shown by [61]. Figure after [72]

Fig. 10. Distribution of the values of θ in zones 2 and 3. We note a shift in the average value of θ of about 40 degrees. The values of θ are more scattered in zone 2. This suggests that some areas have higher values of θ than others.

Fig. 11. Distribution of the values of α for areas south (south island) and north (north island) of the latitude S41. We find that the distribution for South Island shows two peaks that we can associate with the zones 2 and 3 described using the difference the SKS fast axis and GPS compression directions.

Site	Lon.	Lat.	Ve	Vn	Se	Sn
	(deg.)	(deg.)	mm/yr	mm/yr	mm/yr	mm/yr
AUCK	174.83	-36.60	3.7	38.5	0.2	0.2
AUKT	174.77	-36.84	-1.4	31.5	2.0	2.0
BLUF	168.29	-46.59	-36.9	34.5	0.5	0.5
CAST	176.20	-40.91	-29.2	27.4	0.6	0.6
CMBL	174.21	-41.75	-25.7	32.0	0.5	0.5
CORM	175.75	-36.87	3.5	38.3	0.5	0.5
DUND	170.60	-45.88	-37.8	30.4	0.6	0.6
DURV	173.92	-40.80	-6.6	38.6	0.6	0.6
GISB	177.89	-38.64	-1.9	19.8	0.5	0.5
GLDB	172.53	-40.83	-2.6	42.2	0.6	0.6
GUNR	170.39	-43.39	-20.5	12.6	2.0	2.0

Continued on next page

series Table 1 – continued from previous page

HAAS	168.79	-44.07	-15.3	40.1	0.6	0.6
HAMT	175.11	-37.81	1.2	38.9	0.5	0.5
HAST	176.73	-39.62	-6.4	24.4	0.5	0.5
HIKB	178.30	-37.56	5.7	19.4	0.5	0.5
HOKI	170.98	-42.71	-4.7	42.9	0.4	0.4
KTIA	173.27	-35.07	3.5	40.7	2.0	2.0
KUTA	177.07	-39.17	-1.5	15.7	2.0	2.0
LEVN	175.24	-40.59	-23.9	31.1	2.0	2.0
LEXA	169.31	-45.23	-37.0	31.6	0.6	0.6
LKTA	172.27	-42.78	-24.3	32.9	0.5	0.5
MAHA	173.79	-41.29	-19.5	40.4	2.0	2.0
MAHO	174.85	-38.51	0.6	39.1	0.6	0.6

Continued on next page

series Table 1 – continued from previous page

MAVL	168.12	-45.37	-44.6	33.9	0.6	0.6
MQZG	172.65	-43.70	-35.5	31.0	0.4	0.4
MTJO	170.46	-43.99	-29.6	32.5	0.4	0.4
NLSN	173.43	-41.18	-6.5	40.4	0.6	0.6
NPLY	174.12	-39.18	-0.8	39.5	0.5	0.5
OKOH	174.06	-41.02	-20.0	36.4	2.0	2.0
TAUP	176.08	-38.74	5.9	32.2	0.5	0.5
TORY	174.28	-41.19	-12.5	37.8	0.6	0.6
TRNG	176.26	-37.73	3.5	36.9	0.5	0.5
WAIM	170.92	-44.66	-35.3	30.2	0.6	0.6
WANG	174.82	-39.79	-3.4	38.0	0.5	0.5
WARK	174.66	-36.43	-2.0	39.6	2.0	2.0

Continued on next page

series Table 1 – continued from previous page

WEST	171.81	-41.74	-3.5	41.8	0.6	0.6
WGTN	174.81	-41.32	-25.5	32.5	0.3	0.3
WITH	173.98	-41.56	-23.8	35.6	2.0	2.0

Table 1: GEONET velocities in ITRF2000. Velocity field is plotted with respect to New Plymouth (NPLY) on Figure 1

Site	Lat.	Lon	V_{up}	V_{up}/CAST	σ_{up}
	deg.	deg.	(mm/yr)	(mm/yr)	(mm/yr)
AUCK	-36.60	174.83	8.5	2.0	2.2
BLUF	-46.58	168.29	9.6	3.1	2.5
CAST	-40.90	176.20	6.5	0.0	3.1
CMBL	-41.74	174.21	10.4	3.9	2.4
CORM	-36.86	175.74	8.9	2.4	2.4
DUND	-45.88	170.59	9.1	2.6	2.8
DURV	-40.80	173.92	8.0	1.5	2.7
GISB	-38.63	177.88	7.9	1.4	2.3
HAAS	-44.07	168.78	11.0	4.5	2.5
HAMT	-37.80	175.10	8.6	2.1	2.4
HIKB	-37.56	178.30	8.9	2.4	2.4
HOKI	-42.71	170.98	11.6	5.0	2.2
KTIA	-35.06	173.27	10.4	4.0	4.2
LEVN	-40.58	175.24	12.6	6.1	6.4
LEXA	-45.23	169.30	8.7	2.2	2.5
MAVL	-45.36	168.11	9.1	2.6	2.6
MQZG	-43.70	172.65	9.7	3.2	2.2
MTJO	-43.98	170.46	9.5	3.0	2.2
NLSN	-41.18	173.43	8.4	1.9	2.5
NPLY	-39.18	174.11	8.1	1.6	2.4
TAUP	-38.74	176.08	13.3	6.8	2.3
TORY	-41.19	174.28	10.3	3.8	2.7
TRNG	-37.72	176.26	10.2	3.7	2.4
WAIM	-44.65	170.92	9.1	2.6	2.6
WANG	-39.78	174.82	9.2	2.7	2.4
WEST	-41.74	171.80	7.8	1.2	2.6
WGTM	-41.32	174.80	8.4	1.9	2.2

Table 2

GEONET network vertical rates in the ITRF2000 and with respect to the site CAST

Highlights

We compute the strain rate in New Zealand from the GEONET GPS velocity field

We compare the axis of compression from the GPS velocity field with the fast axis of SKS splitting

We show that, in some areas, mantle deformation and present-day crustal tectonic strongly related

Figure 1
[Click here to download Figure: F1-network.F1.eps](#)

Figure 2
[Click here to download Figure: F2-NZ.vert.eps](#)

Figure 3
[Click here to download Figure: F3-NZ.vert.nointerp.eps](#)

Figure 4
[Click here to download Figure: F4-geonet.velo.eps](#)

Figure 5
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Figure 6
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Figure 7
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Figure 8
[Click here to download Figure: F8-molnarformula.eps](#)

Figure 9

[Click here to download Figure: F9-1](#)

No Deformation

Pure shear ($\theta=0$)

Simple shear
 $\tan(2\theta)=2w/d$

Frequency (%)

10

5

0

South of S41

15

10

5

0

Frequency (%)

North of S41

0

20

40

60

80

100

Alpha