Earthquake rate, slip rate, and the effective seismic thickness for oceanic transform faults of the Juan de Fuca plate system

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SUMMARY
The earthquake rate, average fault slip rate, and the effective seismic thickness have been examined for the Revere–Dellwood–Wilson, Sovanco, Nootka, Blanco and Mendocino transform faults, bordering the Juan de Fuca plate system. Seismicity statistics are related to the rate of slip along a given fault due to earthquakes, using the concept of seismic moment. There are significant sources of uncertainty, including: the incompleteness and limited history of the earthquake catalogue, the variety of magnitude definitions which can only be related empirically, empirical moment–magnitude relations (and the effect of their stochasticity), uncertainty in fault lengths and the effective seismic thickness, the recurrence relation and the determination of maximum magnitude and how the recurrence relation is truncated at maximum magnitude. Nonetheless, this method has been used successfully to provide estimates of deformation in good agreement with those from plate models. An agreement between the deformation rate predicted by seismicity statistics for the fault zones and observed deformation from GPS and other geophysical data is used to show the soundness of the method and parameters used. The least constrained parameter is the effective seismic thickness, thus the effect of a 2, 3, 6.5 and 10 km thick zone is investigated for each fault. The selection of a thin effective seismic layer of about 3 km can consistently explain most of the deformation in the region as being seismically accommodated. The upper mantle is inferred to be aseismic, which is consistent with evidence of its serpentinization beneath these faults. The similarity of the deformation estimates based on seismicity and those from plate models shows a remarkable consistency in these rates over a significant temporal range from tens to millions of years.

Key words: deformation, Explorer, Juan de Fuca, oceanic crust, seismicity, transform faults.

1 INTRODUCTION
In this paper we examine the seismic and slip behaviour of the oceanic transform faults bounding the Juan de Fuca plate system. Individual earthquake seismic moments may be summed but the statistical uncertainties tend to be very large. A more stable estimate of the total moment rate can be calculated as the integral over magnitude–frequency of occurrence data, and this rate in turn can be related to the rate of fault slip. A previous study, with limited data, was carried out by Hyndman & Weichert (1983).

The shrinking Farallon Plate, converging with North America over the last 150 million years, has become increasingly fragmented as the plate and oceanic ridges collide with and have been subducted under the continent (Riddihough 1984; Braunmiller & Náblék 2002). Here, we investigate the seismic slip along oceanic faults bounding the surviving northern fragments, namely the Explorer, Juan de Fuca and Gorda plates, off the coast of the Pacific Northwest region of North America. The main Juan de Fuca Plate is moving as a coherent block, but both the Explorer and Gorda ‘plates’ appear to be breaking up and have substantial internal deformation. From north to south, the faults are: the Revere–Dellwood–Wilson faults, marking the southwestern boundary of the Dellwood/Winona Block, part of the Explorer; the Sovanco Fault Zone, marking the southwestern boundary of the Explorer Plate; the Nootka Fault Zone, the transform fault between the Explorer and Juan de Fuca plates; the Blanco Fault Zone, the southwest boundary of the Juan de Fuca Plate and the Mendocino Fault Zone, to the south of the Gorda Plate, as shown in Fig. 1. For each fault, deformation rates due to seismic slip are calculated from earthquake catalogue statistics and these are compared with estimates based on plate models and other geophysical and geodetic data.

2 REVERSE–DELLWOOD–WILSON FAULT ZONE
At the northern tip of the Explorer Plate is the Dellwood/Winona Block separated from the Pacific by the Dellwood–Wilson and Revere–Dellwood faults between the Dellwood, Tuzo Wilson and...
3 THE SOVANCO FAULT ZONE

The Sovanco Fault Zone (Fig. 1), extends northwest from the triple junction between the Pacific, Juan de Fuca and Explorer plates to the Explorer Ridge. This fault zone now represents two different sections in terms of tectonics. The western Sovanco Fracture Zone and southern Explorer Ridge show markedly lower seismicity, which is symptomatic of a new developing Pacific–Explorer transform boundary cutting through the southwest corner of the Explorer Plate. Following Braunmiller & Nábřežek (2002), we call this southwest corner, now apparently transferred to the Pacific Plate, the Southwestern Assimilated Territory (SAT). To the east, the Eastern Sovanco Deformation Zone (ESDZ) shows a broad band of seismicity. Assuming that all the seismicity in this region represents ongoing deformation between the Pacific and North American plates, regardless of fragmentation of the Explorer Plate, we can still use earthquake statistics to predict deformation. A sufficiently large area must be selected to encompass the fracture zone and the SAT. GPS data from the north end of Vancouver Island, when combined with locked subduction thrust fault models, provides an independent estimate of slip rate for comparison (Mazzotti et al. 2003a).

4 THE NOOTKA FAULT ZONE

The Nootka Fault Zone extends from the Juan de Fuca Ridge to beneath the Vancouver Island margin, where a fault–trench–trench triple junction marks the intersection of the Juan de Fuca, Explorer and North American plates (Fig. 1). The fault zone was initially inferred from magnetic anomaly analysis (Riddihough 1977) and substantiated by observations of focused seismicity, reflection seismic profiles, gravity and bathymetric data (Hyndman et al. 1979). Magnetic anomaly, earthquake and GPS data seem to require the Explorer region to be currently independent from the Juan de Fuca and North American plates (Botros & Johnson 1988; Braunmiller & Nábřežek 2002; Mazzotti et al. 2003a), although this has been the subject of debate (Rohr & Furlong 1995; Kreemer et al. 1998; Govers & Meijer 2001). The margin triple junction itself has not previously been examined in detail. Available field data at the Nootka Fault Zone itself are sparse (e.g. Hyndman et al. 1979; Au & Clowes 1982, 1984). The precise location and trend of the Nootka Fault Zone is not well constrained. It appears to be a shear zone some tens of kilometres wide. Further study is imperative in preparation for the NEPTUNE ocean floor observatory and potential future IODP drill holes. This was the initial motivation for this study; we investigated the other faults, which are more readily comparable with plate model relative motions as a means of calibrating our solution for the Nootka Fault Zone and determining appropriate parameters, especially the effective seismic thickness.

5 BLANCO TRANSFORM FAULT ZONE

The Blanco Transform Fault Zone (BTFZ), off the coast of Oregon, marks the southwest boundary of the Juan de Fuca Plate, between the Juan de Fuca and Gorda ridges (Fig. 1). The fault is segmented, bounded by very short ridges with segments separated by short extensional basins. The most notable is the Cascadia Depression, where there is active spreading (Dziak et al. 1991). The longest segment is the 150 km high-angle right-lateral strike-slip fault called the Blanco Ridge (Dziak et al. 2000). It has a small component of dip-slip motion (where the Juan de Fuca is the hangingwall relative to the Pacific). The entire BTFZ is approximately 350 km long. Thus, there is potential for much larger earthquakes than on the faults around the Explorer, provided that the entire fault is capable of rupturing in one earthquake.

6 MENDOCINO FAULT ZONE

The Mendocino Fault Zone extends from the Mendocino triple junction at the intersection of the Pacific, Gorda and North American
7 RELATING SEISMICITY TO DEFORMATION

If we assume, following Anderson (1979) and Hyndman & Weichert (1983), that seismicity follows the Gutenberg–Richter recurrence relation up to an estimated maximum magnitude, we can calculate the total moment rate, and thus the deformation rate. This relation is commonly used in seismic hazard assessment. In an earlier study, Hyndman & Weichert (1983) found good agreement between the deformation rate implied by seismicity and that accorded by the incremental or density recurrence function (Wilson 1989; Silver 1971; Stoddard 1987). The Gorda Plate is deforming internally according to magnetic and earthquake data, rather than fragmenting into coherent pieces like the Explorer which has broken off the Juan de Fuca Plate (Govers & Meijer 2001).

The estimate of both maximum magnitude $M_{\text{max}}$ and the form of the truncation of the recurrence relation near $M_{\text{max}}$ have a significant impact on moment calculation. An abrupt truncation of the cumulative density function at $M_{\text{max}}$ results in a smooth fall-off towards $M_{\text{max}}$ in the cumulative recurrence function (e.g. Weichert 1980). Anderson & Luco (1983) examined the consequences in earthquake statistics and fault slip rate if some fraction of the seismic moment occurs in near-maximum magnitude earthquakes. Field et al. (1999) found good agreement between deformation estimates based on seismicity and those based on geological and geodetic data, assuming a truncated cumulative exponential function and little to no contribution from characteristic earthquakes, for southern California. Likewise, in the Pacific Northwest Cascadia forearc, estimates of the frequency of large crustal earthquakes based on geological and geodetic data matched those observed by seismicity, with the same assumptions (Hyndman et al. 2003). Here also, we assume an abrupt truncation of the incremental function, although recognizing that it represents an uncertainty in the results. The moment rate and fault slip rate may then be computed from the recurrence relation parameters (see Hyndman et al. 2003 and references therein).

The cumulative density function is given by

$$n(M) = \alpha \exp(-\beta M), \quad M \leq M_{\text{max}}$$

(1)

and

$$n(M) = 0, \quad M > M_{\text{max}}$$

(2)

where $\alpha$ and $\beta$ are the density recurrence exponential coefficients, as opposed to the decimal logarithm coefficients $a$ and $b$, as in

$$\log n(M) = a - bM.$$  

(3)

The Gutenberg–Richter cumulative recurrence coefficient $b$ is given by

$$b = \beta / \ln 10.$$  

(4)

The moment–magnitude relation is taken to be deterministic, and moment $M_o$ is given by

$$M_o = \gamma \exp(\delta M)$$

(5)

or

$$\log M_o = c + d M$$

(6)

where $c$ is of the order of 9.05 and $d$ is of the order 1.5 in S.I. units. The total moment rate $M_o'$ (the time derivative of $M_o$) of the incremental or density recurrence function is

$$M_o' = b \times 10^{(a-b)M_{\text{max}} + a + c}(d-b).$$

(7)

For a single earthquake over a fault of area $A$, the average slip displacement $d$ is related to the seismic moment by

$$M_o = \mu A.$$  

(8)

where $\mu$ is the shear modulus. We set $\mu$ to a typical value of $3.3 \times 10^{10}$ N m$^{-2}$ for crustal rock compositions. The slip rate $s$ is proportional to the rate of moment release per unit time per unit fault area such that

$$s = M_o' / \mu A.$$  

(9)

The deformation rate may be estimated, from this result, as

$$s' = C M_o' / 2 \mu A' = C M_o' / 2 \mu W L.$$  

(10)

where $W L$ is the effective width times length, or effective cross-sectional area of the effective seismic zone. $C$ is a parameter which depends on the orientation of the faulting with respect to regional motion. Typically, $C$ varies from 1.0 to 2.0; we can set $C = 2.0$ for these strike-slip faults.

8 EARTHQUAKE DATA SELECTION: REGION, TYPE OF MAGNITUDE AND COMPLETENESS

8.1 Earthquake catalogues and regions investigated

All earthquake data offshore British Colombia, for the RDW, Sovanco and Nootka faults, are from the Geological Survey of Canada (GSC) earthquake catalogue. Data from the Blanco and Mendocino faults are from the US Geological Survey (USGS), the International Seismological Centre (ISC) and the Harvard Centroid Moment Tensor catalogues.

The GSC earthquake catalogue lists earthquakes in a selected region by date, time, estimated depth, calculated magnitude, preferred magnitude (if several are available) and institution at which it was measured. The great majority of magnitudes are defined by the local magnitude $M_L$ scale, but a few were recorded using, in order of frequency, the body wave magnitude $m_b$, moment magnitude $M_s$, surface wave magnitude $M_S$, coda or duration magnitude $M_D$ or other scales. Routine earthquake locations of offshore events have been shown to be systematically biased by tens of kilometres to the northeast, relative to bathymetric features. This is because all monitoring stations have been situated onshore, to the east of epicentres, as well as an inexact velocity model for the oceanic lithosphere (Hyndman & Rogers 1981; Wahlström & Rogers 1992; Dziak et al. 2000; Braunniller & Nábělek 2002). Uncertainty in epicentre locations decreases with time. Prior to 1951, uncertainties in epicentre locations are typically 50 km, and may be as much as 100 km; more recently uncertainties are about 20 km (T. Mulder, GSC, personal communication 2003). There are almost no constraints on event depths from routine processing; some
depth estimates come from moment tensor solutions, as discussed below.

Data for the Blanco Fault were from three USGS databases: the NEIC (1973 onward), USHIS (prior to 1973) and the ANSS (1961 onward). Where the catalogues overlap, their lack of completeness was evident, as there are a number of events in each catalogue which do not appear in one or both of the others. Most of these data are \( m_b \), with some \( M_S \), \( M_w \), \( M_L \) and other magnitudes. Like the data for events off Vancouver Island, these data suffer from a bias in computed earthquake epicentres. The accuracy of locations suffers from only land-based seismic stations, located to the east, as well as inaccurate velocity models (Dziak et al. 1991). Epicentre locations are routinely 20 to 30 km offset to the northeast of the fault zone’s bathymetric expression (Embley & Wilson 1992). Earthquakes located acoustically with the SOSUS array differed from NEIC locations by between 4 and 71 km to the southwest (Dziak et al. 2000). Cronin & Sverdrup (2003) used a joint-relocation procedure on 120 \( m_b > 5.0 \) events; recalculated epicentres were an average of 34.6 ± 15.2 km towards azimuth 196° ± 28° and fell much better on the seafloor mapped structural features.

Data for the Mendocino Fault were from two USGS databases: the NEIC (1973 onward) and the California 1735–1974 catalogue, which were supplemented by data from the Harvard Centroid Moment Tensor catalogue and the International Seismological Centre. Again, there are questions of catalogue completeness as all events in each catalogue are not in every other catalogue. The addition of data from the Harvard CMT and ISC catalogues meant that for many events multiple magnitude estimates were available. For these events, we selected the best estimate based on the type of magnitude and proximity of the institution at which it was measured. We selected \( M_w \), followed by \( M_S \) for large magnitudes determined teleseismically. \( M_L \), \( m_b \) and \( M_D \) were used where no other estimates were available. These data are also subject to biases in position and apparently inconsistent magnitude definitions.

The selected fault seismicity regions encompass not only the fault defined by seafloor mapping, but are chosen to allow for the epicentral uncertainty, known bias and the scatter in the data. Also, the fault regions selected must contain sufficient seismicity data for the statistics to be significant. For faults around the Explorer, the regions selected are illustrated in Fig. 2. One region encompasses all of the Dellwood–Wilson and Revere–Dellwood faults. For the Sovanco Fault Zone, a large region was selected to ensure that all earthquakes pertinent to Pacific–Explorer motion were included, regardless of fragmentation of the Explorer Plate. Two regions of different lengths, for the Nootka Fault, were investigated. The first region extends from the ridge to the continental slope. The second region includes most of the first (it is somewhat farther removed from the ridge) plus the region extending to the coast of Nootka Island. Seismic slip along the fault as it subducts beneath the margin would be included in the second region. Fig. 3 shows the regions selected for the Blanco Fault and the Mendocino Fault. Because of the complex tectonics in the Gorda Plate region and landward of continental slope on the Mendocino Fault, the Mendocino region was limited to the offshore fault. This excludes the seismicity due to north–south deformation within the Gorda Plate and the seismicity of the subduction zone.

8.2 Magnitude scales and magnitude–moment relations

A number of empirical relations were employed to convert different earthquake magnitudes to seismic moment. These relations differ significantly from those found previously for land earthquakes; there appears to be a large onshore–offshore amplitude attenuation. These corrections increase the moment rate and computed slip rate by up to 68 per cent. Offshore British Colombia, most of the preferred earthquake parameter solutions were calculated by the GSC at the Pacific Geoscience Centre (PGC), using the local magnitude \( M_L \) scale. These magnitudes are underestimated by at least 0.5 magnitude units with respect to the moment magnitude scale. Ristau et al. (2003) show that the \( M_L \) values for the region offshore
Figure 4. The relationships between magnitudes (\(M_w\) versus \(M_L, M_S, m_b,\) and \(M_D\), as well as \(M_L\) versus \(M_D\)) on the Mendocino Fault for earthquakes where multiple estimates of magnitude are available. The solid line has a slope of 1, which goes through the origin. The dashed line has a slope of 1, but has intercept equal to the average difference between the types of magnitude. The dotted line is the best least-squares fit. The plot of \(M_w\) versus \(M_D\) also shows a grey line based on \(M_w\) versus \(M_L\) and \(M_L\) versus \(M_D\) fits.

Vancouver Island are systematically less by 0.62 ± 0.08 magnitude units than the more robust moment magnitude (\(M_w\)) values derived from moment tensor analysis. We therefore corrected the \(M_L\) magnitudes according to

\[ M_w = M_L + 0.62. \]  

(11)

Similarly, Braunmiller & Náblé (2002) found that for the Explorer region, that the body wave magnitudes \(m_b\) underestimate \(M_w\) by 0.46 magnitude units and that for surface wave magnitudes \(M_S < 5.8\),

\[ M_w = 2.8 + 0.5M_S \]  

(12)

but for \(M_S \geq 5.8\) they are equal to \(M_w\). Thus, in the Explorer region, all \(M_L, m_b,\) and \(M_S\) values were converted to \(M_w\) according to these empirical relations. A small minority of the data were only available in \(M_D\) (coda or duration) or other scales. These data were not altered. For the Blanco Fault we have converted the data from original magnitudes using

\[ M_w = 1.29 + 0.82m_b \]  

(13)

and

\[ M_w = 2.40 + 0.62M_S, \]  

(14)

provided by Braunmiller (1998). Though comparable corrections may be needed in the vicinity of the Mendocino Fault, no comparisons of magnitude scales were found in the literature.

By supplementing the USGS catalogues by the Harvard CMT and ISC catalogue data, we were able to derive relations between \(M_L, M_S, m_b, M_D\) and \(M_w\). Fig. 4 shows plots of \(M_w\) versus each of \(M_L, M_S, m_b\) and \(M_D\), as well as a plot of \(M_L\) versus \(M_D\) for events in the

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combined catalogues for which estimates were available of multiple types of magnitudes. From least-square fits to the data, we found

\[ M_w = (1.01 \pm 0.031)M_L + (0.15 \pm 0.14). \]  

(15)

If the slope was assumed to be 1,

\[ M_w = M_L + (0.21 \pm 0.079). \]  

(16)

The uncertainties are one standard deviation. Likewise, we found

\[ M_w = (0.72 \pm 0.032)M_S + (1.79 \pm 0.158) \]  

(17)

or, with the slope set to 1,

\[ M_w = M_S + (0.46 \pm 0.149). \]  

(18)

\[ M_w = (0.94 \pm 0.042)m_b + (0.72 \pm 0.194), \]  

(19)

or, with the slope set to 1,

\[ M_w = m_b + (0.44 \pm 0.087). \]  

(20)

\[ M_w = (0.94 \pm 0.060)M_D + (0.62 \pm 0.26), \]  

(21)

or, with the slope set to 1,

\[ M_w = M_D + (0.36 \pm 0.48). \]  

(22)

Since there were only a few events with both \( M_w \) and \( M_D \) estimates, we also found

\[ M_L = (0.99 \pm 0.037)M_D + (0.12 \pm 0.13), \]  

(23)

or, with the slope set to 1,

\[ M_L = M_D + (0.07 \pm 0.055). \]  

(24)

With the exception of \( M_S \) the data can be sufficiently well fitted with a slope set to 1 and adding a constant to convert to \( M_w \) or \( M_L \). We have fitted \( M_S \) by assuming the relations (16) and (24) between \( M_w \) and \( M_L \) and \( M_L \) and \( M_D \) respectively, which gives us:

\[ M_w = M_D + (0.28 \pm 0.055). \]  

(25)

We have applied eqs (16), (19), (20) and (25) to the data for the Mendocino Fault.

8.3 Completeness periods

Accurate calculation of moment rate and fault slip rate requires that for each increment of magnitude, data be included only for time periods during which all events within that increment were recorded. The dates for complete detection vary with magnitude and region. Most of the seismic moment and slip on a fault is due to the largest-magnitude earthquakes. These earthquakes occur the least frequently, but have been measurable for the longest time. Smaller magnitude earthquakes occur more frequently but have been resolvable for a shorter time. If we assume that the rate at which earthquakes occur in any increment of magnitude is constant in time, we can combine data gathered over varying durations. The lowest magnitude for which records are complete in any year can be estimated from where the magnitude–frequency of occurrence plot deviates from linearity or from knowledge of processing analysts. We have used quite conservative completeness limits, although this reduces the number of earthquakes and increases the statistical uncertainty in the recurrence relations (see Table 1).

For the RDW, Sovanco and Nootka faults the catalogue completeness is taken from Hyndman & Weichert (1983) and T. Mulder (GSC, personal communication, 2003). Since the majority of these data were \( M_L \) magnitudes, the values quoted were increased by 0.62 to create the completeness tables. Determining the completeness of data offshore Oregon and California is more problematic than offshore British Columbia, because there are multiple catalogues covering different time periods. According to Hyndman & Weichert (1983), data for the Blanco Transform Fault is complete to 7.0 since 1899, to 5.5 since 1917, to 5.0 since 1965, and data for the Mendocino is complete to 7.0 from 1899, to 5.5 from 1917 and to 4.0 from 1965. Dziak et al. (1991) suggest that the threshold for detection in the northeast Pacific, since 1963, is \( m_b = 4.0 \). However, their data below 4.5 do not fit the recurrence relation in either the northwest or southeast sections of the Blano; though magnitudes below 4.5 could be detected, the catalogue cannot be complete below \( \sim 4.5 \), from 1963. Braunmüller (1998) claims the catalogue is complete to 4.4 since 1964. We have therefore used the values from Hyndman & Weichert (1983) and determined the year of completeness for magnitude 4.0 on the Blanco, by inspection of the data, to be 1985. For the Mendocino, we found some deviation from linearity if we applied the Hyndman & Weichert (1983) table on magnitudes as recorded (prior to application of eqs 6,9,10 and 15), unless we increased the minimum magnitude for complete detection in 1965 to 5.3. We likewise determined the year of completeness for magnitude 4.0, by inspection of the data, to be 1985. Since the majority of the data for this region are \( M_S \), when analysing the modified data, we added 0.21 to each value in the completeness table, according to eq. (16).

9 SELECTION OF PARAMETERS

9.1 Lengths of oceanic transform faults

The moment and slip-rate calculations are applied to specific fault areas, i.e. fault lengths times fault thickness or depth extent. We have estimated the total length \( L \) of the faults from bathymetry and seismicity maps. The Revere–Dellwood and Dellwood–Wilson faults have a combined length of about 160 km. From the triple junction along the Sovanco Fault to the Explorer Ridge is about 140 km. For the Nootka Fault, the length from the continental slope
to the triple junction at the intersection of the Juan de Fuca, Explorer and Pacific plates is about 150 km. The length of the second larger region investigated for the Nootka Fault, which extends to Nootka Island, as illustrated in Fig. 2, is about 160 km. The Blanco fault (Fig. 3) spans 350 km between the Juan de Fuca and Gorda ridges. The Mendocino Fault (Fig. 3) spans 280 km from the Gorda Ridge to the continental margin.

9.2 Effective seismic thickness

The effective seismic thickness of the transform faults is an important part of our study, both for the fault area and for the maximum magnitude. The calculated slip rates are inversely proportional to the seismic thickness assumed if the other parameters are unchanged. However, we also use the seismic thickness in our estimate of the maximum magnitude. The two contributions to the slip rate from varying $W$ partially cancel. The result, as discussed below, is that a change in $W$ of a factor of 5 results in a change of only about a factor of 2 in the computed seismic slip rate.

An alternative approach is to estimate the effective seismic layer thickness $W$ from the seismicity rate, taking the fault slip rates determined independently, for example from plate models. The effective thickness may approximate a true nearly constant thickness along the fault, with that area having close to 100 per cent seismic efficiency. Alternatively, it may represent the overall average of seismogenic patches extending to greater depth separated by aseismic portions of the faults (Boettcher & Jordan 2005, in press). While this possibility cannot be ruled out, we favour the former. It seems unlikely that a collection of seismogenic patches should coincidentally sum to nearly the same effective thickness $W$ for all of the faults. Geological considerations outlined below also support our thin effective seismic layer model.

A number of approaches are available for estimating the effective seismic thickness:

(1) The maximum depth of seismicity may be taken to be the depth of brittle failure in the oceanic lithosphere. The limit has been associated with the $\sim 600 \, ^\circ C$ isotherm (Abercrombie & Ekström 2001) (see also Dziak et al. 2000). This approach assumes that earthquakes occur in the mantle. It results in a thickness that is approximately related to the average age of the oceanic lithosphere on the two sides of the fault (e.g. Boettcher & Jordan 2001). This average age ranges from a few Myr for the RDW (Riddihough 1977) which is bounded by very young lithosphere, to just over 5 Myr (Wilson 1989) for the Mendocino Fault. This approach gives little more than the crust for the RDW to $\sim 10$ km for the Mendocino Fault.

(2) The depths of recorded earthquakes can be determined accurately only by arrays of ocean-bottom seismographs (OBS). However, some depth constraints are provided by earthquake moment tensor solutions. Most OBS arrays have been on or near ridges and the data for transform faults are very limited. In our study area Hyndman & Rogers (1981) found event depths ranging between 3 and 6 km in the Explorer region for a width $W \sim 3$ km. They found similar depths for a few events on the Nootka Fault. Tréhu & Solomon (1983) found most strike-slip earthquakes on the Orozco Transform Fault (off the East Pacific Rise), from their OBS studies, were confined to the 4 km thick crust. Wilcock et al. (2002) recorded thousands of microearthquakes in situ on the Endeavour segment of the Juan de Fuca Ridge at 2–4 km depth. Golden et al. (2003) located thousands of microearthquakes in Middle Valley, northern Juan de Fuca Ridge, which were concentrated at 1–2.5 km depth. We expect the depth of these events on the Juan de Fuca Ridge to be thermally limited, but it is notable that none appear to occur in the mantle. Furthermore, Golden et al. (2003) observed less well-constrained swarms on faults outside their array of OBSs including the Nootka, and reported that hypocentres deepen to $\sim 3$ km away from the vent field.

(3) Some constraint in earthquake depth is available from earthquake moment tensor solutions determined using adjacent land station data. This method has low depth resolution, typically of about $\pm 3$ km (J. Ristau, personal communication 2004). It gives poor depth constraints for shallow earthquakes, which occur near a free surface. Ristau (personal communication 2003) (see also Ristau et al. 2003) found depths in the range 3 to 24 km on the RDW, Sovanco and Nootka transform faults, with most depths around 10 km. Similarly, Braunmiller & Náblék (2002) found average depths on the transform faults of the Explorer of $\sim 10$ km with a standard deviation of 3.0 km. Since the crust is some 7 km thick in the region (Au & Clowes 1982; Hyndman et al. 1979), this depth estimate suggests that most earthquakes are occurring in the uppermost mantle. Braunmiller (1998) found that most BTFZ events occurred at depths of 4 to 6 km and a seismogenic zone of less than 10 km. However, the earth model used in these moment tensor inversions does not include the low-velocity sediments and upper crust, nor the ocean water layer. The problem of a velocity structure that varies along the wave paths from oceanic earthquakes to land stations has also not yet been addressed, but the consequence is that the computed depth from moment tensor solutions should be biased to being substantially too deep. The lack of earthquakes at crustal depths is also puzzling, unless there is a bias to depths that are too great.

Furthermore, there are some important geological constraints to maximum earthquake depths which should be taken into account:

(1) The upper crust has very high porosity and may be sufficiently fractured such that it cannot support significant earthquakes (e.g. discussion by Hyndman & Weichert 1983). On land, the upper few kilometres of crust are commonly aseismic ascribed to stable-sliding clay gouge (e.g. Marone & Scholz 1988).

(2) Serpentinite occurrences are common in oceanic fracture zones and serpentined mantle rocks are probably aseismic (e.g. Aumento & Loubat 1971; Thompson & Melson 1972; Reinen et al. 1991; Cannat et al. 1992; Hyndman & Peacock 2003). If the uppermost mantle beneath the fault zones is commonly serpentined, and the upper crust is aseismic as discussed above, the effective seismic zone may be quite thin, i.e. $\sim 3$ km. Lonsdale (1986) explained the seismic deficiency of the Heezen Transform Fault, in the Eltanin fault system, as due to a thin 1 km crust and pervasive serpentization of subcrustal rocks, rather than suggesting significant aseismic slip over the whole fault. Wilson (1989) explains the uniform positive magnetic anomaly over the Mendocino Ridge by a high-susceptibility source such as serpentinite. Dziak et al. (2000) explain evidence of uplift (from gravity, seismic reflection data, and high magnetization from magnetic data), as suggesting a low-density serpentinite intrusion beneath the Blanco Ridge. They suggest that faulting has led to flow of sea water into the mantle, hydrating it and forming a serpentine intrusion along the fault.

Most of the above suggest an effective seismic thickness of 2–5 km, with the possibility of as much as 10 km. To examine the potential error introduced by the uncertainty in the effective seismic thickness we investigate the deformation rate for all oceanic transform faults bounding the Juan de Fuca, Explorer and Gorda plates.
and search for a single width to match all available plate model slip-rate data. A good agreement between seismic slip rate and plate models is found for all faults with a 3 km effective seismic zone. Fig. 5, adapted from Dziak et al. (2000), illustrates how a serpentine intrusion and fragmented upper crust might lead to a ~3 km effective seismic zone on these oceanic transform faults. This result supports the conclusion that most of the deformation is seismic and in the lower crust only. However, we also investigate the slip rates calculated by setting \( W \) to 2 km, 6.5 km and 10 km as well, as seen in Table 2.

Another useful contribution of the earthquake slip-rate approach is for the Nootka Fault, which has a poorly constrained plate model slip rate. The effective seismic thickness \( W \) may be assumed to be the same as that for the other faults, where their values of \( W \) were chosen to give agreement between the seismicity calculated and the plate model slip rates.

### 9.3 Maximum magnitudes

Relating earthquake rate to slip rate using the recurrence relation also requires an estimate of the maximum magnitude for each fault. The deviation from linearity of the recurrence relation, near \( M_{\text{max}} \) cannot be resolved since the number of earthquakes decreases with increasing magnitude. We must rely on empirical relations between fault area and magnitude such as

\[
M_{\text{max}} = 4.07 + 0.98 \log A,
\]

from Wells & Coppersmith (1994). This relation was derived from a database of continental earthquakes worldwide, so we are assuming that scaling on oceanic transform faults is similar. If \( W = 2, 3, 6.5 \) or 10 km, respectively, this gives maximum magnitudes of about 6.5, 6.7, 7.0 and 7.2 for the RDW faults, 6.5, 6.7, 7.0 and 7.2 for the Nootka Fault, 6.5, 6.6, 7.0 and 7.2 for the Sovanco Fault, 6.9, 7.0, 7.3 and 7.5 for the Blanco Fault, and 6.8, 6.9, 7.3 and 7.4 for the Mendocino Fault. Note that increasing \( M_{\text{max}} \) by 0.5 magnitude units with no change in other parameters approximately doubles the deformation rate calculated. However, because the effective seismic thickness \( W \) is used both directly in the seismic slip-rate calculation (eq. 10) and in the maximum magnitude calculation (eq. 26), a change of a factor of five in \( W \) (from 2 to 10 km) results in only a change of approximately a factor of two in seismic slip rate. For these estimates we have assumed that the largest earthquakes rupture the whole fault length, through structural discontinuities and small offsets. If, for example, the small extensional zone in the middle of the Blanco Fault stops rupture, the maximum magnitude is reduced by about 0.3 and the slip rate (on the Blanco Ridge alone versus the BTFZ) is reduced by about 5 per cent.

### 10 RESULTS

Table 2 summarizes the recurrence parameters and fault seismic slip rate for the RDW faults, the two extents for the Nootka Fault, the Sovanco Fault Zone, the Blanco and Mendocino faults. The effective seismic thicknesses \( W \) are varied from 2 to 10 km.

Our models in which \( W \) is set to 10 km, in a region where the crust is typically 7 km thick must include some mantle material in the effective seismic zone, where \( \mu \) is more of the order of \( 6.0 \times 10^{10} \) N m\(^{-2}\). If we consider the effect of this increase in shear modulus with depth by using a weighted mean value of \( 4.41 \times 10^{10} \) N m\(^{-2}\) for 3 km of mantle material and 7 km of crustal material, we find that deformation estimates would be decreased by ~25 per cent.

Plots of the cumulative frequency versus magnitude for all regions are given in Figs 6–10. The RDW plot (Fig. 6) is reasonably linear within estimated uncertainties. There are two events, \( M = 6.7 \) and 6.8, which are larger than predicted using the Wells & Coppersmith (1994) relation for a thinner effective seismic zone. However they are within the scatter of the data that they used to define the relation. The results for the Sovanco Fault (Fig. 7) are also linear within the uncertainty estimates, although there is a small dip above 5.5.

The thicker effective seismic layer models (i.e. larger maximum magnitudes \( M_{\text{max}} \)) overestimate the data above 5.6. The upper panel of Fig. 8 shows the results for the shorter region selected for the Nootka Fault; the lower panel shows the results for the extended region to the coast. The two regions give very similar deformation rates. The upper panel of Fig. 9 shows the results for the Blanco Fault using catalogue magnitudes; the lower panel shows the results if the magnitudes are corrected as proposed by Braunniller (1998). The corrected Blanco data have unusually high \( b \) values, close to 1.5, the point at which eq. (7) becomes undefined (because \( d = b \)). They also give rather unstable results, highly sensitive to \( M_{\text{max}} \) the minimum magnitude included. Thus, we use the fit to the raw data in the upper panel, which gives a deformation rate comparable to the expected rate for \( W = 3 \) km. Fig. 10 shows the results for the Mendocino Fault. The data are quite linear. The model with \( W = 3 \) km provides the best fit to the data since if \( W \) is thinner, the largest events at \( M = 6.9 \) are above the maximum predicted by Wells & Coppersmith (1994) and if \( W \) is thicker the models are above error bars on the data between magnitudes 6.0 and 6.4. All four models predict slip rates similar to those predicted by plate models, but if \( W = 3 \) km we get a virtually identical slip rate.

In general, our estimates of deformation rates are well within the range of other estimates, based on plate models, marine magnetic anomaly data, seismic moment and seismicity rates, as shown in Table 2. If the plate motions are accommodated seismically within a nearly constant-thickness layer, the thin effective seismic layer model is required to give slip rates similar to those from plate models. Consider Fig. 7, in which the cumulative frequency for the Sovanco Fault Zone is fitted to the truncated recurrence relation for \( W = 2,
Seismic slip rate for OTFs of the Juan de Fuca

3, 6.5 and 10 km respectively. The model with the thickest effective seismic layer, resulting in $M_{\text{max}} = 7.2$, is the least consistent with the available data (although still just within the uncertainties). It overestimates the cumulative frequency at magnitudes greater than 5.5. Since the Sovanco region can be used to calibrate the model parameters for the Nootka Fault, this encourages the selection of an effective seismic layer that is thinner than 10 km, and suggests that a large portion of the deformation is actually accommodated seismically within that thickness.

## 11 ERROR ESTIMATION—THE LOGIC TREE APPROACH

Estimating cumulative error for parameters for which there is considerable uncertainty, and propagating those errors through nonlinear equations is far from trivial. An alternative, commonly used in seismic hazard models, is the logic tree approach (e.g. Mazzotti et al. 2003b). A range of reasonable values for each variable is selected and assigned a likelihood. A solution and its probability is then calculated for every possible combination of parameters. The map of combinations is likened to a tree. Each ‘branch’ represents a different set of Selections of parameters. These each lead to a ‘leaf’, which are determined empirically (e.g. Hyndman & Weichert 1983), were allowed to varied by 13 per cent, based on the uncertainty in the relation by quast on 28 July 2018

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between $M_L$ and $M_w$ we applied in the Explorer Plate (Ristau et al. 2003). Previously, the shear modulus, was set to the typical value of $3.3 \times 10^{10}$ Pa. Here, it was allowed to vary by 30 per cent. Since we investigated two areas of different lengths for the Nootka Fault, the length could vary from 150, to 155, to 160 km. All other fault lengths were set to the values listed in Table 2. The two least constrained parameters are the effective width of the seismic zone, $W$, and the maximum magnitude $M_{\text{max}}$. These two parameters are coupled, if we use the Wells & Coppersmith (1994) relation to predict maximum magnitude based on fault area. Therefore, these two parameters were varied from 2 to 3 to 4 km with the associated calculated $M_{\text{max}}$ for each fault. Each of these parameters is assigned an estimated probability, as shown in Fig. 10. The numbers above the top arrows are associated with the upper estimate, the numbers above the centre arrows are associated with the median estimate and the numbers below the lower arrows are associated with the lower estimates. If a parameter is well constrained the probabilities were set to 0.2, 0.6 and 0.2 for the lower, median and upper values. If the parameter is not well constrained the probabilities were set to 0.3, 0.4 and 0.3.

Figure 6. Calculated cumulative recurrence relation for the Revere–Dellwood and Dellwood–Wilson faults. The error bars assume a Poisson distribution. The maximum likelihood fit for each of $M_{\text{max}} = 6.5$ and $W = 2$ km, $M_{\text{max}} = 6.7$ and $W = 3$ km, $M_{\text{max}} = 7.0$ and $W = 6.5$ km, and $M_{\text{max}} = 7.2$ and $W = 10$ km are shown with increasingly darker grey lines.

Figure 7. Cumulative recurrence relation for the Sovanco Fault. The error bars assume a Poisson distribution. The maximum likelihood fit for each of $M_{\text{max}} = 6.5$ and $W = 2$ km, $M_{\text{max}} = 6.6$ and $W = 3$ km, $M_{\text{max}} = 7.0$ and $W = 6.5$ km, and $M_{\text{max}} = 7.2$ and $W = 10$ km are shown with increasingly darker grey lines.

Figure 8. Cumulative recurrence relation for the Nootka Fault. The error bars assume a Poisson distribution. The maximum likelihood fit for each of $M_{\text{max}} = 6.5$ and $W = 2$ km, $M_{\text{max}} = 6.7$ and $W = 3$ km, $M_{\text{max}} = 7.0$ and $W = 6.5$ km, and $M_{\text{max}} = 7.2$ and $W = 10$ km are shown with increasingly darker grey lines. The upper panel is for the margin to the ridge, whereas the lower panel is for the fault to Nootka Island.
Seismic slip rate for OTFs of the Juan de Fuca

Figure 9. Cumulative recurrence relation for the Blanco Fault. The error bars assume a Poisson distribution. The maximum likelihood fit for each of $M_{\text{max}} = 6.9$ and $W = 2$ km, $M_{\text{max}} = 7.0$ and $W = 3$ km, $M_{\text{max}} = 7.4$ and $W = 6.5$ km, and $M_{\text{max}} = 7.5$ and $W = 10$ km are shown with increasingly darker grey lines.

Figure 10. Cumulative recurrence relation for the Mendocino Fault. The error bars assume a Poisson distribution. The maximum likelihood fit for each of $M_{\text{max}} = 6.8$ and $W = 2$ km, $M_{\text{max}} = 6.9$ and $W = 3$ km, $M_{\text{max}} = 7.3$ and $W = 6.5$ km, and $M_{\text{max}} = 7.4$ and $W = 10$ km are shown with increasingly darker grey lines.

In each case, the results tend to cluster, despite the wide range of combinations of parameters. Thus, the range of allowable solutions can be investigated. The plot of incremental probability versus deformation shows the set of possible solutions and their calculated probabilities. The solutions for each fault include a wide range of possible deformation rates. However, rates far from the predictions listed in Table 2 are highly unlikely. The sigmoidal plot of cumulative probability versus the logarithm of deformation shows the range of values and the number of potential solutions at or below a given value. The steeper the increase from zero to one, the better constrained is the deformation estimate. Fig. 12 shows both the incremental and cumulative probability versus motion for each fault. The deformation rates for cumulative probabilities of 16, 50 and 84 per cent, give an estimate of the spread of the solutions and the sensitivity of predictions to the least well-constrained parameters. A summary of results of predicted total moment rates and deformations is provided in Table 3. The deformation rate at 50 per cent cumulative probability is comparable to, though slightly larger than, our preferred estimates listed in Table 2. With the exception of the RDW and the Mendocino faults, all values are slightly lower than the deformation rates predicted by plate models. The largest discrepancy is for the RDW. The RDW has two fault segments, the Revere-Dellwood and Dellwood–Wilson, and our data include some events which are due to ridge segment spreading. Nonetheless the estimate is within 30 per cent of the rate predicted by plate models.

The entire set of solutions for the Nootka Fault predicts significant deformation. This is inconsistent with the results of Kreemer
et al. (1998) who calculated stain rates from seismicity statistics since 1994 and found little deformation. Their catalogue contained no events greater than 5.4. This shows the value of using the recurrence relation to constrain earthquake statistics. The estimate for the Blanco Fault is quite close to that from plate models, despite the fragmentation of the fault and the complexity of the tectonics. The expected deformation is within the bounds listed in Table 3 for all faults investigated.

12 CONCLUSIONS

In this study we have used seismicity statistics and the concept of seismic moment to estimate the rate of slip due to earthquakes along all of the oceanic transform faults of the Juan de Fuca plate system: the RDW, Sovanco, Nootka, Blanco and Mendocino. Rather than summing individual seismic moments, which is highly sensitive to the statistics of the small number of large earthquakes, the total moment rate can be calculated as the integral over magnitude of the magnitude–frequency of occurrence. The integral can be related to the rate of deformation. With this additional assumption, the far more frequent smaller-magnitude events help constrain the rate of infrequent larger-magnitude events. Sources of uncertainty include the incompleteness and limited history of the earthquake catalogue, the completeness table of the catalogue, varied magnitude definitions, empirical moment–magnitude relations and the effect of their stochasticity, uncertainty in fault lengths and effective seismic
thicknesses, uncertainties in the recurrence relation, the determination of maximum magnitude, and how the recurrence relation is truncated at the maximum magnitude. The least constrained parameters are the effective vertical thickness of the seismic zone $W$ and the maximum magnitude $M_{\text{max}}$. We used the empirical equation $M_{\text{max}} = 4.07 + 0.98 \log A$ (Wells & Coppersmith 1994) to predict $M_{\text{max}}$. Thus the maximum magnitude is related to $W$ and the effect of varying $W$ on slip-rate estimates partly cancels. Estimates range from a thin effective seismic zone and $W = 3$ km (Hynndman & Weichert 1983), to a thicker $W = 10$ km zone (Braunmiller & Náblék 2002; Dziak et al. 1991, 2000). The effect of a 2, 3, 6.5 and 10 km thick zone is investigated for each fault and the predicted deformations are compared with those based on plate models and other means. For a reasonable range of $W$ and $M_{\text{max}}$, for each fault, the predicted deformation rates from seismicity statistics are comparable to plate model predictions and other geophysical data within a factor of two and usually $\pm 25$ per cent. This shows the soundness of the method, robustness of the data and the reasonable selection of parameters. The similarity of the deformation estimates based on seismicity and those from plate models shows a remarkable consistency for timescales ranging over five orders of magnitude, from decades to millions of years.

The best agreement between seismicity and plate model slip rates is for a thin effective seismic thickness of $W \sim 3$ km. There are two possible interpretations. These oceanic transform faults may have thick (approximately 10 km) effective seismic zones and seismicity may only be able to account for a fraction ($\sim 1/3$ to $1/2$) of the deformation. Alternatively, these faults may have thin (approximately 3 km) effective seismic zones in which most of the deformation is occurring seismically. The selection of a thick effective seismic zone is based on moment tensor solutions, but the solutions typically have no more than a 3 km resolution and the largest depths are set equal to the seismic thickness, even though the uppermost crust may not support significant earthquakes. We also argue that such solutions have significant depth bias. A thick $\geq 10$ km effective seismic zone for these and other oceanic transform faults is common in the literature. If such a thick zone is assumed, most of the deformation is determined to be aseismic in origin (e.g. Dziak et al. 1991; Braunmiller 1998; Dziak et al. 2000; Abercrombie & Ekstöm 2001; Braunmiller & Náblék 2002). Assuming a much thicker seismic zone in a study of 75 OTFs, Boettcher & Jordan (2001) calculated that only $\sim 15$ per cent of slip can be accounted for seismically. They concluded that oceanic transform faults are fundamentally different from continental transform faults on which deformation is generally dominantly seismic below an upper crust aseismic zone. If we accept that the effective seismic zone is of the order of 10 km the seismic deformations are $32 \text{ mm yr}^{-1}$ on the RDW, $24$ on the Sovanco, 9 on the Nootka, 21 on the Blanco and 35 on the Mendocino faults, which are significantly less than the deformation rates of plate models. We therefore favour the thin (approximately 3 km) effective seismic zone model.

$W = 3$ km may be explained by a combination of an aseismic sediment and highly porous and fragmented uppermost crust, and pervasive serpentinization in the uppermost mantle. The preferred estimates of seismic deformation rate are $68 \text{ mm yr}^{-1}$ for the RDW, $34 \text{ mm yr}^{-1}$ for the Sovanco, $18 \text{ mm yr}^{-1}$ for the Nootka, $45 \text{ mm yr}^{-1}$ for the Blanco and $54 \text{ mm yr}^{-1}$ for the Mendocino faults. The estimates for the Sovanco, Nootka and Blanco faults are comparable to, but slightly less than, the predictions based on plate models, whereas the prediction for the Mendocino Fault is virtually identical to the plate model prediction. The prediction for the RDW overestimates the plate model deformation. This is a tectonically complex region and some events in our data set may not be associated with slip on these faults. The majority of the deformation on the RDW, Sovanco, Nootka, Blanco and Mendocino faults can be explained seismically if the effective seismic zone is thin.

The uncertainty in these predictions (for $W = 3$ km) is investigated using the logic tree method. This produced a set of solutions, clustered around the preferred solutions described above. The deformation rates for a cumulative probability of 50, 16 and 84 per cent, give an idea of the most likely solution and the spread of solutions (comparable to $\sigma$) as well as the sensitivity of predictions to the least well-constrained parameters. The expected deformation based on plate models is well within the range of solutions for all five faults.

In order to establish the effective thickness of the seismic zone and what proportion of the deformation is occurring seismically, long-term in situ seismic studies are needed. OBS records of the depths of smaller earthquakes or a few large-magnitude events could distinguish between these models and have a significant impact on our understanding of the physical slip behaviour of these faults.

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**REFERENCES**

Abercrombie, R.E. & Ekstöm, G., 2001. Earthquake slip on oceanic transform faults, *Nature*, **410**, 74–77, doi:10.1038/35065064.
