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Evolution and progressive geomorphic manifestation of surface faulting: A comparison of the Wairau and Awatere faults, South Island, New Zealand

R. Zinke[1], J.F. Dolan[1], R. Van Dissen[2], J.R. Grenader[1], E.J. Rhodes[3,4], C.P. McGuire[4], R.M. Langridge[2], A. Nicol[5], and A.E. Hatem[1]

[1]Department of Earth Sciences, University of Southern California, Los Angeles, California 90089, USA
[2]GNS Science, PO Box 30-368, Lower Hutt, New Zealand
[3]Department of Geography, University of Sheffield, Western Bank, Sheffield, S10 2TN, UK
[4]Department of Earth, Planetary, and Space Sciences, University of California–Los Angeles, Los Angeles, California 90095, USA
[5]Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand

Quigley and Pettinga (2016), and Duffy (2016) comment on different aspects of recent analyses by us (Zinke et al., 2015) regarding patterns of off-fault deformation (OFD) at the Branch River (BR) and Saxton River (SR) sites along the Wairau and Awatere faults in South Island, New Zealand.

Quigley and Pettinga (2016) argue that the BR and SR sites are structurally and topographically dissimilar, and cannot, therefore, be compared. As we thoroughly discuss, however, the differences in structural complexity observed between the two sites are exactly what is expected for faults with vastly different cumulative displacements (>150 km for the Wairau and <20 km for the western Awatere fault [Little and Jones, 1998, and references therein]). The BR and SR sites are comparable because of their similarities in tectonic setting, subparallel strikes, climate history, sediment composition and age, and slip accumulated within each terrace. Differences in the structural complexities of the fault traces (including bends, steps, and amount of geomorphically evident OFD) can therefore be attributed to the structural maturity of the underlying faults. Thus, the more structurally complex trace of the Awatere fault at SR relative to that of the Wairau fault at BR is exactly what we would expect, given the differences in structural maturity.

Although there are topographic differences between the two sites—the SR site includes an ~150-m-high bedrock promontory (“bedrock spur”) and the BR site is ~0.5 km from the nearest significant topography—the observed patterns of deformation do not correspond with the topographic differences, as maintained by Quigley and Pettinga. For instance, modeling of gravitationally induced stresses due to topography (St. Clair et al., 2015) shows that failure potential of rock is greatest along and immediately adjacent to steep slopes. Topographically induced fracturing should therefore be more concentrated within and around the bedrock spur. At the SR site, secondary fault strands are most concentrated in the T1 terrace, hundreds of meters away from the break in slope (our figure 2B). In addition, secondary fault strands within the T1 terrace show no preferred orientation relative to the topographic trend of the bedrock ridge. Quigley and Pettinga further suggest that the topography of the underlying bedrock-sediment contact may influence surface fault expression. The limited control on the depth-to-bedrock beneath the terraces at the SR site (~1.2 m in paleoseismic trenches in T1, and ~2 m along a road cut at the southwest edge of T2, as discussed by us), however, suggests a relatively flat underlying bedrock surface that would not gravitationally affect the distribution or character of OFD. These observations obviate topography as a significant control on the patterns of OFD evident at these sites.

Quigley and Pettinga then go on to argue that structural maturity (cumulative offset) may not control the complexity of faulting along the Wairau and Awatere faults, citing examples of structurally complex sections and variable structural complexity along the Alpine and Hope faults in South Island, New Zealand. Quigley and Pettinga point out that despite the fact that the Alpine fault has accommodated >400 km of right-lateral displacement (e.g., Sutherland, 1999), its surface expression is, in many places, structurally complex. However, whereas the Wairau and Awatere faults are steeply dipping strike-slip faults, the Alpine fault is a moderately dipping oblique-fault, along which fault segmentation and structural complexity result from strain partitioning and gravitational effects due, in large measure to its substantial oblique-reverse component (e.g., Cooper and Norris, 1994; Barth et al., 2012). Thus, comparison of the surface expression of the distinctly kinematically dissimilar Alpine fault with the kinematically similar Wairau and Awatere faults is inappropriate.

Unlike the Alpine fault, the Hope fault is a relatively structurally immature fault, having accommodated only ~20 km of cumulative displacement (Freund, 1971). Along-strike differences in structural complexity—ranging from linear, single-stranded, simple sections to extremely complex sections—are common along such immature faults. We explicitly addressed this issue in our primary text, and in supplemental document GSA Data Repository 2015341 Item DR2, acknowledging these differences and showing that the BR and SR sites are representative of the broader structural complexity of the Wairau and Awatere faults. While examples of along-strike variability in the structural complexity of the Hope fault can be pointed out, these limited observations do not change the fundamental point made by us that the decreased structural complexity of the Wairau fault relative to that of the Awatere fault is the result of the different cumulative offsets between the faults, and resulting differences in their structural maturities. We therefore strongly dispute their assertion that “Clearly, structural maturity is not a primary control of OFD complexity and width variations along [the Wairau and Awatere] faults.” In fact, as shown by our analysis and numerous other analyses of faults outside of New Zealand, the association of structural complexity and fault maturity is inescapable (e.g., Wesnousky, 1988; Stirling et al., 1996; Dolan and Haravitch, 2014).

Finally, Quigley and Pettinga assert that strain localizes onto faults within only a few (~2–3) meters of displacement, and thus it is unlikely that the difference in accumulated displacement between the T2 and T3 terraces at SR accounts for the lack of OFD observable in the T3 and younger terraces. In doing so, they seem to have misunderstood that we are discussing two different processes that occur on completely different time scales—the long-term process of fault structural maturation, which occurs during tens of kilometers of fault slip (e.g., Wesnousky, 1988; Stirling et al., 1996), and the progressive manifestation of localized fault slip within relatively young sedimentary deposits, which we maintain occurs over tens of meters of slip. Quigley and Pettinga incorrectly assumed that geomorphically evident OFD observed in the progressively displaced terraces at SR decreases in younger, less displaced terraces due to “structural maturation” of the underlying bedrock-hosted fault. We explicitly stated that this is not the case. The basic point expressed by us is that the structural maturity of the underlying bedrock-hosted fault is roughly constant across all terraces at the SR site, even where it is not geomorphically evident. Recent work by Milliner et al. (2015) indicates that, in fact, several meters of coseismic displacement can be distributed throughout the near surface without any geomorphically discernable evidence in the microtopography. This was also shown in the 2010 Darfield rupture (which Quigley and Pettinga cited as an example of strain localization), where nowhere along the rupture was horizontal shear >30% localized onto a fault; most deformation was distributed over 25–150-m-wide zones—a significant amount of which was not discernible in lidar imagery (Van Dissen et al., 2011). Instead, multiple earthquake cycles are required for OFD to accumulate and coalesce into geomorphically discernable features that are preserved in the landscape. Quigley and Pettinga's argument therefore stems from an invalid understanding of a basic concept discussed in our paper.

Duffy (2016) raises a valid and important point. In retrospect, we should have discussed the impact of the local kinematics more fully, and we welcome the opportunity afforded by Duffy's Comment to describe more fully the structural and geomorphic relationships at the SR site. Duffy correctly points out that the patterns of OFD at the SR site are at least partially controlled by the paired releasing and restraining bends along the Awatere fault. Specifically, deformation within ~100 m of the fault across terrace T1 does indeed reflect oblique-normal faulting associated with the releasing bend. However, deformation farther from the fault in T1 does not. If this distal deformation is related to the adjacent restraining bend, or more generally the structural complexity of the fault expressed in the underlying bedrock (which at SR may be controlled by complex strain transfer southeastward to the Barefell Pass fault), then it should not stop as it does at the T1-T2 terrace riser. Rather, it should extend out to similar fault-perpendicular widths across T2, which it certainly does not. Secondary fault strands are notably absent across most of T2, with almost all OFD concentrated in a narrow, ~20–50-m-wide pressure ridge along the fault trace. The broad regions of T2 devoid of geomorphically discernable OFD are directly adjacent to regions with clear geomorphic evidence for OFD in the T1 terrace (our figure 2). This sharp divide between discernable OFD in the older, more displaced T1 terrace and the younger, less displaced T2 terrace implies that while a significant amount of off-fault strain is accommodated within T2, OFD has not accumulated sufficiently to localize into geomorphically evident fault strands. This observation supports our original conclusion that OFD occurring along most surface ruptures in loose sediments will not be geomorphically discernable in surfaces that have not experienced sufficient overall cumulative slip. Consequently, OFD will become progressively better expressed in older, more displaced features within kinematically similar settings. The fact that greater amounts of slip in older surfaces are not observed in the western part of the Hope fault Poplars Graben site (cited by Duffy as a kinematic and geomorphic analog to SR), where the secondary faults cross terraces of different ages (Cowan, 1990), may be due in part to the position of the releasing bend within the younger deposits, and in part to the reactivation of the secondary faults as landslides down the ~150-m-high bank of the Hope River.

To further illustrate our conclusion that OFD becomes progressively manifest as a function of cumulative displacement, we examine another releasing bend along the Awatere fault, ~3 km west of the SR site (Fig. 1). This releasing bend is kinematically similar to the releasing step at the SR site. However, the Terrace B tread near the releasing bend has experienced ~11 m of offset; channel offsets on the tread of ~4 m indicate limited subsequent flow across the tread in local incised channels. Yet no OFD is geomorphically evident within Terrace B. While OFD almost certainly occurs during slip through this releasing bend, as it does at the SR site, the terrace has not accumulated enough slip for the OFD to become manifest in the microtopography. Taken in context with the more abundant, geomorphically evident OFD in older, more displaced terraces around the releasing bend at SR, these observations show that, as stated by us and shown by studies of surface deformation in recent surface ruptures (e.g., Van Dissen et al., 2011; Milliner et al., 2015), while the mechanisms accommodating OFD are active throughout each earthquake, OFD may not become manifest in the landscape until sufficient slip has accumulated.

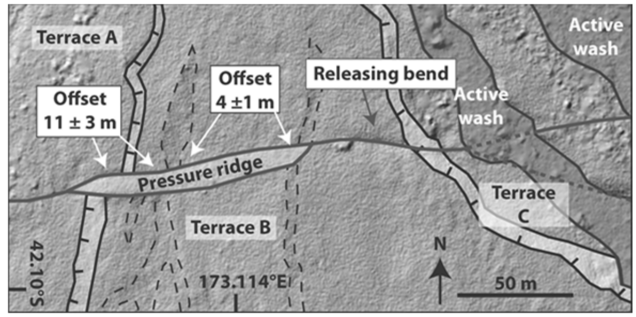

Figure 1. Releasing bend along the western Awatere fault. No off-fault deformation is geomorphically discernible in the vicinity of the bend due to the small amount of offset (4–11 m) accumulated by Terrace B.

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