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Relative displacement across faults: measuring slip rates when both blocks are uplifting

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ABSTRACT: A trench across the main strand of the Red Mountain fault, California, presents problems in calculation of slip rates when both sides of the fault are uplifting. The Red Mountain fault is a reverse fault in the Transverse Ranges of California. It is part of a system of north-dipping reverse faults including the San Cayetano and the Santa Susana faults. The slip rates have been measured at 7.4±3.0mm/y on the San Cayetano fault, and 5.9±3.8mm/y on the Santa Susana fault. This work represents the first slip rate measurement on the Red Mountain fault. The footwall block of the Red Mountain fault has the stage 3c high stand terrace, confirmed using oxygen isotopes. This terrace has uplifted from –39m elevation at 45ka, to +168m today, an uplift rate of 4.6mm/y. The trench, geological mapping, and borehole drilling show that the hanging-wall block has uplifted 34m (0.75mm/y, 1.7mm/y slip on a 25º–dipping fault) relative to the footwall block in that time. We argue that the slip rate on the Red Mountain fault is the combination of these rates, and thus has serious implications to tectonics of the Transverse Ranges and the relative seismic hazard represented by the fault.

1 INTRODUCTION

Trenching, geological mapping, and borehole drilling was conducted to establish a slip rate on the north-dipping Red Mountain reverse fault, in the Transverse Ranges of California, USA. This work comprises the first short term slip rate calculation on the Red Mountain fault.

The stage 3c high stand terrace, the Punta Gorda terrace is uplifted 34m across the fault over the last 45ka. The age of the terrace is confirmed by oxygen isotope dating of Olivella shells. However, the Punta Gorda terrace was deposited at about –39 m water depth. It now is at +168m elevation, implying that the footwall block is uplifting faster that the hanging-wall block. This paper will analyse this and other places where uplift of the footwall block is apparent in order to develop criteria for using the uplift rates of the footwall block in addition to the relative rates measured near the surface or in keeping the two measurements separate.

2 BACKGROUND GEOLOGY

The Red Mountain fault is part of a north-dipping reverse fault system that includes the San Cayetano and Santa Susana faults (Fig 1). There is a complex interaction between this north-dipping fault system and a south-dipping fault system that includes the Northridge thrust in the east beneath the San Fernando Valley, the active segment of the Oak Ridge fault in the centre, and the western inactive segment of the Oak Ridge fault that has transferred its displacement to the Ventura Avenue and the Rincon anticlines. The Northridge thrust is observed only in the subsurface and was responsible for the 1997 Northridge earthquake, Mw6.7. Active deformation in the footwall block of the Santa Susana fault is suggested by the fact that the fault crops out well up into the Santa Susana Mountains, rather that at the foot of the mountains (Huftile and Yeats, 1996).

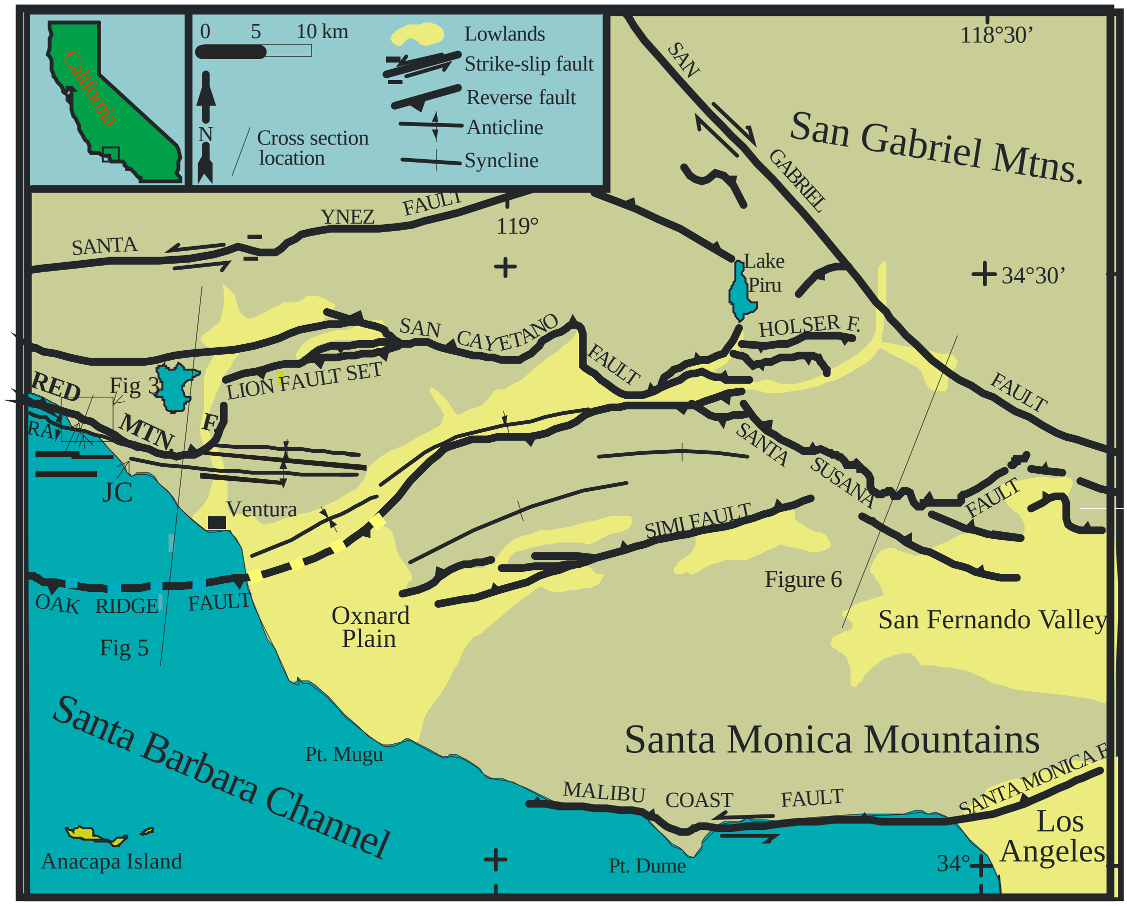


Figure 1: Location map showing the Red Mountain fault study area at far left. Other studies discussed that have uplift of the footwall block are at Javon Canyon (JC), and the Northridge thrust beneath the Santa Susana fault to the east. The Punta Gorda Terrace (PG) is uplifted by folding of the Rincon anticline (RA), the seaward extension of the Ventura Avenue anticline. The Red Mountain fault is part of a system of north-dipping reverse faults that includes San Cayetano and Santa Susana faults. This overrides and interacts with a south-dipping reverse fault system that includes the Northridge thrust in the subsurface beneath the San Fernando Valley, the active segment of the Oak Ridge fault, and the inactive western segment of the Oak Ridge fault that transfers its slip to the Ventura Avenue and Rincon anticlines.

The Santa Clara Valley separates the active segment of the Oak Ridge fault from the San Cayetano fault. The valley is underlain by very thick, ~5km, Plio-Pleistocene sedimentary rocks (Huftile and Yeats, 1995).

There is no topographic relief along the western, inactive segment of the Oak Ridge fault (Fig. 1). Slip is transferred from the fault along a décollement to the Ventura Avenue and the Rincon anticlines.

The anticlines occur directly in the footwall block of the Red Mountain fault because of the large strength contrast between the Oligocene and older rocks in the hanging-wall block and the Miocene to Pleistocene rocks in the footwall block.

3 RED MOUNTAIN FAULT TRENCH

The trench location was chosen because it had a distinct topographic scarp and because it lay along the edge of an alluvial fan that might have contained datable material (Fig. 2).

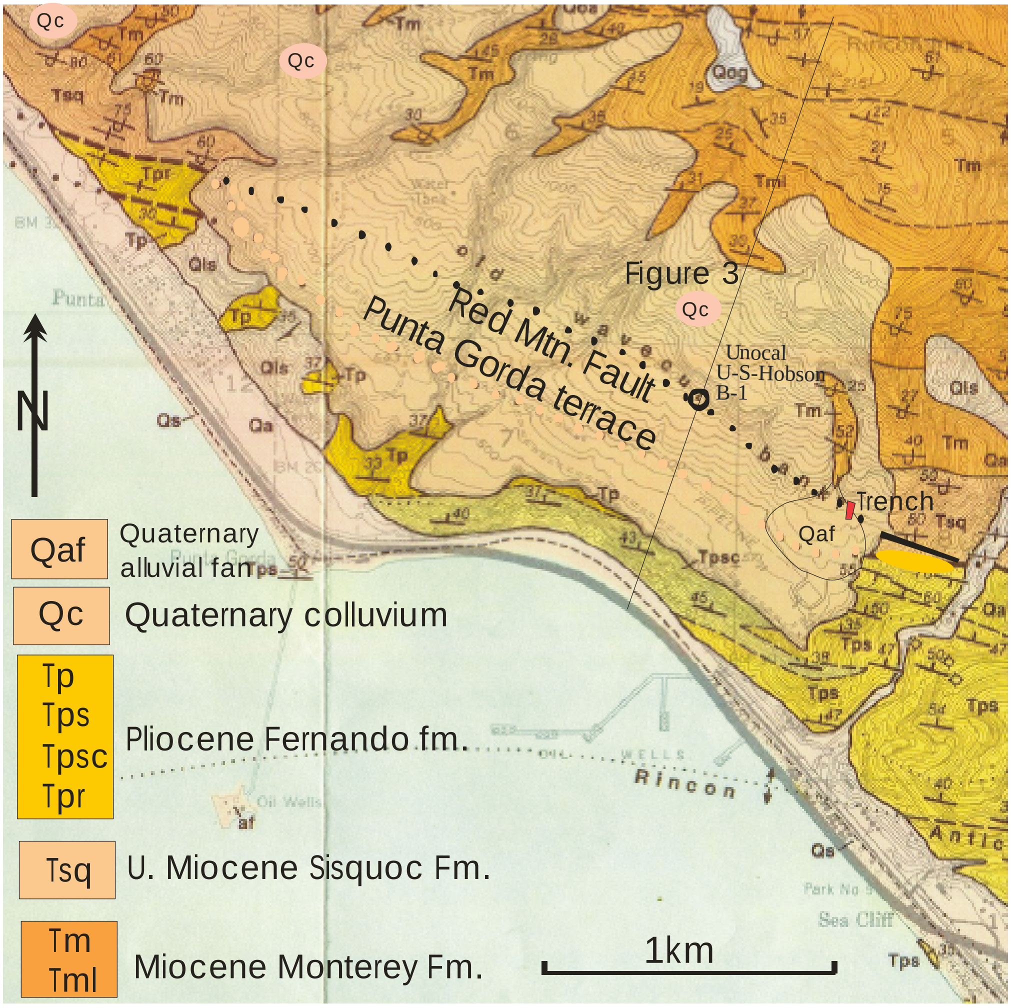


Figure 2: Geologic map near the Punta Gorda terrace after Dibblee (1988). Topographic contours are in feet. The Red Mountain fault is expressed to the east as a topographic scarp. There are only thin terrace deposits north of the fault. An alluvial fan overlies the terrace. The Rincon anticline is the offshore extension of the Ventura Avenue anticline.

Beneath the terrace are Pliocene and Miocene sedimentary rocks. These rocks are folded on the northern limb of the Rincon anticline.

The subsurface is fairly well known through oil wells. Yeats et al. (1987) have mapped it to a depth of 3 km. Figure 3 shows a cross section through the upper 3 km of the fault, through the Hobson B-1 well, near the trench. The fault does shallow at depth to about 30° (Huftile and Yeats, 1995).

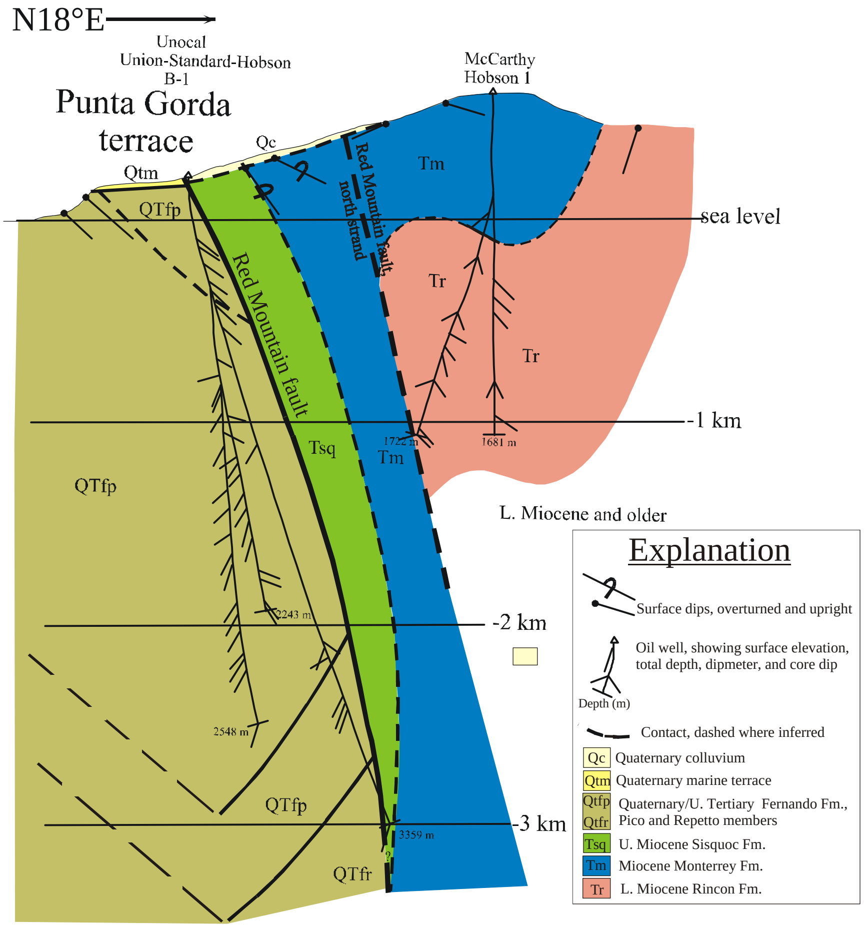


Figure 3: Structural cross section showing the relationship between the Punta Gorda terrace and the underlying bedrock. The north dip beneath the terrace is the north limb of the Rincon anticline (Fig 2). Location shown on Figures 1 and 2.

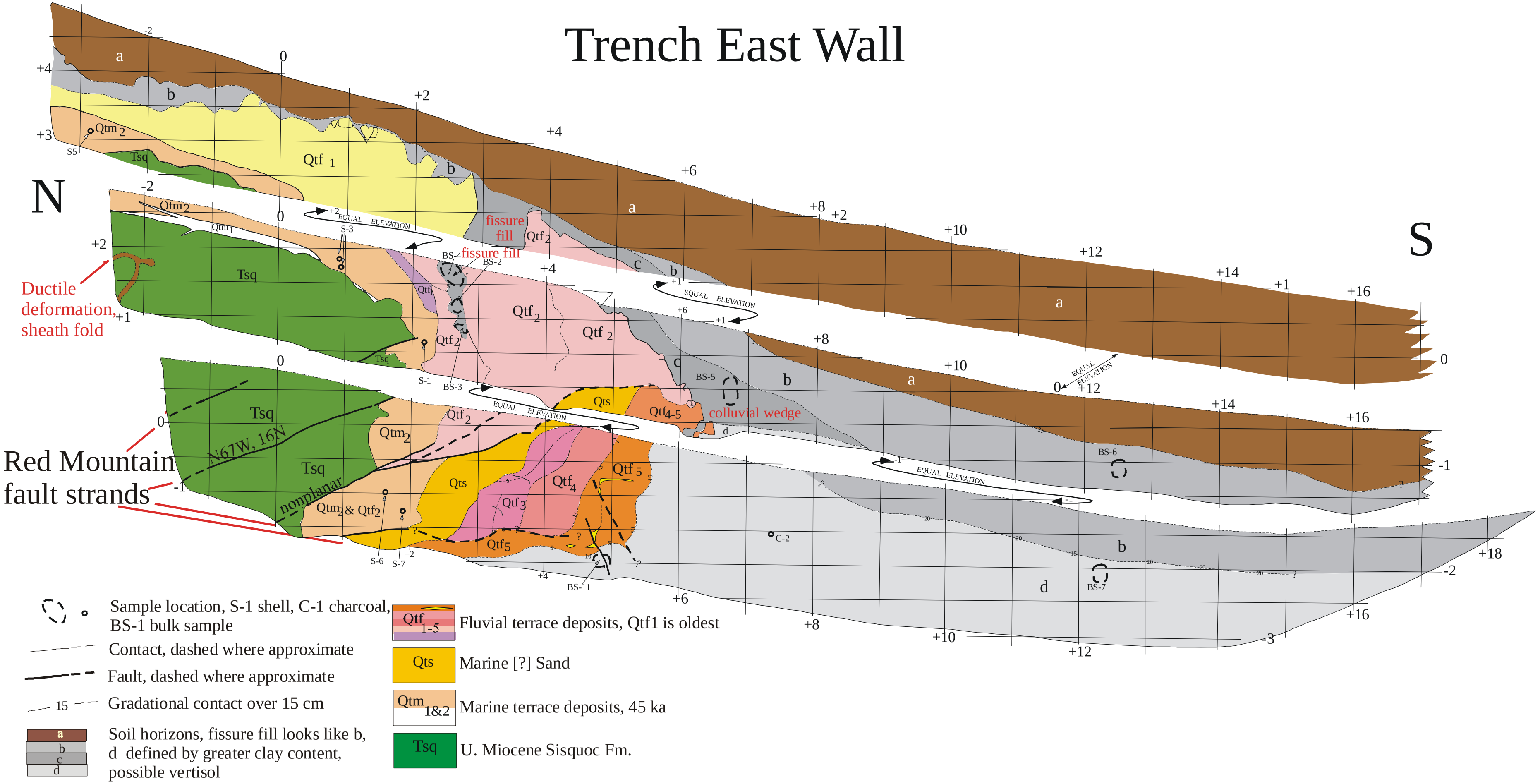
The trench exposures (Fig. 4) reveal that a significant portion of the near surface deformation of this reverse fault has occurred as folding. There is a vertical limb composed of terrace deposits which formed as the 60° dip on the fault, found to 3 km depth in oil wells (Fig. 3), shallows near the surface to ~20°. Subsequent movement on the fault occurred on an upper ~30° dipping fault strand, cutting the hanging-wall block of the fault and isolating the recumbent fold in the footwall block.

There is evidence of past earthquakes in a colluvial wedge and a fissure fill in the hanging-wall block. Attempts were made to constrain the timing of the most recent event by using ^{14}C dating of detrital charcoal fragments found in the fissure fill and the colluvial wedge, but were unsuccessful.

The most meaningful result was the identification of the basal shell lag of the 45ka Punta Gorda terrace occurring in the hanging-wall block of the fault. Precise geodetic measurements of the elevations across the fault show an uplift of 34m. This yields an uplift rate across the fault of 0.75mm/y. Assuming a near surface dip of about 25° similar to the trench (Fig. 4), the slip rate is calculated to be 1.7mm/y. If it is assumed that the dip is 60° as in Figure 3, the slip rate would be 0.9mm/y.

Figure 4: Sketch of terraced trench wall looking east. Grids are ½ X 1m. Vertical grids align, horizontal grids are slightly offset. Terrace deposits are strongly folded, possible due to ductile deformation in bedrock. The thick soils are the alluvial fan deposits (Fig. 2). The trench shows evidence for recent activity in the formation of a colluvial wedge and a fissure fill. Location shown on Figure 2.

Trench East Wall



4 ANALYSIS

The observation that the terrace in the footwall block is uplifting 4.6mm/y and the fault uplifts the hanging-wall block 0.75mm/y presents a problem. If the relative displacement rate across the fault is valid as the slip rate on the entire fault, then the hanging-wall block of the fault would be down dropped, not uplifted. Huftile and Yeats (1995) show that the hanging-wall block is uplifted more than 8 km (Fig. 5a). Because the uplift of the footwall block is independent of the uplift on the fault, then we must conclude that the movement of the hanging-wall block is outpacing the uplift of the footwall block by 1.7 mm/y. Therefore the slip rate on the fault is 6.3mm/y adding the two rates.

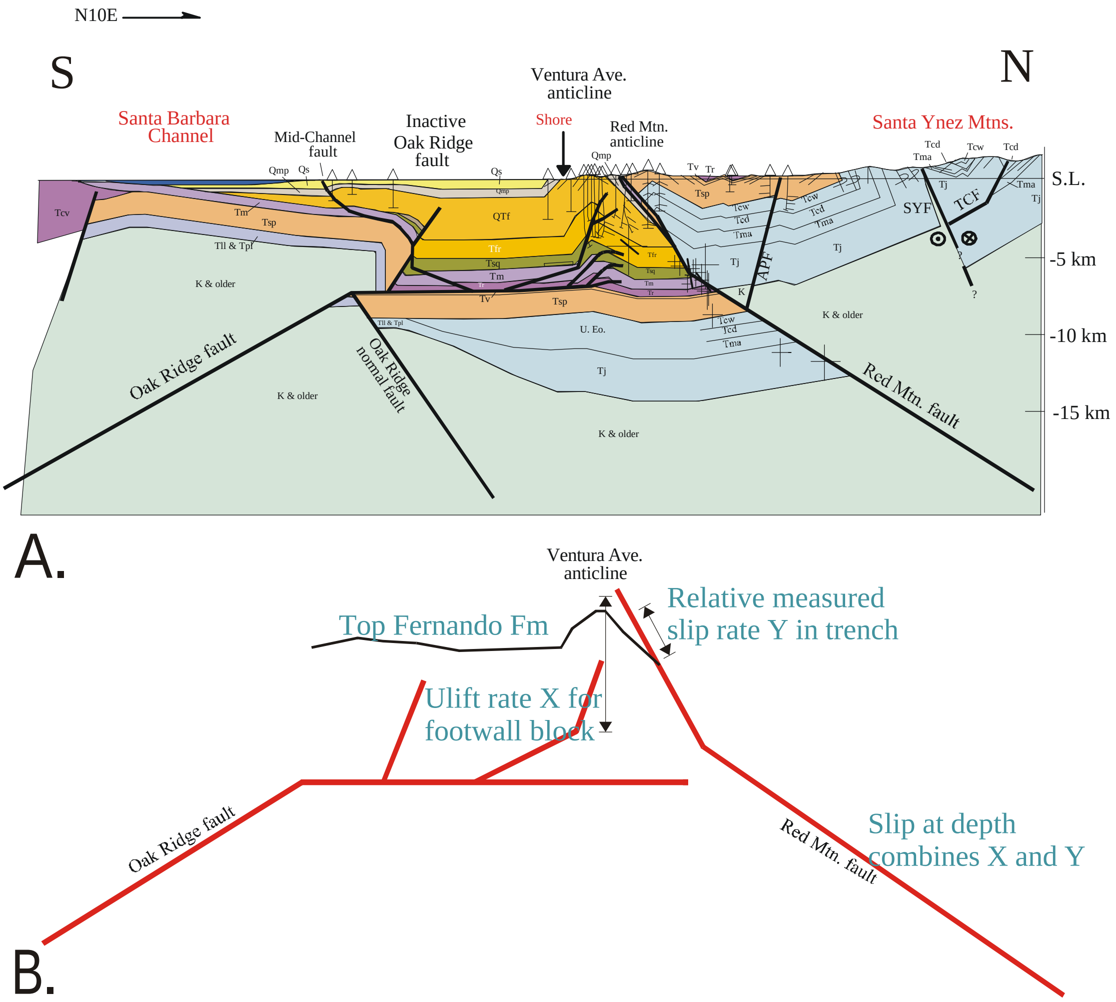


Figure 5: (A) Upper crustal deformation model from Huftile and Yeats (1995). The Oak Ridge fault is inactive to the west (Fig. 1). The slip is transferred along a décollement in Lower Miocene mudstones to the Ventura Avenue anticline. The Red Mountain fault has over 8 km of reverse slip. Earthquakes and modelling of the major syncline in the hanging-wall block suggest a shallower dip at depth. The Ventura Avenue anticline is located immediately in the footwall of the Red Mountain fault because of the strength contrast of the rocks on either side. Pliocene rocks are orange. (B) Because the two fault systems are independent, the slip on the Red Mountain fault measured at the trench is only relative to the uplifting terrace. Therefore, the slip at depth must be sufficient to outpace the uplift of the footwall block.

Another occurrence of footwall block uplift occurs just south east of the Punta Gorda terrace at Javon Canyon. The Javon Canyon fault occurs within the Ventura Avenue anticline. Thus folding of that anticline uplifts both sides. Sarna-Wojcicki et al. (1987) report a slip rate of 1.1mm/y on the fault. This is likely to be valid because the measurement of the relative rate is unaffected by uplift by the folding of the anticline.

The Northridge thrust dips south and occurs in the footwall block of the north-dipping Santa Susana fault. Both faults are thick-skinned. The Northridge thrust caused the Mw 6.7 Northridge earthquake and it was not known before then. The active Santa Susana fault is well known. Two observations may have helped discover the fault prior to the earthquake. First, that the active Santa Susana reverse fault does not crop out at the foot of the mountains as would be expected for an active reverse fault. Rather it crops out well up in the hills, suggesting uplift of the footwall block. Second, oil wells show that the Santa Susana fault is folded, having a shallow dip near the surface and steepening at depth (Yeats, 1987; Huftile and Yeats, 1996).

The uplift of a thick-skinned fault often involves the steepening of a forelimb. That is what we observe in Figure 6. Slip on the Northridge thrust uplifts and deforms the Santa Susana fault. Because of this relationship, the relative slip rate measured across the fault would be an accurate measure of the Santa Susana slip rate.

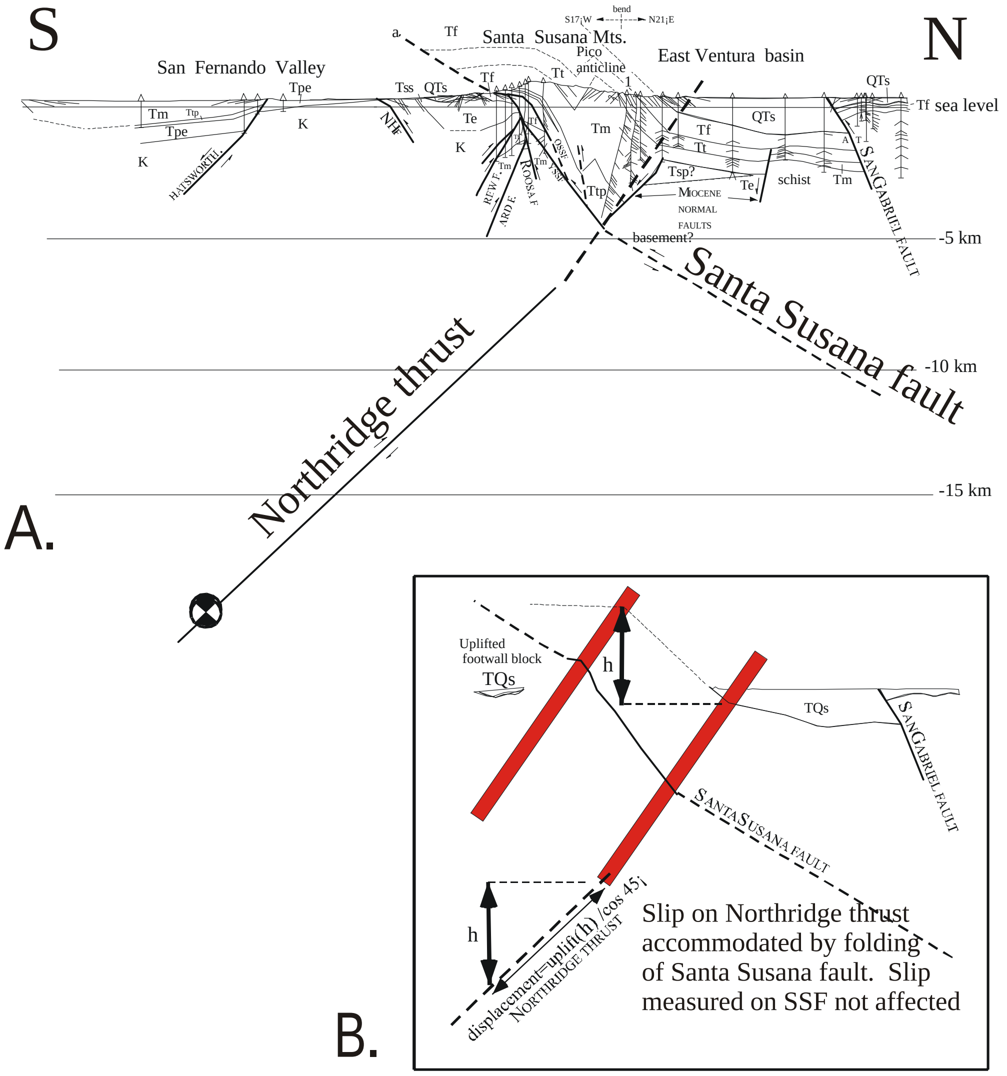


Figure 6: (A) Cross section through the Northridge earthquake and the Santa Susana fault from Huftile and Yeats (1996). Uplift along the Northridge thrust forms a forelimb with the Santa Susana fault shallowly dipping near the surface, more steeply dipping below that to –5km, then shallowly dipping at depth. (B) Uplift on the Northridge thrust is expressed by the separation of the two fold hinges in red.

5 CONCLUSIONS

When the footwall block of a reverse fault is uplifting, one must analyse the reason for the uplift and its affect on the fault in order to determine whether or not the relative slip determined in a trench is valid. Three cases were analysed. At Javon Canyon, the Javon Canyon fault is part of the faulting within the Ventura Avenue anticline (Sarna-Wojcicki et al., 1987). Both sides of the fault are uplifting. Therefore, the relative slip measured across the fault in a trench is valid, because it represents the slip on that fault, independent of uplift on the Ventura Avenue anticline.

The Northridge thrust is a thick-skinned reverse fault in the footwall block of the Santa Susana fault. Movement on the Santa Susana fault is roughly 4 times as fast as on the underlying Northridge thrust (Huftile and Yeats, 1996). Movement on the Northridge thrust is taken up by folding along its forelimb. It does in fact fold the overlying Santa Susana fault and the rocks in its hanging-wall block. So uplift on the Northridge thrust affects both sides of the fault equally. Therefore, measurement of relative slip on the fault is valid.

The Red Mountain fault is different. The fault and the hanging-wall block are unaffected by folding of the Ventura Avenue anticline. In fact the anticline occurs directly in the footwall of the Red Mountain fault because the rocks in the hanging-wall block act as a buttress. Uplift on the Ventura Avenue anticline is independent of slip on the Red Mountain fault. In fact, it must be because the footwall block is uplifting several times faster than the relative slip on the Red Mountain fault measured at the trench. So determination of slip and slip rates on the Red Mountain fault must take into account that relative slip rate and the uplift of the footwall block. This results in a slip rate calculation for the Red Mountain fault of 6.3mm/y.

Comparison of known rates shows a pattern (Fig. 7). The north-dipping faults all have similar slip rates. This would not be the case if we accepted the relative slip rate measured at the trench on the Red Mountain fault. The Red Mountain fault poses a significantly greater seismic hazard than would be expected if the relative rates measured at the trench were accepted as the slip rate for the fault.

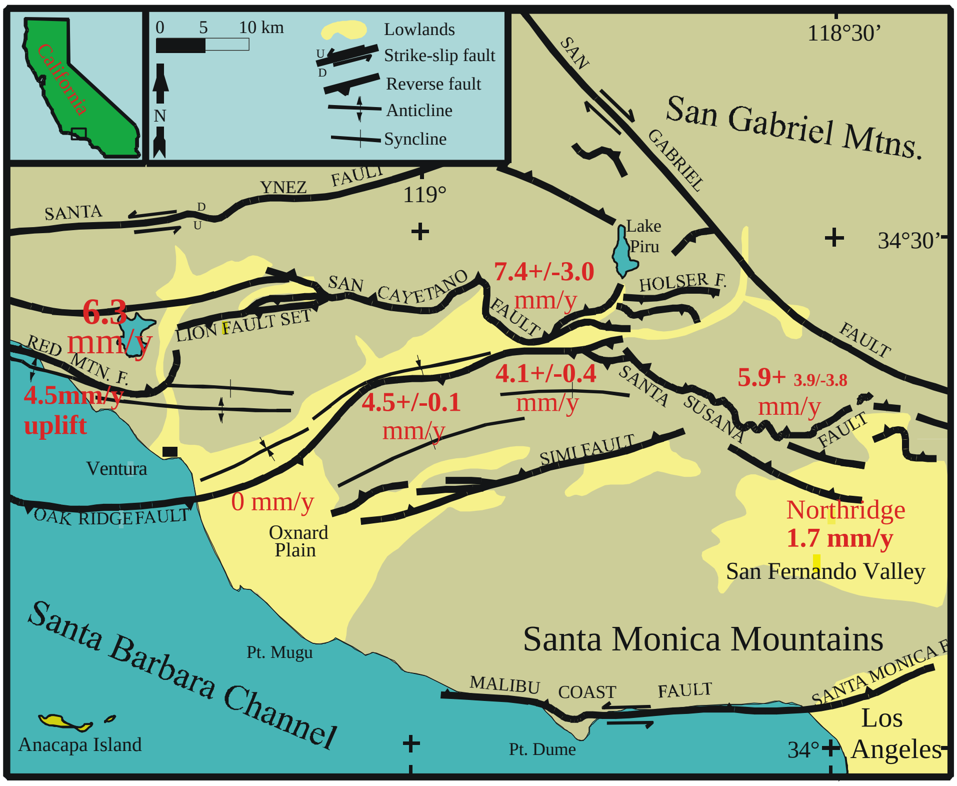


Figure 7: Comparison of rates on the north- and south-dipping fault systems. The north-dipping faults all have similar slip rates. The south-dipping faults increase slip rates to the west.

The south-dipping faults have increasing slip to the west. The Northridge thrust is moving 1.7mm/y. This rate increases along the Oak Ridge fault. Where the slip on the Oak Ridge fault goes to zero, uplift on the Ventura Avenue anticline increase to a similar amount. Assuming this uplift relates to faults with moderate dips as in Figure 5, the slip on those faults could be much higher than on the Oak Ridge fault.

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