THRUST FAULTING AND EARTHFLOWS: SPECULATIONS ON THE SEDIMENT BUDGET OF A TECTONICALLY ACTIVE DRAINAGE BASIN

by

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Introduction

In the last decade, considerable effort has been devoted to the definition and construction of sediment budgets in mountainous terrain, chiefly in Northern California, Oregon, and Washington (e.g., Dietrich and Dunne 1978; Dietrich and others 1982; Lehre, 1982a,b; Lehre, Collins, and Dunne 1983; Kelsey 1980, 1982; Kelsey and others 1981; Reid 1981). These studies have shown the utility of sediment budgets for predicting sediment yield and understanding process linkages; ultimately they should allow us to model landscape evolution. Although these studies were generally conducted in tectonically active areas (e.g., Kelsey 1980), none incorporated the possibility of direct tectonic transfer of material into the drainage basin. Many of these papers assume, in one sense or another, approximate long-term equilibrium between processes and products (e.g., in calculating soil residence time), but none considers the effect of tectonic input on equilibrium. Our objective in this paper is not to present finished research on the relations between tectonism and erosion in the Jacoby Creek basin --for that we have not got--but instead, to stimulate discussion as to what the relations are, how they might be modeled, what sorts of investigations/measurements might be useful in understanding them, and what their equilibrium implies. To this end we use a variety of crude mass-balance models, discussed below.

The Jacoby Creek Basin

The basin of Jacoby Creek above the gaging site is roughly rectangular, averaging 3.3 km wide and 11 km long (fig. 1). It is bounded on the north by Fickle Hill and on the south by Kneeland Ridge. Its vital statistics are summarized in Table 1. The creek heads at elevations of 550-650 m; the stream gage is at about 15 m (fig. 1). Average slope of the north side of the basin is 11°; that of the south side is 14°. The basin is covered chiefly by second-growth coniferous forest, parts of which are currently being logged.

The upper slopes of Fickle Hill consist largely of Franciscan melange and greywacke which have been thrust southward over Pleistocene shallow marine and continental sediments of the Falor Fm (Carver and others 1982; Carver and Stephens 1983; Carver, this volume). Falor sediments form much of the lower slopes of Fickle Hill. A small, nearly-horizontal patch of Falor sands lies in depositional contact with Franciscan melange on the crest of Fickle Hill (fig. 2 and Carver, this vol.) Kneeland Ridge consists chiefly of Franciscan rocks with a thin veneer of northeast-dipping Falor Fm --again in depositional contact with the Franciscan-- present locally near the creek.

Two major thrusts crop out on Fickle Hill about one third of the way between the creek and the divide (fig. 2). These faults, which are no older than about 1 m.y., have a total offset of around 1 km (Carver, this vol.) Estimates of faulting recurrence intervals, based on fault length-magnitude and magnitude-slip relations (e.g., Slemmons 1977), are on the order of

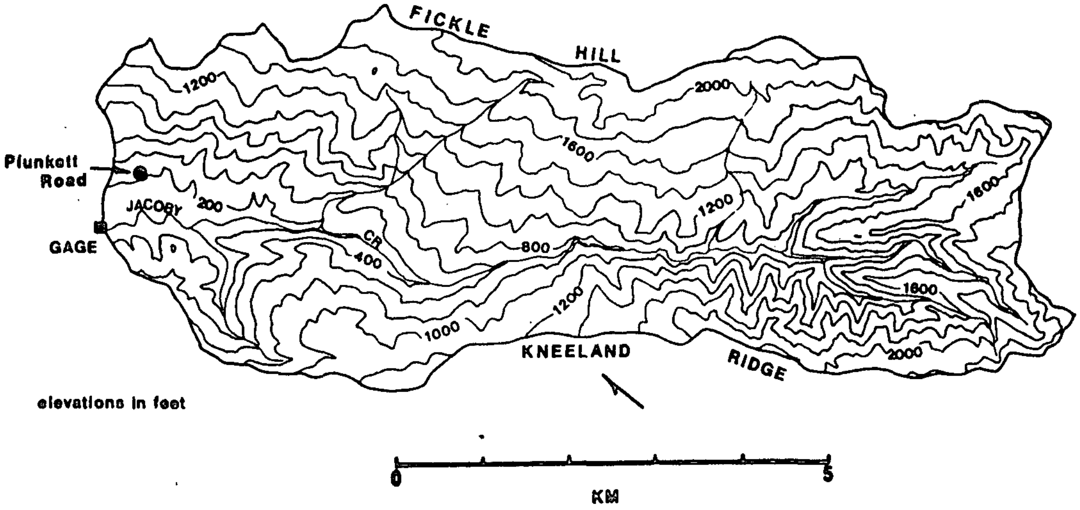

Figure 1. Topographic map of Jacoby Creek drainage basin above Tom Lisle's gage at covered bridge, compiled from Arcata South, Korbel, and Iaqua Buttes 7.5' quadrangles. Gage is located 4.7 km SE of Arcata, CA. Note that elevations are in feet.

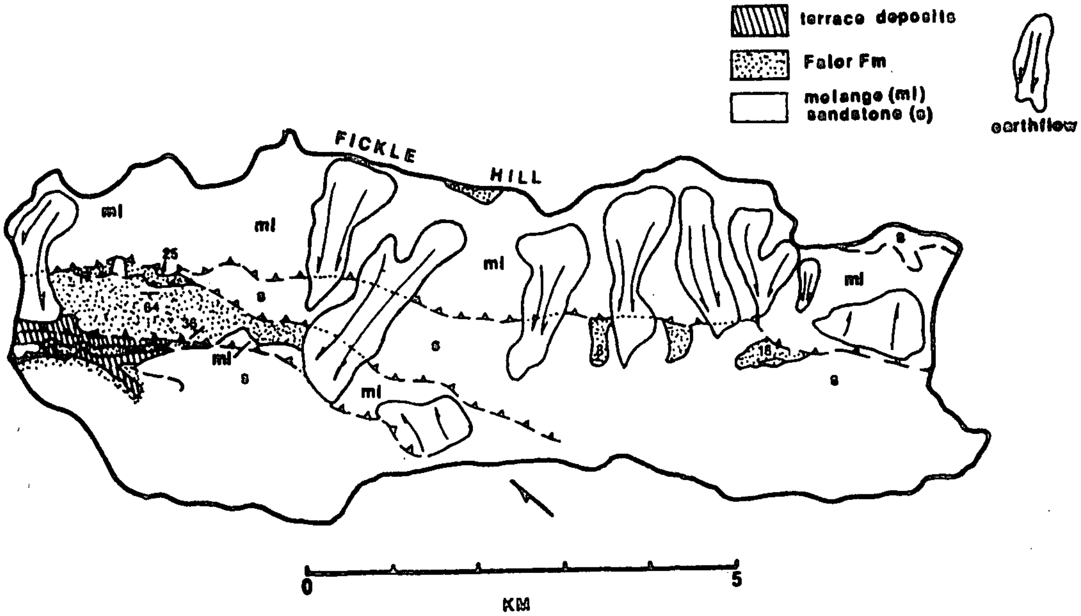

Figure 2. Geologic map of Jacoby Cr basin, simplified from mapping of Carver and Stephens (1985). Melange (ml) and greywacke sandstone (s) belong to the Franciscan group. Only active earthflows are indicated.

Table 1: Vital statistics of the Jacoby Creek basin

quantity	symbol	value	
drainage area	A	35.5	km^2
length of mainstem channel	L_{main}	12.5	km
total length of channels in basin	L_{tot}	160.5	km
drainage density	D_d	4.52	km/km^2
basin volume	V_{basin}	5.0	km^3
mean thickness of thrust sheet at divide	D_{thr}	0.84	km
relief ratio	R_r	64.2	m/km
mean annual discharge	Q_{mean}	0.85	m^3/s

5000-10,000 yr for offsets of 5-10 m/event. A reasonable estimate for mean rate of fault offset (Carver, this vol.) is 1mm/yr (1 m/1000 yr). This rate, which may be in error by 30%, is used throughout this paper.

The overall structure of Fickle Hill is an anticline cut by thrusts on its south flank. Jacoby Cr runs approximately along the axis of the adjacent syncline (fig 3). Structural relief due to folding is unknown, but is at least 200 m.

Erosional Processes in the Drainage Basin

Erosional processes active in the Jacoby Cr watershed are slump-earthflow, shallow debris slides, soil creep, sheet/rill erosion, and fluvial incision. Of these, large, active slump-earthflows originating in Franciscan melange appear the most important; they cover 20% of the drainage area of Jacoby Creek (from mapping of Carver and Stephens, 1985; see also fig. 2.) These earthflows typically head near the crest of Fickle Hill and extend down tributary valleys to Jacoby Creek. Old earthflow deposits and colluvium mantle interfluves between the mapped flows; these deposits (not shown on the geologic map) suggest more widespread earthflow activity in the past.

Shallow debris slides are restricted to colluvial hollows in Franciscan greywacke or are associated with roadcut and fill failures. Preliminary airphoto reconaissance suggests that these are quantitatively much less important than earthflows.

Seasonal and biogenic soil creep, as will be discussed later, are probably relatively unimportant. Sheet and rill erosion are important chiefly where vegetation has been removed by logging and roadbuilding; again, we suspect that they are quantitatively relatively unimportant.

Slopes in the Jacoby Cr drainage have obviously been dissected by streams. We have not yet been able to quantify their contribution to overall sediment yield, but they are clearly important in feeding earthflow debris and other slope-derived material to the main channel.

Sediment Yield of Jacoby Creek

The current sediment yield of Jacoby Creek at the gaging site, estimated by the duration curve - sediment rating curve method, is about 5500 t/yr. The sediment rating curve is based on 109 instantaneous water discharge and suspended-sediment concentration measurements taken during the period December 1978-December 1979 (Tom Lisle, unpub. data). We estimated the duration curve by prorating (by ratio to mean annual discharge) 1956-65 daily discharge data collected at a site 6.5 km upstream (Jorgensen and others, 1971). This technique has proved highly effective for regionalizing duration curves of North Coast streams (Lehre, unpub. data). The suspended load averages about 60% silt/clay and 40% sand (T. Lisle, pers. comm. 1985).

Bedload discharge in Northern California streams averages about 10-15% of suspended load discharge, although observed values range from 1-40% (see Lehre 1982a, Table 55). We have chosen 15% (825 t/yr) as a reasonable value for Jacoby Creek; bedload transport measurements at the site (Tom Lisle, pers. comm. 1985) confirm this. Bedload in Jacoby Cr is largely gravel.

We estimate total particulate load (bedload + suspended) for the creek at 6325 t/yr. Because we have no measurements of dissolved load, we ignore it below.

= .7 T/Ac/YR

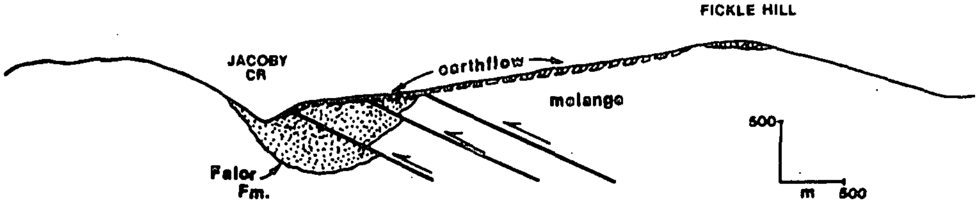

Figure 3. Structural cartoon of the Jacoby Cr basin based on mapping of Carver and Stephens (1985). Contact between Pleistocene Falor Fm. and Franciscan rocks (chiefly melange) is erosional unconformity, in part representing old abrasion platform. Thickness of Falor deposits in valley and amount of offset on individual faults are not known. Aggregate offset on faults in last 1 m.y. is about 1 km; north of Fickle Hill Falor Fm is 1 km thick. Thickness of earthflow deposits is exaggerated.

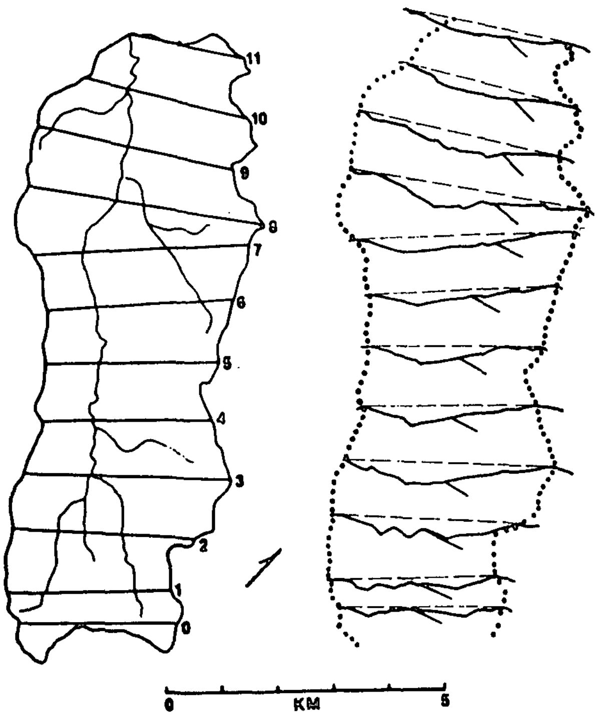

Figure 4. Cross-sections used to determine volume of Jacoby Cr basin. Dashed line is ridge-ridge tangent plane. Uppermost thrust is shown in each cross-section. No vertical exaggeration.

Denudation Rate and Soil Residence Time

Denudation rate for the drainage, assuming uniform lowering of the ground surface and no net storage of material in the basin, is given by a mass balance between sediment discharge and quantity eroded:

$$\text{denudation rate (m/yr)} = Q_s/AP_{rock} \qquad (1)$$

For sediment discharge Q_s of 6325 t/yr (178 t/km^2/yr), A of 35.5 km^2, and P_{rock} of 2.5 t/m^3, the denudation rate (as rock) is 0.07 m/1000 y (.07 mm/yr). For soil with P_{soil} of 1.2 t/m^3, the denudation rate (as soil) is 0.15 m/1000 yr (0.15 mm/yr). In contrast, uplift rates computed from marine terraces in the Arcata-Trinidad area are 0.3-0.6 m/1000 yr (Carver and others 1982; Stephens 1982). Uplift is thus about four to eight times faster than denudation, implying 200 to 500 m of area-wide net uplift in the last 1 m.y. if the rates are valid over that time interval. A patch of shallow marine Falor Fm less than 2 m.y. old lying on top of Fickle Hill at 620 m (fig. 2, and Carver, this vol.) suggests the rates are reasonable.

Soil depth (pedogenic horizons) on hillslopes in the Jacoby Cr basin is on the order of 1.0 m. If we assume that soil thickness at any point stays constant with time (Dietrich and Dunne 1978), then a mass balance gives the number of years needed to erode the mean soil depth, z_{soil}:

$$\text{residence time (yr)} = (AP_{soil}\, z_{soil})/Q_s \qquad (2)$$

This yields a residence time of 6700 yr, which seems exceptionally short for a forested basin. By contrast, Dietrich and Dunne (1978) estimated a 20,500 year residence time for soil in a forested basin in the Oregon Coast Range, and Kelsey (1982) estimated 15,000-50,000 yr of residence for surficial material in the Van Duzen River drainage. Residence times on the order of 12,000-20,000 yr thus seem more reasonable for Jacoby Cr soils. Possible causes of our seemingly low residence time are: 1) soils are at least twice as thick as we estimate, which does not seem reasonable; 2) current sediment yield is at least two times larger than the long term yield, which is possible, but has no supporting evidence; or 3) the assumptions of the residence time model do not apply because mass transport processes (such as earthflows) contribute significant volumes of saprolite, colluvium, and sheared rock as well as soil to the channel system. From fig. 2 this seems the most likely explanation.

Soil Creep vs. Earthflows

Several studies in the coastal mountains of northern California (Lehre 1982a,b), Oregon (Dietrich and Dunne 1978; Dietrich and others 1982), and Washington (Reid 1981) have proposed that sediment is transported from hillslope to stream chiefly by shallow debris slides and flows originating from colluvium-filled bedrock hollows (swales), which episodically fill and evacuate. These hollows fill by soil creep until sufficient material accumulates to allow sliding; thus creep rate, together with spatial frequency of hollows, ultimately determines denudation rate. This model appears generally applicable to steep slopes in weathered coherent rock (e.g., greywacke or volcanics); it is unlikely to be applicable where slope materials contain sufficient clay to allow flowage (e.g., Franciscan melange matrix).

A crude test as to whether soil creep could be responsible for most present-day denudation can be made by using a mass balance to compute the creep rate necessary to provide the observed sediment yield. Assuming a uniform creep rate supplying material to both banks of all channels in the basin:

$$\text{equilibrium creep rate (m/yr)} = Q_s/(2L_{tot}\, z_{cr}\, P_{soil}) \qquad (3)$$

where L_{tot} is the total length of channels in the basin and z_{cr} is mean thickness of the creeping material. Using L_{tot} = 160,500 m and assuming z_{cr} = 0.5 m, the required equilibrium creep rate is 0.033 m/yr (33 mm/yr). If the creeping layer is 1 m thick (which seems unreasonably large) the required creep rate is 0.016 m/yr (16 mm/yr). Since observed rates of seasonal or biogenic soil creep in such environments (Young 1972, Saunders and Young 1983) are on the order of 1-4 mm/yr, it appears unlikely that soil creep could be responsible for most current denudation of the basin. Assuming a 2 mm/yr creep rate over a 0.5 m depth, creep could directly supply only 385 t/yr (11 t/km^2/yr) or 6% of the observed sediment yield.

An analogous computation can be made for earthflows in the basin. Assuming a uniform rate of flowage supplying material to Jacoby Cr:

$$\text{equilibrium flow rate (m/yr)} = Q_s/(L_{ef}\, z_{ef}\, P_{rock}) \qquad (4)$$

where L_{ef} is total mean width of earthflows measured parallel to mainstem Jacoby Cr, and z_{ef} is mean earthflow thickness. For L_{ef} = 5500 m (calculated from fig. 2 by dividing earthflow area by mean length) and z_{ef} estimated at 10 m (c.f. earthflow thicknesses of 5-8 m in Iverson 1984, 10-30 m in Kelsey 1978, and 3-15 m in Swanston and Swanson 1976), the mean flowage rate required for equilibrium with current sediment yield is 0.046 m/yr (46 mm/yr). This rate is reasonable for forested earthflows (c.f. Swanston and Swanson 1976 table 2); but it is at least an order of magnitude less than those measured on grass-covered earthflows nearby (Kelsey 1978; Iversen 1984). The minimum rate of movement of the Plunkett Road earthflow at the west end of the basin (fig. 1), determined from damage to houses and roads, is 0.010-0.025 m/yr (10-25 mm/yr).

These simple calculations suggest that earthflows could easily supply most of the current sediment yield of the Jacoby Cr basin, but that it would be difficult for soil creep to do so. The predicted rate of earthflow movement is reasonable and similar to that actually observed.

Long-Term Erosion Rates

The long-term sediment yield of a drainage basin formed by simple incision of an originally planar surface, with no subsequent internal differential distortion (folding or faulting), is given by:

$$\text{long-term mean sediment yield (t/yr)} = (V_{basin}\, P_{rock})/\, T_0 \qquad (5)$$

where V_{basin} is the volume of the basin below the original planar surface, and T_0 is the time in years since incision began.

Although the Jacoby Cr basin has clearly undergone folding and faulting (figs. 2 and 3), it is instructive to apply this formula to it. Because the original Falor-Franciscan depositional surface --still horizontal-- is exposed on the top of Fickle Hill and, exhumed, forms the north slope of parts of Kneeland Ridge (Carver, this vol.), we approximated the original surface as a plane everywhere tangent to the crest of both ridges. (This is, of course, very crude: it neglects erosion of whatever Falor sediments lay above this surface, and ignores any contribution of tectonism to basin volume.) Basin volume (5.0×10^9 m^3) was calculated from 12 cross-sections spaced approximately 1 km apart (fig. 4).

Substituting present-day sediment discharge for the long-term value in (5) yields a basin age (To) of 1.98 m.y. This is too old: the Falor Fm, which is up to 1000 m thick north of Fickle Hill (Carver, this vol.), contains the 2.0 m.y. Huckleberry Ridge ash near its base (Andrei Sarna-Wojcicki, pers. comm 1985). Even if only 100-200 m of Falor sediments originally covered the top of Fickle Hill, any reasonable deposition rate suggests that a minimum of several hundred thousand years must have passed before erosion of the Jacoby Cr. basin could have begun.

If we assume basin development commenced about 1 m.y. ago (our best estimate), long-term sediment yield, computed from (5), is 12,500 t/yr, or approximately twice the current value. Perhaps this is real; Pleistocene climate changes may at times have produced sediment discharges well in excess of those presently observed. However, the value may be excessive for two reasons: 1) part of the measured basin volume is probably a result of tectonism, not erosion (see subsequent discussion); and 2) when basin relief was low (before appreciable incision or tectonism) erosion rates are likely to have been substantially smaller than current ones. Basin relief today is probably at a maximum. These results suggest that tectonic effects must be incorporated into any sediment budget model if we are to understand basin evolution.

A Simple Model of Basin Development under Thrusting

We propose a very simple-minded tectonic-erosional model as a first approximation for the development of the Jacoby Cr basin (fig. 5). In this model, an initially horizontal surface is thrust southward at a constant rate. The position of the creek is fixed; the divide is taken as a singular point which shifts upward and southward as thrusting continues. All relief between divide and creek is created by the thrusting; there is no differential erosional lowering of divide or creek. Material thrust into the basin (trapezoid ABDE in fig. 5) is regraded to form a slope of uniform angle (line DC) from divide to creek, thus increasing slope volume (triangle CDE); excess material (ABDE-CDE) is transported to the creek and removed. In this model, as thrusting continues, Fickle Hill grows in height and bulk, horizontal distance between creek and divide diminishes, and slope angle increases. Equations defining the model are given Appendix 1.

Figures 6-8 show the model predictions for a thrust fault dipping north at $\beta = 25°$ (the dip measured at the field trip stop) with initial (time-zero) creek-divide distance (L_0) of 3250 m, mean creek-fault distance (L_{cf}) of 900 m, and thrust rate of 1 mm/yr (0.001 m/yr). L_0 was determined from present day mean relief (R_{cd}) of 420 m and mean creek-divide distance (L_{cd}) of 2345 m by:

$$L_0 = L_{cd} + R_{cd} / \tan \beta \qquad (6)$$

This is the mathematical equivalent of sliding the divide back down to the level of the creek along a line parallel to the fault dip (see fig. 5).

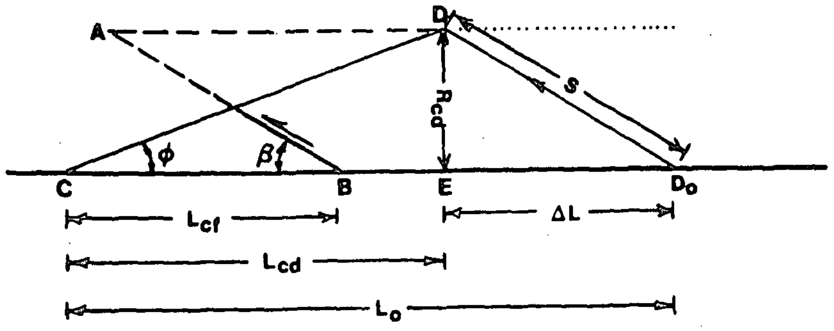

Figure 5. Definition sketch for model of basin development under thrusting. C is creek, D is divide, S is total slip, D_0 is position of divide before thrusting commenced. Initial topography is assumed flat (line C-D_0); dashed line A-D is imaginary position of that surface after slip S on fault has occurred. Line D_0-D shows path of divide as offset continues. Other symbols are discussed in text and appendix. Figure is schematic only.

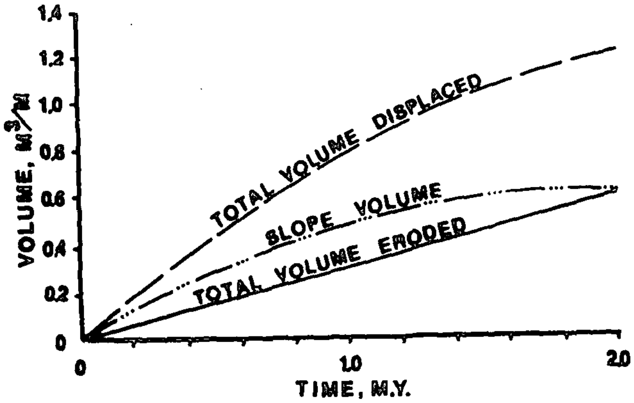

Figure 6. Total volume displaced, slope volume, and total volume eroded (difference between volume displaced and slope volume) as functions of time for model in fig. 5. Computed from eqs. A5-A7 in appendix. See text for discussion.

Total slip required to bring the divide from creek level to its current position is given by

$$S = R_{cd}/\sin \beta \qquad (7)$$

This amounts to 994 m, which, for a slip rate of 1mm/yr, implies a basin age of approximately 1 m.y.

The results of this simple model are illuminating. It suggests a reasonable age for the basin. It predicts a mean sediment yield of 7800 t/yr, only 25% larger than our estimated current yield of 6325 t/yr. If the basin is 1 m.y. old, the model predicts cumulative erosion of 3.1×10^9 m^3, only 11% less than our measured value of 3.4×10^9 m^3 for the volume beneath the ridge-ridge plane north of the creek. Our model thus seems to provide a reasonable first approximation of relations between tectonism and erosion in the basin.

Some Conclusions: Limitations and Implications of the Model

The proposed model has several defects. First, it predicts a uniform sediment yield which does not change with time (fig. 6). This is clearly unreasonable. In the early stages of basin formation, when relief (fig. 7) and slope (fig. 8) are very low, erosional processes should be less effective and sediment yield ought to be small; as relief and slope increase, we would expect increased sediment yield . This argument suggests that hillslope relief and volume initially grow more rapidly than the model predicts; perhaps at some point in slope development a threshold is then crossed which allows a more constant rate of erosion. This threshold might be that associated with the initiation of earthflows.

Second, the model does not explain how or why the slope is regraded to a constant angle. To achieve this, we need conveyor-belt like transport that effectively redistributes excess upper-slope material downslope. Earthflows are a likely candidate. At several sites (e.g., Plunkett Road), Franciscan melange debris has flowed downslope over Falor sediments. The south slope of Fickle Hill, though mantled by earthflows (fig. 2) appears surprisingly uniform in profile (fig. 4).

Third, thrust movement is unlikely to be uniform in time. While the mean slip rate may be 1mm/yr, actual displacement is most likely by increments of 5-10 m per event. We wonder if such sudden inputs of mass could trigger earthflow kinematic waves which would then lead to increased sedimentation in Jacoby Creek.

Fourth, the assumption that the divide and creek are fixed points which undergo no erosional lowering is unrealistic; both almost certainly do. However, the patch of Falor Fm on the crest of Fickle Hill suggests that this rate of lowering is small with respect to the rate of tectonism, and thus no great error is introduced. (We made this assumption because it greatly simplifies the geometry of the model; if we allow the divide to shift because of erosion the problem is much less tractable.)

Fifth, the model does not take into account structural deformation other than thrusting in development of the basin. Since the basin is in fact a syncline (figs. 2,3) a comprehensive model should include the effects of coseismic folding. Qualitatively, the effect of synclinal folding is to require a lower sediment yield than that predicted by our model, since some of the basin volume will be due to the downwarping.

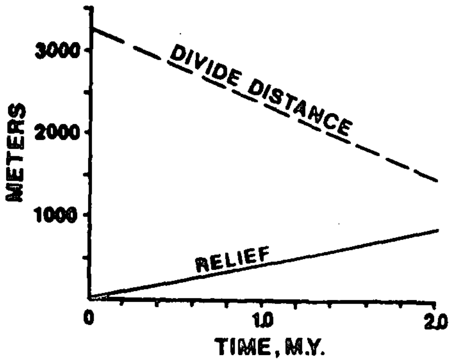

Figure 7. Creek-divide distance (L_{cd}) and relief (R_{cd}) as functions of time for model in fig. 5. Computed from eqs. A3 and A4 in appendix. See text for discussion.

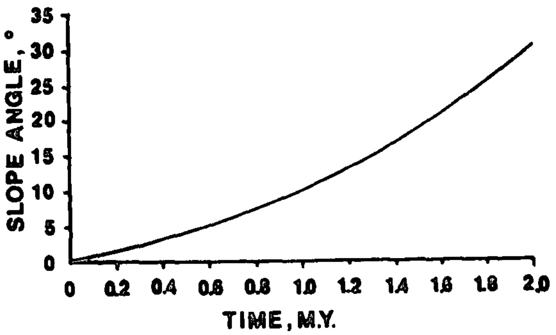

Figure 8. Increase in slope of south side of Fickle Hill with time for model in fig. 5. Computed from eq. A8 in appendix. See text for discussion.

Despite its limitations, the model strongly suggests that thrusting and erosion are not presently in equilibrium, i.e., that Fickle Hill is continuing to grow in relief and steepness. This hypothesis can be tested by a simple mass balance. The sediment yield required for equilibrium between thrusting and erosion is given by:

$$\text{equilibrium sediment yield (t/yr)} = r\, D_{thr}\, L_{thr}\, P_{rock} \qquad (8)$$

where r is thrust rate, D_{thr} is mean thrust plate thickness (measured from fault to divide along a line normal to the fault plane), and L_{thr} is fault length measured parallel to the valley axis. For $r = 0.001$ m/yr (1 mm/yr), $D_{thr} = 840$ m, and $L_{thr} = 10{,}250$ m, equilibrium sediment yield is 21,500 t/yr. This is approximately 3.5 times the current yield, supporting our contention that thrusting and erosion are not in equilibrium.

What does the future hold for the Jacoby Creek basin? According to our model, about 1 m.y. was needed for the south slope of Fickle Hill to attain its present mean gradient of 11°; fig. 8 indicates that it will grow to about 30° over the next million years. We do not believe this is likely; the materials are not strong enough. Instead, we propose that at some (unknown) future slope a threshold will be crossed and flowage rates will either increase greatly, or other processes (e.g., massive slumping or sliding) will take over to bring erosion and tectonism more nearly into equilibrium. We expect that such a transition would lead to major changes in Jacoby Creek. At least initially, the increased sediment input would lead to aggradation and the formation of fill terraces. Beyond this we have not ventured.

Summary

We have used simple mass balance calculations to investigate and model the relations between tectonism and sediment yield in a small basin undergoing active thrust faulting. Our results suggest that: 1) mass-balance approaches like ours can provide useful insight into basin development even if the input data and model are crude; 2) sediment budgets in tectonically active areas need to include explicitly a tectonic component if basin development is to be understood; and 3) "equilibrium" between erosion and tectonism can be best understood through sediment budget models, as these focus attention on the way dominant processes, process-linkages, and thresholds interact and change with time.

Our simple model suggests that tectonism and erosion in the Jacoby Cr drainage are not in equilibrium, and that Fickle Hill continues to grow in relief and bulk. Earthflows, originating in Franciscan melange of the upper thrust plate, redistribute thrust material downslope, and can account for the currently observed sediment yield of the basin.

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APPENDIX: MODEL EQUATIONS

The quantities below are used in the equations defining the model of figure 5:

β: dip angle of thrust plane (°)

r: rate of thrusting (m/yr)

t: time since initiation of thrusting (yr)

S: total amount of slip on fault (m)

L_{cd}: distance from creek to divide, measured horizontally (m)

L_{cf}: distance from creek to fault trace, measured horizontally (m)

L_0: distance from creek to divide at $t = 0$ (m)

ΔL: total change in horizontal distance between creek and divide due to faulting (m)

R_{cd}: relief between creek and divide (m)

V_{trap}: total volume of material thrust into basin per unit length of fault; numerically equivalent to area of trapezoid ABDE ($m^3/m/yr$)

V_{tri}: total volume of hillslope per unit length of fault; numerically equivalent to area of triangle CDE ($m^3/m/yr$)

V_{eros}: total volume of material eroded per unit length of fault; numerically equivalent to ABDE-CDE ($m^3/m/yr$)

$\O$: angle of hillslope from crest to divide (°)

The equations which define the model are:

$$S = rt \tag{A1}$$

$$\Delta L = rt\cos\beta \tag{A2}$$

$$L_{cd} = L_0 - \Delta L \tag{A3}$$

$$R_{cd} = rt\sin\beta \tag{A4}$$

$$V_{trap} = [L_0 - L_{cf} - (\Delta L/2)]\, R_{cd} \tag{A5}$$

$$V_{tri} = 0.5\, R_{cd}\, [L_0 - \Delta L] \tag{A6}$$

$$V_{eros} = V_{trap} - V_{tri} = 0.5\, R_{cd}\, [L_0 - 2L_{cf}] \tag{A7}$$

$$\O = \tan^{-1}(R_{cd}/L_{cd}) \tag{A8}$$