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EVALUATION OF FAULT HAZARDS, NORTHERN COASTAL CALIFORNIA

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INTRODUCTION

Northern coastal California lies at the southern end of the Cascadia subduction zone in a transitional zone between this convergent tectonic regime and the San Andreas transform regime to the south. North of 40.8°N, shortening within the upper plate associated with subduction processes is expressed as north-northwest-trending thrust faults and folds. However, this structural pattern is disrupted in the Cape Mendocino region where active thrust faults and folds developed in the coastal Franciscan block and its offshore equivalent trend west-northwest. This shift in structural orientation likely results from both localized anomalies in Juan de Fuca plate motion adjacent to the Pacific plate and from direct convergence between easternmost Pacific plate and northern California (38 mm/y; directed 340°).

Earthquakes in this tectonically complex region can potentially come from several seismic sources: (1) upper plate crustal sources; (2) interplate megathrust sources; (3) lower plate Juan de Fuca sources; (4) interplate Mendocino fracture zone sources (Figure 1). Historically, earthquakes are most numerous from sources (3) and (4). This report evaluates available fault-hazard research on seismic sources (1) and (2), in particular, late Quaternary faults and folds considered capable of generating M6.5 or greater earthquakes. Existing seismic, geodetic, and paleoseismic data are used to define recurrence rates for characteristic earthquakes on these fault zones. For fault zones lacking sufficient data to constrain recurrence rates, research strategies have been proposed to resolve critical issues. This report focuses on onshore faults with known Quaternary slip and their offshore extensions. Undocumented Quaternary faults, in particular, offshore faults which do not disrupt the sea floor may have been missed in this evaluation.

With a historic lack of major earthquakes from both upper plate and megathrust seismic sources, many fundamental issues regarding the tectonic and seismic behavior of this region remain unresolved, for example: (1) What is the seismic coupling coefficient of this portion of the Cascadia subduction zone? (2) Are megathrust slip events temporally clustered, *i.e.*, would loading of adjacent megathrust segments following rupture of one segment shorten time to their subsequent failure? (3) Do differing structural trends in the accretionary prism away from the deformation front reflect previous, relict subduction parameters or partitioning of current convergence energy? (4) Are the Little Salmon or Mad River fault zones independent seismic sources or do they only slip during megathrust earthquakes? (5) Do the Little Salmon or Mad River fault zones become single rupture surfaces at seismogenic depths?

Acknowledgements

I thank the Humboldt Seismic Hazards Working Group: W. A. Bryant, G. A. Carver, S. H. Clarke, K. J. Coppersmith, H. M. Kelsey, K. R. Lajoie, M. Lisowski, M. H. Murray, D. H. Oppenheimer, K. Piper, C. Wills, D. S. Wilson, and I. G. Wong both for discussions establishing the framework of this evaluation and critical review of the report.

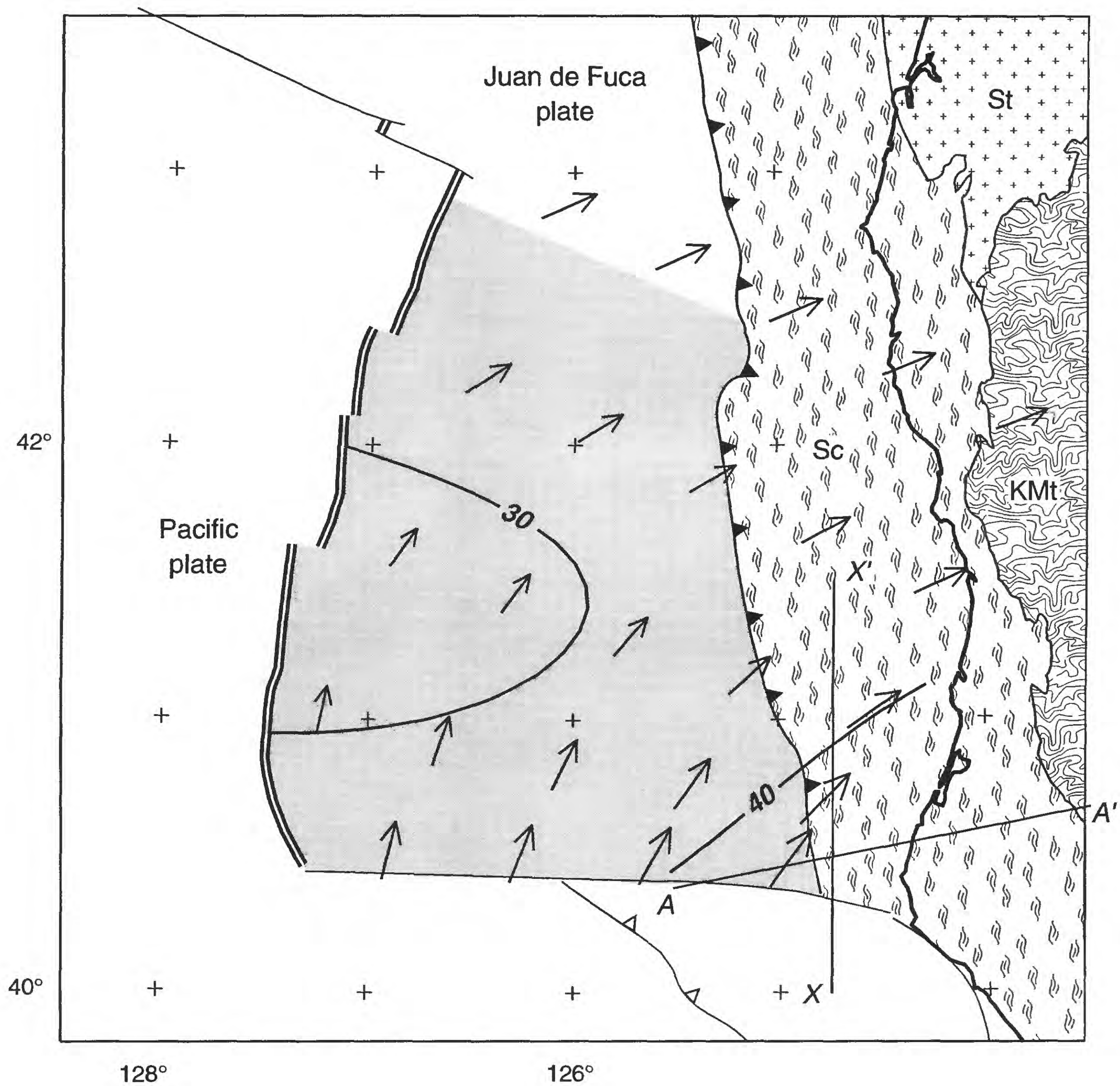

Figure 1*A*. Map of the southern Cascadia subduction margin in its present plate tectonic setting showing location of basement units (modified from McCrory *et al.*, 1995). *Sc* denotes subduction complex, including modern accretionary prism, and Coastal, Central and Eastern belts of the Franciscan complex; *St* denotes Siletz terrane; *KMt* denotes Klamath Mountain terrane. Arrows indicate motion of southern Juan de Fuca plate (gray area) with respect to a fixed northern California reference frame. Contours in mm/y. Profile *AA'* is shown in Figure 1*B*.; profile *XX'* is shown in Figure 1C.

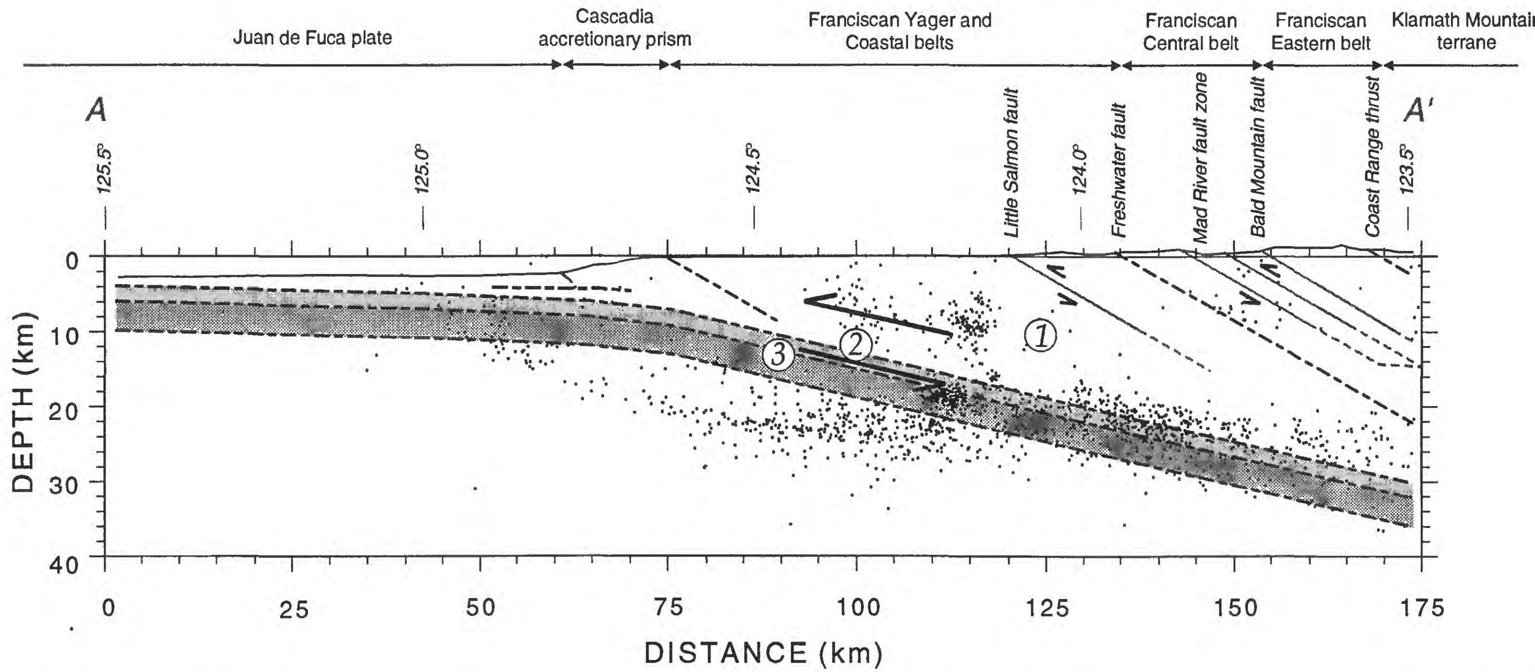

Figure 1*B*. Generalized east-west profile across the southern Cascadia subduction margin showing inferred configuration of major basement units at no vertical exaggeration, location of crustal structures, and locations of potential seismic sources (modified from McCrory *et al.*, 1995). See Figure 1*A* for location of profile. *1* denotes upper plate, northern California crustal sources; *2* denotes interplate megathrust sources; *3* denotes lower plate, Juan de Fuca sources. Location of Juan de Fuca plate beneath the margin based on earthquake hypocenters (from Smith *et al.*, 1993). Layer 2 of the Juan de Fuca crust denoted in light gray; layer 3 denoted in medium gray. Arrows denote relative movement on Cascadia megathrust, and Little Salmon and Mad River fault zones. Dots denote ambient seismicity *ca.* 1975-1996 (from D. Oppenheimer, 1996, written communication. Plot suggests that some ambient crustal seismicity may correlate with mapped Quaternary thrust faults in Franciscan basement block.

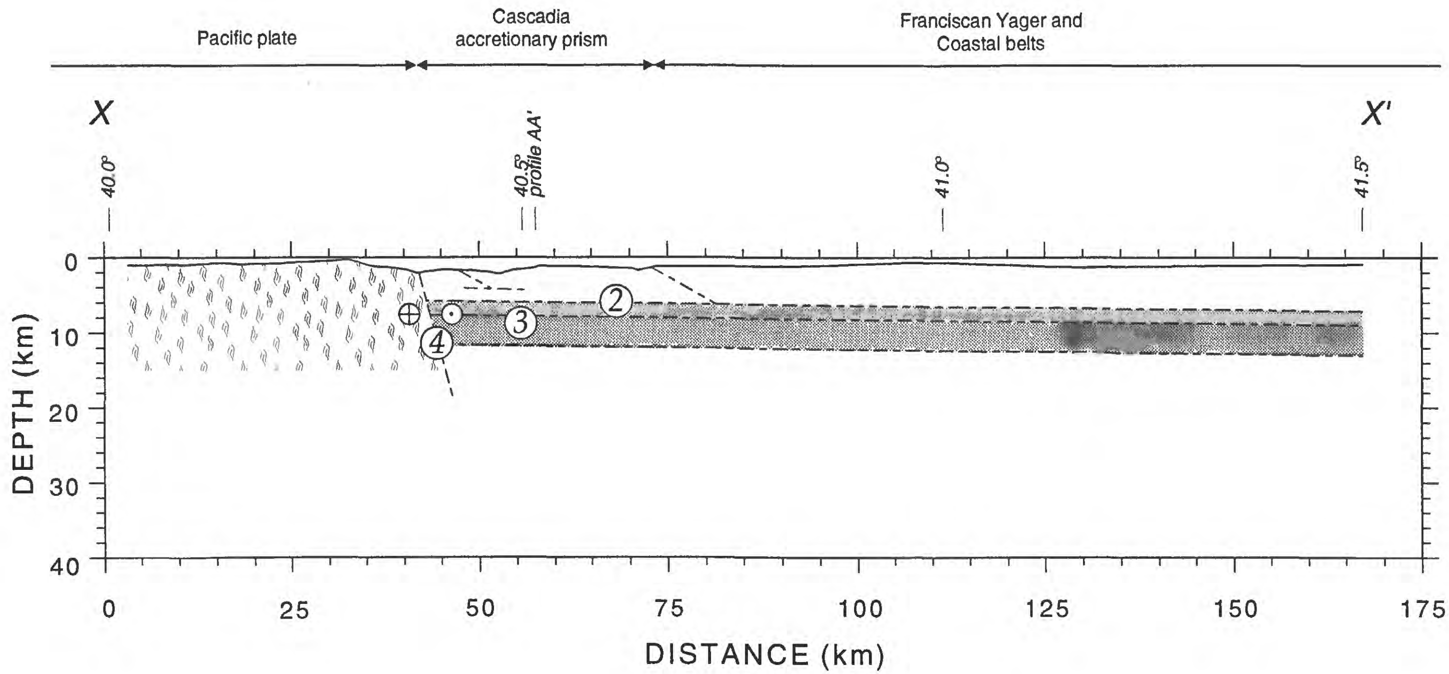

Figure 1C. Generalized north-south profile along the southern Cascadia subduction zone showing inferred configuration of major basement units at no vertical exaggeration (modified from McCrory *et al.*, 1995). See Figure 1*A* for location of profile. *2* denotes interplate megathrust sources; *3* denotes lower plate, Juan de Fuca sources; *4* denotes interplate Mendocino fracture zone sources. Location of Juan de Fuca plate beneath the margin based on earthquake hypocenters (from Smith *et al.*, 1993). Pacific plate denoted in pattern; layer 2 of the Juan de Fuca crust denoted light gray; layer 3 denoted in medium gray.

SOUTHERN CASCADIA CRUSTAL SOURCES

DATA: Surface exposures, trench data, marine-terrace data, well and borehole data, and seismic reflection data along five fault zones in the Humboldt area are used to calculate the shortening rates and net shortening amounts given below.

TABLE 1. Summary of geologic shortening data for crustal structures. See specific site descriptions for discussion of datums used.

Fault [site]	Age (ka)	Quaternary uplift* (m)	Uplift rate (mm/y)	Quaternary shortening* (m)	Shortening rate (mm/y)	Shortening direction (°)
Russ [$\mathbf{R_1}$]	<100	*n/a*	2.2	*n/a*	0.0-0.1	55
Table Bluff [$\mathbf{TB_3}$]	<500	400	0.4*	400ϕ	0.4*	50
Little Salmon [L_1 L_2 & L_3]	<0.5	2200	2.2*	3810†	3.8*	30-60
Mad River [MR_3]	<10	2500	2.5*	3570‡	3.6*	45-55
Big Lagoon [BM_1]	<1000	545	0.5*	945†	0.9*	55
TOTAL		5645 m		8725 m		

* assuming faulting started *ca.* 1 Ma
† using 30° fault dip
‡ using 35° fault dip
ϕ using 45° fault dip

- Shortening associated with subsidence of the Eel River, South-bay, and Freshwater synclines is not included in these estimates because available subsurface data suggests minimal cumulative subsidence has occurred (*i.e.*, <<0.1 s or <<250 m vertical warping since *ca.* 1 Ma is observed within the Eel River and Freshwater synclines on a nearshore seismic profile shown in Figure 6 of Clarke (1992). Offshore, these synclines appear to be defined primarily by uplift of bounding anticlinal folds rather than active subsidence.

- Quaternary shortening across known structures within the Coastal and Central belts of the Franciscan complex is 8725 m directed 55±10° at 8.7 mm/y.

- Quaternary shortening across known structures within the Coastal belt of the Franciscan complex is 4210 m at 4.2 mm/y. Interseismic strain accumulation (1981-1989) across the same crustal block determined from geodetic measurements, is 7±1 mm/y of nearly uniaxial contraction directed 35°±8° (McCrory *et al.*, 1995).

- Quaternary shortening across known structures within the Central belt of the Franciscan complex is 4515 m at 4.5 mm/y.

REFERENCES:

Berger *et al.*, 1991 (R)
Burke *et al.*, 1986 (A)
Carver, 1987 (O)
Carver, 1989*b* (O)
Carver, 1992 (O)
Carver *et al.*, 1982*b* (O)
Carver and Burke, 1988 (O)
Carver and Burke, 1992 (O)
Carver *et al.*, 1985 (O)
Carver *et al.*, 1986*a* (O)
Carver *et al.*, 1986*b* (A)
Clarke, 1990 (R)
Clarke, 1992 (R)
Clarke and Carver, 1992 (R)
Crouch, 1988 (O)
Hart *et al.*, 1991 (O)
Harvey and Weppner, 1992 (O)
Kelsey and Carver, 1988 (R)
Kennedy, 1978 (O)
Lajoie, 1986 (R)
Lajoie *et al.*, 1991 (R)
McCrory, 1989 (R)
McCrory, 1995 (R)
McCrory *et al.*, 1995 (A)
Ogle, 1953 (R)
Rust, 1982 (O)
Sarna *et al.*, 1991 (R)
Stephans, 1982 (O)
Stuiver and Pearson, 1986 (R)
Weaver, 1981 (O)
Wehmiller and Keenan, 1980 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: Two Pleistocene angular unconformities are observed in the Centerville Beach stratigraphic section. The older one occurred *ca.* 1 Ma and separates Rio Dell (upper slope and outer shelf facies) and Carlotta (fluvial facies) Formations (Figure 2). This unconformity is considered a major one because the stratigraphic sequence lacks inner shelf and nearshore facies (Scotia Bluffs Sandstone). The younger unconformity occurred *ca.* 0.5 Ma and separates Carlotta and Hookton Formations. This unconformity is considered less severe because the continuity of depositional environments is not interrupted. The ages assigned to these formations and unconformities in McCrory (1995) are based on extrapolating rates of sediment accumulation from underlying datums, thus, do not account for the amount of missing section or time represented by the hiatus. A calculation of the time missing during the younger hiatus has been attempted by Woodward-Clyde Consultants (1980) by assuming that tilting occurred at a constant rate in the Quaternary. Tilting of Quaternary datums in the Fields Landing area at a rate of 4.35° per 100 ky yields a duration of about 100 ky for this unconformity. A similar calculation for the older hiatus in the Centerville Beach area yields a duration of about 250 to 300 ky for the hiatus centered at about 1 Ma (Rio Dell Formation tilts 9° in the Centerville Beach area; lower unconformity tilts 6°; Carlotta Formation tilts 6°; thus 3° of tilting occurred during hiatus).

The older Pleistocene unconformity is assumed to mark the initiation of the most recent phase of folding and faulting in the Humboldt region. Fault-slip rates, at sites lacking direct age control, are calculated using this *ca.* 1-Ma datum. The 1-Ma age is considered a reasonable first approximation of the age of the unconformity, however, there is some evidence of temporal variation in onset of folding in different parts of the region. In the Rio Dell area, folding of the Grizzly Bluff anticline began earlier, *ca.* 2 Ma (McCrory, 1989). In the Van Duzen River area, folding of the Wolverton syncline also began earlier, *ca.* 1.5 Ma (see discussion under Little Salmon fault zone—Yager fault segment). In the Tompkins Hill area, folding of the Tompkins Hill anticline began after Carlotta deposition (see discussion under Table Bluff-Tompkins Hill fault—site **TB_1**). Nonetheless, at sites where the age of this unconformity can be estimated directly; *e.g.*, at Centerville Beach, Table Bluff, Mad River, Fickle Hill, McKinleyville, and Trinidad sites, the 1-Ma age appears valid. The following slip-rate tables are constructed so that they can be easily updated as new age control becomes available. For purposes of this report, 1.0 ± 0.2 Ma, represents the geologic uncertainty for onset of folding and faulting in the coastal area. Extending this age estimate to the offshore area is considered speculative, until the mechanism(s) which caused the unconformity are established.

Many trenches reveal very shallow fault dips in the uppermost part of a trench wall, however, all these fault traces steepen with depth—even over the 3 to 5 m-deep trench wall. For this reason, when dip-slip rates are calculated from fault-trace dips observed in trenches, the deeper dips are considered to more closely approximate fault dips at depth. This correlation between fault dips at the surface (and shallow subsurface) with subsurface fault dips seems to hold down to depths of at least 7.5 km (or 3 sec; S. Clarke, 1996, written communication) based on offshore seismic reflection profiles. However, there is no information on thrust-fault dips at seismogenic depths (*i.e.*, 8-15 km) or the down-dip extent of these crustal thrust faults.

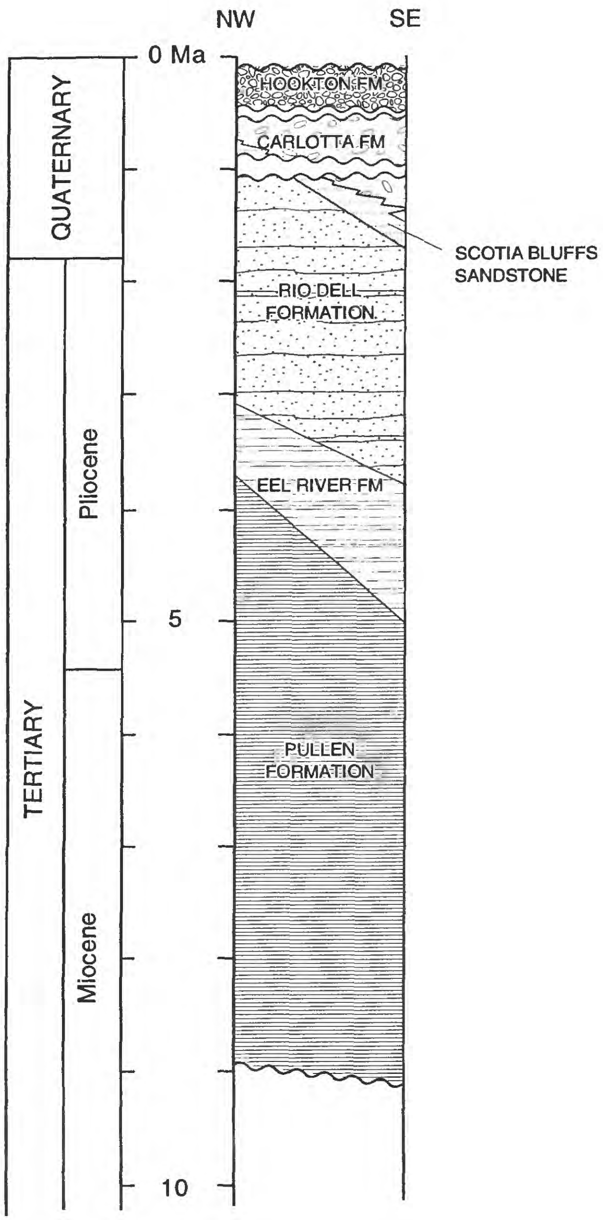

Figure 2. Generalized lithostratigraphy for marine basin fill in Humboldt area showing major Quaternary unconformities (modified from Ogle, 1953; McCrory, 1995). Wildcat Group of Ogle (1953) includes the Pullen, Eel River and Rio Dell Formation, Scotia Bluffs Sandstone, and Carlotta Formation.

FAULT:	Russ-False Cape fault zone
SEGMENT:	Russ fault
SITE(S):	coastal terraces [$\mathbf{R_1}$]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Two marine-terrace platforms are offset across the Russ fault at the coast [site $\mathbf{R_1}$]. The lower terrace is vertically separated about 22 m; the upper terrace is vertically separated about 36 m (Carver *et al.*, 1986*a*) (Plate 2). The best age estimates for these terraces, using the graphical correlation technique (see Lajoie, 1986 for discussion of technique; see Lajoie *et al.*, 1991 for application of technique to California terraces), are *ca.* 100 and 125 ka, respectively (Figure 3). If these age estimates are correct, the rate of vertical separation across the fault is 0.24 mm/y. This separation rate across a specific crustal structure is superimposed on general coastal uplift at a rate of 1.94 mm/y. Together, uplift in the vicinity of Russ fault occurs at a rate of 2.18 mm/y.

FAULT TYPE:	thrust? [R?]
DIP:	75±15° N?
STRIKE:	325°
SLIP RATE :	0.24-0.28 mm/y using fault dips of 90-60°
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-100 ka
SHORTENING RATE:	0.0-0.14 mm/y using fault dips of 90-60°
UPLIFT RATE:	0.24 mm/y (Russ fault only) 2.18 mm/y (combined Russ fault and regional uplift)

REFERENCES:

Carver *et al.*, 1986*a* (O)
Lajoie, 1986 (R)
Lajoie *et al.*, 1991 (R)

DATA LIMITATIONS: The sense of slip for the Russ fault, if the terrace correlations are correct, is <u>south</u>-side-down. In other words, if the Russ fault is a thrust fault, its upper plate is to the north. However, this geometry contradicts the bedrock geology: Wildcat strata on the north side of the fault are juxtaposed against underlying Franciscan bedrock on the south, reflecting a <u>north</u>-side-down geometry. The shear zone at the base of the Wildcat Group at Centerville Beach is vertical, however, this may not be the original dip of Russ fault. Various workers have postulated that the Russ fault has been rotated to a steep dip during ongoing north-south compression associated with the Pacific-North America plate boundary. Because of these inconsistencies in available data, the reliability of the calculated fault-slip rates is considered low.

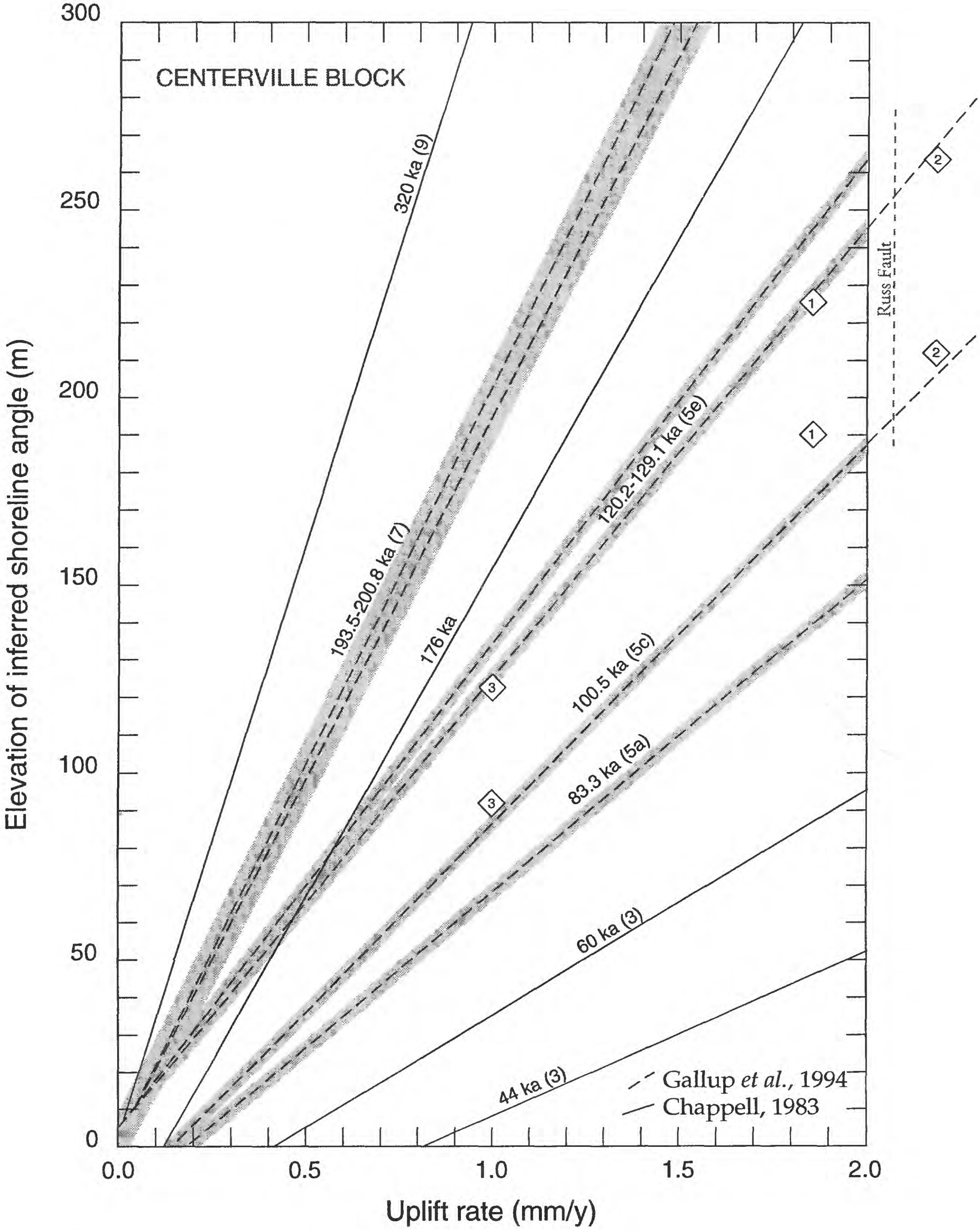

Figure 3. Graphical correlation plot for the Centerville structural block showing the preferred age estimates for marine-terrace platforms and resultant uplift rates. Elevation of shoreline angle inferred from elevation of marine-terrace surfaces and thickness of sediment cover. Terrace-profile elevations from Figure 8 in Carver *et al.* (1986*a*), assuming lowest terrace is *ca.* 100 ka. Gray areas denote uncertainties on age and elevation of sea-level high stands (from Gallup *et al*, 1994) See Plate 2 for locations of profiles.

TABLE BLUFF-TOMPKINS HILL FAULT ZONE, HUMBOLDT COUNTY, CA

DATA: Trench data, marine terrace data, well data, and seismic reflection data at three locations along the onshore Table Bluff-Tompkins Hill fault zone are used to calculate the fault-slip rates given below.

FAULT TYPE:	thrust [R]
DIP:	45±15° N
STRIKE:	275-320°
SLIP RATE:	0.6 mm/y assuming a fault dip of 45° [**TB5** & **TB6**] 1.1? mm/y using a fault dip of 45° [**TB7**]
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE :	post-500 ka
SHORTENING RATE:	0.4 mm/y assuming a fault dip of 45° [**TB5** & **TB6**] 0.8? mm/y [**TB7**]
UPLIFT RATE:	0.4 mm/y [**TB3**, **TB5** & **TB6**] 0.8? mm/y [**TB7**]

REFERENCES:

Berger *et al.*, 1991 (R)
Clarke, 1992 (R)
Crouch, 1988 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: See specific site descriptions.

FAULT: Table Bluff-Tompkins Hill fault zone

SEGMENT:

SITE(S): Tompkins Hill [$\mathbf{TB_1}$ & $\mathbf{TB_2}$]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: The upper plate of the Little Salmon fault overlies the eastern end of the Tompkins Hill anticline. Data from *Texaco Pacific Lumber #1* and *HE-10* wells [sites $\mathbf{TB_1}$ & $\mathbf{TB_2}$] show an uninterrupted sequence of Rio Dell to Carlotta strata within the lower plate of the Little Salmon fault, suggesting that growth of the Table Bluff anticline post-dates Carlotta deposition (Woodward-Clyde Consultants, 1980; Crouch, 1988). This timing contrasts with the Table Bluff area to the west, where a major erosional event removed most of the upper Rio Dell strata prior to deposition of Scotia Bluffs and Carlotta strata. This apparent sequential structural growth, with Tompkins Hill anticline forming later than Table Bluff anticline, suggests that the Table Bluff fault beneath Table Bluff anticline, may be a separate structure from an inferred Tompkins Hill fault beneath Tompkins Hill anticline.

FAULT TYPE: thrust [R]
DIP: *n/a*
STRIKE: 275°

SLIP RATE : *n/a*

SLIP PER EVENT: *n/a*

RECURRENCE: *n/a*

AGE: post-500 ka

SHORTENING RATE: *n/a*

UPLIFT RATE: *n/a*

REFERENCES:

Carver, 1992 (O)
Carver *et al.*, 1986*a* (O)
Clarke, 1992 (R)
Crouch, 1988 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: Various reports (*e.g.*, Carver *et al.*, 1986*a*; Carver, 1992; Clarke, 1992) show a Table Bluff-Tompkins Hill fault zone connecting to the Goose Lake fault trace and alternatively, overridden by the Little Salmon fault in the Tompkins Hill area. Some Little Salmon fault strain may be partitioned onto the Table Bluff-Tompkins Hill fault in the Tompkins Hill area as the slip rate on Little Salmon fault decreases north of Tompkins Hill. The amount of partitioning is likely ≤1 mm/y. The Table Bluff-Tompkins Hill fault zone remains poorly understood and merits further study, in particular, using industry data to correlate subsurface units and to create balanced cross-sections.

FAULT: Table Bluff-Tompkins Hill fault zone

SEGMENT:

SITE(S): Table Bluff [**TB3**, **TB4**, **TB5** & **TB6**]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Locally, the Table Bluff fault dips steeply at about 65° N as documented in *Texaco Quinn #1* well [site **TB3**] (Crouch, 1988). Structural growth of Table Bluff anticline began during or immediately following upper Rio Dell deposition (*ca.* 1.0 Ma) based on erosion of upper Rio Dell strata from the paleo-high surrounding the Table Bluff area. Scotia Bluffs strata overlie the erosional unconformity. This unconformity dates a major episode of thrust fault and fold development in the Table Bluff area (Crouch, 1988). The unconformity can be traced offshore to the west, based on offshore seismic-reflection profiles (Crouch, 1988; Clarke, 1992). In contrast, the Tompkins Hill anticline to the east, has an uninterrupted sequence of Rio Dell to Carlotta strata deposited on it (within the lower plate of the Little Salmon fault). Thus, earliest Quaternary structural growth in the southern Humboldt Bay area apparently occurred along the Table Bluff fault (and Little Salmon fault in the Humboldt Hill area; see discussion under Little Salmon fault zone—Humboldt Hill sites).

Vertical separation across the main Table Bluff fault trace at *Texaco Quinn #1* well (near the axis of Table Bluff anticline) is about 400 m (Crouch, 1988). If faulting began *ca.* 1 Ma, then the rate of vertical separation across the main fault trace is about 0.4 mm/y.

Two trenches cut at site **TB4**, near the western end of Table Bluff, exposed Hookton Formation and overlying marine-terrace deposits (Woodward-Clyde Consultants, 1980). Both trenches displayed minor faulting (<<1 m) of Hookton Formation. The eastern trench (near the axis of Table Bluff anticline) exposed 3 minor reverse faults striking N70-80°W; dipping northeast. The largest observed dip-slip offset was 0.14 m. Faults observed within Hookton Formation did not displace the overlying erosional unconformity between Hookton Formation and marine-terrace deposits. A nearby quarry at Southport Landing [site **TB5**] exposes both reverse and normal faults within Hookton Formation, striking N60-80°W.

Thermoluminescence (TL) dating (Berger *et al.*, 1991) of sediments at 2 sites [**TB5** & **TB6**] on Table Bluff anticline yielded ages of 119±31 ka [site **TB5**] and 170±70 ka [site **TB6**] for two separate marine-abrasion platforms (oxygen-isotope stages 5e and 7.0, respectively). However, it is unclear exactly where the samples were taken—above or below the abrasion surface (*i.e.,* locations shown *in* Figures 5 and 6, Berger *et al.*, 1991, do not match descriptions in text). In addition, the authors erroneously suggest that beach deposits above the marine platform represent a younger marine abrasion surface (*i.e.*, stage 5a). Such a geometry would require post-125 ka subsidence followed by post-83 ka uplift. If the TL date from the second lowest platform is correct, then the uplift rate for the axis of the anticline is 0.4 mm/y (Plate 2; Figure 4) the same rate as calculated from well data.

FAULT TYPE: thrust [R]

DIP: 65° NE

STRIKE: 320°

SLIP RATE: 0.44 mm/y using a fault dip of 65° [**TB3**]
0.57 mm/y assuming a fault dip of 45° [**TB5** & **TB6**]

SLIP PER EVENT: *n/a*

RECURRENCE : *n/a*

AGE : post-500 ka

SHORTENING RATE: 0.19 mm/y using a fault dip of 65° [**TB3**]
0.4 mm/y assuming a fault dip of 45° [**TB5** & **TB6**]

UPLIFT RATE: 0.4 mm/y [**TB3**, **TB5** & **TB6**]

REFERENCES:

Berger *et al.*, 1991 (R)
Clarke, 1992 (R)
Crouch, 1988 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: Cross-sections, maps, and seismic profiles in available reports are contradictory. These reports show the main trace of the Table Bluff fault alternatively north or south of (above and below) the Table Bluff anticline. Some reports show the Table Bluff-Tompkins Hill fault zone connecting to the Goose Lake fault trace, other reports show it overridden by the Little Salmon fault. Fault polarity is reversed offshore (upper plate to south) in one report. Apparently, the Table Bluff-Tompkins Hill fault zone is a complex system with a major backthrust. This fault remains poorly understood and merits further study, in particular using industry data to correlate subsurface units and create balanced cross-sections. The apparent existence of an anticline beneath the Table Bluff fault suggests that there may be two separate structures at Table Bluff, as occurs at Tompkins Hill, with the upper structure perhaps older than the lower.

There is no direct evidence of the Table Bluff fault moving in the last 100 ky. However, the lack of evidence may only reflect lack of surface exposure of the main fault trace. Apparently, the main surface trace has not been trenched. With a slip rate of <1 mm/y, this is not a high priority.

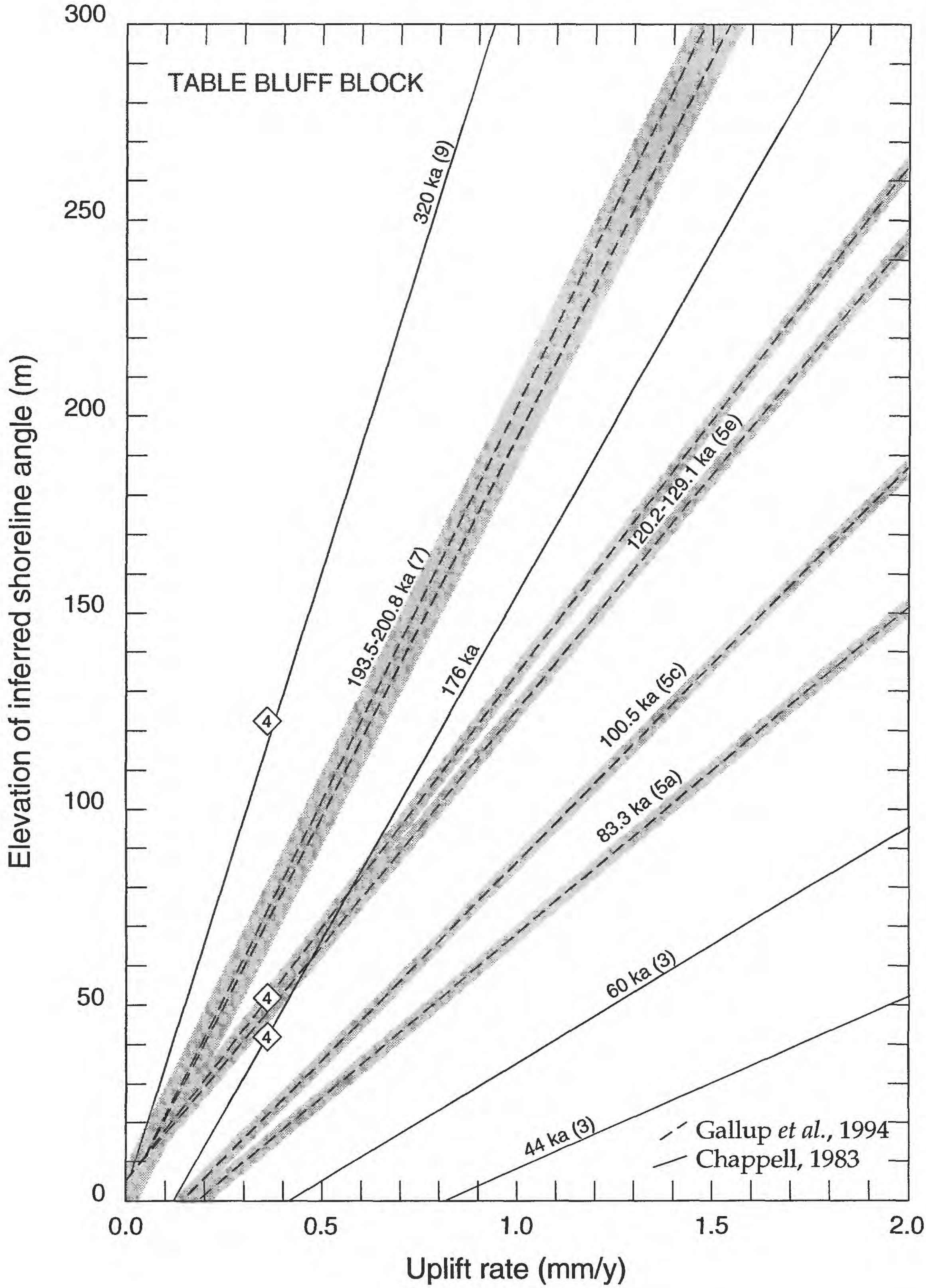

Figure 4. Graphical correlation plot for the Table Bluff structural block showing the preferred age estimates for marine-terrace platforms and resultant uplift rates. Elevation of shoreline angle inferred from elevation of marine-terrace surfaces and thickness of sediment cover. Terrace-profile elevations from Figure 8 in Carver *et al.* (1986*a*), assuming lowest terrace is *ca.* 176 ka and using thermoluminescence dates from Berger *et al.* (1991). Gray areas denote uncertainties on age and elevation of sea-level high stands (from Gallup *et al*, 1994). See Plate 2 for locations of profiles.

FAULT: Table Bluff-Tompkins Hill fault zone

SEGMENT:

SITE: offshore [TB7]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Erosion at the end of Rio Dell time in the Table Bluff area dates a major episode (*ca.* 1.0 Ma) of thrust fault and fold development that is evident offshore as well (Crouch, 1988). About 15 km offshore [site **TB7**], the Table Bluff fault zone is a broad, complex system of north-dipping thrust faults with at least one major backthrust dipping south. This offshore character is similar to the offshore Little Salmon fault, although the Table Bluff fault zone is narrower (4-km wide *versus* 6-km wide). Seismic reflection profiles indicate that timing of deformation for the offshore Table Bluff and Little Salmon faults is similar; although deformation associated with the Table Bluff fault zone is more subdued. Growth of a broad anticlinal fold began during Rio Dell deposition, onlap of the fold occurred during Scotia Bluffs deposition, burial and minor warping of the fold occurred during Carlotta deposition, and continued burial with negligible warping occurred during Hookton deposition (Figure 6 *in* Clarke, 1992).

Approximately 0.3-s structural relief (750 m at 2500 m/s) on the *ca.* 1?-Ma unconformity across Table Bluff anticline offshore (Figure 6 *in* Clarke, 1992) yields an inferred uplift rate of 0.75 mm/y.

On a 1994 seismic reflection profile, about 15 km offshore (*R/V Ewing* line 7; S. Clarke, 1996, written communication), the Table Bluff fault zone reaches and warps the seafloor indicating late Quaternary activity. On this multi-channel seismic profile, the main thrust fault dips about 45° down to about 3 s (or 7.5 km).

FAULT TYPE:	thrust [R]
DIP:	variable, primarily 45°NE
STRIKE:	295°
SLIP RATE:	*n/a*
SLIP PER EVENT :	*n/a*
RECURRENCE:	*n/a*
AGE :	post-500 ka
SHORTENING RATE:	*n/a*
UPLIFT RATE:	0.75? mm/y

REFERENCES:

Clarke, 1992 (R)
Crouch, 1988 (O)

DATA LIMITATIONS: High resolution seismic data are needed to constrain timing and magnitude of deformation associated with the Table Bluff-Tompkins Hill fault zone during Hookton deposition. Detailed well data is not available offshore, so timing of formation of major unconformities is based on correlations with onshore wells and surface sections. Onshore stratigraphic names are used to identify offshore seismic units, however, this correlation is meant to imply equivalent time of deposition rather than equivalent lithofacies.

LITTLE SALMON FAULT ZONE, HUMBOLDT COUNTY, CA

DATA : Trench data, marine terrace data, well data, and seismic reflection data at nine locations along the onshore Little Salmon fault zone are used to calculate the fault-slip rates given below.

FAULT TYPE:	thrust [R]
DIP:	30±5° NE
STRIKE:	300-330°
SLIP RATE:	4.4 mm/y using a fault dip of 30° ("top of Yager" datum) [L_1] 3.3-4.3? mm/y using a fault dip of 30° (main fault trace only) [L_2] 2.8 mm/y using a fault dip of 30° ("top of Yager" datum) [L_5]
SLIP ON SOILS:	1.7-4.2? [L_2]
RECURRENCE:	0.4-1.0? ky [L_2]
AGE:	post-0.48±0.19 ka [L_2]
SHORTENING RATE:	3.8 mm/y using a fault dip of 30° ("top of Yager" datum) [L_1] 2.9-3.6? mm/y using a fault dip of 30° (main fault trace only) [L_2] 2.4 mm/y using a fault dip of 30° ("top of Yager" datum) [L_5]
UPLIFT RATE:	2.2 mm/y ("top of Yager" datum) [L_1] 1.7-2.2? mm/y (main fault trace only) [L_2] 1.4 mm/y ("top of Yager" datum) [L_5]

REFERENCES:

Carver and Burke, 1988 (O)
Clarke, 1992 (R)
Clarke and Carver, 1992 (R)
Crouch, 1988 (O)
Hart *et al.*, 1991 (O)
Kennedy, 1978 (O)
McCrory, 1995 (R)
Ogle, 1953 (R)
Wehmiller and Keenan, 1980 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: See specific site descriptions. Slip rates given above should not be used for offshore segment of Little Salmon fault (see discussion under sites L_8 and L_9).

FAULT: Little Salmon fault zone
SEGMENT: Yager fault
SITE(S): Yager Creek [Y_1]; *Anderson* well [Y_2]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Surface exposure of the Yager fault (a secondary fault trace within the Little Salmon fault zone, NE of the main trace) at Yager Creek [site **Y_1**] reveals Paleogene Yager terrane of the Coastal belt Franciscan complex thrust from the north over Pliocene Rio Dell/Eel River Formation of the Wildcat Group (Ogle, 1953). This field evidence documents post-Pliocene movement on the Yager fault strand. At Grizzly Creek, 14 km east of site **Y_1**, the Yager fault is not observed, and lower Wildcat rocks are in depositional contact with Yager terrane rocks (angular unconformity) (Woodward-Clyde Consultants, 1980).

Texaco Anderson #1 well [site **Y_2**], 2 km west of site **Y_1**, penetrated the top of the Yager terrane at 2680-m depth. Thus, vertical separation on the "top of the Yager" datum between sites **Y_1** and **Y_2** (across both the main Little Salmon fault trace and the Yager fault trace) is at least 2680 m.

Onset of faulting along the eastern portion of the Little Salmon fault system is poorly constrained. Based on surface exposures, the Scotia Bluffs Sandstone abruptly thins from south to north across the Wolverton synclinal axis between Hydesville and Grizzly Creek State Park (a distance of 16 km) (Woodward-Clyde Consultants, 1980). This thinning parallels the Wolverton axis and the Little Salmon fault trace which lies within the north limb of the syncline. The thinning is inferred to have resulted from growth of the northern synclinal limb and movement on the Little Salmon fault during Scotia Bluffs deposition (post-1.5 Ma in Scotia Bluffs area, 4 km to the southeast; McCrory, 1995). If displacement across the Yager and Little Salmon fault traces began *ca.* 1 Ma, as is inferred elsewhere in the Humboldt area, and if these faults are assumed to dip 30°, then the rate of fault slip in this area is about 5.36 mm/y. If displacement began *ca.* 1.5 Ma, then the calculated slip rate is 3.57 mm/y.

FAULT TYPE: thrust [R]
DIP: NE
STRIKE: 300°
SLIP RATE: 3.57-5.36? mm/y assuming a fault dip of 30°
SLIP PER EVENT: *n/a*
RECURRENCE : *n/a*
AGE: post-Pliocene, perhaps post-1.5 Ma
SHORTENING RATE: *n/a*
UPLIFT RATE: *n/a*

REFERENCES:
Hart *et al.*, 1991 (O)
Ogle, 1953 (R)

McCrory, 1995 (R)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: Aerial photographs reveal no geomorphic expression of recent faulting or offset of young alluvial deposits along the Yager fault trace, however, this fault is largely obscured by timber cover (Hart *et al.*, 1991).

The pre-Wildcat geometry of the bedrock units is unknown. For this reason, using vertical separation to calculate fault-slip rates requires several assumptions: (1) the "top of Yager" datum was originally a horizontal surface; (2) no lateral slip has occurred along Little Salmon fault zone; and (3) the exposed "top of Yager" datum on the upper plate at site $\mathbf{Y_1}$ has not been eroded. The vertical separation given for the Yager fault trace by Ogle (1953) was measured across at least two fault traces. This vertical separation largely results from offset across the Little Salmon fault trace.

FAULT: Little Salmon fault zone

SEGMENT: Goose Lake fault

SITE(S): Goose Lake trench [GL_1]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: The Goose Lake fault trace lies 1.5 km south of site **Y_1**, near the eastern end of the Little Salmon fault. A trench cut at site **GL_1** exposed two reverse fault strands, 12 m apart, which cut a sequence of Carlotta Formation overlain by alluvium, in turn overlain by lacustrine and colluvial sediments. These faults strike N75-85°W and dip and an average of 50-60°NE (Woodward-Clyde Consultants, 1980). The most recent displacement, based on conventional radiocarbon dates from the lacustrine unit, occurred **<16.1±0.1 ka** (in **radiocarbon years**; sample collected 1 m below surface of most recently faulted unit) and **>8.7±0.2 ka** (sample collected 2 m above top of the most recently faulted unit). Evidence for at least 2 post-16 ka slip events is based on the formation of colluvium derived from the southern fault scarp and subsequent offset of that colluvium. The rake on slickensides within Carlotta Formation exposed in the trench suggest that dextral strike-slip movement accounts for 30 to 50% of the total slip. Vertical separation of lacustrine sediments across the northern fault strand is 3 to 5 m; vertical separation of lacustrine sediments across the southern fault strand is 2 m. If these lacustrine strata are correlative, post-16 ka vertical separation is at least 5 to 7 m (Woodward-Clyde Consultants, 1980).

FAULT TYPE:	thrust [R-RL?]
DIP:	55±5° NE
STRIKE:	275-285°
SLIP RATE:	0.38-0.54 mm/y using a fault dip of 55° (16.1-ka datum) 0.67-0.95 mm/y using a fault dip of 55° (8.7-ka datum)
SLIP PER EVENT:	*n/a*
RECURRENCE:	2 post-16 ka events
AGE:	post-16.1±0.1 ka; pre-8.7±0.2 ka
SHORTENING RATE:	0.22-0.31 mm/y using a fault dip of 55° (16.1-ka datum) 0.38-0.55 mm/y using a fault dip of 55° (8.7-ka datum)
UPLIFT RATE:	0.31-0.44 mm/y using a fault dip of 55° (16.1-ka datum) 0.56-0.78 mm/y using a fault dip of 55° (8.7-ka datum)

REFERENCES:

Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: It remains unresolved whether the Goose Lake fault is a subsidiary trace of the Little Salmon fault zone—propagating up the syclinal limb of the associated fault-propagation fold or a flexure-slip fault in the northern limb of the Eel River syncline.

Woodward-Clyde Consultants (1980) identified a "fault A", 0.7 km north of the Goose Lake trace. This trace, although not investigated in the field, may have a similar slip rate based on its similar geomorphic expression.

FAULT:	Little Salmon fault zone
SEGMENT:	onshore fault zone
SITE(S):	Tompkins Hill [**TB_1**, **TB_2** & **L_1**]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Vertical separation on the "top of Yager" datum across the Little Salmon fault zone at Tompkins Hill [site **L_1**] is at least 2200 m based on subsurface data from *Texaco Pacific Lumber #1* and *HE-10* wells [sites **TB_1** & **TB_2**] (Woodward-Clyde Consultants, 1980; Crouch, 1988). Where subsurface control is available at Tompkins Hill, the Little Salmon fault dips 25 to 35° (Woodward-Clyde Consultants, 1980). If slip on the Little Salmon fault in the vicinity of Tompkins Hill is assumed to have begun *ca.* 1 Ma as is inferred elsewhere, then a dip-slip rate of 4.4 mm/y can be calculated using a dip of 30°.

The Little Salmon fault dips 35° in borehole *WCC-24* [site **L_1**] (Woodward-Clyde Consultants, 1980). The Railroad Gulch ash was found 117 m below the fault plane (Woodward-Clyde Consultants, 1980) in borehole *WCC-24.* Thus, minimum vertical separation of Railroad Gulch ash datum across the Little Salmon fault zone is 117 m. The Railroad Gulch ash is *ca.* 400 to 470 ka (Sarna *et al.*, 1991), yielding a minimum vertical separation rate of 0.25 to 0.29 mm/y.

FAULT TYPE:	thrust [R]
DIP:	30±5° NE
STRIKE:	315°
SLIP RATE:	0.43-0.51 mm/y using a fault dip of 35° (minimum rate using Railroad Gulch ash datum) [**L_1**] 4.4 mm/y using a fault dip of 30° ("top of Yager" datum) [**TB_1** & **TB_2**]
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-470 ka
SHORTENING RATE:	0.35-0.42 mm/y using a fault dip of 35° (minimum rate using Railroad Gulch ash datum) [**L_1**] 3.8 mm/y using a fault dip of 30° ("top of Yager" datum) [**TB_1** & **TB_2**]
UPLIFT RATE:	0.25-0.29 mm/y (minimum rate using Railroad Gulch ash datum) [**L_1**] 2.2 mm/y ("top of Yager" datum) [**TB_1** & **TB_2**]

REFERENCES:

Crouch, 1988 (O)
Sarna *et al.*, 1991 (R)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: Slip rate calculated using the Railroad Gulch ash datum is a minimum rate because this ash was not found above the Little Salmon fault in borehole *WCC-24* [site **L1**]. Strata in the borehole above the fault plane are lower Wildcat Group rocks whereas the Railroad Gulch ash is typically found in Hookton deposits, stratigraphically above the Wildcat Group. Thus, the calculated slip rate does not include an unknown thickness of Wildcat strata between the fault plane and the ash datum in the upper plate. The lack of this datum on the upper plate may account for the large discrepancy between the slip rate calculated from the "top of Yager" and Railroad Gulch ash datums. Alternatively, this difference may reflect a pre-1 Ma start time for Little Salmon fault slip.

Because the Tompkins Hill anticline is growing beneath the Little Salmon fault, it is unclear how this superimposed deformation affects slip rates determined for the Little Salmon fault at Tompkins Hill. For this fault survey, the Table Bluff-Tompkins Hill structure is considered an independant, non-Little Salmon structure.

FAULT: Little Salmon fault zone
SEGMENT: onshore main fault
SITE(S): Little Salmon Creek trenches [L_2]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: A series of eight trenches was cut across the main trace of the Little Salmon fault 3.5 km north of site L_1 (Carver and Burke, 1988). These trenches exposed a sequence of stacked floodplain deposits in trench walls up to 5-m deep. Data from the seven eastern trenches were compiled to form a composite cross-section. The fault is exposed in the eighth, westernmost trench. The fault trace dips 30° at the base of this trench. Slip estimates given for the main trace of the Little Salmon fault at site L_2 combine slip measured along the fault plane and slip calculated from warping of four buried soil horizons. Most of this slip extimate is derived from warping of the soil horizons, not fault offset. This warping, above an inferred fault-propagation fold, is included as a component of fault slip based on the assumption that folding is a surface expression of coseismic slip at depth.

Units exposed in trenches, from lowest to highest:

Unit 1 Hookton Formation is exposed only in the easternmost trench.

Unit 2 Unit 1 is overlain by colluvium derived from redeposited Hookton material. Radiocarbon date on detrital charcoal from Unit 2 is **26,950 a** ±**120** y (in **radiocarbon years**; sample #QL-4120, Table 3 *in* Carver and Burke, 1988). Note, there are inconsistencies in data—both between figures and text in Carver and Burke (1988) and between the 1988 report and Clarke and Carver (1992). For example, this sample is keyed to Hookton Formation in Figure 13, 1988 report; not colluvium as in 1988 text and Figure 2, 1992 report.

Unit 3a/b Unit 2 is overlain by a massive silt deposit (inferred overbank-flood facies) which is interbedded with a cross-bedded sand deposit (inferred stream-channel facies) and a laminated silt deposit (inferred lacustrine facies). Radiocarbon date on detrital charcoal from a silt unit is **6200 a** ±**30** y (sample #QL-4116, Table 3 *in* Carver and Burke, 1988); *6951-7247 a* (*calibrated age*; Clarke and Carver, 1992). Note, this sample is keyed to the overbank silt below the channel sands in Figure 13, 1988 report; not the overbank silt above the channel sand as in Figure 2, 1992 report.

Unit 3c Units 3a and 3b are overlain by a massive silt deposit (inferred overbank-flood facies) which contains 4 buried soil horizons:

- **Soil 4**: Radiocarbon date on detrital charcoal from Soil 4 is **3130 a** ±**300** y (sample #QL-4184, Table 3 *in* Carver and Burke, 1988); *2149-4802 a* (Clarke and Carver, 1992).
- **Soil 3**: Radiocarbon date on detrital charcoal from overbank silt below Soil 3 is **1970 a** ±**30** y (sample #QL-4117, Table 3 *in* Carver and Burke, 1988); *1820-2039 a* (Clarke and Carver, 1992). Note, 1988 text stated that this sample was collected above Soil 3, however, Figure 13, 1988 report, keys it within Soil 3. Radiocarbon date on detrital? wood from overbank silt above Soil 3 is **1730 a** ±**30** y (sample #QL-4119, Table 3 *in* Carver and Burke, 1988) *1530-1861 a* (Clarke and Carver, 1992). Note, 1988 text stated that this sample was collected below Soil 3, however, Figure 13 (1988 report) keys it above Soil 3. In other words, the text

stated that this sample is inverted with respect to age (the older sample #QL-4117 is above the younger sample #QL-4119), however, Figure 13 (1988 report) shows the opposite.

- **Soil 2:** Radiocarbon date on detrital? wood from Soil 2 is **870 a ±100 y** (sample #QL-4182, Table 3 *in* Carver and Burke, 1988); *540-1169 a* (Clarke and Carver, 1992).
- **Soil 1:** Radiocarbon date on detrital charcoal from Soil 1 is **430 a ±70 y** (sample #QL-4183, Table 3 *in* Carver and Burke, 1988); *290-670 a* (Clarke and Carver, 1992).

IN SUMMARY: (*Calibrated Ages*)

Soil 4: *3.48±1.32 ka* (maximum age of soil from detrital charcoal)
Soil 3: *1.70±0.17 - 1.93±0.11 ka* (age range of detrital material above and below soil)
Soil 2: *0.86±0.32 ka* (maximum age of soil from detrital? wood)
Soil 1: *0.48±0.19 ka* (maximum age of soil from detrital charcoal)

Unit 4 Unit 3 is overlain by a modern soil. Radiocarbon date on detrital charcoal from Unit 4 is **80 a ±20 y** (sample #QL-4118, Table 3 *in* Carver and Burke, 1988); *540-1169 a* (Clarke and Carver, 1992). Note, this sample is keyed to the lacustrine silt in Figure 2 of the 1992 report, not to the modern soil as in the 1988 text, and given an identical age as sample #QL-4182 (from Soil 2).

The component of subsurface slip expressed as surface folding is estimated from vertical separation of the fanning soil horizons, east of the fault plane (upper plate). Calculations of slip associated with folding reported in Carver and Burke (1988) are based on the premise that the soil datums were originally horizontal surfaces. However, at site **L_2** the soils formed on a growing structure with surface relief, so the assumption of originally horizontal soil datums is unrealistic. A more realistic estimate of slip associated with folding is obtained by using the modern dip of the ground surface (approximately 3°) as an analog (Figure 5). In this scenario, vertical displacement of the ground surface triggers a mobilization of surficial sediments, and an equilibrium slope forms prior to development of a soil. This modification of the inferred soil-datum geometry yields lower values of vertical separation.

If Soil 1 formed on a surface with similar slope to the modern surface, 0.8 m needs to be subtracted from the measured 1.3 m of differential tilt (Figure 5), to yield 0.5 m of differential warping. Using a 30° dip on the fault plane yields 1.0 m of dip-slip offset attributed to warping. In addition, 0.7-m displacement of Soil 1 is indicated in Figure 2 of Clarke and Carver (1992). Thus, both slip components indicate about 1.7 m of fault displacement occurred at depth during the post-0.48-ka slip event. The average slip rate isabout 3.54 mm/y.

If Soil 2 formed on a surface with similar slope to the modern surface, 0.8 m needs to be subtracted from the measured 2.1 m of differential tilt (Figure 5) and 0.5 m needs to be subtracted for warping of the younger soil, to yield 0.8 m of differential warping. Using a 30° dip on fault plane yields 1.6 m of dip-slip offset attributed to warping. In addition, 0.3-m displacement of Soil 2 (adjusted for 0.7-m slip on Soil 1) is indicated in Figure 2 of Clarke and Carver (1992). Thus, both slip components indicate about 1.9 m of fault displacement occurred at depth during the post-0.86-ka slip event. The cumulative slip rate is about 4.19 mm/y.

If Soil 3 formed on a surface with similar slope to the modern surface, 0.8 m needs to be subtracted from the measured 3.2 m of differential tilt (Figure 5) and 1.3 m needs to be subtracted for warping of the 2 younger soils yielding 0.8 m of differential warping. Using a 30° dip on fault plane yields 2.2 m of dip-slip offset attributed to warping. In addition, 2.0-m displacement of Soil 3 (adjusted for 1.0-m slip on Soils 1 and 2) is indicated in Figure 2 of Clarke and Carver (1992). Thus, both components indicate about 4.2-m of fault displacement occurred at depth during the post-1.81-ka slip event. The cumulative slip rate is about 4.31 mm/y. Note, the above slip values are calculated by assuming that Soil 3 reaches the upslope datum of Soils 1 and 2, however, no evidence is presented in Carver and Burke (1988) to support this assumption. If the datum is instead placed at the apparent termination of Soil 3—2.1 m below the termination of Soils 1 and 2 (Figure 5), the measured differential tilting is 1.1 m. Using this lower datum yields 0.2 m differential warping or 0.4 inferred dip-slip displacement. (Note, this value is calculated by not correcting for paleoslope—most of the differential warping occurs east of Soil 3—and decreasing the differential warping values from Soils 1 and 2 by 1/3 to account for the shorter baseline—10 m rather than 15 m.) Adding the 2.0-m fault displacement, yields a total of 2.4 m displacement at depth and a cumulative slip rate of 3.32 mm/y.

Auger hole 2 is shown east of the fault trace (upper plate) in Figure 13 of Carver and Burke (1988) and west of the trace (lower plate) in Figure 2 of Clarke and Carver (1992), so Soil 4 is not used for calculating slip rates. The *ca.* 6.2-ka Unit 3a is not shown in trench logs on the west side of the fault (lower plate), so this unit is not used to calculate slip rates. The log of the westernmost trench in Carver and Burke (1988) shows only 0.1 to 0.2-m total dip-slip offset of Soil 3 along the fault trace in contrast with Figure 2 of Clarke and Carver (1992) which shows 3 m offset of Soil 3.

FAULT TYPE:	thrust [R]
DIP:	30° NE
STRIKE:	330°
SLIP RATE:	3.54 mm/y using a fault dip of 30° (Soil 1 datum; post-0.48 ka) 4.19 mm/y using a fault dip of 30° (Soil 2 datum; post-0.86 ka) 3.32-4.31? mm/y using a fault dip of 30° (Soil 3 datum; post-1.81 ka)
SLIP ON SOILS:	1.7 m (Soil 1 datum) 1.9 m (Soil 2 datum) 2.4-4.2? m (Soil 3 datum)
RECURRENCE :	0.4-1.0 ky
AGE:	post-0.48±0.19 ka
SHORTENING RATE:	2.88-3.63? mm/y
UPLIFT RATE (mm/y):	1.66-2.16? mm/y

REFERENCES:

Carver and Burke, 1988 (O)
Clarke and Carver, 1992 (R)

DATA LIMITATIONS: Clarke and Carver (*in* Figure 2 caption, 1992) proposed that the buried soil horizons mark coseismic slip events. In this scenario, each soil formed following a slip event, so the youngest offset soil (Soil 1; calibrated age of *ca. 0.48 ka*) is older than the most recent slip (*i.e.*, 0.48 ka is a maximum age for the most recent slip event). The assumption that these soil horizons mark slip events is based on a model of uplift along the fault plane moving the floodplain sediments on the upper plate out of their depositional environment—interrupting deposition and allowing a soil to form. If this is the case, it is not clear why a correlative soil also formed on the lower plate which presumably was not uplifted out of the floodplain environment.

Neither report (Carver and Burke, 1988; Clarke and Carver, 1992) rules out a model where the soils formed primarily by sedimentological processes; namely, that the soils formed between large flood events (*e.g.*, 500-y floods). In this scenario, the soils would not be directly related to slip events, so they would not document slip events, but rather record subaerial weathering between large flood events. Regardless of whether the soils represent seismic processes or flood processes, the buried soil horizons represent weathering surfaces formed on a massive silt deposits during non-deposition of floodplain sediments, and as such are valuable datums for determining slip rates, documenting progressive offset with depth, and demonstrating the occurrence of repeated slip events.

The fanning geometry of the buried soil horizons suggests apparent subsidence to the west in contradiction with their location on the upper plate of a thrust fault. This paradox may be explained if folding of the upper plate occurs relatively more rapidly than shallow slip along the fault trace. If this is the case, evidence of the expected reverse stacking (oldest on top) of buried soils above the fold has been eroded away during formation of new flatter equillibrium surfaces (*i.e.*, following each uplift event, the upland soil is eroded and redeposited on top of its lowland equivalent degrading the "fold scarp").

Apparently, a subsidiary trace of the Little Salmon fault, east of the main trace, was trenched by Carver post-1988, pre-1992 and this trace also revealed Holocene slip. No data is currently available on this trench site. However, Clarke and Carver (1992) state that dip-slip events observed in this trench are 55 to 70% smaller than events observed on the adjacent main trace, suggesting a substantially smaller slip rate or more frequent slip events. To obtain a full Little Salmon slip rate based on vertical separation of sub-horizontal datums requires comparision of datums which span the entire fault zone. Thus, the estimate given above is not a complete slip rate owing to the lack of slip data for the subsidiary trace. However, slip on the eastern trace appears to be significantly less than on the main trace.

See discussion of various radiocarbon dating techniques and associated analytical errors under Megathrust sources—Eel River syncline section.

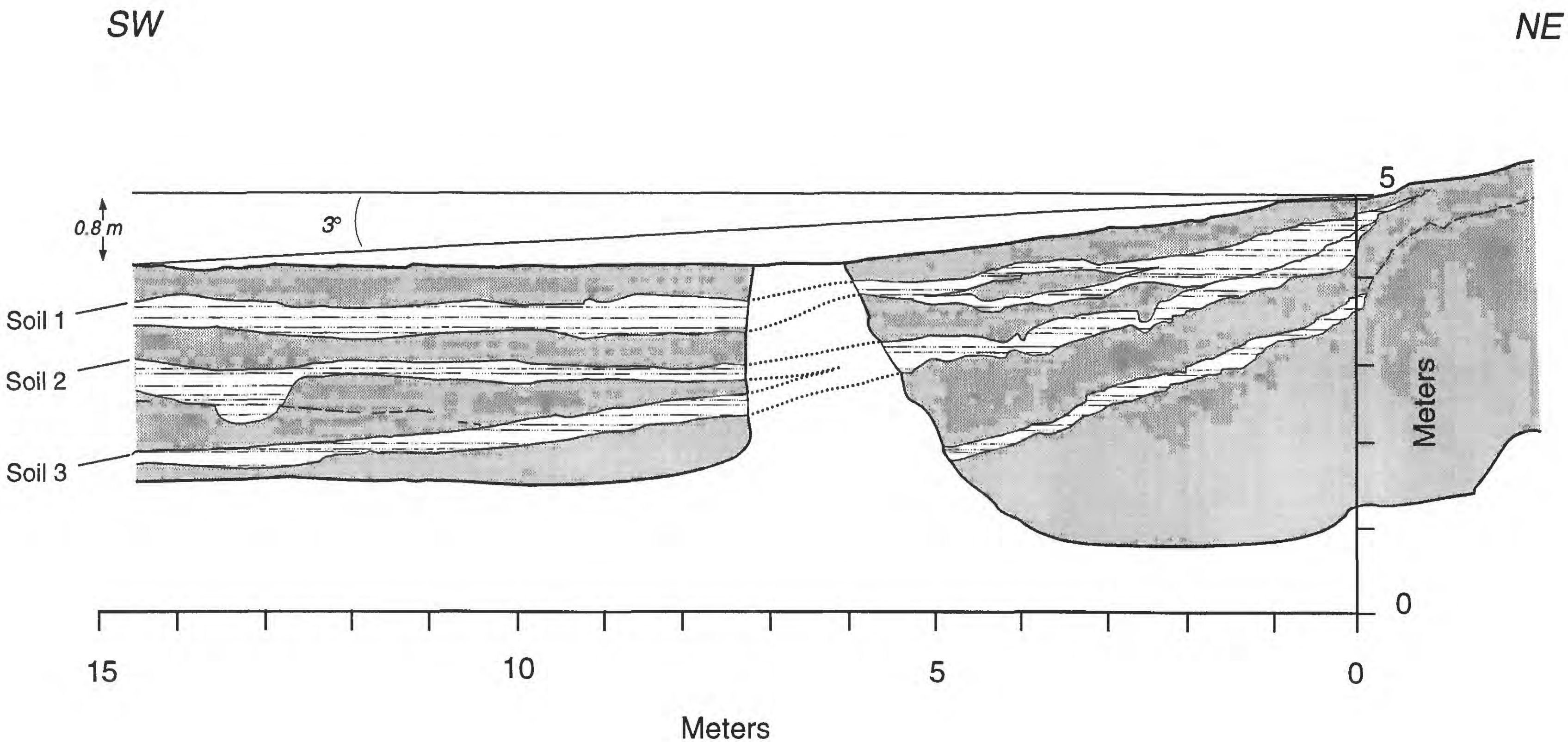

Figure 5. Sketch of Little Salmon Creek trench exposures [site L_2] showing geometry of deformed floodplain silts in upper plate of the Little Salmon fault (modified from Carver and Burke, 1980) and correction from horizonatal datum to an inclined datum. The modern slope dips about 3°; this value is used as an approximation for the inferred paleoslope for each soil formed on a floodplain surface. This revision requires decreasing the values given for vertical separation in Carver and Burke (1988) by 0.8 m (15 m* tan 3° = 0.8 m).

FAULT:	Little Salmon fault zone
SEGMENT:	onshore subsidiary fault
SITE(S):	College of Redwoods trenches [**L3**]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Two trenches cut across the Little Salmon fault zone, 4 km north of site **L2**, exposed a zone of secondary thrust faults and an associated fold in the upper plate of the Little Salmon fault in trench walls up to 5-m deep (Woodward-Clyde Consultants, 1980). The fault traces strike N30-50°W and dip 25-35°NE. The main trace of the Little Salmon fault is inferred to be west of site **L3** based on folding of Hookton sediments (Woodward-Clyde Consultants, 1980). Secondary faults in the trenches equally displace Hookton Formation and the contact between Hookton deposits and overlying colluvium. Faults were not observed to continue into the colluvium, however, the colluvium contains vertical fractures filled with sand which may have formed during post-colluvium ground shaking (seismic mechanism) or by lateral spreading (non-seismic or seismic mechanism). Hookton horizons are offset a maximum of 0.71 m on a single fault plane (dip-slip) and cumulatively about 2 m across all observed faults. Horizons within the Hookton Formation are steeply dipping to overturned, suggesting multiple slip events. If the main fault trace is to the west, slip estimates from this site likely significantly underestimate total slip across entire fault zone.

FAULT TYPE:	thrust [R]
DIP:	30±5° NE
STRIKE:	310-330°
SLIP RATE:	*n/a*
SLIP PER EVENT:	2? m
RECURRENCE:	*n/a*
AGE:	post-Hookton (≤500 ka); pre-colluvium?
SHORTENING RATE:	*n/a*
UPLIFT RATE:	*n/a*

REFERENCES:

Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: No observed Holocene slip; trenches apparently do not expose main trace of the Little Salmon fault (*i.e.*, this is not the same trace as trenched by Carver and Burke, 1988).

FAULT:	Little Salmon fault zone
SEGMENT:	onshore subsidiary fault
SITE:	Brazil Property trenches [L4]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Two trenches cut across the Little Salmon fault zone, 1.5 km north of site L3, exposed a zone of secondary thrust faults in the upper plate of the Little Salmon fault in trench walls up to 5-m deep (Woodward-Clyde Consultants, 1980). Site L4 is located on an uplifted marine-terrace surface cut into the western limb of Humboldt Hill anticline (Woodward-Clyde Consultants, 1980). The western trench exposed Rio Dell strata overlain by sediments of unknown affinity, likely either Hookton Formation or terrace deposits. In this trench, Rio Dell strata are separated from overlying deposits by an unconformity that Woodward-Clyde Consultants (1980) interpreted to be a marine-abrasion surface. The trench exposes NW-striking thrust faults that dip an average of 40°NE. The most recent displacement is post Hookton/terrace deposits. Net dip-slip offset of the unconformity is 5 to 7 m; 3.5-m of this offset occurs on a single fault plane. Offset of the terrace surface (not abrasion platform) is <1 to 2 m. Woodward-Clyde Consultants (1980) inferred repeated slip events at this site based on an adjacent roadcut that apparently exposed Rio Dell strata offset tens of meters over sands of unknown affinity, possibly Hookton Formation.

The marine-terrace platform at site L4 best correlates with the sea-level high stand *ca.* 83 ka (oxygen-isotope stage 5a) based on its elevation of approximately 50 m (Plate 2; Figure 6). The calculations below are based on the assumption that the unconformity at the top of the Rio Dell Formation exposed in the trenches formed *ca.* 83 ka. If this correlation is correct, general uplift of Humboldt Hill anticline is about 0.9 mm/y (1.8 mm/y dip slip; 0.78 mm/y shortening—assuming a fault dip of 30°). Uplift of Humboldt Hill is considered as part of the slip rate in order to obtain a more complete estimate of fault slip at depth.

FAULT TYPE:	thrust [R]
DIP:	40° NE
STRIKE:	320°
SLIP RATE:	0.06-0.08 mm/y using a fault dip of 40° 1.86-1.88 mm/y using a fault dip of 40° plus uplift of Humboldt Hill anticline on inferred fault dipping 30°
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-83 ka?
SHORTENING RATE:	0.05-0.06 mm/y using a fault dip of 40° 0.83-0.84 mm/y using a fault dip of 40° plus uplift of Humboldt Hill anticline on inferred fault dipping 30°
UPLIFT RATE:	0.04-0.05 mm/y 0.94-0.95 mm/y (includes uplift of Humboldt Hill anticline)

REFERENCES:
Carver and Burke, 1988 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: No observed Holocene slip; trenches apparently did not expose main Little Salmon fault trace (*i.e.*, this is not the same trace as trenched by Carver and Burke, 1988).

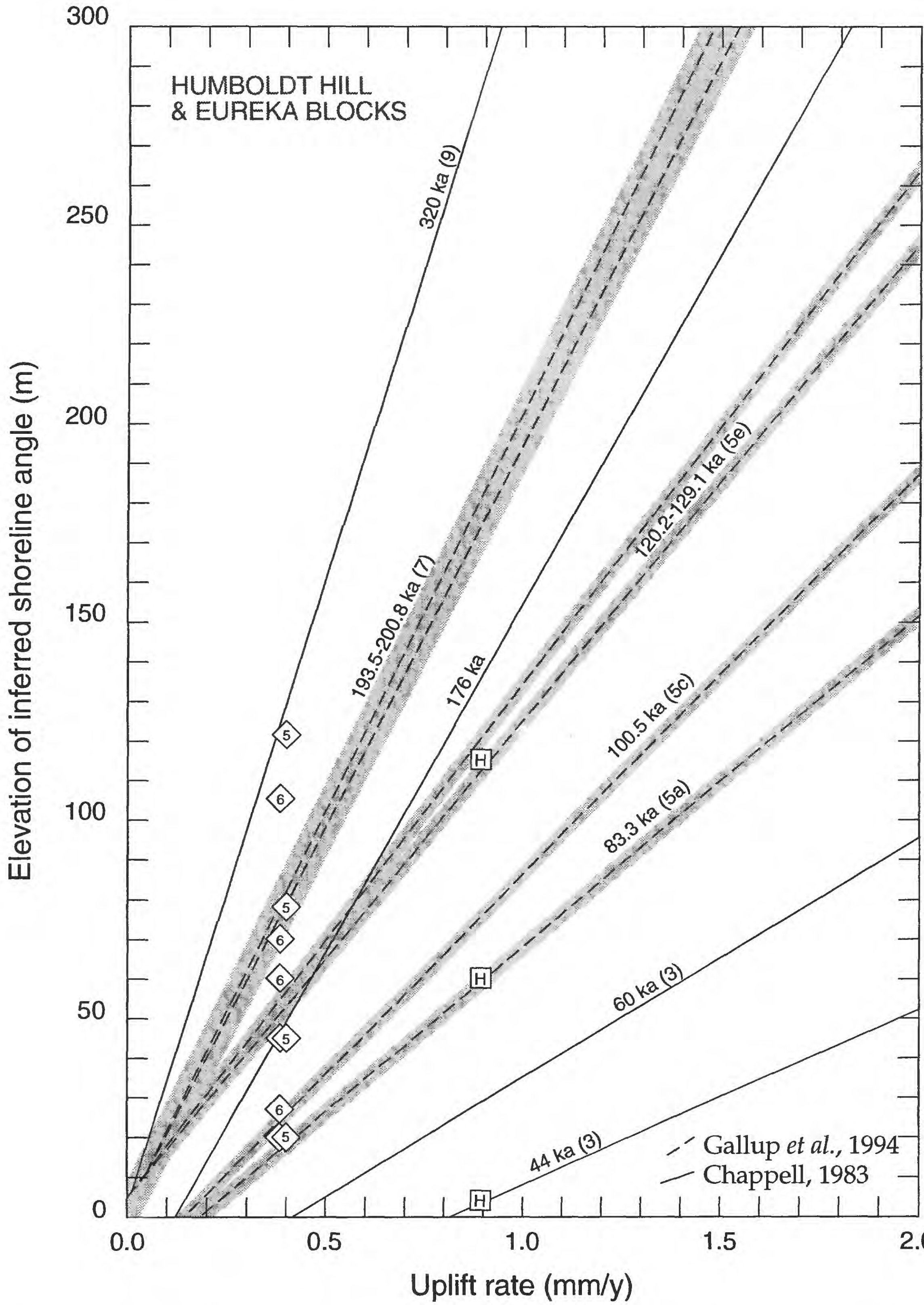

Figure 6. Graphical correlation plot for the Humboldt Hill and Eureka structural blocks showing the preferred age estimates for marine-terrace platforms and resultant uplift rates. Elevation of shoreline angle inferred from elevation of marine-terrace surfaces and thickness of sediment cover. Terrace-profile elevations (diamond symbol) from Figure 8 in Carver *et al.* (1986*a*); reference-section elevations (square symbol) from Table 1 in Carver *et al.* (1986*a*), assuming lowest widespread terrace is *ca.* 83 ka. Gray areas denote uncertainties on age and elevation of sea-level high stands (from Gallup *et al*, 1994). See Plate 2 for locations of profiles.

FAULT:	Little Salmon fault zone
SEGMENT:	onshore fault zone
SITE(S):	Fields Landing/Humboldt Hill [L5, L6, L7, L8 & L9]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: In the Fields Landing area, 2.5 km northwest of site L4, the Little Salmon fault strikes N30°W and dips 30°NE based on borehole data (Woodward-Clyde Consultants, 1980). *Brauner* well [site L5], drilled 2.5 km southeast of Fields Landing near the crest of Humboldt Hill, penetrated the "top of Yager" datum at about 1800-m depth on the lower plate of the Little Salmon fault. *Blackwood Nichols #1* well [site L6], 1.8 km to the east, penetrated the "top of Yager" datum at about 400-m depth. The difference yields about 1400-m vertical separation across the fault (assuming "top of Yager" datum was initially horizontal) in the Humboldt Hill area.

At the northern end of Humboldt Hill, between boreholes *WCC-6* and *L-3* [site L7], dipping strata display progressive warping since Scotia Bluffs Sandstone? time (Woodward-Clyde Consultants, 1980). Units within Scotia Bluffs Sandstone? dip 23°; basal Hookton Formation dips 19°; upper Hookton Formation dips 4°; the terrace surface at the top of Hookton Formation dips 3.5°. The duration of the unconformity between Wildcat and Hookton strata is estimated to be *ca.* 100 ky, assuming a constant rate of warping (Woodward-Clyde Consultants, 1980). For example, at borehole *WCC-6* (Figure 7), the tilt rate is 4.35° *per* 100 ky based on dips of Hookton marker beds. Extrapolating across the basal unconformity, yields 103.5 ky duration. Thus, if the base of Hookton Formation is *ca.* 500 ka, then locally the top of Scotia Bluffs? Sandstone is *ca.* 600 ka.

The age estimate for the "top of lower Hookton" datum ranges from *ca.* 200 to 120 ka (Kennedy, 1978; Wehmiller and Keenan, 1980; Kennedy *et al.*, 1982) based on amino-acid racemization of fossil shell material (*Saxidomus*) from a clay layer near the top of the lower Hookton Formation exposed in a CalTrans roadcut [site L8] at 12.2-m elevation (Woodward-Clyde Consultants, 1980). For the purpose of this fault survey, the "top of lower Hookton" datum is correlated to the 125-ka sea-level high stand (Kennedy *et al.*, 1982). If 125 ka is an accurate age for this datum, then fault offset is post-125 ka.

Lesser separation of progressively younger units (as well as lesser tilts) implies repeated movement on this portion of the Little Salmon fault during Quaternary time. For example, calculated dip-slip displacements, assuming a fault dip of 30°, are given below for borehole *WCC-12* [site L9] (see Woodward-Clyde Consultants, 1980). Note that not all of these data come directly from *WCC-12* ; some of these values are based on projections into borehole *WCC-12* from adjacent boreholes.

- 1760 m separation of "top of Rio Dell" datum @ 1.76 mm/y (if faulting started *ca.* 1 Ma)
- 1130 m separation of "base of lower Hookton" datum @ 2.26 mm/y (if datum is *ca.* 500 ka)
- 360 m separation of "top of lower Hookton" datum @ 2.88 mm/y (if datum is *ca.* 125 ka)

FAULT TYPE:	thrust [R]
DIP:	30° NE

STRIKE :	330°
SLIP RATE :	1.76-2.88 mm/y assuming a fault dip of 30° (borehole data) [L9] 2.8 mm/y using a fault dip of 30° (gas-well data) [L5 & L6]
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-lower Hookton Formation (*ca.* 125 ka) [L8]
SHORTENING RATE:	1.52-2.49 mm/y assuming a fault dip of 30° (borehole data) [L9] 2.43 mm/y using a fault dip of 30° (gas-well data) [L5 & L6]
UPLIFT RATE:	0.88-1.44 mm/y (borehole data) [L9] 1.4 mm/y (gas-well data) [L5 & L6]

REFERENCES:

Crouch, 1988 (O)
Kennedy, 1978 (O)
Kennedy *et al.*, 1982 (R)
Wehmiller and Keenan, 1980 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: No Holocene deposits were penetrated by boreholes, therefore, it is unknown whether Holocene slip has occurred in this area.

Woodward-Clyde Consultants (1980) proposed that slip across the Little Salmon fault in this area followed Rio Dell deposition, based on their estimate that both "top of Yager" and "top of Rio Dell" datums are separated the same amount. Their estimate of 1400-m vertical separation of the "top of Rio Dell" datum was based on the observation that the combined thickness of Rio Dell and Eel River Formations is about 900 m on both upper and lower thrust plates at the *Brauner* well [site L5] and boreholes *WCC-12* [site L9], *AW-4*, and *WCC-3* (Figure 7). However, a cross-section between *Brauner* and *Blackwood* wells by Crouch (1988) contradicts these upper plate values. This cross-section shows about 600 m of Eel River and Rio Dell strata on the upper plate of the Little Salmon fault in both *Brauner* and *Blackwood* wells. In contrast, about 900 m of Eel River and Rio Dell strata are shown on the lower plate of the Little Salmon fault in *Brauner* well (Crouch, 1988) (*Blackwood* well does not penetrate lower plate). The lesser thickness of upper plate Rio Dell strata in both wells appears to have resulted from erosion.

The vertical separation of 880-m given for the "top of Rio Dell" datum in borehole *WCC-12* [site L9] is a minimum estimate, as the "top of Rio Dell" datum was not encountered in the lower plate (TD 975 m) of the fault (Woodward-Clyde Consultants, 1980). Borehole *AW-4* (Figure 7) penetrated the "top of Rio Dell" datum on the upper thrust plate at 430-m depth (Woodward-Clyde Consultants, 1980). Again, the "top of Rio Dell" datum was not penetrated in the lower plate. For this borehole, the datum was projected to 1040-m depth, yielding a minimum estimate of 610-m vertical separation across the fault (Woodward-Clyde Consultants, 1980). In borehole *WCC-3* (1 km south of site L6), vertical separation of Unit O within Scotia Bluffs? Sandstone across the Little Salmon fault is a maximum of 527 m; the Rio Dell Formation was not penetrated in the lower plate.

The vertical separation of the "top of Yager" datum across the Little Salmon fault drops from from 2.7 km at Yager Creek to 2.2 km at Tompkins Hill to 1.4 km at Humboldt Hill. As the surface trace of the Little Salmon swings north in the Fields Landing area, the fault system seems to broaden into several interconnected fault traces. In the Fields Landing area itself, vertical separation of the "top of Rio Dell" datum across the Little Salmon fault decreases from approximately 1.4 km in the southeast (Humboldt Hill) to 0.5 km in the northwest (borehole *WCC-3*), a distance of about 3 km. Woodward-Clyde Consultants (1980) attribute the decrease in vertical separation in the Fields Landing area to steeper dips on strata above the thrust (*i.e.*, upper plate folding) in the northern area, shifting the location of the footwall cutoff.

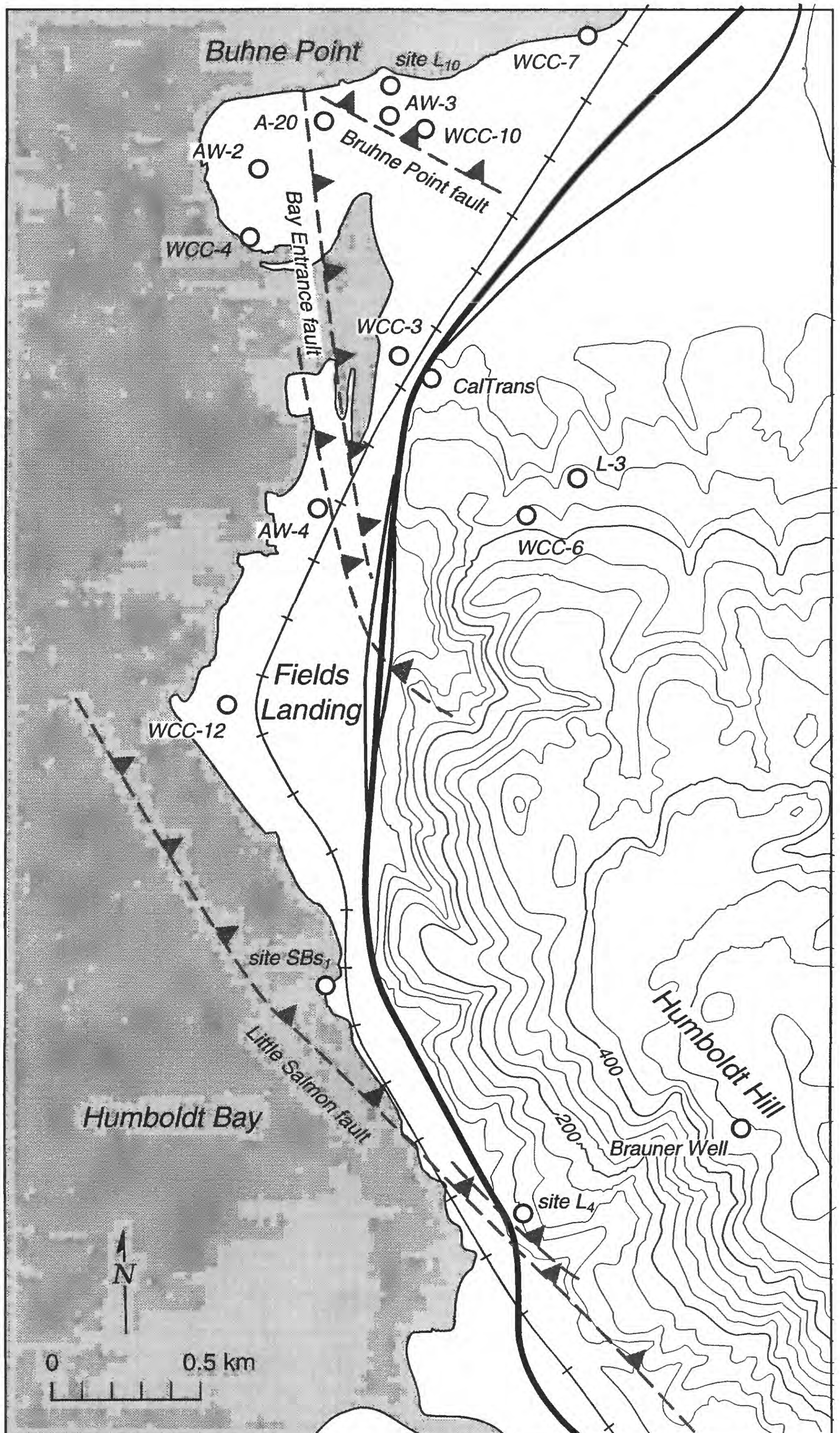

Figure 7. Map showing boreholes in Fields Landing area discussed in text (modified from Woodward-Clyde Consultants, 1980). Brauner well is site L_5; borehole L-3 is site L_7; CalTrans exposure is site L_8; WCC-12 is site L_9. See Plate 1 for location of map. Fault traces shown are projected to surface from borehole data.

FAULT:	Little Salmon fault zone
SEGMENT:	Buhne Point fault
SITE(S):	Buhne Point/Humboldt Hill [L_{10} & L_{11}]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: The Buhne Point site [L_{10}] is located 2 km north of site L_9. Where subsurface control is available at site L_{10}, the Little Salmon fault dips 25-35°NE (Woodward-Clyde Consultants, 1980). A disconformity/unconformity between Rio Dell Formation and Scotia Bluffs? Sandstone is observed in a 3-km long cross-section from Buhne Point south to Humboldt Hill (Figure C-6 *in* Woodward-Clyde Consultants, 1980). This unconformity appears to represent minor onlap on the Humboldt Hill anticline based on subsurface data (Woodward-Clyde Consultants, 1980) and suggests minor structural growth of the anticline during Rio Dell-Scotia Bluffs deposition. Note, there is significant missing section between Rio Dell Formation and Scotia Bluffs Sandstone/Carlotta Formation elsewhere in the Humboldt area (*e.g.*, in the Table Bluff to Centerville Beach area; Crouch, 1988; Hopps and Horan, 1983), suggesting the possibility of pre-Hookton tectonism in the Buhne Point area as well. Woodward-Clyde Consultants (1980) attribute variations in the thickness of Scotia Bluffs? Sandstone (ranging from 170- to 335-m thick) to erosion of the top of Scotia Bluffs? Sandstone. Strata in the Hookton Formation parallel the basal unconformity, and thin and pinch out against Humboldt Hill anticline suggesting continued structural growth of the anticline in Hookton time.

Lower Hookton? Formation sediments overlie a thin marine gravel unit above a marine-abrasion surface in exposures between Humboldt Hill and Freshwater Creek (Woodward-Clyde Consultants, 1980). The abrasion surface cuts unconformably across Rio Dell, Eel River, and Yager rocks. Woodward-Clyde Consultants (1980) traced this surface to site L_{10} where it appears to correlate with the unconformity between Scotia Bluffs? Sandstone and Hookton Formation. In the Elk River area [site L_{11}], about 7 km east of site L_{10} , the Railroad Gulch ash lies about 30 m stratigraphically above this unconformity, constraining the age of the base of the Hookton Formation to *ca.* 500 ka in this area. At this location, Hookton Formation lies directly on the Eel River Formation. It is troubling that the Railroad Gulch ash was not found in any boreholes to the west. However, if the above described correlations are correct, then, by projection, the Railroad Gulch ash should lie between the unconformity at the top of Wildcat strata and Unit K in the Hookton Formation.

Trenches cut at site L_{10} exposed minor, secondary faults (upper-plate faults) related to the Buhne Point fault trace, a subsidiary fault of the Little Salmon system (Woodward-Clyde Consultants, 1980). The youngest observed offset is post-125 ka based on amino-acid racemization of fossil-shell material from equivalent deposits in a roadcut 1-km south of site L_{10} (see discussion under site L_9).

FAULT TYPE:	thrust [R]
DIP:	30±5° NE
STRIKE:	NW
SLIP RATE :	*n/a*

SLIP PER EVENT: *n/a*
RECURRENCE: *n/a*
AGE: post-125 ka [$\mathbf{L_{10}}$]
SHORTENING RATE: *n/a*
UPLIFT RATE: *n/a*

REFERENCES:

Crouch, 1988 (O)
Hopps and Horan, 1983 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: No Holocene slip is observed on the Little Salmon fault at this site. However, in general, the boreholes were drilled in areas lacking upper Hookton deposits, so age constraints are limited to observations of lower Hookton deposits. In addition, no boreholes at site $\mathbf{L_6}$ penetrated the entire stratigraphic section (see discussion under site $\mathbf{L_5}$).

If the Scotia Bluffs? Sandstone/lower Hookton Formation contact is a marine-abrasion surface, then it likely formed within several thousand years, *i.e.*, the unconformity at the top of the Scotia Bluffs? Sandstone is everywhere approximately the same age. However, the age of the base of the lower Hookton Formation is likely time-transgressive as these deposits formed by progradation across the abrasion surface. Therefore, the base of the lower Hookton Formation probably youngs to the west. Correspondingly, the length of time represented by the hiatus likely increases westward.

Comparison of data from the Tompkins Hill and Humboldt Hill areas suggests that substantial displacement may have occurred prior to deposition of the Hookton Formation in the Humboldt Hill area. At Humboldt Hill, the Railroad Gulch ash on the upper plate of the Little Salmon fault [site $\mathbf{L_{11}}$] is approximately 30 m above the base of the Hookton Formation. At this locality, the Hookton Formation rests directly on the Eel River Formation of the Wildcat Group. Approximately 5 km to the south at Tompkins Hill, the Railroad Gulch ash (on the lower plate of the Little Salmon fault) is separated from the Eel River Formation by a 1825-m thick sequence that includes the Carlotta Formation, Scotia Bluffs Sandstone, and Rio Dell Formation of the Wildcat Group.

FAULT: Little Salmon fault zone
SEGMENT: Bay Entrance fault
SITE(S): Buhne Point/Humboldt Hill [L_{10}]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Bay Entrance fault trace, a high-angle reverse fault, within the Little Salmon fault zone strikes N05°W and dips 60°E (Woodward-Clyde Consultants, 1980). This trace may be a northern continuation of the Little Salmon-subsidiary fault trace at site L_2. Crouch (1988) showed the Bay Entrance trace as a high-angle splay above the main Little Salmon trace in cross-sections based on gas-well and borehole data in the Fields Landing area.

Quaternary faulting in the Humboldt area is assumed to have started during formation of the unconformity within upper Wildcat strata *ca.* 1 Ma. However, uniform separation of Rio Dell and Scotia Bluffs? datums (Woodward-Clyde Consultants, 1980) suggests that slip on the Bay Entrance fault may post-date Scotia Bluffs deposition. In addition, 80% of slip on the Little Salmon fault in the Humboldt Bay area occurred before upper Hookton time. In contrast, only 46% of the slip on the Bay Entrance fault occurred before upper Hookton time (Woodward-Clyde Consultants, 1980). This disparity in slip history suggests that although the two fault traces likely merge at depth, they do not typically slip concurrently. Regardless, 64-m of fault displacement (Woodward-Clyde Consultants, 1980) occurred along the Bay Entrance fault trace prior to a hiatus ending *ca.* 500 ka. The Bay Entrance trace was active during Hookton deposition based on increasing offset of Hookton strata with depth (Woodward-Clyde Consultants, 1980). Lower Hookton strata are thrust westward over upper Hookton strata in borehole *A-20* (Figure 7) (Woodward-Clyde Consultants, 1980). The Bay Entrance fault trace has likely slipped during Holocene time, based on 271-m fault displacement since *ca.* 125 ka (Woodward-Clyde Consultants, 1980).

Calculated dip-slip displacements on the Bay Entrance fault trace using a fault dip of 60° and datums from boreholes *AW-3* (upper and lower plate markers), *WCC-4*, *AW-2*, and *WCC-3* (Figure 7) (lower plate markers projected to *AW-3*) (Woodward-Clyde Consultants, 1980):

- 504-m displacement of "top of Rio Dell" datum and datums within Scotia Bluffs? Sandstone since *ca.* 1 Ma? at 0.5 mm/y
- 440-m displacement of "base of lower Hookton" datum since *ca.* 500 ka at 0.88 mm/y
- 64-m displacement between "top of Rio Dell" and "base of lower Hookton" datums, 100-ky duration at 0.64 mm/y
- 169-m displacement during deposition of lower Hookton Formation *ca.* 500-125 ka at rate of 0.45 mm/y
- 271-m displacement of "top of lower Hookton" datum since *ca.* 125 ka at rate of 2.17mm/y

FAULT TYPE: thrust [R-RL?]
DIP: 60° E
STRIKE: 355°

SLIP RATE: 0.5 mm/y @ 1 Ma? using a fault dip of 60°
0.88 mm/y @ 500 ka using a fault dip of 60°

	2.17 mm/y @ 125 ka using a fault dip of 60°
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-125 ka
SHORTENING RATE:	0.25-1.08 mm/y using a fault dip of 60°
UPLIFT RATE:	0.43-1.88 mm/y using a fault dip of 60°

REFERENCES:

Crouch, 1988 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: No Holocene slip is observed on the Bay Entrance fault trace at this site. However, the boreholes were drilled in areas lacking Holocene deposits, so age constraints on faulting are limited to observations of offset Hookton deposits. Variability in slip rates for various Quaternary datums implies ages assigned to datums may need revision or the slip rate is increasing.

The Bay Entrance trace may be a northern extension of the subsidiary Little Salmon trace at site L_2. Alternatively, subsidiary Little Salmon traces may form a complex system of discontinuous surface traces. For example, vertical separation across the Bay Entrance fault trace decreases between site L_6 and boreholes to the south. Woodward-Clyde Consultants (1980) attribute this decrease to steeper eastward dips on lower plate strata. Alternatively, this fault may die out to the south. Boreholes and gas wells in the Fields Landing area penetrated deep enough to cross a subsidiary trace of the Little Salmon fault if one is present, yet cross such a trace only in boreholes *WCC-10* and *WCC-7*? (Figure 7) (Crouch, 1988).

FAULT: Little Salmon fault zone
SEGMENT: offshore fault zone
SITE(S): offshore [L_{12} & L_{13}]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Offshore seismic reflection data adjacent to the onshore Little Salmon fault indicate a different deformation history than the onshore data. The fault is not emergent on the sea floor nor is there surface folding as would be expected from the onshore analog. A seismic reflection profile, about 12 km offshore, displays vertical separation of the top of offshore Unit 3 (time-equivalent to onshore Rio Dell strata) of 0.12 s (Crouch, 1988) or approximately 300 m (at 2500 m/s) across the Little Salmon fault. The main fault trace and associated anticline die midway up offshore Unit 2 (time-equivalent to onshore Scotia Bluffs/Carlotta strata), near a minor unconformity within the section about 0.35 s or 875 m below the sea floor (Crouch, 1988). The Hookton Formation, in the adjacent Fields Landing area, is no more than 600-m thick, therefore, this minor unconformity offshore likely represents the Wildcat Group/Hookton contact and the major unconformity between Units 3 and 4 (at 0.8 s or 2000 m below the sea floor) is likely within Wildcat Group strata. (Note, the accumulation of 600 m of Hookton sediments in 500 ky requires an accumulation rate of 1200 m/My. This rate is similar to the rate estimated in the Scotia Bluffs area for accumulation of shelf and paralic sediments (2000 m/My; McCrory, 1995). For the lower offshore unconformity to be the Wildcat/Hookton contact requires a sediment accumulation rate of 4000 m/My during Hookton deposition—more than 3 times the rate in the Fields Landing area.)

Another seismic reflection profile about 13 km offshore [site L_{12}] (Figure 6 *in* Clarke, 1992) shows the Little Salmon fault system as a zone of discrete fault strands forming a broad anticline about 6-km wide. The anticline apparently folds Unit-3 and older strata. Faulting and folding die out in Unit 2, in agreement with the nearby Crouch (1988) profile. Maximum vertical separation of the top of seismic basement ("top of Yager" equivalent) is approximately 0.5 s or 1250 m; comparable to separations observed in gas wells in the Humboldt Hill area. Folding apparently began after deposition of Unit-4 strata (time-equivalent to onshore Bear River, Pullen, and Eel River strata), continued during deposition of Unit-3 strata, and become insignificant during deposition of Unit-2 and Unit-1 strata (time-equivalent to onshore Hookton strata). Vertical separation on the "base of Hookton" datum in the Fields Landing area is about 500 m; vertical separation on the "top of lower Hookton" datum is about 180 m. Vertical separations of these magnitudes, if present would be discernable on offshore multichannel seismic profiles. However, vertical separation within Unit 1, if any, is restricted to tens of meters; below resolution of the data. Thus, these data suggest that most slip along the offshore segment of the Little Salmon fault occurred prior to slip along the onshore segment.

The Little Salmon fault zone, 45-km offshore [site L_{13}], is about 3-km wide (Figure 7 *in* Clarke, 1992). Structural relief on seismic basement is about 0.3 s or 750 m (at a p-wave velocity of 2500 m/s). The major period of folding and faulting apparently began after deposition of Unit-4 strata. Unit-3 strata onlap, then blanket underlying structural relief.

On a 1994 seismic reflection profile, about 25 km offshore (*R/V Ewing* line 7; S. Clarke, 1996, written communication), the Little Salmon fault zone reaches and warps the seafloor indicating late Quaternary activity.

FAULT TYPE:	thrust [R]
DIP:	NE
STRIKE:	320°
SLIP RATE:	
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-0.5 Ma, perhaps post-125 ka
SHORTENING RATE:	
UPLIFT RATE:	

REFERENCES:

Clarke, 1992 (R)
Crouch, 1988 (O)
McCrory, 1995 (R)

DATA LIMITATIONS: Very few wells have been drilled offshore, therefore ages of seismic stratigraphic units are estimated from extrapolation of onshore analogs. Magnitude of deformation along the offshore Little Salmon fault system varies considerably along strike (S. Clarke, 1996, written communication). On some multi-channel seismic profiles, fault traces reach the surface or folding above buried traces warps the sea floor indicating late Quaternary activity. On other profiles, fault traces and folding die out in strata below the upper Quaternary (*ca.* 0.5 Ma) unconformity. The slip history of the offshore Little Salmon fault zone merits further study, in particular, using high resolution seismic profiles to document Quaternary deformation in detail.

MAD RIVER FAULT ZONE, HUMBOLDT COUNTY, CA

DATA : Surface exposures, trench data, and marine-terrace data at eighteen locations along the onshore Mad River fault zone are used to calculate the fault-slip rates given below.

FAULT TYPE:	thrust [R]
DIP:	35±10° NE
STRIKE :	315-325°
SLIP RATE:	see Tables 2 & 3
SLIP PER EVENT:	1.2 m assuming a fault dip of 35° [MR3] 1.2-2.2? m using a fault dip of 30° [Mc4]
RECURRENCE:	11.9? ky [MR3] 3.5? ky [Mc4]
AGE:	post-10 ka [MR3] post-1.1? ka [Mc5]
SHORTENING RATE:	see Tables 2 & 3
UPLIFT RATE:	see Tables 2 & 3

REFERENCES:

Berger *et al.*, 1991 (R)
Burke *et al.*, 1986 (A)
Carver, 1987 (O)
Carver, 1989*b* (O)
Carver, 1992 (O)
Carver *et al.*, 1982*b* (O)
Carver and Burke, 1988 (O)
Carver *et al.*, 1985 (O)
Carver *et al.*, 1986*a* (O)
Carver *et al.*, 1986*b* (A)
Clarke, 1990 (R)
Clarke, 1992 (R)
Clarke and Carver, 1992 (R)
Hart *et al.*, 1983 (O)
Harvey and Wappner, 1992 (O)
Kelsey and Carver, 1988 (R)
Lajoie, 1986 (R)
McCrory *et al.*, 1995 (A)
Rust, 1982 (O)
Sarna *et al.*, 1991 (R)
Stephans, 1982 (O)
Stuiver and Pearson, 1986 (R)
Weaver, 1981 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: See specific site descriptions. Slip rates given above should not be used for offshore segments of the Mad River fault zone (see discussion under site Tr5). Not enough data is available to model slip behavior of individual fault strands within the Mad River fault system, so the fault system is assumed to merge into a single fault plane at depth. The timing of individual surface ruptures on specific fault traces are assumed to occur independant of each other.

TABLE 2. Slip data derived from "base of Falor" datum (Kelsey and Carver, 1988). Cumulative vertical separation of the "base of Falor" datum across the entire Mad River fault zone (Fickle Hill, Mad River *sensu stricto*, McKinleyville, Blue Lake, and Trinidad faults) is 2500 m. "Base of Falor" datum is *ca.* 2.0 Ma, however, fault slip is assumed to have started *ca.* 1 Ma, yielding a cumulative rate of vertical separation of 2.5 mm/y. The average observed fault dip is 35°, yielding a cumulative rate of dip-slip movement of 4.4 mm/y and a cumulative rate of horizontal shortening of 3.6 mm/y.

Fault trace	vertical m • mm/y	horizontal @35° m • mm/y	dip-slip @35° m • mm/y
Trinidad	575 • 0.58	821 • 0.82	1003 • 1.0
Blue Lake (Korbel)	950 • 0.95	1357 • 1.36	1656 • 1.66
McKinleyville	300 • 0.3	428 • 0.43	523 • 0.52
Mad River	325 • 0.33	464 • 0.46	567 • 0.58
Fickle Hill	350 • 0.35	500 • 0.50	610 • 0.61
TOTAL	2500 • 2.5	3570 • 3.6	4359 • 4.4

TABLE 3. Slip data derived from marine-terrace datums. The calculated rate of dip-slip movement across the entire Mad River fault zone is 2.3 mm/y; the cumulative rate of horizontal shortening is 1.9 mm/y. The rate of vertical uplift for Trinidad anticline is 1.25 mm/y (Figure 9). If uplift of the Trinidad anticline is included in the calculated rates, then total dip-slip movement is is 4.5 mm/y; total shortening is 3.7 mm/y.

Fault trace	ka	vertical m • mm/y	horizontal @35° m • mm/y	dip-slip @35° m • mm/y
Trinidad*	83[a]	19 • 0.23	27.1 • 0.33	33.1 • 0.4
	83[w]	21 • 0.25	30.0 • 0.36	36.6 • 0.44
	100[a]	**25 • 0.25**	**35.7 • 0.36**	**43.6 • 0.44**
Blue Lake				
McKinleyville	83[a]	30 • 0.28	42.8 • 0.52	52.3 • 0.63
	83[b]	**27 • 0.33**	**38.6 • 0.47**	**47.1 • 0.57**
	100[a]	35 • 0.35	50.0 • 0.5	61.0 • 0.61
Mad River†	83[a]	21 • 0.33	30.0 • 0.36	36.6 • 0.44
	83[c]	**35 • 0.42**	**50.0 • 0.60**	**61.0 • 0.74**
	100[a]	38? • 0.38	54.2 • 0.54	66.3 • 0.66
Fickle Hill†	**125[d]**	**40 • 0.32**	**57.1 • 0.46**	**69.7 • 0.56**
	176[a]	40 • 0.23	57.1 • 0.32	69.7 • 0.4
TOTAL		127 • 1.3	181.4 • 1.9	221.4 • 2.3
Trinidad anticline component			1.8	2.2
TOTAL including Trinidad anticline			3.7	4.3

Preferred values in **bold**.

[a], data from Figure 8 *in* Carver, Burke, and Kelsey, 1986*a*
[b], data from Figure 5 *in* Carver, 1987
[c], data from Carver and Burke, 1988
[d], data from Carver, Burke, and Kelsey, 1985
[w], data from Woodward-Clyde Consultants, 1980

* Note, there may be another trace of the Trinidad fault zone between the mainland and Trinidad Head, which offsets the *ca.* 40 or 60-ka terrace about 15 m yielding an average slip rate of 0.38-0.25 mm/y (Rust, 1982).

† Note, terrace datum for southernmost side of fault zone not exposed, so this rate is a minimum.

FAULT: Mad River fault zone
SEGMENT: Fickle Hill fault
SITE(S): [F_1, F_2, F_3 & F_4]

SITE LOCATION(S): see Location Map (Plate 1) for site F_4; locations for sites F_1 F_2 & F_3 not available

DATA CONSTRAINTS: The Fickle Hill fault at the Jacoby Creek site [F_1] dips 25°. Vertical separation of the base of the Falor Formation across the fault trace at this site is 350 m (Kelsey and Carver, 1988). The Huckeberry Ridge ash is found 124 m above the base of the Falor Formation at the Canon Creek site [F_2] (Falor Formation has a faulted base at this site) and 42 m above the base of the Falor Formation at Hatfield Prairie site [F_3] (Falor Formation has a depositional base at this site) (Carver, 1987). The Huckeberry Ridge ash is *ca.* 2 Ma (2.057±0.008 Ma; Sarna *et al.*, 1991), therefore, the age of the "base of Falor" datum is *ca.* 2.0 Ma. However, Quaternary faulting in this region is assumed to have begun *ca.* 1 Ma, contemporaneous with faulting to the south.

At the eastern edge of the coastal plain [site F_4], marine-terrace remnants are offset across a multi-strand Fickle Hill fault. However, the terrace remnant on the southernmost lower plate is buried by alluvium. For this reason, total vertical separation across the multi-strand fault cannot be measured directly (Carver *et al.*, 1986a). The lowest emergent marine terrace has a minimum vertical separation of 40-m (Carver *et al.*, 1986a). Kelsey and Carver (1988) assign a minimum vertical separation rate of 0.48 mm/y across the Fickle Hill fault traces based on a terrace age (*ca.* 83 ka) assigned by Burke *et al.* (1986). However, based on terrace-elevation data from Carver *et al.* (1985) and the graphical correlation technique of Lajoie (1986), the best age estimate for the lowest emergent terrace on the Arcata block is *ca.* 125 ka, yielding a vertical separation rate of 0.32 mm/y.

FAULT TYPE: thrust [R]
DIP: 25°NE
STRIKE: 320°

SLIP RATE: 0.83 mm/y using a fault dip of 25° ("base of Falor" datum) [F_1]
0.56 mm/y assuming a fault dip of 35° (125-ka terrace datum) [F_4]

SLIP PER EVENT: *n/a*

RECURRENCE: *n/a*

AGE: post-125 ka

SHORTENING RATE: 0.39 mm/y using a fault dip of 25° ("base of Falor" datum) [F_1]
0.46 mm/y assuming a fault dip of 35° (125-ka terrace datum) [F_4]

UPLIFT RATE: 0.39 mm/y ("base of Falor" datum) [F_1]
0.32 mm/y (125-ka terrace datum) [F_4]

REFERENCES:

Burke *et al.*, 1986 (A)

Carver, 1989*b* (O)
Carver *et al.*, 1982*b* (O)
Carver *et al.*, 1985 (O)
Carver *et al.*, 1986*a* (O)
Carver, 1987 (O)
Carver, 1992 (O)
Kelsey and Carver, 1988 (R)
Lajoie, 1986 (R)
Hart *et al.*, 1983 (O)
Sarna *et al.*, 1991 (R)

DATA LIMITATIONS: Specific locations at which vertical separation on "base of Falor" datum were measured are not given in relevant reports. These reports also lack discussion of how separation or fault dip were measured at these sites.

Correlations of marine terraces across faults based on soil-profile development and dating of terrace platforms using graphical techniques of Lajoie (1986) by Carver *et al.* (1986*a*) contain significant errors and ambiguities. For example, oxygen-isotope stages are misnamed, water-depth estimates at which abrasion platforms were cut are out-of-date, sea-level low stands are assigned to some of the emergent surfaces. Carver *et al.* (1986*a*) reported significant overlap in soil characteristics developed in platform deposits assigned ages from 60 to 135 ka. Neither this report nor subsequent publications citing the data (*e.g.*, Kelsey and Carver, 1988) discuss whether soils in the fault zones are distinguishable. For these reasons, fault-slip rates calculated using these soil data are not considered reliable. For this study, terrace-age estimates for the Arcata structural block are based on extrapolation from adjacent blocks with better preserved terrace remnants.

Considerable variation in assigned and observed fault dips (35±10°) exists within the Mad River fault zone. For this study, fault segments where fault dip was not directly observed are assigned an average dip of 35° in order to estimate fault-slip rates.

FAULT: Mad River fault zone
SEGMENT: Mad River fault
SITE(S): [MR_1 MR_2 & MR_3]

SITE LOCATION(S) see Location Map (Plate 1) for sites MR_2 & MR_3 location of site MR_1 not available

DATA CONSTRAINTS: Mad River fault at Simpson #5400 Road site [MR_1] dips 35° (Kelsey and Carver, 1988). Vertical separation of the base of Falor Formation across the fault trace at this site is 325 m (Kelsey and Carver, 1988).

At the coast [site MR_2], marine-terrace remnants are offset across a multi-strand Mad River fault. However, the terrace remnant on southernmost lower plate is buried beneath the Mad River floodplain. For this reason, total vertical separation across the multi-strand fault cannot be measured directly (Carver *et al.*, 1986*a*). The lowest emergent marine terrace is vertically separated a minimum of 35 m across the Mad River fault [site MR_2]. Kelsey and Carver (1988) assign a minimum slip rate of 0.84 mm/y across the Mad River fault based on a terrace age (*ca.* 83 ka) assigned by Burke *et al.* (1986) and a 30° dip on the fault. Rate of vertical separation is 0.42 mm/y.

Carver and Burke (1988) cut 2 trenches up to 6-m deep across a scarp on the lowest emergent terrace associated with the northernmost Mad River fault strand at the School Road site [MR_3]. No discrete slip surfaces or faults were observed in either trench (Carver and Burke, 1988). However, a tight overturned anticline interpreted as a fault-propagation fold, was exposed in one of the trenches. This fold involved Franciscan bedrock, marine-terrace deposits, and six stacked colluvial units (Carver and Burke, 1988). The marine-abrasion platform (*ca.* 83 ka) is vertically separated about 6.9 m across the zone of deformation, yielding an uplift rate of 0.08 mm/y. If the inferred buried thrust is assumed to dip 35°, then the dip-slip rate is 0.15 mm/y.

The stacked colluvial units are inferred to be a sequence of deposits derived from degradation of scarps formed during seismic events with surface folding (Carver and Burke, 1988). If this interpretation is correct, seven slip events have been recorded at this site during the past 83 ky, yielding an average recurrence interval of 11.9-ky. Detrital charcoal from the upper part of the second-highest buried colluvium yielded a radiocarbon date of **10.17 ka±0.06 ky** (in **radiocarbon years**). Detrital charcoal from lower part of the highest buried colluvium yielded a date of **10.45 ka±0.08 ky**. Unfortunately, both dates must be considered weak age constraints as the samples were collected from animal-burrow fill. The colluvial units range from 0.4 to 1.0-m thick, averaging 0.7 m (Carver and Burke, 1988). If these thicknesses reflect the magnitude of vertical uplift of the fold scarp during seismic events, then the average fault slip per event can be estimated.

FAULT TYPE: thrust [R]
DIP: 30-35°NE
STRIKE: 315°
SLIP RATE: 0.58 mm/y using a fault dip of 35° ("base of Falor" datum) [MR_1]

	0.84 mm/y using a fault dip of 30° (83-ka terrace datum) [MR_2]
SLIP PER EVENT:	1.2 m assuming a fault dip of 35° (using an average vertical separation of 0.7-m) [MR_3]
RECURRENCE:	11.9 ky [MR_3]
AGE:	post-10 ka [MR_3]
SHORTENING RATE:	0.46 mm/y using a fault dip of 35° ("base of Falor" datum) [MR_1] 0.69 mm/y using a fault dip of 30° (83-ka terrace datum) [MR_2]
UPLIFT RATE:	0.33 mm/y ("base of Falor" datum) [MR_1] 0.42 mm/y (83-ka terrace datum) [MR_2]

REFERENCES:

Berger *et al.*, 1991 (R)
Burke *et al.*, 1986 (A)
Carver, 1987 (O)
Carver, 1992 (O)
Carver and Burke, 1988 (O)
Carver *et al.*, 1986*a* (O)
Kelsey and Carver, 1988 (R)
Lajoie, 1986 (R)
Hart *et al.*, 1983 (O)
Harvey and Weppner, 1992 (O)

DATA LIMITATIONS: See discussion of marine-terrace datums under section on Fickle Hill fault. Specific locations at which vertical separation on "base of Falor" datum were measured are not given in relevant reports. These reports also lack discussion of how separation or fault dip were measured at these sites. See discussion of various radiocarbon dating techniques and associated analytical errors under Megathrust sources—Eel River syncline section.

Considerable variation in assigned and observed fault dips (35±10°) exists within the Mad River fault zone. For this study, fault segments where fault dip was not directly observed are assigned an average dip of 35° in order to estimate fault-slip rates.

Carver and Burke (1988) referred to a second Mad River fault trace displaying slip events, however, no data on this trench? site is available. For this reason, some reported slip events and associated magnitude of displacement cannot be verified.

Tidal-flat mud facies just below the marine-abrasion surface near the mouth of Mad River (and south of the McKinleyville fault trace) yielded a thermoluminescence (TL) date of 176±33 ka (Berger *et al.*, 1991). The elevation of the marine-abrasion surface is not given in Berger *et al.* (1991), however, it is apparently at least 40 m above sea level based on the thickness of the measured stratigraphic section given in Figure 3 of Berger *et al.* (1991). The apparent elevation conflicts with that given in Harvey and Wappner (1992), who reported the elevation of the marine-terrace surface as 32 m, and the elevation of the tidal-flat mud from which the TL data came as 31 m. (Note, that the Harvey and Wappner (1992) report does not define the 0-m datum with respect to sea level.)

FAULT:	Mad River fault zone
SEGMENT:	McKinleyville fault
SITE(S):	[Mc1, Mc2, Mc3 & Mc4]

SITE LOCATION(S): see Location Map (Plate 1) for sites Mc2, Mc3 & Mc4; location of site Mc1 not available

DATA CONSTRAINTS: McKinleyville fault at the Simpson #4500 Road site [Mc1] dips 35° (Kelsey and Carver, 1988). Vertical separation of the base of Falor Formation across the fault trace at this site is 300 m (Kelsey and Carver, 1988).

At the coast [site Mc2], the McKinleyville fault is partially exposed in the sea cliffs as several closely spaced thrust strands dipping 10-25°NE. Marine-terrace remnants are offset across a multi-strand McKinleyville fault. Terrace remnants on both sides of the fault are emergent, so vertical separation can be measured directly (Carver *et al.*, 1986*a*). Carver (1987) reported 23-m vertical separation of the lowest emergent terrace. Neither Carver (1987) nor references cited in this report give the location of the terrace profile used to determine this offset. Carver (1987) and Kelsey and Carver (1988) assigned a dip-slip rate of 0.9 mm/y to the McKinleyville fault based on a 25° dip on the fault and a terrace age (*ca.* 64 ka) assigned by Carver *et al.* (1986*a*). However, Carver *et al.* (*in* Figure 7, 1986*a*) and Carver and Burke (1988) assign the lowest emergent terrace an age of *ca.* 83 ka. If elevations from the northern McKinleyville terrace profile and the McKinleyville reference profile (Carver *et al.*, 1986*a*) are not composites (these appear to be the same data), the best age estimate for the lowest terrace is *ca.* 83 ka (Plate 2; Figure 8).

The McKinleyville reference profile contains a double lowest terrace. The lower of the two terraces may be a fluvial terrace associated with the Mad River (Weaver, 1981). Because of this ambiguity, vertical separation of the upper terrace is used to calculate fault-slip rates. Vertical separation of the upper terrace at site Mc2 is 27 m (Carver, 1987). If this terrace is *ca.* 83 ka, the rate of vertical separation of 0.33 mm/y. Applying this rate to the 300-m separation measured at site Mc1, suggests that faulting began *ca.* 0.9 Ma at site Mc1.

A trench cut at the McKinleyville site [Mc3] exposed a thrust fault striking N45°W, dipping 17-25°E (Woodward-Clyde Consultants, 1980). The fault displaces "Crannell sands" (time-equivalent to lower Hookton Formation), marine-terrace deposits, and 2 colluvial units (Woodward-Clyde Consultants, 1980). Secondary faults and fractures were observed in the upper plate of the fault. The marine-abrasion platform is vertically separated about 8 m between a test pit (in the lower plate) and the trench (in the upper plate). Using a fault dip of 25° and a platform age of *ca.* 83 ka, yields a dip-slip rate of 0.23 mm/y (Woodward-Clyde Consultants, 1980). However, the platform surface is highly irregular so this value is not well constrained. Vertical separation of the "Crannell sands" (Loleta ash in basal Crannell deposits is *ca.* 390 ka; Sarna *et al.*, 1991) is about 60 m (Woodward-Clyde Consultants, 1980). Woodward-Clyde Consultants (1980) inferred that the two colluvial units represent deposits derived from degradation of scarps formed during seismic events. If this interpretation is correct, at least 2 slip events have been recorded at this site during the past 83 ky.

A trench cut at the Blue Lake site [Mc4] exposed a strand of the McKinleyville fault dipping up to 27° (Carver and Burke, 1988). The trench exposed a cobble unit overlain by a silt unit in turn overlain by stacked colluvial units. The cobble unit (interpreted to be stream-terrace facies) was separated 6.8 m vertically across the fault. Minimum age of this deposit is constrained by radiocarbon dates of **24.77 ka ± 0.15 ky** (accelerator (AMS) date on detrital charcoal in **radiocarbon years**) and **25.7 ka ± 1.0 ky** (conventional date on *in situ* peat) from samples in the overlying silt unit (interpreted to be overbank-flood facies). If the cobble unit is *ca.* 26 ka, this yields a calculated dip-slip rate of 0.52 mm/y using a fault dip of 30°.

Two unconformities within the silt unit may also mark seismic slip events. Unfortunately, these potential datums cannot be matched across the fault to constrain offset. The three stacked colluvial units above the silt unit, are inferred to be a sequence of deposits derived from the degradation of scarps formed during seismic events with surface faulting (Carver and Burke, 1988). If this interpretation is correct, the amount of cumulative slip associated with the lowest colluvial unit can be estimated. Vertical separation of this unit in the trench is about 1.4 m (Carver and Burke, 1988). Using a fault dip of 30°, yields 2.8-m cumulative dip-slip for this unit. The 3 colluvial units average 0.9-m in thickness (0.7-1.1 m). If their thickness approximates the magnitude of vertical separation preceding their accumulation, then each unit represents about 1.8 m of dip-slip displacment. However, if the upper two colluvial units (0.7- and 1.1-m thick) represent 2 slip events (1.4- and 2.2-m displacments, respectively), then the cumulative 2.8-m offset observed on the lowest colluvial unit is overestimated by 0.8 m or 20%. These calculations are not adequate for defining characteristic slip on this fault, however, if each slip event results in approximately 1.8-m offset; a slip event occurs an average of every 3.5 ky or about 7 events are represented by 13.6 m dip-slip offset of the cobble unit. The middle colluvial unit was only observed on the lower plate, so this datum cannot be used to estimate slip displacement. The uppermost, modern colluvial unit is not faulted. Detrital charcoal from animal-burrow fill in the middle colluvial unit yielded a radiocarbon date of **7.47 ka ± 0.05 ky** (Carver and Burke, 1988). This date must be considered a poor constraint due to the mode of deposition of the sample.

Clarke and Carver (1992) considered an emergent Holocene shoreline angle at the Clam Beach site [Mc2] to be evidence of coseismic uplift related to slip on the McKinleyville fault. They used mean higher high water (MHHW) as the datum to estimate magnitude of uplift. Clarke and Carver (1992) showed the shoreline angle at 2 m above MHHW (Figure 3 *in* Clarke and Carver, 1992), however, the associated text described the shoreline angle as 1 m above mean high tide. (Note, that no information was given on how these elevations were measured). The critical issue in terms of estimating magnitude of Holocene uplift, is determining the relationship between the shoreline angle and mean high water during its formation. In this area, the mean tidal range is 1.5 m (Crannel 7.5-min topographic quadrangle), therefore the shoreline angle was likely cut at mean high water ± 1 m. If correct, uplift of this datum is between 0 and 2 m. A radiocarbon date on detrital wood within the beach deposits overlying the abrasion platform is **1.16±0.03 ka** in **radiocarbon years** or *1.07+0.08/-0.02 ka* in *calibrated years* (Berger *et al.*, 1991). This date constrains the minimum age of the platform. It is not clear from the information given in Berger *et al.* (1991), Carver (1992) or Clarke and Carver (1992) exactly where the Clam Beach site is located relative to the McKinelyville fault zone. Only generalized location maps are given in these reports, so uplift of this feature cannot be tied to a specific fault strand. Regardless, this site appears to preserve evidence of at least one uplift event post *ca.* 1.1 ka. If the 0.33-mm/y rate of vertical separation observed at site Mc_2 is applied to the Clam Beach terrace, this yields about 0.36 m of uplift since 1.1 ka, within the estimated range of observed uplift (0-2 m).

Two dune-sand units overlie the beach deposits at site Mc_5. Samples from the upper surface of the lower unit all have calibrated radiocarbon ages of ≤250 years ago (sample #4317: **0.08±0.04** ka or *0.25+0.02/-0.03 ka* on rooted tree wood; sample #4316: **0.12±0.02** ka or *0.14±0.02 ka*; *0.22±0.02 ka*; *0.25±0.01 ka* on peat; Berger *et al.*, 1991). A proposed second uplift event *ca.* 300 years ago is based on the assumption that the upper dune unit accumulated following uplift of its sand source out of the shore zone (Clarke and Carver, 1992). However, the possibility that the dune deposits are derived from a Mad River source and instead herald a shift in location of its mouth from Arcata Bay (a sediment sink) to a location near the current one (about 1 km from the Clam Beach site) has not been ruled out. If the dune units do in fact record coseismic uplift, then the time interval between seismic events on one strand of the McKinleyville fault may be as short as 0.5 to 0.6 ky.

FAULT TYPE:	thrust [R]
DIP:	30±5°NE
STRIKE:	320°
SLIP RATE :	0.52 mm/y using a fault dip of 35° ("base of Falor" datum) [Mc_1] 0.78 mm/y using a fault dip of 25° (83-ka terrace datum) [Mc_2]
SLIP PER EVENT:	1.2-2.2? using a fault dip of 30° [Mc_4]
RECURRENCE :	3.5 ky [Mc_4]
AGE:	post-25.7 ka; possibly post-7.5 ka [Mc_4] post-1.1? ka; possibly post-0.25 ka [Mc_2]
SHORTENING RATE:	0.43 mm/y using a fault dip of 35° ("base of Falor" datum) [Mc_1] 0.71 mm/y using a fault dip of 25° (83-ka terrace datum) [Mc_2]
UPLIFT RATE:	0.3 mm/y ("base of Falor" datum) [Mc_1] 0.33 mm/y (83-ka terrace datum) [Mc_2]

REFERENCES:

Berger *et al.*, 1991 (R)
Burke *et al.*, 1986 (A)
Carver and Burke, 1988 (O)
Carver *et al.*, 1986*a* (O)
Carver *et al.*, 1986*b* (A)
Carver, 1987 (O)
Carver, 1992 (O)
Clarke and Carver, 1992 (R)
Kelsey and Carver, 1988 (R)
Hart *et al.*, 1983 (O)
Sarna *et al.*, 1991 (R)
Stuiver and Pearson, 1986 (R)
Weaver, 1981 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: See discussion of marine-terrace datums under section on Fickle Hill fault section. Specific locations at which vertical separation on "base of Falor" datum were measured are not given in relevant reports. These reports also lack discussion of how separation or fault dip were measured at these sites. See discussion of various radiocarbon dating techniques and associated analytical errors under Megathrust sources—Eel River syncline section.

Considerable variation in assigned and observed fault dips (35±10°) exists within the Mad River fault zone. For this study, fault segments where fault dip was not directly observed are assigned an average dip of 35° in order to estimate fault-slip rates.

Radiocarbon dates and sample locations presented in Berger *et al.* (1991) for the Clam Beach site [Mc_2] differ from those presented in Clarke and Carver (1992). Sample #4316 in Berger *et al.* (1991) is located in a peat horizon and *<0.26 ka*; in Clarke and Carver (1992), this sample is located in rooted tree and *<0.3 ka.* Sample #4317 in Berger *et al.* (1991) is also *<0.26 ka*, in Clarke and Carver (1992), it is *<0.28 ka.* Sample #4180 in Berger *et al.* (1991) is *1.05-1.15 ka*; in Clarke and Carver (1992), it is *0.96-1.26 ka.* Both reports cite Stuiver and Pearson (1986) as the source of the calibration curve used for calender-year corrections.

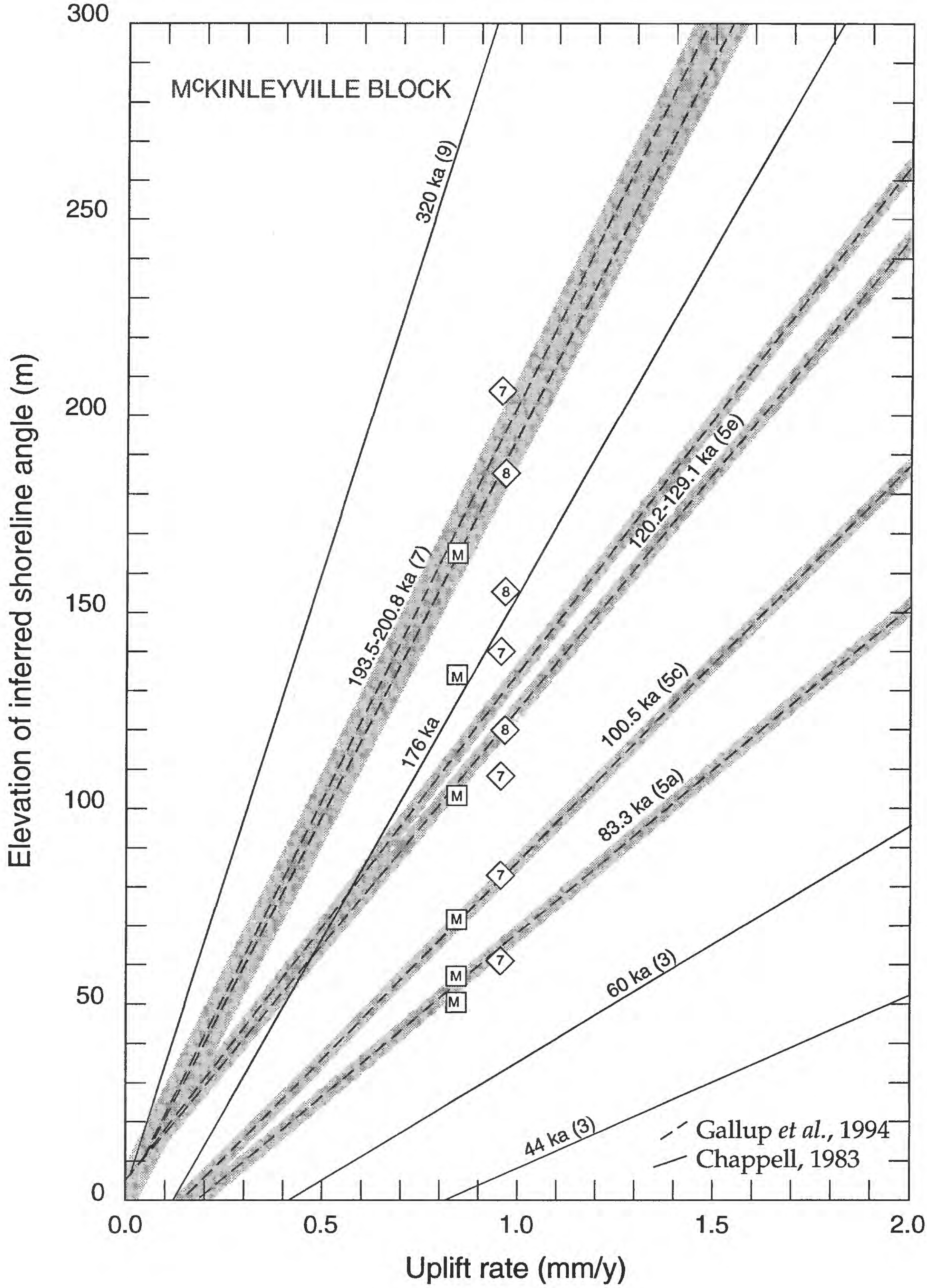

Figure 8. Graphical correlation plot for the McKinleyville structural block showing the preferred age estimates for marine-terrace platforms and resultant uplift rates. Elevation of shoreline angle inferred from elevation of marine-terrace surfaces and thickness of sediment cover. Terrace-profile elevations (diamond symbol) from Figure 8 in Carver *et al.* (1986*a*); reference-section elevations (square symbol) from Table 1 in Carver *et al.* (1986*a*), assuming lowest terrace is *ca.* 83 ka. Gray areas denote uncertainties on age and elevation of sea-level high stands (from Gallup *et al*, 1994). See Plate 2 for locations of profiles.

FAULT: Mad River fault zone
SEGMENT: Blue Lake fault
SITE(S): [BL_1 & BL_2]

SITE LOCATION(S): *n/a*

DATA CONSTRAINTS: Blue Lake fault at the Korbel site [BL_1] dips 35° (Kelsey and Carver, 1988). Vertical separation on the base of Falor Formation across the Blue Lake fault at this site is given as 950 m in Kelsey and Carver (1988) and 930 m in Carver (1987). Blue Lake fault at the Canon Creek site [BL_2] dips 40°. Vertical separation of the base of the Falor Formation across the Blue Lake fault at site BL_1 is 750 m (Kelsey and Carver, 1988). Blue Lake fault does not displace upper Pleistocene deposits nor does the surface trace extend to the coast (Kelsey and Carver, 1988).

FAULT TYPE: thrust [R]
DIP: 35-40°NE
STRIKE: 320°

SLIP RATE: 1.66 mm/y using a fault dip of 35° ("base of Falor" datum) [BL_1]
1.17 mm/y using a fault dip of 40° ("base of Falor" datum) [BL_2]

SLIP PER EVENT: *n/a*

RECURRENCE : *n/a*

AGE: *n/a*

SHORTENING RATE: 1.36 mm/y using a fault dip of 35° ("base of Falor" datum) [BL_1]
0.89 mm/y using a fault dip of 40° ("base of Falor" datum) [BL_2]

UPLIFT RATE: 0.95 mm/y ("base of Falor" datum) [BL_1]
0.75 mm/y ("base of Falor" datum) [BL_2]

REFERENCES:
Carver, 1987 (O)
Kelsey and Carver, 1988 (R)
Hart *et al.*, 1983 (O)

DATA LIMITATIONS: Blue Lake fault trace does not extend to the coast, so there is no marine-terrace datum with which to evaluate late Quaternary offset rates. Specific locations at which vertical separation on "base of Falor" datum were measured are not given in relevant reports. These reports also lack discussion of how separation or fault dip were measured at these sites.

FAULT:	Mad River fault zone
SEGMENT:	Trinidad fault
SITE(S):	[Tr1, Tr2, Tr3 & Tr4]

SITE LOCATION(S): see Location Map (**Plate 1**) for sites **Tr2, Tr3 & Tr4**; location for site **Tr1** not available

DATA CONSTRAINTS: Trinidad fault at the Canon Creek site [**Tr1**] dips 40° (Kelsey and Carver, 1988). Vertical separation on the base of Falor Formation across the Trinidad fault at this site is given as 575 m in Kelsey and Carver (1988) and as 570 m in Carver (1987).

At the coast [site **Tr2**], marine-terrace remnants are offset across a multi-strand Trinidad fault. Terrace remnants on both sides of the Trinidad fault are emergent, thus vertical separation can be measured directly (Carver *et al.*, 1986*a*). The lowest emergent terrace, Patrick's Point terrace (PPt), is vertically separated about 19 m across the Trinidad fault (Woodward-Clyde Consultants, 1980; Stephans, 1982; Carver *et al.*, 1986*a*). Carver *et al.*, (1986*a*) assign a slip rate of 0.9 mm/y across the Trinidad fault based on a terrace age (*ca.* 64 ka) assigned by Burke *et al.* (1986) and presumably a fault dip of about 25°. However, the best estimate of the age of the lowest emergent terrace (PPt) is *ca.* 83 ka based on the graphical correlation technique (Figure 9). If the 83-ka age assignment is correct, the rate of vertical separation is 0.23 mm/y and the rate of uplift of the Trinidad block is 1.2 to 1.3 mm/y (Figure 9). (Fault-slip rates calculated from offset terrace datums need to include uplift of the Trinidad anticline as fault-related folding on the upper plate.) Older marine terraces are warped and tilted along the Trinidad anticline indicating that the rate of folding has not been uniform in this area (Woodward-Clyde Consultants, 1980). Therefore, the assumption of constant, uniform uplift, although reasonable, is not completely accurate for this structural block.

Trinidad fault crosses the marine-terrace sequence at Trinidad Head. Two trenches cut at the Trinidad Head site [**Tr3**] both exposed Fransican bedrock unconformably overlain by marine-terrace deposits (Woodward-Clyde Consultants, 1980). Terrace gravels overlying Franciscan bedrock have been faulted and folded on the leading edge of the thrust and are overturned with steep dips to the east (Woodward-Clyde Consultants, 1980). Terrace deposits on the downthrown block are overlain by scarp-derived colluvium. No evidence of post-colluvium offset was observed in the trenches, constraining the most recent surface faulting at this site to post-deposition of terrace gravels and pre-deposition of colluvium. The fault exposed in the trenches strikes N45°W and dips 45°NE (Woodward-Clyde Consultants, 1980). At the trench site, the PPt surface (not the buried abrasion platform) is separated vertically 10 m. If the 83-ka age assignment is correct, the rate of vertical separation across these fault strands is 0.12 mm/y.

The character of the Trinidad fault strands exposed in the sea cliff at the Anderson Ranch site [**Tr4**], 1.6 km NW of site Tr3, is similar to that observed in the trenches at site **Tr3**. Marine-terrace deposits are thrust over scarp-derived colluvial deposits along 2 fault strands dipping about 45°. The two fault strands displace the colluvium 2.5 and 0.5 m (using a 45° dip) respectively (Woodward-Clyde Consultants, 1980). If 3 m represents a typical slip event for the Trinidad fault, then the recurrence interval is 8.3 ky. Rust (1982) indicated that vertical separation of the marine platform in the sea cliffs is 6 m, however, Woodward-Clyde Consultants (1980) indicated that vertical separation of the marine terrace is about 21 m at site **Tr4**. The lower value may only span a limited portion of the fault zone.

Evidence of two discontinuous sets of terrace remnants below Patrick's Point terrace (at about 20-m and 45-m elevations) along headlands in Trinidad Head area add weak support to the 83-ka age assignment for the Patrick's Point terrace (Figure 9). These remnant platforms may have formed *ca.* 44 ka and 60 ka, respectively (Rust, 1982).

FAULT TYPE:	thrust [R]
DIP:	40-45°NE
STRIKE:	325°
SLIP RATE:	0.9 mm/y using a fault dip of 40° ("base of Falor" datum) [**Tr1**] 0.4 mm/y assuming a fault dip of 35° (83-ka terrace datum) [**Tr2**] 0.36 mm/y uisng a fault dip of 45° (83-ka terrace datum) [**Tr4**] 2.62 mm/y using a fault dip of 35° (includes uplift of Trinidad anticline) [**Tr2**]
SLIP PER EVENT:	3 m? [**Tr4**]
RECURRENCE:	8.3? ky [**Tr4**]
AGE:	post-83 ka
SHORTENING RATE:	0.82 mm/y using a fault dip of 40° ("base of Falor" datum) [**Tr1**] 0.33 mm/y assuming a fault dip of 35° (83-ka terrace datum) [**Tr2**] 0.26 mm/y using a fault dip of 45° (83-ka terrace datum) [**Tr4**] 2.15 mm/y using a fault dip of 35° (includes uplift of Trinidad anticline) [**Tr2**]
UPLIFT RATE:	0.58 mm/y ("base of Falor" datum) [**Tr1**] 0.23 mm/y (83-ka terrace datum) [**Tr2**] 0.25 mm/y (83-ka terrace datum) [**Tr4**] 1.25 mm/y (uplift of Trinidad anticline) [**Tr2**]

REFERENCES:

Burke *et al.*, 1986 (A)
Carver *et al.*, 1986*a* (O)
Carver, 1987 (O)
Hart *et al.*, 1983 (O)
Kelsey and Carver, 1988 (R)
Rust, 1982 (O)
Stephans, 1982 (O)
Woodward-Clyde Consultants, 1980 (O)

DATA LIMITATIONS: See discussion of marine-terrace datums under the Fickle Hill fault section. Specific locations at which vertical separation on "base of Falor" datum were measured are not given in relevant reports. These reports also lack discussion of how separation or fault dip were measured at these sites.

Considerable variation in assigned and observed fault dips (35±10°) exists within the Mad River fault zone. For this study, fault segments where fault dip was not directly observed are assigned an average dip of 35° in order to estimate fault-slip rates.

Fault-slip rates calculated from offset terrace datums need to include uplift of the Trinidad anticline as fault-related folding on the upper plate. Such composite rates match well with rates based on the Falor datum, as uplift of the Trinidad anticline appears to incorporate the relatively high slip value of the Blue Lake fault. (Combined Trinidad fault and Blue Lake fault uplift of Falor datum is 1.53 mm/y; combined Trinidad fault and Trinidad anticline uplift of terrace datum is 1.45 mm/y.)

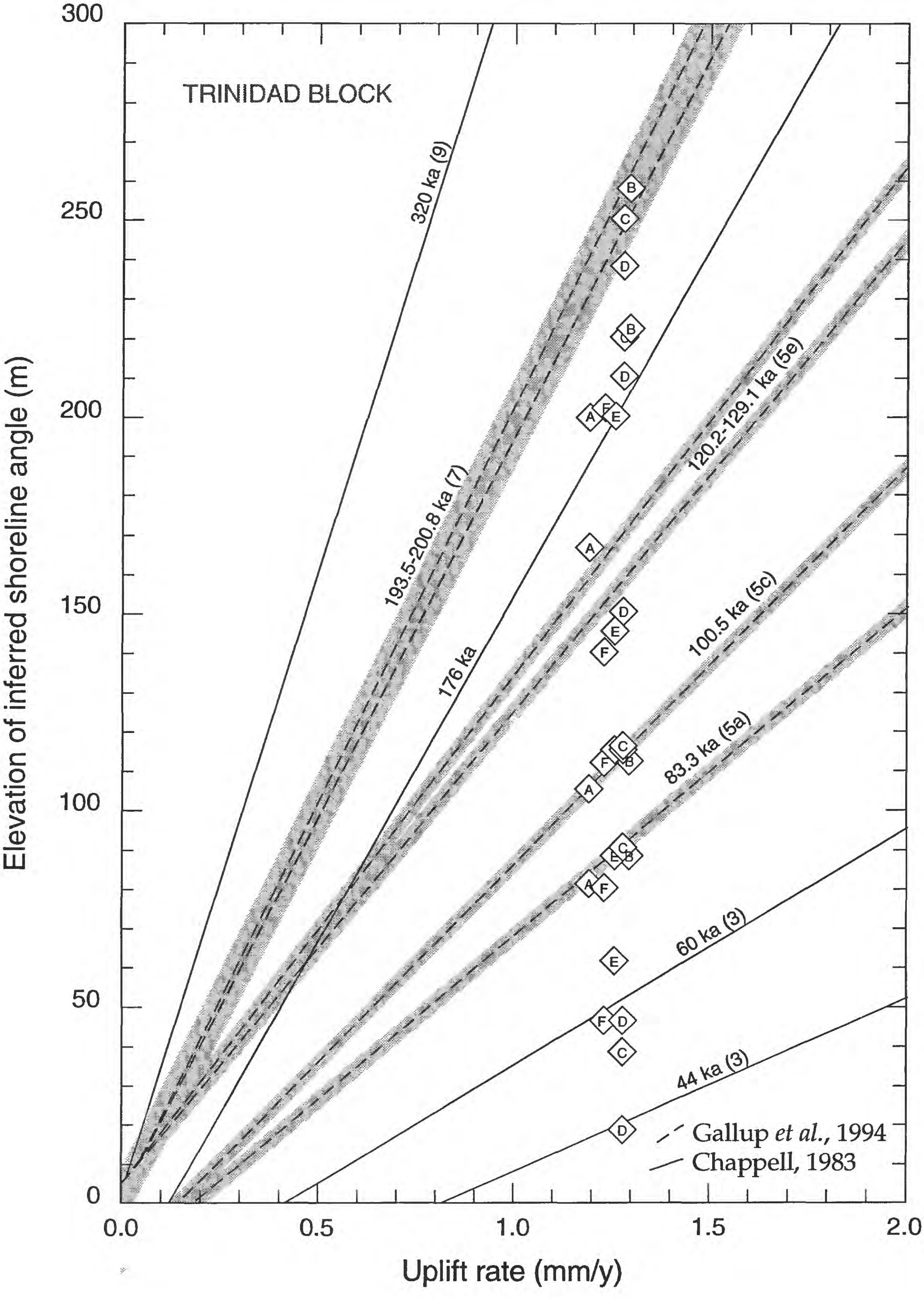

Figure 9A. Graphical correlation plot for the Trinidad structural block showing the preferred age estimates for marine-terrace platforms and resultant uplift rates. Elevation of shoreline angle inferred from elevation of marine-terrace surfaces and thickness of sediment cover. Terrace-profile elevations from Figure B-10 in Woodward-Clyde Consultants (1980), assuming lowest widespread terrace is *ca.* 83 ka. Elevations for *ca.* 44- and 60-ka terraces from Rust, 1982; *this study*. Gray areas denote uncertainties on age and elevation of sea-level high stands (from Gallup *et al*, 1994). See Plate 2 for locations of profiles.

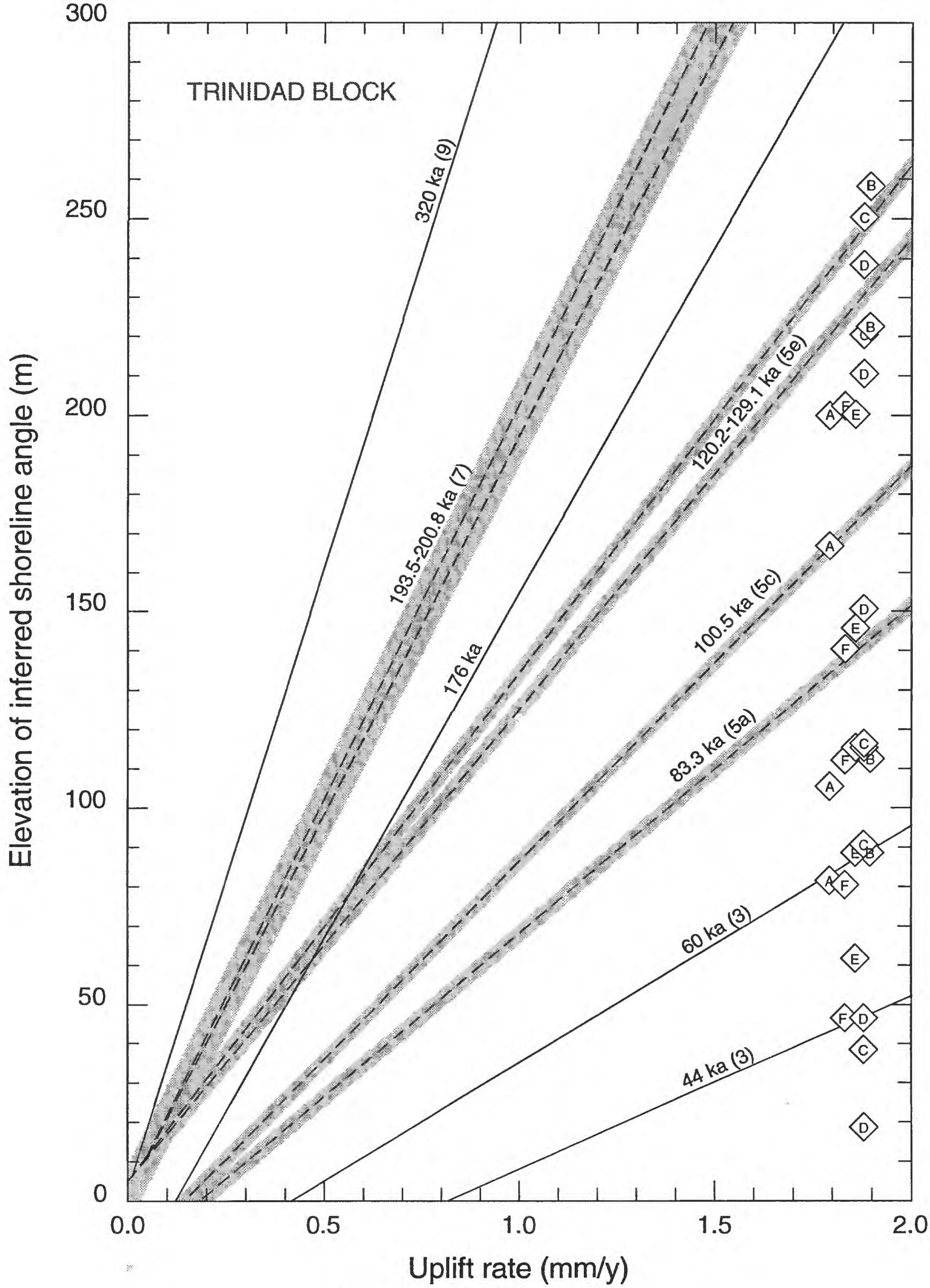

Figure 9*B*. Graphical correlation plot for the Trinidad structural block showing the age estimates for marine-terrace platforms and resultant uplift rates assuming lowest widespread terrace is *ca.* 60 ka (from Burke *et al.*, 1986). Note cluster of terrace platforms between 60- and 83-ka lines which do not correlate with a sea-level high stand and mismatch of terrace platforms below the 120-ka line .

FAULT:	Mad River fault zone
SEGMENT:	Trinidad fault
SITE(S):	offshore [**Tr5**]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Trinidad fault is the longest fault trace in the Mad River fault zone, extending about 50 km offshore (Clarke, 1992). Vertical separation of Franciscan basement along the offshore extension of the Trinidad fault is as much as 650 m, east-side-up (Clarke, 1992). Note, that Clarke (1992) showed this fault as separating Coastal and Central belt Franciscan rocks, however, it more likely is within the Central belt Franciscan rocks (Clarke, 1990; McCrory *et al.*, 1995). In a seismic reflection profile about 14-km offshore [site **Tr5**] from Trinidad Head (Figure 7 *in* Clarke, 1992), Trinidad fault appears to offset a major unconformity in Quaternary strata (*ca.* 1? Ma), however, the fault does not appear to disrupt the seafloor. The amount of vertical separation of the *ca.* 1?-Ma unconformity cannot be measured in this profile as the unconformity is not observed on the northeastern side of the fault.

FAULT TYPE:	thrust [R]
DIP:	NE
STRIKE:	335°
SLIP RATE:	*n/a*
SLIP PER EVENT:	*n/a*
RECURRENCE:	*n/a*
AGE:	post-1? Ma
SHORTENING RATE:	*n/a*
UPLIFT RATE:	*n/a*

REFERENCES:

Clarke, 1990 (R)
Clarke, 1992 (R)
McCrory *et al*, 1995 (A)

DATA LIMITATIONS: Very few wells have been drilled offshore, therefore the ages of seismic stratigraphic units are estimated from onshore analogs. More recent seismic reflection profiles indicate that total vertical separation of basement along the trend of the offshore Trinidad fault varies considerably, in general, between 0.3 to 0.6 s (750-1500 m at 2500 m/s) (S. Clarke, 1996, written communication). Offsets are typically larger in convex westward bends of the fault trace and diminish in magnitude to the northwest. Further study using high resolution seismic profiles would be useful for documenting Quaternary deformation in detail.

FAULT: Bald Mountain-Big Lagoon fault zone

SEGMENT:

SITE(S): [BM_1]

SITE LOCATION(S): *n/a*

DATA CONSTRAINTS: Vertical separation of the Pliocene Klamath saprolite (a paleo-weathering surface) across the Big Lagoon fault at site BM_1 is 545 m (Carver, 1987; Carver, 1992). If fault slip began *ca.* 1 Ma, then the slip rate—assuming a 30° fault dip is 1.09 mm/y.

FAULT TYPE: thrust [R]

DIP: NE

STRIKE : 325°

SLIP RATE: 1.09? mm/y assuing a fault dip of 30°

SLIP PER EVENT: *n/a*

RECURRENCE: *n/a*

AGE : post-1? Ma

SHORTENING RATE: 0.94? mm/y assuming a fault dip of 30°

UPLIFT RATE: 0.55? mm/y

REFERENCES:

Carver, 1987 (O)
Carver, 1992 (O)

DATA LIMITATIONS: Specific locations at which vertical separation on "Klamath saprolite" datum were measured are not given in relevant reports. No discussion of how separation was measured at these sites is given in these reports either. No available data on dip of Big Lagoon fault.

The calculated slip rate is based on the assumption that faulting began *ca.* 1 Ma during a regional tectonic phase. There are no independant lines of evidence to test this hypothesis which becomes more tenuous as it is stretched northeastward away from the Mendocino area. For this reason, the slip rate calculated above is considered poorly constrained.

FAULT: Grogan fault zone
SEGMENT:
SITE(S): offshore [G_1]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Recent seismic reflection profiles indicate that total vertical separation of seismic basement (inferred Franciscan complex rocks) along the trend of the offshore Lost Man fault varies considerably, up to a maximum of 0.5 s (1250 m @ 2500 m/s) at site G_1 (S. Clarke, 1996, written communication).

FAULT TYPE: thrust [R]
DIP: NE
STRIKE : 330°
SLIP RATE: *n/a*
SLIP PER EVENT: *n/a*
RECURRENCE: *n/a*
AGE : post-Quaternary
SHORTENING RATE: *n/a*
UPLIFT RATE: *n/a*

REFERENCES:
Kelsey and Cashman, 1983 (R)

DATA LIMITATIONS: Very few wells have been drilled offshore, therefore the age of seismic stratigraphic units are poorly constrained. Further study using high resolution seismic profiles would be useful for documenting Quaternary deformation in detail.

FAULT: Lost Man fault zone

SEGMENT:

SITE(S): offshore [LM_1]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Recent seismic reflection profiles indicate that total vertical separation of basement along the trend of the offshore Lost Man fault varies considerably, up to a maximum of 0.7 s (1750 m @ 2500 m/s) at site LM_1 (S. Clarke, 1996, written communication).

FAULT TYPE: thrust [R]
DIP: NE
STRIKE : 320°

SLIP RATE: *n/a*

SLIP PER EVENT: *n/a*

RECURRENCE: *n/a*

AGE : post-Quaternary

SHORTENING RATE: *n/a*

UPLIFT RATE: *n/a*

REFERENCES:
n/a

DATA LIMITATIONS: Very few wells have been drilled offshore, therefore the age of seismic stratigraphic units are poorly constrained. Further study using high resolution seismic profiles would be useful for documenting Quaternary deformation in detail.

SOUTHERN CASCADIA MEGATHRUST SOURCES

DATA: Coastal marsh data at five locations along three onshore synclines in the Humboldt area are used to calculate the subsidence rates and reccurrence intervals given below.

FAULT TYPE: thrust [R]
DIP: *n/a*
STRIKE : *n/a*

SLIP RATE: *n/a*

SUBSIDENCE PER EVENT: 0.2-1.3? m [$\mathbf{ERs_1}$ & $\mathbf{FWs_3}$]

RECURRENCE:
0.3-0.9? ky [$\mathbf{CM_1}$]
0.2-0.6? ky [$\mathbf{ERs_1}$]
0.4-0.6? ky [$\mathbf{SBs_1}$]
0.2-0.8? ky [$\mathbf{FWs_1}$]
0.3-0.4? ky [$\mathbf{FWs_2}$]

AGE : Holocene?

SHORTENING RATE: *n/a*

SUBSIDENCE RATE:
1.4-2.7? mm/y [$\mathbf{ERs_1}$]
1.4-3.3? mm/y [$\mathbf{FWs_2}$]

REFERENCES:

Carver, 1992 (O)
Carver *et al.*, 1989 (A)
Carver *et al.*, 1992 (A)
Carver *et al.*, 1993 (O)
Carver *et al.*, 1994 (R)
Clarke and Carver, 1992 (R)
Jacoby *et al.*, 1993 (A)
Lajoie, 1992 (A)
Lajoie *et al.*, 1991 (R)
Li and Carver, 1992 (A)
Li, 1992*a* (O)
Li, 1992*b* (O)
Manhart, 1992 (O)
Merrits *et al.* 1992 (A)
Murray *et al.*, 1996 (R)
Nelson, 1992*a* (R)
Nelson and Atwater, 1993 (A)
Nelson *et al.*, 1994*a* (A)
Nelson *et al.*, 1994*b* (A)
Nelson *et al.*, *1996* (R)
Oppenheimer *et al.*, 1993 (R)
Shivelle *et al.*, 1991 (A)
Valentine, 1992 (O)

Valentine *et al.*, 1990 (A)
Vick, 1988 (O)
Vick and Carver, 1988 (A)

DATA LIMITATIONS: See specific site descriptions. Rates given above do not apply to slip associated with the 1992 M7.0 Petrolia earthquake.

Based on criteria described in published reports on intertidal stratigraphy along the Cascadia subduction boundary, the submergence of at least two coastal marsh soils is attributed to subsidence during earthquakes of regional extent in the past few thousand years (Nelson *et al., 1996*). Well preserved features are associated with the soil that subsided about 0.3 ka; substantial subsidence and tsunamis apparently affected much of the Cascadia subduction zone at this time. These features may record either a single earthquake of about magnitude 9 along the megathrust or a series of smaller earthquakes during an interval of a few decades. At many sites in southern Washington and northern Oregon, the upper contact of a soil that was submerged about 1.7 ka apparently meets many of the most diagnostic criteria, and so it probably records subsidence during a similar earthquake or earthquakes on the megathrust. Evidence for a coseismic origin is more equivocal, however, for the 1 to 3 peat-mud contacts that occur between the 0.3-ka and 1.7-ka soils at some sites and for at least three deeper contacts dating from 2 to 5 ka. Most of the other peat-mud contacts lack documented contrasts in lithology or fossils suggestive of more that half a meter of submergence, well-studied tsunami deposits, and/or precise ages needed for regional correlation. Some contacts may have formed through sudden local changes in estuarine hydrography or through rapid changes in sedimentation and sea-level; others were probably produced by coseismic subsidence of less than half a meter (Nelson *et al.*, 1996).

AREA: southern Cascadia megathrust
SEGMENT: Cape Mendocino-False Cape
SITE(S): Cape Mendocino [CM_1 & CM_2]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Lajoie (1992) attributed a sequence of 6 Holocene stream terraces at Ocean House [site CM_1] to coseismic events occurring between 7 and 3.5 ka. Vertical separation between terraces ranges from 0.7 to 1.8 m. The time interval between terraces ranges from 250 to 900 years, assuming a constant uplift rate of 2.7 mm/y. Up to 1 m of coseismic uplift occurred in this area during the M7 1992 Petrolia earthquake.

The M7 1992 Petrolia earthquake elevated about 25 km of the coast from 3 km south of Punta Gorda to Cape Mendocino (Oppenheimer *et al.*, 1993). Maximum observed uplift was 1.2 to 1.6 m at Mussel Rock [site CM_2] and 0.4 to 0.5 m at Cape Mendocino. The pattern of broad regional upwarping of the newly emergent marine platform is similar in character to adjacent Holocene marine platforms suggesting similar slip events have occurred repeatedly in this region (Merritts *et al.*, 1992). Modeling of geodetic data, based on assumptions of uniform slip and a rectangular rupture plane, suggests 4.9 m of slip occurred at depth on a 14- by 15-km rupture plane, dipping 28° SE (Murray *et al.*, 1996). If repeated ruptures of the southernmost segment of Cascadia megathrust are entirely responsible for Quaternary uplift in this region, then a reccurrence interval of 0.2 to 0.27 ky is required.

FAULT TYPE: thrust [R]
DIP: 13-28° ENE-SE (Petrolia earthquake)
STRIKE : 350° (Petrolia earthquake)
SLIP RATE: *n/a*
SLIP PER EVENT: 2.7-4.9 m (Petrolia earthquake)
VERTICAL: 1.4 m (Petrolia earthquake)
HORIZONTAL: 0.4 m (Petrolia earthquake)
UPLIFT PER EVENT: 0.7-1.8 m? [CM_1]
RECURRENCE: 0.25-0.9 ky [CM_1]
AGE : active
SHORTENING RATE: *n/a*
UPLIFT RATE: 2.7 mm/y [CM_1]

REFERENCES:
Carver *et al.*, 1994 (R)
Lajoie, 1992 (A)
Lajoie *et al.*, 1991 (R)
Murray *et al.*, 1996 (R)
Merritts *et al.*, 1992 (A)
Oppenheimer *et al.*, 1993 (R)

DATA LIMITATIONS: Available data from the 1992 Petrolia earthquake leaves unresolved the question of whether slip occurred on the megathrust *sensu stricto* or on a slip plane a few kilometers above the megathrust within the lower accretionary prism.

AREA:	southern Cascadia megathrust
SEGMENT:	Eel River syncline
SITE(S):	Eel River delta [**ERs1**]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Li and Carver (1992) interpreted a sequence of stacked tidal-flat mud layers and salt-marsh peat layers at site **ERs1** to record abrupt subsidence events during a sequence of five megathrust earthquakes. Mud layers are in sharp depositional contact with underlying peat layers and gradational contact with overlying peat layers. The uppermost peat layer correlates laterally to a weak soil with *in situ* tree stumps (Li, 1992*a*). Radiocarbon dates from the peat layers and fossil stumps are *ca. 0.2, 0.8, 1.3, 1.5*, and *1.9 ka* in *calibrated years* (Li and Carver, 1992).

The sharp contacts between peat layers and overlying mud layers correlate with abrupt shifts in foraminiferal assemblages from higher-marsh assemblages to lower marsh-intertidal assemblages. Such shifts in assemblages require 0.2 to 1.3 m subsidence (Manhart, 1992). Composite stratigraphic section from vibracore samples:

Peat 1 @ 0.8 m below modern high-marsh surface:

ERSB-T-2A	*0.22±0.08 ka*	3.6? mm/y subsidence

Peat 2 @ 1.2-2.2 m below modern high-marsh surface:

ER-VC-07	*0.81±0.07 ka*	1.5-2.7 mm/y subsidence

Peat 3 @ 1.8-2.8 m below modern high-marsh surface:

ER-VC-11	*1.29±0.06 ka*	1.4-2.2 mm/y subsidence

Peat 4? @ 2.1-3.3 m below modern high-marsh surface:

ER-VC-07	*1.52±0.07 ka*	1.4-2.2 mm/y subsidence

Peat 5 @ 3.0 m below modern high-marsh surface:

ER-VC-06	*1.91±0.06 ka*	1.6 mm/y subsidence

FAULT TYPE:	thrust [R]
DIP:	*n/a*
STRIKE :	*n/a*
SLIP RATE:	*n/a*
SUBSIDENCE PER EVENT:	0.2-1.3? m
RECURRENCE:	0.45? ky
AGE :	Holocene?
SHORTENING RATE:	*n/a*
SUBSIDENCE RATE:	1.4-2.7? mm/y (based on Peats 2-5)

REFERENCES:

Li and Carver, 1992 (A)
Li, 1992*a* (O)
Li, 1992*b* (O)
Manhart, 1992 (O)
Nelson, 1992*b* (R)
Nelson *et al.*, 1994*b* (A)
Nelson *et al*, *1996* (R)

DATA LIMITATIONS: The Li (1992*b*) report does not establish a megathrust earthquake source for the buried soils within the Eel River syncline. This syncline merits further study, given the potential to distinguish megathrust and crustal earthquake sources using the stratigraphic record preserved within it. The Li (1992*b*) report lacks a location map, discussion of control studies or modern studies of the tidal ranges of marsh sub-zones in the Eel River delta, and reference to a modern datum (this study assumes that the modern high-marsh datum was used). The conventional radiocarbon dating technique used to date samples by Li (1992*b*) lacks the precision needed to infer regional correlation between subsidence events (see discussion below on diagnostic criteria for establishing a megathrust source). The possibility of differential preservation of foraminiferal tests in different sediment facies is not considered, even though this process appears to significantly alter the composition of foraminiferal assemblages elsewhere in the Pacific Northwest (see discussion under Mad River slough section; Manhart, 1992).

Studies inferring subduction earthquakes from submerged coastal marsh soils need to document two main features: (1) coseismic origin and (2) widespread synchroneity (Nelson *et al.*, *1996*). In general, available reports on submerged soils for the Humboldt area are works-in-progress which meet to varying degrees of reliability, some of the diagnostic criteria presented in Nelson *et al.* (*1996*).

PROBLEMS DOCUMENTING COSEISMIC ORIGIN

Abrupt, conformable, coseismic contacts are difficult to distinguish from some conformable contacts formed by non-seismic processes (such as barrier bar breaching), except where the contacts extend across two or more intertidal environments with different types of vegetation or sediment (suggesting synchronous burial) and where changes in fossil assemblages suggest at least half a meter of submergence (Nelson *et al.*, *1996*).

PROBLEMS DOCUMENTING WIDESPREAD SYNCHRONEITY

At many sites in the Cascadia subduction zone, some abrupt peat-mud contacts apparently differ in age by less than a few hundred years, which is too small a time span for conventional radiocarbon dating to distinquish between them (Nelson *et al.*, *1996*). Great earthquakes have occurred only hours to years apart in some subduction zones, therefore, no geologic dating methods can demonstrate that coseismic contacts are truly synchronous. However, if suitable material is available, high-precision methods may distinguish contacts along the Cascadia subduction zone that differ in age by as little as a few decades. Such contacts could form through nonseismic processes, earthquakes on shallow structures in the upper plate that occur independently of megathrust earthquakes, or megathrust earthquakes with ruptures of limited extent (<200 km) (Nelson *et al.*, *1996*). Except when the times of earthquakes in the upper plate differed by more than a few decades from the times of megathrust earthquakes, even high-precision dating may not be able to distinquish contacts that record subsidence during earthquakes on shallow faults from contacts formed by earthquakes on the megathrust (Nelson *et al.*, *1996*).

Comparison of conventional radiocarbon ages for different materials from the same buried soils shows that they contain materials that differ in age by many hundreds of years. Errors in calibrated soil ages represent about the same length of time as recurrence times for submergence events (150-500 y). This precludes using conventional radiocarbon ages to distinguish buried soils along the Cascadia coast (Nelson, 1992*b*). High-precision (HP) radiocarbon dating of tree rings yields estimates of subsidence times with errors of 20 to 40 years. However, only one soil (300 a) has been dated with high-precision methods and only at four sites along the 1100-km length of the Cascadia zone. Averages of 6 to 8 accelerator (AMS) radiocarbon ages for above-ground plant parts from the same buried soil yield mean ages with errors larger (calibrated-age errors of 150 years) than those for HP ages, however, the multiple-AMS method can be applied to many soils at most buried-soil sites (Nelson *et al.*, 1994*b*).

AREA:	southern Cascadia megathrust
SEGMENT:	Humboldt Bay-south bay syncline
SITE(S):	Humboldt Bay [SBs_1]

SITE LOCATION(S): see Location Map (Plate 1)

DATA CONSTRAINTS: Carver (*in* Figure 8, 1992) gave radiocarbon dates for five subsidence events in Humboldt Bay, presumably associated with the south-bay syncline, as *ca. 0.2*, *0.7*, *1.2*, *2.6*, and *3.2 ka* in *calibrated years* (citing Valentine, personal communication).

FAULT TYPE:	thrust [R]
DIP:	*n/a*
STRIKE :	*n/a*
SLIP RATE:	*n/a*
SLIP PER EVENT:	*n/a*
RECURRENCE:	0.5? ky
AGE :	Holocene?
SHORTENING RATE:	*n/a*
SUBSIDENCE RATE:	*n/a*

REFERENCES:

Carver, 1992 (O)
Valentine, 1992 (O)
Valentine *et al.*, 1992 (A)

DATA LIMITATIONS: See discussion of various radiocarbon dating techniques and associated analytical errors under Eel River syncline section. See discussion of coastal marsh datums under the Eel River section. Specific locations at which samples were collected or stratigraphic sequences measured are not given in Carver (1992). The reliability of these data cannot be evaluated from the available report. Available reports do not establish a megathrust earthquake source for the buried soils within the south-bay syncline, in particular, the possibility that inferred tectonic subsidence of the south-bay syncline is controlled in part by slip along the Little Salmon fault zone. This syncline merits further study, given the potential to distinguish megathrust and crustal earthquake sources using the stratigraphic record preserved within it.

AREA: southern Cascadia megathrust
SEGMENT: Freshwater syncline
SITE(S): Arcata Bay [FWs1]

SITE LOCATION(S): *n/a*

DATA CONSTRAINTS: Carver (Figure 8 *in* 1992) gave radiocarbon dates for nine subsidence events in Arcata Bay, presumably associated with the Freshwater syncline, as *ca. 0.2, 0.4, 0.6, 1.2, 1.5, 1.8, 2.6, 3.0,* and *3.3 ka* in *calibrated years* (citing Valentine, personal communication).

FAULT TYPE: thrust [R]
DIP: *n/a*
STRIKE : *n/a*
SLIP RATE: *n/a*
SLIP PER EVENT: *n/a*
RECURRENCE: 0.39? ky
AGE : Holocene?
SHORTENING RATE: *n/a*
SUBSIDENCE RATE: *n/a*

REFERENCES:
Carver, 1992 (O)
Valentine, 1992 (O)

DATA LIMITATIONS: See discussion of various radiocarbon dating techniques and associated analytical errors under Eel River syncline section. See discussion of coastal-marsh datums under section on Eel River syncline. Specific locations at which samples were collected or stratigraphic sequences measured are not given in Carver (1992). The reliability of these data cannot be evaluated from the available report. Available reports do not establish a megathrust earthquake source for the buried soils within the Freshwater syncline, in particular, the possibility that inferred tectonic subsidence of the Freshwater syncline is controlled in part by slip along the Mad River fault zone. This syncline merits further study, given the potential to distinguish megathrust and crustal earthquake sources using the stratigraphic record preserved within it.

AREA:	southern Cascadia megathrust
SEGMENT:	Freshwater syncline
SITE(S):	Mad River slough [**FWs2**, **FWs3** & **FWs4**]

SITE LOCATION(S): see Location Map (Plate 1) for sites **FWs2** & **FWs3**; location for site **FWs4** not available

DATA CONSTRAINTS: Vick and Carver (1988) interpreted a sequence of stacked salt-marsh peat layers and tidal-flat mud layers within Freshwater syncline in Arcata Bay to record abrupt subsidence events during a series of three megathrust earthquakes.

At the mouth of the Mad River slough [site **FWs2**], five buried marsh or forest horizons yielded radiocarbon dates (Figure 4 *in* Clarke and Carver, 1992). Carver *et al.* (1993) interpret the first buried peat at this site to have resulted from a storm event rather than from coseismic subsidence. Composite stratigraphic section:

- Peat 1 @ 1 m below modern high-marsh surface:

B#25016	*<0.62 ka*	
QL#4260	*<0.46 ka*	
QL#4261	*<0.28 ka*	
QL#4262	*<0.29 ka*	
QL#4263	*<0.28 ka*	
QL#4320	*<0.5 ka*	

- Peat 2 @ 1.8 m below modern high-marsh surface:

B#25438	*0.90±0.36 ka*	1.43-3.33? mm/y subsidence

- Peat 3 @ 2.5 m below modern high-marsh surface:

B#25017	*1.25±0.32 ka*	1.59-2.69? mm/y subsidence
B#25439	*1.25±0.28 ka*	

- Peat 4 @ 2.7 m below modern high-marsh surface:

B#25440	*1.10±0.30 ka*	
B#25441	*1.24±0.28 ka*	1.78-3.38? mm/y subsidence

- Peat 5 @ 3.3 m below modern high-marsh surface:

QL#4321	*1.52± 0.17 ka*	
QL#4322	*1.61±0.09 ka*	1.95-2.44? mm/y subsidence

Note, that the radiocarbon dates do not distinguish between Peat 3 and Peat 4. These two peat layers are considered a "seismic couplet" (Manhart, 1992).

At site **FWs3**, 1 km north of the mouth of Mad River slough, Carver *et al.*, (1993) interpreted the first buried peat to have resulted from coseismic subsidence. At this site, the first buried peat yielded a microfaunal assemblage associated with higher high water (HHW) overlain by a mud layer which yielded a transitional? fauna associated with the sub-zone between mean tidal level (MTL) and mean high water (MHW). The resolvable range in magnitude of subsidence between deposition of the peat and overlying mud is the difference between HHW and both MHW and MTL or 0.2 to 1.3 m (Manhart, 1992; Carver *et al.*, 1993). The radiocarbon age obtained from plant macrofossils collected from the first buried peat at site FWs3 is *ca. 0.9 ka.* This peat was expected to be *ca. 0.3 ka* based on the widespread nature of the *ca. 0.3-ka* horizon. However, samples from the second buried peat at this site yielded radiocarbon dates of *ca. 1.3 ka* which supports the possiblility that the *0.3-ka* peat layer is missing rather than mis-dated at this site. A locality 2-km north of the mouth of Mad River slough yielded equivocal results; fauna from neither the first nor second buried peat surfaces showed change in marsh sub-zone (Carver *et al.*, 1993).

TIDAL DATUMS	
MTL	0.0 m datum
MLHW	0.7 m datum
MHW	0.9 m datum
HHW	1.1*-1.3† m datum

* from NOS, 1981-1985 (used in Carver *et al.*, 1993)
† from Manhart, 1992 (used in Manhart, 1992)

Control studies of low, transition, and high marsh microfauna in Arcata Bay and Mad River slough are in progress (Carver *et al.*, 1993). Modern tidal marshes of coastal North America contain a low diversity of foraminiferal species, the same 6 to 10 species are the dominant fauna in all marshes studied (Manhart, 1992). In the high marsh sub-zone, within a few centimeters of HHW datum, the foraminiferal assemblage is almost entirely one species, *Trochammina macrescens* Brady (Manhart, 1992). Determining the upper bound of the modern tidal marsh in Arcata Bay and Mad River slough is hampered by extensive cultural modifications (*i.e.*, dikes). The foraminiferal assemblage found in the low marsh sub-zone varies between marshes, however, appears to be uniform within a specific marsh. In Mad River slough, *Millammina fusca* Brady dominates the low marsh assemblage (Manhart, 1992). Manhart (1992) has also identified a transitional assemblage associated with the tidal range between MTL and MHW, however, because of the overlap in species with the adjacent zones, the transitional zone appears poorly constrained. The wide vertical range in the marsh sub-zones limits the precision of deducing magnitude of subsidence using foraminiferal assemblages (Manhart, 1992).

FORAMINIFERAL SUB-ZONES (above MTL)	
mud flat	0.0-0.6 m
low marsh	0.6-0.8 m
transitional marsh	0.8-1.0 m
high marsh	1.0-? m

In a recent study on the east coast, the decrease in relative abundance of *M. fusca* with depth (≥ 10 cm) was attributed to bacterial degradation of test cement rather than change in marsh sub-zone (Manhart, 1992). (Note, *Miliammina* has a porcelaneous test; *Trochammina* and *Haplophragmoides* have agglutinated tests—which may affect their preservation potential.) At site FWs3, *Haplophragmoides* and *Miliammina* drop out of the stratigraphic section (< 5% of sample) at 1.8 m below the modern surface suggesting a shift to a higher marsh sub-zone, even though the facies shift from peat to mud implying a deepening in marsh sub-zone (Manhart, 1992). The disappearance of these species strongly suggests that differential preservation biased the foraminiferal assemblages (Manhart, 1992). Control studies are needed to investigate whether the variation in preservation potential of agglutinated and porcelaneous forms is dependant on pore-fluid chemistry of the peat and mud horizons.

Four high-precision (HP) radiocarbon dates on either *in situ* herbs or trees from Mad River slough [site FWs4] yielded a mean age of *0.124±0.007 ka* in *calibrated years* (Nelson and Atwater, 1993) or 1700-1720 AD (2σ range) (Carver *et al.*, 1992). Tree-ring analysis of root sections from 8 trees indicate that all tree deaths took place within 4 years (Jacoby *et al.*, 1993). The drowned swamp correlates laterally to a buried marsh in lower Mad River slough, where fossil plants, in growth position, are enclosed in tidal-flat mud that overlies the marsh (Carver *et al.*, 1992) implying abrupt burial. An independant age for this buried marsh horizon (not given in Carver *et al.*, 1992) would be useful considering the difficulties other workers encountered in attempting to document a *ca.* 300-year old buried marsh horizon in the Mad River slough. In addition, the *ca. 0.08* to *0.15-ka* horizon identified by Carver *et al.* (1992) as the *ca.* 300-year old megathrust event apparently has a different age than the *ca. 0.28* to *0.62-ka* horizon identified by Clarke and Carver (1992) as the *ca.* 300-year old event.

FAULT TYPE:	thrust [R]
DIP:	*n/a*
STRIKE :	*n/a*
SLIP RATE:	*n/a*
SUBSIDENCE PER EVENT:	0.2-1.3 m?
RECURRENCE:	0.35? ky
AGE :	Holocene?
SHORTENING RATE:	*n/a*
SUBSIDENCE RATE:	1.43-3.33? mm/y (based on Peats 2 & 3)

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Valentine, 1992 (O)
Valentine *et al.*, 1990 (A)
Vick, 1988 (O)
Vick and Carver, 1988 (A)

DATA LIMITATIONS: See discussion of various radiocarbon dating techniques and associated analytical errors under Eel River syncline section. See discussion of coastal-marsh datums under section on Eel River syncline. Specific locations at which samples were collected or stratigraphic sequence measured are not given in Clarke and Carver (1992). Available reports do not establish a megathrust earthquake source for the buried soils within the Freshwater syncline, in particular, the possibility that inferred tectonic subsidence of the Freshwater syncline is controlled in part by slip along the Mad River fault zone. This syncline merits further study, given the potential to distinguish megathrust and crustal earthquake sources using the stratigraphic record preserved within it.

HP radiocarbon dating of trees killed by sudden subsidence at four coastal sites does not rule out an earthquake rupture that may have extended from central Washington to Humboldt Bay, about 1680-1720 AD (Nelson *et al.*, 1994*b*). However, precisely dated trees in Humboldt Bay are 530 km south of the nearest other site with dated trees. A more recent study of correlative buried soils, which are dated by multiple marsh-plant AMS radiocarbon ages, does not rule out synchronous subsidence at seven sites along 440 km of the Oregon and Washington coast (Nelson *et al.*, 1994*b*). Such ages are consistent with either a magnitude 9 on the megathrust or a series of magnitude 8 earthquakes after 1650 AD. However, the only site with precisely dated marsh plants in central and southern Oregon is on the Coquille River, 260 km north of Humboldt Bay (Nelson *et al.*, 1994*b*). The paleoseismic record in the southern Cascadia subduction boundary is probably more complex than the record farther north owing to active onshore thrust faults in this region. Coseismic uplift or subsidence of coastal sites in this zone may or may not be synchronous with great earthquakes on the megathrust (Nelson *et al.*, 1994*b*).

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