QUATERNARY TECTONICS NORTH OF THE MENDOCINO TRIPLE JUNCTION THE MAD RIVER FAULT ZONE

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Introduction

Coastal California north of Cape Mendocino has been the locus of strong crustal compression during the Quaternary. Large northwest trending folds and parallel northeast dipping thrust and reverse faults have deformed Pleistocene deposits and influenced landforms throughout the region (Ogle, 1952, Woodward-Clyde Consultants, 1980, Carver et al., 1982). At the coast, localized uplift and subsidence associated with these structures is expressed as alternating reaches of emergent and submergent shoreline. Uplifted thrust blocks and large anticline crests form headlands sculpted by flights of raised glacio-eustatic marine terraces, while down-faulted blocks and synclinal troughs are occupied by lagoons, bays, and estuary-delta complexes. Steep youthful mountains, vigorous slope processes, deeply incised river valleys, and high fluvial sediment yields reflect the active tectonics of the northcoast region.

Regional Tectonic Setting

Although considerable information concerning tectonics of northwestern California has been developed in the past few years, a detailed regional tectonic model has not yet emerged. Throughout the late Tertiary the north coast region of California was situated along the Farallon-North American Plate boundary, a subduction margin (Atwater, 1970). Migration of the Mendocino Triple Junction into the north coast region occurred largely during the Quaternary.

The present tectonic setting of the northern California coast is strongly influenced by the triple junction and its northward movement. Quaternary structures resulting from thrust faulting and folding near the coast north of Cape Mendocino give way to high angle strike slip faults of the San Andreas system to the south and east (Herd, 1978, Kelsey and Allwardt, 1983) (Figure 1). Offshore Quaternary sediments of the continental shelf and slope are deformed by large youthful folds and faults (Fields et al. 1980, Silver, 1971); these structures are probably northern continuations of the onshore thrust faults and folds. Offshore of Oregon, these structures merge into the Juan de Fuca-Gorda subduction zone. Both the transform boundary south of the triple junction and the subduction margin to the north include broad complex systems of faults. The transition from transform to subduction tectonics, i.e., the triple junction, encompasses an equally broad and highly complex zone of transitional tectonics.

Compressional Tectonics North of the Mendocino Triple Junction

At least a dozen major Quaternary thrust faults or fault zones and several large youthful folds traverse the coastal region of California north of the triple junction (Ogle, 1952; Woodward-Clyde Consultants, 1980; Carver et al., 1982). Their cummulative Quaternary displacement represents at least 15 km of NE-SW crustal shortening. These northwest-trending northeast-dipping faults form a complex imbricate thrust belt within the overriding margin of the North American Plate along its boundary with the subducted southern portion of the Gorda Plate. The compression of the North American Plate margin may be the result of coupling between the accretionary wedge of the North America Plate and the underlying Gorda Plate, with outboard portions of the overriding wedge being rafted downward with the subducting plate. Internal deformation of the southern Gorda plate along northeast-trending left-lateral strike slip faults (Smith and Knapp, 1980; Smith, et. al. 1981), and the northward movement of the Pacific Plate result in a change in Gorda, North American convergence from east-west along the extreme northern California coast to nearly north-south near the triple junction. This change in convergence direction is reflected in compressional structures along the coast; principal folds and thrust faults strike nearly east-west at Cape Mendocino and gradually rotate to northwest-southeast further north (Figure 1). Magnetic anomalies on the Gorda plate show that this rotation in convergence was probably established during the Quaternary (Riddenhauf, 1984).

The Mad River Fault Zone

The Mad River Fault Zone (MRFZ), a prominent zone of imbricate thrust faults and associated folds, extends along the Mad River about 50 km from the coast inland to the vicinity of Maple Creek. The MRFZ is about 15 km wide and trends N35^{o}W. It contains 5 principal thrusts (Trinidad, Blue Lake, McKinleyville, Mad River, and Fickle Hill Faults) and numerous minor ones (Figure 2, 3). The Fickle Hill anticline, the Jacoby Creek syncline, and the Blue Lake anticline constitute major folds within the zone. At it's southeast end, near Maple Creek, compressional structures of the MRFZ merge with strike slip faults of the Eaton Roughs Fault Zone, a part of the San Andreas system (Kelsey and Allwardt, 1983). The dips of MRFZ faults range from 15^{o}-25^{o}NE at the coast to 35^{o}-45^{o}NE near Maple Creek. The folds are asymmetrical, with northern anticlinal limbs dipping northeast 20^{o}-30^{o}, and southern limbs near vertical and locally overturned. Their axis parallel the trend of the thrusts (N35W) and they plunge very gently NW. The fold limbs are cut by the thrust faults.

Stratigraphy

Assessment of the Quaternary tectonics of the Mad River Fault Zone is based on mapping and interpretation of several Quaternary stratigraphic datums. These include 1) the Klamath saprolite, 2) the Falor Formation, 3) the Patricks Point Terrace, and 4) fluvial terraces. These datums are widespread across the MRFZ, and were formed on nearly horizontal low relief surfaces. Approximate ages of these datums have been determined. In addition, each of these stratigraphic features has tectonic significance relevant to the Quaternary development of the MRFZ. The MRFZ stratigraphy is summarized in Table 1.

The Klamath Saprolite

The Klamath saprolite is a very thick, very strongly developed weathering profile formed on pre-Quaternary rocks of north western California, especially the Franciscan Complex and Redwood Creek Schists.It mantles an extensive pre-Quaternary erosion surface of very low relief which Diller (1902) called the Klamath Peneplain. Locally the saprolite is many tens of meters thick, bright red, and clay-rich. It attests to a long period tectonic stability, low relief landscapes, little erosion, and prolonged chemical weathering. North of the MRFZ the saprolite is present on concordant flat topped ridges and mountains and extends into southwest Oregon. Within the MRFZ the saprolite is folded and displaced by faults. Early Quaternary marine and fluvial sediments of the Falor Formation lie depositionally on the saprolite limiting its age to late Tertiary. Preservation of the saprolite during the initial Falor transgression suggests tectonic processes in the region were relatively quiet at the end of the Tertiary.

Falor Formation

The Falor Formation (Manning and Ogle, 1950) includes locally thick sequences of poorly consolidated interbedded shallow marine sands and pebbly sands, estuarine and bay sands, silts, and clays, and fluvial gravels, sands, and silts. The deposits were laid down in a slowly subsiding depositional basin which extended across the MRFZ and was probably continuous with the Eel River basin to the south. Subsequent faulting has thrust Franciscan Complex rocks over the Falor deposits. In all measured stratigraphic sections of the Falor Formation, the top of the section has been removed by faulting, allowing determination only of minimum section thickness. Locally over 938 meters of Falor sediments are present in the MRFZ.

The age of the Falor Formation is constrained by a well-preserved volcanic ash layer present near its depositional base. This ash has been correlated on the basis of chemistry to the 1.8-2.0 m.a. Huckleberry Ridge Tuff from the Yellowstone caldera (A. Sarna-Wojcicki, pers. comm., 1983). The internal stratigraphy of the Falor Formation is complex and not well known. A widespread basal member composed of well-sorted quartz-rich sand containing well rounded silicous pebbles suggests open coastline conditions during initial Falor deposition. Higher in the section shallow open-marine sedimentation dominated in western portions of the MRFZ while estuarine and bay environments were present in the east. The entire section is punctuated by fluvial sand and gravel sequences, representing repeated transgression-regression cycles, possibly the result of early and mid Quaternary glacio-eustatic sea level fluctations. Representative stratigraphic sections of the Falor Formation in the eastern portion of the MRFZ are shown in Figure 4.

The lack of angular unconformities or disconformities with significant stratigraphic relief indicates MRFZ faulting and folding were not active during the deposition of the Falor sediments. About 1 km of subsidence at a rate slow enough to allow sedimentation in near sea level depositional settings is suggested by the formation's sedimentology and thickness. Development of fault and fold structures of the MRFZ probably terminated Falor deposition. Assuming sedimentation rates of 1 meter per 1000 years, tectonic activity in the MRFZ was initated no more than about 1 million years ago.

Patricks Point Terrace

Late Pleistocene marine terraces are present on headland sections of the coast in the vicinity of the MRFZ. Especially well developed is a sequence of at least six raised marine terraces at Trinidad (Stephens, 1982, Woodward-Clyde Consultants, 1980). The lowest of these, the Patricks Point Terrace, extends along the coast across the MRFZ. This terrace has been assigned an age of 85,000 years (isotope stage 5a) on the basis of soil development, stratigraphic position and comparison with worldwide sea level curves (Bloom et al., 1974). The terrace is displaced by each of the principal faults of the MRFZ. Prominent scarps and mole track ridges mark the fault traces, and the terrace surface is displaced vertically as much as 35 meters. These raised and deformed marine terraces indicate considerable tectonic activity in the MRFZ throughout the late Pleistocene.

Fluvial Terraces

Holocene and latest-Pleistocene fluvial terraces are present along the lower reaches of the Mad River and Jacoby Creek. The Holocene terraces are graded to modern sea level and lack of soil development; indicating they are less than 6000 years old. Raised fluvial terraces mantled with very weakly-developed soils represent latest Pleistocene river deposits. Locally, fault scarps up to 7 meters high cut these young fluvial terraces.

Activity of the MRFZ

Structural and stratigraphic reltionships indicate the MRFZ was initiated in the mid Pleistocene, perhaps about 1 million years ago. The existence of little-eroded saprolite beneath the Falor Formation and the lack of evidence of significant deformation during the deposition of the Falor Formation suggest the late Tertiary and early Quaternary landscape lacked relief associated with active folding and faulting.

Franciscan complex rocks have been thrust over Falor Formation sediments more than 1 km on each of the principal faults of the MRFZ. Minimum slip rates for these faults based on measured displacement of the base of the Falor Formation and the thickness of Falor sections beneath the overthrust Francisan range around 1 mm/year. Similar rates are derived from displacement of the late Pleistocene Patricks Point Terrace. Across the MRFZ cummulative displacement rates have been about 4 mm per year for the late

Quaternary. Fault displacements and slip rate determinations for the MRFZ are summarized in Table 2.

Conclusions

The MRFZ is a major northeast-dipping imbricate thrust fault and fold system of the mid and late Quaternary age in coastal northern California. It is a part of a broad region of compressional tectonic structures which define the Gorda-North American Plate Margin north of the Mendocino Triple Junction. To the south and east this system of compressional structures merges with the northern end of faults of the San Andreas Transform system. Thrust faulting and folding associated with the MRFZ was initated in the mid-Pleistocene after deposition of the Falor Formation. Prior to this thrusting, the tectonics of the area were relatively quiet. The onset of faulting in the MRFZ may represent the migration of the Mendocino Triple Junction northward into the northernwestern California region. Slip rates for principal faults within the MRFZ have been about 1 mm per year since the mid Pleistocene, and about 4 mm per year for the entire zone. Faulting, folding, and uplift associated with the mid and late Quaternary activity of the MRFZ and related compressional structures in the north coast region has generated the relief expressed by the present landscape and the structural complexity apparent in early and mid Quaternary deposits of coastal northern California.

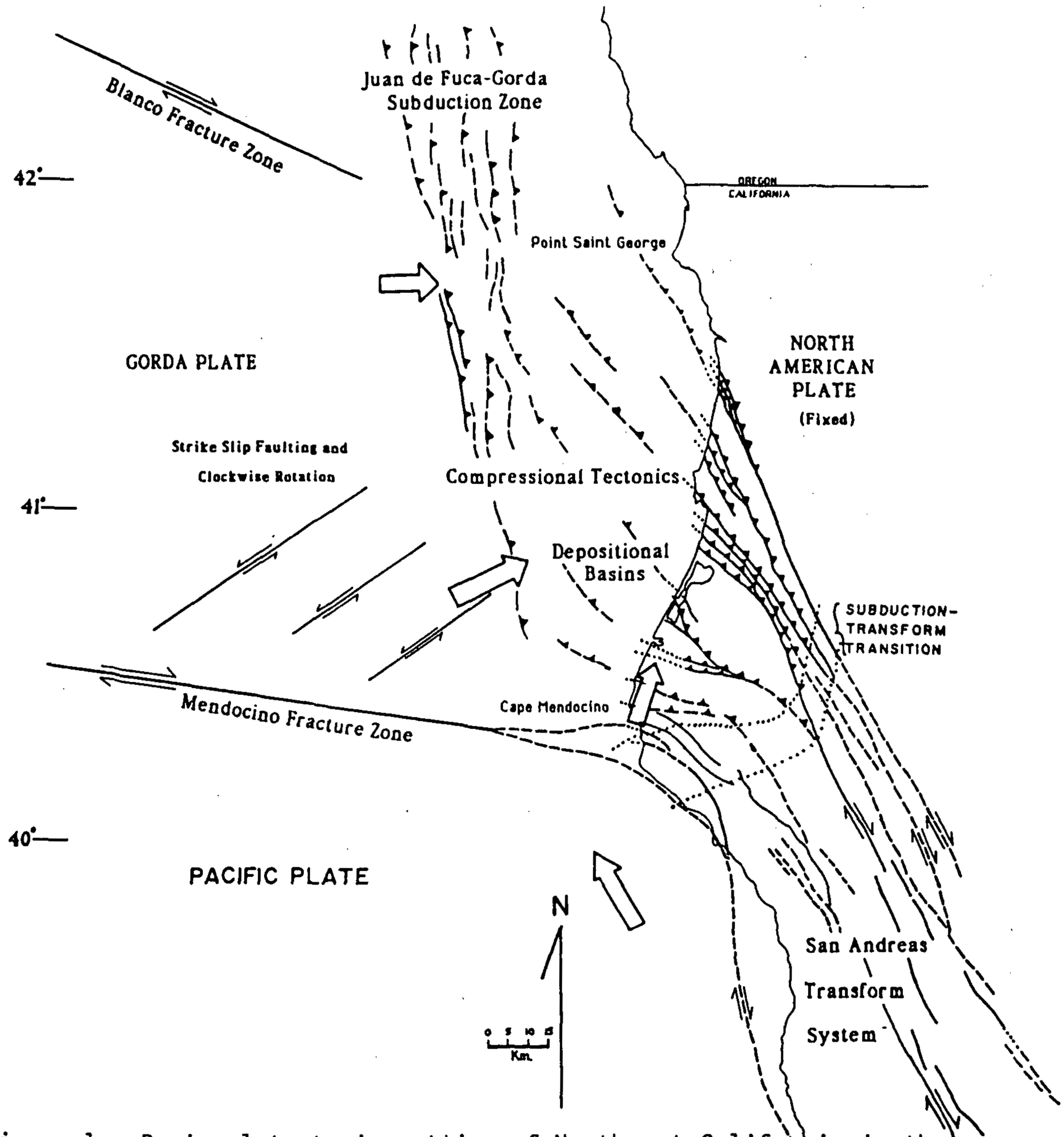

Figure 1. Regional tectonic setting of Northwest California in the vicinity of the Mendocino Triple Junction. Compressional structures of the Juan de Fuca-Gorda subduction zone trend onshore at their southern end and merge with strike slip faults of the San Andreas transform system. Large open arrows depict plate motion for the Pacific and Gorda Plates relative to a fixed North American Plate.

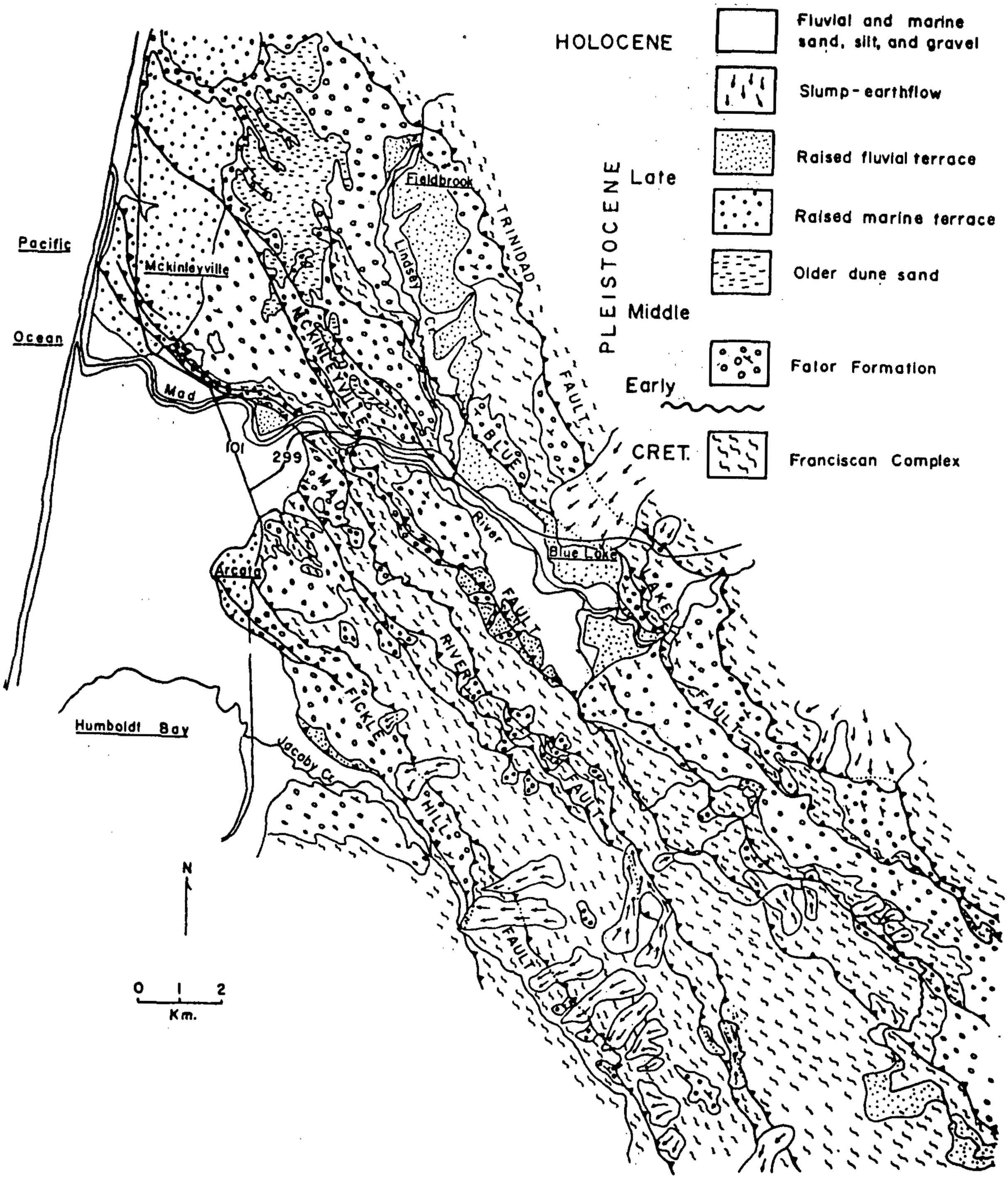

Figure 2. Quaternary Geologic Map of the Mad River Fault Zone.

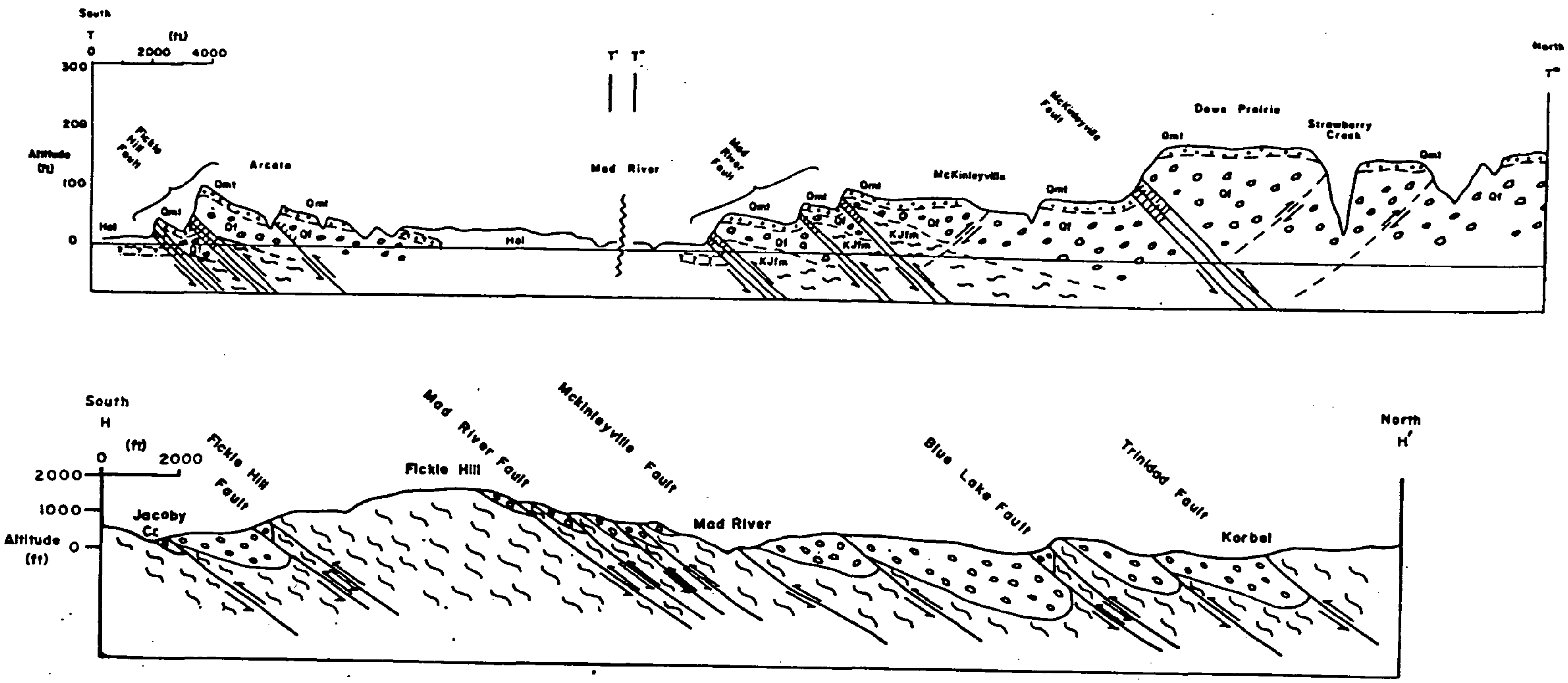

Figure 3. Geologic cross sections across the Mad River Fault Zone. Section T-T'-T'' is along the coast and illustrates the deformation of the late Pleistocene coastal terraces. Section H-H' is across the MRFZ near Korbel, and illustrates the deformation of the early Pleistocene Falor Formation.

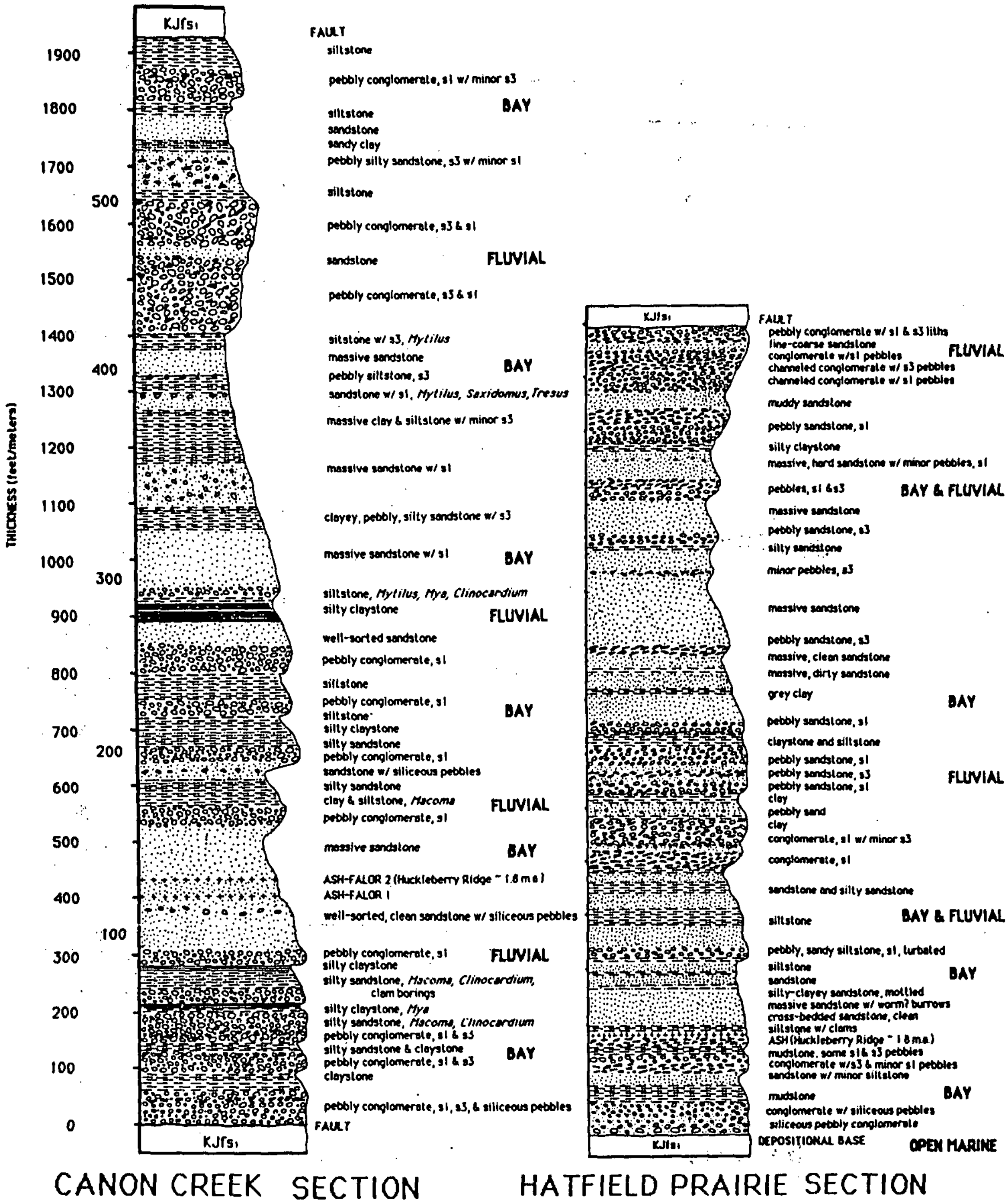

Figure 4. Stratigraphic sections through the Falor Formation at Canon Creek and Hatfield Prairie. Above a basal sequence of shallow open marine deposits thick sequences of fluvial and bay sediments alternate. The Huckleberry Ridge ash (1.8-2.0 ma) lies in the lower portion of the bay facies just above the open marine sands. The sections lack angular unconformities or major disconformities and indicate slow continuous subsidence during deposition. The tops of the sections are terminated by thrust faults.

	Age	Stratigraphic Unit		Tectonic/Sedimentologic
	MODERN	----ACTIVE CHANNEL DEPOSITS		
	HOLOCENE	-----FLOOD PLAIN TERRACES--		THRUST/REVERSE FAULTING--UPLIFT?
		FLUVIAL TERRACES		
			PATRICK'S PT.	85,000 THRUST/REVERSE FAULTING
	LATE PLEISTOCENE	TRINIDAD TERRACE SEQUENCE	WESTHAVEN	125,000 RAPID UPLIFT
			SAVAGE CREEK	LOCALLY--GLACIO-EUSTATIC TERRACE CUTTING AND DEPOSITION
			SKY HORSE	
			A-LINE	
			MAPLE STUMP	
		UNCONFORMITY		
QUATERNARY	MIDDLE PLEISTOCENE	FALOR FM.	MOONSTONE DEPOSITS	U SERIES DATE? >450,000 THRUST/REVERSE FAULTING-UPLIFT
			CRANNELL SANDS *CRANNELL ASH?	>400,000
			AGATE BEACH DEPOSITS	FLUVIAL AND SHALLOW MARINE DEPOSITION-- MANY TRANSGRESSION AND REGRESSION CYCLES
	LOWER PLEISTOCENE		HATFIELD PRAIRIE ASH	1.8 M.a.
				WEST / EAST: OPEN OCEAN / ENCLOSED BASIN
				SLOW TECTONIC SUBSIDENCE-- -MARINE TRANSGRESSION AND DEPOSITION
		LOCAL UNCONFORMITY		
TERTIARY	LATE TERTIARY	SAPROLITE/HALTER RIDGE GRAVELS		-TECTONIC QUIESCENCE -EXTENSIVE WEATHERING -LOCAL FLUVIAL DEPOSITION?
	EARLY TERTIARY	UNCONFORMITY		REGIONAL UPLIFT AND EROSION
MESOZOIC		FRANCISCAN COMPLEX		SUBDUCTION ACCRETION
		KERR RANCH SCHIST		

Table 1. Stratigraphy of the Mad River Fault Zone and tectonic and sedimentologic interpretation of the development of the stratigraphic sequence.

Fault	Location	Datum	Age (m.a.)	Dip	Vertical Displacement (meters)	Dip Slip Displacement (meters)	Slip Rate (mm/yr)
Trinidad Fault	Anderson Ranch-Trinidad	Pat. Pt. Terrace	.85	25^{o}	18	43	.50
Trinidad Fault	Jager Property-Trinidad	Pat. Pt. Terrace	.85	25^{o}	14	33	.38
Trinidad Fault	Canon Creek	Falor Fm	1	40^{o}	570	886	.88
Blue Lake Fault	Canon Creek	Falor Fm	1	40^{o}	755	1174	1.11
Blue Lake Fault	Korbel	Falor Fm	1	35^{o}	938	1631	1.64
McKinleyville Fault	Humboldt County Airport	Pat. Pt. Terrace	.85	25^{o}	32	75	.64
McKinleyville Fault	Mad River Fish Hatchery	Fluvial Terrace	.02	30^{o}	7	14	.70
McKinleyville Fault	Simpson Timber Co. Rd 4500	Falor Fm	1	35^{o}	300	523	.52
Mad River Fault	School Road McKinleyville	Pat. Pt. Terrace	.85	25^{o}	46	109	1.09
Mad River Fault	North Bank Road	Fluvial Terrace	.006	25^{o}	3	7.1	.71
Mad River Fault	Simpson Timber Co. Rd 5400	Falor Fm	1	35^{o}	330	575	.57
Fickle Hill Fault	Arcata	Older Marine Terrace	.2	25^{o}	31	73	.36
Fickle Hill Fault	Jacoby Creek	Falor Fm	1	25^{o}	350	828	.82
Mad River Fault Zone	Coastline	Pat. Pt. Terrace	.85	25^{o}	127	300	3.53
Mad River Fault Zone	Jacoby Creek-Korbel Section	Falor Fm	1	35^{o}	2305	4018	4.02

Table 2. Summary of displacement measurements and slip rates for faults in the MRFZ.

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