Late Neogene and Quaternary landscape evolution of the northern California Coast Ranges: Evidence for Mendocino triple junction tectonics

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ABSTRACT

A landscape records the surface response to tectonics at time scales intermediate between short time-scale information derived from seismic imaging and global positioning systems and the long-term geologic record. We link late Neogene and Quaternary deposits and landforms in the northern California Coast Ranges to the tectonics of the Mendocino triple junction. In the northern California Coast Ranges, the Mendocino crustal conveyor geodynamic model describes crustal thickening, thinning, and dynamic topography that produce a "double-humped" pattern of uplift that migrates northward with the Mendocino triple junction. The tectonics are manifest in the drainage system and elevation pattern of the Coast Ranges. At long wavelengths, the elevation pattern closely matches the predicted double-peaked shape of Mendocino crustal conveyor topography, and the high points of uplift control the location of drainage divides. Presently, the divide between the Russian and Eel Rivers and the divide between the Eel and Van Duzen Rivers approximately correspond to the peaks of uplift predicted by the Mendocino crustal conveyor model. As the triple junction migrates northward,

the double-humped pattern of uplift and subsidence migrates, and the Coast Ranges emerge. Smaller drainages develop and evolve by stream capture and flow reversal, and the two main divides migrate in concert with the triple junction. In contrast to the systematic development of the small streams, the largest trunk streams can maintain grade through regions of high uplift, and coastal river mouths remain stationary despite the uplift moving north. Before ca. 2 Ma, the majority of the Coast Range drainage flowed to a southern coastal outlet near the present mouth of the Russian River. At 2 Ma, facilitated by headwater stream capture at key locations, the drainage direction reversed, and the majority of Coast Range rivers now drain into the north-flowing Eel River. The major drainage reorganization at 2 Ma highlights the potential for complexity in geomorphic response to tectonics.

Keywords: northern California Coast Ranges, landform evolution, Mendocino triple junction, drainage evolution, geodynamics, tectonic geomorphology.

INTRODUCTION

An orogen and its landscape develop in direct response to underlying tectonic driving forces. As a result, the geomorphology and geology of a region record a tectonic history that contains information about deep-seated geodynamic processes. In this paper, we explore the links between the surface and tectonics in the northern California Coast Ranges (Fig. 1A) using our understanding of the lithospheric forces that have built the orogen, and recognizing the tectonic signal recorded by the landscape. We describe how the surface responds to tectonics in northern California, and we use the tectonic signal contained in the landscape to test and develop our understanding of the geodynamics.

A variety of mechanisms has been proposed to explain the timing of uplift of the northern California Coast Ranges. Dumitru (1989), using results of fission-track analyses, argued that primary uplift of the Coast Ranges occurred in association with Cretaceous subduction. Abundant late Neogene marine sediments that outcrop throughout the area indicate that while Cretaceous uplift may reflect a period of substantial exhumation, it cannot be responsible for the development of the present area of high elevation. Alternatively, uplift of the Coast Ranges could be driven by transpression along the developing San Andreas fault system, in a fashion similar to the Southern Alps of New Zealand (Walcott, 1998). However, at latitudes north of the San Francisco Bay, plate motion on the San Andreas fault system is almost entirely parallel to the trend of the fault (DeMets et al., 1990) (Fig. 1A).

Rather than transpression-driven or subduction-related uplift, the underlying cause for the formation of the Coast Ranges is more likely processes associated with the passage of the Mendocino triple junction (Zandt and Furlong, 1982; Furlong et al., 1989; Merritts and Bull, 1989). The Mendocino triple junction lies at the junction between the Pacific, North American, and Juan de Fuca (or Gorda) plates (Fig. 1A). The triple junction is migrating to the northwest

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GSA Bulletin; September/October 2006; v. 118; no. 9/10; p. 1232–1246; doi: 10.1130/B25885.1; 9 figures; 1 table.

at ~5 cm/yr (Sella et al., 2002). Zandt and Furlong (1982) proposed that the high elevations of the Coast Ranges could be a response to the influx of asthenosphere and resulting high temperatures in the "slab window" that forms in the wake of a triple junction. Since these initial studies, seismic images have shown that crustal thickness beneath the Coast Ranges varies spatially and reaches thicknesses of up to 40 km (Beaudoin et al., 1996, 1998; Villasenor et al., 1998; Verndonck and Zandt, 1994). Furlong and Govers (1999), in an attempt to explain the variable crustal structure, developed the Mendocino crustal conveyor (MCC) model (Fig. 1B). The MCC is built on a numerical geodynamic model in which uplift is driven by a combination of crustal thickening and dynamic topography, with a minor component of thermally driven uplift.

The purpose of this paper is to depict the landscape evolution of the northern California Coast Ranges by integrating the MCC geodynamic model with geomorphic and geologic data from the Coast Ranges. We review geologic and geomorphic data that provide evidence of paleocoastlines, drainages, and topography in the late Neogene Coast Ranges, then outline the salient points of the MCC geodynamic model. We test whether the MCC model predictions are reflected in the topography and geomorphic evolution of the Coast Ranges. First, the MCC model predicts that there is a double-peaked uplift in the Coast Ranges that follow in the wake of the triple junction. Second, streams should respond to the MCC predicted topography by lengthening longitudinally (in a N-NW-S-SE direction) in the wake of the triple junction. Third, E-W-trending stream divides in the Coast Ranges should migrate N-NW in the wake of the triple junction. Finally, the Coast Ranges should sequentially emerge with passage of the triple junction such that remnant marine sediments that outcrop in the now-emergent Coast Ranges young in age to the north. If the topography and geomorphic evolution is inconsistent with the MCC model and more consistent with Coast-Range-axis-normal convergence, then there will be no northward-younging age progression to drainage development or Coast Ranges emergence and no evidence for N-NW stream lengthening or the migration of E-Wtrending stream divides.

The discussion integrates the geologic and geomorphic attributes of the Coast Ranges with our understanding of the tectonics to depict the landscape evolution of the northern California Coast Range. By making the link between the surface and tectonics, we achieve two goals. One, we can use the paleogeomorphology inferred from the preserved geologic deposits



Figure 1. (A) Location map of the northern Coast Ranges of California showing the Mendocino triple junction (MTJ), which marks the intersection of the Pacific, North America, and Gorda (or Juan de Fuca) plates. The triple junction has been migrating to the northwest at a steady rate for the last 8 m.y. Line A–B delineates the location of the two-dimensional Mendocino crustal conveyor (MCC) model (Furlong and Govers, 1999), which predicts a pattern of uplift of the northern California Coast Ranges. (B) Schematic cross section showing the main geodynamic processes in the MCC model along line A–B in part A. Deformation occurs as hot asthenosphere fills the gap left by the migrating Gorda plate, causing viscous coupling between the Gorda slab and the base of the North American crust. As the Gorda plate moves to the north, the North American plate thickens, then thins, driving isostatic uplift. Flow in the mantle causes dynamic topography that adds to the uplift and subsidence. and landforms to constrain and extend our knowledge of the Mendocino triple junction geodynamic processes. Two, our analysis provides an integrated explanation of the complex drainage, sedimentation, and topographic pattern of the northern California Coast Ranges.

GEOLOGIC CONSTRAINTS ON NORTHERN COAST RANGES EVOLUTION

The late Neogene and Quaternary history of the northern Coast Ranges, recorded by remnants of Miocene and younger sediments that overlie the Mesozoic Franciscan complex, is largely one of rock uplift and erosion (Irwin, 1960; Bailey et al., 1964; Wahrhaftig and Birman, 1965). Cover sediment that survives as isolated remnants (Table 1) partially chronicles this uplift and erosion history (Fig. 2). The mostly metasedimentary Franciscan rocks were accreted to the North American continent as parts of subduction zone complexes and subsequently translated northwestward to their present latitudinal position (Blake et al., 1985). With the possible exception of the King Range terrane (McLaughlin et al., 1982; Fig. 2), the Franciscan rocks in northern California were all in place by 10 Ma. A portion of the overlying cover sediments was deposited when the triple junction was located to the south of the present Coast Ranges (Fig. 1A); these sediments are largely marine and older than 5 Ma. The rest of the cover sediment, and the volcanic rocks, record the passage of the triple junction.

The present Coast Ranges drainage is characterized by N-NW-trending trunk streams linked by E-W-trending streams (Fig. 2). Two major river systems drain the Coast Ranges between San Francisco and Humboldt Bay: the Eel River and the Russian River. Streams of the Eel River drainage are mainly north-flowing and drain into the Pacific Ocean north of Cape Mendocino (Fig. 2). The majority of streams in the Russian River system flow south to an outlet at latitude 39.3°N (Fig. 2). At present, the Eel River drains an area approximately three times that of the Russian River. However, using the late Neogene Coast Ranges cover sediments, we show that the Russian River drained a far greater area of the northern California Coast Ranges in the late Neogene and early Quaternary.

Geologic Constraints on Paleodrainage

The most significant late Neogene Coast Ranges cover sediment sequences that record paleodrainage are deposits associated with the paleo-Russian River and deposits associated with the emergence of the Eel River Basin.

Deposits and Landforms of the Paleo-Russian River

The once-extensive Russian River gravel, which extends 110 km upvalley from Wilson Grove to north of Ukiah (Fig. 3), records a paleo-Russian River larger in size than its modern namesake. The river at one time extended as far north as the Little Lake Valley, which presently drains to the north into the Eel River basin. Remnants of alluvial fill, deposited by a onceextensive paleo-Russian River, are exposed discontinuously from the northwestern margin of the Santa Rosa Basin northward through the Alexander Valley (Glen Ellen Formation of Weaver, 1949, and Fox, 1983) to the Hopland, Ukiah, and Redwood valleys ("continental" deposits of Cardwell [1965]) (Table 1). We depict deposits in the Alexander Valley as the Glen Ellen gravel and deposits in the Hopland, Ukiah, and Redwood valleys as the Russian River gravel (Figs. 2 and 3). The modern Russian River flows through the Alexander, Hopland, Ukiah, and Redwood valleys.

Based on records of dozens of well logs, deposits of the paleo-Russian River are tens to hundreds of meters thick. In northwesternmost Santa Rosa Basin and in the valleys of the Russian River, gravel deposits are over 500 m thick (California Department of Water Resources, 1956; Cardwell, 1965). In an exploration borehole for a dam site near Ukiah, the gravel is 450 m thick (Treasher, 1955).

Valley fill deposits of Little Lake Valley, 3 km north of the northern extent of the Russian River gravel, are also part of the paleo-Russian River drainage. Pleistocene Little Lake Valley deposits, which are 30 m to at least 140 m thick (Cardwell, 1965), presently are within the Eel River drainage and are separated from the Russian River gravel by a low divide (Figs. 2 and 3). However, all paleoflow indicators in the Pleistocene deposits are to the south, opposite in flow direction to the modern surface drainage in the valley (Woolace, 2005). Little Lake Valley fill deposits are similar to the Russian River gravels in that they are fine to coarse fluvial sediment deposited as part of a through-going fluvial system, in contrast to the geographically confined, single-drainage-outlet valley that characterizes the modern Little Lake Valley (Woolace, 2005). Therefore, the paleo-Russian River drainage extended farther to the north than its modern counterpart.

Limited age data indicate that fluvial sediment of the paleo-Russian River gravel as a whole may be time transgressive with younger deposits to the north (Fig. 3). In the south, the gravel is likely late Pliocene based on its interfingering relationship with the marine strata of the Wilson Grove Formation, which contains late Pliocene "Merced" fauna (Travis, 1952), and based on its interfingering relationship with Sonoma volcanic rocks (2.6–7.9 Ma) (Gealey, 1950; Travis, 1952; Fox et al., 1985). In the north, the gravel in Little Lake Valley contains the ca. 0.6 Ma Rockland and the 0.7 Ma Thermal Canyon tephra (Meyer et al., 1991; Lanphere et al., 1999; Woolace, 2005).

The geomorphic setting of the Russian River gravel is consistent with a late Pliocene and Pleistocene age. The gravel is young enough such that most of the paleoriver valley in which it was deposited still exists as the modern Russian River valley, but the gravel is old enough to be cut by faults and has a regional dip of 5° to 7° north (Treasher, 1955; Cardwell, 1965). Its original depositional morphology has been destroyed by erosion and drainage divide migration, and late Pleistocene fluvial terraces are cut into the gravel.

Humboldt Basin Shallow-Marine and Fluvial Sediment

The first appearance of the fluvial Hookton Formation (Ogle, 1953) signals the emergence of the lower Eel River drainage basin in response to rock uplift ("Humboldt basin fluvial," Fig. 2). The Hookton Formation lies unconformably above a deformed late Neogene marine Humboldt basin section ("Humboldt basin marine," Fig. 2) (Ogle, 1953; Woodward-Clyde Associates, 1980) (Table 1). These fluvial deposits chronicle erosion from the Eel River drainage. As the Bruhnes-Matayama boundary (780,000 yr B.P.) is near the top of the marine Eel River group but not within the overlying Eel River alluvium (Woodward-Clyde Associates, 1980), initial deposition of alluvium at the modern coastline began shortly after 0.8 Ma. Strata of the Humboldt Basin are time transgressive and have equivalent facies that are progressively older to the east (Woodward-Clyde Associates, 1980); therefore, the base of the fluvial section would be older eastward up the Eel River valley. Earliest fluvial deposits in the Eel Basin, although now eroded, probably date from ca. 2.0 Ma. Shallowing and emergence of the Humboldt Basin at ca. 2 Ma is consistent with a late Neogene and Quaternary geohistory analysis of the basin (McCrory, 1989), which indicates rapid emergence of the basin ca. 2.5 Ma.

Uplift Rates Derived from Ohlson Ranch and Fort Bragg Marine Terrace Deposits

Cover sediments between the Russian River mouth and Fort Bragg (Fig. 2) provide broad constraints on coastal uplift rates over time scales of hundreds of thousands to a few million years. The Ohlson Ranch Formation (Fig. 2; Table 1) is

Unit or formation name	Environment	Comments	Age	References
Robinson Creek	Marine	Oyster-bearing conglomerate	Probable Miocene age	Orchard (1979)
Temblor Formation: deposits near Covelo	Fluvial and marine	Marine and estuarine clay and silt interbedded with fluvial gravel, sand, and coal	Miocene	Clark (1940), Kelsey and Carver (1988)
Deposits of the Garberville area	Marine	Fossiliferous sand and silt	Late early Miocene to Pliocene (based on mollusks and diatoms)	MacGinitie (1943), Menack (1986), Kelsey and Carver (1988)
Scattered deposits, Van Duzen and northern Eel River Basin	Marine	Fossiliferous sand and silt	Pliocene	Irwin (1960), Wahrhaftig and Birman (1965), Kelsey (1977)
Humboldt (Eel River) Basin sediment	Marine estuarine and fluvial	Marine strata unconformably overtain by Pleistocene fluvial and estuarine sediment	Miocene Pliocene and Pleistocene	Ogle (1953), Woodward-Clyde Associates (1980), McCrory (1989)
Wilson Grove Formation	Fluvial and marine	Sediment is preserved on broad, flat-topped interfluves south of the Russian River and on the west side of the Santa Rosa valley. The ca. 6 Ma Roblar tuff (Fig. 3) is interbedded within the marine section. Marine sediment interfingers eastward with fluvial and volcanic (Sonoma volcanic, 2.6–7.9 Ma) deposits. At their eastern margin, these deposits record a long-lived (late Miocene to late Pliocene) marine to nonmarine transition.	Miocene and Pliocene	Johnson (1934), Gealey (1950), Travis (1952), Mankinen (1972), Bartow et al. (1973), Sarna-Wojcicki (1976), Fox (1983), Fox et al. (1985), Sarna- Wojcicki (1992)
Glen Ellen Formation; Russian River and Little Lake Valley sediments	Fluvial and lacustrine	Remnants of a once-extensive alluvial fill that outcrops discontinuously from the northwestern margin of the Santa Rosa Basin northward to the Little Lake Valley (Willits)	Pliocene and Pleistocene	Weaver (1949), Gealey (1950), Travis (1952), Treasher (1955), California Department of Water Resources (1956), Cardwell (1955), Fox (1983)
Ohlson Ranch Formation	Marine	Beach and nearshore deposit, primarily fine sand; mantles a wave-cut platform, 250–470 m above sea level. A fission-track age on an interbedded tuff is 3.3 \pm 0.8 Ma.	Ca. 3.5–1.7 Ma, based on invertebrate marine fossils	Higgins (1960), Peck (1960), Prentice (1989)
Deposits of Little Sulfur Creek	Fluvial	Fluvial sediments deposited within an actively deepening and extending basin along the propagating Maacama fault zone.	Inferred to be 4.0 Ma or younger	McLaughlin and Nilsen (1982)
Cache Formation	Fluvial	Fluvial deposits with rare occurrences of quiet water deposits; ~4000 m thick. Minimum age constrained by overlying 1.66 \pm 0.10 Ma Clear Lake volcanics.	1.8–3.0 Ma, based on fossil mammal remains	Brice (1953), Donnelly-Nolan et al. (1981), Rymer (1981), Rymer et al. (1988)
Navarro River and Anderson Valley deposits	Fluvial	Sand and gravel with interbedded lacustrine clay, over 70 m thick in places, crops out at elevations of 90–190 m elevation along $\sim\!12$ km of Navarro and Anderson Valleys.	Coeval with the Fort Bragg marine terrace deposits to the west	California Department of Water Resources (1956), Jennings and Strand (1960)
Fort Bragg area marine terrace deposits	Marine	Beach and nearshore deposits, as much as 15 m thick (California Department of Water Resources, 1956).	Pleistocene	Wahrhaftig and Birman (1965), Kennedy (1978), Kennedy and Lajoie (1982), Merritts and Bull (1989)
Kettenpom gravel	Fluvial	Three ~30-m-thick fill terrace sequences that step up from the North Fork Eel River to the divide with the Van Duzen River.	Pleistocene	Koehler (1999)

a fine sandy beach and nearshore marine deposit that mantles one or several elevationally closely spaced wave-cut platforms (Higgins, 1960). The eastern margin of this deposit is bounded by a paleo-sea cliff. The underlying composite platform is tilted and faulted with a structural relief of ~200 m. The Ohlson Ranch deposits are part of an uplifted wave-cut platform and paleo-sea cliff landscape that developed on a late Pliocene coast. We infer a rock uplift rate of 0.08–0.2 m/ k.y. using the current elevation of the deposit (250–470 m) and assuming a shoreline age of the highest Ohlson Ranch beach of ca. 3 Ma (Table 1; Peck, 1960; Higgins, 1960; Prentice, 1989). The ca. 3 Ma age for the Ohlson Ranch Formation is based mainly on a fission-track



Figure 2. Map depicting all postsubduction accretion cover sediment in the Coast Ranges on the North American plate east of the San Andreas fault in the area drained by the Russian and Eel Rivers and by intervening coastal streams (see compiled references, Table 1). Boundaries of cover sediment are smoothed and consolidated in cases where actual cover sediment is patchy due to erosion. CM—Cape Mendocino.

age on zircons separated from a tephra within the deposit (Prentice, 1989) rather than on fossils (Higgins, 1960).

Extending along 60 km of the northern California coast near Fort Bragg (Fig. 2), beach and nearshore marine deposits as much as 15 m thick (California Department of Water Resources, 1956) are preserved on interfluves as four to six marine terraces. The terraces are up to 8 km wide and range in elevation from 12 to 240 m (Wahrhaftig and Birman, 1965; Merritts et al., 1991). In this area, we infer a rock uplift rate around 0.1-0.4 m/k.y. using the lowest three marine terraces, which were formed during oxygen isotope stage 5 highstands (~125-75 ka) (Kennedy, 1978; Kennedy and Lajoie, 1982; Merritts and Bull, 1989; Merritts et al., 1991), and the California sea-level curve (Muhs et al., 1992).

Coastal Drainage Outlet Positions

At least since the late Miocene, the time span over which remnant cover sediment is preserved, there have been only two coastal outlets for rivers draining the interior of the northern California Coast Ranges: a southern outlet near the modern Russian River mouth and a northern outlet in the vicinity of the Humboldt Basin (Fig. 3). The Delgada fan (Fig. 2), now displaced to the north along the San Andreas fault, was at the latitude of the Wilson Grove Formation at 5-6 Ma (Sarna-Wojcicki, 1992). The Delgada fan grew rapidly between 6 and 2 Ma (Drake et al., 1989). Sandy facies in the Wilson Grove Formation have been interpreted as turbidite flows feeding into the fan (Allen and Holland, 1999). Thus, the marine and fluvial Wilson Grove Formation and the Delgada fan may have been deposited synchronously and so may record the paleo-Russian River mouth as a long-lasting marine-nonmarine transition between 2 and 6 Ma. Sediments in the Delgada fan (Fig. 2) indicate rapid fan growth starting at ca. 6 Ma (Drake et al., 1989), which is when we infer the paleo-Russian River began to deliver sediment from the interior Coast Ranges through the southern outlet (Fig. 3).

The interior location of the marine Wilson Grove Formation (Fig. 2) means the modern Russian River mouth is located 20–25 km west of the paleomouth. Higgins (1952) argued that the Russian River mouth migrated westward as the Wilson Grove Formation became emergent in the last 2 m.y. and the river incised a canyon across the emerging coastal plain. Therefore in the interval ca. 6–2 Ma, paleo-Russian River–derived sediment must have been transported across a 20–25-km-wide shelf, which was a low-lying coastal plain at times of lower



Figure 3. Latitude-time distribution of Neogene cover sediments and location of the Mendocino triple junction (MTJ). Fluvial-marine transitions record a northward-progressing emergence of the northern California Coast Ranges in concert with the northward migration of the Mendocino triple junction.

relative sea level, to the site of the Delgada fan. The permanent emergence of the shelf at 2 Ma promoted incision of the lower Russian River canyon. Using the current elevation, we estimate uplift rates that accompanied canyon incision to be on the order of 0.1-0.4 m/k.y., similar to the uplift rate over the last 125 k.y. for the Fort Bragg marine terraces ~100 km to the north.

Alluvial fill of the Cache Formation (Figs. 2 and 3; Table 1) represents another outlet to the south that drained the interior of the Coast Ranges in the late Neogene. The Cache Formation outlet probably drained southeastward to the Central Valley of California rather than to the coast.

The Humboldt Basin (Fig. 2) is the northern drainage outlet for the interior of the Coast Ranges. While the basin has been a marine depocenter since the Miocene, on the basis of alluvial sediment at the top of the Humboldt Basin, it has been the down-valley end of a large interior drainage only since ca. 2 Ma.

Timing and Pattern of Coast Ranges Emergence

Defined by the age and location of the marine and fluvial sediments described in the previous sections, the submerged western part of what is now the Coast Ranges emerged in the late Neogene. Emergence started in the south and progressed northward. We delineate the approximate position of the Miocene (ca. 10 Ma) shoreline (bold shaded line, Fig. 2) as that N-NW-trending boundary east of which there is no evidence of late Neogene marine rocks. West of this line, remnant marine cover sediment indicates that the Coast Ranges were submerged until emergence began as the triple junction migrated northward (Fig. 3).

The age and position of marine cover strata argue for a time-transgressive, younging-to-thenorth emergence of the Coast Ranges. South of 39.75°N, marine sediment remnants in the nowemerged Coast Ranges (Temblor Formation and Robinson Creek; Figs. 2 and 3; Table 1) are Miocene in age. North of 39.75°N, marine cover remnants in the now-emerged Coast Ranges are Pliocene (Garberville and other scattered marine remnants) or as young as early Pleistocene in the case of the most northerly sediments in the Humboldt Basin (Figs. 2 and 3; Table 1).

Another indication of northward time-transgressive emergence is that at ca. 3 Ma, the coastline in the south was already situated where it is today, whereas the coastline in the north had not yet started to retreat westward. The paleo-sea cliff for the ca. 3.0 Ma Ohlson Ranch Formation shoreline is only 8 km east of the modern coast at latitude 38.5°N to 38.7°N (Fig. 2), whereas in the latitude range 40.1°N to 40.6°N, the ca. 3.0 Ma paleoshoreline for the Garberville and other Pliocene marine sediments is at least 60 km east of the modern coast (Fig. 2).

The onset of fluvial deposition at the mouth of the northern Eel River outlet, recorded by the emergence of the Humboldt marine basin at ca. 2 Ma (Ogle, 1953; Woodward-Clyde Associates, 1980; McCrory, 1989), marks the

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uplift and westward movement of the northern part of the coastline to reach its present location (Fig. 2).

Evidence of Drainage Reorganization

Geomorphic indicators of stream capture and drainage reversal in the Coast Ranges are consistent with a decrease in the volume of sediment discharged from the southern outlet at the same time as an increase in fluvial sediment discharge at the northern outlet. Two topographic attributes of the predominantly north-flowing modern Coast Ranges drainage network, fishhooked streams (streams that initially flow south before turning 180° to drain to the north) and wind gaps, are indications that the paleodrainage network flowed primarily to the south. The upper reaches of the North Fork Eel River, the Middle Fork Eel River, and the main Eel River all flow south before turning to flow to the north (Fig. 4); in each of the three cases, the bends in the streams (fishhooks) are trunk stream valleys that flow E-W (henceforth called cross-streams) in a trend cutting across the N-NW structural grain (Fig. 4).

The headwaters of several major tributaries in the Eel River Basin initiate in wind gaps (Fairbridge, 1968), that is, low divides that were formerly occupied by a water course (located by triangles in Fig. 4). The wind gaps are between N-NW-trending trunk valleys containing streams that flow in opposite directions (south-flowing to the south of the gap and north-flowing to the



Figure 4. Prominent wind gaps (triangles) and fishhooked rivers (shaded curved arrows) in the northern California Coast Ranges. The two main drainage divides (dashed shaded lines) are located at the peaks of Mendocino crustal conveyor (MCC) uplift. The E-W-trending sections of rivers are what we refer to as cross streams. CM—Cape Mendocino.

north of the gap). The wind gaps may connect a formerly through-going trunk valley that contained a through-flowing stream. For instance, the Kettenpom gravel (Figs. 2 and 3; Table 1) is evidence that the North Fork Eel River and the headwater reach of the current Van Duzen River were once a joined, through-flowing drainage. The Kettenpom gravel can be traced northward toward the Hettenshaw wind gap (Fig. 4), which drained headwater streams southward into the North Fork of the Eel River prior to abandonment of the gap as a result of headwater capture by the north-flowing Van Duzen River (Koehler, 1999). Presently, recapture is imminent at several of the low divides depicted in Figure 4, notably Railroad and Potter Valley, where south-flowing headwater streams will capture and redivert north-flowing headwater reaches. As explained next, a pattern of capture and recapture at wind gaps is a consequence of drainage adjustment to the Mendocino crustal conveyor.

MENDOCINO TRIPLE JUNCTION TECTONICS AND THE MENDOCINO CRUSTAL CONVEYOR

The Mendocino triple junction marks a fundamental change in tectonic regime along western North America from the subduction zone of the Cascadia margin north of the triple junction to the transform zone between the Pacific and North American plates south of the triple junction (Dickinson and Snyder, 1979; Zandt and Furlong, 1982; Furlong et al., 1989). A variety of seismic studies (Verdonck and Zandt, 1994; Beaudoin et al., 1996, 1998; Henstock et al., 1997) has shown that crustal structure varies substantially throughout northern California. Crustal thicknesses double from the initial ~20 km in the accretionary margin of northern California and reach maximum thicknesses exceeding 40 km near the southern edge of the subducting Gorda plate (Beaudoin et al., 1996, 1998; Villasenor et al., 1999). Because the spatially varying crustal thickness is attributed to triple junction tectonics, triple junction migration has driven an ephemeral thickening of the North American crust along coastal California (Furlong and Govers, 1999).

Based on a finite-element numerical model, Furlong and Govers (1999) proposed that the observed thickness variation of the North American crust is a consequence of the migration of the Mendocino triple junction. In the model, crustal thickening occurs by viscously coupling the southern edge of the Gorda slab to the base of the overlying North American crust (Fig. 1B). Coupling the overlying North American crust to the migrating Gorda slab causes the North American crust above the triple junction to be pulled into itself to the north, causing thickening, and stretched away to the south, causing crustal thinning. The geodynamic processes described by the Mendocino crustal conveyor (MCC) model are predicted to thicken the North American crust in advance of the triple junction and subsequently thin the crust in the wake of the Mendocino triple junction (Furlong and Govers, 1999; Furlong and Guzofski, 2000; Furlong and Schwartz, 2004). The model predicts that the crust should be thickened and then thinned back to its original thickness over ~10 m.y. as the triple junction passes (Fig. 1B). Such substantial changes in crustal thickness will cause isostatic uplift, and thus MCC-described processes can drive the northward progressing uplift and emergence of the northern Coast Ranges recorded in the cover sediments.

Mendocino Crustal Conveyor Model Uplift Rates

The MCC model describes rock uplift that is driven by two mechanisms: the isostatic response to crustal thickening and a dynamic response to mantle flow. The model predicts that crustal thickening rates of \sim 3–5 mm/yr in advance of the triple junction will double the thickness of the crust over just 5 m.y. (Furlong and Govers, 1999; Fig. 5). For typical crustal and upper-mantle densities, 3–5 mm/yr crustal thickening equates to isostatic uplift rates of \sim 0.5–1 mm/yr, with similar subsidence rates as the crust thins. Actual uplift rates will depend on whether local isostasy or flexure is the dominant response to crustal thickening and thinning. The details of the crustal thickening and thinning rates are secondarily dependent on the initial crustal thickness and whether the crustal deformation is uniform throughout the thickness of the crust or is localized at certain depths.

Although in the MCC model uplift is mostly the response to crustal thickening (Fig. 5A), the model predicts an additional component of uplift from dynamic topography (Fig. 5B). Dynamic topography is a consequence of the migrating geodynamic processes. Two modes of dynamic topography exist in the MCC model. First, subhorizontal flow induced in the slab window by migration of the Gorda plate produces a "low pressure" in the slab window that results in a downward flexure of the overlying crust (Fig. 5B). The model predicts flexure with an amplitude of up to 2 km and a wavelength of ~100 km centered on the southern edge of the slab. The second component of dynamic topography occurs ~100-150 km south of the model slab edge, where asthenospheric mantle flows into the slab window, producing surface uplift. In the model, the domal uplift caused by the upwelling mantle flow is up to 1 km in magnitude and has a 100+ km wavelength (Fig. 5B). The two components of dynamic topography combine with the isostatic uplift to produce the total predicted uplift (Fig. 5C). The downward flexure is located near the region of thickest crust, reducing the net uplift, while the positive buoyancy force causes uplift and delays the subsidence produced by crustal thinning. When the dynamic topography is superimposed on the broad domal uplift generated by crustal thickening and thinning, the model result is a "double-humped" surface pattern (Fig. 5C; Furlong and Govers, 1999). The "double-humped" pattern migrates with the triple junction, driving uplift and subsidence rates up to ~1.5 mm/yr (Fig. 5D).

Spatial Extent of the MCC Model

As a two-dimensional model, the MCC model describes processes and predicts uplift along a line that trends NW-SE in the direction of plate motion (Fig. 1A). The model does not place limits on the aerial extent of the predicted uplift. However, because the primary effect of MCC processes is to thicken and thin the crust, we use the crustal thickness in the Coast Ranges to place limits on the lateral extent of the region affected by MCC modeled processes. Seismic imaging, both active source (e.g., Beaudoin et al., 1998; Henstock et al., 1997) and local crustal tomography (e.g., Villasenor et al., 1998; Fig. 6) provide useful constraints on the pattern and magnitude of crustal thickness variation beneath the northern Coast Ranges. The tomography (Fig. 6) shows a relatively complex pattern of crustal thickness with two main areas of thickened crust. The thickest crust lies beneath



Figure 5. The combination of isostatic uplift (A) and dynamic topography (B) results in a double-humped pattern of uplift (shown at 1 Ma and present) (C), which migrates to the northwest at a rate of ~40–50 mm/yr driving rock uplift and subsidence rates up to 2 mm/yr (D). The peaks in the pattern of uplift correspond closely to the location of the two major divides in the Coast Ranges depicted in Figure 4. MTJ—Mendocino triple junction.





Figure 6. Tomography in the northern California Coast Ranges (from Villasenor et al., 1998) at a depth of 25 km and NW-SE-oriented cross sections. The tomography data image the high-velocity bodies of the subducting Gorda plate in the north and the Pioneer fragment farther south. These features are moving to the northwest, causing crustal thickening of the overlying North American crust. MCC—Mendocino crustal conveyor.

the center of the northern Coast Ranges, and a more subdued region of thick crust lies beneath the Mendocino Range (Figs. 6 and 7). MCC modeled processes can explain the thickened crust beneath the central Coast Ranges, which shows that the spatial extent of effects of the migrating slab window extend from the Russian River-Eel River corridor to just less than 100 km to the east. The high elevation in this area is the isostatic response to the thickened crust. In the N-S direction, MCC-driven crustal thickening begins ~150 km north of the triple junction (Figs. 5A and 6). The effects of the MCC model extend south to the latitude of Clear Lake. In total, processes described in the MCC model modify an ~4000 km² area of the northern California Coast Ranges.

Although the processes modeled by the MCC explain much of the uplift and emergence of the Coast Range, they cannot be used to explain uplift of the Mendocino Range west of the present Russian River valley nor can they explain uplift of the King Range (Fig. 7). Rapid uplift of the King Range terrane recorded by marine terraces (Merritts and Bull, 1989) is a localized uplift driven by the transport of this terrane onto the western margin of North America (McLaughlin et al., 1982). The crustal structure beneath the King Range is not anomalously thick, and MCC-predicted isostatic uplift and dynamic topography do not extend this far west (Fig. 6).

The tomography illuminates an area of thickened crust beneath the Mendocino Range that is spatially correlated with a high-velocity body just north of the Mendocino Range (Figs. 6 and 7). This area of thickened crust cannot be driven by processes related to the slab window left by the Gorda slab, because the thickened crust is located too far south of the Mendocino triple junction. We consider the high-velocity body north of the thickened crust to be the "Pioneer fragment," and we infer that the Mendocino Range uplift is driven by the fragment's migration. The Pioneer fragment represents a remaining bit of the Farallon plate. In the early stages of the development of Mendocino triple junction, the triple junction was located at the



Figure 7. Map of northern California Coast Ranges showing hypothesized zones of uplift in response to different tectonic drivers. Uplift of the Central Range is driven by the migration of the southern edge of the Gorda slab. Uplift of the Mendocino Range occurs in response to the migration of the Pioneer fragment. King Range uplift is due to docking of a crustal fragment (McLaughlin et al., 1982) and not due to the Mendocino triple junction (MTJ) migration. MCC—Mendocino crustal conveyor.

intersection of the Pioneer fracture zone and the North American margin (Atwater, 1970). A short ridge segment linked the Pioneer and Mendocino transform faults/fracture zones. As the ridge segment approached the margin, spreading ceased, and the triple junction jumped to its present position at the end of the Mendocino fracture zone (Atwater and Stock, 1998). The abrupt jump of the triple junction likely led to the abandonment of a small subducted fragment (the Pioneer fragment) that was attached to the Pacific plate along the extinct ridge segment.

The subducted Pioneer fragment has been translating beneath the margin of North America since its capture by the Pacific plate at ca. 25 Ma. The fragment, which would cause crustal thick-ening and dynamic topography similar to the migrating edge of the subducted Gorda slab, is presently located in the vicinity of the coastal bight slightly north of Fort Bragg. There is an associated crustal thickening and thinning in the fragment's wake, albeit of reduced magnitude (maximum crustal thickness of 30–35 km compared with 40 km in the Coast Ranges) (Fig. 6).

DISCUSSION: INTEGRATING CRUSTAL DYNAMICS AND SURFACE PROCESSES

Evolution of Coast Ranges Morphology

In an active orogen, crustal thickness is the result of tectonically driven crustal thickening and thinning, modified by erosion or other surface processes that redistribute crustal mass. A weakness of geodynamic models such as the MCC is that they do not typically include the effects of erosion or any other modification of the crust by surface processes. Without incorporating surface processes, the prediction of crustal thickness from a geodynamic model should have misfits with the observed crustal thickness and isostatic topography. In order to compare MCC predictions to the elevations observed in the Coast Ranges and to place robust constraints on the geodynamic model, we use the crustal structure imaged by seismic tomography (Fig. 6). Assuming typical crust and mantle densities, isostatic elevation is calculated from tomography-derived crustal thickness along the transect of the MCC model (Fig. 8A). If the height of the Coast Ranges is controlled solely by the isostatic response to crustal thickness, the observed elevations should more or less mimic the calculated isostatic pattern. Making the comparison between the observed and isostatic elevations, there is a reasonable match in the overall wavelength, but the observed elevations are significantly less than those obtained assuming local isostasy (Fig. 8A). If we instead

assume that flexure is the response to crustal loading, the result is even higher elevations, and such overestimation shows that isostasy is a more dominant control on elevation than flexure. Thus, the crust in northern California has a relatively small effective elastic thickness, in agreement with the small effective elastic thickness found by McNutt (1983).

The substantial differences between the calculated isostatic and actual elevation (Fig. 8A) mean there must be forces in addition to isostasy controlling elevations. The misfit between the isostatic elevation and actual elevation has a shape, wavelength, and magnitude comparable to the dynamic topography force predicted by the MCC model, suggesting that dynamic topography is the missing force needed to explain the height of the Coast Ranges. Adding the MCC-predicted dynamic topography (Fig. 8B) to the isostatic elevation calculated from the observed crustal structure (Fig. 8A) produces a pattern that has a shape, wavelength, and magnitude comparable to Coast Ranges elevation (Fig. 8C). The good fit between the sum of the isostatic and dynamic elevations and the observed elevations in Figure 8C provides support for the MCC model-determined viscosity in the slab window and the 5-10 km effective elastic thickness of the North American crust (Furlong and Govers, 1999).

If the MCC does indeed explain the mechanism driving crustal thickening and uplift of the northern Coast Ranges, the amount of exhumation in the Coast Ranges is the difference between MCC-predicted uplift (i.e., using the MCC model-predicted uplift, not the isostatic uplift derived using the seismically imaged crustal thickness) and the observed elevations. This difference between predicted uplift and observed elevations reaches a maximum of ~2 km, consistent with Cretaceous (i.e., unreset) apatite fission-track apparent ages of Dumitru (1989), which indicates less than ~4–5 km of erosion.

Although we cannot make a quantitative comparison of MCC-predicted uplift rates with uplift rates based on geomorphic constraints, there is agreement between the northward progressing emergence of the Coast Ranges and the northward migration of the Mendocino triple junction. MCC uplift begins ~150 km in advance of the triple junction and northwardprogressing emergence of the Coast Ranges moves with the northward-migrating Mendocino triple junction. Currently, uplift driven by triple junction tectonics is responsible for the continued emergence of Humboldt Bay. We interpret the emergence of the fold-and-thrust belt near Humboldt Bay (McCrory, 2000) to be the onset of the predicted NW-SE-directed MCC-driven crustal shortening.



Figure 8. (A) Isostatic elevation calculated from crustal structure derived from seismic tomography and maximum observed elevations taken along a 50-km-wide swath trending N24W. If the Coast Ranges were purely isostatically compensated, the observed elevations would match the isostatic elevation. (B) Dynamic topography as predicted by the Mendocino crustal conveyor (MCC) model. (C) The solid black line shows the superposition of MCC-predicted dynamic topography and the isostatic elevation. X1, X2, and X3 mark the locations of E-W-trending cross streams. X1 is the cross stream of the North Fork Eel River, X2, the South Fork Eel River, and X3, the main Eel River headwaters. The triangles mark the two main drainage divides that approximately correspond to the peaks of the MCC-predicted uplift. (D) Difference between the MCC-predicted elevation and the actual elevation; the difference between these two lines is the amount of exhumation. MTJ—Mendocino triple junction.

The two geodynamic processes that drive uplift, isostatic uplift and dynamic topography, combine to produce the predicted doublehumped elevation pattern in the Coast Ranges. The location and separation of the two major drainage divides-between the Eel and the Russian Rivers in the south and the Eel and Van Duzen Rivers to the north (Fig. 2)-correspond to the MCC-predicted double hump (Figs. 5C and 8D). Evidence for stream capture and flow reversal provides additional support that the location of the drainage divides represents the migrating peaks of uplift. For example, at the southern divide, which separates the Russian River and Eel River, recapture of several northflowing headwaters of the Eel River by the south-flowing headwaters of the Russian River is imminent at the Railroad and Potter Valley low divides (Fig. 4). At the northern divide at the Hettenshaw gap, capture occurred relatively recently (within the past million years), and recapture is imminent (Koehler, 1999). If the drainage divides migrate in concert with the triple junction, as their current location implies, migration rates are on the order of 40 mm/yr. We infer that tectonically imposed gradients that lead to flow reversal within established valleys (other than the major trunk streams) and leave the observed wind gaps. Although the drainage divides delineated by smaller streams migrate with the triple junction, the highest-order, major trunk stream of the Eel River has sufficient stream power to cut through the northern peak of uplift. But the same northern peak of uplift marks the transition between the two lowerorder rivers, the upper reaches of the northflowing Van Duzen River, and the south-flowing smaller upper reaches of the Eel River.

Evolution of Coast Ranges Drainage

In most convergent orogenic belts that share the same long linear shape of the Coast Ranges, streams flow predominantly perpendicular to the axis of the orogen, as in the Coast Ranges of Oregon or the Southern Alps of New Zealand (Kelsey et al., 1994; Hovius, 1996; Burbank and Anderson, 2000). In contrast, major Coast Ranges rivers trend NW-SE, parallel to the trend of the orogen (Figs. 2 and 4), a drainage trend that suggests the Coast Ranges landscape is driven by more than simple convergence. The NW-SW-trending rivers include many shorter reach streams and are separated by low divides that are oriented NW-SW, perpendicular to the trend of the mountain belt (Fig. 1).

Our interpretation of drainage evolution in the Coast Ranges integrates geological and geomorphic constraints with geodynamic predictions of the MCC model. In general, a drainage pattern should mimic elevation change with flow from high elevation to low elevation. If rivers followed this pattern over an MCC double-hump shape (Fig. 5), streams flow down the topographic gradient and migrate along with the triple junction. In advance of the triple junction, the development of a northwest topographic gradient would form northwesterly flowing streams. Between the two uplift peaks, overall flow would be internal with both northwest and southeast flow directions. After passage of the second peak, rivers would flow to the southeast. This pattern of stream flow is seen in the smaller, lower-order streams in the Coast Ranges and in the capture and recapture scenarios at wind gaps, but not in the highest-order trunk streams of the Eel River (Fig. 4). The drainage areas of the trunk streams where they cut through the uplift highs are ~2800 km² (South Fork Eel River), and ~6800 km² (main fork Eel River). It seems that while larger reaches of the trunk streams continue to downcut with increasing uplift, smaller upper reaches with smaller drainage areas are unable to keep pace with uplift. Smaller streams cannot modify their slope and erode as fast as the changing uplift and instead are passively draped on the local topographic gradient created by the tectonics. The history of the drainage divide between the Van Duzen and the North Fork of the Eel River, the Hettenshaw drainage divide (Fig. 4), exemplifies the systematic migration of drainage divides in lower-order drainage as the triple junction translates to the north.

In contrast to the evolving drainage pattern in lower-order streams, the long-lived relative stability of the paleo–Russian River outlet causes a more complex response to triple junction migration by the two major trunk streams of the Eel and the Russian Rivers. By 6 Ma, the paleo–Russian River drainage system was established (Fig. 9A). Initiation and subsequent anchoring of the main outlet at the Russian River between 8 and 6 Ma occurred at a time when the Russian River Basin lay in the trough

between the two uplift peaks (our interpretation is that it was subsiding or at least experiencing only a small amount of uplift), accommodating Russian River outlet formation at that location. As the triple junction migrated northward, the Russian River, a large established drainage system, could downcut through the uplifting southern peak, and the location of the coastal outlet remained stationary in spite of the migrating uplift. The main stem of the paleo-Russian River continued to downcut through the uplift peak in the same way that the trunk stream of the Eel River currently cuts through the northern peak of the uplift predicted by the MCC (Figs. 9B and 9C). The stream capture and flow reversal observed at the headwaters of the Eel River today (Railroad and Potter Valley wind gaps, Fig. 4) is a process that has continued through time, causing steady divide migration. From 6 Ma to perhaps as recently as 3 Ma, the Russian River lengthened by capturing streams in its headwaters to reach a maximum length of more than 100 km, spanning from Wilson Grove north to Little Lake Valley (north of Ukiah) and depositing the extensive Neogene fluvial gravels of the Glen Ellen, Russian River, and Little Lake gravels (Figs. 2, 9A, and 9B).

At 2 Ma, the upper reaches of the Russian River could no longer cut through increasing uplift of the second migrating uplift peak, perhaps because its average slope had decreased as the river lengthened or because the river was trying to defeat two and not just one uplift high. As a result, the upper portion of the Russian River started to be captured by the north-flowing Eel River system with its outlet at Humboldt Bay (Fig. 9B). Because a large segment of the high-elevation drainage is linked to a main stem by a few E-W-flowing cross streams, the major drainage reversal from a south to a north draining system required only a few breaches of the northern divide to capture the majority of Coast Ranges drainage. Such an event appears to have occurred at ca. 2 Ma, based on the onset of rapid sedimentation in Humboldt Basin. Following this major capture at 2 Ma, it took more than 1 m.y. for the Eel River drainage to extend southward and capture the northernmost headwaters of the Russian River drainage, because streams in the Little Lake Valley (which now flow to the north) were still flowing to the south at ~0.5 m.y. (Woolace, 2005). At 2 m.y., the drainage area of the Russian River at the location where it cut through the southern peak of uplift was ~1800 km2. Based on the modern drainage pattern, the southern uplift peak defeated the upper reaches of the Russian River at ~0.5 m.y., when the drainage area upstream of the southern peak had diminished to less than 800 km².

Streams that are initiated in advance of the triple junction are long-lived, and their channels are subsequently occupied by either NW- or SEflowing streams. The NW-SE pattern is likely in part a consequence of streams preferentially eroding along N-NW-trending subductionrelated faults in the Franciscan rocks. The length of streams formed in advance of the triple junction should be on the order of 75 km, because that is the distance that MCC-driven uplift currently operates to the north of the triple junction. It also is the distance between the northern divide and the present coastline at Humboldt Bay. Prior to 2 Ma, the northern (Eel River) outlet drained the emerging coastal region north of the first divide. We envision that the paleo-Eel River northern outlet resembled the drainage pattern of the modern-day Van Duzen River system.

From the regular 35-40 km spacing of E-Wflowing cross streams, we infer that cross stream formation may be controlled in part by the MCC pattern of uplift. With triple junction migration rates of 40-50 mm/yr, a distance of 35-40 km corresponds to an E-W trunk stream being initiated or occupied every 0.75-1 m.y. Rather than behaving in a buzz-saw fashion, moving northward as the triple junction migrates, the cross streams maintain their latitudinal position. The northernmost and youngest cross stream is located just north of the area of thickened crust in the trough of the uplift (Fig. 8A). If this youngest cross stream formed recently, and if formation of E-W stream segments of main trunk streams occurs in the trough of the MCCuplift pattern, then a new cross stream will not form for another ~1 m.y. As an alternative, a preexisting feature, for instance the E-W-flowing section of the Van Duzen River, may become an E-W-flowing cross stream (Fig. 8A).

Pioneer Fragment and Uplift of the Mendocino Range

The post–3 Ma emergence of the Ohlson Ranch Formation (Fig. 4) and post–late Pliocene incision of the Russian River canyon (Higgins, 1952, 1960) (Fig. 3) chronicle late Pliocene to early Pleistocene uplift of the Mendocino Range (Fig. 6). The marine Ohlson Ranch Formation (Fig. 2) emerged 3–4 m.y. after passage of the triple junction (Fig. 4). Similarly, downcutting of the Russian River canyon between Healdsburg and the coast, and formation and uplift of the Fort Bragg marine terraces, has occurred in the last 2 m.y.

We suggest that emergence of the Ohlson Ranch Formation, uplift of the Fort Bragg marine terraces, and downcutting of the Russian River canyon were all driven by migration



Figure 9. Drainage evolution and emergence of the northern California Coast Ranges. Uplift and emergence of the Coast Ranges propagate north as the triple junction migrates. Bold line in A through C shows the progressive advance of the coastline with the Mendocino triple junction (MTJ). In each time frame, the position of the coastline is constrained by the location and age of fluvial and marine deposits. The locations of the two small stream drainage divides, controlled by the position of the peaks in the pattern of uplift (black double-humped profile), migrate as small streams are captured and flow reverses. The overall drainage evolution does not migrate smoothly with the triple junction. A major reorganization occurs at ca. 2 Ma, when the Eel River captures much of the upper Russian River to become the primary river draining the Coast Ranges. The switch is recorded by a decrease in sedimentation in the Russian River Basin and an increase in sedimentation near the lower Eel River mouth at ca. 2 Ma ("Humboldt basin fluvial," frame D). See text for details. LLV—Little Lake Valley; MCC—Mendocino crustal conveyor.

of the Pioneer fragment. The amount of crustal thickening observed in the tomographic model (Fig. 6), ~14 km, should drive ~2-3 km of isostatic uplift. However, if the geodynamic effects of the Pioneer fragment mimic MCC processes, we would expect a dynamic topography to be superimposed on the isostatic component of uplift, reducing the total amount of uplift. If so, dynamic topography associated with migration of the Pioneer fragment has a magnitude >1 km, reducing the net uplift from the 2-3 km isostatic response to the ~500 m elevation currently observed for the maximum elevation of the Ohlson Ranch Formation. The smaller amplitude of the dynamic topography associated with the Pioneer fragment (>1 km) compared with the magnitude of the dynamic topography associated with the MCC (~2 km) is compatible with the smaller residual isostatic gravity anomaly in the Mendocino Range (Jachens and Griscom, 1983). Based on the current elevation of the Mendocino Range and the Ohlson Ranch Formation, we infer that Pioneer-related dynamic topography is insufficient to generate the trough in the isostatic uplift that is evident in the main Coast Ranges. Rather, we infer that the total uplift in response to the Pioneer fragment is plateau-like with rapid uplift (rates ~0.5 km/yr) followed by a relative stasis. This inference is consistent with the current <500 m elevation of the Ohlson Ranch Formation and with ~0.1-0.4 mm/yr long-term (hundreds of thousands to a few million year) uplift rates, discussed previously, for the Russian River to Fort Bragg coastal segment.

Uplift associated with the migrating Pioneer fragment drove westward migration of the coastline to reach its present shape. As a result, the characteristic shape of the coastline of northern California is a superposition of MCC uplift with Pioneer uplift. This configuration of the coastline with its characteristic "nose-shape" at the triple junction and the change in strike of the coast northwestward south of Cape Mendocino to northeastward north of Cape Mendocino have been used to argue that the Mendocino triple junction is an unstable triple junction that should lead to extensional tectonics or abrupt jumps in its location (Dickinson and Snyder, 1979; Jachens and Griscom, 1983). However, based on the fluvial and marine sediments that constrain the development of the coastline over the past 6-8 m.y., the coastal planform has remained similar to today (Fig. 9A-D). If the coastline does indeed reflect emergence due to migratory triple junction-generated thickening of the accretionary margin, then the abrupt change in strike of the coastline at the triple junction does not reflect an intrinsic characteristic of the geometry of the plate margin, but

simply records stable migration of the triple junction. Similarly, the San Andreas fault zone develops atop the ephemerally thickening crust, and the shape of the coastline is driven more by emergence due to migratory crustal thickening than it is by the development of the San Andreas transform zone in the wake of the triple junction. In the future, the triple junction will continue to migrate in a stable fashion lengthening the Coast Ranges to the northwest.

CONCLUSION

Uplift and emergence of the northern California Coast Ranges results from the migration of the Mendocino triple junction. Transient crustal thickening and dynamic topography caused by the triple junction's migration drive a northwardmigrating, double-humped pattern of uplift that is the primary control on the topography and evolving drainage pattern in the northern California Coast Ranges and on the shape of the coastline. Small streams respond to the changing uplift by stream capture and flow reversal to cause a systematic migration of divides in tandem with triple junction migration. Although the flow direction in the channels reverses, the channels themselves are long-lived features. Northweststriking and northwest-flowing streams form as uplift begins, and flow direction changes from northwest to southeast as the uplift signal moves to the northwest. Flow reversal is facilitated by the existence of a few E-W-trending streams that link the upper reaches of small streams to the main trunk streams.

The progressive stream capture in lowerorder rivers is concordant with the continuously migrating stable triple junction, but the overall drainage system in northern California developed in a more punctuated way with a major reorganization at ca. 2 Ma. The prominent role of only two large river systems in the Coast Ranges drainage evolution may appear inconsistent with a smoothly migrating triple junction, but the major drainage reorganization at ca. 2 Ma is compatible with the Mendocino crustal conveyor geodynamic model and demonstrates the potential for complexity of the geomorphic response to tectonics. The Russian River outlet was the primary outlet from 6 to 2 Ma, and the Eel River has drained the majority of the Coast Ranges for the last 2 m.y. Because the highest-order paleo-Russian River trunk stream could defeat the effects of uplift, the outlet stayed at the location of the present Russian River mouth during much of Coast Ranges development. The ability of higher-order trunk streams to maintain grade across a northwardmigrating uplift has been the primary cause of the punctuated response of the large rivers to

Mendocino crustal conveyor migratory uplift and has caused the fundamentally different response to the same tectonic forcing between larger compared with smaller rivers.

ACKNOWLEDGMENTS

This research was partially supported by National Science Foundation (NSF) grants EAR-9902937 to K. Furlong, R. Slingerland, and H. Kelsey, and EAR-0221133 to K. Furlong. We thank A. Sarna-Wojcicki for identifying the 0.7 Ma Thermal Canyon tephra in Little Lake Valley and R. McLaughlin, T. Nilson, and M. Larsen for help and advice in the field. Reviews by K. Grove, J. Roering, D. Merritts, N. Snyder, and F. Pazzaglia have substantially improved the paper.

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Manuscript Received 8 August 2005 Revised Manuscript Received 5 February 2006

MANUSCRIPT ACCEPTED 26 FEBRUARY 2006

Printed in the USA