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Geomorphologic controls on the age of particulate organic carbon from small mountainous and upland rivers

EL Leithold

NE Blair

DW Perkey
Virginia Institute of Marine Science

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Elana L. Leithold,[1] Neal E. Blair,[1] and David W. Perkey[2]

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[1] To assess the role that erosion processes play in governing the character of particulate organic carbon (POC) discharged from small mountainous and upland rivers, a suite of watersheds from Oregon, California, and New Zealand was investigated. The rivers share similar geology, tectonic setting, and climate, but have sediment yields that range over 3 orders of magnitude. The ^{14}C age of the POC loads is highly correlated with sediment yield. Carbon isotope mass balances reveal that the rivers carry bimodal mixtures of modern-plant- and ancient-rock-derived OC. At lower yields, modern plant OC dominates the material delivered to the river by sheetwash and shallow landsliding. With increasing yield, a progressively larger part of the POC is contributed directly from bedrock erosion via deep gully incision. Our results support the inference that active margin watersheds are important sources of aged POC to the ocean.

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1. Introduction

[2] Small mountainous and upland rivers are important sources of ancient sedimentary organic carbon to the ocean margins [*Kao and Liu*, 1996; *Masiello and Druffel*, 2001; *Leithold and Blair*, 2001; *Blair et al.*, 2003; *Gomez et al.*, 2003a; *Komada et al.*, 2004]. Tens of thousands of such steep rivers, with watersheds of area <10,000 km^2, are located at convergent plate boundaries and most are underlain primarily by sedimentary rocks [*Veizer and Jansen*, 1985; *Wold and Hay*, 1990; *Milliman and Syvitski*, 1992]. Collectively these rivers may carry as much as 40 Tg of rock organic carbon (OC) to the continental shelves annually, chiefly in the form of insoluble, high-molecular-weight material known as kerogen [*Blair et al.*, 2003]. A large influx of randomly structured, ^{14}C-depleted material of mainly marine origin via active margin rivers potentially explains observations that the oceanic OC pool is highly aged and generally poor in identifiable terrestrial fractions [*Hedges*, 1992; *Eglinton et al.*, 1997; *Hedges et al.*, 1997; *Bauer and Druffel*, 1998; *Bauer et al.*, 2002; *Blair et al.*, 2003; *Raymond et al.*, 2004]. Evidence for the recycling of this material, moreover, compels us to revaluate models of long-term carbon cycling, which balance OC burial with kerogen oxidation upon exhumation [*Hedges*, 1992].

[3] Rapid uplift, seismic activity, steep slopes, and abundant precipitation result in high rates of erosion and relatively short residence times for particles in small mountainous and upland watersheds. As a result, kerogen is incompletely weathered and survives to become an important component of riverine POC loads. In our previous investigation of the Eel River and adjacent continental margin in northern California, kerogen C was shown to constitute nearly half of the OC associated with clay-sized particles in soils, the riverine suspended load, and in surface marine deposits [*Blair et al.*, 2003]. Stable and radiogenic carbon isotopic mass balances indicated that the remaining fine POC in the Eel River is primarily modern, plant-derived material. Young, thin soils developed on steep, rapidly eroding hillslopes are apparently more important sources of sediment and associated OC to the river than older, more stable horizons found in the watershed. On the basis of results from the Eel, a bimodal mixture of ancient kerogen and modern plant-derived OC was hypothesized to be characteristic of small mountainous and upland watersheds in general, with the ratio of kerogen to modern C determined primarily by watershed processes that dictate the residence time of particles in the regolith. This idea is supported by the work of *Komada et al.* [2004], who utilized data from their investigation of the Santa Clara River in southern California as well as results from the Eel [*Blair et al.*, 2003] and Lanyang-Hsi in Taiwan [*Kao and Liu*, 1996], to argue for a correlation between sediment yield and $\Delta^{14}C$ of riverine POC.

[4] The goal of the present study is to utilize a suite of small steepland watersheds to test the idea that bimodal mixtures of ancient and modern POC are typical, and to examine the relationship between erosion rate, expressed as sediment yield, and the age of POC in a systematic fashion. In addition to the Eel, five small mountainous/upland rivers, including the Siuslaw in central Oregon, the Noyo and Navarro in northern California, and the Waipaoa and Waiapu on the North Island of New Zealand were investi-

[1]Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina, USA.

[2]Virginia Institute of Marine Sciences, College of William and Mary, Gloucester Point, Virginia, USA.

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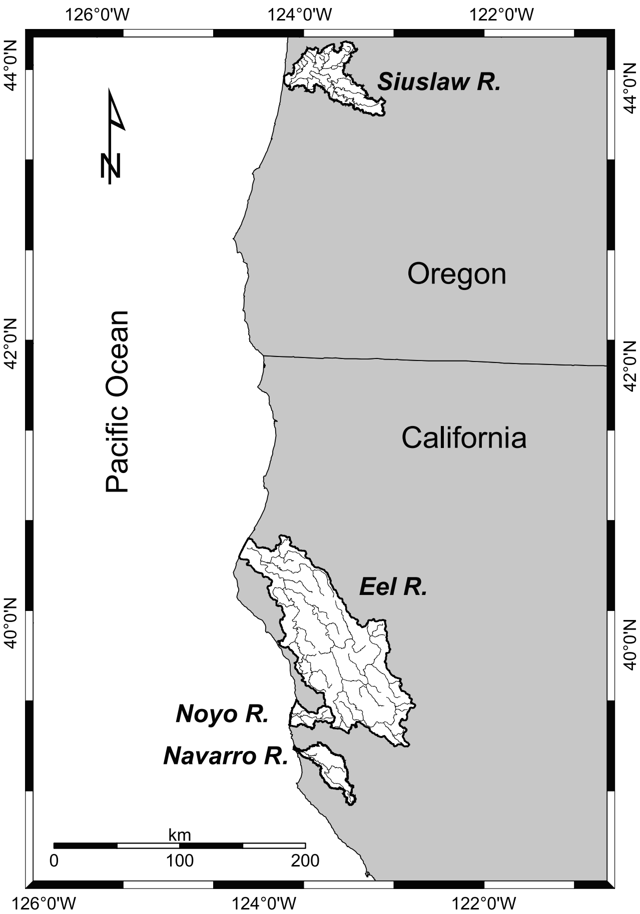

Figure 1. Location of the Siuslaw, Eel, Noyo, and Navarro watersheds in Oregon and California.

gated (Figures 1 and 2). The watersheds all are located at convergent margins and are undergoing active uplift, are underlain almost exclusively by sedimentary rocks, share temperate climates with moderately abundant but episodically intense rainfall, and have been strongly impacted by human activities including land clearance and timber harvesting (Table 1). Their sediment yields, however, range over 3 orders of magnitude, from about 125 to 20,000 metric tons km^{-2} yr^{-1} (Figure 3). A particular objective of our study was to examine how different geomorphic processes in these watersheds, which underlie the large range of erosion rates, control the contributions of various POC fractions and ultimately the age of the material discharged.

2. Methods

[5] Suspended sediment samples were collected from bridges over each of the rivers during high flows in 1999 through 2004. The flows sampled generally had discharges between about 5 and 15 times the mean flows of the rivers (Figure 4). Samples were collected from just below the water surface with a Wildco Beta Plus horizontal water bottle. The samples were frozen within hours after collection and were later thawed, concentrated by centrifugation, and freeze-dried. A subset of river samples was separated into light (<1.8 gm cm^{-3}) and dense (>1.8 gm cm^{-3}) fractions by flotation in a sodium polytungstate solution.

[6] Samples of predominant lithologic units in each of the watersheds were collected from surface exposures. Care was taken to retrieve relatively unweathered samples that were uncontaminated by plant debris and soil. In the laboratory, rock samples were ground to a powder with a ceramic mortar and pestle.

[7] The clay-sized (<4 micron) particle fraction was isolated from a subset of river and ground rock samples. The samples were suspended in a small amount of deionized water and were sonicated for 5 min in glass beakers that were partially immersed in an ultrasonic bath. The samples were washed through a 25-micron stainless steel sieve, the fine (<25 μm) fractions were suspended in aqueous solution of sodium metaphosphate (1 g L^{-1}) to prevent flocculation. The clay fraction was then collected by standard settling techniques, centrifuged, and freeze-dried.

[8] In preparation for OC, C/N, $\delta^{13}C$, $\Delta^{14}C$ analyses, bulk samples and isolates were treated with aqueous 4 N HCl for 48 hours to remove carbonates. Aqueous HCl rather than vapor was found to be necessary to completely remove all carbonate fractions. The unrinsed samples were then dried in vacuo at room temperature in glass beakers. The dried sample was carefully removed from the beakers and homogenized. Weighed subsamples were placed in tin boats and were analyzed for their carbon and nitrogen concentrations (mg C or N per g dry weight sample) using a Thermo-Electron EA 1112 elemental analyzer. The OC and N contents were corrected to account for the weights of salts formed during HCl treatment. The relative precision of the

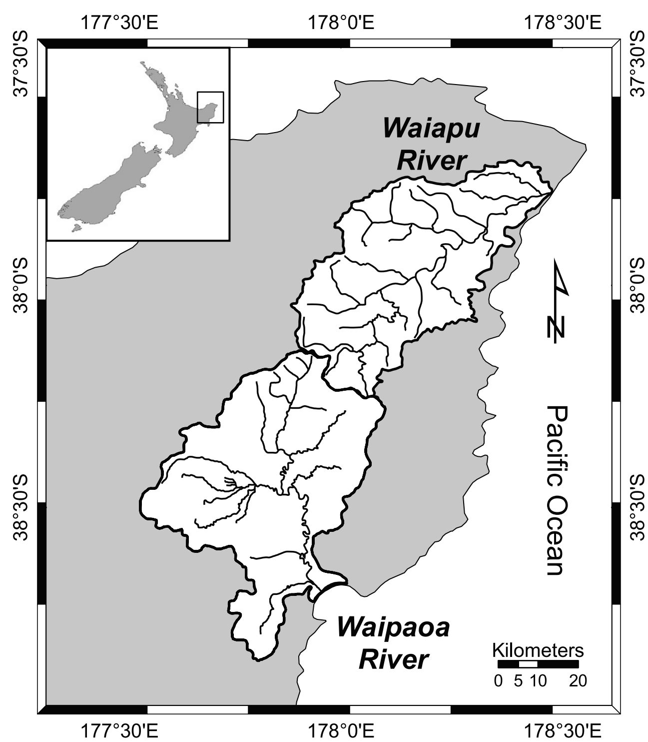

Figure 2. Location of the Waipaoa and Waiapu watersheds in the East Cape region of the North Island of New Zealand.

Table 1. Characteristics of the Studied Watersheds[a]

River	Location	Drainage Area, km^2	Geology	Maximum Elevation, m	Suspended Sediment Load ($\times 10^6$ t/yr)	Annual Precipitation, mm	Suspended Sediment Yield, $t/km^2/yr$
Siuslaw	central Oregon	1523	sandstone and siltstone of the Eocene Tyee Formation	2000	0.19	1300–1500	125
Noyo	northern California	293	Central Belt (1.2% of total area) and Coastal Belt Franciscan Complex	870	0.069	1500–1600	234
Navarro	northern California	816	Central Belt (7.7% of total area) and Coastal Belt Franciscan Complex	920	0.56	900–1300	683
Eel	northern California	8063	Central Belt (60% of total area) and Coastal Belt Franciscan Complex	2220	14	1000–2000	1700
Waipaoa	North Island of New Zealand	2205	Cretaceous-Tertiary marine sedimentary rocks (10% of area prone to gully erosion)	970	15	1000–2500	6800
Waiapu	North Island of New Zealand	1734	Cretaceous-Tertiary marine sedimentary rocks (21.7% of area prone to gully erosion)	1750	36	1600–4000	20520

[a]Data sources include: *Gomez et al.* [2004], *Hicks et al.* [2000], *Karlin* [1980], *Mazengarb and Speeden* [2000], *Milliman and Syvitski* [1992], National Weather Service Forecast Office, Eureka, California, 2005 (http://www.wrh.noaa.gov/eka/rivers/), *Page et al.* [2001a, 2001b], *Syvitski and Morehead* [1999], and *US Environmental Protection Agency* [1999a, 1999b, 1999c, 2000]. The area of the Noyo, Navarro, and Eel River watersheds underlain by Central Belt Franciscan Complex was quantified using ESRI ArcMap 9.1 software and data from *Alexander et al.* [1999], *California Department of Conservation*, 1999, *Saucedo et al.* [2000], and *Steeves and Nebert* [1994].

measurements was 2%. The CO_2 produced by oxidation of the OC was trapped cryogenically for carbon isotopic analyses. A Finnigan MAT Delta E isotope ratio mass spectrometer was used to make the isotopic measurements. Based on replicate analyses, the absolute precision of the entire analytical procedure was 0.2‰.

[9] A subset of the cryogenically collected CO_2 samples were sent to the National Ocean Sciences AMS (NOSAMS) facility at Woods Hole Oceanographic Institution where they were converted to graphite and analyzed for ^{14}C by accelerator mass spectrometry. ^{14}C contents are reported as fraction modern relative to the National Bureau of Standards and Technology (NBS) Oxalic Acid I Standard normalized to a $\delta^{13}C$ of -19‰ [*Olsson*, 1970]. The values of the samples were normalized to -25‰ to correct for natural fractionations. The relative precisions for the NBS-22 hydrocarbon standard were 12% for the fraction modern and 2% for the ^{14}C age.

[10] Standards were analyzed isotopically as a function of size to determine blank contributions for both $\delta^{13}C$ and $\Delta^{14}C$ measurements. Sample sizes were then chosen to avoid significant blank effects.

3. Results

3.1. Elemental Composition

[11] The concentration of POC in the river suspensions decreases exponentially with sediment yield, from a high of about 7% for the Siuslaw River to an asymptotic value of approximately 0.5–0.6% for the Waipaoa and Waiapu Rivers (Figure 5 and auxiliary material[1] Table S1). Density separations indicate that between 9 and 26% of the OC in the river suspensions is contained in discrete fragments of organic material (32.4 ± 8.7% OC, n = 4), while the remainder is bound to mineral grains (Figure 6). Atomic C/N ratios decrease with increasing sediment yield from an average of about 20 in the Siuslaw to about 12 in the Waipaoa and Waiapu (Figure 5 and auxiliary material Table S1).

[12] Rocks in the watersheds contain between 0.14 to 1.1% OC, and have atomic C/N ratios between 7 and 16 (Figure 7 and auxiliary material Table S2). The range of average OC content for rocks reflects in part the predominance of low OC sandstone in some watersheds (e.g., the Siuslaw, Noyo, Navarro and Waipaoa) and larger outcrop areas of higher OC mudstone in others (i.e., the Eel and Waiapu).

3.2. Isotopic Composition

[13] The stable carbon isotopic composition of the riverine POC shows a general pattern of more positive $\delta^{13}C$ values with increasing sediment yield (Figure 7 and auxiliary material Table S1). With increasing yield, the $\delta^{13}C$ of the riverine suspensions more closely approaches the average $\delta^{13}C$ of rocks in the watershed. The light (<1.8 gm cm^{-3})

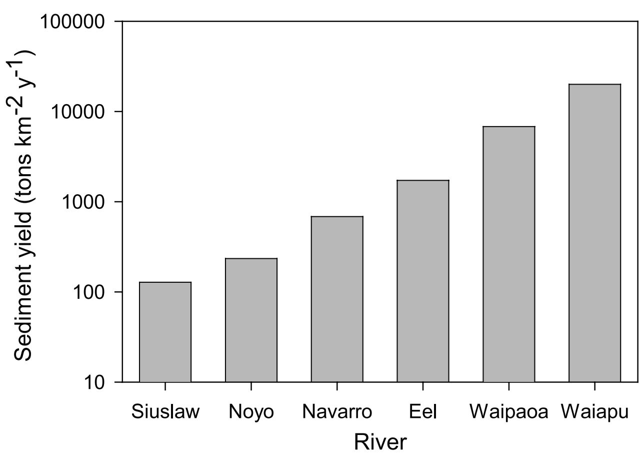

Figure 3. Sediment yield for the studied watersheds. Data sources are cited in Table 1.

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gb/2005gb002677.

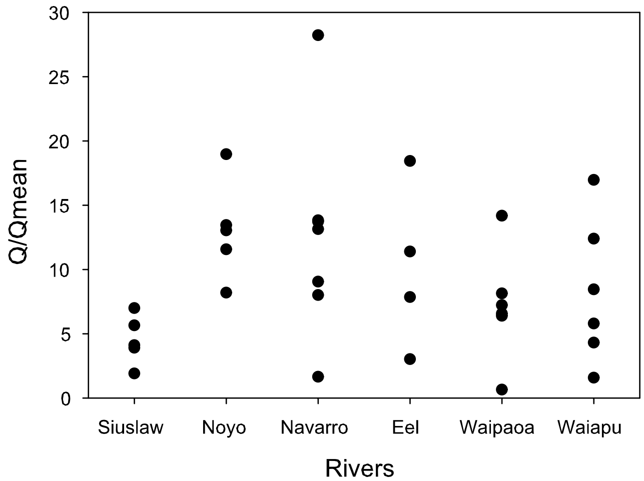

Figure 4. River discharge during sampling relative to mean discharge. Data are from the US Geological Survey Water Resources (http://water.usgs.gov/), *Hicks et al.* [2000, 2004], and Dave Peacock, Gisborne District Council (NZ) (personal communication, 2004).

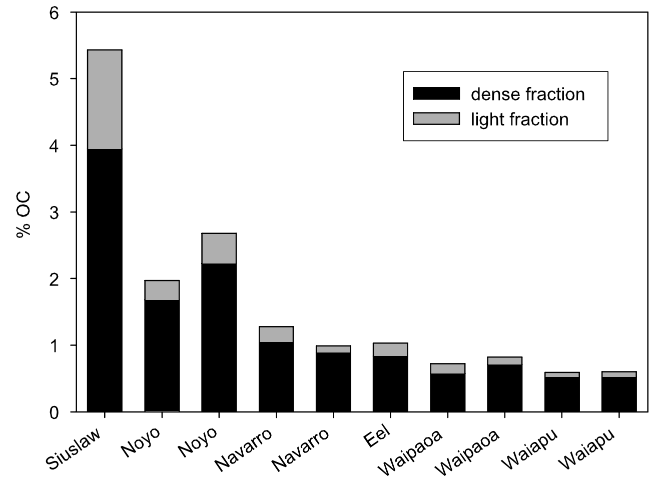

Figure 6. Apportionment of organic carbon in suspended sediment samples between light (<1.8 gm cm^{-3}) and dense (>1.8 gm cm^{-3}) fractions. Each bar depicts results from samples recovered on separate occasions from the rivers. The OC content of the light fraction averages about 32% by weight (n = 4).

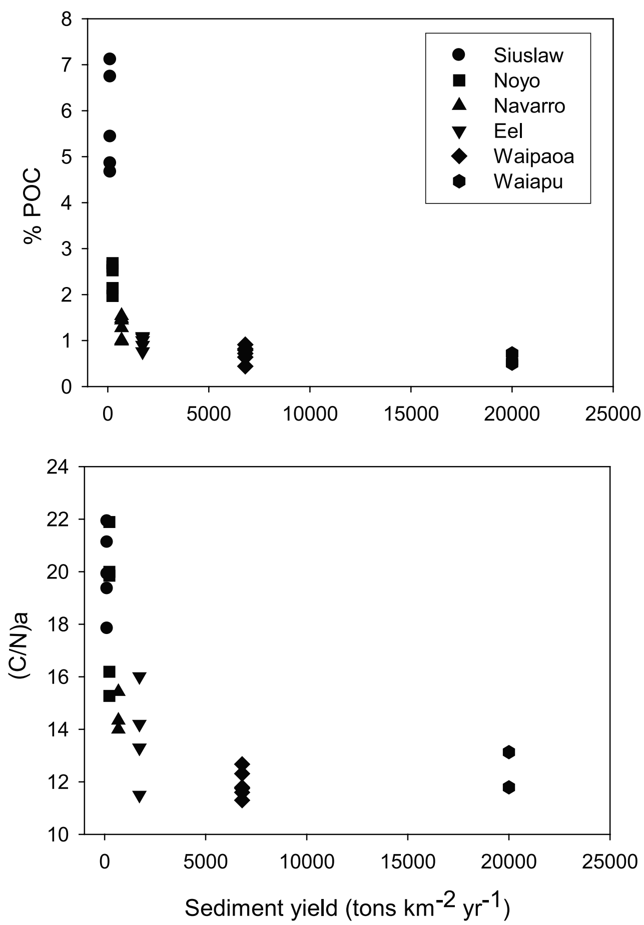

Figure 5. Relationship between sediment yield and the weight percent particulate organic carbon (POC) and atomic carbon to nitrogen ratio ($(C/N)_a$) of bulk suspensions in the studied rivers.

fraction isolated from suspensions has an average value of −27.4 ± 0.2 (n = 4).

[14] The ^{14}C content of the riverine POC decreases exponentially with increasing yield, from a fraction modern carbon of ∼1.0 in the Siuslaw to ∼0.2 for the Waiapu. This corresponds to a near contemporary ^{14}C age for POC in the Siuslaw and a maximum age of about 13,000 years in the Waiapu (Figure 8 and auxiliary material Table S1).

4. Discussion

4.1. Mixing of POC Fractions

[15] There are many possible sources of POC to the rivers, including in situ productivity, litterfall, soil fractions of various ages and types, and sedimentary rocks. The systematic trends in the elemental and isotopic composition of POC with sediment yield, however, point to the mixing of two dominant end-members. At the high end of yield, the strong similarity in the %OC, C/N, and δ^{13}C of the Waiapu suspensions and mean values of rocks sampled in the watershed (Figure 7), point to sedimentary rock OC, or kerogen, as one end-member. With diminishing sediment yield, kerogen appears to be progressively diluted with a younger, higher C/N and more ^{13}C-depleted OC fraction (Figures 5, 7, and 8). To evaluate the age and composition of this younger fraction, we employed a mass balance approach, using the equations

$$OC_r = OC_k + OC_a \tag{1}$$

$$X_r\,OC_r = X_k\,OC_k + X_a\,OC_a, \tag{2}$$

where OC_r, OC_k, and OC_a are the weight percent values of OC in the river suspensions, sedimentary rocks, and younger, added fraction, and X_r, X_k, and X_a are the F_{mod},

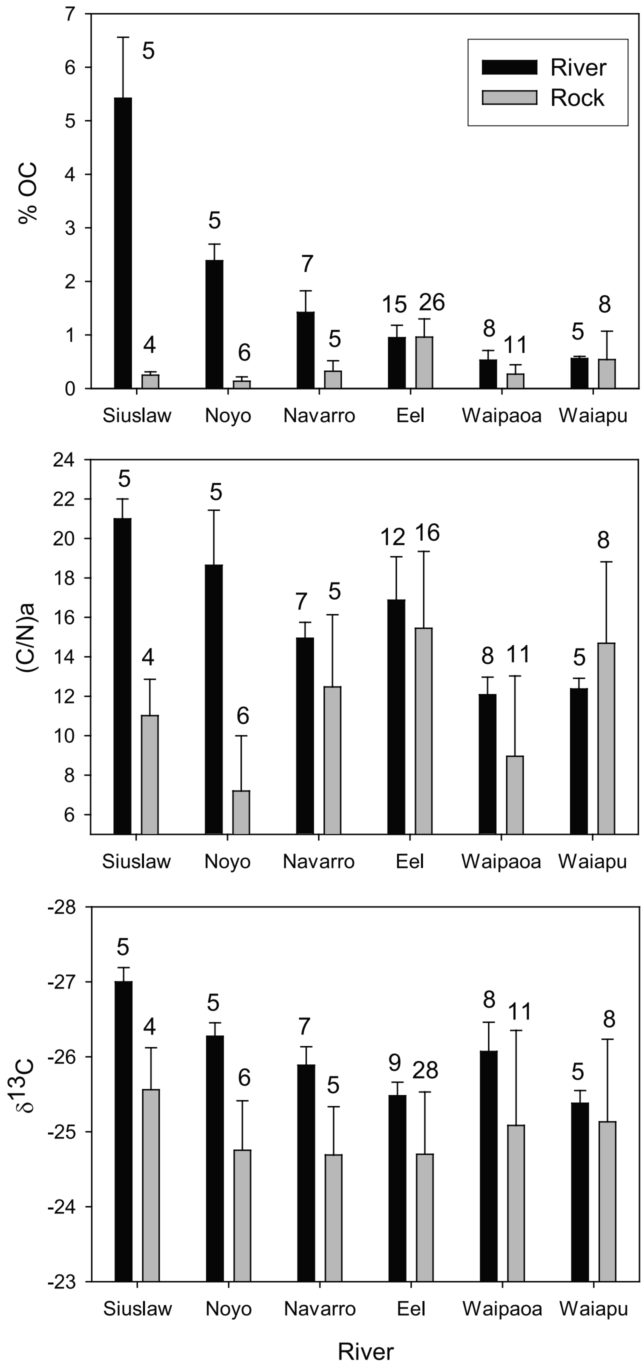

Figure 7. Mean and standard deviations of %OC, atomic C/N, and δ^{13}C for river suspensions and rocks. The number of samples analyzed from each watershed is shown. Eel watershed rock results are for the clay-sized (<4 micron) fraction only; all other results are for bulk samples.

atomic C/N, and δ^{13}C values of OC in the river suspensions, kerogen fraction, and added OC fraction, respectively. Note that equation (1) is valid only if the denominator, the total sediment dry weight, is the same in each term. This is a reasonable constraint given that small quantities of OC are being added to the inorganic phase that constitutes ~99% of the sample. Combining and rearranging these equations yields

$$X_r\,OC_r = X_a OC_r + OC_k(X_k - X_a). \qquad (3)$$

[16] Plotting OC_r against X_rOC_r produces a set of linear relationships with slopes indicative of the composition of the added OC [*Blair et al.*, 2003] (Figure 9). The atomic C/N value of 21 and δ^{13}C value of −27.1‰ argue for a source from vascular plants (typical atomic C/N >20 and δ^{13}C of about −25 to −28‰ for C3 plants [*Smith and Epstein*, 1971; *Hedges et al.*, 1997; *Kendall et al.*, 2001]). The results indicate that the elevated concentrations of POC with decreasing sediment yield are not likely the result of increased contributions from riverine production (C/N of 5–8, δ^{13}C of about −30 to −40 ‰ [*Forsberg et al.*, 1993; *Kendall et al.*, 2001]). This conclusion is consistent with the recovery of all of our samples during times of high flow and turbidity (Figure 4), when in situ productivity is unlikely to have made an appreciable contribution to the POC load.

[17] The fraction modern OC of 1.10 in the added material indicates incorporation of bomb-produced carbon and is close to the atmospheric value when the samples were recovered [*Levin and Kromer*, 1997, 2002; *Levin and Hesshaimer*, 2000; *Tierney and Fahey*, 2002]. This result suggests a dominance of recent plant-derived OC, presumably derived from the uppermost soil horizons. As noted above, although some of this plant material is discrete organic matter including wood, leaf, and root fragments, most of it is bound to mineral grains (Figure 6). The rapid transfer of recent, high Δ^{14}C OC to mineral fractions, either by occlusion in soil aggregates or by sorption onto particle surfaces, has been documented in a number of studies [*Trumbore et al.*, 1989; *Golchin et al.*, 1994; *Boone*, 1994; *Trumbore and Zheng*, 1996, *Swanston et al.*, 2005].

[18] It should be noted that the regressions shown in Figure 9 are dominated by the end-member values, and in particular those associated by the high %OC results. Even so, separate analyses of the data from the Siuslaw, Noyo, Navarro, Eel, and Waipaoa rivers indicate that added material has fraction modern OC values between 1.00 and 1.20. This result further supports the hypothesis that modern OC is a dominant component of the fluvial load. The data from the Waiapu River do not span a sufficient %OC range to permit meaningful analysis.

[19] An isotope mass balance can be used to evaluate the relative percentages of the two end-members, kerogen and modern plant-derived OC, in the POC loads of each of the rivers using the equations

$$\delta_s = f_k(\delta_k) + f_t(\delta_t), \qquad (4)$$

$$F_s = f_k(F_k) + f_t(F_t), \qquad (5)$$

$$1 = f_k + f_t, \qquad (6)$$

where δ_s, δ_k, and δ_t are the δ^{13}C values of suspended sediment samples and the kerogen and terrestrial plant C

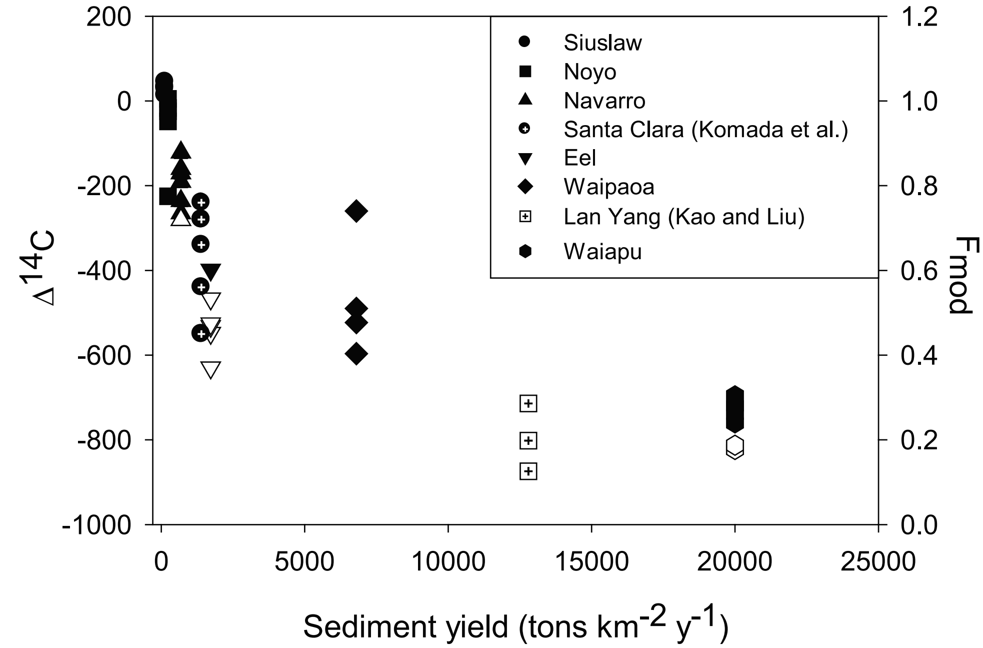

Figure 8. Sediment yield versus Δ^{14}C and F_{mod}. In addition to the six rivers investigated here, data for the Santa Clara (southern California [*Komada et al.*, 2004]) and Lan Yang (Taiwan [*Kao and Liu*, 1996]) rivers are included. Sediment yield values for those rivers are from *Milliman and Syvitski* [1992] and *Kao and Liu* [2002], respectively. Unfilled symbols for the Navarro, Eel, and Waiapu rivers depict results for <4-micron (clay) size separates. All other data are from bulk river suspensions.

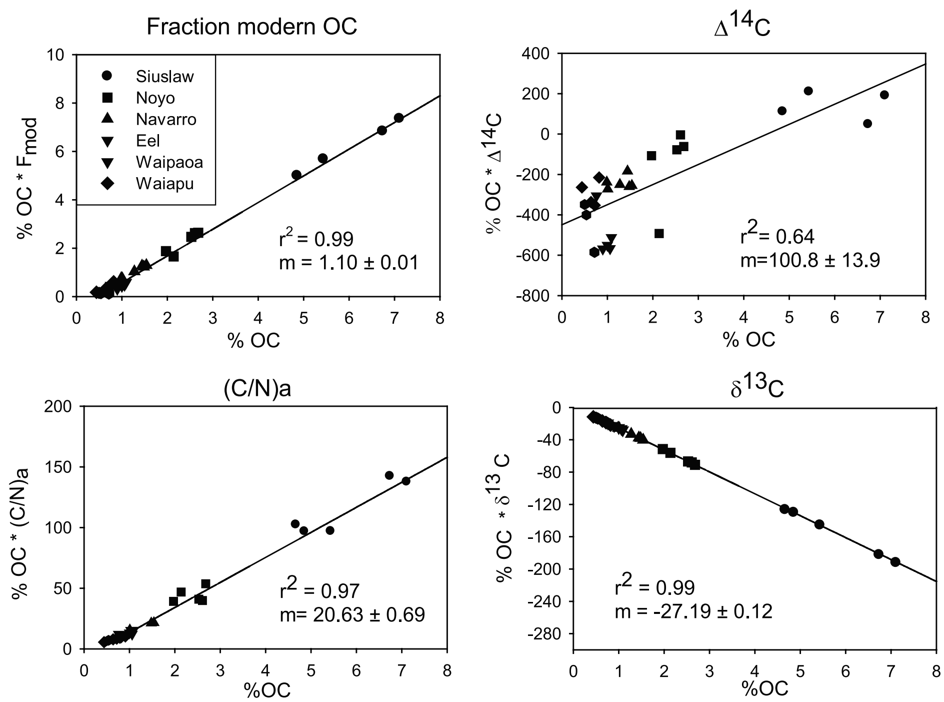

Figure 9. Signatures of OC added to sedimentary rock carbon (kerogen) in the river suspensions. The slopes of the best fit lines indicate the F_{mod}, Δ^{14}C, C/N, and δ^{13}C of the OC responsible for progressively greater concentrations of OC in the rivers. The poorer fit for the Δ^{14}C relationship is an artifact of the equation defining that parameter. More accurate mass balances are achieved using F_{mod}.

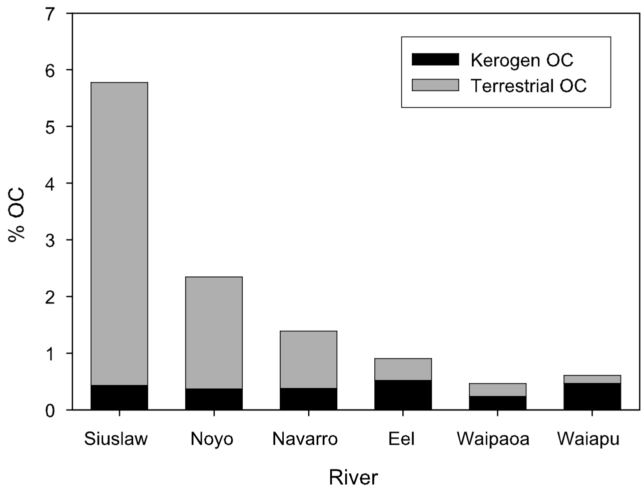

Figure 10. Sources of OC in bulk river suspensions from the studied rivers based on simultaneous solution of $\delta^{13}C$ and $\Delta^{14}C$ mass balance equations.

end-members, and f_k and f_t are the fractions of each component [*Blair et al.*, 2003]. Similarly, F_s, F_k, and F_t represent the F_{mod} for the samples and end-members. The $\delta^{13}C$ for the terrestrial plant end-member (−27) was based on analysis of the light (<1.8 gm cm^{-3}) fraction of suspensions from each of the rivers and on the entire data set as shown in Figure 9. The $\delta^{13}C$ for kerogen was determined from analysis of rocks samples from each watershed. Values of 0 and 1.1 were used for F_k and F_t, respectively, based on the age of the rocks (>1 million years) and the results shown in Figure 9.

[20] Simultaneous solution of these equations (Figure 10) indicates that kerogen OC comprises between about 7 and 75% of the riverine POC loads. The weight percent kerogen in the suspended sediments from each of the rivers is relatively constant, ranging from about 0.3 to 0.5%. Similar concentrations of kerogen have been noted in the suspended sediment loads of other rivers [*Meybeck*, 1993; *Blair et al.*, 2003; *Komada et al.*, 2004] and have been suggested to reflect a common control, perhaps owing to a protective association with mineral surfaces.

4.2. Geomorphology and OC Sources

[21] The systematic trends in the composition and age of POC with sediment yield in the studied rivers are clearly not accidental. These relationships indicate instead that the geomorphic processes that underlie the range of yields also control the delivery of the two OC end-members, kerogen and modern plant OC. This conclusion is made especially clear by comparison of the three California watersheds, the Noyo, Navarro, and Eel, which share the same tectonic and climatic setting. These watersheds share similar geology as well, but differ in the relative percentages of area underlain by relatively coherent, resistant sandstones of the Coastal Belt Franciscan Complex and more friable rocks of the Central Belt Franciscan, including highly sheared, shale-rich, mélange (Table 1). The strong correlations between watershed area underlain by Central Belt Franciscan lithologies with sediment yield and $\Delta^{14}C$ (Figure 11) point definitively toward erosion processes that deliver large amounts of sediment and kerogen from such areas.

4.2.1. Delivery of Old POC

[22] Deeply incised gullies (permanent gullies, in the sense of *Poesen et al.* [2003]) are major sources of relatively unweathered sediment and associated organic carbon in portions of the Noyo, Navarro, and Eel watersheds underlain by the Central Belt Franciscan Complex. These weak, tectonically crushed rocks are prone to earthflows that cover areas up to 2 km^2 and have failure planes several tens of meters below ground level [*Kelsey*, 1978]. The highly disrupted surfaces of earthflows are typically covered by a network of rills and gullies that merge into one axial gully as much as several meters deep [*Kelsey*, 1978]. *Kelsey* [1980] showed that between 1941 and 1975, streams flowing through these gullies contributed about 73% of the sediment supply to the Van Duzen River, the largest tributary to the Eel, or about 92% if a single large storm in 1964 were excluded from the sediment budget.

[23] Gully erosion is similarly a dominant process in the New Zealand watersheds, providing about 50% of the

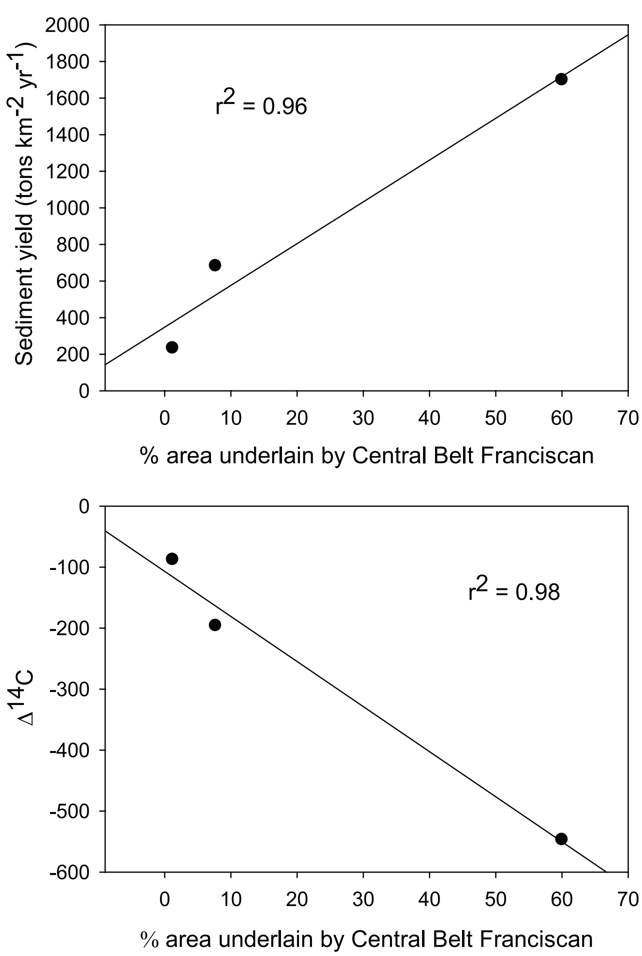

Figure 11. Correlation of the area underlain by Central Belt Franciscan Complex in the Noyo, Navarro, and Eel watersheds with sediment yield and average $\Delta^{14}C$ for river suspensions.

sediment load of the Waipaoa River, and a substantially greater portion of the Waiapu load [*Page et al.*, 2001a, 2001b; *Hicks et al.*, 2000, 2004]. In these watersheds, gullies form in tectonically deformed mudstones and sandstones of predominately Cretaceous to Paleocene age, and in some cases are associated with major faults along which crushing has been extensive [*Mazengarb and Speeden*, 2000; *Betts et al.*, 2003; *Gomez et al.*, 2003b]. Gully erosion has been particularly well studied in the headwaters region of the Waipaoa system, where two large gully complexes of about 0.2 km^2 in area each incised to depths of 45–70 m below the surface between 1958 and 1992 [*De Rose et al.*, 1998; *Gomez et al.*, 2003b]. Sediment is generated from the gullies primarily by mass failures of the gully walls in response to gradual steepening by channel incision [*Betts et al.*, 2003]. *Hicks et al.* [2000, 2004] showed that gullies provide a fairly continuous source of sediment to the Waipaoa and Waiapu rivers, with about half contributed during rainfall events with return periods of $\leq$1 year.

[24] High rates of gully erosion insure that the eroded bedrock has a short residence time in the weathering mantle, or regolith. *Kelsey* [1978] and *Gomez et al.* [2003b] documented sediment yields of more than 20,000 tons km^{-2} yr^{-1} for gullied areas in the Van Duzen and upper Waipaoa watersheds, respectively. Assuming a bedrock density of 2.5 gm cm^{-3}, this yield indicates erosion rates of about 0.8 cm yr^{-1} and residence times of bedrock in the upper meter of the regolith of 125 years. The lifetime of kerogen in surficial environments is uncertain, but studies imply timescales of 10^4 years [*Petsch et al.*, 2000]. Gully erosion can thus be expected to be an important source of kerogen to the rivers.

4.2.2. Delivery of Young, Plant-Derived OC

[25] Shallow landslides and debris flows are the dominant modes of sediment delivery from steep, soil-mantled hillslopes in all of the watersheds, and are potential sources of young, plant-derived OC to the rivers. The mechanisms and timing of these mass wasting processes have been particularly well studied in the Siuslaw watershed, where a highly dissected topography is underlain by thickly bedded, relatively undeformed, Eocene turbidites of the Tyee Sandstone [*Dietrich and Dunne*, 1978; *Reneau and Dietrich*, 1991; *Benda and Dunne*, 1997]. Sediment production from the Tyee rocks involves the development of exfoliation sheets parallel to the ground surface and their subsequent disaggregation by tree roots and burrowing animals on ridges and side slopes [*Reneau and Dietrich*, 1991; *Heimsath et al.*, 2001]. Slow, diffusive transport of the colluvium leads to the accumulation of soil mantles of several meters thickness in the intervening unchanneled valleys (termed bedrock hollows), where they are stabilized by tree roots [*Dietrich and Dunne*, 1978; *Reneau and Dietrich*, 1991; *Benda and Dunne*, 1997]. During episodic storms when rainfall thresholds are exceeded, these areas are prone to shallow landslides, with slip planes located at the soil-bedrock interface. These landslides commonly evolve to debris flows that deliver sediment to higher order channels, where much of it goes into temporary storage [*Benda and Dunne*, 1997]. Between storms, the stored material is slowly delivered further downstream by fluvial transport [*Benda and Dunne*, 1997; *May and Gresswell*, 2003]. After evacuation, bedrock hollows slowly refill with colluvium, reaching thicknesses where gravitational forces exceed root strength and failure occurs again over timescales of a few thousand years [*Reneau and Dietrich*, 1991; *Benda and Dunne*, 1997]. Similar episodic shallow landsliding characterizes portions of each of the other watersheds where sandstones underlie steep, soil-mantled slopes [*Kelsey*, 1978, 1980; *Trustrum and DeRose*, 1988; *Smale et al.*, 1997; *US Environmental Protection Agency*, 1999a, 1999b, 1999c, 2000; *Sloan et al.*, 2001].

[26] Shallow landslides potentially deliver organic carbon of a range of ages to the Siuslaw and other rivers. The organic carbon stored in bedrock hollows is primarily derived from in situ primary productivity [*Yoo et al.*, 2005]. The evacuation of the hollows by landslides thus mobilizes soil profiles that have developed over several thousands of years [*Yoo et al.*, 2005]. Because of steep downward gradients in the concentration and age of soil OC, however, the material will be dominated by younger fractions. In a detailed study of soil carbon cycling in a temperate forest (Harvard Forest, Massachusetts), for example, *Gaudinski et al.* [2000] showed that 80% of the OC inventory of an approximately 0.6-meter-thick soil profile was contained in the upper 0.15 m, comprising the O and A soil horizons. $\Delta^{14}C$ values for soil horizons in the studied profile, which were sampled in 1996, ranged from 151–172 for the O horizon to −171 in the B-horizon, indicating a post-modern (bomb-influenced) age for the near-surface material and a ^{14}C age of 1557 years for the material at depth. Because of the concentration gradient, if the entire soil profile investigated by *Gaudinski et al.* [2000] were to be delivered to a river by a landslide, the homogenized mass would have a $\Delta^{14}C$ value of 40, corresponding to a fraction modern carbon of 1.03.

[27] It is important to emphasize that shallow landsliding is a threshold phenomenon, typically occurring during intense storms with recurrence intervals of several years or more [*Dietrich and Dunne*, 1978; *Benda and Dunne*, 1997; *Reid and Page*, 2002; *Hicks et al.*, 2004; *Page et al.*, 2004]. In the Siuslaw watershed, for example, the most recent episode of widespread landsliding occurred in February of 1996, when an intense and prolonged storm triggered 106 slides in a 22 km^2 area near Mapleton, Oregon [*Robinson et al.*, 1999]. The river flow at that time peaked at 1552 m^3s^{-1}, about 27 times greater than the mean annual flow. The suspended sediment samples collected for this study were all recovered during more moderate flows (Figure 4), when landsliding was not extensive. Under these circumstances, other processes, including bank erosion and sheetwash were likely more important sources of sediment and OC to the rivers.

[28] Sheetwash is not generally considered an important process of sediment delivery in undisturbed humid, forested watersheds, but may be locally important sources of sediment and POC where soils have been laid bare by deforestation, road building, intense grazing, or shallow landsliding [*Swanson et al.*, 1982; *Larsen et al.*, 1999; *Page et al.*, 2004]. Because low-density plant debris is easily transported, it is likely to represent a large fraction of the material delivered by sheetwash [e.g., *Jacinthe et al.*, 2004; *Page et al.*, 2004]. *Larsen et al.* [1999] demonstrated

that fine litter (mainly leaves and twigs) constituted from 18 to 56% of material transported annually by sheetwash at two forested sites on steep hillslopes in the Luquillo Experimental Forest in Puerto Rico. Although this overland flow contributed only a small part (~5%) of the annual sediment yield in the watershed they studied, particularly in comparison to landslides (73% of the annual sediment yield), it represented a steady and important source of sediment and carbon to the river even during years when high intensity storms did not occur. Similarly, *Page et al.* [2004] estimated about 21% of the sediment and about half of the organic carbon delivered to Lake Tutira in New Zealand between 1887 and 2001 was transported by sheetwash. During rainfall events below the threshold for landsliding in this largely deforested, heavily grazed watershed, sheetwash contributed 64% of the sediment load.

5. Implications

[29] Processes of sediment production and delivery in small mountainous and upland watersheds not only drive sediment yield, but also control the sources and hence ages of riverine POC loads. On the lower end of sediment yield, for example, are soil-mantled watersheds such as the Siuslaw. Here the production of sediment by mechanical and chemical weathering keeps pace with the delivery of the weathered material to the river network, so that virtually all particles spend time in soil profiles [*Reneau and Dietrich*, 1991; *Heimsath et al.*, 2001]. On the other end of the spectrum is the Waiapu watershed, where erosion into soft, tectonically crushed bedrock drives a sediment yield that is roughly 150 times greater. In such watersheds, where the erosion rate is transport-limited rather than weathering-limited [*Stallard*, 1995], virtually unweathered bedrock is delivered directly from hillslopes to river channels.

[30] Over millennial timescales, the maximum rate of rock-to-regolith conversion measured in diverse settings is about 0.35 mm yr^{-1} [*Burbank*, 2002; *Lavé and Burbank*, 2004]. Thus, for watershed denudation to occur at a higher rate, direct input from bedrock erosion must occur [*Lavé and Burbank*, 2004]. Assuming an average bedrock density of 2.5 gm cm^{-3}, and that dissolved load and bed load each account for 5–20% of annual denudation [*Dethier*, 1986; *Inman and Jenkins*, 1999], this constraint implies that sustained sediment yields of more than about 600–800 t km^{-2} yr^{-1} can only be accommodated by contributions from bedrock. On the basis of this threshold, bedrock erosion is estimated to contribute to the sediment loads of a minimum of three-quarters of the small mountainous rivers and about half of the small upland rivers catalogued by *Milliman and Syvitski* [1992]. In the watersheds investigated here, deeply incised gullies are the primary sources of unweathered bedrock, but elsewhere, bedrock landslides are important [e.g., *Burbank et al.*, 1996; *Hovius et al.*, 1997; *Lavé and Burbank*, 2004].

[31] The delivery of bedrock materials with very short weathering histories enhances the chance that kerogen will survive to be recycled into contemporary sedimentary systems. Our results (Figure 10) indicate that kerogen survives in the relatively young soils of steep watersheds as well, and is delivered to rivers via shallow landslides. The young age of these soils, however, also means that they will be dominated by recent plant-derived OC fractions. At the same time, sheetwash erosion of plant fragments and mineral particles appears to be an important source of young POC to small steep rivers, particularly during rainfall events below the intensity required to initiate widespread landsliding. Thus, as indicated by earlier studies in the Eel watershed [*Blair et al.*, 2003], the POC carried by small mountainous and upland rivers tends to be bimodal in age. Although aged soil fractions are certainly present, they appear to be minor contributors to the riverine POC loads.

[32] Traditionally, investigations of the role of rivers in linking terrestrial and marine components of the carbon cycle have focused on large passive margin rivers which are responsible for large fluxes of sediment and OC to the oceans. Individually, small active margin watersheds play only minor roles in the global transport of particulate materials from land to the sea. Although each system is unique, our results demonstrate strong commonalities among these systems, which collectively carry nearly half of the sediment and particulate organic carbon (POC) delivered to the oceans annually [*Milliman and Syvitski*, 1992; *Lyons et al.*, 2002]. On the basis of these results, active margins are predicted to be important sites not only for the reburial of ancient, rock-derived OC but also for the sequestration of modern terrestrial OC fractions.

[33] The correlation of ^{14}C age with sediment yield further supports the inference that small, active margin rivers are major sources of aged POC to the deep ocean. Owing to high suspended sediment concentrations, the rivers draining the most rapidly eroding watersheds, which carry the highest concentrations of kerogen, will have an elevated probability of discharging as hyperpycnal flows [*Mulder and Syvitski*, 1995; *Mulder et al.*, 2003; *Hicks et al.*, 2004; *Milliman and Kao*, 2005]. Such flows may bypass the generally narrow active margin shelves entirely, funneling terrestrial sediment directly to the continental slopes or to the deep ocean via submarine canyons [*Milliman and Kao*, 2005].

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N. E. Blair and E. L. Leithold, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, 1125 Jordan Hall, Raleigh, NC 27695, USA. (neal_blair@ncsu.edu; leithold@ncsu.edu)

D. W. Perkey, Virginia Institute of Marine Sciences, College of William and Mary, P.O. Box 1346, State Route 1208, Gloucester Point, VA 23062, USA. (dwperkey@vims.edu)