Dynamic equilibrium among erosion, river incision, and coastal uplift in the northern and central Apennines, Italy

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ABSTRACT

Erosion, river incision, and uplift rates in the northern and central Apennines, Italy, since 0.9 Ma, are determined from new cosmogenic nuclide data. Beryllium-10 concentrations in modern and middle Pleistocene sediments indicate erosion rates from 0.20 to 0.58 mm/yr. These rates are similar to estimates of sediment yield (0.12–0.44 mm/yr), river incision (0.35 mm/yr), and uplift (0.01–1.0 mm/yr) rates inferred from other methods that integrate landscape process rates since the early Pleistocene. These rates of landscape change are significantly lower than long-term exhumation rates of ~1.2 mm/yr since ca. 4.5 Ma, inferred from thermochronometry. Collectively, these data suggest that hillslope erosion and river incision rates in the northern and central Apennines have balanced local uplift rates for ~1 My, but that exhumation rates have slowed significantly since emergence of the mountain chain in the Pliocene. This condition of dynamic equilibrium was potentially achieved within ca. 3 Ma, similar to some model predictions of hillslope and fluvial system adjustment.

Keywords: Landscape evolution, dynamic equilibrium, cosmogenic nuclides, erosion, northern Apennines, Italy.

INTRODUCTION

Under conditions of steady uplift, many landscape evolution models predict a condition of steady state, in which erosion rates, river incision rates, and relief are everywhere adjusted to match local uplift rates. It has been argued that steady state is difficult to achieve in natural landscapes, primarily because the response times of hillslope and fluvial systems are long with respect to variations in climate (e.g., Zhang et al., 2001). Nonetheless, a dynamic equilibrium between erosion and uplift that reflects prevailing climatic conditions may potentially be achieved (Hack, 1960; Howard, 1982; Whipple, 2001). Such a dynamic equilibrium, however, may only exist over limited spatial and temporal scales (Schumm and Lichty, 1965).

Dynamic equilibrium in mountain belts over time scales of 10^3 to 10^6 years is supported by various cosmogenic nuclide studies, which show that spatially averaged millennial-scale erosion rates are comparable to exhumation rates over millions of years. This has been documented in a variety of tectonic environments (Riebe et al., 2000; Kirchner et al., 2001; Matmon et al., 2003; Vance et al., 2003; Safran et al., 2005). However, to ascertain over what time scales and spatial scales dynamic equilibrium can exist in an active orogen, a more comprehensive test, in which erosion rates, river incision rates, and uplift rates are determined by independent methods and over a range of time scales in the same landscape, is needed.

In this paper, we compare erosion, incision, and uplift rates inferred from nine different methods in the tectonically active northern and central Apennines. We use new cosmogenic nuclide data to infer (1) erosion rates, (2) middle Pleistocene paleoerosion rates, and (3) river incision rates. We then compare these to previous estimates of (4) short-term sediment yield determined from reservoir sedimentation, (5) long-term sediment yield from basin sedimentation, (6) fluvial incision rates from terrace stratigraphy, (7) mountain uplift rates from geodetic re-leveling, (8) coastal uplift rates from uplifted shorelines, and (9) long-term exhumation from thermochronometry. Together, these data indicate to what degree and over what scales this landscape has achieved steady state.

COSMOGENIC NUCLIDE METHODS

Millennial-Scale Erosion Rates

The concentration of ^{10}Be in quartz-bearing fluvial sediment reflects the spatially averaged erosion rate of a watershed measured over the time scale required to erode one secondary cosmic-ray penetration length, ~60 cm of rock (Lal, 1991; Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Application of this method requires that (1) quartz is evenly distributed throughout the watershed, (2) sediment is well mixed and representative of hillslope erosion rates, and (3) sediment transport time is short relative to sediment residence time on hillslopes.

Burial Ages and Paleoerosion Rates

The burial age of quartz-bearing sediment can be determined from the differential radioactive decay of the cosmogenic nuclides ^{26}Al ($t_{1/2}$ = 0.72 My) and ^{10}Be ($t_{1/2}$ = 1.34 My). Quartz sediment initially acquires ^{26}Al and ^{10}Be during hillslope erosion and transport. If the sediment is buried deeply enough that it is shielded from secondary cosmic rays, then the ^{26}Al/^{10}Be ratio will decrease through time, and the age of sediment burial can be determined (Granger and Muzikar, 2001).

In addition to dating sediment burial, cosmogenic nuclides can be used to determine paleoerosion rates. By accounting for post-burial radioactive decay, the original ^{26}Al and/or ^{10}Be concentrations can be determined, indicating the erosion rate in the watershed at the time of sediment deposition (Schaller et al., 2004; Balco and Stone, 2005). This paleoerosion rate represents the millennial-scale, catchment-averaged erosion rate of the watershed at the time of sediment deposition, rather than a long-term average. Paleoerosion rates are calculated simultaneously with ^{26}Al/^{10}Be burial ages, but can also be determined using independently known ages and a single cosmogenic nuclide (Schaller et al., 2004). This method assumes that the mean elevation, latitude, and geometry of the drainage basin have not changed significantly through time so that the modern catchment-averaged production rates of ^{26}Al and ^{10}Be can be applied.

River Incision Rates

River incision rates can be determined by measuring the elevation difference between a dated fluvial terrace and the modern river channel. In special cases, incision rates can be constrained by using caves preserved in the walls of river gorges (e.g., Granger et al. 1997; Stock et al., 2004). We use burial dating of cave deposits and fluvio-marine terraces to infer river incision rates in our study area.

SITE DESCRIPTIONS

The northern and central Apennines expose a Mesozoic to Pleistocene sequence of sedimentary rocks that have been uplifted above the retreating Adriatic subduction zone since late Neogene time (Lucchi, 1990). Our study area is limited to the Adriatic (northeastern) side of the mountain range, where rivers have similar drainage areas and share a common base level and uplift history. We present cosmogenic nuclide data to infer millennial-scale erosion, paleoerosion, and river incision rates from three separate areas (Fig. 1).

Romagna Apennines

We determined erosion rates using ^{10}Be in quartz sediment from rivers of the Romagna Apennines, in the central portion of our study area (Fig. 1). These mountains expose a spatially homogeneous, quartz-rich turbidite sandstone (Lucchi, 1990). There is no evidence of glaciation in our sampled watersheds. Hillslope erosion is dominated by shallow landsliding (Simoni et al., 2003; Servizio Geologico, Sismico, e dei Suoli, 2005) and rivers have bedrock channels with only a thin (<1-m), sand-sized alluvial cover (Spagnolo and Pazzaglia, 2005).

To document the spatial distribution of millennial-scale, catchment-averaged erosion rates across the Romagna Apennines, we collected eight samples from either the active channel or overbank deposits at locations in both the upper and lower reaches of three watersheds. All of the sampled watersheds are contained entirely within the turbidite sandstones to avoid lithologic control on the pattern of erosion rates.

Esino River Basin

We determined paleoerosion, river incision, and coastal uplift rates in the Esino River valley, in the southern part of our study area (Fig. 1). The middle portion of the Esino River has incised through a series of limestone-cored anticlines (Calamita et al., 1994). Caves in the limestone were originally formed near the water table but are now perched high above the river and record long-term river incision rates. One of these caves, the Grotta della Madonna, is now 150 m above the modern channel and contains quartz-bearing fluvial sediment, suitable for burial dating, that was washed into the cave by the Esino River. The lower portion of the Esino River flows across an uplifted Plio-Pleistocene fluvial and littoral sequence (Colalongo et al., 1979). The most laterally extensive fluvio-marine deposits stretch over much of the Adriatic coast and have been biostratigraphically correlated to the Early-Middle Pleistocene. The Early-Middle Pleistocene terrace includes the Sabbie Gialle (next section); it has an age of 0.9 ± 0.1 Ma, inferred from its reversed magnetic polarity (Marabini et al., 1995) combined with electron spin resonance (ESR) dating (Falgueres, 2003). These deposits are currently ~100 m above sea level in our study area.

We used the concentrations of cosmogenic ^{10}Be and ^{26}Al to infer the depositional age and paleoerosion rate of sediment collected from the Grotta della Madonna. We also determined paleoerosion rates from a fluvial facies of the Early-Middle Pleistocene fluvio-marine terrace. We collected samples from a depth of 27 m at a recently abandoned sand pit near the town of Castelfidardo, and from a depth of 22 m at a similar pit on Monte San Pellegrino. Coastal uplift rates were inferred from the depositional age of the Castelfidardo and Monte San Pellegrino deposits and the elevation of the sampling site above modern sea level. At this location, the river is graded to sea level; therefore, incision and uplift rates are equivalent.

Sabbie Gialle

We determined paleoerosion rates from an additional site on the Early-Middle Pleistocene marine terrace, in the Sabbie Gialle Formation near the city of Imola, at the northern limit of our study area (Fig. 1). The Sabbie Gialle is composed of poorly indurated, shallow marine and fluvial sandstone and mudstone (Marabini et al., 1995). We collected four samples from depths of 8–20 m in an active sand pit.

RESULTS

Modern Erosion Rates in the Romagna Apennines

Catchment-averaged erosion rates across the Romagna Apennines determined from ^{10}Be in stream sediment are shown in Table DR1 in the GSA Data Repository[1] and Figures 1 and 2. They range from 0.28 $^{+0.02}/_{-0.01}$ to 0.58 $^{+0.11}/_{-0.08}$ mm/yr, and display no pattern with respect to elevation within the watersheds or location within the mountain range. Variability is within a factor of two, both among sites and in replication. Two samples collected from the same location but at different times of the year yield erosion rates of 0.29 $^{+0.03}/_{-0.02}$ and 0.46 $^{+0.10}/_{-0.07}$ mm/yr. Such variability is not unexpected with cosmogenic nuclide-based erosion rates, particularly in catchments dominated by landsliding (Niemi et al., 2005), where sediments may not be fully mixed from throughout the watershed.

Paleoerosion and Uplift Rates in the Esino River Basin

Paleoerosion, fluvial incision, and coastal uplift rates determined from sedimentary deposits in the Esino River valley are shown in Table DR2 and Figures 1 and 2. Fluvial sand in the Grotta della Madonna has a burial age of 0.75 ± 0.26 Ma and a paleoerosion rate of 0.20 ± 0.04 mm/yr. Considering that the Grotta della Madonna is now 150 m above the modern channel, we infer an incision rate of the Esino River of 0.20 ± 0.1 mm/yr. We obtain similar paleoerosion rates from the Early Middle Pleistocene terrace. At both Castelfidardo and at Monte San Pellegrino, we infer paleoerosion rates of 0.24 ± 0.06 mm/yr.

[1]GSA Data Repository item 2008031, cosmogenic nuclide data, landscape process rates inferred from cosmogenic nuclide data, and a comparison of our results with previous estimates of landscape process rates in Tables DR1–DR3, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

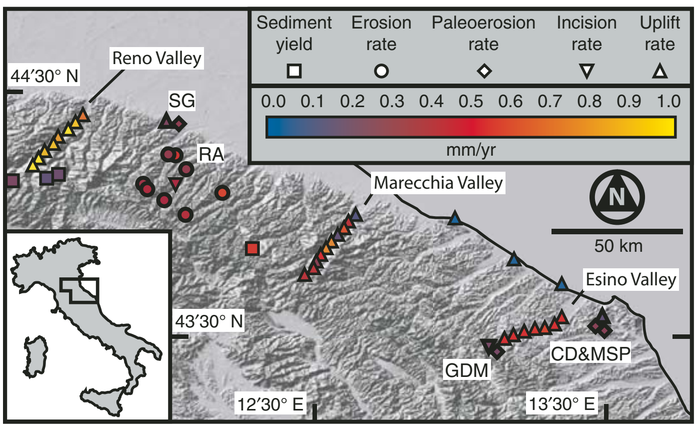

Figure 1. Shaded 90-m-resolution digital elevation model (source: Shuttle Radar Topography Mission [SRTM], U.S. Geological Survey, http://seamless.usgs.gov/) of the northern and central Apennines, Italy. Symbols show the spatial distribution of erosion, incision, and uplift rates from previously published research and new data from this study (bold symbols). Location abbreviations: SG—Sabbie Gialle; RA—Romagna Apennines; GDM—Grotta della Madonna; CD—Castelfidardo; MSP—Monte San Pellegrino.

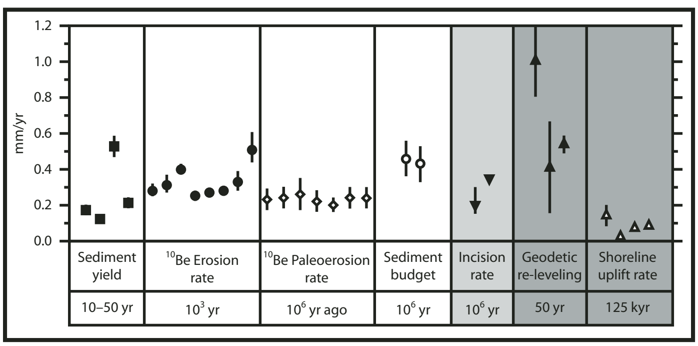

Figure 2. Rates of denudation (white area), fluvial incision (medium-gray area), and uplift (dark-gray area) in the northern and central Apennines inferred from seven different techniques over decadal- to million-year time scales.

Paleoerosion Rates from the Sabbie Gialle

Paleoerosion rates inferred from the Sabbie Gialle are shown in Table DR2 and Figures 1 and 2. We infer a weighted mean paleoerosion rate of 0.23 ± 0.03 mm/yr.

DISCUSSION

Our cosmogenic nuclide data show that millennial-scale erosion rates, paleoerosion rates, fluvial incision rates, and coastal uplift rates are all similar to within a factor of two (Figs. 1 and 2, Table DR3). Collectively, these data suggest that catchments within the northern and central Apennines are in a state of dynamic equilibrium. If this is true, then we would expect similar results from other methods that measure erosion, incision, and uplift rates over different time scales, but over a similar spatial scale.

Short- and Long-Term Sediment Yield

Sediment yields from northern and central Apennines catchment basins have been estimated for both decadal and million-year time scales (Table DR3). Estimates of the sediment yield of over 40 Italian catchments have been compiled by deVente et al. (2006) using reservoir sedimentation data. Assuming a rock density of 2.6 g/cm^3, their data indicate catchment-averaged erosion rates between 0.12 ± 0.01 and 0.53 ± 0.09 mm/yr over the past ~50 yr.

Long-term sedimentation rates have also been estimated for this part of the Apennines chain. Bartolini et al. (1996) used the volumes of sedimentary basin fills to estimate denudation rates of the watersheds feeding the Po Plain and northern Adriatic Sea, including the northern and central Apennines. Erosion rates of 0.44 ± 0.04 mm/yr during the Pleistocene and 0.44 ± 0.11 mm/yr during the Holocene are similar to both our millennial-scale and paleoerosion rates inferred from cosmogenic nuclide data.

Fluvial Incision Rates

The incision rate of the Lamone River in the Romagna Apennines has been determined from a 15-ka fluvial terrace (Table DR3). Simoni et al. (2003) estimate an incision rate of 0.35 ± 0.02 mm/yr, comparable to our millennial-scale erosion rates in the same watershed as well as the longer-term incision rate over the past 750 ka at the Grotta della Madonna (although we cannot rule out fluctuations in river incision rates over intermediate time scales).

Short- and Long-Term Uplift Rates

Short- and long-term estimates of uplift rate across the northern and central Apennines have been determined using two different methods. D'Anastasio et al. (2006) used geodetic re-leveling to estimate uplift rates along three transects in our study area normal to the crest of the Apennines (Table DR3). They infer mean uplift rates of 1.0 ± 0.2 mm/yr to the north of our study area, in the Reno valley near Bologna, 0.41 ± 0.26 mm/yr in the Marécchia valley at the southern edge of the Romagna Apennines, and 0.54 ± 0.05 mm/yr in the Esino River valley, relative to a benchmark at Genoa. The uncertainties stated in this paper reflect the standard deviation across the re-leveling transect. Variability in uplift rate may reflect actively growing structures in the north.

Coastal uplift rates can be inferred over a longer time scale from the elevation of a marine terrace assigned to marine isotope stage (MIS) 5e at 125 ka. Vannoli et al. (2004) infer coastal uplift rates between 0.01 and 0.08 mm/yr. However, they suggest that uplift rates farther inland may be significantly faster. Fluvial terraces correlated with the MIS 5e marine terrace in six central Apennines river valleys suggest that uplift rates at the central Apennines mountain front may be as high as 0.3 mm/yr (Vannoli et al., 2004).

Long-Term Dynamic Equilibrium of the Northern and Central Apennines

Together, these data, compiled for a broad swath of the northern and central Apennines, suggest that erosion, river incision, and uplift have maintained a dynamic equilibrium to within roughly a factor of two over the past 900 ky. With few exceptions, erosion, incision, and uplift rates determined for the past ~1 My are constrained within a narrow range of 0.2 to 0.5 mm/yr (Figs. 1 and 2, Table DR3). The Apennines are a young and tectonically active mountain range, having been uplifted above sea level primarily within the Pliocene (Lucchi, 1990). This raises the question of the time scale required to achieve dynamic equilibrium. One way that we can address this problem is to compare our erosion rate data to exhumation rates over a longer time scale, comparable to the emergence of the Apennines.

Exhumation rates in the Romagna Apennines have been inferred from apatite fission track (AFT) thermochronometry (Zattin et al., 2002). Using AFT, minimum ages from across the Romagna Apennines, and a geothermal gradient inferred from vitrinite reflectance and modern heat-flow measurements, Zattin et al. (2002) estimate rapid exhumation of ~1.2 mm/yr since ~4.5 m.y. ago (Table DR3).

The exhumation rate inferred by Zattin et al. (2002) is significantly faster than our cosmogenic nuclide erosion and paleoerosion rates. Although uncertainties may exist in the geothermal gradient or thermal evolution of the mountain range as a result of changes in exhumation rates, the AFT data suggest that erosion rates in the Apennines have decreased over time. One explanation may be that the thermochronometric data indicate more rapid erosion of relatively weak lithologies soon after emergence of the Apennines. If so, then the transition to a slower erosion rate occurred within ~3 My.

Although a variety of data suggests that steady state among erosion, incision, and uplift has existed since the Middle Pleistocene, the discrepancy with long-term exhumation rates indicates that this is probably a dynamic equilibrium and that relief is changing over longer time scales. It is important to realize that dynamic equilibrium between landscape components can exist over one spatial and temporal scale, while other elements of the landscape may have transient behavior over longer or shorter time scales (e.g., Schumm and Lichty, 1965). One way to understand this is through the response times of various components of the landscape. For example, hillslopes that are eroding by diffusive processes have a response time proportional to the time taken to erode one hillslope height (Fernandes and Dietrich, 1997). Rivers that are incising according to the stream power law have a response time approximately equal to the time required to incise through one fluvial relief (Whipple and Tucker, 1999). Mountain belts evolving according to critical wedge theory have a response time proportional to the time required to erode one wedge volume (Whipple and Meade, 2004). Using these simple scaling arguments and values appropriate for the northern and central Apennines, we expect that the time scale for localized hillslope adjustment to changes in river incision rates is ~0.1 My, the time scale for adjustment of river profiles is ~2–3 My, and the response time for the entire wedge is ~20–60 My. Our conclusion that watersheds within the northern and central Apennines have achieved dynamic equilibrium within only a few million years, but that orogenic relief may be changing over longer time scales, is consistent with these estimates.

One potential implication of this work is that millennial-scale erosion rates determined from cosmogenic nuclides may be used to infer uplift and incision rates in other landscapes where there is good evidence for dynamic equilibrium (e.g., Wobus et al., 2005).

CONCLUSIONS

Our cosmogenic nuclide data from the northern and central Apennines show that millennial-scale erosion rates, paleoerosion rates, fluvial incision rates, and coastal uplift rates are similar to one another to within a factor of two. Comparison with incision and uplift rates, and sediment yield data from other studies, suggests that dynamic equilibrium of the hillslopes and fluvial network has existed in this part of the Apennines for ~1 My. In contrast, thermochronometric data show rapid exhumation over the past 5 My. We suggest that dynamic equilibrium between uplift rates and both the hillslope and fluvial systems was achieved within a few million years from emergence of the Apennines.

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REFERENCES CITED

Balco, G., and Stone, J.O., 2005, Measuring middle Pleistocene erosion rates with cosmic ray-produced nuclides in buried alluvial sediment, Fisher Valley, southeastern Utah: Earth Surface Processes and Landforms, v. 30, p. 1051–1067, doi: 10.1002/esp.1262.

Bartolini, C., Caputo, R., and Pireri, M., 1996, Pliocene-Quaternary sedimentation in the Northern Apennine foredeep and related denudation: Geological Magazine, v. 133, p. 255–273.

Bierman, P.R., and Steig, E.J., 1996, Estimating rates of denudation using cosmogenic isotope abundances in sediment: Earth Surface Processes and Landforms, v. 21, p. 125–139, doi: 10.1002/(SICI)1096-9837(199602)21:2<125::AID-ESP511>3.0.CO;2-8.

Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., and Yiou, F., 1995, Denudation rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico: Earth and Planetary Science Letters, v. 129, p. 193–202, doi: 10.1016/0012-821X(94)00249-X.

Calamita, F., Cello, G., Deiana, G., and Paltrinieri, W., 1994, Structural styles, chronology, rates of deformation, and time-space relationships in the Umbria-Marche thrust system (central Apennines, Italy): Tectonics, v. 13, p. 873–881, doi: 10.1029/94TC00276.

Colalongo, M.L., Nanni, T.I., and Lucchi, F., 1979, Sedimentazione ciclica nel Pleistocene anconetano: Geologica Romana, v. 18, p. 71–92.

D'Anastasio, E., De Martini, P.M., Selvaggi, G., Pantosti, D., Marchioni, A., and Maseroli, R., 2006, Short-term vertical velocity field in the Apennines (Italy) revealed by geodetic levelling data: Tectonophysics, v. 418, p. 219–234, doi: 10.1016/j.tecto.2006.02.008.

de Vente, J., Poesen, J., Bazzoffi, P., van Rompaey, A., and Verstraeten, G., 2006, Predicting catchment sediment yield in Mediterranean environments: The importance of sediment sources and connectivity in Italian drainage basins: Earth Surface Processes and Landforms, v. 31, p. 1017–1034, doi: 10.1002/esp.1305.

Falgueres, C., 2003, ESR dating and the human evolution: Contribution to the chronology of the earliest humans in Europe: Quaternary Science Reviews, v. 22, p. 1345–1351, doi: 10.1016/S0277-3791(03)00047-7.

Fernandes, N.F., and Dietrich, W.E., 1997, Hillslope evolution by diffusive processes: The timescale for equilibrium adjustments: Water Resources Research, v. 33, p. 1307–1318, doi: 10.1029/97WR00534.

Granger, D.E., and Muzikar, P.F., 2001, Dating sediment burial with in situ-produced cosmogenic nuclides: Theory, techniques, and limitations: Earth and Planetary Science Letters, v. 188, p. 269–281, doi: 10.1016/S0012-821X(01)00309-0.

Granger, D.E., Kirchner, J.W., and Finkel, R., 1996, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediment: The Journal of Geology, v. 104, p. 249–257.

Granger, D.E., Kirchner, J.W., and Finkel, R., 1997, Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic 26Al and 10Be in cave-deposited alluvium: Geology, v. 25, p. 107–110, doi: 10.1130/0091-7613(1997)025<0107:QDROTN>2.3.CO;2.

Hack, J.T., 1960, Interpretation of erosional topography in humid temperate regions: American Journal of Science, v. 258-A, p. 80–97.

Howard, A.D., 1982, Equilibrium and time scales in geomorphology: Application to sand-bed alluvial streams: Earth Surface Processes and Landforms, v. 7, p. 303–325, doi: 10.1002/esp.3290070403.

Kirchner, J.W., Finkel, R., Riebe, C.S., Granger, D., Clayton, J.L., King, J.G., and Megahan, W.F., 2001, Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales: Geology, v. 29, p. 591–594, doi: 10.1130/0091-7613(2001)029<0591:MEOYKY>2.0.CO;2.

Lal, D., 1991, Cosmic-ray labeling of erosion surfaces: In situ nuclide production-rates and erosion models: Earth and Planetary Science Letters, v. 104, p. 424–439, doi: 10.1016/0012-821X(91)90220-C.

Marabini, S., Taviani, M., Vai, G.B., and Vigliotti, L., 1995, Yellow sand facies with Arctica islandica: Low-stand signature in an early Pleistocene front-Apennine: Giornale di Geologia, v. 57, p. 259–275.

Matmon, A., Bierman, P.R., Larsen, J., Southworth, S., Pavich, M.J., and Caffee, M.W., 2003, Temporally and spatially uniform rates of erosion in the southern Appalachian Great Smoky Mountains: Geology, v. 31, p. 155–158, doi: 10.1130/0091-7613(2003)031<0155:TASURO>2.0.CO;2.

Niemi, N.A., Oskin, O., Burbank, D.W., Heimsath, A.M., and Gabel, E.J., 2005, Effects of bedrock landslides on cosmogenically determined erosion rates: Earth and Planetary Science Letters, v. 237, p. 480–498, doi: 10.1016/j.epsl.2005.07.009.

Lucchi, F., 1990, Turbidites on foreland and on-thrust basins of the northern Apennines: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 77, p. 51–66, doi: 10.1016/0031-0182(90)90098-R.

Riebe, C.S., Kirchner, J.W., Granger, D., and Finkel, R., 2000, Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic ^{26}Al and ^{10}Be in alluvial sediment: Geology, v. 28, p. 803–806, doi: 10.1130/0091-7613(2000)28<803:EEADIT>2.0.CO;2.

Safran, E.B., Bierman, P.R., Aalto, R., Dunne, T., Whipple, K., and Caffee, M.W., 2005, Erosion rates driven by channel network incision in the Bolivian Andes: Earth Surface Processes and Landforms, v. 30, p. 1007–1024, doi: 10.1002/esp.1259.

Schaller, M., von Blackenburg, F., Hovius, N., Veldkamp, A., van den Berg, M.W., and Kubik, P.W., 2004, Paleoerosion rates from cosmogenic ^{10}Be in a 1.3 Ma terrace sequence: Response of the River Meuse to changes in climate and rock uplift: The Journal of Geology, v. 112, p. 127–144, doi: 10.1086/381654.

Schumm, S.A., and Lichty, R.W., 1965, Time, space, and causality in geomorphology: American Journal of Science, v. 263, p. 110–119.

Servizio Geologico, Sismico, e dei Suoli, 2005, Determinazione di soglie pluviometriche per innesco di fenomeni franosi nell'Apennino settentrionale: Convenzione Tra Arpa—Servizio Idrologico Regionale e Servizio Geologico Sismico e dei Suoli Regional per il Supporto alle Attivita' del Centro Funzionale, Regione Emilia-Romagna: http://www.regione.emilia-romagna.it/wcm/geologia/canali/frane/rel_scien/val_risch_fr/soglie_pluviometriche.pdf (August, 2007).

Simoni, A., Elmi, C., and Picotti, V., 2003, Late Quaternary uplift and valley evolution in the Northern Apennines: Lamone catchment: Quaternary International, v. 101–102, p. 253–267, doi: 10.1016/S1040-6182(02)00106-4.

Spagnolo, M., and Pazzaglia, F.J., 2005, Testing the geological influences on the evolution of river profiles: A case from the Northern Apennines (Italy): Geografia fisica e dinamica quaternaria, v. 28, p. 103–113.

Stock, G.M., Anderson, R.S., and Finkel, R., 2004, Pace of landscape evolution in the Sierra Nevada, California, revealed by cosmogenic dating of cave sediments: Geology, v. 32, p. 193–196, doi: 10.1130/G20197.1.

Vance, D., Bickle, M., Ivy-Ochs, S., and Kubik, P.W., 2003, Erosion and exhumation in the Himalaya from cosmogenic isotope inventories of river sediments: Earth and Planetary Science Letters, v. 206, p. 273–288, doi: 10.1016/S0012-821X(02)01102-0.

Vannoli, P., Basili, R., and Valenise, G., 2004, New geomorphic evidence for anticlinal growth driven by blind-thrust faulting along the northern Marche coastal belt (central Italy): Journal of Seismology, v. 8, p. 297–312, doi: 10.1023/B:JOSE.0000038456.00574.e3.

Whipple, K., 2001, Fluvial landscape response time: How plausible is steady-state denudation?: American Journal of Science, v. 301, p. 313–379, doi: 10.2475/ajs.301.4-5.313.

Whipple, K., and Meade, B.J., 2004, Controls on the strength of coupling among climate, erosion, and deformation in two-sided, frictional orogenic wedges at steady state: Journal of Geophysical Research, v. 109, doi: 10.1029/2003JF000019.

Whipple, K., and Tucker, G.E., 1999, Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs: Journal of Geophysical Research, v. 104, p. 17,661–17,674, doi: 10.1029/1999JB900120.

Wobus, C., Heimsath, A., Whipple, K., and Hodges, K.V., 2005, Active out-of-sequence thrust faulting in the central Nepalese Himalaya: Nature, v. 434, p. 1008–1011, doi: 10.1038/nature03499.

Zattin, M., Picotti, V., and Zuffa, G.G., 2002, Fission-track reconstruction of the front of the northern Apennine thrust wedge and overlying Ligurian Unit: American Journal of Science, v. 302, p. 346–379, doi: 10.2475/ajs.302.4.346.

Zhang, P.Z., Molnar, P., and Downs, W.R., 2001, Increased sedimentation rates and grain sizes 2–4 Myr ago die to the influence of climate change on erosion rates: Nature, v. 410, p. 891–897, doi: 10.1038/35069099.

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