University of Nevada, Reno

Investigating the tectonic geomorphology of the Santa Ynez Mountains, CA and developing middle school geoscience lessons

A thesis submitted in partial fulfillment of the requirements for
the degree of Master of Science in Hydrology

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December 2023

THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

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entitled

Investigating the tectonic geomorphology of the Santa Ynez Mountains, CA and developing middle school geoscience lessons

be accepted in partial fulfillment of the
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ABSTRACT

The understanding of how topography responds to tectonic and climatic forcings to shape landscapes (1) and engaging young people in the geosciences (2) are the two focuses of my thesis. First, I discuss my tectonic geomorphology work in the Santa Ynez Mountains, CA (SYM), then my work planning, teaching, evaluating, and publishing a pair of lessons about rock weathering I taught to ~300 middle schoolers. The tectonic geomorphology project is being prepared for publication, and my outreach work has been accepted to the National Science Teachers Association's Magazine 'Science Scope'.

The SYM is a case study landscape in which climate is held constant while tectonic and lithologic forcings vary. Compiling past thermochronology and marine terrace exhumation/uplift rate data in addition to new cosmogenic radionuclide erosion rates, we analyze the spatial and temporal changes in uplift/erosion in the SYM. The relief of the SYM reflects the million-year timescale exhumation rate gradient from west to east, while more recent active faulting is impacting marine terrace uplift rates on the order of 50 thousand years. Erosion rates from CRN are an order of magnitude lower than exhumation/uplift rates, and do not show any trend with topography or exhumation/uplift rates. Additionally, our topographic analysis shows that relative channel steepness and mean hillslope angle increase along the west east transect, with rock strength controlling smaller scale steepness and gradients. This study shows that while topography does respond to variation in tectonic forcing and rock strength, the timescales of response can vary.

In middle school classrooms we taught students about rock weathering, both with respect to impacts on long term climate and soil formation through hands on experiments. Lesson 1 has students investigate how changing the temperature and acidity of weathering agents affects the rate of rock weathering of sandstone and limestone (using sugar cubes and chalk, respectively, as models) and if the products of weathering different rock types impact the climate on geologic timescales by adding CO_2 to the atmosphere or not. Lesson 2 focuses on how weathering impacts our day to day lives. Students perform experiments simulating how bedrock weathering of different rock types (mudstone and granite) occur at different rates, produce different small particles, and interact with weathering agents differently. These lessons bring rock weathering into the classroom with cross cutting concepts and connect the earth, climate, and human society together in an interactive way.

ACKNOWLEDGEMENTS

Funding for this thesis was done through the National Science Foundation under grant NSF EAR 2141519. A huge thanks to my advisor, Dr. Joel Scheingross, for all your support throughout this project. Thank you to my master's committee, not only for being flexible with your time but for supporting me as I graduate. Graduate school would not be possible for me without support from my undergraduate advisor Dr. Kristina Faul, all my undergraduate friends and childhood friends and family. My time at Los Alamos National Lab as a post-baccalaureate intern was invaluable, thank you to all the people who supported me through that journey, especially my PI Dr. Cathy Wilson and co-PI Brent Newman. My thesis would never have been finished without the support of my partner Alex, thank you so so much.

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CHAPTER 1: INFLUENCE OF TECTONICS AND LITHOLOGY ON TOPOGRAPHIC FORM SPANNING MILLENNIAL AND MILLION-YEAR TIMESCALES IN THE SANTA YNEZ MOUNTAINS, TRANSVERSE RANGES, CA

Topography is used to infer tectonic and climatic processes that shape landscapes. Here we use the Santa Ynez Mountains, Transverse Ranges, CA (SYM) as a case study landscape in which climate is held constant while tectonic and lithologic forcings vary. In this contribution we: 1. Compile and contribute to uplift/erosion rate data within the SYM over thousand, tens of thousands, and million-year time scales, 2. Perform a topographic analysis on channels and hillslopes in the SYM. Our findings show a threefold increase from west to east in exhumation rate from ~0.5 to 1.8 mm/y averaging over million-year timescales. Marine terrace uplift rates show an increase (~1.1 to 1.5 mm/y) in uplift at the South Branch of the Santa Ynez Fault (SBSYF) averaging over tens of thousands of years. New basin averaged erosion rates show a slight (~doubling) increase in erosion rates from west to east, ranging from ~0.14 to 0.28 mm/y averaging over thousands of years. Our topographic analysis shows that relative channel steepness and mean hillslope angle increase along the west east transect, with rock strength controlling smaller scale steepness and gradients. This study shows that while topography does respond to variation in tectonic forcing and rock strength, the timescales of response can vary.

1.0 INTRODUCTION

Topographic metrics are commonly used to infer the climate and tectonic history in landscapes. However, it is not always clear over what timescales topography is set and how modern topography reflects active forcing. At the largest scale, the existence of mountain ranges is set by the My timescales over which plate tectonics operate. Whereas at smaller scales, landscapes can record variation in tectonic or climatic forcing. For example, climate forcing associated with Milankovitch cycles can be recorded in river terraces and alluvial fan chronologies (e.g., (Hodges et al., 2004; Schildgen et al., 2009, 2018; Tofelde et al., 2017)) Similarly, spatial gradients in uplift and climate across a mountain range can track with topographic metrics such as channel steepness, mean hillslope angle, hilltop curvature and more (Hurst et al., 2012; Kirby and Whipple, 2012; Leonard et al., 2023; DiBiase et al., 2023). These patterns can be complicated by variations in rock strength; for example, hillslopes have been shown to respond primarily to rock strength rather than uplift rates (Korup, 2008) and channel steepness can be impacted by the strike and dip at changes in rock strength(Yanites et al., 2017; Bernard et al., 2019). In cases when there is both spatial and temporal variability in tectonic forcing, coupled with lithologic heterogeneity, the response of landscapes can be complex.

Here, we examine such a case in the SYM, California where the landscape is shaped by a combination of variation in tectonic forcing and variation in rock strength. We do this by comparing topographic metrics derived from the modern landscape with uplift and erosion estimates averaging over ~4 ky to >1 My timescales. We first review the study area and then then present methods, results, and discussion on quantifying the spatial and temporal variability in uplift across the SYM using a combination of data including compiled thermochronology data, compiled marine terrace uplift rates, and newly collected cosmogenic radionuclide (CRN) erosion rates. We then present new rock strength data from Schmidt hammer measurements on twelve lithologic units in the Santa Ynez, adding to data from (Duvall, 2004). Next, we present methods and results for topographic analyses of bedrock channels and hillslopes in the SYM and compare topographic expression to uplift/erosion rates. Finally, we discuss what timescale of forcing the Santa Ynez's landscape records and speculate about how uplift and erosion rates are spatially similar but an order of magnitude faster along the marine terraces than in the basins.

1.0.1 Study Area

The SYM are an east-west striking mountain range within the Western Transverse Ranges of California. The range is ~125 km long and increases in relief and width from its western (~400 m relief and ~4 km width) to eastern extent (~1400 m relief and ~10 km width) (Fig. 1.1). The underlying geology consists primarily of near shore to deep marine sedimentary rocks ranging in age from Eocene to Miocene {Citation}. The lithology alternates between east-west striking bands of sandstones, siltstones, and mudstones which predominantly dip to the south (with overturned, north-dipping beds becoming more common in the eastern extent of the range) (Dibblee, 1982) (see Fig. 1.1). The area has a Mediterranean climate with mean annual precipitation (dominated by rainfall) ranging from ~300 mm/y to ~900 mm/y (Fig. 1.1) and mean annual temperature ranging from ~12-18 ºC (Minnich, 2007; PRISM, 2014).

Exhumation of the SYM began in the Pliocene (Minor et al., 2009). Both a west-to-east gradient in cooling ages and evidence for eastward migration of the San Cayetano Fault suggest that exhumation began in the western extent of the range and migrated eastward (Fig. 1.1) (White, 1992(Townsend et al., 2021). Exhumation of the range was driven by regional transpressional tectonics and clockwise rotation of crustal blocks, related to contrasts in lithospheric basement strength and only to the development of a restraining bend along the San Andreas Fault system (Townsend et al., 2021). There exist documented pulses of episodic uplift over the last 100 ky that are thought to be related to changes in how slip along the large detachment fault associated with the San Cayetano fault is transferred to surface faults in the region (Levy et al., 2019; Kelty and Onderdonk, 2022). Uplift rates over the last ~50 ky are thought to be primarily accommodated by the offshore Pitas Point-North Channel fault system as well as the Santa Ynez Fault, a south dipping fault that bounds the northern side of the Santa Ynez (Fig. 1.1) (Levy et al., 2019; Townsend et al., 2021; Kelty and Onderdonk, 2022) with uplift along the SBSYF separating the more slowly uplifting western extent of the range from the more rapidly uplifting eastern extent of the range (Morel et al., 2021).

As we review in more detail below, multiple lines of evidence point to a west to east increase in uplift along the SYM, but disagree on the magnitude of the uplift gradient. Inferring uplift rates from thermochronometers and dating of marine terraces suggest uplift may increase by less than 50% to greater than a factor of five moving from west to east (Trecker et al., 1999; Gurrola et al., 2014; Morel et al., 2021). In a study examining bedrock rivers draining the southern flank of the SYM, Duvall et al., (2004) found that rivers systematically increase their gradient and narrow their width moving from west to east across the range, consistent with a west to east increase in uplift, but that this relationship can be modulated by lithologic heterogeneity. Since the work of Duvall et al. (2004), there has yet to be a new and systematic topographic analysis of how variation in uplift and rock strength are recorded in the SYM, despite the development of new topographic analysis techniques (e.g., (Hurst et al., 2012; DiBiase et al., 2012; Perron and Royden, 2013; Mudd et al., 2018; Gailleton et al., 2021) and new geochronology documenting uplift rates (Morel et al., 2021; Townsend et al., 2021).

1.1 QUANTIFICATION OF EXHUMATION, UPLIFT, AND EROSION RATES

Our goal is to assess how spatial and temporal variation in tectonic uplift is recorded in the modern topography of the SYM. In this section, we provide methods and results for quantification of uplift rates over ky to My timescales, including compiling data from published datasets along with the presentation of new erosion rates millennial scale erosion rates derived from cosmogenic radionuclides. To assess whether this is a statistically significant increase in uplift/erosion rates moving from west to east across study area, we use Pearson correlation coefficients, ρ and p. ρ values of 1 indicate perfectly linear positive correlation, while $\rho = 0$ indicates no correlation. A p value < 0.05 indicates a statistically significant relationship.

1.1.1 Compilation of Existing Data

1.1.1.1 Exhumation Rates from Thermochronometry

We compiled time-averaged exhumation rates in our study area which show an approximately three-fold increase in exhumation from ~0.5 mm/y at the western extent of the SYM to ~1.8 mm/y at the eastern extent (Fig. 1.2, Table 1.S1). Two of these exhumation rate estimates come from collection samples collected along elevation transects with exhumation estimated via age-depth relationships (Townsend et al., 2021). Townsend et al (2021) analyzed samples for Apatite (U-Th-Sm)/He ages (Ap-He) and Zircon (U-Th)/He (ZHe) ages, and used these ages, in conjunction with one previously existing Apatite Fission Track (Ap FT) age (White, 1992) in an inverse thermal model (QTQt, Gallagher, 2012) to develop thermal histories. This analysis shows a systematic increase in exhumation rate from ~0.9 mm/y at Rattlesnake Canyon (~85 km east of Point Conception) to ~1.2 mm/y at the eastern extent of the SYM (Matilija Canyon, ~130 km east of Point Conception), and further increases to up to ~1.6 mm/y in the Topatopa Mountains further to the east (Fig. 1.1, Table 1.S1).

The remaining exhumation rate estimates come from Ap FT data collected by White (1992). White (1992) estimated uplift rates ranging from ~0.5 mm/yr to ~1.8 mm/yr based on their Ap FT tracks and assuming a closing temperature of 110°C and a geothermal gradient of 30°C/km to estimate the depth associated with the start of the fission track chronometer. While White (1992) did not report the results of this calculation for all their Ap FT, we have performed this same back-of-the-envelope calculation on all their data (excluding one sample in the far western extent of the study area that yields an Ap FT age older the lithologic age, indicating the sample was not rest) to provide a crude approximation of the west to east gradient in exhumation. The White (1992) data shows a steady increase in exhumation moving from east to west across the study area. In one location (~130 km from Point Conception, Fig. 1.2) where exhumation rates from both White (1992) and Townsend et al. (2021) exist, the White (1992) sample yields exhumation rates ~50% higher than the Townsend et al. (2021) estimate (1.8

mm/yr vs. 1.2 mm/yr). While we interpret the Townsend et al. (2021) estimates to be more robust and likely more accurate (due to the use of modern techniques and collection of multiple samples) in estimating the exhumation rate magnitude, we interpret the consistent west to east increase in exhumation from the White (1992) Ap FT as being excellent evidence of a west to east increase in exhumation, even if the exhumation rate magnitude is not fully constrained. Pearson's ρ indicates a strong positive linear correlation ($\rho = 0.8$), while $p = 0.2$ indicates that this relationship is not statistically significant (Fig. 1.2). Combing both the White (1992) and Townsend et al. (2021) datasets yield cooling ages ranging from ~3 to ~10 My, thus, these exhumation rate estimates represent My timescales of uplift.

1.1.1.2 Uplift Rates from Marine Terraces

Multiple studies report uplift rates derived from marine terraces along the southern edge of the SYM (cite all the studies here, Table 1.S2). Estimating uplift rates from marine terraces requires both an accurate constraint on the age of the terrace and an accurate reconstruction of paleo sea level to determine the total vertical displacement of the terrace since its formation. Both dating techniques (e.g., (Rhodes, 2011) and paleo sea level reconstruction techniques (e.g., (Simms et al., 2016) have improved over the ~30 years since the first uplift estimates using marine terraces were reported in the study area.

The most recent uplift estimates from marine terraces come from Morel et al. (2021) who re-dated several marine terraces along the Santa Barbara coastline using a combination of radiocarbon, optically stimulated luminescence (OSL) on quartz and infrared stimulated luminescence on feldspar. Morel et al. (2021) calculated the magnitude of vertical uplift since terrace formation as the difference between the modern terrace elevation and the terrace elevation at the time of formation as given by a paleo sea level reconstruction (Simms et al., 2016). This uplift magnitude is used together with the terrace age to calculate an uplift rate (Fig. 1.1,2; Table 1.S2). The Morel et al. (2021) uplift rate estimates extend across the western half of our study area from Point Conception (the western extent of the SYM) to Isla Vista, CA (~ 65 km east of Point Conception) (Fig. 1.2). Marine terrace uplift rates are approximately constant at ~1.1 mm/y up until the SBSYF (~25 km from Point Conception). There is an apparent stepwise increase in marine terrace uplift rates to ~1.5 mm/y when crossing the SBSYF, followed by a steady decrease in uplift rates down to ~0.8 mm/y moving further east toward Isla Vista, CA (Fig. 1.2).

Gurrola et al. (2014) measured uplift rates in the eastern half of our study area. They used a combination of methods to date the first emergent marine terraces, including uranium-series dating on marine terrace corals, ^{14}C dating on shells and charcoals, OSL on quartz, and oxygen isotopic signatures on shells. These dating techniques were performed on all studied terraces and approximate terrace ages were calculated from these dates. Using Muhs et al. (2012)'s paleo-sea level reconstruction they calculated uplift rates for each terrace (Fig. 1.2). The Gurrola et al. (2014) data show a decrease in uplift rates from west to east ranging from ~1.8 mm/y near Isla Vista (~65 km from Point Conception) to ~0.5 mm/y further to the east (~95 km from Point Conception). Pearson's ρ indicates a negative linear correlation ($\rho = -0.3$), and $p = 0.3$ indicates that this relationship is not statistically significant (Fig. 1.2).

There is one location where both Morel et al. (2021) and Gurrola et al. (2014) calculated uplift rates on the same terrace. In this location (the Isla Vista/Ellwood Mesa terrace), samples yielded similar ages and both studies had similar paleo sea-level estimates, but the two studies differed on their estimate of the elevation of the first emergent terrace, resulting in marine terrace uplift rates that differ by over a factor of two (~0.8 mm/y versus ~1.8 mm/y in Morel et al. (2021) and Gurrola et al. (2014), respectively) (Table 1.S2).

1.1.2 New Cosmogenic Radionuclide Erosion Rates

1.1.2.1 Methods

To estimate denudation rates over shorter timescales, we collected and processed samples for both basin-averaged erosion rates and soil production rates using the cosmogenic nuclide ^{10}Be in quartz. Samples were collected in separate campaigns in 2004 and 2022-2023.

To estimate basin-averaged erosion rates we collected fluvially deposited sand at or near the outlet of eight streams (six on the south side and two on the north side of the main divide) draining the SYM (Fig. 1.1). In two neighboring catchments on the south flank of the range, we additionally collected sand at major tributary inputs to assess spatial variability in erosion rates within individual catchments (Fig. 1.1). For basin-averaged erosion samples collected in 2022-2023 sediment was sieved to 210-500 µm at the University of Nevada Reno (UNR) and then sent directly to the Purdue Rare Isotope Measurement Laboratory (PRIME) for quartz separation and purification, chemical preparation, and Accelerated Mass Spectrometry (AMS) instrument measurements.

Samples collected in 2004 were processed at Arizona State University and measured at the Center for AMS analysis at Lawrence Livermore National Lab.

We complement these basin-average samples with an additional eight soil-production rate estimates distributed on hillslopes throughout the SYM (Fig. 1.1). For all soil-production rate estimates, we collected material from soil-saprolite boundary. Soil production rate samples collected in 2022-2023 were all collected in shale units along the main crest of the SYM while. These samples were crushed to 425-750 µm using a disc mill and mortar and pestle at UNR and then put through a rigorous purification process at Purdue University. The first step of purification used pyrophosphoric acid, purifying fine-grained quartz, which is then put into a centrifuge to settle the quartz after acid treatment. Following selective dissolution in pyrophosphoric acid, the quartz is further purified gravimetrically using the heavy liquid lithium heteropolytungstate in a centrifuge. Heavy minerals such as zircon and rutile are separated and removed by freezing the centrifuge tip in liquid nitrogen. The remaining quartz is purified by repeated leaching in dilute HCl/HF or HNO_3/HF, and the quartz purity is assessed by ICP-OES determination of the aluminum content. After the quartz is pure, we use standard ^{10}Be chemistry methods. Soil production samples collected in 2004 were from hillslope adjacent to the nested tributaries sampled for basin-averaged erosion rates.

To convert measurements of ^{10}Be concentrations to soil production rates and basin-averaged erosion rates we used the online CRONUS-Earth online calculator version 3 (https://hess.ess. washington.edu, wrapper 3.0, erates 3.0, muons 3.1, validate_v2_input.m—3.0, constants 2020-08-26), with LSDn scaling and standard atmospheric model and LSDTopotools basin-averaged code, respectively (Mudd et al., 2016). For basin averaged erosion rates, we assumed zero topographic shielding (DiBiase, 2018). For soil-production rates, we calculated shielding using sample density, which we assumed to be 2,650 kg/m^3, and the depth of the soil-saprolite boundary where the sample was taken from following Heimsath et al. (1997) (Tables S3, S4, S5).

1.1.2.2 Results and Discussion

^{10}Be-derived basin-averaged erosion rates in the SYM range from 0.16 ± 0.049 to 0.41 ± 0.62 mm/y. Assuming an average sediment density of 1700-2650 kg/m^3 (porosity dependent) (Heimsath et al., 1997) and a cosmic ray penetration depth of 60 cm (Granger et al., 1996), our cosmogenic radionuclide data average erosion rates over a timescale of ~4-7 ky. We use the basin-average erosion to examine trends in spatial variability in erosion across the SYM. While there is an ~60% increase in basin-average erosion rates from west to east across the range (rates of 0.18 ± 0.05 mm/y at Point Conception to rates of 0.28 mm/y ± 0.06 mm/y at ~124 km from Point Conception), this trend is not statistically significant (ρ =0.3, p = 0.4).

For one basin (Refugio Creek) that was sampled both in 2004 and 2022, we observe a factor of ~2 different in erosion rates (0.41 ± 0.62 mm/y from the 2004 sample versus 0.17± 0.048 mm/y in the 2022 sample) (Fig. 1.2 or 3, Table 1.S4). The Refugio Creek watershed and the neighboring El Capitan Creek watershed were the locations for our nested tributary sampling in 2004. The two nested tributary samples in the Refugio Creek watershed also differ by a factor of ~2 (0.36 ± 0.29 mm/y and 0.16 ± 0.037 mm/y), whereas in the neighboring El Capitan watershed nested tributary erosion rates are largely similar (0.21 ± 0.087 mm/y, 0.26 ± 0.25 mm/y, and 0.27 ± 0.25 mm/y) and match the erosion rate estimated on the mainstem near the basin outlet (0.26 ± 0.18 mm/y) (Fig. 1.3).

In the eastern portion of the SYM, both the San Ysidro and Santa Ana watersheds yielded relatively high basin-average erosion rates of 0.31 ± 0.09 mm/y and 0.28 ± 0.06 mm/y, respectively (Fig. 1.3). San Ysidro Creek experienced a large degree of scour and sediment remobilization during the 2018 Montecito post-wildfire debris flow event (Morell et al., 2021). Previous work sampling sediment before and after debris flows shows an increase in ^{10}Be-derived erosion rates by a factor of two following large debris flow events (Kober et al., 2012) and we posit that our ^{10}Be-derived basin averaged erosion rate for San Ysidro Creek may be artificially high relative to our other sampled catchments that did not experience large debris flows in the 2018 Montecito. Similarly, the Santa Ana watershed experienced a high degree of scour and sediment remobilization in flooding during atmospheric river events in winter 2022-2023 that was visible during our sampling in February 2023. This flooding may also result in elevated cosmogenic radionuclide erosion rates. In contrast, other basin-averaged erosion estimates reported here came from catchments that were not recently affected by recent debris flow activity.

^{10}Be derived soil production rates in the SYM range from 0.04 ± 0.002 to 0.28 ± 0.05 mm/y, similar in magnitude to the basin-average erosion rates (Table 1.S3). Soil production rates show no obvious west to east gradient across the range; however, samples from hillslopes in the Refugio and El Capitan watersheds are typically lower (~0.09 mm/y to 0.14 mm/y) than both the nested tributary and basin-averaged erosion rates for those watersheds (Figs. 1, 2, 3) and lower than the soil production rates on the range crest which range from ~0.0371 to 0.28 mm/y.

1.2 COMPARISON OF UPLIFT RATES ESTIMATED OVER KY TO MY TIMESCALES

Our newly collected cosmogenic nuclide erosion rates and compilation of previously reported uplift rates from marine terrace dating and thermochronology average uplift and erosion over timescales from ~5 ky to ~50 ky to >1 My, respectively. Uplift rates from marine terrace dating are approximately an order of magnitude higher than the cosmogenic radio nuclide erosion rates, and exhumation rates from thermochronology are intermediate between the two (Fig. 1.2). Furthermore, the thermochronology-derived exhumation rates show an approximately threefold increase from west to east across the SYM, whereas the marine terrace data suggests a step-wise increase in uplift crossing the Southern Branch of Santa Ynez Fault followed be a decrease in uplift moving further to the east, and the ^{10}Be derived basin averaged erosion rates show no statistically significant change in erosion rate from west to east.

These data raise two important questions for the region, for which we can primarily only speculate answers to. First, what is controlling the order of magnitude difference in rates between the marine terrace and cosmogenic nuclide data? The CRN data are recording erosion rates over ~5 ky, while the marine terraces are recording uplift rates over ~50 ky. The data indicate that, at minimum, over the last ~5 ky the region is experiencing transience with uplift out competing erosion.

Second, why do these three methods yield different spatial trends in uplift and erosion across the SYM? The exhumation rate gradient from west to east is most likely associated with the eastward migration of the San Canteyano Fault (Fig. 1.1) (Townsend et al., 2021). The slight increase in uplift rate that spatially correlates with the SBSYF indicates that uplift occurring over the last ~50 ky could be related to Quaternary faulting; however, it is difficult to test with our cosmogenic data if there is also a statistically significant increase in basin average erosion rates across the SBSYF. The complexity of the tectonic forcings in this region are clearly impacting the SYM landscape evolution and it is possible that the marine terraces are recording a change in tectonics in the last ~50 ky. In the sections below, we both quantify rock strength within our study area and performed topographic analyses to get better constraints on spatial variation in uplift as recorded in the topography of the SYM.

1.3 QUANTIFICATION OF ROCK STRENGTH

Exploring how spatial and temporal variations in uplift are recorded by topography within the SYM requires quantifying spatial variability in rock strength across the range. The SYM (Duvall et al., 2004) and countless other landscapes (e.g., Bernard et al. (2019); Gailleton et al. (2021)) have been shown to adjust their morphology in response to lithologic heterogeneity. Here, we add to the Schmidt hammer rebound dataset from Duvall et al. (2004) and use this new, enlarged dataset to classify lithologic units in the SYM as either weak, moderate strength, or hard.

1.3.1 Methods

We quantified rock strength using a type-N Schmidt hammer to make point-measurements of rebound values on bedrock outcrops. These measurements follow similar methods and complement an existing database of 986 rebound values collected on bedrock exposed in river channels (Duvall et al., 2004) (Table 1.S6). We collected an additional 1,625 rebound values at 32 different locations in August 2023 (Table 1.S6). Our measurements cover the twelve major lithologies exposed in the study area (including 5 lithologic units not previously measured), and were collected at bedrock outcrops exposed in road and trail cuts as well as bedrock in river channels (Table 1.S6). In all locations, we made measurements on intact, competent rock (removing any weathered bedrock, if present, prior to measurements). We sampled each lithologic unit in at least two different outcrop locations (separated by between minimum of 0.5 km), and we took a minimum of 50 rebound measurements at each sampling location (Fig. 1.1). For each lithologic unit, we combined the new measurements collected here and pre-existing measurements (Duvall et al., 2004) to report a representative rebound value as the median value averaged across all measurements with rebound values greater than 10, $\widetilde{R}$ (Fig. 1.4). Rebound values less than 10 were below the detection limit of our Schmidt hammer, and we report these measurements as 'no rebound' and calculated the total fraction of no rebound measurements within each lithology as $f_{nr} = N_{no\_rebound} / N_{total}$ where $N_{no\_rebound}$ and N_{total} are the total number of no rebound measurements and the total number of measurement (including no rebound and rebound value) made within in a given lithologic unit, respectively (Fig. 1.4). For each lithologic unit, we used the median rebound value, the fraction of no rebound values, lithologic descriptions (Dibblee, 1982), and our field observations to categorize lithologic units as either weak, moderate, or hard rock strength.

After classifying lithologic units as weak, moderate, or hard, we also calculated the relative abundance of each rock strength category moving from west to east across the study area. We did this by measuring the fraction of area of each rock strength category in thirty-five ~3.8 km wide swaths distributed across the range (Fig. 1.1).

1.3.2 Results

Across all twelve lithologic units, median Schmidt Hammer rebound values ranged from $\sim 10 < \widetilde{R} < \sim 40$ and the fraction of no rebound values within a given lithology ranged from $0.0 < f_{nr} < 0.7$ (Fig. 1.4, Table 1.S6). The Rincon, Cozy Dell, Juncal and Jalama Formations are composed of shales, siltstones, and thin beds of unconsolidated sandstones. These units were unique relative to the other measured lithologies in that they had both relatively low rebound values ($12 < \widetilde{R} < 22$) and a high fraction of no rebound returns ($0.5 < f_{nr} < 0.8$). We used this data, combined with our field observations that these units were very easily weathered and friable, to classify these units as weak in rock strength (Fig. 1.4, Table 1.S6).

The Alegria, Coldwater, Sespe, and Vaqueros Formations are primarily weakly consolidated sandstones, with occasional conglomerate layers (Dibblee, 1982). These units also comprised a unique grouping in that they had relatively low rebound values ($19 < \widetilde{R} < 22$), but, unlike the weak units, these formations had a relatively low fraction of no rebound returns ($0.0 < f_{nr} < 0.2$). We use these data as justification to classify these lithologies as moderate in rock strength (Fig. 1.4, Table 1.S6).

Finally, we classified the remaining lithologic units (the Gaviota, Matilija, Monterey and Sacate formations), as hard in rock strength. The Gaviota and Matilija formations were classified as hard based on the combination of their relatively high rebound values ($30 < \widetilde{R} < 38$) and their low fraction of no rebound returns ($0.01 < f_{nr} < 0.02$) (Fig. 1.4, Table 1.S6). The Gaviota and Matilija formations are composed primarily of well consolidated, thick-bedded sandstones (Dibblee, 1982). The Monterey formation outcrops primarily as resistant chert with minor siltstone and shale outcrops, and due to the high $\widetilde{R}$ value (28) we classified the Moneterey as hard in rock strength despite $f_{nr} = 0.2$ (Dibblee, 1982). The Sacate formation is extremely heterogenous and outcrops with interbedded hard sandstone beds ranging from ~0.2-1m thick with weak siltstones and shales interbedded at similar bedding scales (Dibblee, 1982). The Sacate $\widetilde{R}$ value of 32 with $f_{nr} = 0.4$ was difficult to categorize. We chose to classify the Sacate as hard in rock strength following Duvall et al. (2004) despite the high f_{nr} value (Fig. 1.4, Table 1.S6).

Our rock strength classification is like that proposed by Duvall et al. (2004) but adds an intermediate strength category to allow for more detailed examination of the role of rock strength. Examining the distribution of rock strength along the southern flank of the SYM shows that the relative proportion hard lithologies decreases from west to east, while moderate lithologies show a non-monotonic increase in area and the proportion of weak units stays approximately constant (Fig. 1.2).

1.4 INFLUENCE OF ROCK STRENGTH AND VARIABILITY IN TECTONIC FORCING ON TOPOGRAPHY

Previous studies indicate that rock strength and uplift rate control channel morphology in the SYM (Duvall et al., 2004). Here we strive to add to that understanding through a detailed channel and hillslope morphology analysis on the south flank of the Santa Ynez.

1.4.1 Theoretical Background and Methods

The analysis of channel morphology to link topography and tectonics has resulted in a large suite of quantitative tools to link the two (e.g., Ahnert, 1970; Goren, 2016; Hack, 1960; Kirby & Whipple, 2012; Schoenbohm et al., 2004; Seagren & Schoenbohm, 2019; Willett & McCoy, 2014). Most topographic analyses linking river profiles and tectonic forcing start from the observation that channel slope (S) and drainage area (A) are related,

$$S = k_s A^{\theta} \qquad (1),$$

where the exponent θ is commonly referred to as the concavity index, and k_s is channel steepness and represents channel slope normalized for drainage area. Combining this observation with the stream power incision model,

$$E = KA^{m}S^{n} \qquad (2)$$

where K is an erodibility coefficient that incorporates lithology, climate variability and more, and m and n are empirical constants, and assuming $\theta = m/n$ and steady state (i.e., erosion is equal to uplift, U), allows solving for channel steepness, allows solving for channel steepness as (e.g., Kirby and Whipple, 2012, Wobus et al., 2006).

$$k_s = (U/K)^{1/n} \qquad (3)$$

Equation 3 suggests that in landscapes with uniform K and n, channel steepness should track with tectonic uplift. In practice, the concavity index varies across and within landscapes, so inferring uplift from channel steepness requires setting a reference concavity index, θ_{ref}, and calculating a normalized channel steepness, k_{sn},

$$k_{sn} = S/A^{\theta ref} \tag{4}$$

This approach has been shown to allow for inferring variation in uplift in landscapes from solely from topographic measurements of channel slope and drainage area (e.g., Whipple et al., 2022; Kirby and Whipple, 2012). However, this approach can break down in cases with spatially heterogeneous rock strength and/or climate.

There have been recent advances in quantitively separating topographic signals related to varying lithology and tectonics in the same landscape (e.g., Gailleton et al., 2021)). In a classic channel steepness analysis, a single θ_{ref} is to output a single k_{sn} for the entire landscape. Gailleton et al. (2021) used a Monte Carlo approach and input θ_{ref} and k_{sn} iteratively within each channel reach segment (limited by DEM resolution) for each channel of a landscape. To do this Gailleton et al. (2021) went back to the basic parameters that define a channel's steepness: S, A, and θ. These parameters change within a single channel depending on the length of channel over which you are calculating them; hence the development of θ_{ref} and k_{sn}. By calculating the landscapes range of k_s based on its range of S, A, and θ for a set length of channel and iterating throughout the landscape, Gailleton et al. (2021) found the median channel steepness of a landscape. From this, Gailleton et al. (2021) developed a modified z-score approach that relates the median channel steepness of the study area's landscape to the channel steepness indices in the rest of the landscape (Gailleton et al., 2021) which is called the relative channel steepness ($M_{i,j}$), defined as:

$$M_{i,j} = 0.6745 \times (k_{sn,i,j} - \tilde{k}_{sn,j})/MAD_j \quad (4),$$

where the median absolute deviation (MAD) for parameter combination (MAD_j) is

$$MAD_j = \text{median}(|k_{sn,i,j} - \tilde{k}_{sn,j}|) \quad (5),$$

With subscripts i and j refer each pixel and parameter, respectively. The k_{sn} within equations (4) and (5) are z-score population values that are calculated with the parameters j: number of nodes (in the case of a digital elevation model (DEM) this would be equal to pixels, which are m in the case of channel morphology analysis) (n_{tg}), the number of nodes to skip when performing this analysis iteratively up a channel length (n_{sk}), and θ, based upon the minimum segment length that is being iterated over, for each pixel i. We determined our range of θ to be 0.1-0.8 following Mudd (2018), and chose the other $M_{i,j}$ parameters based upon Mudd et al. (2014) and our knowledge of the landscape to be n_{tg} from 10 to 100 with a spacing of 10, n_{sk} from 0 to 4 with a spacing of 1, and a minimum segment length of 10 (Clubb et al., 2017). In addition, we incorporated a parameter sigma (σ) that accounts for geomorphic variability that can be detected on a DEM (Mudd et al., 2014); chose $\sigma = 3$ m for our analysis in order to smooth channel boulders but not exclude any possible knickpoints that would be detectable on a 10 m DEM. We performed our $M_{i,j}$ analysis on the southern flank of the Santa Ynez, with a threshold drainage area of 1 km^2 (most basins $A = \sim 10\text{-}20$ km^2), totaling 57 basins for our channel morphology analysis (Fig. 1.1).

This resulted in over 80,000 median $M_{i,j}$ values for our study area (Table 1.S8). These values are interpreted in the following way: a $M_{i,j}$ value of 0 is the median channel steepness for the study area, with positive values indicating statistically steeper channels, and negative values statistically gentler channel slopes (Gailleton et al., 2021) (Fig. 1.1, Table 1.S8).

To analyze this data in conjunction with the rest of the study, we calculated the median relative channel steepness for each basin (Fig. 1.2). To determine the influence of rock strength on relative channel steepness we performed the same analysis as above, but include only median $M_{i,j}$ values that intersect with weak, moderate, and hard rock strength categories in each basin before taking the median of those values (Fig. 1.2).

We paired our relative channel steepness measurements with measurements of mean hillslope gradient. Mean hillslope gradient has been shown to increase with increasing uplift rate in landscapes up to a a threshold hillslope angle (S_c) above which further increases in uplift are accommodated by increasing landsliding (Burbank et al., 1996; Roering et al., 2001; DiBiase et al., 2012; Larsen and Montgomery, 2012).

Like our relative channel steepness analysis, we measured the variation in mean hillslope gradient across the southern flank of the SYM to assess if there are spatial variations in hillslope gradient that can be associated with variation in rock uplift. To perform this analysis, we divided the southern flank of the range into thirty-five equally spaced 3.8 km-wide swaths which extended from the range crest to the mountain front (Fig. 1). Within each swath, we used the Matlab package Toptoolbox arcslope function (Schwanghart and Scherler, 2014) which calculates the mean gradient in a pixel from its

8 neighboring pixels. We performed these calculations on 1 m^2 resolution lidar available from the USGS 3D Elevation Program. To ensure our measurements came primarily from hillslopes, we attempted to filter out channels, terraces, and floodplains by removing all pixels with slope < 5^o and then calculating median hillslope gradient in each swath on the remaining pixels. To determine the influence of rock strength on mean hillslope gradient we repeated this analysis on each swath and collected the mean hillslope gradient for pixels underlain by lithologies classified as weak, moderate, and hard rock strength separately respectively (Fig. 1.2, Table 1.S7). Performing our hillslope analysis on range-perpendicular swaths, rather than individual drainage basins as done for the relative channel steepness analysis, allows us to sample all hillslopes present in the study area, including hillslopes in small catchments not included in the channel steepness analysis (Fig. 1).

1.4.2 Results

Basin median $M_{i,j}$ values calculated across all rock strength categories range from -0.75 ±0.13 to 2.45 ± 1.95 for the 57 watersheds in our study area (Figs. 1 and 2). $M_{i,j}$ values are variable, but show a statistically significant increase from west to east along the southern flank of the SYM as quantified by the Pearson correlation coefficient (ρ = 0.35, p = 0.009) (Fig. 1.2). There is an abrupt increase in $M_{i,j}$ coincident with crossing from west to east across the SBSYF (Figs 1 and 2). East of the SBSYF ~26% of channels have $M_{i,j} < 0$ (Figs 1, 2). $M_{i,j}$ values within hard, moderate, and weak rock strength categories for each basin range from: -0.42 ± 0.004 to 4.70 ± 1.8, -0.70 ± 2.23 to 2.20 ± 1.75, -0.84 ± 0.31 to 2.83 ± 0.88, respectively (Table 1.S8). Channel segments underlain by harder rock units tend to have higher $M_{i.j}$ values than channel segments underlain by moderate strength or weak rock, consistent with the idea that channel slope is sensitive to rock strength Korup et al. (2008).

Mean hillslope angle for all lithologies ranges from 24 ± X to 35° ± 10° for the 3.8 km wide swaths (Fig. 1.2). Mean hillslope gradient shows a systematic and statistically significant increases from ~2X degrees in the west to ~30-35 degrees in the east ($\rho = 0.76$, $p < 10^{-3}$) (Fig. 1.5). Hillslope angle values within hard, moderate, and weak rock strength categories range from approximately 24° to 43°, 28° to 34°, 23° to 37°, respectively (Fig. 1.2). Mean hillslope gradient and $M_{i,j}$ show a statistically significant correlation ($\rho = 0.43$, $p = 0.01$) (Fig. 1.5).

1.5 COMPARISON OF TOPOGRAPHIC METRICS WITH SPATIAL AND TEMPORAL VARIATION IN UPLIFT RECORDED BY THERMOCHRONOLOGY, MARINE TERRACE DATING AND COSMOGENIC RADIONUCLIDES.

The thermochronology compilation from the literature shows a clear west to east increase in exhumation rates, whereas this is not reflected in the marine terrace record from the literature or the new CRN erosion rate data (Fig. 1.2). This west to east increase in exhumation is reflected in the topography by the increase in median hillslope gradient. We interpret this to suggest that the broadscale hillslope and relief is set predominately by million-year timescale processes in uplift rather than more recent tectonic activity. Unlike the hillslope gradients, our relative channel steepness analysis suggest bedrock rivers may be recording tectonic forcing over multiple timescales, as we see both an abrupt increase in relative channel steepness crossing the SBSYF, consistent with the marine terrace uplift data, and a more general west to east increase in median channel steepness consistent with the My timescale exhumation data (Fig. 1.2).

Unlike previous studies that have found correlations between topographic metrics and basin-averaged erosion rates derived from cosmogenic radionuclides (e.g., (Binnie et al., 2007; DiBiase et al., 2010, 2023; DiBiase, 2018) we observed no statistically-significant correlation between our basin averaged cosmogenic erosion rates and either $M_{i,j}$ ($\rho = 0.45$, $p=0.2$) or mean hillslope gradient ($\rho = 0.25$, $p = 0.5$).

We interpret both variation in uplift and erosion over ky to My timescales as parametrized by thermochronology, marine terrace dating and cosmogenic nuclides, as well as the lack of correlation between topographic metrics and basin-average erosion rates to suggest that the landscape is in a state of transience. The fact channels seem to be recording the change in uplift across the SBSYF, but that this is not reflected in the hillslope gradients suggests that river channels may be responding faster to recent perturbations in tectonic forcing than hillslopes, in contrast to studies showing relatively rapid hillslope response relative to upstream knickpoint propagation (e.g., (Hurst et al., 2012).

1.6 CONCLUSIONS

Our study shows that while topography does respond to variation in tectonic forcing and rock strength, the timescales of response can vary. In the SYM, hillslopes appear to recording My timescale gradients in exhumation rate, whereas channel steepness appears to record both shorter timescale forcing as evidence by the agreement between M_{ij} and the marine terrace uplift estimates (averaging over ~50 ky) showing abrupt increases in uplift across the SBSYF, and longer timescale forcing as shown by the general west to east increase in M_{ij} across the range, consistent with the My timescale thermochronolgy data. Estimates of basin averaged erosion in the SYM averaging over ~5 ky timescales show order of magnitude lower rates than the marine terrace uplift rates, suggesting that the landscape is in transience.

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FIGURES

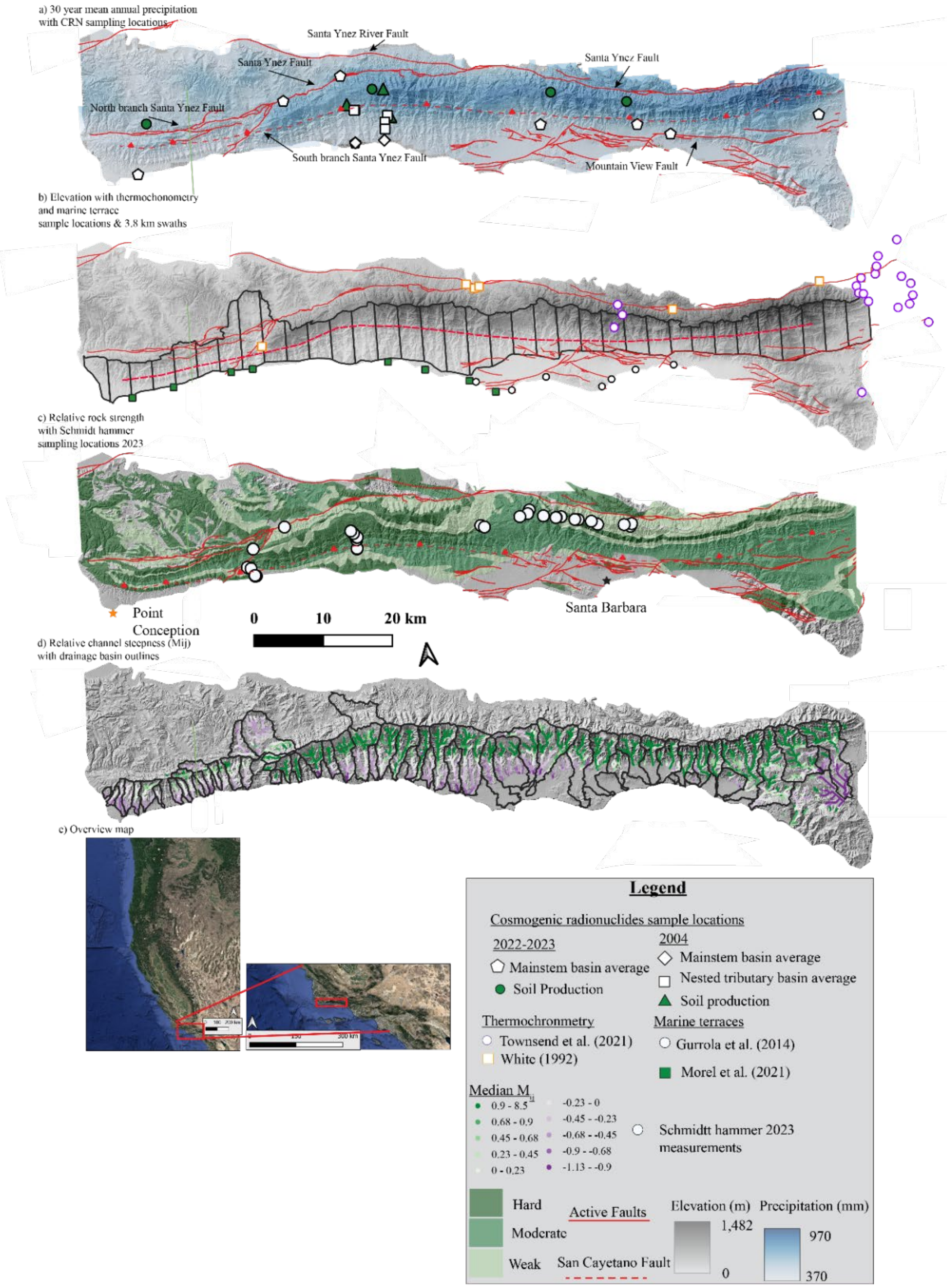

a) 30 year mean annual precipitation
with CRN sampling locations
Santa Ynez River Fault
Santa Ynez Fault
Santa Ynez Fault
North branch Santa Ynez Fault
South branch Santa Ynez Fault
Mountain View Fault
b) Elevation with thermochonometry
and marine terrace
sample locations & 3.8 km swaths
c) Relative rock strength
with Schmidt hammer
sampling locations 2023
Point
Conception
Santa Barbara
0
10
20 km
d) Relative channel steepness (Mij)
with drainage basin outlines
e) Overview map
Legend
Cosmogenic radionuclides sample locations
2022-2023
Mainstem basin average
Soil Production
2004
Mainstem basin average
Nested tributary basin average
Soil production
Thermochronmetry
Townsend et al. (2021)
White (1992)
Marine terraces
Gurrola et al. (2014)
Morel et al. (2021)
Median M_ij
0.9 - 8.5
0.68 - 0.9
0.45 - 0.68
0.23 - 0.45
0 - 0.23
-0.23 - 0
-0.45 - -0.23
-0.68 - -0.45
-0.9 - -0.68
-1.13 - -0.9
Schmidtt hammer 2023
measurements
Hard
Moderate
Weak
Active Faults
San Cayetano Fault
Elevation (m)
1,482
0
Precipitation (mm)
970
370

Figure 1.1: Overview of the Santa Ynez Mountains, CA. a) Locations of CRN sampling from 2004 and 2022-2023 campaigns in relation to active faults and the San Cayetano fault. b) Thermochronometry and marine terrace sampling locations from Morel et al. (2021) and Gurrola et al. (2014) in relation to 3.8 km swaths and faulting. c) Simplified geologic map of relative rock hardness, locations of 2023 Schmidt hammer measurements, Point Conception location, and faulting in the study area. d) Map of relative channel steepness for the southern flank of the Santa Ynez Mountains and all drainage basins for the study. e) Overview of the western United States, red box shows inset map of the Santa Barbara and Los Angeles, CA area with a red box indicating our study area.

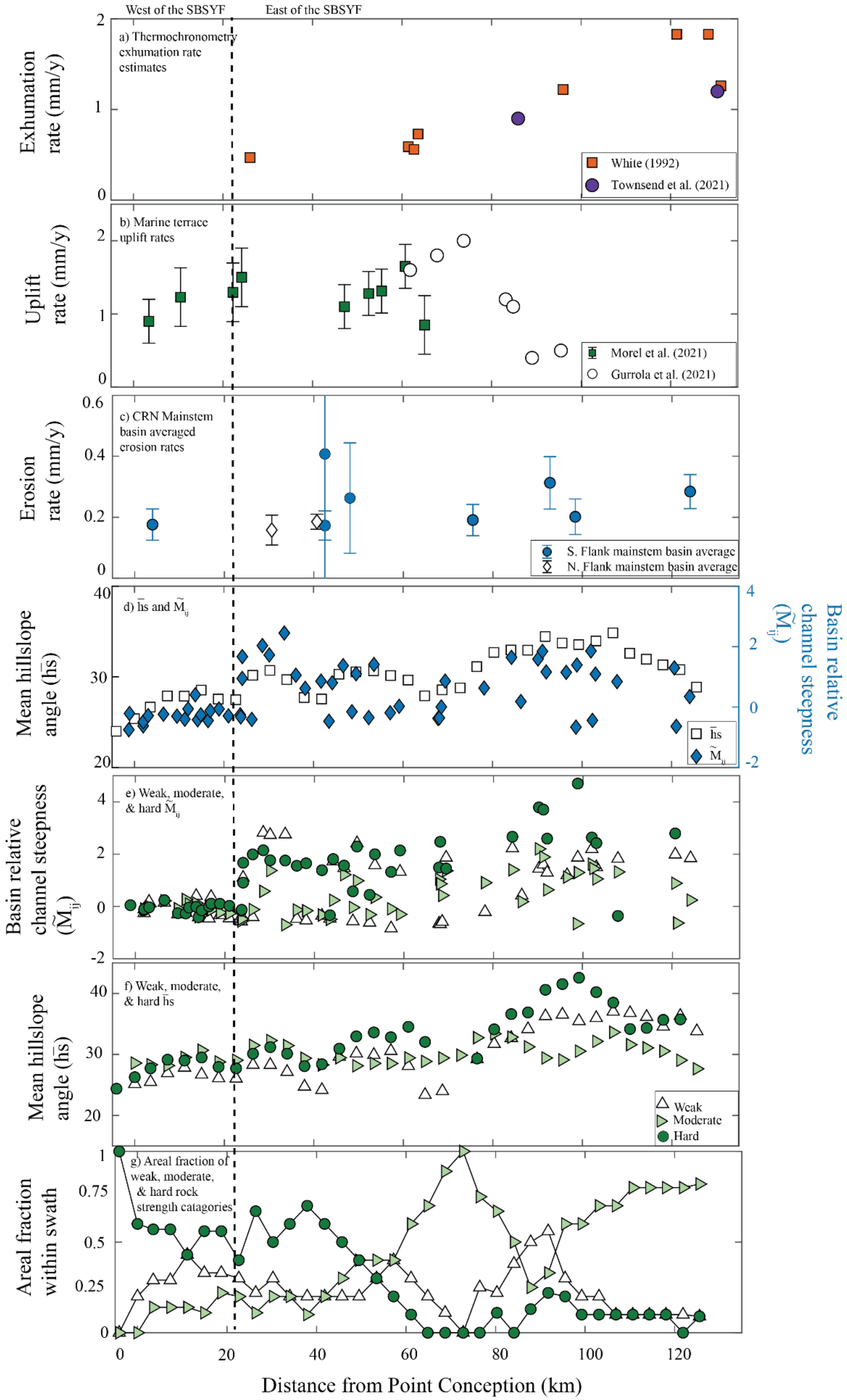

West of the SBSYF
East of the SBSYF
a) Thermochronometry exhumation rate estimates
Exhumation rate (mm/y)
White (1992)
Townsend et al. (2021)
b) Marine terrace uplift rates
Uplift rate (mm/y)
Morel et al. (2021)
Gurrola et al. (2021)
c) CRN Mainstem basin averaged erosion rates
Erosion rate (mm/y)
S. Flank mainstem basin average
N. Flank mainstem basin average
d) h̄s and M̃ij
Mean hillslope angle (h̄s)
Basin relative channel steepness (M̃ij)
h̄s
M̃ij
e) Weak, moderate, & hard M̃ij
Basin relative channel steepness (M̃ij)
f) Weak, moderate, & hard h̄s
Mean hillslope angle (h̄s)
Weak
Moderate
Hard
g) Areal fraction of weak, moderate, & hard rock strength catagories
Areal fraction within swath
Distance from Point Conception (km)
0
20
40
60
80
100
120

Figure 1.2: Summary of compiled thermochronometry and marine terrace uplift rates, new cosmogenic radionuclide basin average erosion rates, and topographic metrics versus distance from Point Conception. The approximate distance from Point Conception of the South Branch of the Santa Ynez Fault (SBSYF) is indicated with a dashed line, left of this line is west of the SBSYF and right of this line is east of the SBSYF. a) Compiled thermochronometry data from Townsend et al. (2021) and White (1992) showing exhumation rate estimates. b) Compiled marine terrace uplift rates from Morel et al. (2021) and Gurrola et al. (2014). Error shown as standard error. c) New CRN mainstem basin average erosion rates collected in 2004 and 2022-2023. Note the difference in y axes values in comparison to uplift and exhumation rate data due to lower rates from CRN data. d) Basin median relative channel steepness values and whole swath mean hillslope angle values. e) Basin median relative channel steepness values for weak, moderate, and hard rock strength categories. f) Mean hillslope angle for weak, moderate, and hard rock strength categories. g) Areal fraction of weak, moderate, and hard bedrock within 3.8 km swaths.

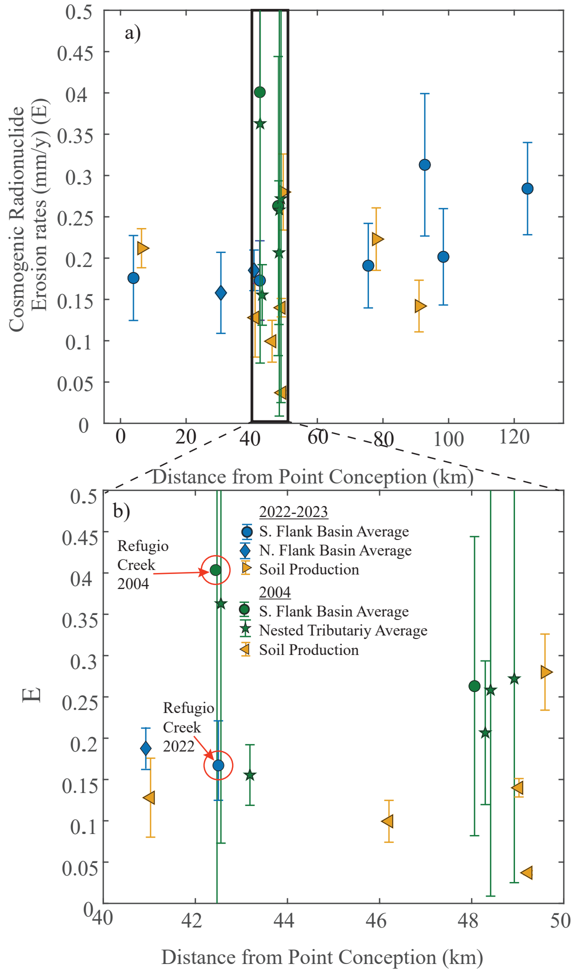


Figure 1.3: All cosmogenic radionuclide data from 2004 and 2022-2023 campaigns versus distance from Point Conception. Error is total uncertainty (instrumental and external). a) All CRN data, black box shows location of area with a high density of data which is expanded in b). b) Data from 40-50 km from Point Conception to show Refugio Creek and El Capitan Creek data clearly.

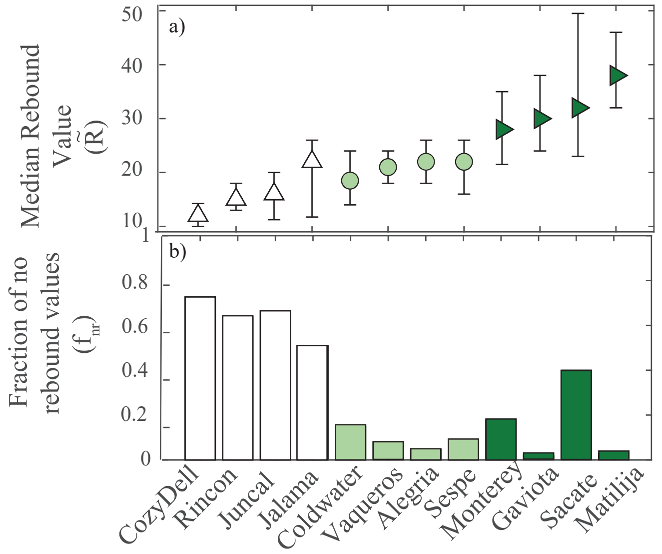


Figure 1.4: Schmidt hammer rebound values from Duvall et al. (2004) and August 2023 measurements. a) Median rebound value for each lithologic unit with interquartile range error shown. b) Fraction of no rebound values for each lithologic unit.

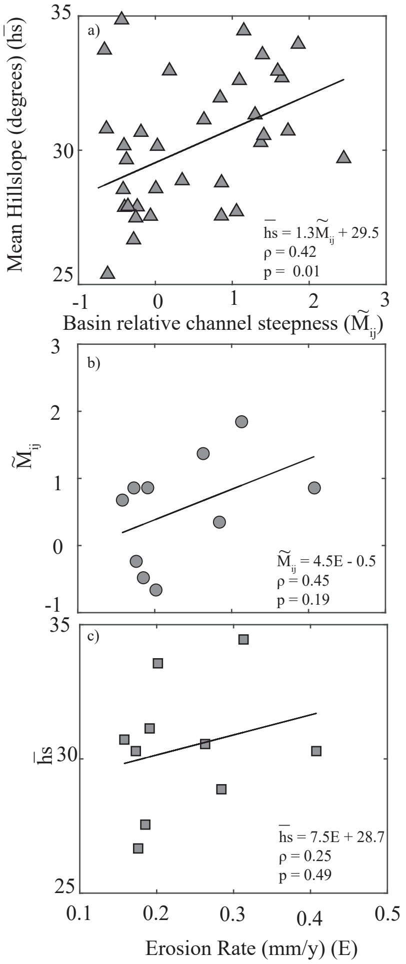


Figure 1.5: Correlation plots and Pearson coefficients (significant $p < 0.05$, ρ 0.2) for mainstem basin average erosion rates from CRN, basin median relative channel steepness, and mean hillslope angle for the southern flank of the Santa Ynez Mountains a) Mean hillslope angle versus basin median relative channel steepness. b) Basin median relative channel steepness versus erosion rate. c) Mean hillslope angle versus erosion rate.

SUPPLEMENTAL TEXT

Cosmogenic ^{10}Be in quartz from shale and siltstone

The quartz purification chemistry that we use is based on that of Talvitie (1951), who used pyrophosphoric acid to separate quartz in airborne dust for assessing silicosis hazard. Talvitie showed that pyrophosphoric acid will only negligibly dissolve quartz, while completely dissolving most other minerals--especially aluminosilicates--in minutes. The method was scaled for cosmogenic nuclide sample preparation by Granger in his dissertation (1996), and a version was published by Mifsud et al. (2013). The main difficulty with purifying fine-grained quartz with this method is that the quartz dust is easily suspended in the viscous acid. We use a centrifuge to settle the quartz after acid treatment, which does an excellent job at collecting the grains within a few minutes at most. Following selective dissolution in pyrophosphoric acid, the quartz is further purified gravimetrically using the heavy liquid lithium heteropolytungstate (LST) in a centrifuge. Heavy minerals such as zircon and rutile are separated and removed by freezing the centrifuge tip in liquid nitrogen. The remaining quartz is purified by repeated leaching in dilute HCl/HF or HNO_3/HF, and the quartz purity is assessed by ICP-OES determination of the aluminum content. After the quartz is pure, we use standard ^{10}Be chemistry methods.

We intentionally select grain sizes greater than about 15 microns to avoid any effects due to recoil or implantation associated with cosmogenic nuclide production. Typical recoil lengths associated with cosmogenic nuclide production are 2-3 microns (Ott & Begemann, 2000; Trappitsch & Leya, 2013), so very small grains will potentially be subject to significant losses. It is likely that most recoil losses will be balanced by implantation from neighboring minerals in rocks.

In detail, the quartz preparation and chemistry procedure is as follows:

1) The sample is crushed to <0.5 mm.
2) It is oxidized in a furnace at 800°C for 10 hours in an unlidded ceramic crucible to remove organics.
3) The oxidized sample is boiled in 25% sodium hydroxide for 30 minutes to dissolve some clays.
4) It is transferred to a centrifuge bottle and rinsed with deionized water. It is centrifuged prior to decanting the water.
5) Transfer to a 500 ml polypropylene bottle, add 2.5M HCl and ultrasonicated 6-8 hours. The sample is allowed to settle overnight before decanting the acid solution.
6) The sample is triple-rinsed with deionized water and allowed to settle until the water is clear.
7) Transfer the sample together with 15 g sodium hexametaphosphate into a 1-liter bottle filled with deionized water. Ultrasonicate for 1.5 hours. The sample is diluted by a factor of two.

8) The bottle is shaken and allowed to settle for one hour. The uppermost 13 cm of solution is removed by gentle pumping from above with a tube to remove clays, and repeated 3 times.
9) The bottle is shaken and allowed to settle for 15 minutes. The uppermost 15 cm of solution is removed by pumping from above with a tube to remove grains <15 microns. By Stokes Law, all grains with an effective diameter >15 microns will have settled more than 15 cm in that time. The grain size separation is repeated 5 times.
10) For your samples, some grains were still observed to be cemented, so the sample was ultrasonicated and step 9 was repeated.
11) The remaining sample is oven-dried and massed.
12) Approximately 40 g of sample is introduced into a round-bottom flask with 400 ml of phosphoric acid. The flask is heated to 240°C, converting the acid to pyrophosphoric acid. It is held at 240°-250°C for 30 minutes to dissolve non-quartz minerals.
13) The acid is allowed to cool to <100°C and is decanted and rinsed into centrifuge bottles. The bottles are centrifuged to settle the remaining minerals in the bottoms of the bottles, and the solution is decanted. The remaining material is rinsed with water and centrifuged.
14) The sample is boiled in 25% NaOH for 10 minutes to dissolve amorphous silica.
15) The alkali solution is allowed to cool to <100°C and is decanted and rinsed into centrifuge bottles. The bottles are centrifuged to settle the remaining minerals in

the bottoms of the bottles, and the solution is decanted. The remaining material is triple rinsed with water and centrifuged.

16) The sample is oven-dried and massed. If multiple batches of pyrophosphoric acid treatment were required, they are combined at this time.
17) The sample is placed in a 50 ml centrifuge tube with sufficient lithium heteropolytungstate (LST) at density 2.68 to float the quartz (typically 20-30 ml). The tube is then centrifuged to separate the heavy minerals to the bottom. The tube is gently agitated to disperse the light fraction, and centrifuged again. The heavy minerals are frozen into the end of the tube by submerging the tip into liquid nitrogen, or else gently separated by pouring. The light mineral fraction is decanted to another 50 ml centrifuge tube and rinsed to collect the quartz.
18) The remaining minerals are very nearly 100% quartz. The quartz is put into a centrifuge bottle and agitated in 1%HF/1M HCl overnight for cleaning and etching the outside of the mineral grains. This step quantitatively removes any meteoric ^{10}Be contamination. After centrifugation, the acid is decanted and the sample is rinsed. The final leaching step is repeated for a total of 2 times. The sample is triple rinsed and dried, centrifuging each time.
19) A small aliquot (0.125 g) of quartz is removed and dissolved in 5:1 concentrated HF/HNO_3 to assay its purity by ICP-OES.
20) If the quartz is clean enough (with less than about 500 ppm aluminum), it is massed and dissolved in 5:1 HF/HNO_3.
21) A spike of beryllium carrier solution prepared in-house is added gravimetrically.
22) The sample is dissolved in a closed Savillex Perfluoroalkoxy (PFA) jar on heat.

23) After complete dissolution, the jar is opened, and 1-2 ml of concentrated H_2SO_4 is added as a keeper solution.
24) The acid is evaporated, volatilizing silica and leaving trace metals in solution in the remaining sulfuric acid puddle.
25) Sulfuric acid is mixed with water and transferred to a centrifuge tube, then taken to a neutral pH with the careful addition of sodium hydroxide. pH is determined with the addition of bromothymol blue as an indicator.
26) The pH is adjusted volumetrically to 14 with the addition of sodium hydroxide. This step removes nearly all elements by precipitation except aluminum and beryllium, which are amphoteric. The tube is centrifuged, and the solution containing Al and Be are decanted to a second centrifuge tube.
27) The pH in the second tube is adjusted to 7-8 with nitric acid, using ~1 ml of ammonium hydroxide as a buffer. This step precipitates Al and Be as hydroxides.
28) The hydroxides are centrifuged and rinsed twice with water. They are dissolved in 0.4M oxalic acid.
29) The oxalic acid solution is passed through a 2 ml anion exchange column (Dowex AG1-X8) to remove aluminum.
30) The solution drips from the anion column into a cation exchange column (Dowex AG50W-X8) to collect beryllium. The sample is rinsed with 10 ml 0.4M Oxalic Acid, followed by 10 ml of pure water.
31) Beryllium is eluted from the cation exchange column in 10 ml of 4M HNO_3, and precipitated by adjusting to pH 8 with ammonium hydroxide.
32) The pure beryllium hydroxide gel is centrifuged and rinsed twice with water.

33) The beryllium gel is transferred to a quartz crucible and dried.

34) It is calcined in an acetylene flame to convert to beryllium oxide.

35) The pure beryllium oxide is mixed with niobium metal and pressed into a target for analysis by AMS.

SUPPLEMENTARY TABLES

Table 1.S1: Complied thermochronology data from White (1992) and Townsend et al. (2021)

Reference	Sample or transect name	Latitude (decimal degrees)	Longitude (decimal degrees)	Point Conception
White 1992	NF2	34.49689059	-120.2190825	26
White 1992	CC1	34.54187792	-119.8865857	61
White 1992	CC2	34.54372527	-119.8792761	63
White 1992	CC3	34.54783033	-119.8983808	64
White 1992	FR12	34.48969922	-119.5888425	96
White 1992	WG1	34.48523184	-119.4737157	109
White 1992	WG2	34.48002815	-119.4526174	111
White 1992	WG3	34.489057	-119.433212	113
Townsend et al (2021)	Rattlesnake Canyon	34.4745445	-119.6804733	85
Townsend et al (2021)	Matilija Canyon	34.4946327	-119.3057785	127

* Exhumation rates are directly reported in Townsend et al. (2021), White (1992) did not calculate and rates reported here are using the White (1992) methodology, see text for details.

Thermochronometer system	**Exhumation rate (mm/y)***
Ap-FT	0.5
Ap-FT	0.6
Ap-FT	0.6
Ap-FT	0.7
Ap-FT	1.2
Ap-FT	1.8
Ap-FT	1.8
Ap-FT	1.3
Ap-He and Zr-He	0.9
Ap-He and Zr-He	1.2

exhumation rates directly for all samples

Table 1.S2: Complied marine terrace data from Gurrola et al. (2014) and Morel et al. (2021)*

Reference	**Sample name**	**Latitude (decimal degrees)**	**Longitude (decimal degrees)**	**Terrace name**
Morel et al. (2021)	COJ 1	34.4495	-120.424	Cojo Bay 1
Morel et al. (2021)	COJ 2	34.4495	-120.424	Cojo Bay 2
Morel et al. (2021)	WGV 2	34.46876	-120.24541	W. Gav. Canyon 2
Morel et al. (2021)	WGV	34.46986	-120.23647	W. Gav. Canyon
Morel et al. (2021)	WLV 1	34.44647	-119.97463	W. Las Varas 1
Morel et al. (2021)	WLV 2	34.44647	-119.97463	W. Las Varas 2
Morel et al. (2021)	ENP	34.4353	-119.95427	E. Naples Point
Morel et al. (2021)	EBC 1	34.42673	-119.90907	E. Bell Canyon 1
Morel et al. (2021)	EBC 2	34.42673	-119.90907	E. Bell Canyon 2
Morel et al. (2021)	IV 1	34.40938	-119.87068	Isla Vista 1
Morel et al. (2021)	IV 2	34.40938	-119.87068	Isla Vista 2
Morel et al. (2021)	WSAG_osl1	34.4575	-120.35961	West San Agustin Beach 1
Morel et al. (2021)	WSAG_osl2	34.45764	-120.35849	West San Agustin Beach 2
Morel et al. (2021)	EAC_osl	34.4689	-120.26965	East Alegria Canyon
Morel et al. (2021)	WEC_osl	34.46106	-120.02977	West El Capitan
Morel et al. (2021)	WLV_osl	34.4464	-119.97441	West Las Varas Canyon
Morel et al. (2021)	WNP_osl	34.43627	-119.957	West Naples Point
Morel et al. (2021)	ENP_osl1	34.43547	-119.95453	East Naples Point 1
Morel et al. (2021)	ENP_osl2	34.43547	-119.95453	East Naples Point 2
Gurrola et al. (2014)		34.42447	-119.89922	niversity of California-Santa Barba
Gurrola et al. (2014)		34.40931	-119.8461	Ellwood Mesa
Gurrola et al. (2014)		34.42146	-119.79188	More Mesa
Gurrola et al. (2014)		34.40205	-119.70848	Santa Barbara Point
Gurrola et al. (2014)		34.40999	-119.69279	Santa Barbara City College
Gurrola et al. (2014)		34.41886	-119.65468	Santa Barbara Cemetary
Gurrola et al. (2014)		34.41994	-119.59605	Summerland

*Morel et al. (2021) reports the median calibrated age for radiocarbon and IRSL age +- 2 standa
age based upon both radiocarbon and Uranium series dating.

Terrace age (ky B.P.)*	Elevation Reported (m)	Paleo sea level elevation relative to current (m)	Uplift rate (mm/y)
48.1 ± 1.6	4.1 ± 1.5	–38 ± 16	0.8 ± 0.3
44.9 ± 0.9	4.1 ± 1.5	–42 ± 16	1.0 ± 0.4
45.2 ± 0.9	28.6 ± 1	–43 ± 16	1.6 ± 0.4
44.2 ± 1.2	25.1 ± 1	–42 ± 16	1.5 ± 0.4
42.2 ± 0.5	10.3 ± 1	–51 ± 16	1.4 ± 0.4
41.1 ± 0.9	10.3 ± 1	–54 ± 16	1.5 ± 0.4
47.9 ± 1.7	17.2 ± 0.5	–39 ± 16	1.2 ± 0.3
42.5 ± 0.5	16.2 ± 1	–50 ± 16	1.5 ± 0.4
39.6 ± 0.7	16.2 ± 1	–57 ± 16	1.8 ± 0.4
48.8 ± 1.6	7.6 ± 0.5	–34 ± 16	0.8 ± 0.3
48.0 ± 1.7	7.6 ± 0.5	–38 ± 16	0.9 ± 0.3
55.5 ± 6.6	8.1 ± 1.5	–42 ± 16	0.9 ± 0.3
42.5 ± 4.4	8.4 ± 1.5	–49 ± 16	1.4 ± 0.4
54.7 ± 7.5	30.2 ± .5	–42 ± 16	1.3 ± 0.4
53.5 ± 6.8	14.3 ± 0.5	–42 ± 16	1.1 ± 0.3
51.6 ± 5.2	11.7 ± 1.0	–35 ± 16	0.9 ± -.3
47.2 ± 5.5	18.5 ± 1.5	–41 ± 16	1.3 ± 0.4
46.9 ± 5.5	18.4 ± 0.5	–43 ± 16	1.3 ± 0.4
51.2 ± 6.2	18.8 ± 0.5	–36 ± 16	1.1 ± 0.3
48	14	–62	1.6
48	24	–62	1.8
48	35	–62	2
58	15	–55	1.2
70	30	–44	1.1
80	25	–10	0.4
105	34	–14	0.5

rd deviation; Gurrola et al. (2014) reports an approximate

Table 1.S3: Summary of all cosmogenic radionuclide data and erosion rates in the SY

Sample name	Collection year	^{10}Be Concentration (atoms/g)	^{10}Be concentration uncertainty (atoms/g)[†]
SY_22_MRN_18_CRN	2022	16561.12271	1795.382679
SY_22_MRN_22	2022	20730.55123	2330.88405
SY_23_HZ_03	2023	10653.01126	710.1082094
SY_23_HZ_06	2023	35813.01417	5359.827416
SB1	2004	26919.8838	6987.065548
SB2	2004	35016.96398	6106.975278
SB11	2004	26780.006	1010.681852
SB12	2004	150753.5507	3641.991076
SB3	2004	16898.5351	9796.252232
SB4	2004	14166.05946	8457.348929
SB5	2004	22515.63823	7105.43583
SB9	2004	12214.6769	6590.467114
SB10	2004	29117.77053	1387.803871
SB7	2004	17018.32356	8335.505418
SB8	2004	9737.248797	7038.218276
SY_23_MRN_04_CRN	2023	17977.45591	2630.852299
SY_23_MRN_03_CRN	2023	24460.53434	2500.239602
SY_22_MRN_09_CRN	2022	20560.14592	2779.327324
SY_23_MRN_02_CRN	2023	21856.30061	2659.081793
SY_22_MRN_05_CRN	2022	22260.00252	2849.480922
SY_22_MRN_04_CRN	2022	13676.16446	1822.076284
SY_22_MRN_03_CRN	2022	19189.21493	2865.316716
SY_23_MRN_07_CRN	2023	16077.79982	2088.88134

[†] uncertainty is total uncertainty - includes AMS and external from sample/sample prep

M both from 2004 and 2022-2023 collection years

Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (m)	Shielding correctio	Erosion rate (mm/y)
Soil Production				
34.50555	-119.75302	939	0.995043574	0.28
34.53384	-120.03383	976	0.975462316	0.223
34.51936	-120.39494	223	0.861515269	0.212
34.48316	-119.63491	1060	0.985204298	0.142
34.495367	-120.008736	331	0.990111714	0.128
34.495797	-120.009083	345	0.990111714	0.0994
34.517158	-120.076308	452	0.990111714	0.14
34.532494	-120.016236	1004	0.990111714	0.0371
Nested Tributaries				
34.497667	-120.013958	260	1	0.27196801
34.4891	-120.019025	176	1	0.2583253
34.480717	-120.020333	123	1	0.20660499
34.508778	-120.064778	141	1	0.36285719
34.508828	-120.065539	141	1	0.15542454
Basin Average				
34.464383	-120.022769	32	1	0.26302617
34.467447	-120.069919	13	1	0.40759485
34.454623	-120.416435	13	1	0.17594461
34.530029	-120.175719	264	1	0.15796136
34.465986	-120.069251	13	1	0.17290639
34.554921	-120.081722	215	1	0.18522634
34.464697	-119.774429	129	1	0.19087577
34.451793	-119.621977	184	1	0.31296996
34.43486	-119.571168	153	1	0.2015987
34.423233	-119.340822	192	1	0.28415144

eration reported by the laboratory

Erosion rate uncertainty (mm/y)[†]
0.04605779
0.037827239
0.023640008
0.03127459
0.047803766
0.025324297
0.011145412
0.002545547
0.24684621
0.24951833
0.086957049
0.290
0.037
0.18102832
0.627
0.051
0.049
0.048
0.025
0.051
0.086
0.058
0.056

Table 1.S4: Raw laboratory data CRN

PRIME lab at Purdue: 2022-2023 Samples

Submitter Name	Nuclide Id	Sample Id	Aliquot Id	User Identification	Sample Mass (g)	Native Beryllium (mg)
Soil Production Samples						
Scheingross	1	202301704	A	SY_22_MRN_	14.174	
Scheingross	1	202301705	A	SY_22_MRN_	13.468	
Scheingross	1	202301706	A	SY_23_HZ_03	11.81	
Scheingross	1	202301707	A	SY_23_HZ_06	19.936	
Basin Average Samples						
Scheingross	1	202300568	A	23_MRN_04_	40.507	
Scheingross	1	202300569	A	23_MRN_03_	39.141	
Scheingross	1	202300570	A	22_MRN_09_	42.366	
Scheingross	1	202300571	A	23_MRN_02_	40.406	
Scheingross	1	202300572	A	22_MRN_05_	40.388	
Scheingross	1	202300573	A	22_MRN_04_	40.406	
Scheingross	1	202300574	A	22_MRN_03_	40.289	
Scheingross	1	202300575	A	23_MRN_07_	40.181	

9Be Carrier (mg)	Average Current (nA)	Interference (Counts/Sec)	10Be Ratio (x10-15)	10Be Std Dev (x10-15)	Total 10Be Atoms	Std Dev	Carrier-Corrected Total 10Be Atoms	Carrier-Corrected Std Dev
0.2975	4728.44	10.06894713	12.5162	1.15453	248852	22954.8	234737	24015.6
0.3311	4782.19	10.12432445	13.3274	1.18532	294908	26228.7	279199	27379.9
0.2978	4116.59	9.16241093	7.03135	1.05484	139941	20993.9	125812	22151.1
0.2993	4401.13	9.368630567	36.4035	2.43239	728169	48654.4	713968	49169.9
0.2697	4177	13	40.40	2.76	728,213	49,761	728,213	49,864
0.2749	3372	11	52.11	5.10	957,410	93,666	957,410	93,723
0.2748	2652	8	47.43	3.51	871,051	64,436	871,051	64,519
0.2754	3363	11	47.98	3.94	883,126	72,588	883,126	72,662
0.2767	3808	15	48.62	3.80	899,037	70,232	899,037	70,309
0.2743	3746	13	30.14	2.26	552,599	41,477	552,599	41,605
0.2756	3583	11	41.97	2.81	773,114	51,776	773,114	51,879
0.2765	3643	11	34.96	2.69	646,022	49,723	646,022	49,832

Cosmogenic 10Be Atoms per gram SiO2	Std Dev	Relative Uncertainty (%)	Uncertainty in the AMS Measurement (%)
16561.12271	1694.34	10.2308	9.224285664
20730.55123	2032.96	9.80659	8.893857776
10653.01126	1875.62	17.6065	15.00195479
35813.01417	2466.39	6.88685	6.681747637
17,977	1,231	6.8	6.8
24,461	2,394	9.8	9.8
20,560	1,523	7.4	7.4
21,856	1,798	8.2	8.2
22,260	1,741	7.8	7.8
13,676	1,030	7.5	7.5
19,189	1,288	6.7	6.7
16,078	1,240	7.7	7.7

Std Dev	Relative Uncertainty (%)	Uncertainty in the AMS Measure
1694.34	10.2308	9.22429
2032.96	9.80659	8.89386
1875.62	17.6065	15.002
2466.39	6.88685	6.68175
1,231	6.8	6.8
2,394	9.8	9.8
1,523	7.4	7.4
1,798	8.2	8.2
1,741	7.8	7.8
1,030	7.5	7.5
1,288	6.7	6.7
1,240	7.7	7.7

Lawrence Livermore National Lab: 2004 samples

		B F.O.M.	10Be/Be ratio		Background		Bkgd-corrected				
NAME	CAMS #		ratio	±	ratio	±	ratio	±	x10^15		Err
SB1	BE19191	0.9984	5.9E-14	1.8E-15	2E-14	1E-14	3.9E-14	1E-14	39.168	10.1661	25.955
SB2	BE19192	0.98285	7.8E-14	2.2E-15	2E-14	1E-14	5.9E-14	1E-14	58.6835	10.2344	17.44
SB3	BE19193	0.99553	2.1E-14	9.8E-16	2E-14	1E-14	2.1E-14		20.7	12	57.971
SB4	BE19194	0.99479	1.6E-14	7.9E-16	2E-14	1E-14	2E-14		20.1	12	59.7015
SB5	BE19195	0.99852	5.2E-14	1.7E-15	2E-14	1E-14	3.2E-14	1E-14	32.1287	10.1391	31.5578
SB7	BE19196	0.99621	2.4E-14	1.1E-15	2E-14	1E-14	2.5E-14		24.5	12	48.9796
SB8	BE19197	0.99722	3.4E-14	1.4E-15	2E-14	1E-14	1.4E-14	1E-14	13.9607	10.091	72.2814
SB9	BE19198	0.99749	3.9E-14	1.8E-15	2E-14	1E-14	1.9E-14	1E-14	18.8316	10.1607	53.9553
		B F.O.M.	10Be/Be ratio		Background		Bkgd-corrected				
NAME	CAMS #		ratio	±	ratio	±	ratio	±	*10^15		
SB10	BE19199	0.99864	3.6E-14	1.7E-15	6.2E-16	2.2E-16	3.6E-14	1.7E-15	35.9375	1.71284	
SB11	BE19200	0.9984	3.9E-14	1.4E-15	6.2E-16	2.2E-16	3.9E-14	1.5E-15	38.798	1.46424	
SB12	BE19201	0.99971	2.2E-13	5.2E-15	6.2E-16	2.2E-16	2.2E-13	5.2E-15	216.973	5.24175	
Sample	Weight	Carrier m	Be in car	total atom	Ratio(10	error (*1	conc [Be]	+/-			
NP300	59.0213	0.32776	0.52674	3.5E+22	4.22015	3.41441	2520.15	2038.98			
SB 1	51.9416		0.53352	3.6E+22	39.168	10.1661	26919.9	6987.07			
SB 2	59.1725		0.52768	3.5E+22	58.6835	10.2344	35017	6106.98			
SB 3	43.1808		0.52682	3.5E+22	20.7	12	16898.5	9796.25			
SB 4	50.0184		0.52683	3.5E+22	20.1	12	14166.1	8457.35			
SB 5	50.0827		0.52453	3.5E+22	32.1287	10.1391	22515.6	7105.44			
SB 7	50.3308		0.52249	3.5E+22	24.5	12	17018.3	8335.51			
SB 8	50.3585		0.52492	3.5E+22	13.9607	10.091	9737.25	7038.22			
SB 9	54.0047		0.5235	3.5E+22	18.8316	10.1607	12214.7	6590.47			
SB 10	42.9672		0.52028	3.5E+22	35.9375	1.71284	29117.8	1387.8			
SB 11	50.4382		0.5203	3.5E+22	38.798	1.46424	26780	1010.68			
SB 12	50.0724		0.51994	3.5E+22	216.973	5.24175	150754	3641.99			

SB 2	59.1725	0.52768	3.53087E+22	58.6835	10.2344
SB 3	43.1808	0.52682	3.52508E+22	20.7	12
SB 4	50.0184	0.52683	3.52519E+22	20.1	12
SB 5	50.0827	0.52453	3.50977E+22	32.1287	10.1391
SB 7	50.3308	0.52249	3.49611E+22	24.5	12
SB 8	50.3585	0.52492	3.5124E+22	13.9607	10.091
SB 9	54.0047	0.5235	3.50288E+22	18.8316	10.1607
SB 10	42.9672	0.52028	3.48135E+22	35.9375	1.71284
SB 11	50.4382	0.5203	3.48145E+22	38.798	1.46424
SB 12	50.0724	0.51994	3.47905E+22	216.973	5.24175

35017	6106.98
16898.5	9796.25
14166.1	8457.35
22515.6	7105.44
17018.3	8335.51
9737.25	7038.22
12214.7	6590.47
29117.8	1387.8
26780	1010.68
150754	3641.99

Table 1.S5: erosion rate calculation inputs all data

Basin average erosion rate calculations: LSD Topotools through google Colab

sample_name	sample_latitude	sample_longitude	nuclide	concentration
SY_23_MRN_04_CF	34.454623	-120.416435	Be10	17977.45591
SY_23_MRN_03_CF	34.530029	-120.175719	Be10	24460.53434
SY_22_MRN_09_CF	34.465986	-120.069251	Be10	20560.14592
SY_23_MRN_02_CF	34.554921	-120.081722	Be10	21856.30061
SY_22_MRN_05_CF	34.464697	-119.774429	Be10	22260.00252
SY_22_MRN_04_CF	34.451793	-119.621977	Be10	13676.16446
SY_22_MRN_03_CF	34.43486	-119.571168	Be10	19189.21493
SY_23_MRN_07_CF	34.43988145	-119.3343064	Be10	16077.79982
SB3	34.497544	-120.01396	Be10	16898.5351
SB4	34.489317	-120.019087	Be10	14166.05946
SB5	34.480303	-120.019822	Be10	22515.63823
SB7	34.465855	-120.022828	Be10	17018.32356
SB8	34.46629	-120.068914	Be10	9737.248797
SB9	34.508821	-120.064387	Be10	12214.6769
SB10	34.607805	-120.061875	Be10	29117.77053

		Soil production rate calculations: Balco et	
AMS_uncertainty	**standardisation**	**Sample name**	**Lat (decimal degrees N + S -)**
2630.852299	07KNSTD	SY_22_MRN_18_C	34.50555
2500.239602	07KNSTD	SY_22_MRN_22	34.53384
2779.327324	07KNSTD	SY_23_HZ_03	34.51936
2659.081793	07KNSTD	SY_23_HZ_06	34.48316
2849.480922	07KNSTD	SB1	34.495367
1822.076284	07KNSTD	SB2	34.495797
2865.316716	07KNSTD	SB11	34.517158
2088.88134	07KNSTD	SB12	34.532494
9796.252232	KNSTD		
8457.348929	KNSTD		
7105.43583	KNSTD		
8335.505418	KNSTD		
7038.218276	KNSTD		
6590.467114	KNSTD		
1387.803871	KNSTD		

al. (2008) CRONUS calculator v3

Lon (E + W -)	elevation/pressure (meters or hPa	Elev tag (std for all)	sample thickness (cm)	Sample density (g/cm3)	shielding correction (bet 0 and 1)	erosion rate inferred from independent evidence (cm/yr)
-119.75302	939	std	1	2.65	0.99504357	0.13
-120.03383	976	std	5	2.65	0.97546232	0.13
-120.39494	223	std	30	2.65	0.86151527	0.13
-119.63491	1060	std	3	2.65	0.9852043	0.13
-120.008736	331	std	2	2.65	0.99011171	0.13
-120.009083	345	std	2	2.65	0.99011171	0.13
-120.076308	452	std	2	2.65	0.99011171	0.13
-120.016236	1004	std	2	2.65	0.99011171	0.13

date collected (yyyy)	**end line w/ semicolon**	**Sample name (exact col A)**	**Be-10**	**quartz**	**nuclide conc (atoms/g)**	**uncertaintity (atoms/gram)**
2022	;	SY_22_MRN_18_CRN	Be-10	quartz	16561.12	1795.382679
2022	;	SY_22_MRN_22	Be-10	quartz	20730.55	2330.88405
2023	;	SY_23_HZ_03	Be-10	quartz	10653.01	710.1082094
2023	;	SY_23_HZ_06	Be-10	quartz	35813.01	5359.827416
2004	;	SB1	Be-10	quartz	26919.88	6987.065548
2004	;	SB2	Be-10	quartz	35016.96	6106.975278
2004	;	SB11	Be-10	quartz	26780.01	1010.681852
2004	;	SB12	Be-10	quartz	150753.6	3641.991076

same standard	**semicolon**
07KNSTD	;
07KNSTD	;
07KNSTD	;
07KNSTD	;
KNSTD	;
KNSTD	;
KNSTD	;
KNSTD	;

Table 1.S6: Schmidtt hammer rebound values for 12 lithologic units in the SYM from previously published 2003 (Duvall et al. (2004)) data and new August 2023 data*

Lithologic Unit	Median Rebound Value[*]	25th percentile	75th percentile	Total number of samples	Total number of no rebound values (R greater than or equal to 10)	Fraction of no rebound values
Alegria	22	18	26.00	151.00	7	0.0464
Coldwater	18.5	14.00	24.00	148.00	22	0.1486
Cozy Dell	12.00	10.00	14	150	109	0.7267
Gaviota	30.00	24.00	38	517	9	0.0174
Jalama	22.00	11.75	26	100	51	0.51
Juncal	16.00	11.25	20	200	133	0.665
Matilija	38.00	32.00	46	157	4	0.0255
Monterey	28.00	21.50	35	225	40	0.1778
Rincon	15.00	13.00	18	50	32	0.64
Sacate	32.00	23.00	50	180	72	0.4
Sespe	22.00	16.00	26	446	41	0.0919
Vaqueros	21.00	18.00	24.00	247.00	20.00	0.081

[*] Median, 25 percentile and 75 percentile are taken from the rebound values > 10

Table 1.S7: Mean hillslope angle and standard error

	All Lithologies		Weak Lithologies		Moderate Lithologies		Hard Lithologies	
Swath distance from Point Conception (km)	Mean hillslope angle	Standard error (°)	Mean hillslope angle (°)	Standard error (°)	Mean hillslope angle (°)	Standard error (°)	Mean hillslope angle (°)	Standard error (°)
-4.84-0	24	9	n.p.[*]	n.p.[*]	n.p.[*]	n.p.[*]	24	9
0 - 3.5	25	9	25	8	29	9	26	9
3.5- 7.3	27	9	25	8	28	9	28	9
7.3 - 11.1	28	9	27	9	28	10	29	9
11.1 - 14.9	28	9	28	9	30	10	29	9
14.9 - 18.7	29	9	27	8	31	10	30	10
18.7 - 22.6	28	9	26	8	29	10	28	9
22.6 - 26.4	27	10	26	9	29	11	28	10
26.4 - 30.3	30	10	28	9	31	11	30	10
30.3 - 34	31	10	28	9	32	10	31	10
34.0 - 37.9	30	10	27	9	31	10	30	10
37.9 - 41.8	28	10	25	8	29	10	28	10
41.8 - 45.7	28	10	24	8	28	9	28	10
45.7 - 49.5	30	10	30	10	29	10	31	10
49.5 - 53.4	31	10	30	10	28	10	33	10
53.4 - 57.2	31	10	30	10	29	10	34	10
57.2 - 61.1	30	10	31	10	29	10	33	10
61.2 - 64.9	30	10	28	10	29	10	35	9
64.8 - 68.7	28	10	23	8	29	10	n.p.[*]	n.p.[*]
68.7 - 72.8	29	10	24	8	29	10	n.p.[*]	n.p.[*]
72.6 - 76.5	29	10	n.p.[*]	n.p.[*]	30	10	32	10
76.5 - 80.3	31	10	29	10	33	10	29	9
80.3 - 84.1	33	11	32	10	33	11	34	11
84.1 - 87.8	33	11	33	9	33	11	37	11
87.8- 91.8	33	10	34	9	31	11	37	10
91.8 - 95.5	34	11	36	10	29	10	41	11
95.5 - 99.2	34	11	37	10	29	11	42	10
99.2 - 103.1	34	11	35	9	31	10	43	9
103.1 - 106.9	34	11	36	9	32	11	40	10
106.9 - 110.6	35	11	37	9	34	11	38	10
110.7 - 114.3	33	10	37	9	32	10	34	10
114.4 - 118.1	32	11	36	9	31	11	34	10
118.1 - 121.9	31	10	35	9	31	10	36	9
121.9 - 125.6	31	11	36	9	29	10	36	11
125.6 - 128.6	29	10	34	9	28	10	n.p.[*]	n.p.[*]

[*] n.p. means not present within the corresponding swath

Table 1.S8: Relative channel steepness for drainage basins on the southern flank of the Santa Ynez Mountains

	All Lithologies		**Weak Lithologies**		**Moderate Lithologies**		**Hard Lithologies**	
Basin outlet distance from Point Conception (km)	**Median Mi,j**	**Mi,j Interquartile Range (IQR)**	**Median Mi,j**	**Mi,j IQR**	**Median Mi,j**	**Mi,j IQR**	**Median Mi,j**	**Mi,j IQR**
-1.253	-0.7492047	0.57821941	n.p.*	n.p.*	n.p.*	n.p.*	n.p.*	n.p.*
-1.105	-0.2122503	0.32596364	n.p.*	n.p.*	n.p.*	n.p.*	0.04564304	0.70485749
1.953	-0.6213783	0.53008757	-0.2555893	0.146446	-0.1416988	0.09780294	-0.1396426	0.18491229
1.955	-0.4894677	0.19066519	-0.1043494	0.512859	-0.0940376	0.01220824	-0.1084157	0.84955326
3.057	-0.2829115	1.95613443	0.17913425	0.058851	-0.0067248	2.23792232	-0.0343203	0.19066519
6.479	-0.2356061	1.9957005	0.1434178	2.165949	0.2146829	0.36083952	0.23843765	1.5736238
9.497	-0.3002904	1.70069061	-0.3022284	0.52212	-0.0886627	0.22658223	-0.2579646	1.50665616
11.25	-0.4014468	0.44368273	-0.2428405	0.87478	0.2655014	2.20847725	-0.2711151	1.16780236
11.984	-0.0612108	1.2277782	-0.0505507	0.006202	0.0884969	0.3932061	-0.0462147	0.05768873
13.585	0.40640051	0.12986217	0.40328488	3.50657	0.123989	0.02708585	-0.0145585	0.94991603
14.11	-0.4187102	0.77226431	-0.4202494	0.778085	-0.3965552	0.47919953	-0.4167251	0.8201787
14.814	-0.2555446	0.64185323	-0.2944771	0.606217	-0.2444576	0.09986389	-0.1518703	0.61850911
16.448	-0.446892	0.38931694	-0.4591341	0.090003	-0.0454525	0.74212104	-0.0004189	0.56287446
16.921	-0.122525	1.92726234	0.36655954	1.974668	-0.1324206	0.56970178	0.1055552	1.40873766
18.887	-0.0637198	2.51870779	-0.3276704	0.253676	-0.2367979	0.06832828	0.10047562	1.63338002
20.994	-0.2906695	0.08721361	-0.4510744	0.044734	-0.2684595	0.45968245	0.02289944	0.14133173
23.637	-0.2547608	1.99079964	-0.5681049	0.385852	-0.5637622	0.03492379	-0.1664918	1.53915066
23.743	-0.3259977	0.48607372	-0.366675	0.04416	-0.4833254	0.87522716	-0.1300633	0.45066251
24.073	0.94658407	1.39091646	1.10124069	1.171016	n.p.*	n.p.*	0.91023724	2.13558803
24.089	1.66909851	0.38722896	n.p.*	n.p.*	n.p.*	n.p.*	1.66909851	0.03545071
26.214	-0.408233	0.37833724	-0.4043373	0.019877	-0.1205223	0.29660345	1.9893858	0.43856592
28.575	2.03386675	0.04414919	2.8245954	0.16566	0.5776958	0.20067385	2.14668872	0.00464962
30.118	1.72483999	1.8820159	2.735628	0.061234	1.3725962	0.00878187	1.7638662	1.0493893
33.476	2.44956074	0.61166879	2.75695513	2.083672	-0.7024524	0.82604202	1.75523266	0.07875067
36.062	1.05507971	0.9106991	-0.4700443	1.327249	-0.1365907	0.24927181	1.55466976	1.04198745
38.144	0.61900213	0.60977521	-0.5340405	0.25039	-0.1645321	0.02731678	1.64823481	0.18816215
41.684	0.85823349	0.35611967	-0.3549851	0.919607	-0.3312278	0.01630088	1.38465682	0.24128907
43.46	-0.4669463	0.14914553	-0.468359	0.063941	-0.4942985	0.03693434	-0.3373717	0.03409165
44.184	0.80432361	0.34356644	1.72537049	0.160975	0.2355363	0.21300159	1.81142076	0.00536016
46.622	1.36990279	0.71412457	1.46888084	0.525545	1.2136006	0.04335856	1.56213698	0.70978317
48.589	-0.1530088	0.44918577	-0.5665919	0.176761	-0.0410948	0.20618394	0.57462965	0.27202434
49.513	1.10255592	2.05366157	2.41998278	2.162693	0.9813009	1.20563074	2.29024954	0.50184103
52.335	-0.3482749	0.38927647	-0.6207032	0.104033	-0.3146638	0.00852862	0.44344174	0.0980029
53.502	1.40992615	0.59993431	1.57810989	0.059581	0.3493847	0.29886825	1.99428134	0.30467871
57.133	-0.1873737	0.71647796	-0.8369925	0.314267	-0.0930425	0.40767041	1.31918045	0.60452216
59.13	0.02593698	2.31812509	1.32808046	0.205997	-0.3021613	2.61233009	2.14123067	2.02950032
67.829	-0.3764146	2.32473014	-0.6601941	0.243926	1.0381485	3.05602308	1.48620614	1.96265444
68.108	-0.3569785	1.99287915	-0.6747466	2.406593	0.8654184	0.57856273	2.47223878	0.19553766
68.551	0.00566648	2.01622377	-0.5857915	1.499986	0.4209033	1.64630651	n.p.*	n.p.*
69.418	0.86031494	0.23282511	1.86888661	0.465635	1.3640745	0.23282511	1.45036943	4.50923871
78.114	0.63178124	1.32708898	-0.2107792	1.083639	0.9075671	1.74693216	n.p.*	n.p.*
84.231	1.64561385	1.18387794	2.22763022	2.755556	1.3990872	1.47842176	2.66592093	0.89079778
86.325	0.18301567	2.48219875	0.42189227	0.283373	0.1830568	2.33460389	n.p.*	n.p.*

90.153	1.59039953	0.00281447	1.44373374	0.415773	2.2016452	0.00281447	3.78833046	0.02649549
91.145	1.84428986	0.33897796	1.60429736	0.256733	1.8900234	0.63936188	3.70252396	1.80051516
91.99	1.16225763	0.40985779	1.29514795	0.562744	0.6348189	0.43483857	2.59382711	2.06633358
96.454	1.14912937	0.69894836	1.1967221	1.493069	1.1210821	0.49419379	n.p.*	n.p.*
98.632	-0.6623725	1.76928986	1.87276102	0.20934	-0.6623725	1.77649262	n.p.*	n.p.*
98.835	1.3921714	1.79253785	n.p.	n.p.	1.2989601	1.42035501	4.70068656	4.34854377
101.979	1.85670559	2.64719237	n.p.	n.p.	1.6176216	2.98386338	2.63667005	0.31753358
102.313	-0.4389072	1.48259702	2.19702881	0.320204	1.4508709	1.38863021	n.p.*	n.p.*
102.995	1.09157215	1.43733304	1.50136694	1.454763	1.0513216	1.2193805	2.42530531	1.48463485
107.809	0.84216516	2.42049536	1.82607741	0.447525	1.3189406	2.67174638	-0.3632045	0.89823941
120.612	1.29640026	0.93599008	1.98524483	3.161959	0.8857009	0.86510637	2.79242525	0.32162685
121.037	-0.6368748	2.79523436	1.84800468	0.577369	-0.6368748	2.53418682	n.p.*	n.p.*
124.038	0.34841514	1.66740231	n.p.	n.p.	0.2406007	1.78902146	n.p.*	n.p.*

*n.p. means not present within the corresponding basin

CHAPTER 2: HANDS ON ROCK WEATHERING: LESSONS FOR MIDDLE SCHOOLERS

In the earth sciences, weathering encompasses all the physical, chemical, and biological processes that break down rocks in place. Rock weathering takes decades to millions of years and impacts climate and soil formation. In our two-part lesson, students develop an understanding of weathering and how it can influence climate and human society through hands-on experiments. Lesson 1 has students investigate how changing the temperature and acidity of weathering agents affects the rate of rock weathering of sandstone and limestone (using sugar cubes and chalk, respectively, as models) and if the products of weathering different rock types impact the climate on geologic timescales by adding CO_2 to the atmosphere or not. Lesson 2 focuses on how weathering impacts our day to day lives. Students perform experiments simulating how bedrock weathering of different rock types (mudstone and granite) occur at different rates, produce different small particles, and interact with weathering agents differently. Students begin the soil formation process by shaking these rocks in water, they apply this knowledge to societally relevant topics including agriculture, city planning, drinking water quality, and atmospheric composition. These lessons bring rock weathering into the classroom with cross cutting concepts and connect the earth, climate, and human society together in an interactive way.

2.0 INTRODUCTION

Mountain ranges, flowing rivers, and a diversity of rock types are evidence of a wide range of geologic processes. However, geologic processes often occur over large temporal scales that can be difficult to grasp. Here, we share a two-part lesson with hands-on laboratory experiments that allow students to speed up and observe the geologic process of rock weathering. Weathering encompasses all the physical, chemical, and biological processes that break down rocks in place. Occurring over decades to millions of years, rock weathering impacts global climate, soil development, water quality and more. While not all rock weathering is observable on human timescales, many natural and artificial materials weather on short timescales. For example, paint peeling on a building, concrete cracking, rusting, and soft rock weathering into soil (Figure 1.2) are all commonly observed weathering phenomena. In our two-part lesson, students develop an understanding of weathering through experiments, and we engage students in discussion of how weathering influences climate and human society. We taught our lessons twenty times in a variety of middle school classrooms in a suburban area.

2.0.1 LESSON OVERVIEW

We designed our paired lessons to fit within both the Next Generation Science Standards (NGSS) and Common Core Standards shown in Table 1 (NGSS Lead States, 2013). Each lesson follows the 5E Instructional Model (Engage, Explore, Explain, Elaborate and Evaluate) and we modified classic weathering experiments to focus on questions relating the importance of rock weathering to climate and society (NGSS MS-ESS2-2). The lessons can be linked with an adult supervised interactive take-home activity. Our lessons can be adapted for students of different abilities and backgrounds, and our lessons are gender inclusive (see the Teacher Guide for details). We connect these topics to societally-relevant issues, such as climate change, to allow all students to engage with and build appreciation for the geosciences. Socially-relevant issues that go beyond "just rocks" help diverse students, including girls and underserved groups within the geosciences, connect with the geosciences more deeply (Murray et al. 2012).

2.1 LESSON 1: CHEMICAL WEATHERING AND CLIMATE CHANGE IMPLICATIONS

In Lesson 1, students investigate how changing the temperature and acidity of liquids affect rock weathering. We use this to discuss if and how rock weathering adds CO_2 to the atmosphere, and how that can affect climate over geologic timescales. This hands-on lesson gives students a tangible example of connections between the rock cycle and climate.

Engage: To engage students with this topic we suggest using a combination of real-world examples and pop culture references (see Teacher Guide for links and details). What weathering is and how weathering impacts climate is a difficult topic to grasp, which is why showing examples of weathering in visual and pop culture references can assist students' understanding. For our lessons, we engaged students with the think-pair-share method by prompting students for examples of weathering in their own lives. Starting with students' familiarity that burning fossil fuels releases CO_2, we explained that rocks can contain carbon, and therefore rock weathering can release CO_2 to the atmosphere. We reinforced our engagement section by dissolving chalk in vinegar and having students observe the resulting CO_2 release (Figure 2.2).

Explore: Students performed a hands-on activity to explore how fast rocks weather when exposed to liquids of varying temperature and acidity. We used sugar cubes as a model for sandstone, a rock type that does not release CO_2 to the atmosphere during weathering, even though sugar, like chalk (analogous to limestone), contains carbon. Students dissolved sugar cubes using solutions of white vinegar (5% vinegar, 95% water, pH = 2), diluted white vinegar (0.25% vinegar, 99.75% water, pH = 4) and tap water (pH = 7) (Figure 2.2). We provided these solutions at room temperature and heated to ~160° Fahrenheit (F). Students worked in pairs to write a hypothesis explaining which solution they thought would dissolve a sugar cube fastest. Students then recorded the total time to completely dissolve a sugar cube with 50 milliliters of solute. While students were actively dissolving their sugar cubes, we walked around the classroom and asked students to explain what was happening and why their reactions with sugar did not produce bubbles. We recommend eye protection, gloves, and optional aprons as personal protective equipment for this activity.

Explain: After completing the experiments, the class regrouped to explain the observations. We plotted students' data in real time showing the time for sugar cube dissolution for each liquid (Figure 2.3). While plotting, we paused to have students discuss and predict the time it would take to dissolve a sugar cube in the next liquid. Students consistently observed that 160º F solutions dissolved sugar cubes faster than room temperature solutions, and that acidic solutions dissolved sugar cubes faster than neutral solutions. In some cases, students observed slower dissolution times using vinegar relative to water, which allowed us to discuss human and measurement error.

Elaborate: We elaborated on our activity by using the time for sugar cube dissolution to explain how climate affects rock weathering. For example, some students deduced that weathering may proceed faster in the tropics relative to deserts due to the high temperature and water availability in tropical environments. We incorporated place-based learning by discussing local weathering phenomena. Limestone is a common sedimentary rock that is primarily composed of calcium carbonate ($CaCO_3$). When limestone is weathered by rain, the water reacts with $CaCO_3$, releasing CO_2 to the atmosphere. We contrasted this with sandstone, another common sedimentary rock; however, sandstone is composed primarily of the mineral quartz, SiO_2, which does not release CO_2 during weathering. Due to these different chemical compositions, we were able to demonstrate that some rocks, like limestones, can affect climate during weathering, whereas other rocks, like sandstone, do not.

Evaluate: We evaluated student learning using pre- and post-lesson multiple-choice quizzes. Each quiz had the same three questions (Figure 2.4), all of which related to the lesson focus. During the lesson we addressed each quiz question directly, making sure students were aware of the main lesson goals. Comparing quiz scores before and after the lesson showed that, on average, students learned that rock weathering can affect climate, and that limestone is an example of a rock that releases CO_2 during weathering.

2.2 TAKE-HOME ACTIVITY: MUDSTONE WEATHERING IN REAL TIME.

Although we were not able to incorporate this in our lessons, we recommend extending Lesson 1 with a take-home activity on mudstone weathering. Students start by making predictions of what will happen to a piece of mudstone left outside and subjected to weather (e.g., rain, sunshine, etc.) for two weeks. Instructors then provide students with mudstone pieces to place outside and have students take daily photos and record daily journal entries describing any changes in the mudstone (adult supervision required). Mudstone weathers rapidly (especially when subjected to wetting and drying cycles), allowing students to observe the development of fractures and the breakdown of the rock over a few days. If needed, the process can be accelerated by manually subjecting mudstone to wetting and drying cycles (Figure 2.5). Students should repeat cycles of submerging rocks in water for ~24 hours, and then drying rocks (e.g., in an oven at low heat) for about 1 hour, making sure to photograph the rock and record journal entries between each cycle. If desired, instructors can ask students to do this activity with multiple rock types (e.g., mudstone, granite, and limestone), which will illustrate that not all rocks weather at the same rate. This activity serves as a natural segue to Lesson 2, which links rocks weathering to soil formation.

2.3 LESSON 2: PHYSICAL WEATHERING AND SOIL FORMATION

Lesson 2 focuses on how weathering impacts society on human timescales, thereby providing a contrast to Lesson 1's focus on geologic time scales. In Lesson 2, students perform experiments simulating bedrock weathering and soil formation processes and apply this knowledge to societally-relevant topics including agriculture, city planning, drinking water quality, and atmospheric composition.

Engage: To engage students, we began the lesson using the think-pair-share method to discuss how weathering can impact human society in positive and negative ways. Student answers for negative impacts from weathering ranged from adding CO_2 to the atmosphere, to more common observations of weathering as a nuisance in everyday life (e.g., cracked sidewalks and rust (Figure 1.2)). With prompting, students connected rock weathering to soil formation, and we discussed this concept as a class. Using think-pair-share we discussed that soil forms over periods of decades to thousands of years and emphasized the importance of soil to ecosystems and society. We additionally discussed that weathering of rocks with high metal concentrations (e.g. rocks left over from mining campaigns) often leads to drinking water contamination, with negative societal consequences. We acknowledge we used the same engagement strategy (think-pair-share) in both Lessons 1 and 2. Diversifying the engagement strategy, for example by incorporating relevant pop culture references, could enhance student interest.

Explore: Students explored the physical breakdown of rocks into smaller particles (the start of soil formation) with a hands-on experiment shaking rocks in a container to simulate physical weathering. We used mudstone and granite to demonstrate how rock type affects weathering and soil formation rates. Students, working in pairs, were given ~30 g of mudstone or granite chips (Figure 2.6). Students examined each rock type and recorded predictions of arguing why one rock type may break down faster than the other before starting their experiment. In the experiment, students first weighed and recorded their rock chip mass. Students then added the rock chips and a small amount of water to a plastic container and shook the rock/water combination for 3-5 minutes. As students worked on the activity we walked around to assist and asked prompting questions such as: Has the appearance of the water/rock mixture changed since you started shaking the rocks (and if so, why?)? Can you already tell if the different rock types behave differently? After shaking, students re-grouped as a class, and we demonstrated how to sieve the rock/water mixture through a 3-millimeter mesh screen into a waste container (Figure 2.6). Students kept and dried the large rock chips that stayed on top of the mesh before weighing these chips to estimate a mass loss from physical weathering. Students additionally made observations on the appearance of the rock chips after the experiment relative to the initial appearance. We recommend personal protective equipment during the experiment including eye protection, gloves, and aprons.

Explain: Using a graphing program, as a class we explained the experiment results by plotting the mass difference values on the board (Figure 2.7). While plotting the student-collected data, we asked students to discuss potential sources of error. Mudstone typically showed more mass loss than granite; however, mudstone is also better at retaining water, which, in cases, resulted in a mass gain for mudstone due to insufficient drying. Additionally, we observed that some students dropped rocks on the floor without noticing, and/or misused the scales, resulting in unreasonable mass values. Qualitatively, we also had students discuss observations on the color and opacity of the water/rock mixture. The mudstone water was often brown in color and very opaque (due to the large number of small particles produced), whereas the granite water was often a grey-ish color and more transparent than the mudstone experiment (due to fewer small particles produced). Students concluded that mudstone generally weathers faster than granite.

Elaborate: We elaborated on the data by showing a soil map of the USA (Supplementary Material). These maps show the general distribution of soil types (e.g., the relative proportions of sand, clay, and/or organic material in a soil). In the classroom we asked students where their food is grown and showed that common food-producing regions have similar soil types. This is partially due to the weathered bedrock the soils start from, although vegetation, water availability, and age of the soil are also important. Additionally, we discussed some of the negative impacts of weathering on human society (e.g., acid mine drainage) (Supplementary Material).

Evaluate: As in Lesson 1, we evaluated students using a set of identical pre- and post-lesson multiple-choice quizzes specific to Lesson 2. Although we focused on soil formation primarily during the lesson, we made sure that students made connections to acid mine drainage during the elaboration part of the lesson. We suggest focusing only on soil formation as our data showed that students had difficulty connecting both soil formation and acid mine drainage in a single class period. Comparing pre- and post-lesson answers, we found that students were already knowledgeable that soil was a positive impact of weathering prior to the lesson, whereas the lesson improved students' knowledge about the relative rate of weathering between different rock types (Figure 2.7).

2.4 CONCLUSIONS

Our lessons allow middle school students to investigate how rock weathering impacts both global climate and human society. These lessons could be expanded; for example, by having repeating Lesson 1 or 2 with chalk cubes or additional rock types, respectively. Alternatively, students could manually crush different rock types with a mortar and pestle and explore if it is possible to grow a plant in the crushed rock. Our lessons highlight how weathering is an example of a geoscience concept that combines aspects of chemistry, biology, physics, and engineering; therefore, these lessons can be appropriate for a wide range of classrooms and provides a tangible, real-world examples for students to explore cross-cutting concepts.

2.5 REFERENCES

NGSS Lead States. 2013. Next Generation Science Standards: For states, by states. Washington, DC: National Academies Press. https://doi.org/10.17226/18290

Kent S. Murray, Jacob Napieralski, Gail Luera, Karen Thomas-Brown & Laura Reynolds-Keefer (2012) Broadening Diversity in the Geosciences Through Teacher–Student Workshops That Emphasize Community-Based Research Projects, Journal of Geoscience Education, 60:2, 179-188, DOI: 10.5408/10-215.1

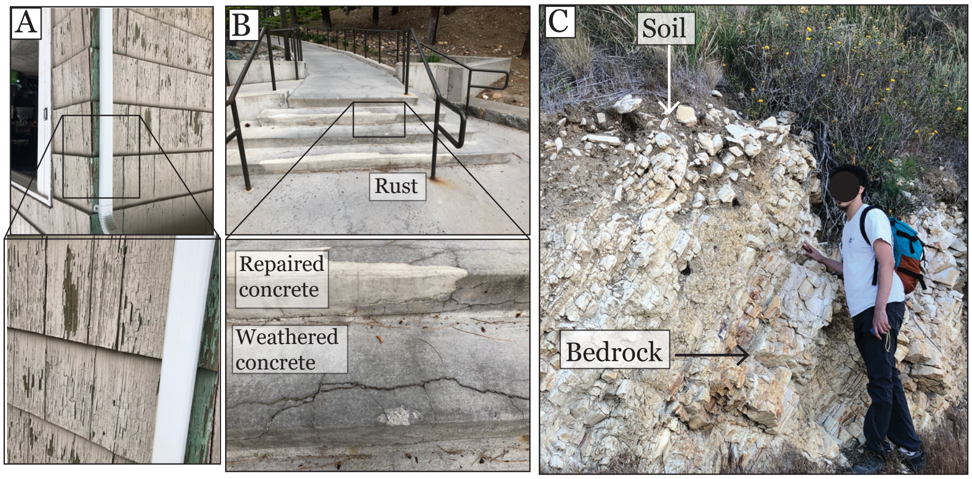


Figure 2.1: Examples of weathering. (A) Paint peeling on the side of a house. (B) Concrete cracking and metal rusting. (C) Example of bedrock weathering and incorporation of weathered rock into soil.

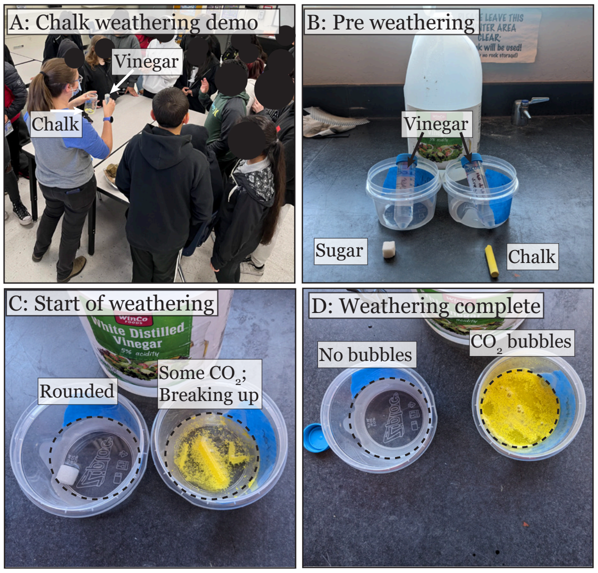


Figure 2.2: (A) An instructor demonstrating chalk weathering for students. (B) – (D) Staged Lesson 1 activity showing weathering a sugar cube and chalk stick in 5% white vinegar. (B) Initial set up, (C) the beginning of the weathering process (note that sugar cubes become rounded and do not release CO2, whereas the chalk stick breaks into several small pieces and bubbles indicating CO2 release). (D) Near the end of the experiment after the sugar cube and chalk stick have almost completely dissolved. Dotted ellipses in (C) and (D) show the liquid level in container.

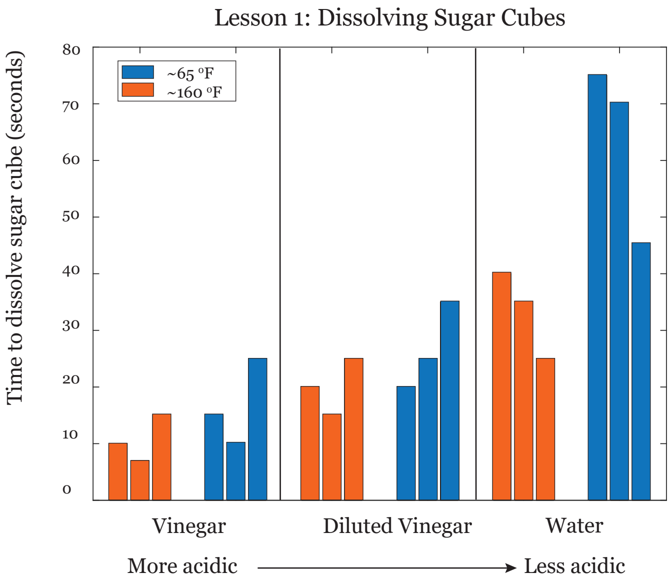
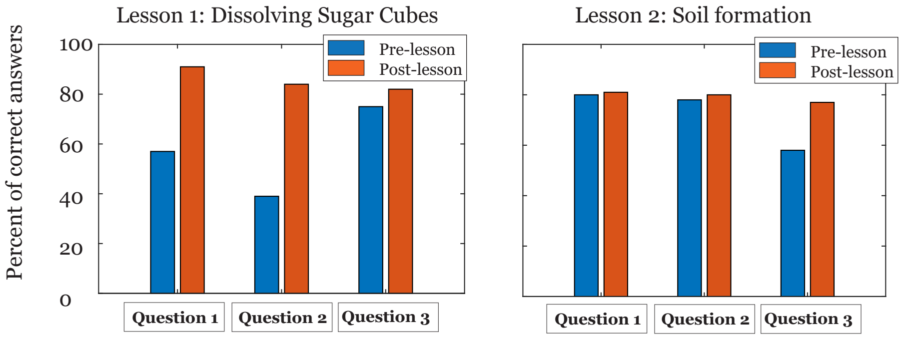


Figure 2.3: Example data from Lesson 1 showing time to dissolve a sugar cube as a function of solute acidity and temperature. Orange and blue bars represent hot and room temperature liquids, respectively. Each bar represents a different student group's data.



Q1: The weathering of rocks can impact climate.
a) Yes
b) No
c) I don't know.

Q2: Which of these rocks adds CO2 to the atmosphere when it weathers?
a) Limestone
b) Sandstone
c) Granite
d) I don't know.

Q3: Which of these liquids will weather a rock the fastest?
a) Acid rain
b) Tap water
c) I don't know.

Q1: Which of the following impacts of weathering could have a positive impact to humans?
a) Rocks breaking up into small pieces to help make soil.
b) Rocks left over from mining getting rained on and leaking metals into drinking water.
c) I don't know.

Q2: Which of the following impacts of weathering could have a negative impact to humans?
a) Rocks breaking up into small pieces to help make soil.
b) Rocks left over from mining getting rained on and leaking metals into drinking water.
c) I don't know.

Q3: Which rock type weathers faster?
a) Mudstone
b) Granite
c) I don't know.

Figure 2.4: Results of the pre- and post-lesson quizzes combined from all twenty of our lessons (~300 students). The questions for each quiz are shown below the bar chart for clarity.

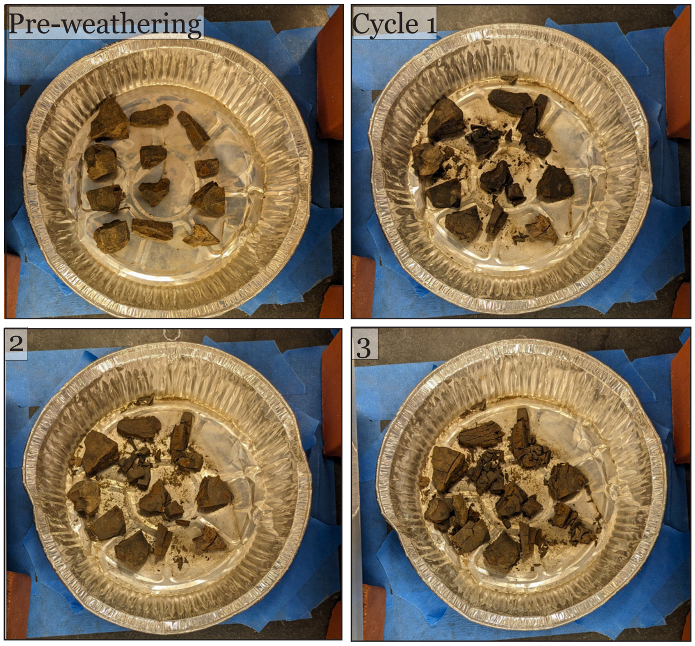


Figure 2.5: Example of mudstone weathering from manual wetting and drying cycles. Each cycle represents mudstone being put into a container of water for ~24 hours, then oven-dried at ~200 °F for ~1 hour. The pie tray is 12 cm in diameter for scale.

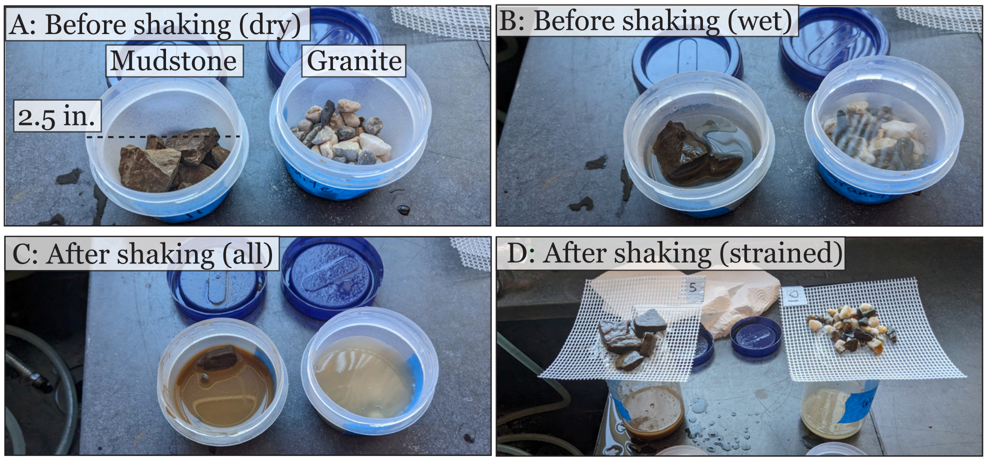


Figure 2.6: Staged example of the Lesson 2 soil formation experiment. (A) The initial set up with ~30-50 grams of each rock type in a small, labeled container. (B) After filling each container approximately halfway with water. (C) After ~3-5 minutes of shaking. Note the change in the wastewater color for both rock types. (D) Example of straining rocks through a ~3 mm mesh into a waste container. Note the difference in size and shape of the rocks pre- and post-shaking.

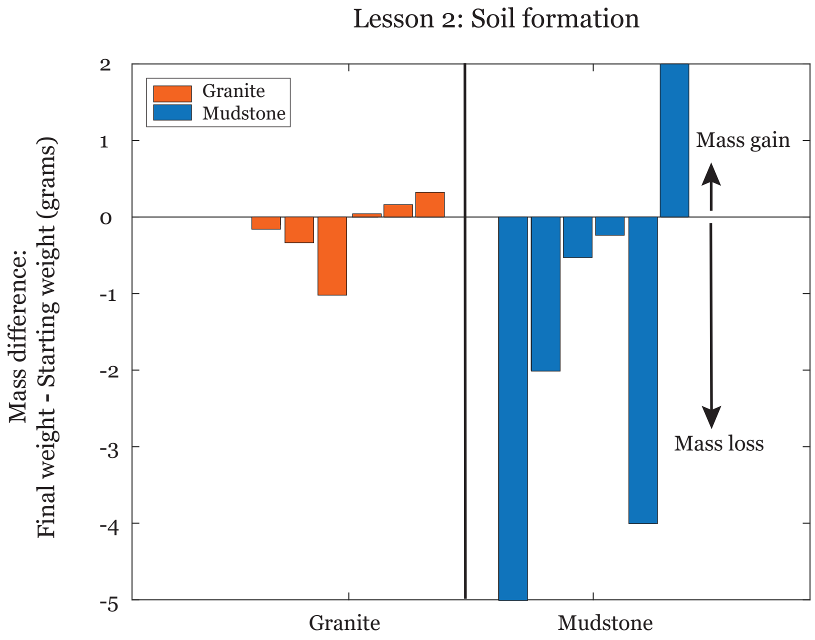


Figure 2.7: Example classroom data from Lesson 2 showing granite and mudstone mass loss after the shaking experiment. Each bar represents a different student group's data.

SUPPLEMENTARY MATERIALS

Adult supervision guide: Rock weathering take-home activity

Concept statement: Give students the opportunity to observe weathering over a longer period than a single class period and allow students to visualize how weathering happens in nature. ***Note: Adult supervision required during this activity at all stages**

Objectives: Students will be able to apply knowledge from this activity to the second lesson about soil formation and investigate how rock weathers over ~1-2 weeks in a semi-artificial environment.

Pre-lesson set-up done by teacher and given to student in the classroom for them to take home.

- Obtain mudstone (~2 pieces/student, ~30-50 g each)
- Put rock pieces into a small 3x5 inch aluminum bread pan (2 pieces per tray).
- Make sure students have access to a camera and/or pen and paper to record observations.

Materials:

- Mudstone
- Aluminum pans/containers
- Water

- Heat source (Option 2 only)
- Area for weathering outside (Option 1 only)
- Eye protection
- Gloves and aprons
- Description of activity and permission sheet for adult guardians assisting students with activity.

Lesson plan:

- Option 1: Give material to individual students to take home and put outside their residence for 2 weeks. Students observe the natural weathering from the elements over this period. Adult supervision at all stages.
- Option 2: Perform the activity at home but accelerated. Students soak rock pieces in water for ~24 hours, then dry mudstone in an oven at ~180° F for ~1 hour. Repeat daily for at least 5 days.
- For both options, have students take daily photographs and make written observations about the progressive weathering.

Permission slip: I, ________________________________, give permission for my student ____________________________ to do this activity at home and will assist them at all stages.

Signature of parent/guardian: _____________________________________

Date:__________________

Lesson 1 evaluation

Name:__________________________

1. The weathering of rocks can impact climate.
    a. Yes
    b. No
    c. I don't know.

2. What is an example of a rock that adds CO_2 to the atmosphere when it weathers?
    a. Limestone
    b. Sandstone
    c. Granite
    d. I don't know.

3. Which of these liquids will weather a rock the fastest?
    a. Acid rain
    b. Tap water.
    c. I don't know.

Lesson 1 worksheet

Name:_________________________________

Focus Question: Can the weathering of rocks affect climate?

Chalk + Vinegar demonstration:

1) What rock type is represented by the chalk? (circle one)

Granite Limestone Sandstone

2) True or false: The vinegar is an acid (circle one)

True False

3) Do you think that the chalk weathering is interacting with the atmosphere? In what ways?

____

____

____

____

____

Sugar cube experiment:

4) Will sugar cubes dissolve fastest in hot or room temperature liquids? (circle one)

Room temperature liquids   Hot liquids

Why? Write your answer in 1-2 sentences below.

____

____

____

____

______

5) Will sugar cubes dissolve fastest in water, diluted vinegar, or full-strength vinegar? (circle one)

Water   diluted vinegar   full-strength vinegar

Why? Write your answer in 1-2 sentences below.

____

____

____

____

______

6) Which liquid does your group have (circle one):

water   diluted vinegar   full-strength vinegar

7) What temperature is your groups liquid (circle one):

hot room temperature

Activity goal:

Measure the time to completely dissolve the sugar cube (you'll know the cube is dissolved when there's no grains of visible sugar left in the Tupperware)

Instructions:

1. Make a prediction about what will cause the sugar cube to dissolve fastest (questions 4 and 5), everyone must write something; however, you can discuss as a group.
2. Take out the Tupperware that has the sugar cube in it and the capped tube that has your groups liquid. Make sure your group has a timer of any kind.
3. One person pours the liquid into the cup, hitting the sugar cube as they pour from around an inch above the cup.
4. One person starts the timer when the liquid starts to enter the cup.
5. Once the liquid is poured in, swirl the cup, **keeping the cup bottom on the table.**
6. Both observe what happens as the initial dissolving occurs as the liquid hits the sugar cube.

7. Wait until you can't see the sugar in the cup, stop the timer.
8. Record the time to dissolve the sugar
9. Convert your time to seconds, see conversion below:

Please report your time in SECONDS

Conversion from minutes to seconds: 1 minute = 60 seconds

For example, 1 minute 15 seconds is: 60 seconds + 15 seconds = **75 seconds**

How long did it take to dissolve your sugar cube:

____

10. Please take your Tupperware, tube, and timer to the specified location. Dump and rinse out the Tupperware in a sink. Dry your container.

Answer these final questions after we plot all the data we collected as a class

Was your hypothesis correct? Was it wrong? Either way, can you explain the trend on the graph?

____

____

____

____

Do you have any ideas on why groups using the same liquid have different times?

Which rock type does sugar seem most analogous to? (circle one)

Sandstone Limestone

Why? Write your answer in 1-2 sentences below.

Use the space provided below to draw the weathering of A. limestone OR B. Sandstone. You must include: 1. The rock, 2. The liquid/thing weathering the rock, 3. Any products that result from weathering.

Lesson 2 evaluation

Name:__________________________

1. Which of the following impacts of weathering could have a positive impact to humans?
    a. Rocks breaking up into small pieces to help make soil.
    b. Rocks left over from mining getting rained on and leaking metals into drinking water.
    c. I don't know.

2. Which of the following impacts of weathering could have a negative impact to humans?
    a. Rocks breaking up into small pieces to help make soil.
    b. Rocks left over from mining getting rained on and leaking metals into drinking water.
    c. I don't know.

3. Which rock type weathers faster?
    a. Mudstone
    b. Granite
    c. I don't know.

Lesson 2 worksheet
Name:

Focus Question: What impacts can weathering have on human communities?

Experiment (Soil formation):

Experiment goal: Determine which rock type makes fine particles fastest.

1) Which rock type do you think will break up the most? (circle one)

Granite Mudstone I don't know.

2) Why? Write your answer in 1-2 sentences below.

Instructions:

11. Which rock type do you have? (circle one)

Granite Mudstone

12. Weigh the rock chips and record weight in grams:________________________

13. Observations about your rock chips (do this for the type of rock that you have):

a. Mudstone: Round or sharp edges tan or gray smooth or rough

b. Granite: Round or sharp edges tan or gray smooth or rough

14. Put rock chips into container.
15. Fill the container half full of water and close lid tightly.
16. Turn on the timer and start shaking
17. Take turns and shake for a total of 3 minutes.
18. Stop shaking
19. Carefully remove the lid.
20. Place the plastic mesh over the pie tray, making sure it's facing so it will be 'cup' shaped
21. Pour the contents out of the jar onto the mesh, if there are any chips stuck in the container put a small amount of water in the container and repeat.
22. When chips are out of the shaking jar, dry the chips and jar, clean the mesh and pie tray.
23. What happened to the edges of the rocks? Did they get (circle one):

    Rounder Sharper Stayed the same
24. What happened to the size of the rock chunks? Did they get (circle one):

    Bigger Smaller Stayed the same size
25. Weigh these rock chips and record the weight in grams:________________________
26. Subtract the final weight from the initial weight:

Final weight (#15): _______ g

Final weight – Initial weight: _______ g

Initial weight (#2):________ g

Answer these final questions after data is plotted and we have discussed what happened:

3) Which place would you expect to have the fastest forming soil?

An area with lots of granite   An area with lots of mudstone   I don't know.

4) Which of the following factors can also affect how soil forms?
    a. Climate
    b. Life
    c. Time
    d. All the above

5) Thinking about the last weathering lesson; if an area experienced acid rain and a hot climate, do you think the soil would form faster or slower?

Faster   Slower   I don't know.

Using the space provided below, please draw: 1. An environment that weathers rocks easily and 2. An environment that does not weather rocks easily.

You must include the following: Rock, what the weather looks like, any plant life present/not present. Optionally each drawing can have different time periods in the same area.

Rubrics

Lesson 1:

Worksheet key for educators: *please note that the authors did not grade the worksheets, and these rubrics are written with the intention of guiding students to think critically rather than to be graded for points, which is the intent of the evaluations.

Chalk + Vinegar demonstration section:

Number 1: Correct answer is: **Limestone** is a rock that is represented by chalk.

Number 2: Correct answer is: **True,** vinegar is an acid.

Number 3: *Note: answers will vary, intent is critical thinking and forming an argument for the students answer.

Example answer: Chalk weathering does interact with the atmosphere. When a liquid, especially an acid like vinegar, is applied to chalk there is a chemical reaction between the two materials, and one of the products of that reaction is carbon dioxide (CO_2) gas, which enters the atmosphere.

Sugar cube experiment section: Please note that these are all intended as hypotheses questions and are phrased to make students think critically prior to performing the experiment.

Number 4: Correct answer is: **Hot liquids,** as heat applied to a molecule will in most cases help to break apart the material.

Number 5: Correct answer is: **Full strength vinegar,** as this is the strongest acid we are using in this experiment. The more concentrated the acid, the easier it can break apart materials.

Post experiment questions:

Possible sources of error include: 1. Hot liquids not being kept at the same temperature, and so being cooler than would be effective to weather the material faster than the room temperature liquids. 2. Timers being started and/or stopped at the incorrect time(s). 3. Conversion from minutes to seconds done incorrectly. 4. Students not fully weathering their material (e.g. the cube may have weathered into small pieces, but that does not count as fully weathered). 5. Students swirling their solutions at different speeds.

The sugar cubes are analogous to sandstone because they are compacted small particles.

Lesson 1:

Evaluation key for educators:

Question 1: Correct answer is: **Yes**, the weathering of rocks can impact climate.

NGSS standard MS-ESS2-2.A: We are asking learners to think about Earth's materials and systems.

Question 2: Correct answer is: **Limestone** is an example of a rock that adds CO_2 to the atmosphere when it weathers.

NGSS standard MS-ESS2-2: We are asking students to construct explanations using their observations from their experiments.

Question 3: Correct answer is: **Acid rain** will weather a rock fastest out of the liquids provided.

Question	Correct	Incorrect	Answered I don't know	Did not answer
1	1 pt	1 pts	1 pts	0 pts
2	1 pt	1 pts	1 pts	0 pts
3	1 pt	1 pts	1 pts	0 pts

NGSS standard MS-ESS2-2.C: We are asking learners to think about the roles of water in Earth's surface processes.

Before lesson: ___/3 pts

After lesson: ___/3 pts

Question	Correct	Incorrect	Answered I don’t know	Did not answer
1	1 pt	0 pts	.5 pts	0 pts
2	1 pt	0 pts	.5 pts	0 pts
3	1 pt	0 pts	.5 pts	0 pts

Lesson 2:

Worksheet key for educators: *please note that the authors did not grade the worksheets, and these rubrics are written with the intention of guiding students to think critically rather than to be graded for points, which is the intent of the evaluations.

Soil formation experiment section:

Numbers 1 and 2: Correct answer is: **Mudstone** break up the most because the rock strength of mudstone is much lower than granite's (you can think of rock strength like density for middle school students).

Number 3: Correct answer is: **An area with lots of mudstone** will have faster forming soil than an area with lots of granite, however there are lots of factors that go into soil formation in addition to parent material.

Number 4: Correct answer is: **Climate, life, and time** in addition to rock weathering are all factors that help soil form.

Number 5: Correct answer is: Soil would form **faster** in an environment that experienced acid rain and a hot climate.

Lesson 2:

Evaluation key for educators:

Question 1: Correct answer is: **Rocks breaking into small pieces to help make soil** is a positive impact to humans.

NGSS standard MS-ESS2-2: We are asking students to construct explanations using their observations from their experiments.

Question 2: Correct answer is: **Rocks left over from mining getting rained on and leaking metals into drinking water sources** is a negative impact of rock weathering on humans.

NGSS standard MS-ESS2-2.A: We are asking learners to think about Earth's materials and systems.

Question	Correct	Incorrect	Answered I don't know	Did not answer
1	1 pt	1 pts	1 pts	0 pts
2	1 pt	1 pts	1 pts	0 pts
3	1 pt	1 pts	1 pts	0 pts

Question 3: Correct answer is: **Mudstone** will weather faster than granite.

NGSS standard MS-ESS2-2: We are asking students to construct explanations using their observations from their experiments.

Before lesson: ___/3 pts

After lesson: ___/3 pts

Question	Correct	Incorrect	Answered I don't know	Did not answer
1	1 pt	0 pts	.5 pts	0 pts
2	1 pt	0 pts	.5 pts	0 pts
3	1 pt	0 pts	.5 pts	0 pts

Side Column information

Content area: Earth and Space Sciences

Grade Level: 6-8

Big idea/unit: Rock weathering influences climate and soil production

Essential pre-existing knowledge for educators: Basic geoscience knowledge is helpful, but not required.

Cost: For both Lesson 1 and Lesson 2, we estimate a cost of $10-20 (low estimate) to $150 (maximum estimate) for a class of 30 students for ~10 periods (~ 300 students). Costs vary depending on if hot water kettles or hot plates are available and if rocks are collected in the field or bought at a landscaping store. Most materials can be re-used, excluding sugar cubes, vinegar, and the 'soft' rock chips. To reduce costs, we suggest the following. For lesson 1: heating liquids on a stove in a pot either in a school kitchen or at home and transferring those liquids into an insulated container to keep liquids hot. Containers for lesson 1 can be any container that can be heated. Lesson 1 is effective using sugar cubes and not including the optional chalk cube experiment (chalk cubes are significantly more expensive than sugar cubes). For lesson 2: Collecting a harder rock and/or a softer rock from local outcrops or streams on public lands can reduce costs. Additionally, the harder rock can also be reused as it experiences significantly less weathering during the experiment relative to soft rock. If scales are not available and are too expensive to purchase, teachers can teach this lesson without the quantitative explanation (see main text). Terri clothes are an alternative for 3 mm mesh.

Safety:

We suggest eye protection as a precaution when using vinegar and breaking rock chips. For the take home activity, oven mitts can be useful if students are using an oven to dry rocks. Adult supervision during take home activity is required.

Teacher's Guides

Teacher's Guide: Lesson 1

Concept statement: Rocks weather at different rates depending on the temperature and acidity of solutions. Depending on the rock type, this weathering can result in increasing carbon dioxide levels in the atmosphere and warming the planet.

Objectives: Students will be able to investigate how temperature and acidity affect rock weathering.

Pre-lesson set-up:

- Print student worksheets and evaluations (cut evaluations in half for pre/post quizzes)
- Put 1 sugar cube into each container (we recommend 1 container per group of 2-3 students)
- Prepare diluted vinegar (see main text for proportions).
- Put solutes in containers with lids, hot liquids should be put in containers right before activity starts, aluminum foil can be used to help retain heat in warmed liquids.
- For each student group put together: sugar cube, container, solute, stopwatch.

Materials:

- Sugar cubes
- Optional: chalk cubes
- Containers for weathering
- Water
- Diluted vinegar
- Eye protection
- 5% white vinegar
- Paper towels
- Hot water kettles
- Aluminum foil
- Stopwatches
- Gloves and aprons

1. **Engagement (5-7 minutes):**

Discussion of what weathering is, provide common everyday weathering examples (e.g., rust, peeling paint, etc.) and/or local examples of weathering, demonstrate how limestone weathering can release CO_2 to the atmosphere. This is a great video to show to students to engage them in the topic: https://www.youtube.com/watch?v=pmF41T52nJs.

Also reading from Rick Riordan's book The Battle of the Labyrinth, excerpt here: "… 'scoop up some dirt'…. I crouched down and scooped up a handful of Texas dirt. It was dry and black and spotted with tiny clumps of white rock… No, something besides rock. 'Those are shells… petrified seashells. Millions of years ago… this land was under water. It was part of the sea.' Suddenly I saw what she meant. There were little pieces of ancient seas urchins in my hand, mollusk shells. Even the limestone rocks had impressions of seashells embedded in them."

Teacher tasks:

- During the introduction slides, discuss weathering in your area and ask students for examples of weathering. All types of geologists and people should be represented in slides to show the diverse range of people who practice geology.
- Discuss how humans affect the carbon cycle.
- Demonstrate and discuss CO_2 release from chalk weathering.

Student tasks:

- Interact with demonstration.
- Think-pair-share activity focused on climate change and global climate.
- Discuss any other pop culture references to weathering and/or climate that they know about.
- Include all classmates in the discussion.

Suggested questions to engage critical thinking:

- Where does gasoline come from?
- Why does limestone bubble after adding vinegar?
- What causes paint to peel on the side of a house?
- How could you use all your senses to tell if a rock is weathered?

2. **Exploration (20-25 minutes):**

Groups dissolve sugar cubes in three different solutes: vinegar, diluted vinegar, and tap water, each at two different temperatures (room temperature and ~160° F). This allows students to determine weathering rates under different climate conditions. This activity can also be done with chalk cubes.

Teacher tasks:

- Split students into groups
- Hand out supplies and worksheets.
- Go through worksheet instructions interactively.
- Monitors activity and asks students questions to encourage critical thinking.
- Provides any additional materials/assistance for diverse learners and students of differing abilities.

Student tasks:

- Perform activity described on worksheet/by the teacher.
- Think about and answer critical thinking questions asked by the teacher.
- Include all lab partners in the activity.

Suggested questions to engage critical thinking:

- Does the sugar cube bubble like the chalk during dissolution? Why/why not?
- What is an example of a liquid in nature that vinegar can represent?
- What do you smell? Hear? See? Feel? Is the weathered solution sticky?

Safety considerations:

- Heated solution will be ~160° F and won't hurt students unless they are exposed to it for long time periods. Household vinegar is acidic (pH ~2) but safe for consumption and can be spilt onto bare skin without safety consequences. We recommend eye protection to keep vinegar out of students' eyes, and optional masks to reduce the strong odor from the vinegar.

3. Explanation (5-7 minutes)

Discussion and plotting of student-collected data

Teacher tasks:

- Ask students for their data by solute groups.
- Plot data on the excel datasheet.
- Ask if students can explain what the data shows and why.
- Wrap up with local rock weathering impacts.

Student tasks:

- Report data to the teacher
- Interpret the plots.
- Think critically about the experiment.
- Draw the weathering of limestone or sandstone as described on the worksheet.

Suggested questions to engage critical thinking:

- What does this plot mean?

- What implications does this have for weathering rocks and global climate?
- Did the sugar cubes bubble as they dissolved? Why or why not?
- If the sugar cubes have carbon in them and so does the chalk, why didn't the sugar bubble as it dissolved?

4. **Elaboration (3-5 minutes):**

Discuss how differences in rock type affect the weathering rates and climate.

Teacher tasks:

- Prompt discussion of how
  - Humid vs arid and rainy vs dry climates can affect weathering rates.
  - Different bedrock weathering products can add, take away, or have no effect on atmospheric CO_2 levels.
- Discuss how geologic can add and take away other gases from the atmosphere (e.g., volcanic eruptions release CO_2 to the atmosphere, as well as sulfur and other chemicals).

Student tasks:

- Think about the climate in their hometown, is it humid? Dry? Rainy? How might this affect weathering rates?
- Optional homework assignment suggestions:
  - Watch this video about how the arches formed in Arches national park and write a paragraph applying knowledge from this lesson to how the arches

formed in this landscape. https://www.nps.gov/arch/learn/photosmultimedia/geologyvideo.htm.

  - Find an example of weathering from a piece of media you like and share it with the teacher.

Suggested questions to engage critical thinking:

- What does humidity feel like? Aridity?
- How do you think these different climates interact with the rock that is weathering?
- Do volcanoes release gas? How do you think that affects the climate?

5. **Evaluation (3-4 minutes):**

Provide the same quiz at the beginning and end of the lesson as an entry and exit ticket. Modify as needed for students of different abilities.

Teacher tasks:

- Pass out evaluation and gives students ~1-2 minutes to answer questions.

Student tasks:

- Take the quiz to the best of their ability before and after the lesson.

Suggested questions to engage critical thinking:

- Questions, their NGSS associations, and rubrics are included in supplemental material.

Teacher's Guide: Take-home activity

Concept statement: Give students the opportunity to observe weathering over a longer period than a single class period and allow students to visualize how weathering happens in nature. ***Note: Adult supervision required during this activity at all stages**

Objectives: Students will be able to apply knowledge from this activity to the second lesson about soil formation and investigate how rock weathers over ~1-2 weeks in a semi-artificial environment.

Pre-lesson set-up:

- Obtain mudstone (~2 pieces/student, ~30-50 g each)
- Put rock pieces into a small 3x5 inch aluminum bread pan (2 pieces per tray).
- Make sure students have access to a camera and/or pen and paper to record observations.

Materials:

- Mudstone
- Aluminum pans/containers

- Water
- Heat source (Option 2)
- Area for weathering outside (Option 1)
- Eye protection
- Gloves and aprons
- Description of activity and permission sheet for adult guardians assisting students with activity.

Lesson plan:

- Option 1: Give material to individual students to take home and put outside their residence for 2 weeks. Students observe the natural weathering from the elements over this period. Adult supervision at all stages.
- Option 2: Perform the activity supervised at home. Students will soak rock pieces in water for ~24 hours, then dry them in an oven at ~180° F for ~1 hour. Repeat daily for at least 5 days. Adult supervision at all stages.
- For both options, have students take daily photographs and make written observations about the progressive weathering.

Teacher's Guide: Lesson 2

Concept statement: Rock weathering can impact human society, for example rocks can weather into soil. The rate at which rocks weather depends on the rock type.

Objectives: Students will be able to determine how rock type affects weathering rate and apply this knowledge to soil formation.

Pre-lesson set-up:

- Print student worksheets and evaluations (cut evaluations in half for pre/post quizzes)
- Obtain rocks necessary for the activity (rock chips should be around ½ inch to ¼ inch in size, break apart with a hammer if necessary). Note that common gravel bought at a landscaping or hardware store can be an alternative for granite.
- Place ~30-50 grams total of ~5-10 gram pieces of a single rock type in containers, make around ½ of the containers granite and ½ mudstone (goal is approximately equal amount of data for each rock type), and put a lid on each container.
- Prepare sieves: either a cloth and rubber band per rock container (strain through cloth into waist container), or a piece of ~3 mm diameter mesh cut to fit over the waste container lid with some space for error when students pour the rock and water mixture (see main text for example figure).
- Put water in waste container for students to easily add to their shaking container.
- Set up scale station(s).
- Each group should have: a container of rock, waste container with water, piece of mesh or cloth for sieving, stopwatch, optional calculator.

Materials:

- Mudstone
- Granite/gravel
- Containers for weathering
- Water
- Waste containers
- Eye protection
- Sieve material
- Paper towels
- Scales
- Stopwatches
- Rock hammer (teacher prep only)
- Gloves and aprons

Lesson plan:

1. **Engagement (5-7 minutes)**

Introduce lesson and discuss soil formation: what is soil formation and why is it important? Optional discussion of take-home activity experiences and results.

Teacher tasks:

- Lead discussion of soil formation, why soil is important, how rock type effects weathering rate. Optional discussion of the take-home activity.
- Provide visuals for prompting discussion of how soil forms and what is the ‘parent material’ soil forms from.
- Optional: Discuss water contamination due to weathering (e.g. acid mine drainage).
- Refer to soil in The Battle of the Labyrinth and discuss if they have ever seen shells in soil before.

Student tasks:

- Hypothesize about how long it takes for soil to form, and what elements (besides weathering) contribute to soil formation.
- Discuss why soil is important and what the soil looks like in their community.
- Discuss if weathering has negative impacts for society and the environment (e.g. water contamination, cracked roads, paint peeling, and weathering of buildings).

Suggested questions to engage critical thinking:

- What did you think would happen if mudstone sat outside for two weeks in summer (and never got wet) versus the winter (and got rained or snowed on every day)?
- What is the first step in soil formation?
- Why is soil important?
- What do you see on your way to school that is weathered? Does this weathering have a negative or positive impact for society?

2. **Exploration (20-25 minutes):**

   Groups shake rock chips in water for three to five minutes, measuring rock chip mass before shaking and after sieving and shaking. Students will make observations of changes to the rock chips and water before, during and after shaking. Students will calculate the difference in rock chip mass before and after the activity to show how different rocks weather at different rates.

Teacher tasks:

- Split students into groups.
- Hand out supplies, worksheets.
- Demonstrate shaking and sieving of rock. Makes sure that students correctly weight rock chips (explain how to use scales if needed).
- Make sure to encourage students to use all their senses to see how the rocks weather. Students with different physical abilities are included in this activity as all stages: observation of rocks before shaking can be performed using all senses. Shaking can be visually observed, done, or even smelled (the mudstone will smell ‘dirty’ while the granite will smell approximately the same). Make sure that students of all genders are included in the shaking of the rocks.

Student tasks:

- Perform activities as described in lesson plan and on worksheet.
- Think about and answers questions that teachers asks to encourage critical thinking.
- Include all classmates in the activity.

Suggested questions to engage critical thinking:

- Which rock do you think will break up the most? Why?
- What color is the waste water? Does this depend on the rock type?

- Which rock type do you think makes soil faster? Why?

Safety considerations:

- Optional eye protection suggested to prevent rock chips or water from entering eyes.

3. Explanation (5-7 minutes):

Plot data and discuss results, verbally and with their worksheet questions and drawings.

Teacher tasks:

- Ask students for their experimental data and plot data on the excel spreadsheet.
- Discuss the connection between rocks and soil formation, and which rocks weather fast versus slow.
- Lead broader discussion on additional soil formation requirements.

Student tasks:

- Analyze and interpret the data plotted on the excel worksheet.
- Apply their qualitative observations during the activity to the quantitative data.
- Think about soil formation and why soil formation is important.

- Draw the two environments as described on the worksheet.

Suggested questions to engage critical thinking:

- How are density and the rate rocks weather into smaller pieces related?
- Is soil formation important? Why?
- Are all soil types the same?

4. **Elaboration (~3 minutes):**

Discuss real-world implications of soil formation and (if time) water contamination due to weathering.

Teacher tasks:

- Discuss how soils are influenced by parent bedrock, show a soil map for the US and discuss where agriculture occurs and how the soil type relates to agriculture.

Student tasks:

- Think about soil and water in their community.
- Engage in discussion of agriculture in the US.
- Optional homework assignment suggestions:
    - Write up a formal report about your experiment's findings. Within this report describe a landscape of your choosing and describe: 1. What the bedrock is, 2. Does it weather quickly into small

particles? 3. Is there any soil? Why or why not. This could be any landscape, real or fictional.

  - How fast do you think sandstone could make soil? Respond in 1-3 sentences.

Suggested questions to engage critical thinking:

- Do soil characteristics stay the same across the US? Why or why not?
- Where is it important to have healthy soil? Why?
- Optional: Are water treatment plants important? Would the location of a water treatment plant be an important decision for city planners?

5. Evaluation (3-4 minutes):

Provide the same quiz at the beginning and end of the lesson as an entry and exit ticket. Modify as needed for students of different abilities.

Teacher tasks:

- Pass out evaluation and gives students ~1-2 minutes to answer questions.

Student tasks:

- Take the quiz to the best of their ability before and after the lesson.

Suggested questions to engage critical thinking:

- Questions, their NGSS associations, and rubrics are included in supplemental material.

SUPPLEMENTARY TABLES

Table 2.S1: Materials used during activities.

Lesson 1	**Take home activity**	**Lesson 2**
Sugar cubes/chalk cubes	Mudstone	Mudstone
Weathering and solute containers	Container	Granite/gravel
Water	Camera (optional)	Shaking containers
Diluted vinegar	Pen/paper	Waste containers
5% white vinegar	Oven (optional)	3 mm mesh/Terri clothes
Aluminum foil		Paper towels
Paper towels		Water
Hot water kettle or hot plate/pot		Scales
Stopwatches		Stopwatches