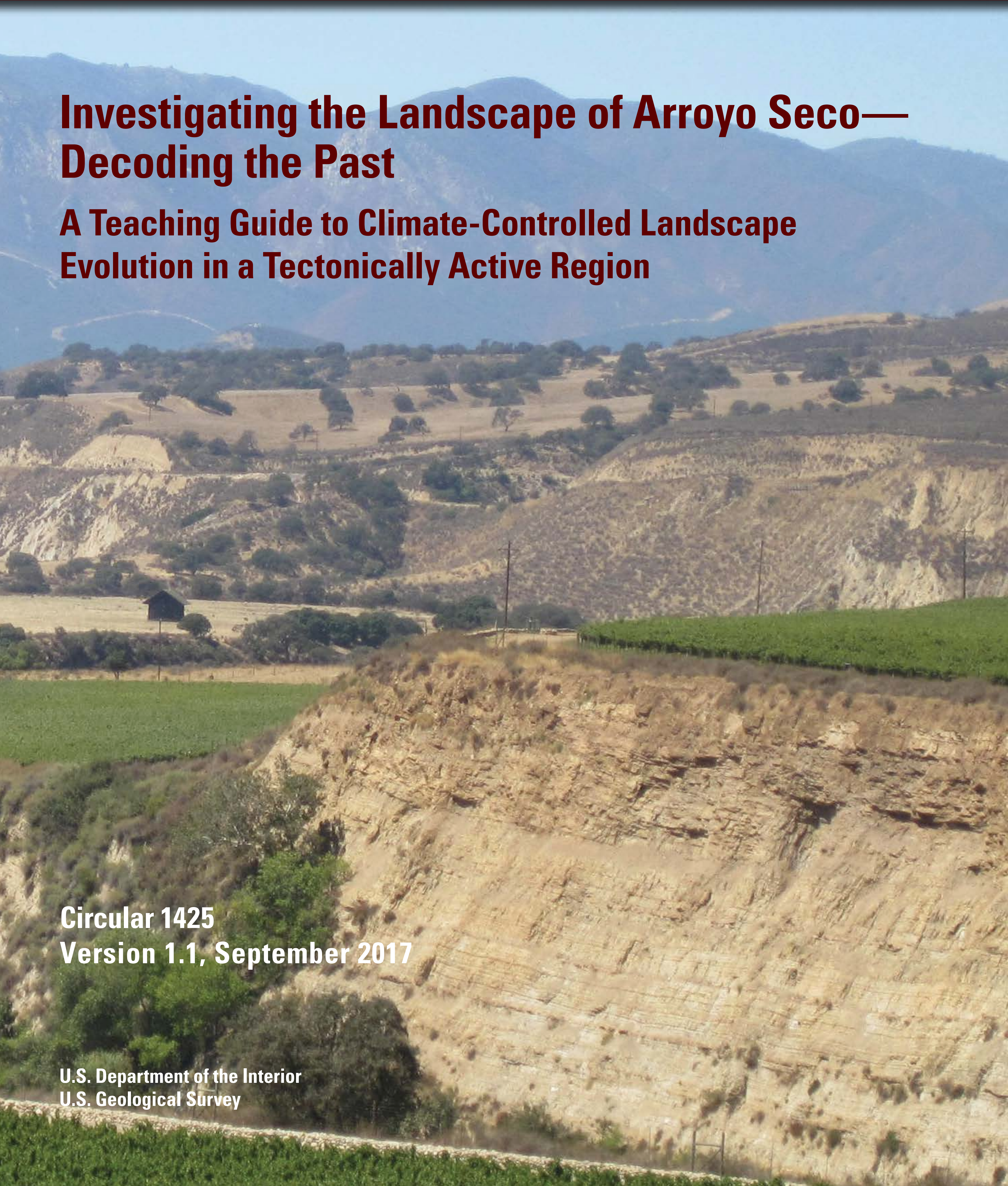
Investigating the Landscape of Arroyo Seco—Decoding the Past

A Teaching Guide to Climate-Controlled Landscape Evolution in a Tectonically Active Region



Circular 1425
Version 1.1, September 2017

U.S. Department of the Interior
U.S. Geological Survey

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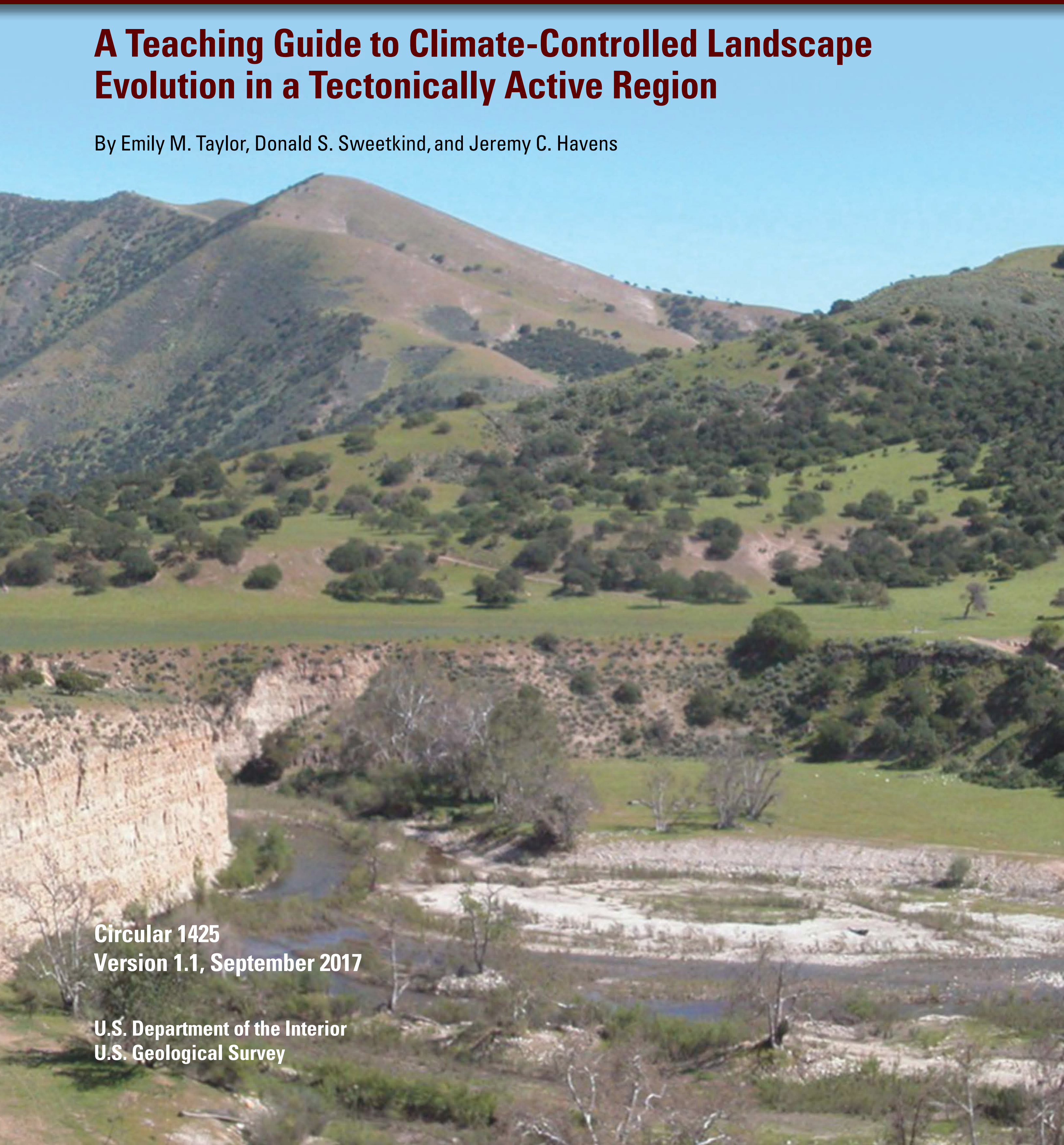

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U.S. Geological Survey

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Thank you to the many families in Arroyo Seco who provided permission for land access. With the exception of Arroyo Seco recreation area, land is private, and access is difficult. Thank you also to the Big Sur Land Trust for allowing us into Arroyo Seco Ranch. Lew Rosenberg and John Tinsley provided valuable time and ideas talking about work they had completed in Arroyo Seco. Thank you to Dan Sudan, director of the San Francisco-based Mission Science Workshop, for suggesting this project to make geology and climate change more accessible to middle and high school students.

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Figures

Conversion Factors

Inch/pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Investigating the Landscape of Arroyo Seco—Decoding the Past

A Teaching Guide to Climate-Controlled Landscape Evolution in a Tectonically Active Region

By Emily M. Taylor,[1] Donald S. Sweetkind,[1] and Jeremy C. Havens[2]

Introduction

Arroyo Seco is a river that flows eastward out of the Santa Lucia Range in Monterey County, California. The Santa Lucia Range is considered part of the central California Coast Range. Arroyo Seco flows out of the Santa Lucia Range into the Salinas River valley, near the town of Greenfield, where it joins the Salinas River. The Salinas River flows north into Monterey Bay about 40 miles from where it merges with Arroyo Seco. In the mountain range, Arroyo Seco has cut or eroded a broad and deep valley. This valley preserves a geologic story in the landscape that is influenced by both fault-controlled mountain building (tectonics) and sea level fluctuations (regional climate).

Broad flat surfaces called river terraces, once eroded by Arroyo Seco, can be observed along the modern drainage. In the valley, terraces are also preserved like climbing stairs up to 1,800 feet above Arroyo Seco today. These terraces mark where Arroyo Seco once flowed. The terraces were formed by the river because no matter how high they are, the terraces are covered by gravel deposits exactly like those that can be observed in the river today. The Santa Lucia Range, Arroyo Seco, and the Salinas River valley must have looked very different when the highest and oldest terraces were forming. The Santa Lucia Range may have been lower, the Arroyo Seco may have been steeper and wider, and the Salinas River valley may have been much smaller.

Arroyo Seco, like all rivers, is always changing. Sometimes rivers flow very straight, and sometimes they are curvy. Sometimes rivers are cutting down or eroding the landscape, and sometimes they are not eroding but depositing material. Sometimes rivers are neither eroding nor transporting material. The influences that change the behavior of Arroyo Seco are mountain uplift caused by fault moment and sea level changes driven by regional climate change. When a stream is affected by one or both of these influences, the stream accommodates the change by eroding, depositing, and (or) changing its shape.

In the vicinity of Arroyo Seco, the geologically young faulting history is relatively well understood. Geologists have some sense of the most recent faulting event and of the faulting in the recent geologic past. The timing of regional climate changes is also well accepted. In this area, warm climate cycles tend to cause the sea level to rise, and cool climate cycles tend to cause the sea level to fall. If we understand the way the terraces form and their ages in Arroyo Seco, we can draw conclusions about whether faulting and (or) climate contributed to their formation.

This publication serves as a descriptive companion to the formal geologic map of Arroyo Seco (Taylor and Sweetkind, 2014) and is intended for use by nonscientists and students. Included is a discussion of the processes that controlled the evolution of the drainage and the formation of the terraces in Arroyo Seco. The reader is guided to well-exposed landscape features in an easily accessible environment that will help nonscientists gain an understanding of how features on a geologic map are interpreted in terms of earth processes.

[1]U.S. Geological Survey

[2]ADC Management Services, Inc.

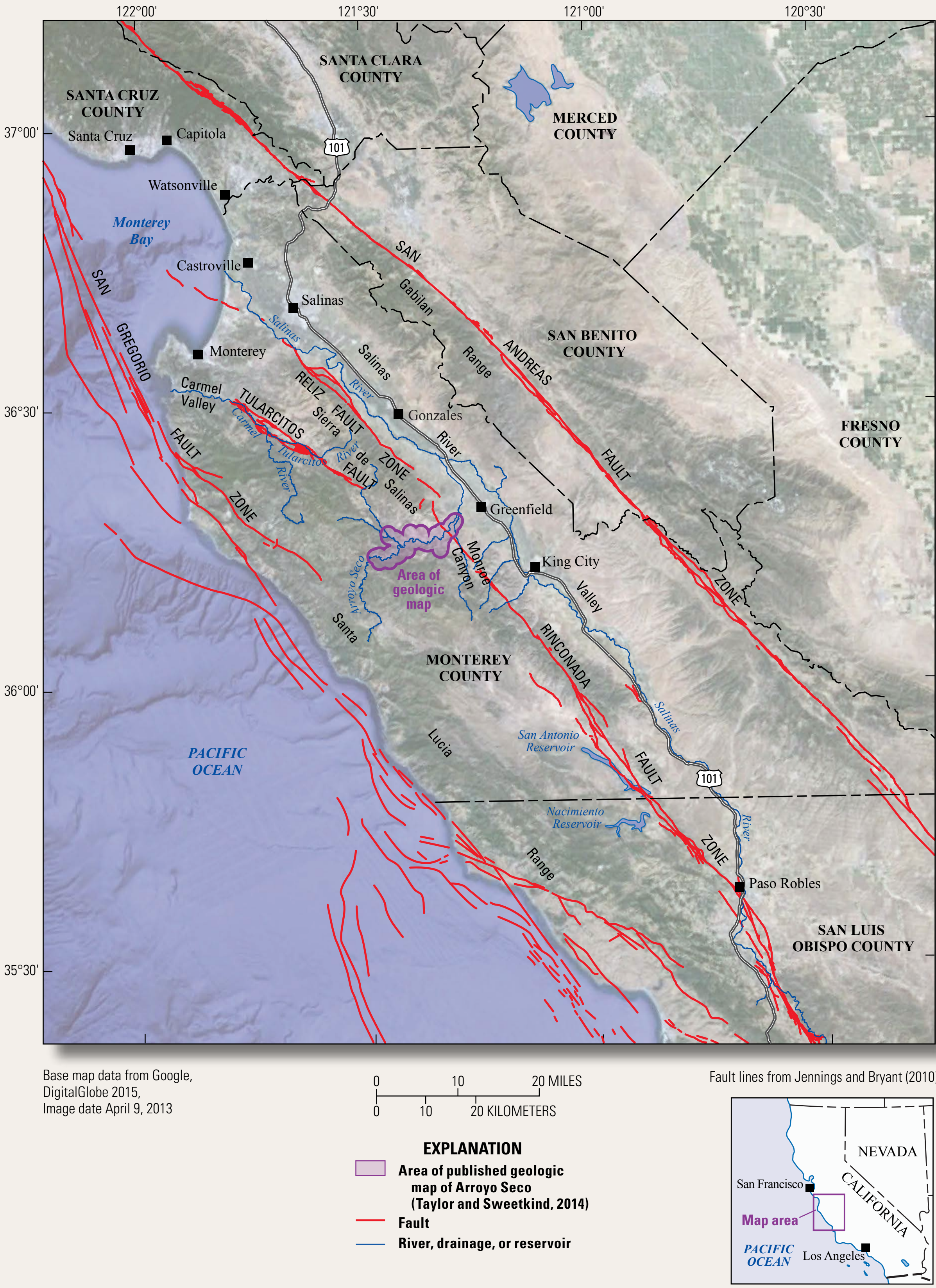


Figure 1. Map of the location of Arroyo Seco.

Background

Arroyo Seco is a **perennial drainage** (text in bold is defined in the glossary) in the Santa Lucia Range of the central Coast Ranges of California and is one of the largest **tributary** drainages of the Salinas River (fig. 1). In Arroyo Seco, the **geomorphic features** record the complex evolution of a stream drainage in the Coast Ranges. Here, one can observe a sequence of **strath or abandoned erosional terrace** surfaces carved into an upward-migrating mountain range (Taylor and Sweetkind, 2014). Strath terraces exposed in Arroyo Seco are spectacular examples of an environment altered over a long period of geologic time by processes controlled by **global climate change** and regional **tectonics**. Not every environment responds to climate change and tectonics in the same way, although parts of the processes observed in Arroyo Seco are shared in many environments. This guide provides a general introduction to these geologic processes as well as a road log that can be used to locate examples of features formed by the described processes in the field.

A recently published geologic map of Arroyo Seco includes a more regional map centered on Arroyo Seco, **mapped at a scale** of 1:50,000, and an inset map that focuses on the Arroyo Seco drainage, mapped at a scale of 1:24,000 (Taylor and Sweetkind, 2014). On these maps, terrace deposits have been identified and correlated using a variety of geologic mapping techniques and digital datasets. Figure 2 shows an example, in perspective view, of the geologic mapping of the terrace deposits, with terraces of similar age shown in the same color and label, as viewed looking upstream up the Arroyo Seco drainage.

During the course of the geologic mapping, several local stakeholders expressed interest in a layperson's guide to the geology and evolution of the Arroyo Seco drainage for use as a teaching and explanatory tool. This publication serves as a descriptive companion to the formal geologic map of Arroyo Seco (Taylor and Sweetkind, 2014) and is intended for use by nonscientists and students. In it, the reader will be guided to well-exposed geomorphic features in an easily accessible environment that will help the nonscientist gain an understanding of how features on a geologic map are interpreted in terms of earth processes.

This guide includes

- A discussion of the processes that controlled the evolution of the drainage and the formation of the terraces in Arroyo Seco. The majority of the discussion is specific to the processes that occur here and not in every geologic environment. Readers will learn how geologists interpret observations in terms of earth processes and link physical features to other lines of evidence related to past climate and tectonic activity.
- A description of the types of geologic features observed, their shape and extent, and the criteria for mapping and identifying specific geologic features.
- A road log that describes a driving route and short hikes to view examples of geomorphic features and representative exposures.

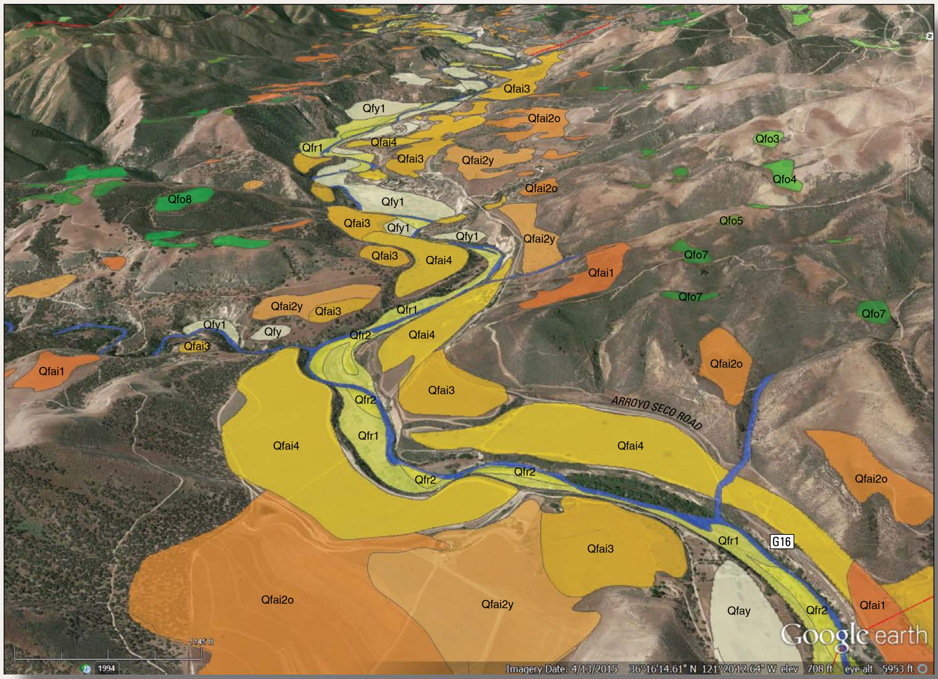


Figure 2. Perspective view of Arroyo Seco, looking upstream, with terrace deposits mapped by Taylor and Sweetkind (2014).

Physical and Geologic Setting of Arroyo Seco

Geologists create geologic maps by studying the location, distribution, and physical and chemical properties of rocks and sediments. These rocks and sediments are typically exposed at the surface, but they can also be studied in the subsurface by drilling boreholes. Rocks and sediments are altered over time by weathering, erosion, and faulting. Weathering alters rocks and sediments, erosion transports weathered rocks by water and gravity, and faults rearrange rocks and sediments. Geologists can distinguish the effects of geologic time on different kinds of rocks and sediments over time. They interpret and distinguish the effects of tectonic activity, faulting, and physical and chemical weathering. A geologic map attempts to separate different geologic units in a meaningful way so that geologists can better understand the evolution of the regional rocks and sediments. Our goal was to better understand the formation of the strath terraces that are easily observed in the broad valley and surrounding ranges at Arroyo Seco.

Strath terraces are surfaces cut into bedrock by eroding streams. Streams commonly alternate between periods of eroding (or downcutting), and periods of depositing (or accumulation) of sediments (fig. 3*A*). Stream terraces form during pauses in the downcutting processes so each terrace level records the profile of the stream. An eroding episode typically ends with a prolonged period where the stream stays at the same position in the landscape (**stream equilibrium**), and a **flood plain** is formed. Stream gravel is both eroding the bedrock on the flood plain and being transported downstream (fig. 3*B*). This relatively brief pause when the flood plain is forming is followed by renewed stream-channel downcutting that preserves the beveled terrace surface (Bull, 2007). A change takes place for climatic and (or) tectonic reasons, and the stream or river cuts down to a new level, leaving the former flood plain as a strath terrace, underlain by a thin veneer of gravel (fig. 3*C*). This continues to happen episodically, and the result is strath terraces at different elevations in the valley with higher terraces being older (fig. 3*D*). The challenge to the geologist is to figure out the terrace ages, the relation between terraces across the drainage, and establish whether climate or tectonics drives the formation of the terrace (fig. 3*E*).

On the geologic map of the Arroyo Seco drainage, different colored polygons represent different aged geologic units and are labeled according to the identity of the unit (figs. 2 and 4). Note that deposits associated with each strath terrace consist of many separated polygons of the same unit (same color and label). These now discontinuous features record the presence in the past of a once-continuous surface that was an older flood plain of Arroyo Seco, now uplifted and dissected by erosion. Older terrace surfaces are higher in elevation than the youngest terrace adjacent to Arroyo Seco. In addition to the mapped terrace deposits, the surrounding bedrock is mapped as undifferentiated **basement rock** shown in purple in the southwestern part of the map (labeled as MzPzub on fig. 4) and the Monterey Formation in brown elsewhere on the map (labeled Tms on fig. 4).

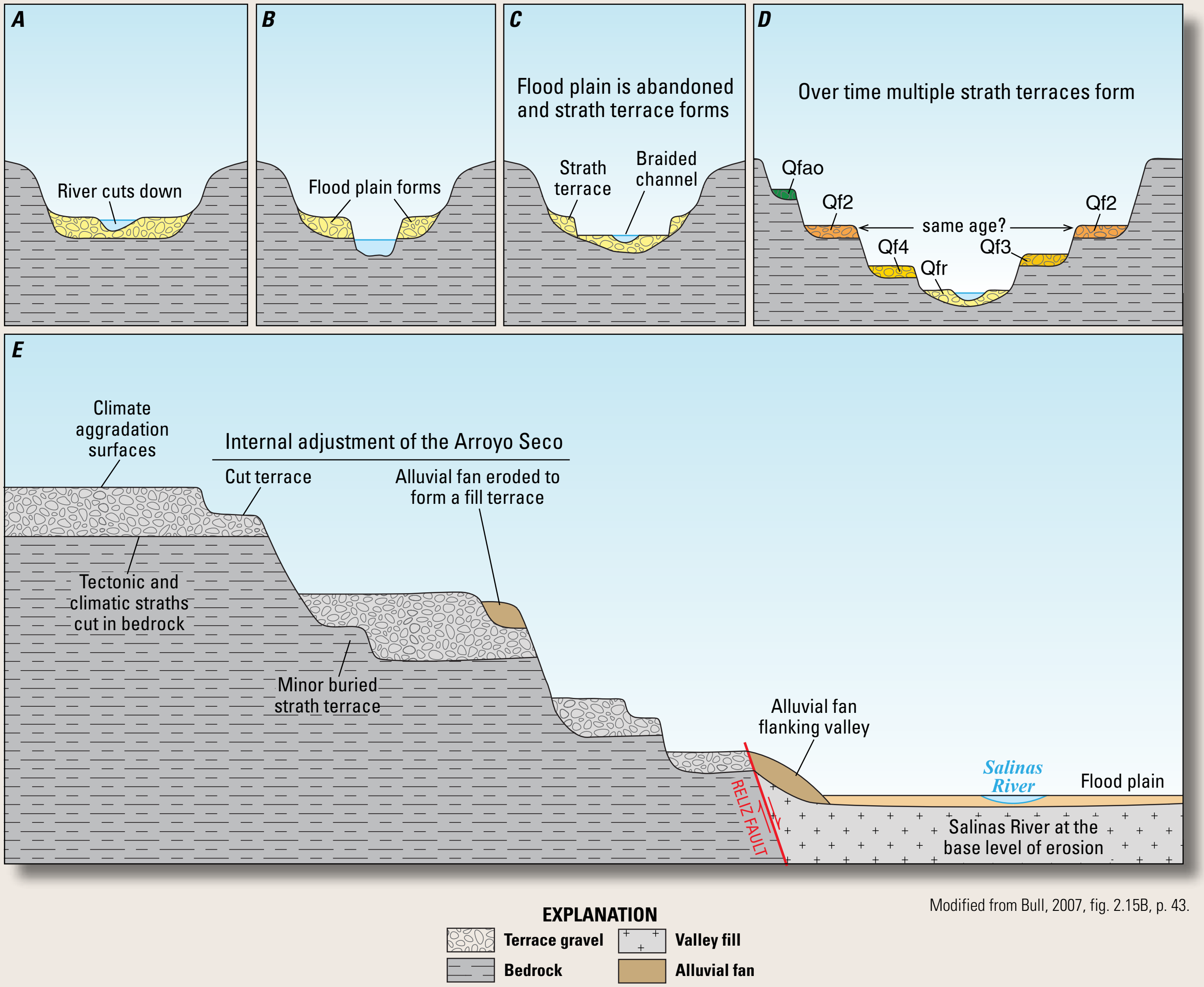
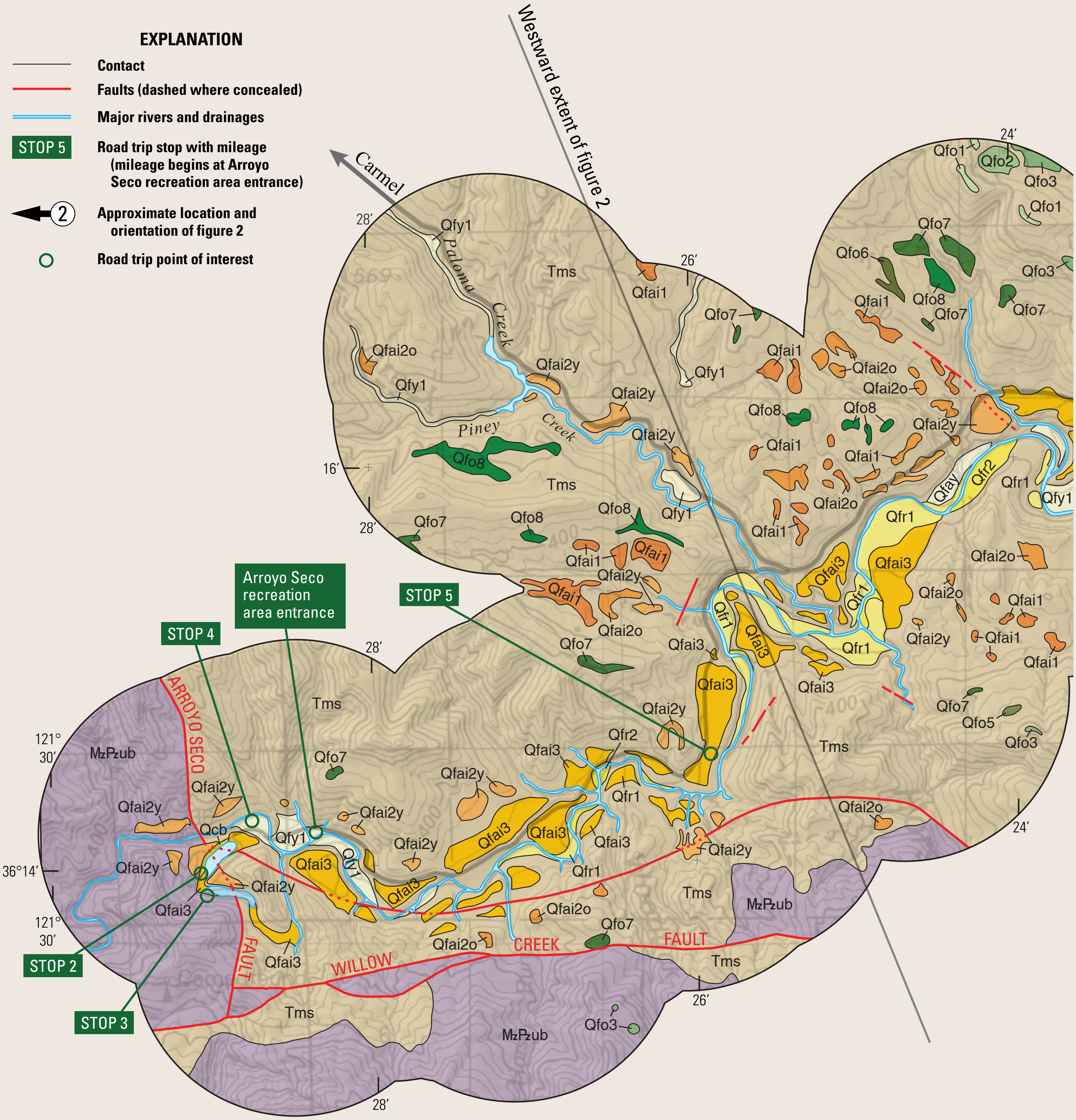


Figure 3. Strath terrace formation.

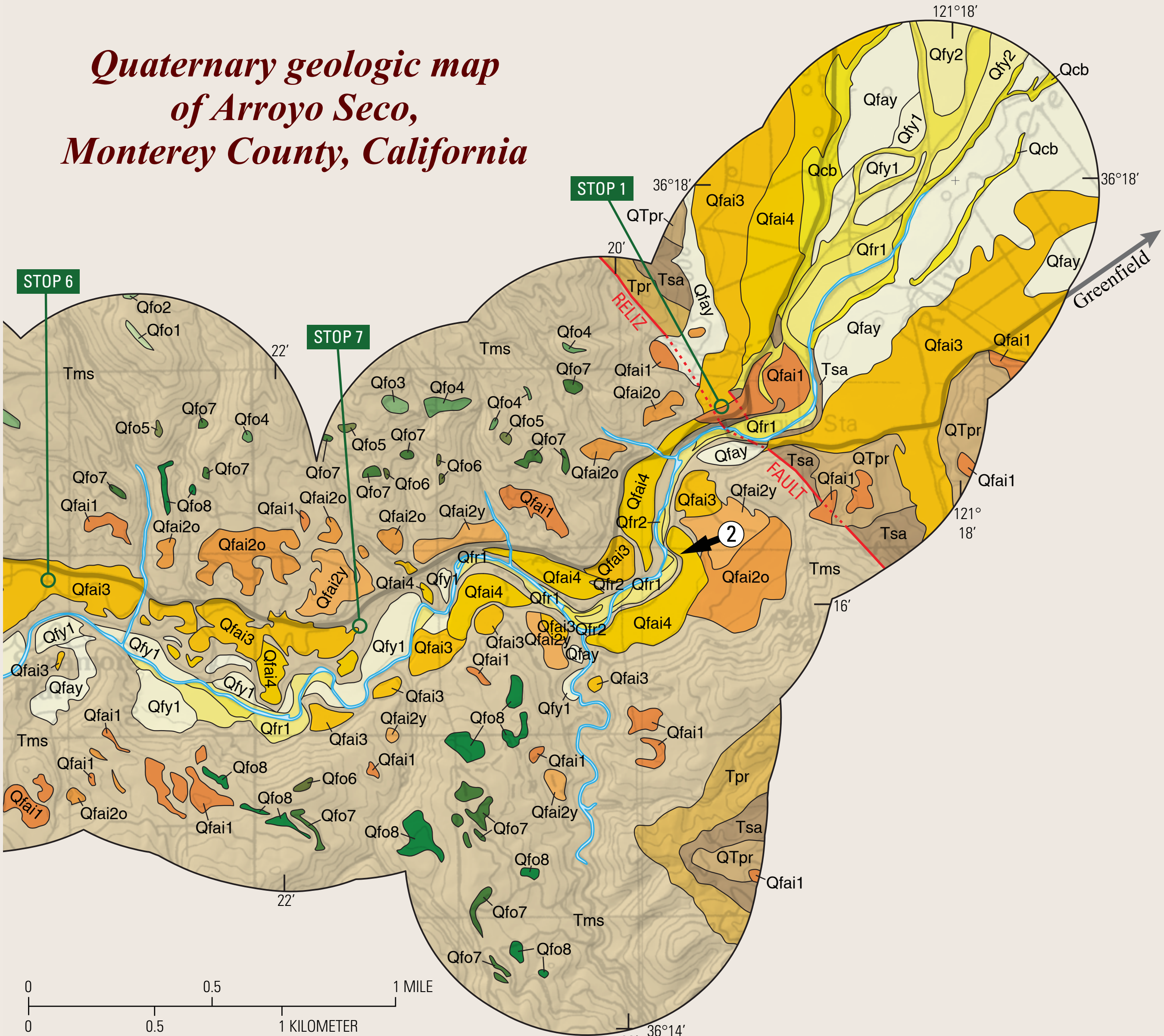
Although Arroyo Seco extends well up into the Santa Lucia Range, the region of interest (and covered by this field guide) extends from the contact of the resistant basement rocks (fig. 4, MzPzub), which underlie the higher parts of the Santa Lucia Range, and the downstream end where Arroyo Seco leaves the mountains to join the Salinas River. For the most part, the stream section runs through the comparatively softer and more easily eroded sedimentary rocks of the Monterey Formation (fig. 4, Tms). The different rock types play an important role in the evolution and resulting shape of the eroded valley where Arroyo Seco flows. Arroyo Seco is constrained to a narrow canyon where it flows through resistant basement rocks (figs. 5*A* and 5*B*), but opens eastward to a broad, 11-mile long valley with broad terraces where the drainage flows over of the Monterey Formation (figs. 5*C* and 5*D*). Arroyo Seco declines in elevation from about 850 feet to 150 feet in the area of interest.



Base from U.S. Geological Survey 1:100,000-scale digital data, 1982, Universal Transverse Mercator, zone 10, North American Datum of 1983 (NAD 83).

Figure 4. Quaternary geologic map of Arroyo Seco, Monterey County, California. Modified from Taylor and Sweetkind, 2014.

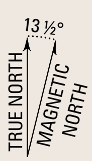
Quaternary geologic map of Arroyo Seco, Monterey County, California



0 0.5 1 MILE

0 0.5 1 KILOMETER

CONTOUR INTERVAL 33 FEET (10 METERS)
NATIONAL GEODETIC VERTICAL DATUM OF 1929



APPROXIMATE MEAN DECLINATION, 2014

CORRELATION OF MAP UNITS

[Angled boxes represent estimated range of age uncertainty; Holocene and Pleistocene subdivisions and boundary ages are from Gibbard and others, 2010, p. 99]

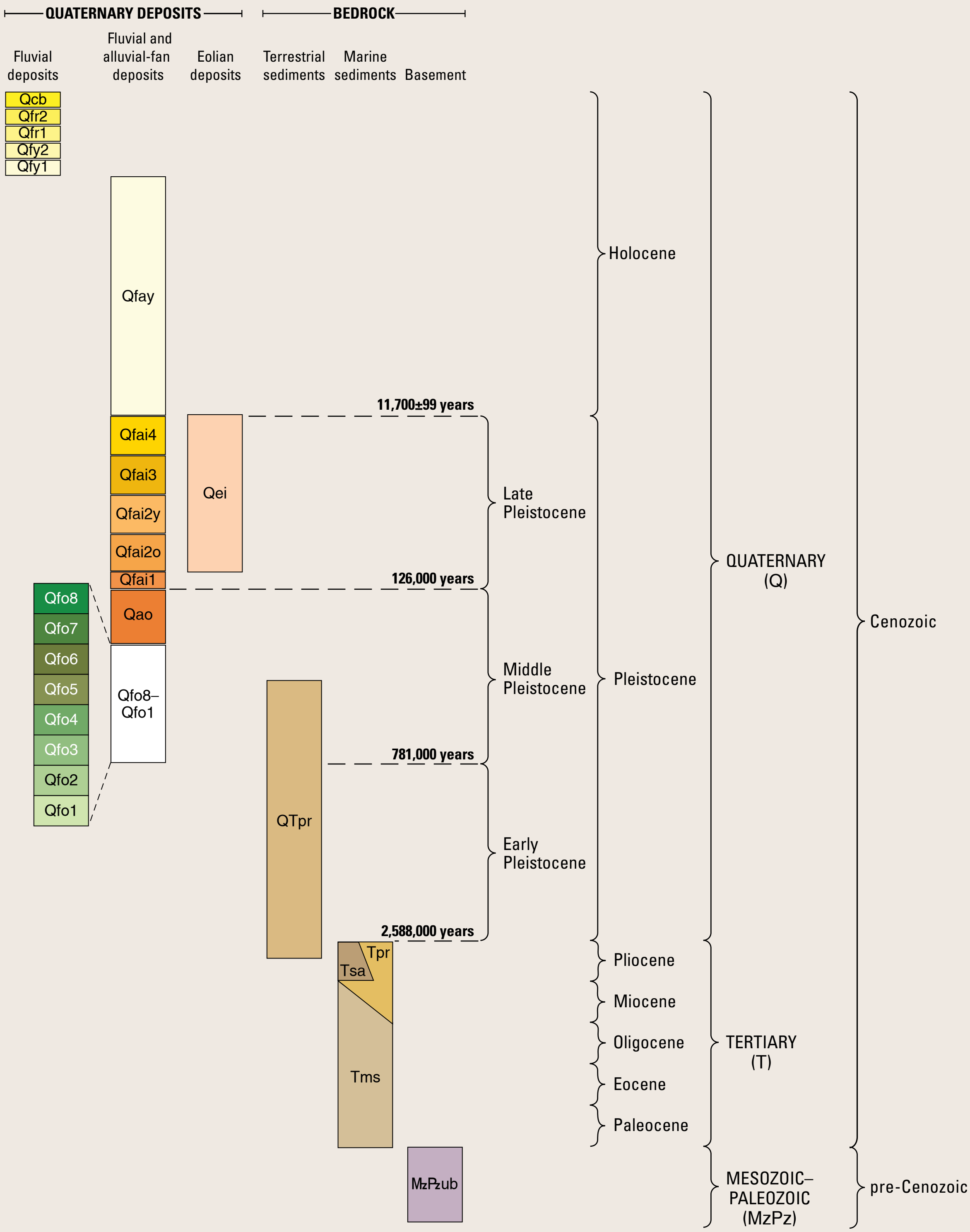


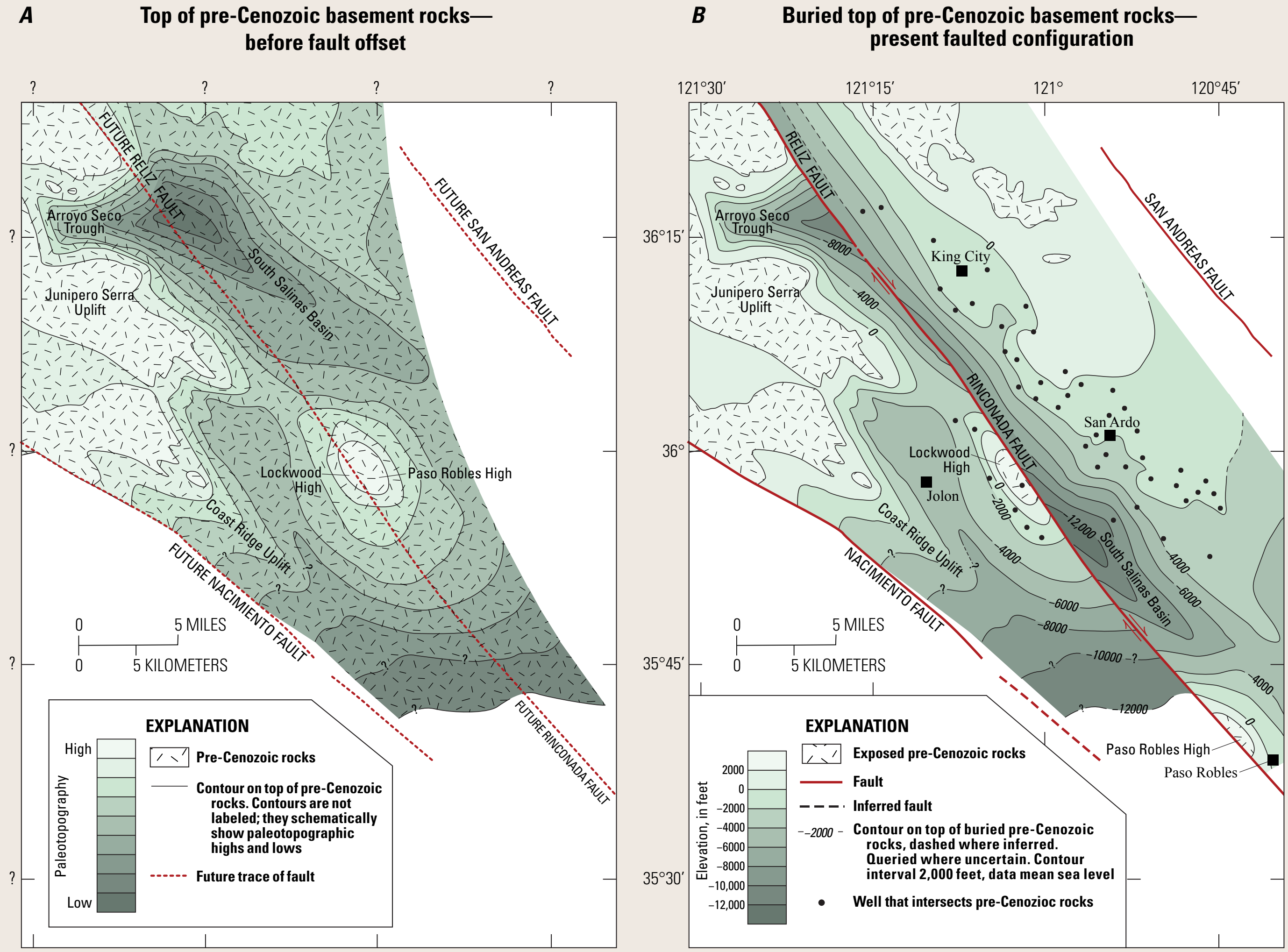
Figure 4. Quaternary geologic map of Arroyo Seco, Monterey County, California.—Continued.

Photographs by E.M. Taylor, U.S. Geological Survey, March 2015

Figure 5. A narrow canyon (*A*) formed in pre-Cenozoic basement rocks (*B*) and the broad valley (*C*) formed in the Tertiary Monterey Formation (*D*).

The Monterey Formation exposed in Arroyo Seco is bounded on the east by the Reliz fault, a north-south trending fault on the west side of the Salinas River valley (figs. 1 and 4; Rosenberg and Clark, 2009). Vertical offset on this fault is one of the causes of changes in **base level** contributing to the formation of strath terraces in Arroyo Seco (Finnegan and Balco, 2013). The Reliz fault begins 5 miles south of Arroyo Seco at Monroe Canyon and continues northward along the west side of the Salinas River valley to Monterey Bay (fig. 1). The Reliz fault extends north and slightly east from the terminus of the Rinconada fault (fig. 1), a much longer fault that extends from Monroe Canyon southeast for 140 miles. These faults are mapped as separate features because they have different structural characteristics, do not respond to offset in the same way, and ruptured at different times in the past. The Rinconada fault moves predominantly in a horizontal direction (strike-slip), and the Reliz fault moves predominantly in a vertical direction (dip-slip). The Rinconada fault has evidence for recent offset; in contrast, the last offset on the Reliz fault occurred more than 100,000 years ago (Rosenberg and Clark, 2009).

The landscape around Arroyo Seco has looked different in the geologic past (Durham, 1974; Dibblee, 1976; Graham, 1978). The area that is now called Arroyo Seco was once a deep trough (fig. 6*A*) in the pre-Cenozoic basement rocks and later filled in with a thick accumulation of marine sediments that form the Monterey Formation. This deep trough was mapped in the subsurface using evidence from the geology exposed at the surface and from the depths at which pre-Cenozoic basement rocks are intercepted in deep drill holes (fig. 6*B*). Horizontal (strike-slip) motion on the Rinconada fault has split the once-continuous trough and offset it nearly 24 miles (fig. 6*B*). The marine sediments deposited in the deep trough form the Monterey Formation and are up to 12,000 feet thick in Arroyo Seco and to the east are buried by younger sediments that fill the Salinas River valley.



Modified from Durham (1974), Dibblee (1976), and Graham (1978)

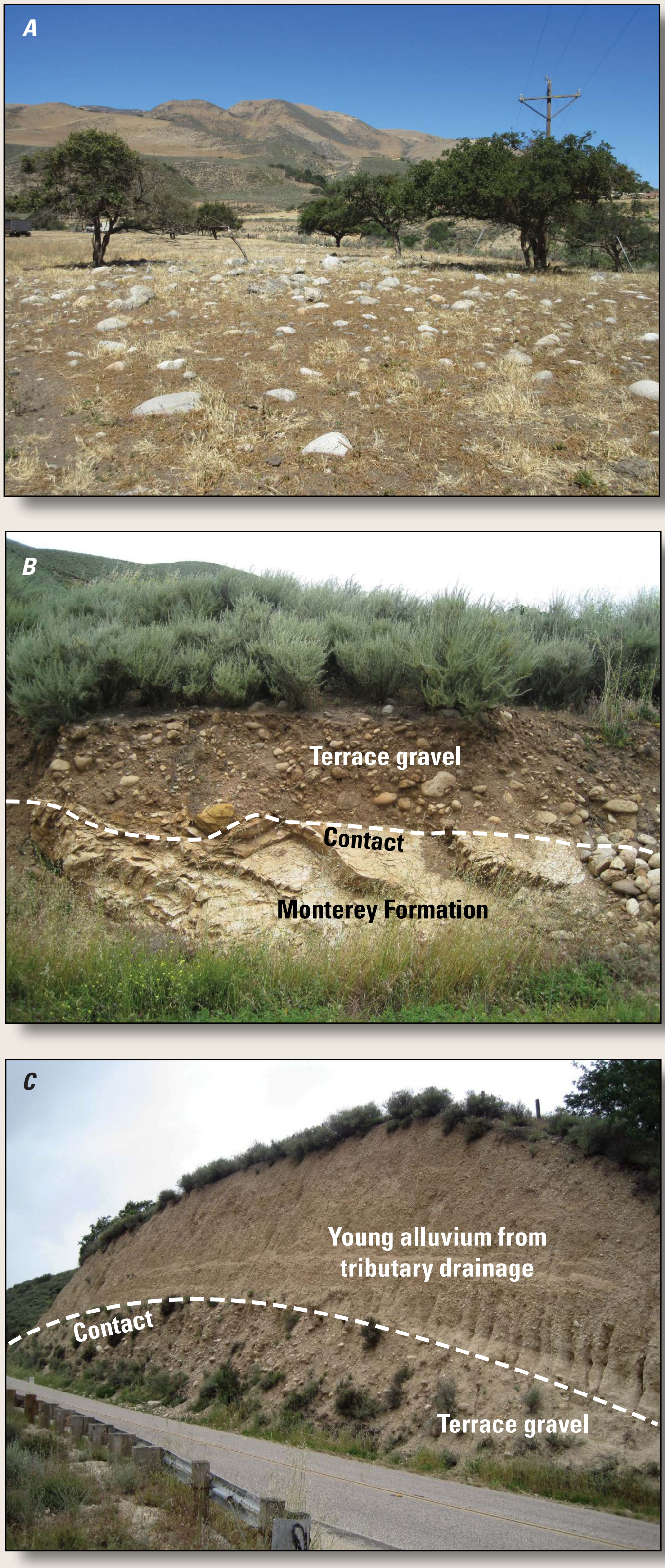
Figure 6. Contoured map showing the elevation of the top of pre-Cenozoic rocks: *A*, prior to offset on the Reliz and Rinconada faults and *B*, present faulted configuration.

Strath Terraces in Arroyo Seco

The erosional strath terrace is the fundamental geomorphic feature in Arroyo Seco and was the focus of the Arroyo Seco geologic map (fig. 4). Strath terraces provide an important record for interpreting tectonic and climate history. In many actively incising river canyons, gravel-capped bedrock strath terraces are tens to hundreds of feet above the active channel and extend discontinuously for miles. Strath terraces represent ancient and now-abandoned river flood plains that formed during periods of valley-bottom widening and planation (DeVecchio and others, 2012; Finnegan and Balco, 2013).

Strath terraces preserve the incision history of Arroyo Seco. Older strath-terrace deposits (shown in shades of green in figs. 2 and 4, map units Qfo1–Qfo8) are preserved to elevations as much as 1,800 feet above the modern drainage whereas younger terraces (shown in shades of orange and yellow in figs. 2 and 4) are from 500 to less than 3 feet above the modern drainage. The terraces are capped by coarse, rounded gravel consisting of granitic rocks (figs. 3*E* and 7*A*) derived from the upstream basement rocks in the Santa Lucia Range. These gravelly **alluvial deposits** are typically less than 6 feet thick and lie directly on the bedrock; the contact between the alluvial deposits and the bedrock is clear and abrupt (figs. 3*E* and 7*B*). Road cuts and natural exposures in Arroyo Seco also expose younger alluvium deposited by tributary drainages in some drainages and **colluvium** that bury terrace gravel (figs. 3*E* and 7*C*).

When looking at a stream or river, geologists consider the shape of the river to help understand the history of the drainage. Stream channel shapes or patterns are straight, meandering, braided, or a combination of these shapes. Pattern is controlled by gradient (valley slope), sediment load (amount of gravel, sand, silt, and clay) and stream power (amount of water and velocity). Channel patterns have been classified by experimentally varying these parameters (Schumm and others, 2000). By understanding what we observe experimentally, we can say something about what we observe in nature. For example, braided streams are defined by a broad flood plain with multiple shallow channels, high stream gradient, and coarse sediment load, whereas meandering streams may also have a broad flood plain but are typically confined to a narrow, deep channel and transport much finer sediment.



Photographs by E.M. Taylor, U.S. Geological Survey, April 2010

Figure 7. Exposures of rounded gravel deposits as follows: *A*, rounded gravel deposits can be observed on terrace surfaces; *B*, road cut exposure of gravel directly overlying the Monterey Formation; and *C*, road cut exposure of gravel buried by younger fine-grained alluvium.

Strath terraces preserved well above the modern drainage and occurring at the same elevations on both sides of Arroyo Seco suggest the previous existence of a wide, erosive channel cutting a broad flood plain. In the past, the Arroyo Seco drainage appears to have consisted of a large braided network of channels that migrated across a broad flood plain, reflecting a high stream gradient and a coarse bedload (fig. 8*A*). Today, Arroyo Seco is a form of braided stream called a single channel, gravel-bed river—a braided system with the reaches of a single channel, indicating that the factors controlling stream channel shape have changed. The gradient has decreased, the bedload has decreased, and the stream power has potentially increased. In places over time, as the stream gradient decreased, the Arroyo Seco flood plain evolved into a single channel and confined to a narrow river system with steep banks (fig. 8*B*).

The observed rounded gravel at Arroyo Seco is consistent with the model that alluvium smooths the stream bed and remains as a thin mantle when the surface is abandoned. Braided stream systems typically deposit thin mantles of gravel. Three independent actions occur over time to form and abandon a strath terrace: (1) the depositional cycle—increased bed load and decreased stream power or the amount of water, (2) the erosion cycle—the formation of the flood plain caused by increased lateral erosion and decreased vertical incision, followed by (3) vertical incision and abandonment of the flood plain (Pazzaglia, 2013).

Factors that control the shape of a stream are directly controlled by tectonics and (or) climate. Lateral erosion and formation of strath terraces begin when sediment is available to scour and erode the stream bed (fig. 8). Abrasion of bedrock in a channel only occurs if sediment is available. Sediment tends to be available when climate changes from a relatively cooler, wetter climate to a warmer, drier climate because decreases in vegetation during drier climates result in bare slopes that are easily eroded.

Strath terraces preserved well above the modern drainage and occurring at the same elevations on both sides of Arroyo Seco suggest the previous existence of a wide, erosive channel cutting a broad flood plain.

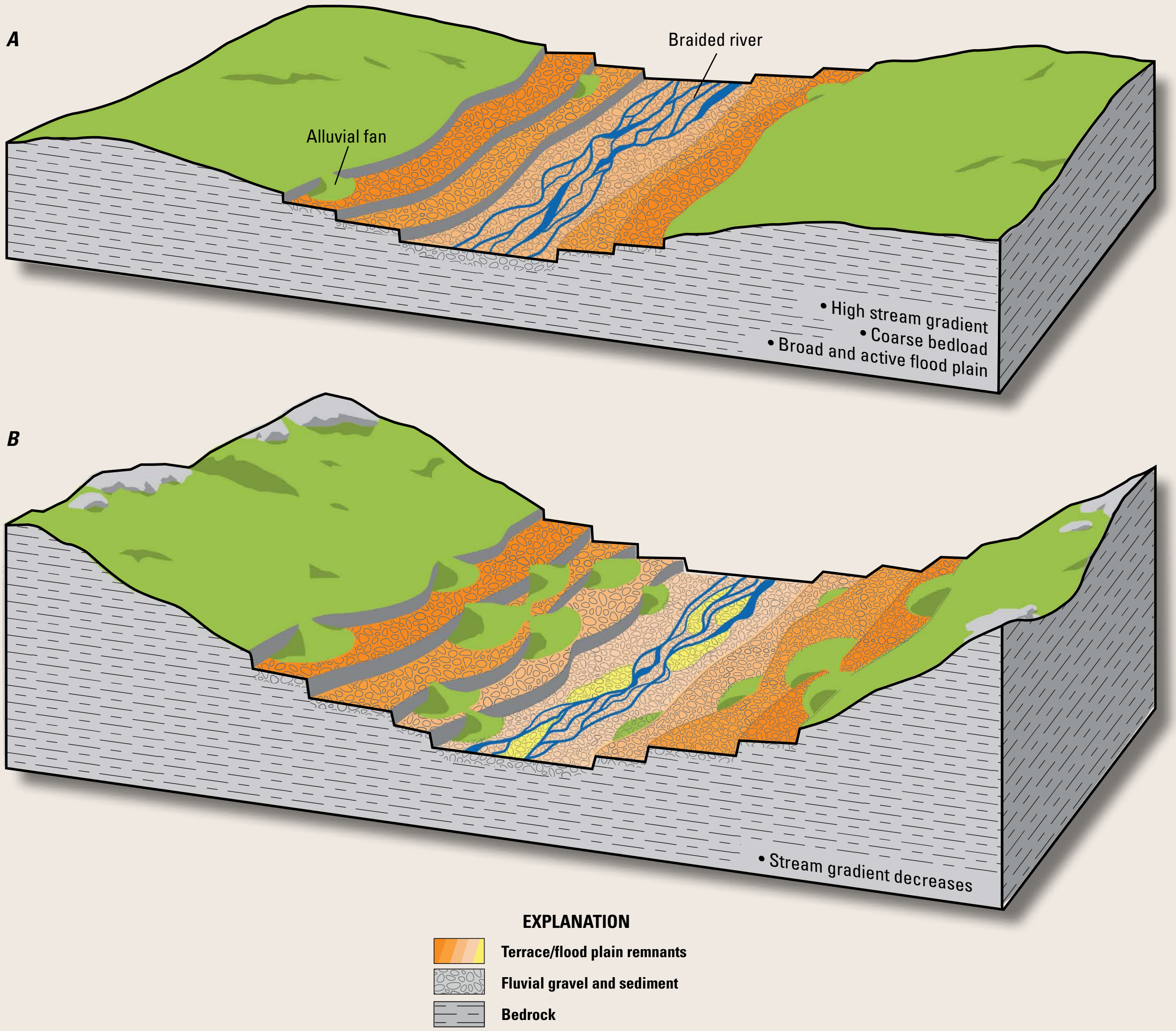


Figure 8. Physical characteristics of Arroyo Seco strath terrace evolution as stream gradient decreased over time.

Once a surface is abandoned by a stream, soil formation can begin on the terrace surface, but soils develop slowly (Birkeland, 1999). Unconsolidated gravel begins to weather by physical and chemical processes that break down the gravel to smaller mineral fragments. Windblown dust begins to infiltrate into the weathering gravel. In the most general terms, soils develop layers in a vertical sequence over time called A, B, and C **soil horizons**, and their sum constitutes a soil profile. Soil A horizons consist of the accumulation of decomposing organic matter mixed with the mineral fraction. Soil B horizons, below the A horizons, tend to be weathered from the original sediment or rock and include materials moved downward from the overlying horizons and deposited in the B horizon. Soil C horizons lack properties of the A and B horizons and are most like the original sediment or rock where the soil is developed.

Soils exhibit a development sequence with time (fig. 9*A*; Birkeland, 1999). Young soils are poorly consolidated, have little or no soil horizons, and retain many of the characteristics of the original deposit. Older young soils have an A horizon over a C horizon. A clay-enriched B horizon forms over time, and the total amount of clay increases. Gravel clasts in the soils also show progressive weathering with time.

In Arroyo Seco, the soils formed on the strath terraces demonstrate a clear progression of soil characteristics over time (fig. 9*B*). Soils less than 9,000 years old (Qfay) (IRSL from Taylor and Sweetkind, 2014) consist mainly of an A horizon. Older soils become more cemented and exhibit soil horizons that are progressively thicker and B horizon colors change from yellow-brown to reddish-brown to red. B horizon clay content also increases and reaches a maximum of 60 percent in the oldest soils. Soils older than 120,000 years old (IRSL from Taylor and Sweetkind, 2014) have decomposed granitic clasts. The oldest terrace remnants (Qao) tend to be eroded, and thus the soils are eroded and thin (fig. 9*B*). The Arroyo Seco geologic map (Taylor and Sweetkind, 2014) contains a detailed discussion of the ages of the soils and terrace deposits.

Once a terrace surface is abandoned by Arroyo Seco, soil formation can begin. Older soils look very different than younger soils.

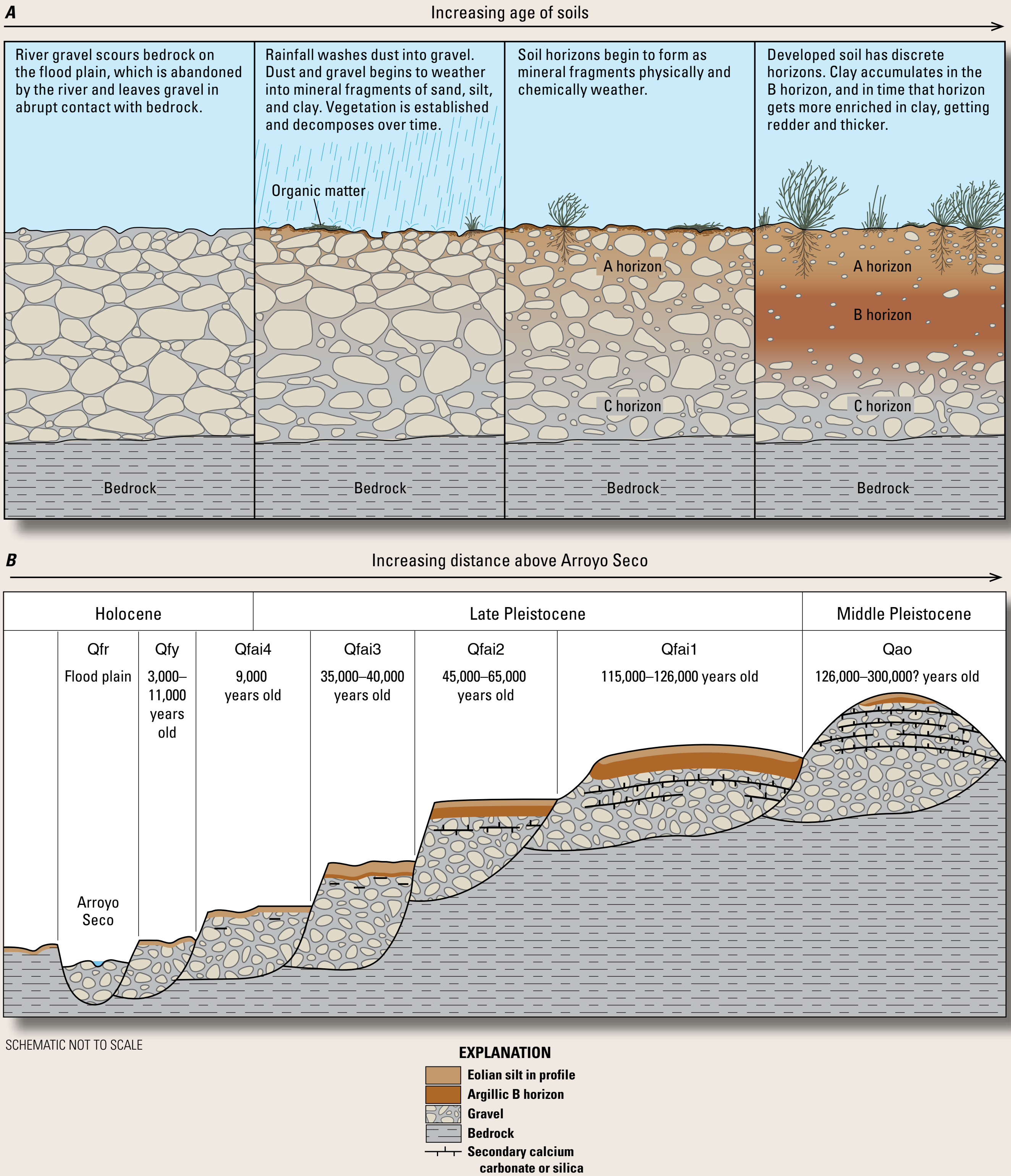
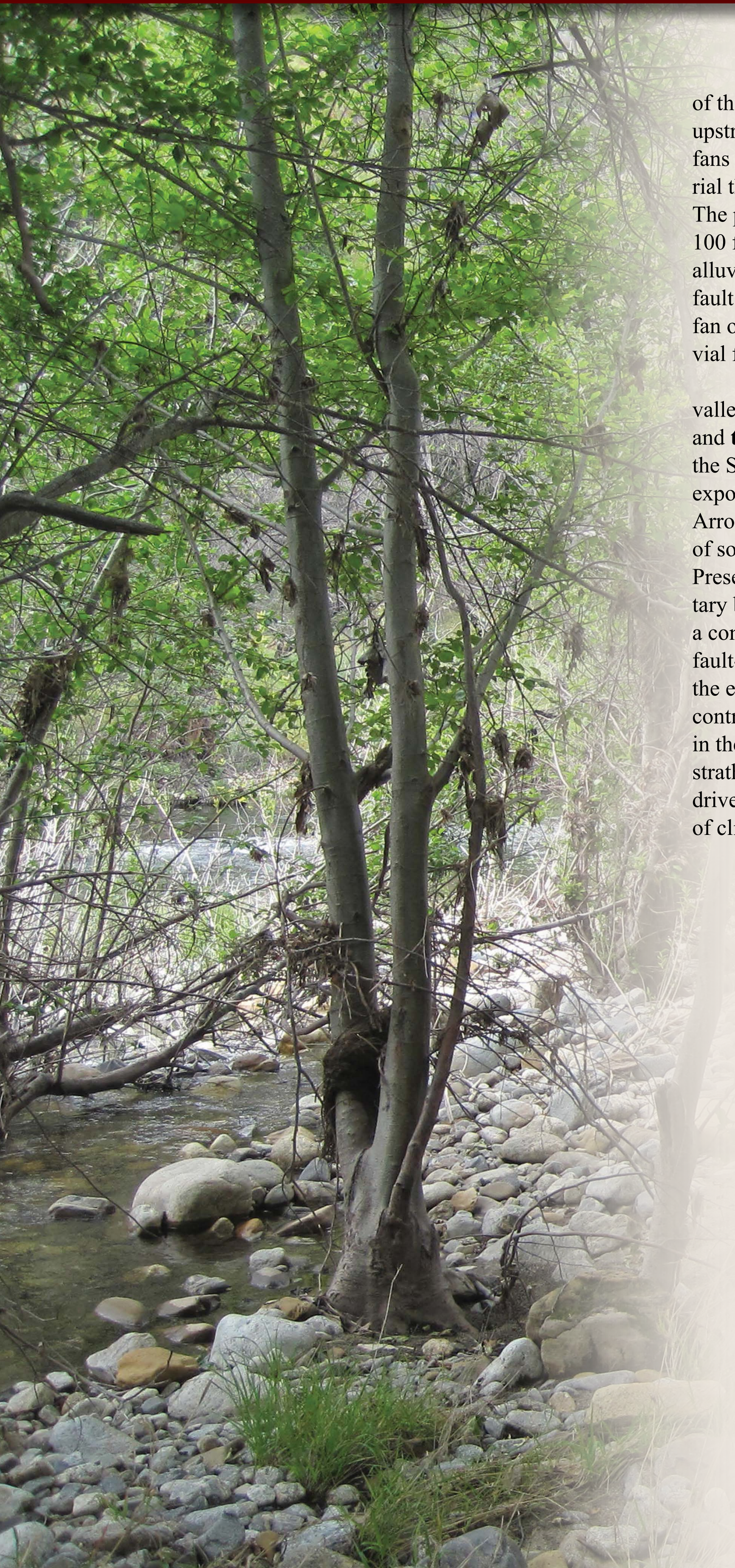


Figure 9. Development of soil horizons for *A*, time-related development of soil horizons and *B*, schematic cross section showing development of soil profiles on terraces in Arroyo Seco.

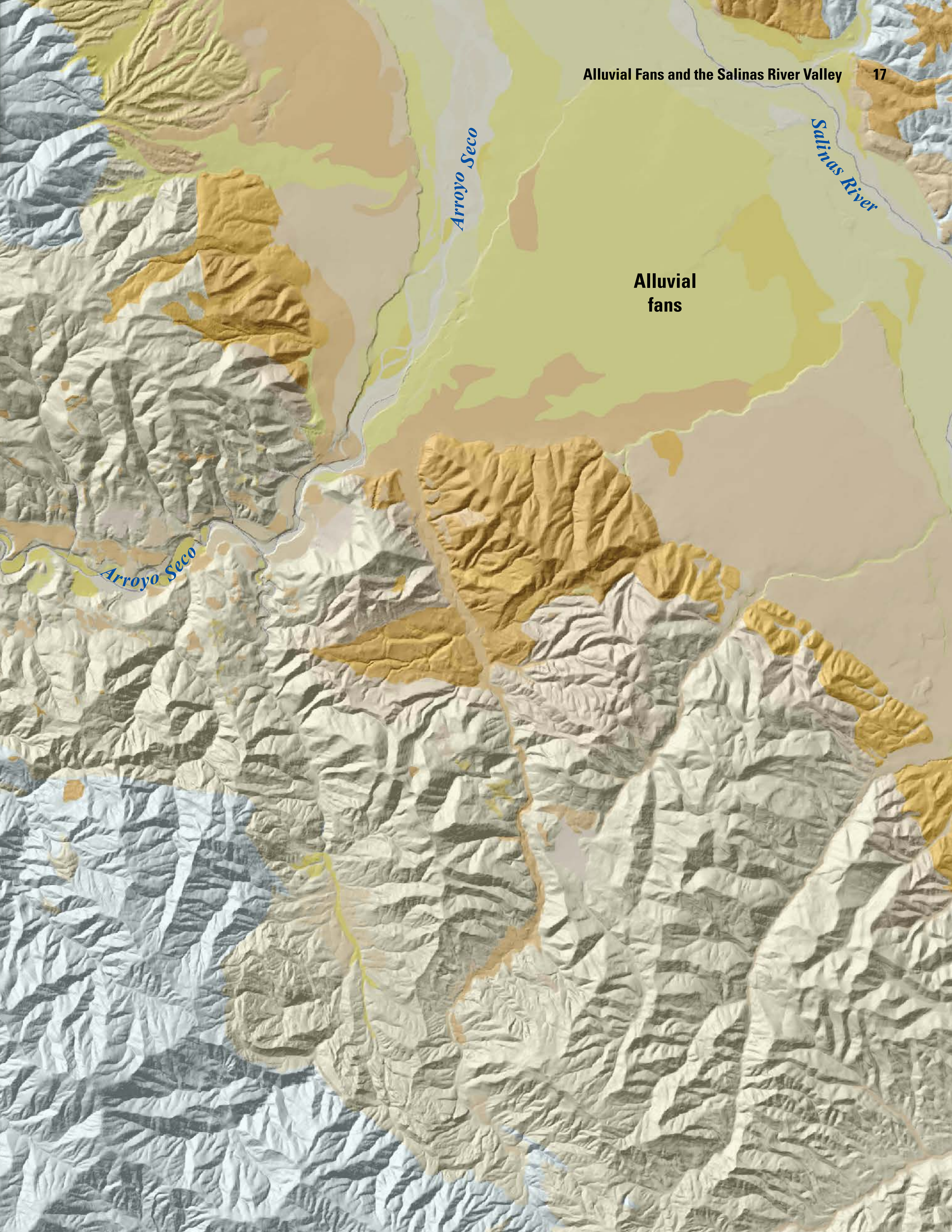
Alluvial Fans and the Salinas River Valley



Where Arroyo Seco enters the Salinas River valley, east of the Reliz fault, the river deposits the sediments eroded from upstream as a broad **alluvial fan**. Some of the younger alluvial fans can be correlated to the ages of terraces because the material that eroded to form the strath terraces has not been buried. The predominant terrace levels (Qfai3 and Qfai4; fig. 4), 80 to 100 feet (ft) above the active drainage, correlate with a large alluvial fan adjacent to the range front and east of the Reliz fault. Both erosion of the strath terrace and deposition of the fan occurred at the same time. Some younger terrace and alluvial fan deposits were formed at the same time.

We know from drill hole data that the Salinas River valley is a **sedimentary basin** filled with **marine sediments** and **terrestrial sediments**. Below the sediments, at depth in the Salinas Valley, are ancient basement rocks similar to those exposed today at high elevations in the Santa Lucia Range. Arroyo Seco has eroded an extensive valley that is the source of some of the material that fills the Salinas River valley. Preserved stream-terrace deposits within and near sedimentary basins are a record of the erosional history that provide a context for downstream **basin aggradation**; basin-margin, fault-related uplift; and **paleoclimate events**. Understanding the erosion of sediments from Arroyo Seco is a significant contribution to understanding the evolution of sedimentation in the northern part of the Salinas River valley. Arroyo Seco strath terraces mark stable periods between base-level changes driven by tectonics or sea-level fluctuations, an indirect result of climate change.

Understanding the erosion of sediments from Arroyo Seco is a significant contribution to understanding the evolution of sedimentation in the northern part of the Salinas River valley.


Arroyo Seco
Salinas River
Alluvial fans
Arroyo Seco

Landscape Evolution Resulting from Changes in Global Climate and the Effects of Active Tectonics

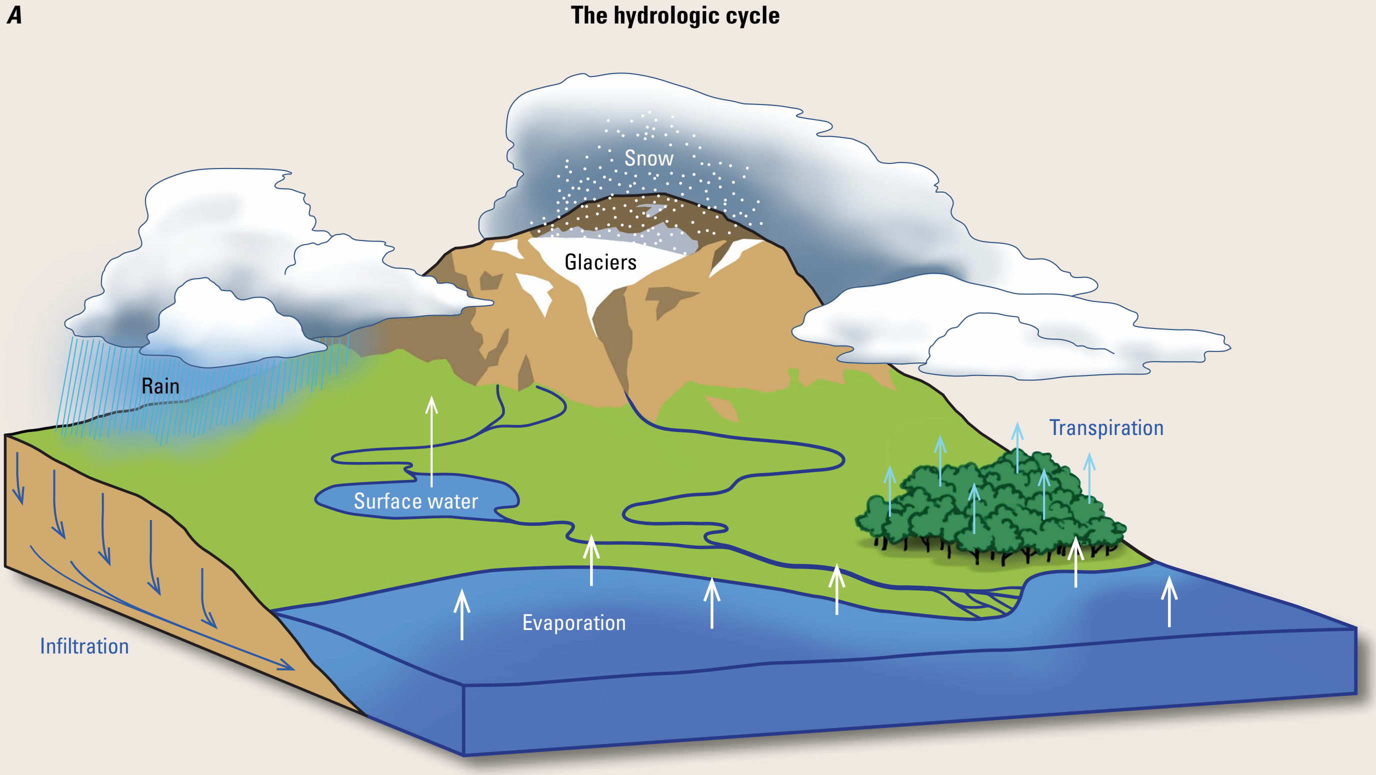
Terrace treads are capped by gravel that records the past existence of a broad stream flood plain. Subsequent stream erosion into bedrock and abandonment of the old flood plain indicates a change in stream equilibrium, probably in response to changes in the base level. In Arroyo Seco, both mountain uplift by fault movement and base-level changes driven by climate change contributed to the timing of terrace formation. We know that the Reliz fault (fig. 4) has had some movement during the time the terraces were forming (Rosenberg and Clark, 2009; Finnegan and Balco, 2013), and we know that during that same time period, the sea level has fluctuated as a result of global climate (Alexander, 1953; Bradley and Addicott, 1968; Imbrie and others, 1984), resulting in periods of rapid incision downstream of the Reliz fault (Bull, 1990). Both tectonics and climate change have directly influenced the formation of strath terraces in Arroyo Seco.

Climate Cycles and Their Effect on Global Sea Level

The amount of water on Earth is always the same and is constantly cycling between the sea, the land, and the sky (fig. 10*A*). This cycle of evaporation, transpiration, and precipitation is referred to as the **hydrologic cycle**. Water changes phase or form as it moves through the hydrologic cycle. Water is most often a liquid, sometimes it is solid in the form of ice and snow, and sometimes it is a gas in the form of water vapor (fig. 10*A*).

The fluctuations in global climate change where water is stored on Earth. During relatively warm climate cycles, water is liquid and stored primarily in the oceans. During relatively cold climate cycles, precipitation is frozen in the form of snow and is stored as ice. During the last glacial maximum, about 18,000 years ago, about 73 percent of the fresh water was stored in the form of ice; today, the amount of fresh water stored in the form of ice has decreased to about 69 percent (fig. 10*B*). Recent estimates of the last glacial maximum are as old as 19,000 to 20,000 years ago (Clarke and others, 2009).

During cooler climate cycles, water is stored in glaciers and ice caps at high latitudes (closer to the north and south poles) and elevations (height above sea level) (fig. 11*A*). During the last major glaciation, about 18,000 years ago, the Arctic Ocean was frozen and glaciers covered the northern parts of North America, Europe, and Asia (fig. 11*A*). Today, massive ice in the Northern Hemisphere is isolated primarily to Greenland and the Arctic Ocean (fig 11*A*). Because the amount of water on Earth is constant, as the climate cooled and glaciers formed, the transfer of water to land caused sea level drop and new coastlines to from at a lower elevation. The last low stand at about –425 ft (Chappell and Shackleton, 1986; Clark and others, 2009) was 18,000 years ago (fig. 11*A*). When the global landscape is dominated by fluctuating snow and ice, it is referred to as a **glacial cycle**. As the global climate warmed, melting snow and ice returned water to the oceans and sea level rose. Sea covered the exposed coast that once surrounded the ice-covered continents.



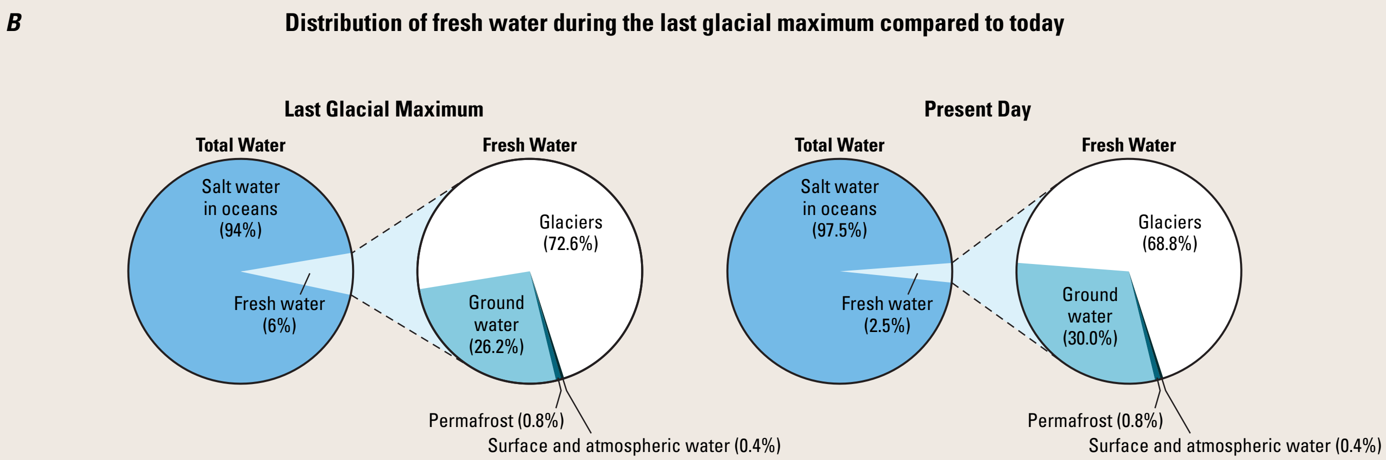
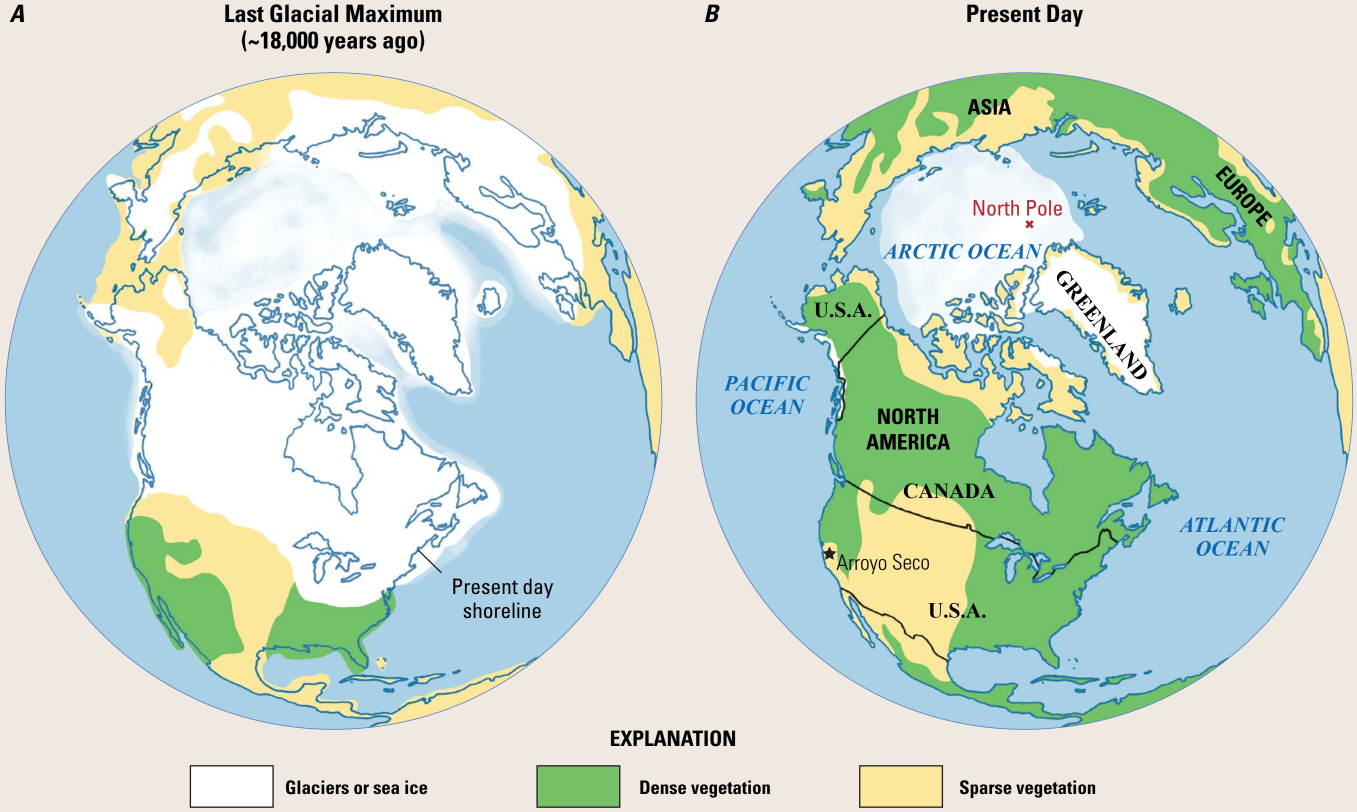


Figure 10. *A*, Hydrologic cycle and *B*, the distribution of ice during cold wet cycles (glacial events) and warm dry cycles (interglacial events). %, percent.



Ice Age sea level modified from National Oceanic and Atmospheric Administration, 2008. Vegetation density map simplified from Adams and Faure, 1997.

Figure 11. Map of the distribution of ice and vegetation density on earth in the *A*, last glacial maximum and *B*, present day. Snow is white, desert and grassland are tan, and forest is green.

Parts of the glacial cycle can be quantified. During the last glacial maximum, about 32 percent of the total land area was covered by ice, and sea level was at least 425 ft lower than it is today (Chappell and Shackleton, 1986). A series of shelves under the water mark former shorelines. Today—an interglacial—10 percent of land area on Earth is covered in glacial ice, and sea level is at the present position (fig. 11*B*). During warm interglacials, global sea level generally rises to a level close to the present level. But during the last major interglacial, about 120,000 years ago, the seas were about 15 to 20 ft higher than today.

Ice sheets exerted considerable pressure on the Earth's crust around and beneath them, and these areas adjusted to the ice load by elastic bending and plastic flow. Conversely, the ocean floors lighten by the removal of water. These cycles are referred to as the **global eustatic record** and contribute to the evolution of **marine terraces** near Arroyo Seco (Andrews, 1975).

The climate change record is a complex but well-understood history although the ultimate causative factors that drive swings between warm and dry and cool and wet cycles is less understood and probably more controversial. The climate cycles in the last 2 million years are generally well understood. Sea level rises during warm and dry interglacials and falls during cold and wet glacials. The Earth today is in an interglacial cycle. Sea levels are relatively high, and the climate is relatively warm and dry. These changes in base level, driven by the changes in sea level, directly influence the terrace formation in Arroyo Seco.

During the last glacial maximum, about 18,000 years ago, the sea level was at least 425 feet lower than it is today.

Marine Sediments—A Geologic Record of Past Climate Cycles

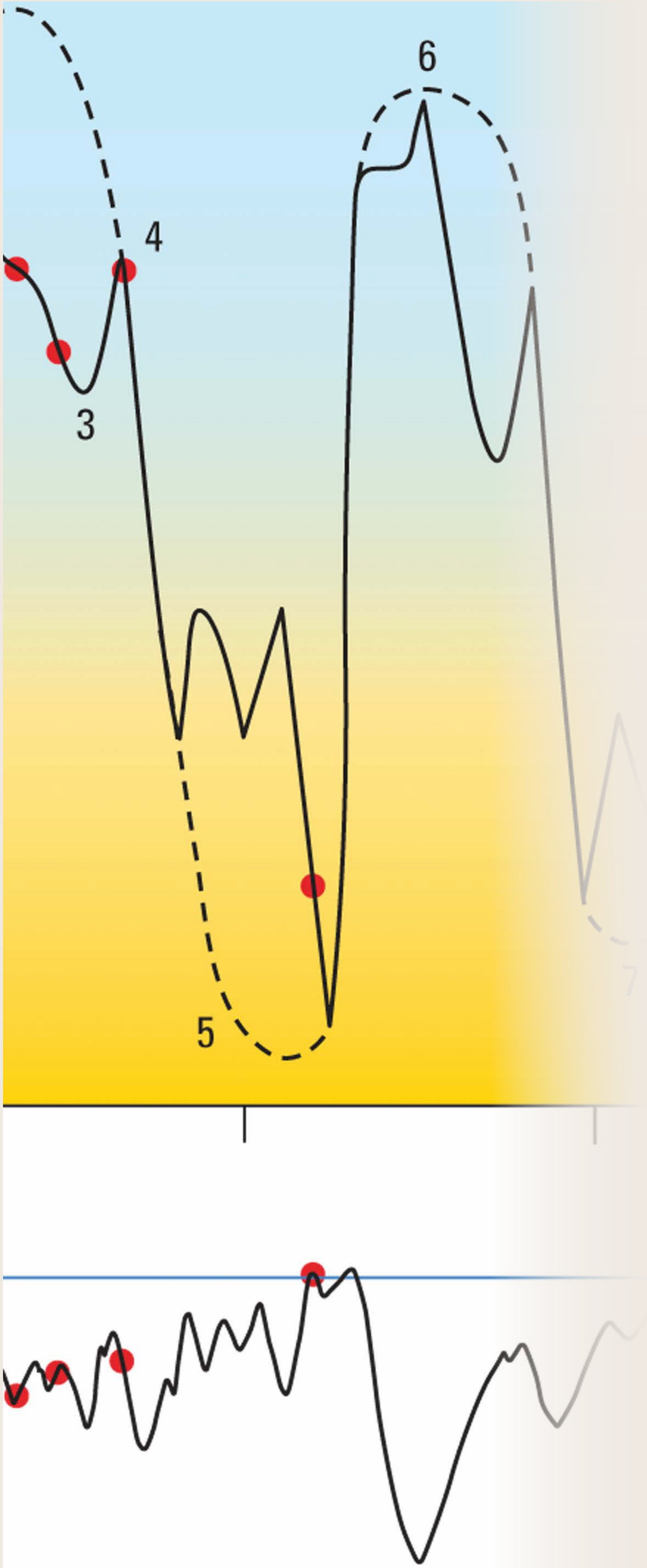
Marine-sediments have physical, chemical, and biological properties that can be used directly and indirectly to distinguish cool climates from warm climates. These sediments can be sampled by drilling and sampling the sea floor. Large ships mounted with drill rigs are used to core and retrieve ocean sediments (fig. 12*A*). Marine sediment cores display a variety of sediment types that are sampled and analyzed (fig. 12*B*). Cores are typically split in half, where half the core is sampled and half is archived for future analysis (fig. 12*C*).

Source: https://en.wikipedia.org/widi/File:JOIDES_Resolution_2009.jpg,
Photo is released into the public domain by its author
Integrated Ocean Drilling Program.

Source: https://commons.wikimedia.org/wiki/File:PS1920-1_0-750_sediment-core_hg.jpg,
Photo is released into the public domain by its author
Hannes Grobe.

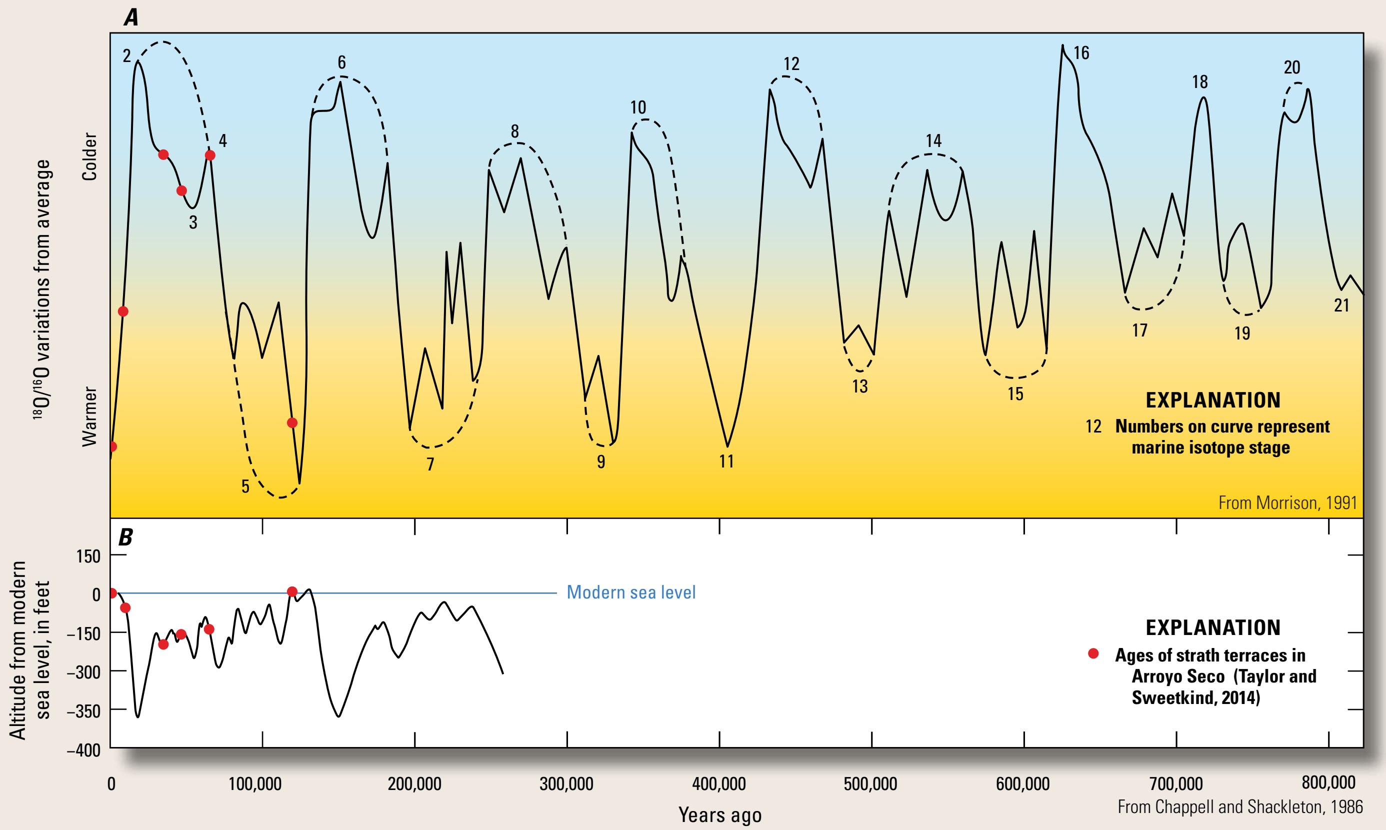
Source: http://www-odp.tamu.edu/public/slideset_photos/slide23.jpg,
Photo is released into the public domain by its author
Integrated Ocean Drilling Program Slide Set.

Figure 12. Marine cores are collected and sampled for analysis to distinguish past climates.



Data from sampled intervals from cores of marine sediments are used to interpret global ice volume, and this is used to infer climate. Shells of tiny plants, animals, and corals in marine sediment layers are typically made of calcium carbonate ($CaCO_3$). As the shells form, they incorporate oxygen from the seawater. The concentration of different forms or isotopes of oxygen in the $CaCO_3$ reflect both the ice volume and the temperature of the seawater. During cool climate cycles, heavy oxygen (^{18}O) is found in higher concentrations relative to light oxygen (^{16}O), and the reverse is true during warm climate cycles. The higher concentrations of ^{18}O in the ocean are the result of ^{16}O being preferentially transferred from oceans to glaciers. When glaciers melt during interglacials, the ^{16}O is returned to the oceans. This fluctuation in the ratio of the isotopes ($^{18}O/^{16}O$) gives a regular pattern of ice volume with time (fig. 13*A*). The highs and lows are numbered and known as **marine isotope stages** (**MIS),** with MIS 1 being the last 18,000 years, and the numbers increase with age. The marine-sediment record suggests that relatively long glacial periods are spaced about 100,000 years apart, develop slowly, and terminate abruptly with warm interglacial periods lasting between 10,000 and 15,000 years (fig. 13) (Imbrie and others, 1984; Chappell and Shackleton, 1986). In the last 400,000 years, sea level has only reached current levels during the warmest part of the interglacial cycles (fig. 13). The last major sea level rise occurred about 120,000 years ago, during MIS 5 (fig. 13).

Marine sediments have physical, chemical, and biological properties that can be used directly and indirectly to distinguish cool climates from warm climates.



C

Sample number (map unit)	Age (years)[a]
AS10-9-7 (Qfy1)	1,030±150
AS10-9-8 (Qfy1)	1,590±190
AS12-6-1 (Qfay)	9,570±680
AS12-6-2 (Qfai4)	8,770±350
AS12-6-3 (Qfai3)	35,350±3,680
AS10-9-9 (Qai2y)	50,640±2,980 45,960±1,840 <65,000
AS10-9-6 (Qfai2o)	>65,000
AS10-9-5 (Qfai1)	>120,000

[a]Modified from Taylor and Sweekind, 2014, table 3.

Figure 13. Graphs and tables showing geologic time versus *A*, ^{18}O curve and *B*, sea level.

Geologic and Climatic History Recorded by Marine Terraces

Along the California coast, marine terraces provide a geologic record of sea level fluctuation and tectonics. Erosion at the present shore creates a seaward-sloping platform overlain with beach sediment (fig. 14*A*). At the inner edge of the beach is a sea cliff. Higher platforms are called marine terraces and are markers of sea level in the geologic past (fig. 14*B*). Marine terraces are capped usually by marine sand and include coral and shells. North of Salinas, on Monterey Bay, a terrace occurs about 100 ft above the beach and the ancient sea cliff (fig. 14*A*). This terrace has been interpreted as having formed during the last major interglaciation or warm climate cycle, 124,000 years ago (Lajoie and others, 1991).

The coast of California has been affected by both the rise and fall of the sea level caused by global climate change and by regional tectonics (Muhs and others, 2003). In a tectonically stable, near-shore environment, the highest marine terrace was eroded about 124,000 years ago during the last major interglacial warm climatic cycle (fig. 15*A*). In an environment undergoing active faulting, terraces record uplift events and climate cycles (fig. 15*B*). During this interglacial warm climate-cycle, the sea level was higher than it had ever been in the last 400,000 years (fig. 13), and this terrace will be preserved as long as present-day beach erosion has not been extensive enough to remove it.

In contrast, a coast undergoing uplift has a flight of marine terraces that record past interglacials (fig. 15*B*). Once formed, uplift takes them above present-day beach erosion, thus preserving them. Ideally, all major interglacials are recorded. Along the California coast, north of Monterey, the coast is being uplifted, and there are terraces above the dated 124,000-year-old terrace (MIS 5). Regional faults cause tectonic movement, consistently upward, that result in a constantly and slowly emerging coastline along much of the California coast (fig. 15*B*). Thus, the regional effects of climate change resulting in sea-level fluctuations and regional tectonics both explain the marine terraces.

Marine terraces can be used to estimate the rate of coastal uplift. Figure 13*B* indicates the elevation of global sea level. If one can identify the marine terrace elevation corresponding to each interglacial, then the difference in elevation is the amount of uplift, and combining that with the estimated age gives the estimated rate of uplift. Tectonic uplift must be considered in conjunction with the eustatic record before uplift rates are calculated because not all uplift is tectonic. Some uplift is the result of the earth's surface rebounding as the ice sheets melt (Muhs and others, 2012). If the age of a single terrace and the eustatic record are known, an uplift rate can be calculated. If the rate is assumed to be constant over time, ages of terraces at higher and lower elevations can be estimated. For the California coast, Muhs and others (2003) calculate a rate that varies from 0.005 to 0.5 inches (in.) per year. Using the higher rate, a MIS 7 terrace is expected to be 888 ft above sea level.

A **Marine terrace at Capitola**

B **Watsonville marine terraces**

Photographs taken by E.M. Taylor, U.S. Geological Survey, March 2015

Figure 14. Photographs of the *A*, modern marine beach and sea cliff at Capitola and *B*, ancient marine terraces at Watsonville.

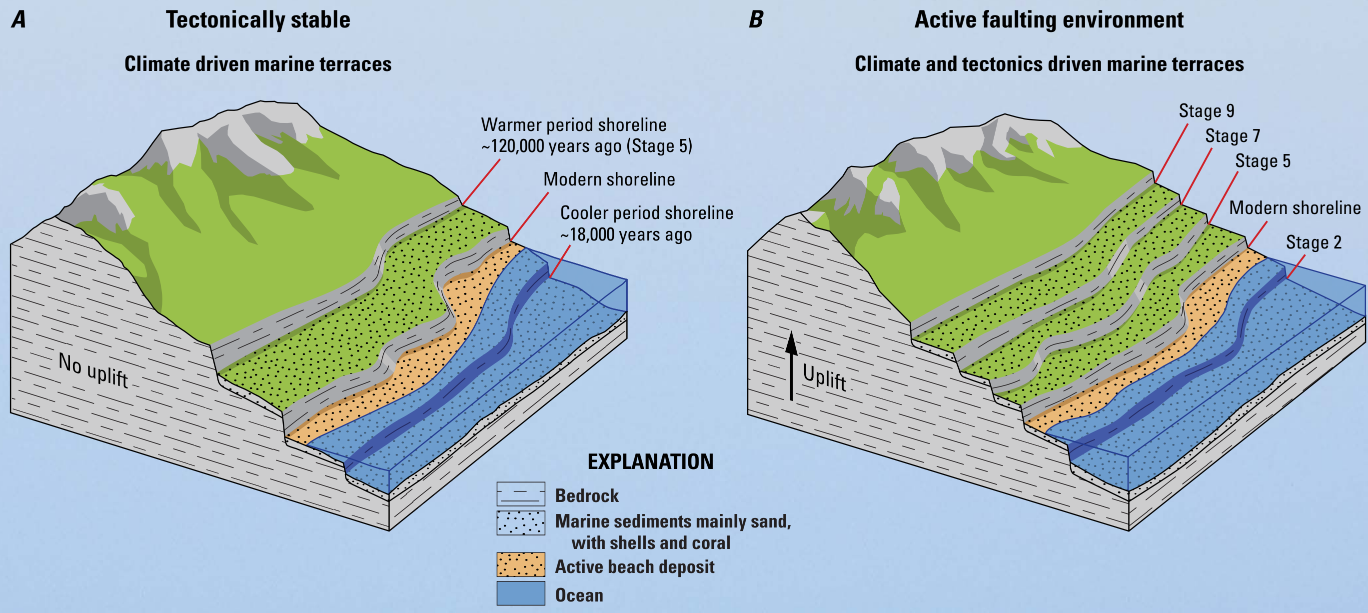


Figure 15. Marine terrace evolution in *A*, tectonically stable and *B*, actively faulting environments.

Tying Arroyo Seco Terraces to the Coastal Record

Because some of the terraces at Arroyo Seco have been dated (Taylor and Sweetkind, 2014; fig. 13*B*), they can be tied to the coastal terrace record because the formation of the stream terraces is correlative in time to the formation of the marine terraces. Marine and stream terraces in central California formed as a result of sea-level high stands superimposed on a tectonically uplifting coast (Alexander, 1953). Driven by tectonics, mountains move up, and driven by climate change, sea level fluctuates. When the mountains go up, or the sea level drops, streams actively respond by eroding a new flood plain. By looking at the shape of the stream and the shape of the terraces in the mountains, geologists know if and when the stream is moving fast or slow, and if the stream is eroding or depositing. When a stream is in equilibrium, it is essentially neither eroding nor depositing, but rather maintaining the stream channel and flood plain. However, when there is tectonic activity or climate change, the base level of the stream changes and new processes begin. If the mountain goes up or the sea level drops, streams erode until they reach equilibrium. When the stream reaches equilibrium, erosion stops and again the stream is constrained to its channel and flood plain. With each cycle of mountain building or sea level drop, the stream responds by abandoning its former flood plain and eroding downward. All these processes are at play in Arroyo Seco.

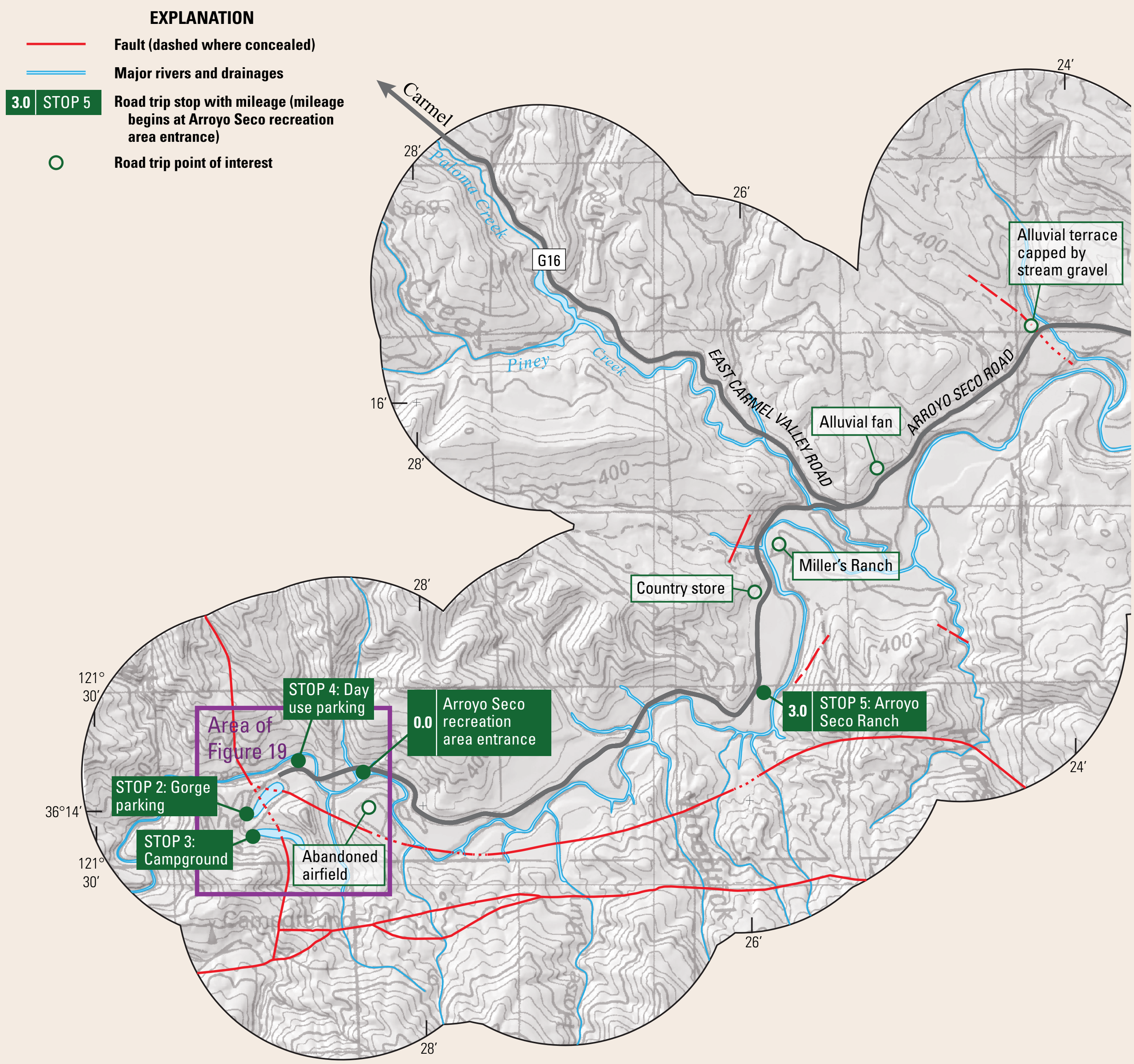
When sea level fluctuates, the Salinas River responds by changing its gradient in an attempt to reach equilibrium. Arroyo Seco follows the response of the Salinas River. When the sea level goes down during glacial cycles, the rivers cut down, and when sea level comes back up, the Salinas River should aggrade to the interglacial sea level. During interglacials, seawater extended from the Monterey Bay to the town of Gonzales (about 24 miles). At depth, two clay-rich marine estuarial deposits are recognized in drill holes. They are distinctive, contain marine fossils, and represent periods of marine encroachment from high sea level (Tinsley, 1975). These clay deposits occur at approximately –180 and –400 ft and define the tops of two aquifers. The base of the –180-ft aquifer (–145 ft) and the base of the –400-ft aquifer (–270 ft) are in the same range for elevation estimates for sea level lows during the last glaciation (Muhs and others, 2003; MIS 2–4, fig. 13).

The ages of terrace formation in Arroyo Seco (fig. 13; Taylor and Sweetkind, 2014) suggest that strath terraces formed at high stands of sea level. At high sea stands, Arroyo Seco cut back and forth on the Monterey shale, formed a flood plain, and then with constant coastal uplift, the river downcut and formed a new flood plain leaving a strath terrace above stream level. Flights of paired strath terraces observed in older higher terraces in Arroyo Seco are common in tectonically active terrains (Bull, 2007).

Terraces formed in Arroyo Seco that postdate the last known movement on the Reliz fault must be eroded and abandoned as a result of base-level changes beyond the range front fault driven by climate change. In this area of California, the upward migration is one driving force causing erosion and abandonment of terrace surfaces. The raising and lowering of sea level also influences Arroyo Seco's erosional history. Both processes contribute to the strath terrace formation.

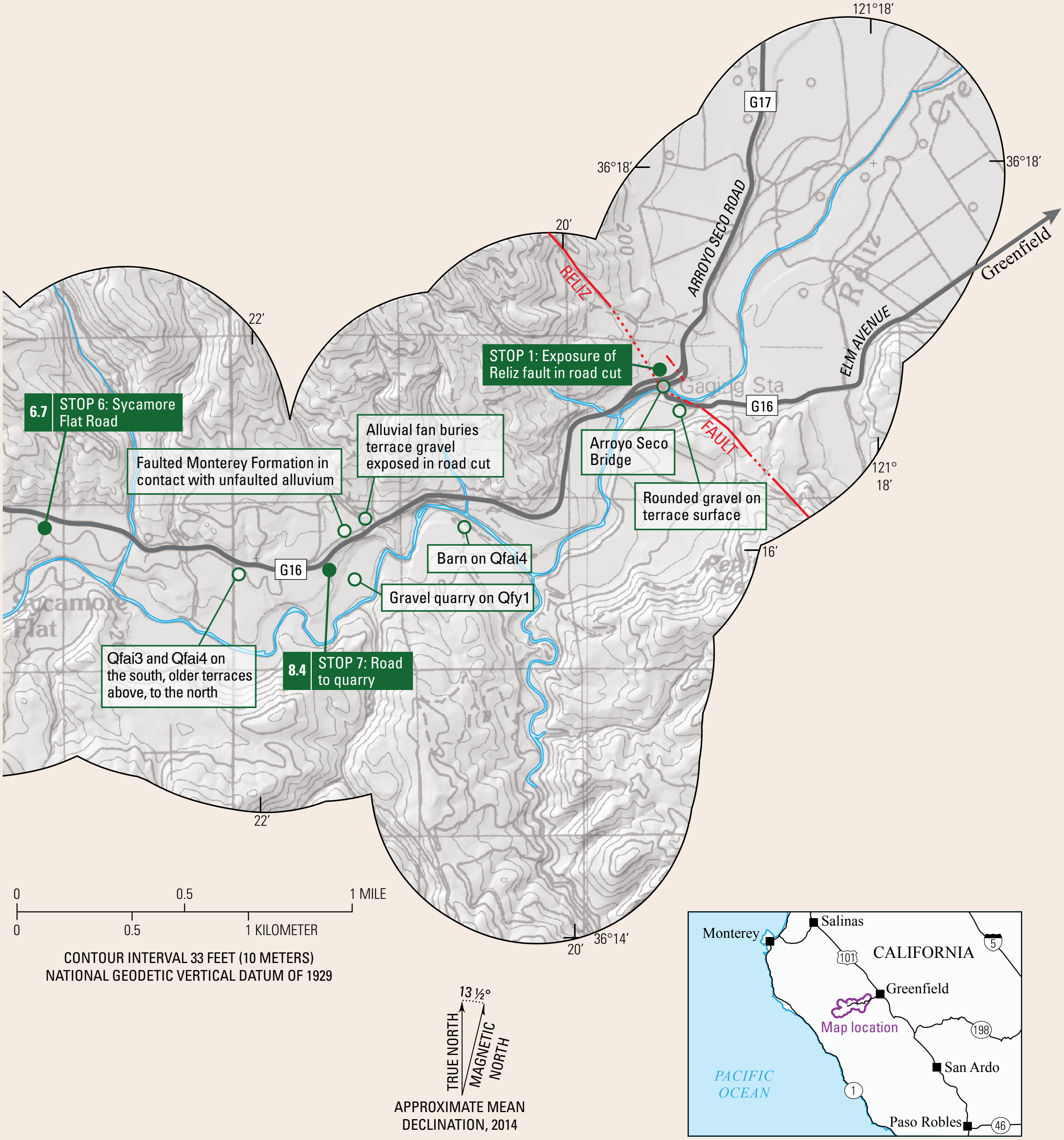
Road Log Map

This road log describes suggested stops on the 11 mile-long road along Arroyo Seco.



Base from U.S. Geological Survey 1:100,000-scale digital data, 1982,
Universal Transverse Mercator, zone 10, North American Datum of 1983 (NAD 83).

Figure 16. Field guide map. Modified from Taylor and Sweetkind, 2014.


121°18′
36°18′
36°18′
20′
22′
22′
121° 18′
16′
20′
36°14′
G17
G16
G16
ARROYO SECO ROAD
ELM AVENUE
Greenfield
RELIZ
FAULT
Gaging Sta
Sycamore Flat
STOP 1: Exposure of Reliz fault in road cut
Arroyo Seco Bridge
Rounded gravel on terrace surface
6.7 STOP 6: Sycamore Flat Road
Faulted Monterey Formation in contact with unfaulted alluvium
Alluvial fan buries terrace gravel exposed in road cut
Barn on Qfai4
Gravel quarry on Qfy1
Qfai3 and Qfai4 on the south, older terraces above, to the north
8.4 STOP 7: Road to quarry
0 0.5 1 MILE
0 0.5 1 KILOMETER
CONTOUR INTERVAL 33 FEET (10 METERS)
NATIONAL GEODETIC VERTICAL DATUM OF 1929
13 ½°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2014
Monterey
Salinas
CALIFORNIA
101
5
Greenfield
Map location
198
PACIFIC OCEAN
San Ardo
1
Paso Robles
46

Road Log

This road log describes suggested stops on the 11 mile-long road along Arroyo Seco (fig. 16). The log begins at a general meeting place at the Arroyo Seco bridge at the intersection of Arroyo Seco Road and Elm Ave, about 6 miles west of the town of Greenfield (fig. 16). After that, for logistical and safety reasons, the reader is directed to drive to the west end of the canyon. Stops are described from upstream to downstream starting at the Arroyo Seco U.S. Department of Agriculture Forest Service recreation area entrance, 11 miles west of the Arroyo Seco bridge, eastward to the Salinas River valley. Mileage is given from the west end of the road and is listed as total miles. Pullout locations are described as of spring 2016; road conditions may have changed since then. Arroyo Seco Road is narrow and winding and can be busy. Pullouts in this road log are typically for one vehicle. Do not expect to be able to pull out if you are in a larger group. Drive cautiously and avoid summer weekends. All exposures and overviews are accessed on public land along the right of way. If there is a road or a fence that says private property, keep out, or no trespassing, do not drive or walk beyond those signs. As of this writing (fall 2016), no cell phone coverage exists in Arroyo Seco beyond the bridge.

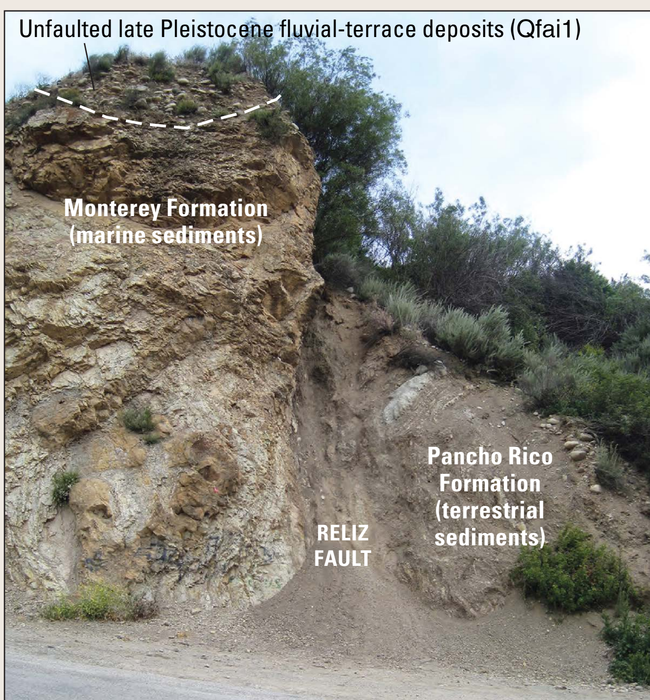
Arroyo Seco recreation area is popular in the warm summer months when families come to camp, swim, picnic, and hike (http://www.fs.usda.gov/recarea/lpnf/recarea/?recid=10906). There is limited parking April through September. Parking in the park is on a daily basis and day use closes at 6 p.m. It is a good idea to begin early in the day when the sun angle is low and you are sure to have access and parking in the recreation area. Descriptions of pullouts, road conditions, and fees may have changed since this report was published.

Stop 1

At the intersection of Arroyo Seco Road and Elm Avenue, on the north side of the Arroyo Seco bridge, there is a small pullout on the north side of the road, directly in front of an exposure of the Reliz fault (fig. 17). In the fault exposure, younger terrestrial sediments of the Pancho Rico Formation (23–2.6 million years old) are to the east of the fault, and older marine sedimentary rocks of the Monterey Formation (65–5.3 million years old) are to the west of the fault. Relative to the Monterey Formation, the Pancho Rico Formation has been offset in both a downward direction and southward. The Reliz fault is the range-front fault along which the Santa Lucia Range is uplifted. Offset causes change in the base level and results in Arroyo Seco downcutting in response to the uplift. Outcrops of the Monterey Formation continue westward from this point until nearly the west end of Arroyo Seco Road.

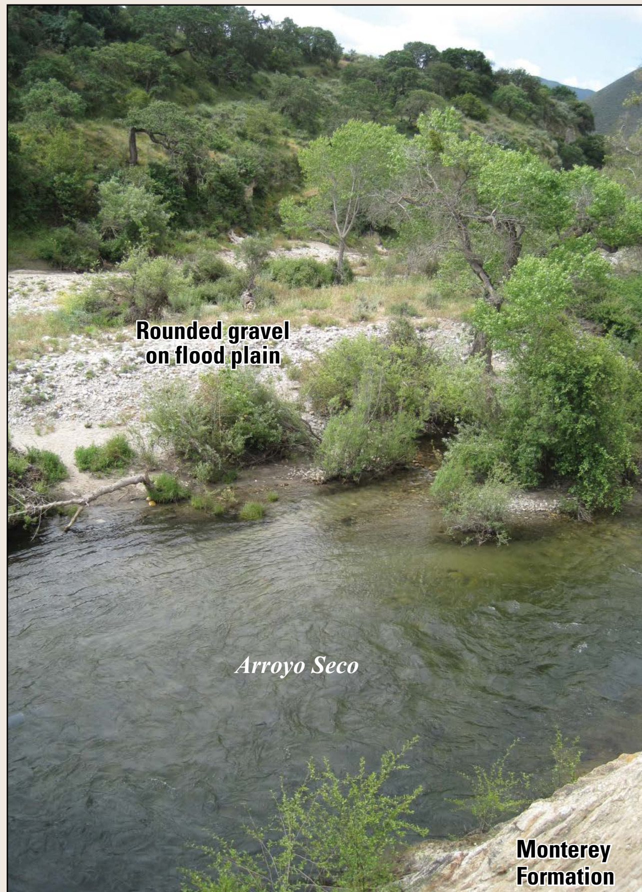
Notice to the left and right of the fault, rounded gravel are preserved at the top of the bedrock exposures. Immediately above the fault, however, the gravel has been eroded, but the surface does not appear to be offset. This gravel is a former alluvial flood plain, and when Arroyo Seco cut down, it was left as a strath terrace. This happened, at this location, more than 120,000 years ago (fig. 13*C*) (IRSL from Taylor and Sweetkind, 2014).

Look down into Arroyo Seco, and you will see rounded gravel in and adjacent to the river (fig. 18). These rounded gravel are derived from the resistant basement rocks far upstream. As the bedrock eroded, rocks were transported to the river by gravity and running water. They were rounded by tumbling together as they moved downstream. Most of the flat terrace surfaces you see in Arroyo Seco are capped by similar rounded gravel (fig. 7*A*) and mark where Arroyo Seco once eroded a flood plain. The gravel is usually exposed overlying the Monterey Formation and sometimes buried by younger deposits in road cuts.



Photograph by E.M. Taylor, U.S. Geological Survey, April 2010

Figure 17. Reliz fault zone exposure.



Photograph by E.M. Taylor, U.S. Geological Survey, March 2015

Figure 18. Photograph of the active drainage in Arroyo Seco.

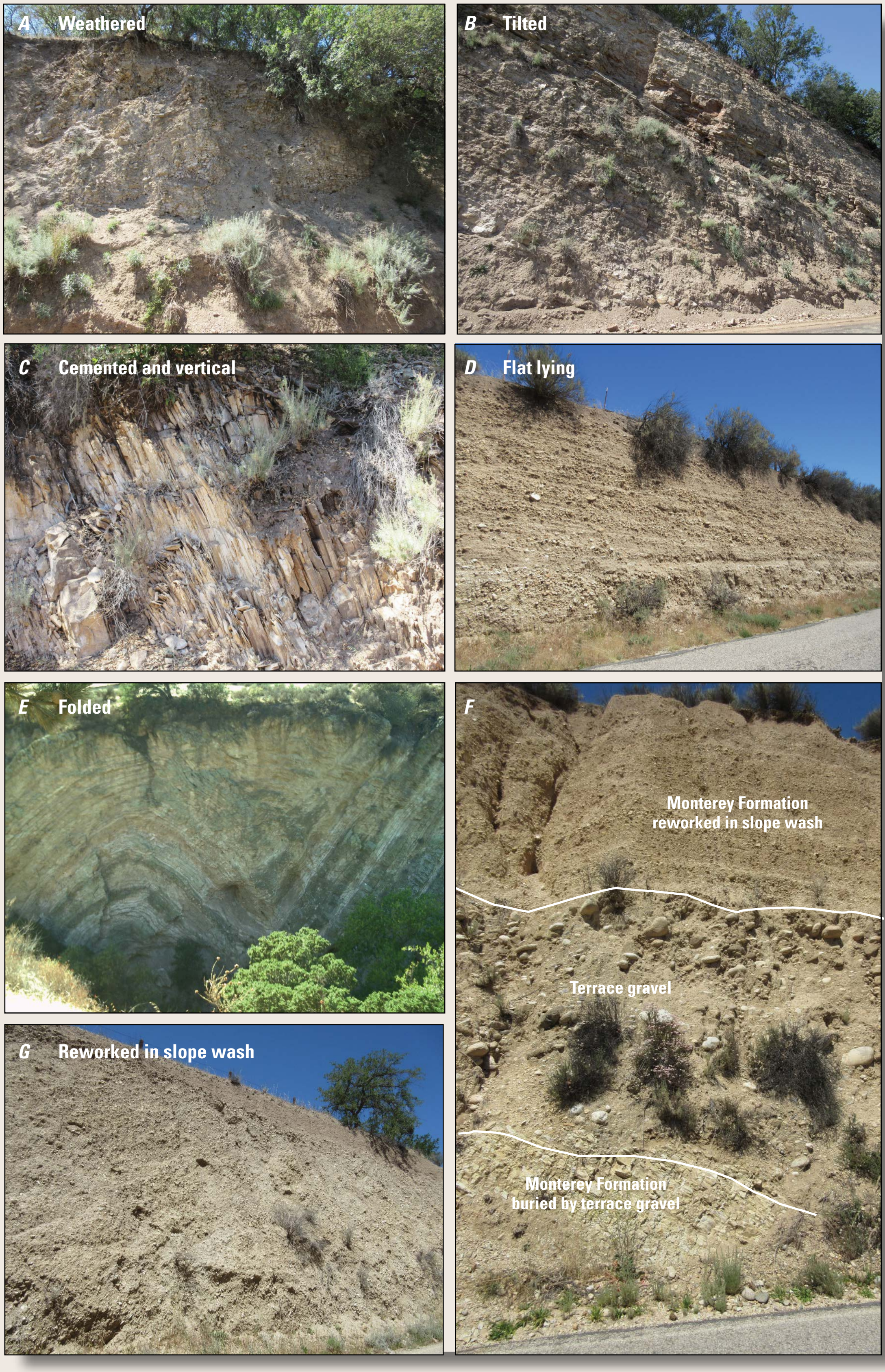
Drive from Arroyo Seco Bridge to Arroyo Seco Recreation Area

The drive up to Arroyo Seco recreation area provides an excellent opportunity to observe the geology and erosional processes. Figure 16 is annotated with things to observe on your drive to the Arroyo Seco recreation area. Above Arroyo Seco bridge, Arroyo Seco is confined to a meandering and narrow flood plain (fig. 5*C*). A few reaches are braided. Almost all of the flat surfaces you observe were eroded by Arroyo Seco in the geologic past. Higher terraces are preserved both north and south of the stream. When Arroyo Seco was flowing over those high surfaces, the river flood plain was much wider.

In Arroyo Seco where the stream is currently eroding bedrock, the Monterey Formation is exposed at or near the surface. Road cuts commonly expose Monterey Formation, overlying terrace gravel and associated soils, and at the top sometimes, a younger deposit derived from the slope above or from a tributary stream. The Monterey Formation can be weathered (fig. 19*A*), tilted (fig. 19*B*), cemented and vertical (fig. 19*C*), flat lying (fig. 19*D*), and folded (fig. 19*E*). Slope deposits moved downslope under the influence of gravity and may bury alluvial terrace deposits (fig. 19*F*). Weathered Monterey Formation can also be moved down the slope as slope wash (fig. 19*G*), debris flows, colluvium, and landslides.

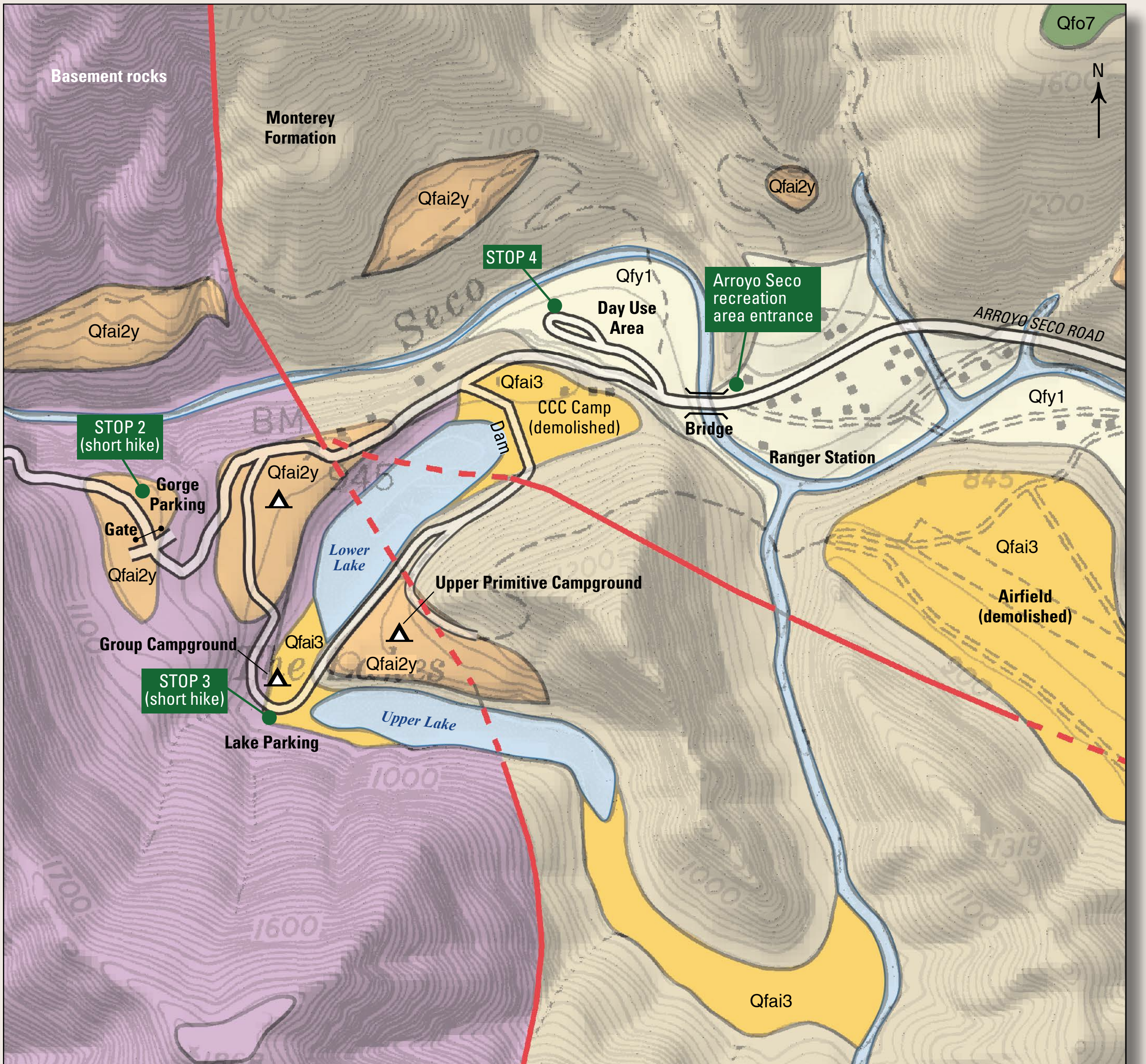
Drive up Arroyo Seco Road and stop at the Arroyo Seco recreation area (fig. 20) kiosk to pay the entrance fee ($10 as of summer, 2016), and ask for the parking pass to the Gorge parking area. If it is not too crowded, ask if you can briefly visit the day use area on your way out of the park. There are two different colored parking passes for the two parking areas. Drive over the bridge, past the campground, and continue to the end of the road to the Gorge parking area. On the way, look at the exposed rocks and consider how different this part of the Arroyo Seco looks compared to the broad agricultural valley downvalley. When you get to the Gorge parking area, you will be in a narrow canyon because the surrounding basement rocks are much more resistant to erosion than the softer Monterey Formation. These resistant rocks are the source of the rounded gravel in the river and the strath terraces. The relatively soft Monterey Formation rocks and the resistant basement rocks are separated by a fault at the mouth of the canyon (fig. 20). You will see the abrupt change in the rocks shown by color, to your right (north), across Arroyo Seco, as you drive to the parking area.

Arroyo Seco recreation area provides an excellent opportunity to observe the geology and erosional processes.



Photographs by E.M. Taylor, U.S. Geological Survey, April 2010

Figure 19. Monterey Formation exposed in road cuts and natural exposures.



Base from U.S. Geological Survey 1:100,000-scale digital data, 1982,
Universal Transverse Mercator, zone 10, North American Datum of 1983 (NAD 83)

Polygon colors represent different aged terrace deposits.
See figure 3 for geologic explanation of colors and symbols.

0 500 1,000 FEET

0 250 500 METERS

scale = 1:8,000

EXPLANATION

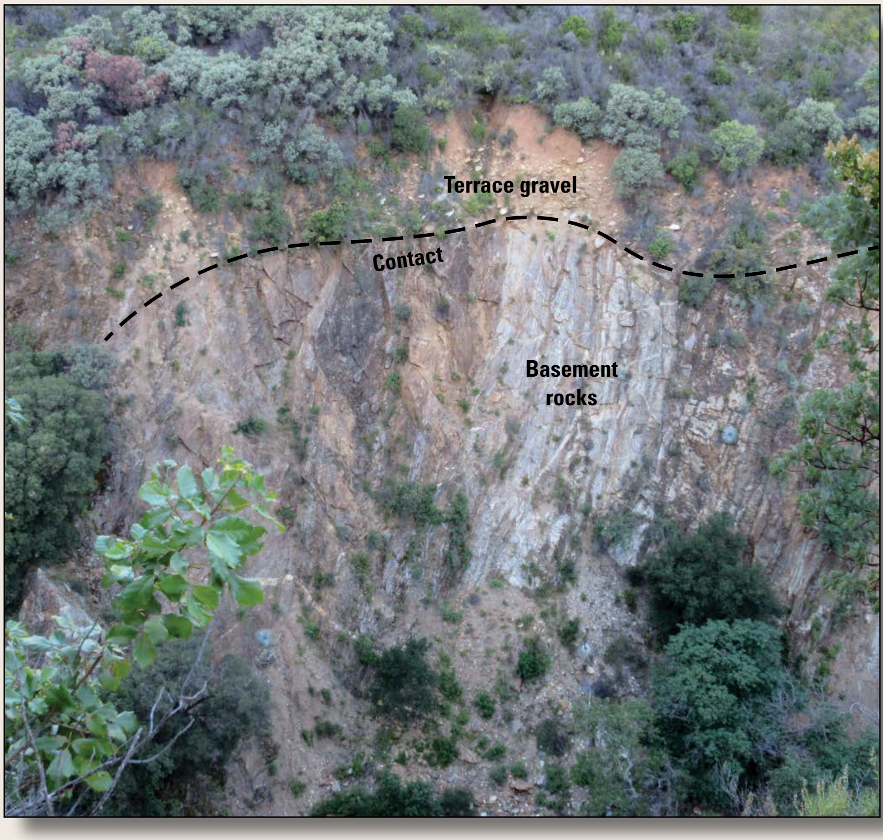
- Qfai3 — Geologic map unit, see fig. 4
- Fault (dashed where concealed)
- Campground

Figure 20. Arroyo Seco recreation area map.

Stop 2

Park in the Gorge parking area and prepare for an easy walk up the old Arroyo Seco Road, west of gate. The parking area is on a terrace surface. Until 1995, when a landslide buried part of the road, cars could drive this road through the east side of the Santa Lucia Mountains to Fort Hunter Liggett and Mission San Antonio de Padua near the town of Jolon. The old road provides beautiful views up and down Arroyo Seco Canyon.

The goal of the canyon walk is to look for rounded gravel capping terraces that are eroded into the resistant basement rocks. The best exposures are across the stream (fig. 21); a few small terrace remnants are preserved above the road. Rather than the broad flat terraces that dominant the lower part of the drainage, terraces in the canyon are poorly preserved and narrow.



Photographs by E.M. Taylor, U.S. Geological Survey, April 2010

Figure 21. Terrace gravel deposit on basement rocks.

Stop 3

Return to the car and follow the signs to the Upper Primitive Campground, but before you reach the Upper Campground (fig. 20), park on the left at the Group Camp and "Information Board" (fig. 20, Lake Parking). Take the short trail to the upper lake, east of where your car is parked. On your left, as you walk to the Upper Lake (fig. 20), is a strath terrace. Rounded gravel clasts are present at the surface and are exposed in the bank. The terrace gravel here is larger than those farther downvalley, a common characteristic of most streams. The Upper Primitive Campground is on this terrace. You can walk to the terrace surface by walking down the road past the Lower Lake and following the sign to the Upper Campground. Look north across the valley to see more terraces surfaces. All three campgrounds are on terrace surfaces.

Streams deposit larger stones closer to the mountain front and gravel size decreases farther from the mountain front. Enormous rounded stones, deposited where the recreation area is today and collected from the terrace surface, were used to make the road and parking area at the Upper Campground. This is a common tactic where gravel is available on strath terraces. Geologists often look at landscaping material to locate terrace surfaces where the gravel may be buried or removed.

Return to the car and continue down the one-way road. The Lower Lake can be viewed to the left and was once connected to the upper lake. In wetter years, the lakes are both filled with water and connect. The two lakes were part of a **meander sweep** of Arroyo Seco that eroded into the surrounding bedrock (fig. 20). Now the stream is located to the north, and the lakes are isolated from the drainage. These isolated lakes are called **oxbow lakes** and are common in meandering stream systems.

At the end of the lower lake is a dam probably built by the Civilian Conservation Corp (CCC) to enhance the natural lake. As you drive over the dam, you are near the former CCC camp that has been demolished (fig. 22). A few stone chimneys still exist. In this area, the CCC worked on building and maintaining bridges, roads, and trails for about 10 years beginning in 1933.

Figure 22. Photograph of the Civilian Conservation Corps Camp Arroyo Seco, 1936. Source: Salinas Public Library, https://www.flickr.com/photos/67808015@N05/9307677747/in/phptpstream/.

Stop 4

As you approach the park entrance, the day use area is on your left. It is a great place to picnic and swim; however, on a hot summer day, it can be crowded. The parking area is on a young terrace just feet above the active drainage (fig. 20). This young surface is often covered with large sycamore trees that do not grow on older terraces, probably because sycamore trees require groundwater at a shallow depth. The soil developed on this surface is weak with little or no soil horizons. Look north across Arroyo Seco from the day use parking area at the Monterey Formation; it extends from here to the Reliz fault where the river intersects the Salinas River valley. The fault-contact between the Monterey Formation and the basement rocks can also be seen from the bridge just before you leave the park and the guard shack.

0.0 Leave the day use area and proceed to the guard shack at the Arroyo Seco recreation area entrance where your odometer should be reset to 0.0 to begin the drive down Arroyo Seco Road. Just outside the park entrance is Arroyo Seco Resort, a cluster of privately owned houses nestled along a young terrace of the Arroyo Seco.

0.4 The terrace across Arroyo Seco to your right was once an airfield or landing strip probably used by the CCC (fig. 20) and later for firefighting planes. There is a small pullout at 0.6.

0.8 The road cut on the left is colluvium. The colluvium is pale brown to brown, poorly sorted with little or no bedding. The clasts are typically angular, less than 3–4 in. long, in a fine-grained matrix of silt and sand.

1.1 The road cut on the left is Monterey Formation. The top has been eroded flat by Arroyo Seco. The overlying rounded gravel is a strath terrace and was deposited by Arroyo Seco.

1.5 Look straight ahead at the multiple terrace surfaces as you descend the valley. Each surface is capped by rounded gravel and records where the Arroyo Seco once flowed. Mountain building by tectonics has raised the terraces above the elevation at which they formed.

1.7 Big Sur Land Trust manages Arroyo Seco Ranch, the property on your right. The property includes a 2-mile stretch of the Arroyo Seco, which has been named a priority steelhead restoration site.

2.1 On your left is a good example of a narrow canyon; the wall provides the alluvial and colluvial material that buries the terrace gravel and can be observed in the road cuts.

2.4 The narrow terrace tread on your right is used as a house site.

Stop 5

3.0 Entrance to Arroyo Seco Ranch. You can pull over here to the right and look down the valley to where it widens. The flat surface in the foreground is a broad terrace that is mapped as Qfai3 (fig. 4) and is approximately 35,000 to 40,000 years old (fig. 13*C*) (IRSL from Taylor and Sweetkind, 2014). Geologic mapping units Qfai3 and Qfai4 are the predominant terrace surfaces in Arroyo Seco. Combined, they extend the full length of Arroyo Seco and mark former extensive broad flood plains about 80 to 100 feet above the stream. The soil developed on this surface is characterized by an argillic B horizon with 25–35 percent clay.

3.1 Albertola Estates is a private development north of the stream that extends to the northern ridges of Arroyo Seco. House lots take advantage of the terrace remnants up to 1,000 ft above Arroyo Seco (fig. 4).

3.2 Coelho-Ford Fire Station and Arroyo Seco Community Center. Look to your right at the dramatic sequence of terraces in the valley. The lower, gently sloping surface to your right is typical of a terrace that has been buried by colluvium derived from the adjacent slopes.

3.4 Country Store. Sometimes it is open.

3.7 Miller's Ranch, in its heyday after World War II, was a family resort with Quonset huts and a dance hall. It is developed on one of the youngest terraces (Qfy1) and is identified by the presence of sycamore trees.

3.8 Tilted Monterey Formation, with a well-preserved bedding plane, is exposed in the road cut.

4.0 Continuation of Arroyo Seco Ranch is on the right.

4.1 On the right, just before you cross the bridge over Piney Creek, there is a terrace remnant capped by rounded gravel.

4.4 Intersection with East Carmel Valley Road. The valley broadens downvalley from this point where Piney Creek merges with Arroyo Seco.

4.8 A small, legal pullout allows you to look at the broad open valley and the set of terraces along Arroyo Seco that are not visible from the road. The road cut on the left is a good example of weathered Monterey Formation buried by colluvium.

Stop 6

6.7 Pull over on your right at the intersection of Sycamore Flat Road. You are parked on an extensive Qfai3 terrace, the same one seen at Stop 5. This terrace surface is often used for agriculture, including grapes. Terrace remnants of Qfai1 are above the road to the north. The steep eroded bluffs across Arroyo Seco to the south are good exposures of the Monterey Formation. Sycamore Road allows you access to the Arroyo Seco and a look at the youngest, gravel-covered terraces (Qfy1). Houses are developed among the sycamore trees on the terrace about 6 ft above Arroyo Seco.

Stop 7

8.4 Pull over on your right and onto a paved road to a gravel quarry. From here, you can look down to one of the youngest surfaces (Qfy1) that has been quarried for sand and gravel. Up valley is the Qfai3 terrace, and immediately above the road is the Qfai2 terrace. The soil developed on the terrace has an argillic horizon with at least 35 percent clay, and the soil is about 50,000 years old (fig. 13*C*) (IRSL from Taylor and Sweetkind, 2014). Across the valley you can see a Qfai3 above Qfai4 which extends downvalley. Both terraces are correlative with alluvial fans at the intersection of the Salinas River valley (fig. 4).

8.5 Pullout on the right—“No Dumping Subject to $100 fine” sign. Ideal view of lower terraces. Colluvium eroded into and burying Monterey Formation in road cut.

8.6 Pullout on the right—Look at the exposure in the road cut. There is a thin deposit of colluvium above a bed of rounded gravel (Qfai2o) which in turn lies on Monterey Formation exposed in the base of the road cut. The top of the alluvial sediment was dated to estimate the time of abandonment of the ancient flood plain and the maximum age of the colluvium (>65,000 years old by IRSL from Taylor and Sweetkind, 2014).

8.7 Pullout on right

8.8 Buried terrace gravel in road cut. Look for rounded gravel on Monterey Formation in road cuts as you drive down the valley.

11 Bridge crossing Arroyo Seco. End of field guide.

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Glossary of Geologic Terms

A

Alluvial deposits Sediments composed of unconsolidated gravel, sand, silt, and clay deposited by a river or stream.

Alluvial fans River deposits adjacent to mountain fronts, typically in a fan shape.

B

Base level The altitude below which a stream cannot downcut. Sea level is the ultimate base level.

Basement rock A complex of pre-Cenozoic rocks below the Monterey Formation in Arroyo Seco. They are igneous and metamorphic rocks. Rounded granitic rocks derived from this unit occur in the soils and at the surface of the strath terraces.

Basin aggradation The process by which a basin or valley is filled by sediments.

C

Clast An individual weathered fragment of stone or rounded gravel.

Colluvium Sediment moved by gravity, generally down slopes. It is unsorted, made up of a mixture of sizes.

F

Flood plain The smooth land adjacent to a river channel that is covered by water when the river overflows its bank.

G

Geomorphic features A general term to describe a configuration of the Earth's surface that is specifically used in this report to describe landforms produced by erosion or deposition.

Glacial cycle An interval of time marked by one or more major ice advances and separated by an interglacial.

Global climate change The fluctuation of temperature and precipitation that is felt globally.

Global eustatic record The record of global sea level independent of local factors, and resulting from fluctuations of the Earth's surface elevation where land subsides beneath the weight of ice sheets and the subsequent uplift and rebound when ice sheets melt.

H

Hydrologic cycle The constant circulation of water from the sea to the atmosphere, returning to land and plants, and eventually back to the sea.

M

Map scale The relationship between a measurement on the map and a corresponding distance on the surface being mapped. For example, a map scale of 1:50,000 means 1 inch on the map equals 50,000 in. (about 0.8 mile) on the Earth's surface.

Marine isotope stage (MIS) Alternating warm and cool periods in the Earth's paleoclimate, deduced from oxygen isotope data measured from deep sea sediment core samples.

Marine sediments Sediments deposited in an ocean.

Marine terraces Eroded wave-cut platforms that record sea level in the geologic past.

Meander sweep One of a series of curves, bends, loops, turns, or windings naturally developed in the course of a stream.

O

Oxbow lake A crescent-shaped lake in an abandoned channel of a meander.

P

Paleoclimate events Climates that have occurred in the past.

Perennial drainage A stream drainage that flows year round as opposed to an intermittent drainage that only flows seasonally.

S

Sedimentary basin A depression filled over time with sediment that is often transported by water.

Soil horizons Layers within a soil that are distinguishable from adjacent layers by characteristic physical properties and are often horizontal at varying depths below land surface.

Strath or erosional terrace A bedrock surface once eroded by an active river and capped with stream gravel that was deposited by the stream as it cut the surface. It lies above the present flood plain.

Stream equilibrium In terms of stream dynamics, a state of neither erosion nor deposition where river discharge and sediment load are in balance.

T

Tectonics Large-scale processes affecting the structure and properties of the Earth's crust and its evolution through time. Examples of results are mountains and basins.

Terrestrial sediments Sediments shed off eroding mountains and generally deposited by streams in nonmarine environments. Terrestrial sediments also include slope wash and colluvium. Other common terrestrial sediments are those deposited in lakes or as sand dunes.

Tributary A stream that joins the main drainage.

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