GEOLOGIC, CLIMATIC, AND VEGETATION HISTORY OF CALIFORNIA

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Introduction

The dawning of the "Anthropocene," the era of human-induced climate change, exposes what paleoscientists have documented for decades: earth's environment—land, sea, air, and the organisms that inhabit these—is in a state of continual flux. Change is part of global reality, as is the relatively new and disruptive role humans superimpose on environmental and climatic flux. Historic dynamism is central to understanding how plant lineages exist in the present—their journey through time illuminates plant ecology and diversity, niche preferences, range distributions, and life-history characteristics, and is essential grounding for successful conservation planning.

The editors of the current *Manual* recognize that the geologic, climatic, and vegetation history of California belong together as a single story, reflecting their interweaving nature. Advances in the sciences of geology, climatology, and paleobotany have shaken earlier interpretations of earth's history and promoted integrated understanding of the origins of land, climate, and biota of western North America. In unraveling mysteries about the "what, where, and when" of California history, the respective sciences have also clarified the "how" of processes responsible for geologic, climatic, and vegetation change.

This narrative of California's prehistory emphasizes process and scale while also portraying pictures of the past. The goal is to foster a deeper understanding of landscape dynamics of California that will help toward preparing for changes coming in the future. This in turn will inform meaningful and effective conservation decisions to protect the remarkable diversity of rock, sky, and life that is our California heritage.

California's Prehistory: A Tale of Time and Space

The concept of scale is central to understanding history. Time scale can be especially difficult to untangle in resolving past landscapes because there are many histories depending on context. These range from details of the last 200 years in the Lake Tahoe Basin, for example, to the grand sweep of time since the origin of North America. When millions of years are swept into a single phrase ("the Sierra Nevada was uplifted"), it becomes easy to forget that shorter processes also ensued in the distant past and were as important in shaping the landscape and biota as they are at present. In a similar manner, spatial complexities challenge interpretation of landscape-defining events. The land that is now California has been fragmented, stretched, rearranged, uplifted, and submerged in many ways, shapes, and forms. In the past as in the future, there is no California distinct from its continental and global context. This perspective is adopted in outlining the history that follows.

Forces That Shape Change

Whereas time, like a river, flows one way, many processes that affect landscapes, climate, and vegetation recur. Knowing something about these forces helps to make sense of the big and small pictures of the past. Our ability to understand history in turn relies on methods for resolving conditions now long gone. While these scientific techniques have improved dramatically, bias always remains, and in historic vision we continue to "see through a glass darkly."

At the longest historic scale, center stage is taken by geologic drama. Plate tectonics demonstrate that continents are land masses riding on buoyant lithospheric plates, which move over the earth's viscous upper mantle (asthenosphere) powered by convection currents created by the immense heat generated from the hot molten core. Over hundreds of millions of years, earth's crust oscillated through phases of aggregation and dispersal. When continents collided, supercontinents formed. In contrast, breaking-up (rifting) of supercontinents led to dispersal and fragmentary landmasses. These super-continental cycles take about 300–500 million years to complete. Earth is currently in a dispersed-continent phase.

Plate tectonic processes and super-continental cycling affect landscape-building forces. When plates move toward each other, they collide in a boundary that is active or convergent (which may or may not result in subduction, where one plate passes under the other); when plates move away from each other, the boundaries are passive or divergent (plates spread apart along a rift zone). Active boundaries are associated with volcanism, mountain building, faulting, and earthquakes in the adjacent regions; passive boundaries are associated with quiescent continental margins, and erosion dominates. Over time, boundaries can change from active to passive. To the extent that we can trace the land we call California through billions of years, the region has drifted through many degrees of longitude and latitude, switched from active to passive boundaries multiple times, witnessed mountain ranges rise and erode, harbored inland seas, and at times in part been submerged beneath the ocean. The California margin has changed from passive to convergent to the present situation of a combination of transform (side-by-side movement) and convergent.

Climatic changes at this scale were similarly enormous, involving evolution of the atmosphere as well as responses that reflect movement of the continents. Tectonics of super-continental cycles influence an analogous icehouse-greenhouse climate cycle, whereby global climate regimes alternated over hundreds of millions of years between end states. Icehouse conditions tend to (but do not always) occur when global continents accrete and supercontinents form, sea levels are low, polar and continental ice caps are extensive, and global climates are cold-arid. Contrasting greenhouse periods have high sea levels, little or no land ice, and warm, humid climates. Earth at present is in a warm interglacial interval of a longer icehouse phase.

Geologic and climatic cycling strongly influence organic evolution. Dominant at the longest time scale are processes that led to the origin and diversification of life and the rise of the first land plants. Much of our knowledge of the earliest living forms derives from fossils exposed in eastern California. Nested within these long cycles are mid- and short-term processes. Plate tectonics influences geologic processes not only at continental scales but at regional and local scales as well, affecting locations and magnitudes of earthquakes, volcanism and mountain-building, sea level and tides, and the erosion and exposure of underlying rocks. Similarly, superimposed within the current icehouse climate phase are shorter glacial-interglacial oscillations of tens of thousands of years in duration. Modern orbital theory explains these as paced by the oscillating pattern of earth's relationship to the sun. At successively shorter times, diverse climate cycles come into focus, driven by fluxes in solar variability, atmospheric dust concentrations, and ocean circulation. Interannual modes such as the El Niño/La Niña cycle, for example, are paced by changes in ocean patterns.

Plants and animals respond to geologic and climatic processes at each of these scales via changes in distribution as well as through evolution. As the earth below and the atmosphere above changes, plants migrate, expand and contract in range, and die out locally and recolonize. Vegetation composition is scrambled as new patterns emerge, often in quasi-cyclic manner. In so doing, these changes result in differential birth and death of lineages, subjecting plant populations to natural selection as well as random forces of genetic change. Subspecies evolve, hybridization and gene flow dissolve taxonomic boundaries, and species go extinct as new biodiversity flourishes.

Finally, anomalous events have created many of the defining trajectories on earth. From asteroid impacts to methane hydrate releases, volcanic eruptions to the rise of *Homo sapiens*, surprise events have changed the history of earth — and the California landscape — in unparalleled ways many times.

Late Precambrian through Paleozoic Eras: 1.2 Billion Years (Ga) to 250 Million Years (Ma) Ago

(Refer to the stratigraphic chart at the end of the chapter for reference to time periods)

The early phases of earth's history involved major geologic construction as continents developed, rifted, and re-formed. The Precambrian era includes the earliest period of history, starting with the origin of the earth about 4.6 billion years ago (Ga). By 1.2 Ga, land was beginning to emerge in western North America, and California history comes into focus. Climates of early California were influenced by varying paleolatitudes as the land masses drifted north and south. This in turn affected the course of biotic—and eventually plant—evolution. California was submerged below shallow (east) to deep (west) seas during much of the early period. Starting about 400–350 million years ago (Ma), major mountain building occurred offshore (Antler and Sonoma episodes). As the continent drifted westward, the continental margin repeatedly collided with these offshore island mountain chains, which were added successively to the continent, contributing land mass to California and extending the shoreline from western Nevada into present-day California.

This period of earth's history also included dramatic climatic change. From the earliest time, the sun was young and faint, atmospheric methane and carbon dioxide concentrations were much higher than at present, and atmospheric oxygen evolved only in association with the origin and expansion of photosynthetic life. This period experienced one of the most severe icehouse climates in earth's history, known as Snowball Earth, when ice sheets covered the continents and extended to equatorial latitudes. Glacial till in the Kingston Range near Death Valley documents that California was locked in ice, as was much of the rest of the earth. With the end of the Snowball Earth interval, climate entered a multi-million-year greenhouse phase, beginning about 600 Ma. California lay at low latitudes then, and climates were correspondingly warm.

The first life on earth evolved during this period, with radiation into the major clades or kingdoms. Whereas most life forms were long thought to have evolved after 542 Ma, fossils have been found in recent decades that incontrovertibly document an earlier origin. Although these bear little resemblance to modern plants and animals, the eukaryotic plan is clearly recognizable by 1.7 Ga. In California, photosynthetic cyanobacteria dating to about 650 Ma are recorded in stomatolites (fossil mats) found in the Kingston Range near Death Valley and outcrops of the Nopah Range near Tecopa. Vascular plants first appeared about 420 Ma; seed plants appeared in the fossil record abruptly, at about 360 Ma. Gymnosperms evolved in this interval and are represented by radiations of *Ginkgo,* now with only one (E. Asian) species, *G. biloba*, and now-extinct conifer forms. Extant conifer lineages did not appear for another 100 million years.

Mesozoic Era: 250 Million Years to 65 Million Years Ago

Geology. The direction of subduction along the western margin of North America reversed ~215 Ma, when sea floor (the Farallon plate) began subducting under the North American continent in the

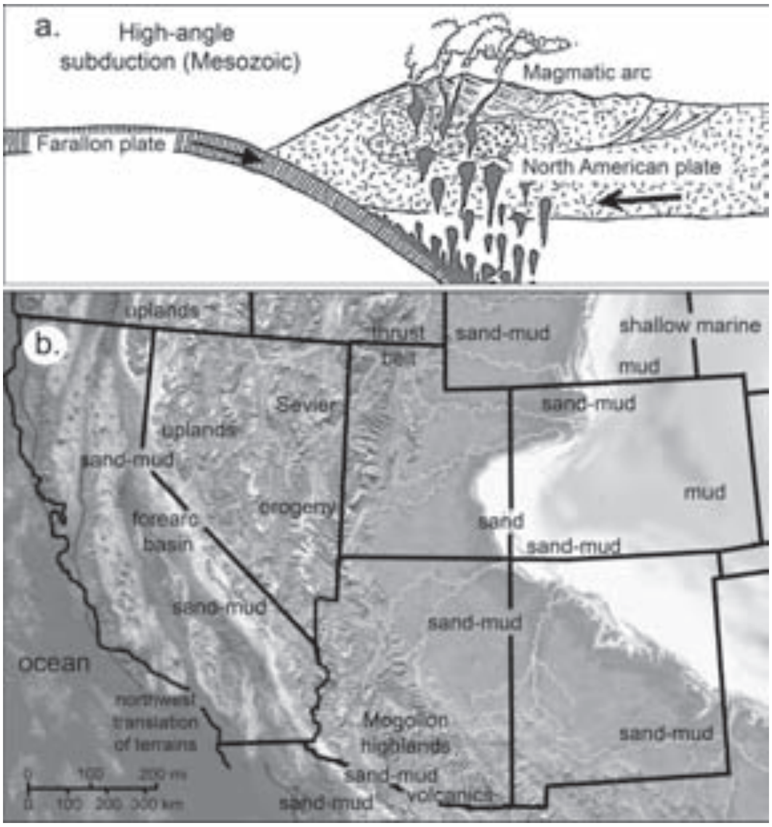

Figure 1. Southwestern North America, ~75 million years ago. (a) The western margin of the continent was an active subduction zone, catalyzing volcanism and mountain building inland of the Sevier and Nevadan ranges and intrusion belowground of magmatic batholiths that would later be exposed as granitic rocks in mountains of California. The volcanic uplands of present-day Nevada were important for the development of California flora. (b) Much of California was submerged as the so-called fore arc basin west of the continental margin. To the east, the Western Interior Seaway divided the continent nearly in half. Reconstructions (a) modified from F.L. DeCourten, 2003 *The Broken Land,* University of Utah Press; (b) modified from Ron Blakey, Colorado Plateau Geosystems and Northern Arizona University, http://jan.ucc.nau.edu/~rcb7/RCB.html; cross-sections.

vicinity of the present-day Sierra Nevada (Fig. 1a). This resulted in part as the supercontinent Pangea split and cores of Africa and South America rifted off the eastern and southern parts of Pangea, triggering an increase in the rate at which North America moved west over the adjacent sea floor. Subduction under North America led to a dramatically altered geologic history in California, and marked the beginning of several long, complex, and significant mountain-building episodes inland. Between 200 Ma and 70 Ma, two major episodes of thrust faulting led to the Nevadan and Sevier orogenies (Sierran arc volcanoes), which resulted in extensive north-south volcanic mountain chains. Rocks of this age are exposed in the Klamath Ranges, Sierra Nevada, Basin and Range Province, Mojave Desert, and Peninsular Ranges. Much of the interior of California and the Great Basin became elevated plateaus (steppe) built by this volcanic activity.

Subduction during this period also resulted in placement of intruded (unerupted) magma, mostly granitic, far underground. The above-ground mountain ranges and below-ground plutons extended from the latitude of Baja California to Canada. Plutons from this age are found in the Klamath Ranges, Sierra Nevada, Basin and Range Province, Mojave Desert, and Peninsular Ranges. The greatest volume of magma was intruded ~100 Ma, which resulted from subduction of the Farallon plate under North America. By ~85 Ma emplacement of the granitic batholiths ended.

East of the large Nevadan and Sevier mountain chains lay a large inland sea, the Western Interior Seaway, which divided the continent in half. West of the volcanic arc and east of the subduction trench, a large shallow marine (forearc) basin extended the length of California in what is now the Central Valley (Fig. 1b). Over subsequent millions of years, erosion from the volcanic mountains of the Nevadan and Sevier orogenies deposited material into this basin, sediments of which today represent the primary evidence for these immense mountain chains. By the end of the interval (~65 Ma), the Interior Seaway had disappeared and the continental halves united as land.

Offshore older terranes (fragments of crustal material, in this case from offshore volcanism) continued to be added onto the North American continent by accretion. These appear as NE-SW trending discontinuous belts of rocks of different age and composition in the Klamath Ranges and northern Sierra Nevada. The subduction zone moved westward after each accretion event and triggered successive cycles of accretion of increasingly younger terranes onto California. Accretion by subduction along the northern California margin in the Coast Ranges from Sonoma County to Oregon continued well into the Tertiary. California drifted on the continental plate northwest during this period from sub-tropical and tropical latitudes at 250 Ma to middle latitudes by ~65 Ma.

Climate. The climate of this interval continued to be highly variable, alternating from extremely cold glacial periods to the highest global temperatures documented in the last 545 million years. California was at tropical latitudes at the beginning of the Mesozoic, about 250 Ma. Annual temperatures were 10°C warmer and winter temperatures 15–20°C warmer than present. The extensive Western Interior Seaway mitigated climate extremes and enforced warm conditions throughout the American Southwest. Rainshadows developing over the Nevadan and Sevier volcanic ranges began to wring humidity from the air, creating drier climates. By 140 Ma, mild icehouse conditions developed following the breakup of Pangea, which nonetheless left the California region on average warmer than present. The latest part of this interval was characterized by multiple abrupt climate events.

Vegetation. Some ancient gymnosperm lineages, such as cycads, Taxodiaceae (in the old sense), and Ginkgoaceae, had their heyday during the Mesozoic. Many forms of the last two families extended across the Northern Hemisphere, including western North America. Taxodiaceous taxa appeared in the Mesozoic, with *Sequoia* and relatives dating to ~200 Ma. *Sequoiadendron* is not known from the Mesozoic although the diversity of forms appearing after 65 Ma suggests that it had earlier origins. By ~200 Ma modern conifer families are recognizable. Early forms of Pinaceae appeared by 150 Ma, although their radiation lagged those of other conifers. *Pityostrobus,* a group of Pinaceae taxa that disappeared by 33–30 Ma, and *Pinus* are among the oldest records for this family. In addition to gymnosperms, ferns (including *Equisetum*) radiated and expanded worldwide starting ~150 Ma.

Rapid diversification of angiosperm taxa began ~110 Ma with almost exponential increase in taxonomic diversity. By this time, angiosperms were abundant on a worldwide basis, and by 65 Ma, they had become the most diverse and floristically dominant group of plants, as evidenced by the composition of numerous macrofossil and pollen floras. In North America, the Cretaceous Western Interior Seaway separated two principal floristic provinces. The western province is distinguished by the abundance of *Aquilapollenites*, an early angiosperm pollen taxon resembling grains of modern Santalales (e.g., Comandraceae, Viscaceae) but likely representing a broad polyphyletic clade. Closed-canopy forests of broad-leaved evergreen angiosperms and conifer forests dominated in the warm humid environments, suggesting little seasonality and annual mean temperatures of 20–25°C. Middle latitude west-coast forests contained araucarian, rosid, platanoid, and hamamelid elements including species of Betulaceae, Ulmaceae, Tiliaceae, Juglandaceae, and Santalales. There is also evidence for a continental margin floristic province based in part on pollen samples from California. This province is recognized by absence or low abundance of *Aquilapollenites.* Indications are that angiosperms first spread to California between 120 Ma and 100 Ma. During this and subsequent tens of millions of years, angiosperms in California appear to have been most extensive and abundant in coastal and fluvial environments, while conifers remained dominant in well-drained and upland areas.

The end of the Cretaceous period was marked by earth's second largest global extinction event, the Cretaceous-Tertiary extinction at 65.5 Ma. This event is attributed to collision of an asteroid or comet with the earth. The impactor probably measured more than 10 km wide, and it left an impact crater 180 km in diameter in the Gulf of Mexico near the Yucatan Peninsula. In addition to non-avian dinosaurs and many other animal lineages, many plant genera went extinct in this event, especially at locations near the impact site. Broad-leaved evergreen trees were at higher risk of extinction whereas taxa with dormancy adaptations (e.g., deciduous leaves) fared better during the "impact winter" that followed. Although California was relatively near the impact site and would thus have been severely affected, no records from the time are firmly documented in our region. The best records are in western interior North America, in a zone from New Mexico north into Canada. Sites in this belt clearly indicate mass plant kills, with estimates of 50–75% extinction of earlier taxa.

Cenozoic Era: 65 Million Years to Present

1. Tertiary Period: 65 Million Years to 2.6 Million Years Ago

Geology. Before the asteroid impact, North America had begun to rift away from Europe, increasing the speed at which it moved westward. This increase in rate of movement is thought to have lessened the angle of subduction of the Farallon (oceanic) plate under the western margin of North America, transferring volcanic activity from the Pacific west (California-Nevada) into the interior (Colorado-Montana). This catalyzed initial uplift of the Rocky Mountains and began to shut off arc volcanism in much of California and the Great Basin. As a result, the early Tertiary was a period of relative volcanic quiescence in this region.

In the early Tertiary, the region at the eastern margin of California (now the Great Basin) was an elevated upland that drained to the west via rivers that flowed through California to the Pacific Ocean (Fig. 2). A steep gradient existed along what is now the west slope of the Sierra Nevada, but the Sierra Nevada was not the major hydrologic divide that it is now. Rather, to the east lay mountains of significant and apparently greater elevation (likely > 2750 m), with the hydrologic crest in the vicinity of central Nevada. The uplands of what is now the Sierra Nevada were the western edge of a generally mountainous region that extended eastward. This region has been called the Nevadaplano as it reflects similar character to South America's Altiplano.

About 40 Ma, for still poorly understood reasons, the angle of subduction of the Farallon plate re-steepened again (Fig. 3a). As the steeply diving portion of the Farallon plate migrated eastward, it fell away from the bottom of the overriding continent like a trap door slowly opening from east to west (Fig. 3b). This had many consequences, one of which was to relieve compressive forces that had existed in the region of the Rocky Mountains and eastern Great Basin. The change in plate angle also exposed the bottom of the continent to the underlying mantle's heat. Partial melting of the deep crust in response to upwelling hot mantle led to massive volcanic eruptions regionally. Exposure to deep heat also caused the continent to become less rigid, and to thin and stretch. As this occurred, the entire Nevadaplano region subsided, like the domed top of a cake sinking as it comes from the oven (Fig. 3c). This subsidence marked the beginning of the evolution of internal drainage and the birth of the hydrologic Great Basin.

These events also set the stage for a new era of mountain building. Regional subsidence, release of

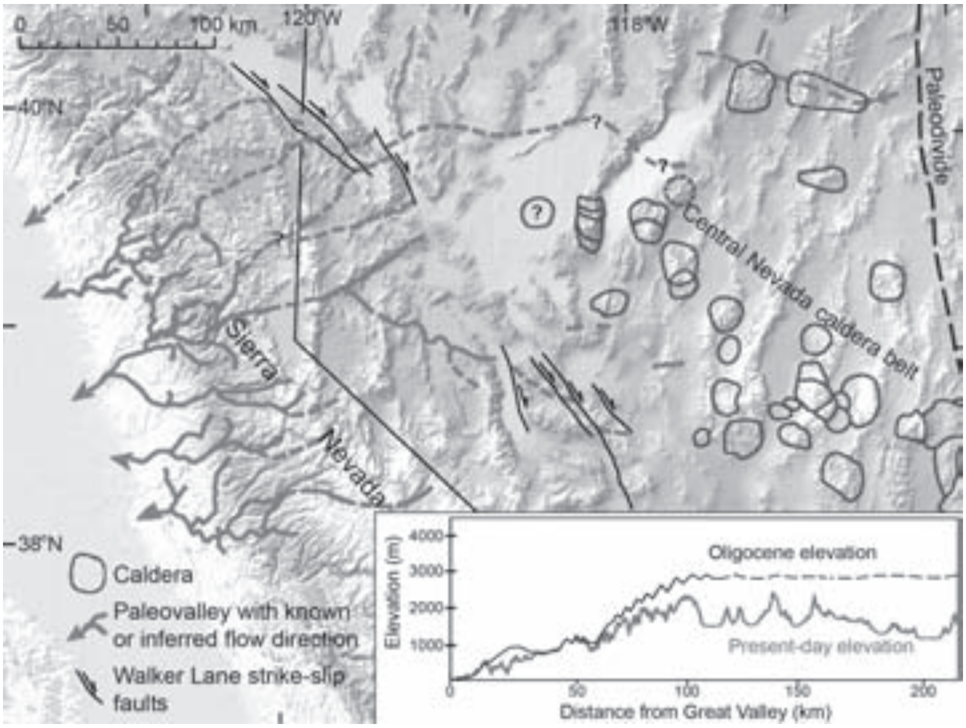

Figure 2. Reconstruction of the Nevadaplano, ~30 million years ago. The Sierra Nevada formed the western flank of a large volcanic upland that extended through the present Great Basin region. Elevation was ~2800 m at the latitude of Lake Tahoe and summit elevations increased eastward to a paleo-divide in central Nevada. Streams flowed westward from the divide, crossing through the Sierra Nevada to the Pacific Ocean, which filled the current Central Valley. Inset shows the greater elevation and different topographic profile of the Nevadaplano relative to the modern mountain crests. Much of the evidence for this reconstruction comes from analyzing tuff deposits from volcanoes and calderas of the central Nevadaplano. Modified from C. Henry, Uplift of the Sierra Nevada, California, 2009, *Geology* 37:575–576.

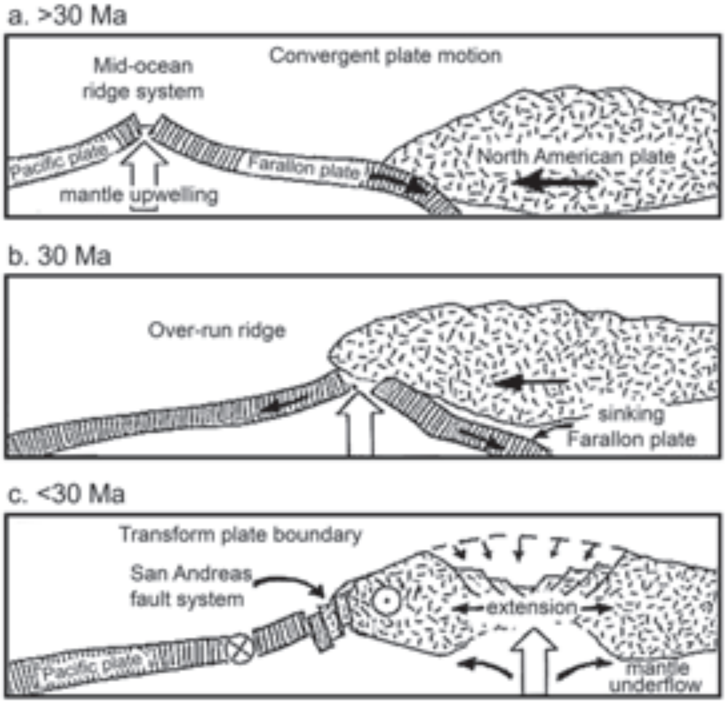

Figure 3. Plate tectonics and the relationship of Great Basin extension and origin of the San Andreas fault system over the past 30 million years. (a) Subduction prior to 30 Ma was active as the Farallon plate dove under the North American plate. (b) Extension of the Great Basin region began when the North American plate overrode the Farallon ridge system in the Pacific Basin about 30 Ma. (c) Contact of the Pacific plate with the North American plate changed boundary dynamics from subduction to lateral shear in northwest-southeast directions. This marked the beginning of the San Andreas fault system. Lateral motion is shown by symbols: the circled X indicates motion away from the viewer and the circled dot indicates motion toward the viewer. Modified from F.L. DeCourten, 2003, *The Broken Land,* University of Utah Press.

compression forces, and crustal extension affected the upper crust in a new way. Because the crust is brittle, it responded to changes deep below the surface by breaking along increasingly numerous normal (extensional) faults to accommodate stretching. Continuous stretching caused blocks of the continental crust to tilt along faults, giving rise to more than 300 fault-block mountain ranges and adjacent basins that characterize the present Basin and Range province. Continued extension of the Basin and Range over the past 30 million years has more than doubled the amount of land between the western (Sierra Nevada) and eastern (Wasatch Mountains-Colorado Plateau) edges of the province, adding 400 km of new landscape in the process.

At about the same time, a major change occurred along the western margin of North America as the eastward-moving oceanic Farallon plate was consumed under North America (Fig. 4a–d). This allowed the North American and Pacific plates to come into direct contact for the first time. Meeting of these two plates fundamentally changed the nature of the contact along western California, converting the boundary from one of subduction to lateral shear along what is known as a transform fault zone. This shear zone was the ancestral San Andreas fault system, which developed about 25–20 Ma. The reason for the new plate boundary behavior was related to change in the dominant directions of movement of the contacting plates. Subduction occurred when plates collided directly, as did the eastward-moving Farallon and westward-moving North American plates before 30 Ma. When the northwestward-moving Pacific and the North American plates came into contact, however, their movement in the same general direction caused the boundary to change to side-slip (lateral shear). Northwest movement of the Pacific plate exerted a drag effect on the continent, adding to the crustal extension of the Great Basin. Subduction continued north and south of the contact between the Pacific and North American plates, where the Farallon plate was disappearing under the continent. The meeting points of the three plates are known as triple junctions. As the Farallon plate was consumed increasingly under North America, the San Andreas fault boundary lengthened accordingly, and the two triple junctions became more widely separated (Fig. 4b–d).

This change from subduction to shear marked a significant transition in the geologic processes that influence California to this day. The transform zone has continued to grow over the past 25 million years as more of the Farallon plate is consumed, leading to an ever-larger area of contact between the North American and Pacific plates. At present, the northernmost point where the Farallon plate is passing under the continent is at Cape Mendocino, California. This seismically important location is known as the Mendocino Triple Junction, because the Pacific, Gorda (the name for the northern relict fragment of the Farallon plate), and North American plates meet there. North of the triple junction, subduction under the North American plate continues along the Cascadia subduction fault zone of Oregon and Washington, with ongoing volcanic arc orogeny inland. A similar situation persists south of Baja California where the Rivera Triple Junction marks the southern edge of the transform fault zone. Cumulative movement along the San Andreas fault zone has resulted in 160–370 km displacement over the past 25 million years, with the area west of the fault moving northwesterly and the continental area now moving southeasterly.

The history of the Sierra Nevada is closely linked to these tectonic events and the landscape evolution of the Nevadaplano and Great Basin. It has long been assumed that the present-day Sierra Nevada is a young uplifted mountain range resulting from extensional forces and faulting described above for the Great Basin ranges. Although mountains have long been recognized to have existed in the late Mesozoic and early Tertiary where the present day Sierra lie, the prevailing view was that this ancient range had never gained elevation > ~2000 m, and eroded to lowlands during the early-mid Tertiary. Fault-block tilting in the past 10–5 million years was believed to have created the high elevation of the modern Sierra Nevada.

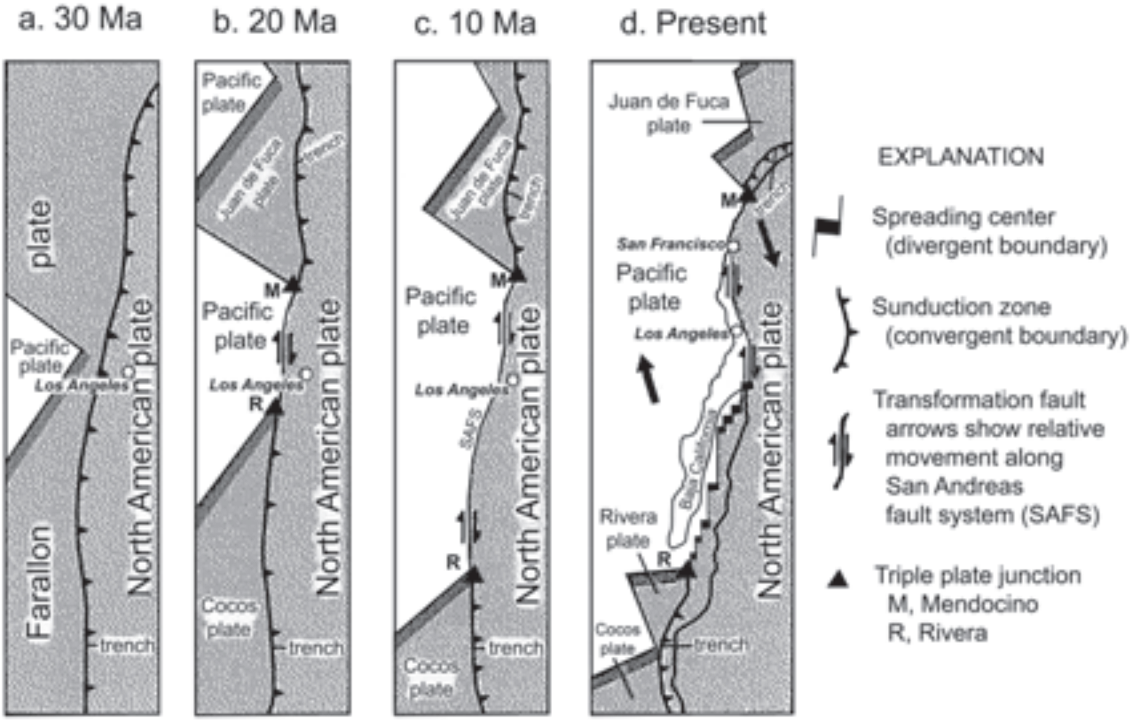

Figure 4. Development of the San Andreas fault system from 30 Ma to present. (a) As the Farallon plate was consumed under the North American plate, the Pacific plate was brought into contact with the North American plate and the San Andreas fault system was initiated. (b and c) As the San Andreas system expanded over time, the two triple junctions (Mendocino in the north, Rivera in the south) migrated farther from each other. (d) Cumulative movement along the San Andreas fault system has resulted in about 300 km displacement over 30 million years. Modified from F.L. DeCourten, 2003, *The Broken Land,* University of Utah Press.

Although some lines of evidence still support this view, an increasing body of research, including paleobotanic records, suggests that the Sierra Nevada achieved heights > 2800 m in the early Tertiary and remained high through subsequent millennia. The mountains of the Nevadaplano to the east of the ancient Sierra Nevada were even higher during this interval (Fig. 2).

This new evidence about elevation of the Sierra Nevada does not suggest that the range was exempt from effects of the extensional and faulting processes that were occurring. The form, topography, and elevation of the modern Sierra Nevada were strongly influenced by those events. For one, the processes that led to general subsidence of the domed Nevadaplano and created the internal drainage of the Great Basin appear similarly to have lowered rather than elevated (as was earlier interpreted) the Sierra Nevada relative to its early Tertiary heights (Fig. 3c).

Further, by the middle to late Tertiary, new patterns of tectonism in the California and western Nevada region strongly influenced the form of the present Sierra Nevada (Fig. 5). At about 10 Ma, shear stress of the Pacific and North American plates along the southern San Andreas began to be displaced inland. This is recognized by a series of fault complexes that describe the chronological development of the displacement. These faults extend eastward along what is known as the Eastern California Shear Zone (ECSZ) in the region of the present Transverse Ranges, continue eastward around the base of the Sierra Nevada and White Mountains, then turn abruptly northward along overlapping sets of echelon faults to the south end of the Tahoe Basin. There the fault zone forks, with one branch extending through Lake Tahoe and the other along the eastern foot of the Carson Range. These zones then become diffuse but eventually strike westward through northern California, converging at the Mendocino Triple Junction.

Figure 5. Major fault zones of the past 10 million years. Activity along the San Andreas fault system (SAFS) began to be displaced inland along the Eastern California Shear Zone (ECSZ) and Walker Lane (WL) about 10 million years ago, forming the new Sierran microplate (SN). Tectonic activity along this fault zone is shaping Sierra Nevada topography by processes related to (but distinct from) those affecting the Basin and Range province. [Note: Gorda plate = northern fragment of Farallon plate] Modified from J. Wakabayashi and T. Sawyer, Stream Incision, Tectonics, Uplift, and Evolution of Topography of the Sierra Nevada, California, 2001, *The Journal of Geology* 109:539–562. © 2001 by The University of Chicago.

This arc of faults is now recognized to define the boundaries of a new contintental plate, the Sierra microplate. The west margin is the San Andreas fault, thus the microplate contains the Sierra Nevada, the Central Valley, and some of the Coast Ranges (Fig. 5). The Sierra microplate accommodates 15–25% of the shear motion of the San Andreas zone. Relative to stable North America, the microplate is moving northwestward at about 12 mm/yr. This compares to the movement of the Pacific plate along the San Andreas Fault of about 50 mm/yr. Because the faults that carved this microplate from the continent are relatively young, they exist as a zone of multiple short faults, rather than coalesced into a single prominent fault such as the San Andreas, which by comparison is considered mature. The eastern portion of the microplate fault zone is an obvious topographic belt of low relief that extends northwesterly through eastern California and western Nevada, known as the Walker Lane. West of the Walker Lane are mountains of the Sierra microplate; east are mountains of Basin and Range origin.

Despite being a separate plate, the Sierra microplate remains coupled to the Pacific plate along the San Andreas, and tectonic activity of the San Andreas Fault translates to the Walker Lane and ECSZ. This plate-edge tectonic action, rather than extensional faulting related to the passage of the Farallon plate under the continent, appears responsible for having given shape (tilting and fault boundaries) to the present Sierra Nevada during the last 10 million years. Landmarks such as the Tahoe Basin, Carson Valley, and Owens Valley owe their origins to these forces, all within the past 5 million years.

Uplifting and tilting of the Sierra Nevada and down-dropping of basins had an important effect on the nature of exposures in this region. As slopes were tilted, fault-bordered surfaces were exposed and erosion accelerated, exposing underlying rocks. Included in the exposures are the granitic batholiths emplaced during subduction between 200 Ma and 70 Ma, as well as rocks from far older eras when California was submerged below seas. The latter are exposed as so-called roof-pendants in places such as the steep escarpment faces above Convict Lake in the eastern Sierra Nevada and throughout the southern part of the range.

Extensional forces that thinned the crust and generated basin and range topography also influenced topography in interior California. Especially in the Mojave Desert, faults formed as the crust stretched starting ~35 Ma. In many desert locations, so much crust was displaced that much older rocks below were exposed. The creation of faults via extension triggered volcanic activity in the Basin and Range and Mojave provinces, and many eruption centers arose around fault zones starting ~20 Ma. The Transverse Ranges derive their origin and orientation from lateral shear action along the Pacific and North American plates, but with a unique twist. As the Pacific plate moved northwest relative to the continent, a piece of the North American plate broke off in southern California but remained attached at the eastern margin. Detachment and continued shearing transferred this portion to the Pacific plate and in the process rotated the mountain axis clockwise, creating the east-west oriented Transverse Range. As this rotation proceeded, it created extension forces to the south that led to the development of the Los Angeles Basin and offshore islands.

The current Coast Ranges are geologically young and owe their origin to diverse and still poorly understood activities of plate contact as the lateral shear zone has increased. Extension, fault-block tilting, and uplift contributed relief to this region as well as volcanic activity along the newly propagating fault areas of the San Andreas. Elsewhere forces remained that derived from subduction and included compression forces, bends in regional faults, and thrust uplifting. Between the ancient Sierra Nevada and Coast Ranges lay the San Pablo Sea, a shallow inland water body, which dried at its north end ~9 Ma. A shallow sea persisted in the San Joaquin Valley to ~2 Ma.

Climate. New analytic methods have prompted re-interpretation of Tertiary climate processes. Early views regarded the climate since 65 Ma to have begun in warm greenhouse conditions followed by gradual cooling to the current icehouse regime beginning ~2 Ma. The picture now emerging is of much greater complexity and variability (Fig. 6). The time interval began with a greenhouse climate regime, with peak warmth at about 52–50 Ma (Fig. 6a). A slight cooling trend followed that terminated with an abrupt and defining global cooling at 33.5 Ma, the Eocene-Oligocene event. Temperatures at California latitudes during this event dropped by 6–8°C.

The Eocene-Oligocene event marked the return of a global icehouse regime that continues to present (Fig. 6a). Ice-cap development began in Antarctica, and only much later extended into the Northern Hemisphere. Global sea levels dropped by 70 m, reflecting the buildup of polar ice. Two global warming periods interrupted the background icehouse conditions. Peaking at 15–17 Ma was the middle Miocene climatic optimum, after which global temperatures gradually declined and Northern Hemisphere glaciations began. Another brief warming period, the early Pliocene climatic optimum, occurred from 4.5 to 3.5 Ma, when Northern Hemisphere ice melted and temperatures were much warmer than present (as much as 19°C in the Arctic). This was followed by climatic deterioration into fluctuations of the ensuing ice ages, which started about 2.6 Ma.

Most of the warming and cooling trends from 65 to 2.6 Ma are explained by the pacing of tectonic and orbital cycles. Superimposed on these trends, however, were four major climatic aberrations or anomalous periods with highly non-linear response. Two warm events are the hot spike at 65.5 Ma, attributed to the asteroid impact, and a short hot pulse centered at 55.8 Ma, the Paleocene-Eocene Thermal Maximum (PETM), which lasted 170,000 yrs (Fig. 6a). During the PETM, global temperatures increased by 5–10°C in less than 20,000 years. The cause of the PETM is still being debated but is widely attributed to spontaneous release of massive stores of methane hydrates from the ocean floor.

Two other anomalous pulses were global cooling events. These resulted from unusual coincidences in earth's orbital and tectonic cycles. The switch to an icehouse regime at 33.5 Ma appears related to the tectonic opening of the deep-water passage between South American and Antarctica. Superimposed on this were peaks in several orbital cycles of the earth's orientation toward the sun. The cumulative effect of these conditions turned what would have been a gradual trend into an abrupt temperature decline and catalyzed a deep 400,000 year glaciation.

By all indications, Early Tertiary warm humid lowlands and the cooler uplands alike in the California region were characterized by precipitation that was distributed throughout the year; persistent drought was uncommon. Truly arid climates and dry environments did not develop until middle-late Tertiary, and seasonality increased only after the Eocene-Oligocene event. The California Current, an ocean circulation pattern that exists at present, began to evolve about 15 Ma. This current is a primary driver of Mediterranean climates in the California region, and also regulates the steep summer thermal gradient from the coast to the interior. Loss of summer rain as a result and extension of a long sum-

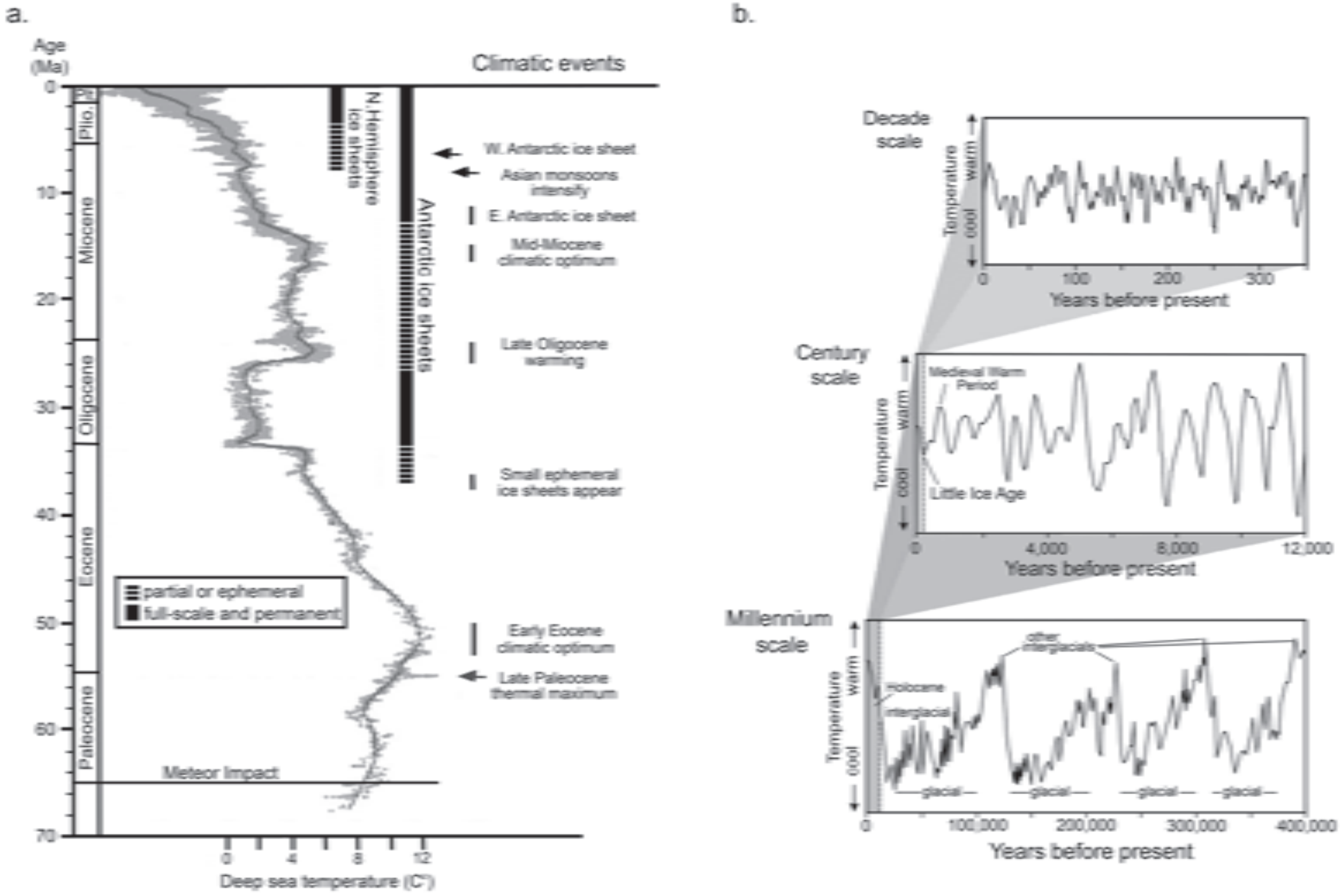

Figure 6. Major trends in global temperature at multiple scales. (a) Climate, tectonics, and biota over the past 65 million years. Modified from J. Zachos et al., 2001. Trends, Rhyths, and Aberrations in Global Climate 65 Ma to Present, *Science* 292:686–693. Reprinted with permission from AAAS. (b) Nested temperature cycles of the past 400,000 years, showing major glacial cycles (bottom), driven by variations in the orbit of the earth around the sun; ~1470 yr Bond cycles, related to variation in solar activity (middle); and cycles of the Pacific Decadal Oscillation, forced by varying patterns of ocean circulation (top). Modified from C. Millar, 2003, USFS, *Science Perspectives,* and sources therein.

mer drought became important influences on the evolution of the modern California flora. Significant regional rain shadows developed with evolution of Sierran and Basin and Range topography, marking initiation of summer-dry climates and the first appearance of desert environments. A Mediterranean climate pattern appears to have evolved in California by 7–4 Ma as the California Current strengthened, although some regions retained a pattern of summer precipitation.

Vegetation. During the Tertiary we can trace the roots of California's modern flora with satisfying detail. The story of this development mirrors events in the geologic and climatic history of the interval. Early in the period, angiosperm and gymnosperm taxa and community assemblages reflected adaptations to warm-temperate conditions similar to those of the late Mesozoic, i.e., to conditions warmer than present and with precipitation distributed year-round. Records from Wyoming during the PETM indicate that this hot episode created a global floristic upheaval likely experienced in California as well. Evidence points to massive plant species range shifts of 1500 km that occurred in less than 10,000 years in response to rapid warming. These dynamics were highly individualistic: some taxa persisted in place while others underwent significant displacement.

In California, angiosperm diversity appears to have been relatively low before 55 Ma. Fossil taxa bear scant affinity to modern lineages, but show warm-temperate and some subtropical adaptations (Fig. 7a, b). Increasing temperatures and humidity ~50–52 Ma triggered significant floristic shifts toward species adapted to tropical conditions and having affinities to taxa now in rain forests of eastern Asia, southern Mexico, and Amazonia. The Chalk Bluffs fossil flora near Colfax in Nevada County contains one of the richest floras in the West from this climatic period (Fig. 7b). Many species belong to families long extinct in California. More than 71 taxa are identified, including many evergreen angiosperms, as well as deciduous species. Few taxa overlap current native species. Five genera of laurels (including *Persea*), a palm, and *Viburnum* are included, as well as now-exotic genera such as *Perminalia*, *Phytocrene, Magnolia, Cedrela, Hyperbaena, Artocarpus, Ficus*, and *Meliosma*. Only one gymnosperm, a cycad, is present as a leaf fossil, although temperate conifers including *Pinus, Abies*, and *Picea* are represented by pollen. Such conifers are not recorded in other floras of this age in California. These and other taxa recorded only as pollen in these fossil beds, such as *Platycarya, Juglans, Carya*, and *Liquidambar*, have pollen widely dispersed by wind that may have drifted from uplands either in the Klamath or proto-Sierra ranges to the east. Warm-humid tropical adaptations are reflected in floras elsewhere in California, which had multi-storied rain forests containing, for example, *Cinnamomum*, *Laurus*, *Juglans*, *Magnolia,* and *Zamia*, and rich understories and diverse ground layers.

Whereas western California was blanketed by rich subtropical plant communities prior to about 33.5 Ma, upland regions to the east in the Great Basin high plateau harbored refugial populations of temperate-adapted species, including many conifers and associates now present in the modern flora. These upland populations were important not only as sources for colonizing California following climatic cooling but also as biogeographic crucibles for significant conifer evolution.

Following the climatic deterioration at about 33.5 Ma, abrupt changes in floristic composition and structure took place in California. Tropical-adapted woody angiosperm species disappeared within two million years. Throughout California, temperate-adapted species re-appeared, especially cool-adapted broad-leaved deciduous species and conifers, although the taxa differed from those previously present in California. These new plant communities had affinities to modern communities and high diversity, reflecting the heterogeneous climate and environmental conditions at that time. Taxa such as *Metasequoia, Sequoia, Pinus, Liquidambar, Carya, Juglans, Sorbus, Platanus, Acer, Crataegus, Ulmus, Zelkova, Rhus,* and *Tilia* appear. Notable for the first time in western records are terrestrial herb groups. Pollen records in particular document the expansion and widespread diversification of Asteraceae in the Oligocene. Increasing winter cold was likely a trigger for herb expansion.

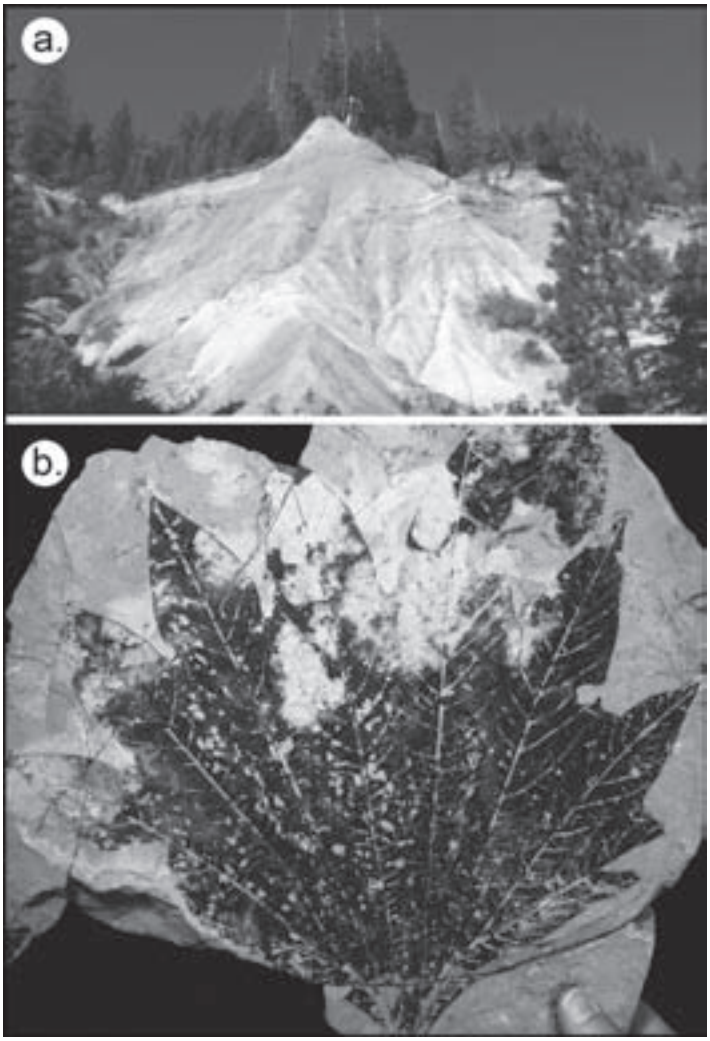

Figure 7. Eocene fossils of the northern Sierra Nevada, California. (a) At the late Eocene LaPorte Flora south of Quincy, CA, sediments are exposed of a paleochannel that was part of the ancestral Yuba River system (see Fig. 2). These preserve a diversity of fossils of warm-humid tropical and subtropical plant species that were characteristic of California in the early Tertiary. (b) Impression leaf fossil from another Eocene site, the Chalk Bluffs Flora east of Nevada City, CA, of the extinct genus *Macginitiea* (Platanaceae). Photos courtesy of Diane M. Erwin, UC Museum of Paleontology.

Floras younger than 23 Ma include highly diverse assemblages with taxa present in California today as well as many native to climates warmer and milder than California and having year-round rainfall. They indicate distinctions between upland and coastal communities, and reveal earliest adaptations to summer drying. During the warm climatic optimum at 17–15 Ma global temperatures rose to the highest levels reached during the past 23 million years. Floras throughout the West from this period reflect adaptations and range shifts in response to these conditions, with increasing latitudinal gradients from coastal environments to inland mountains. Associations of taxa unknown at present persisted in many locations, however, such as in the Tehachapi Mountains, where dry-adapted species occurred together, including *Hesperocyparis arizonica, Pinus cembroides, Arctostaphylos, Arbutus, Umbellularia, Cercocarpus*, several shrubby *Quercus*, *Viburnum,* and *Fremontodendron* alongside now-exotic taxa such as *Ficus, Persea, Dodonea viscosa,* and *Cedrela*.

Inland, in the higher ranges of western Nevada and northeast California, fossil assemblages contained diverse conifers, including *Chamaecyparis, Ginkgo, Abies, Pinus,* and *Torreya,* and hardwoods such as *Castanea, Cedrella, Fagus, Quercus, Carya, Umbellularia, Cercis, Fraxinus, Platanus, Prunus, Sorbus, Tilia*, and *Ulmus* in the Upper Cedarville Flora (16–15.5 Ma); the conifers *Abies, Pinus, Chamaecyparis,* and *Picea breweriana*, and hardwoods *Carya, Quercus, Alnus, Betula, Acer, Platanus,* *Ulmus,* and *Zelkova* in the Fingerrock Flora (15.5 Ma); and *Thuja*, *Abies, Picea, Pinus, Sequoiadendron*, along with *Acer, Berberis, Arbutus, Quercus, Persea, Robinia, Platanus, Cercocarpus*, and *Styrax* in the Middlegate Flora (15.5 Ma).

Intensification of the Mediterranean climate with decreased summer rainfall is reflected in younger floras (< 7 Ma) of the California region, which have increasing representation of taxa adapted to mild and cooling temperatures with dry summers. These floras also show spatial partitioning. Increasing abundance of hypsodont fossil horses corroborate the evolution and spread of California grasslands. A flora of this age in Contra Costa County, for example, is dominated by evergreen *Quercus*, with abundant *Platanus, Populus, Salix*, and understory taxa allied to *Dendromecon, Celtis, Berberis, Cercocarpus, Prunus, Lyonothamnus, Arctostaphylos, Ceanothus, Fremontodendron, Rhus*, and many grasses.

By the end of the Tertiary (2.6 Ma), many species and vegetation elements of modern California and recognizable species affinities were in place. Here and there remained species that are exotic to the modern flora, and many locations of native species were different than at present.

2. Quaternary: 2.6 Million Years Ago to Near-Present

Zooming the focus to the Quaternary introduces processes that occur at increasingly shorter time scales, dynamics that are blurred in discussion of deep time. In this section geology and climate are discussed together, as this time interval reveals how processes are interwined when resolution is high.

Geology and Climate. As the earth cooled over the last 4 million years, and earth's orbital relationships intensified icehouse conditions, a discernible transition in climate variability began, ~2.6 Ma. Early understanding of Quaternary climate relied on geomorphic evidence that painted the time interval in broad strokes. Collectively these data led to interpretations of the Pleistocene (2.6 to 0.01 Ma) as a long cold interval, or the "great ice period" of Agassiz. By the late 19th century, evidence for multiple glaciations accumulated and led to description of four major glacial periods. The ice ages were regarded as ending about 10,000 years ago (10 ka) with the arrival of our recent warm epoch, which was called the Holocene to signify its novel character.

New high-resolution methods that analyze stratified ice from polar ice caps and deep ocean sediments, however, revealed surprising variability. Rather than one or a few long-persistent ice ages, ice-core records show a pattern of over 40 cycles of glacial (cold) and interglacial (warm) intervals, each lasting from 40,000 to 100,000 years. The ice-core data reveal further variability nested within major glacial and interglacial phases. During a glacial episode extensive cold-glacial periods (stadials) were regularly interrupted by shorter warmer periods (interstadials) as well as by very short (~1,000 year) flip-flops between extreme cold and relatively warm conditions (Fig. 6b). Interglacials, by contrast, began abruptly, although not without a series of short (~1,000 year) reversals, peaked in temperature during early to middle cycle (the middle 4,000–5,000 years), and ended (last 4,000–5,000 years) in a series of steps of decreasing temperature, each with rather abrupt transitions, into the cold of another glacial period. The cumulative effect is a sawtooth pattern typical of Quaternary climate records from around the world. A startling insight from this revised view of the Quaternary is the overall similarity of the Holocene (now formally starting 11,700 years ago) to interglacial periods throughout the Pleistocene. The Holocene is, in fact, not novel.

During glacial periods of the Quaternary, polar ice sheets expanded in Greenland and Antarctica. Continental ice sheets developed across northern North America and parts of northern Eurasia, and glaciers formed on continental mountains to the south of the ice sheets. In California, glaciers formed in the Trinity Alps, Salmon Mountains, Cascade Ranges (Mt. Shasta, Mt. Lassen, Medicine Lake), Warner Mountains, Sweetwater Range, White Mountains, Sierra Nevada, and San Bernardino Mountains. By far the most extensive glaciations occurred in the Sierra Nevada, where, during the coldest parts of glacial periods, an ice cap extended over most of high parts of the range. During the last glacial maximum (~20 ka), the Sierran ice cap was 125 km long, 65 km wide, and extended downslope to about 2600 m in elevation. Valley glaciers, fed by the ice cap, extended 65 km down Sierra Nevadan west slope canyons, and at most 30 km down the shorter but steeper eastern escarpment canyons. Glacial meltwater flowed into valleys below.

As a result of ice buildup on land during glacial periods, global ocean levels fluctuated greatly throughout the Quaternary, declining about 150 m relative to present during the last and penultimate glacial maxima (20 ka and 140 ka). Declines of 60 m in sea level characterize less severe stadial periods during the last two glacial cycles. Along the Pacific margin, for example, the California coastline retreated about 80 km to a position west of the Farallon Islands, rendering San Francisco Bay, Eureka Bay, and other low basins as dry land. Increased precipitation and decreased evaporation during glacial periods led to formation of inland lakes and waterways. These included large lakes in the Central Valley (e.g., Lake Clyde, which filled the San Joaquin Valley 700–600 ka) and Great Basin (e.g., Pleistocene versions of Mono and Owens lakes), and higher river levels throughout California.

The present-day California Current system, which is responsible for maintaining the dry Mediterranean climate of our region as well as the cool coastal fog belt, wavered in its intensity through the Quaternary. When strong, as now, the California Current brings cool, relatively fresh water from the Oregon coast equator-ward along the California margin to just south of the U.S.-Mexico border. This current promotes favorable conditions for upwelling of cold water throughout much of the year, particularly in the summer months. During the peaks of glacial periods, however, continental ice sheets reached a large enough size to reorganize the wind systems over the North Pacific Ocean. These perturbations to wind fields caused the California Current to weaken, triggering large differences in ocean-surface temperatures relative to those of interglacial times. Collapse of the California Current during these millennia translated to weakening of the Mediterranean climate regime over California, reducing thermal gradients from coast to inland, and diminishing fog belts along the California coastal zone as warmer waters came near the coast.

During interglacial periods, most of these patterns reversed. As global ice melted, ocean levels rose, coastlines moved eastward forming bays and inlets, and inland water levels lowered or dried. The oldest evidence for the San Francisco Bay estuary system is about 600 ka; at 10 ka rising water began to fill the San Francisco Bay, which retreated partially during the middle Holocene dry and warm period, and then reached a maximum extent about 4 ka. The California Current, with correlated summer coastal fog belt, thermal gradients, and long summer droughts, developed most strongly during peak interglacial times and the modern pattern of the current evolved about 3 ka.

Over the last 2.6 million years, ongoing tectonic changes resulting from the Great Basin expansion and processes along the California Shear Zone contributed to the increasing development of the southern Sierra Nevada, White Mountains, and Carson Range escarpments, producing, for example, the deep and sharp-bordered Owens and Carson valleys, as well as deepening of the Lake Tahoe Basin. As the mountain ranges acquired their modern geometry, glacial action in turn carved the landscape in new ways. The Quaternary glaciers of California deposited prominent moraines, etched glacial cirques and valleys, and sculpted arêtes and matterhorn topography.

As the Sierra Nevada continued to be influenced by extensional and micro-plate tectonic processes of tilting and subsidence, the rivers running off both slopes eroded deep incisions and charted new courses. An example of the combined effect of river and glacier forces is Yosemite Valley. *Deepening* of the valley is attributed equally to the forces of glacial and river erosion. *Widening* of the valley, by contrast, is considered primarily the work of glaciers.

Major volcanic events continued in California throughout the Quaternary, centered along extensive fault zones of the Sierra Nevada and Coast Ranges. A globally significant example is the Long Valley eruption of eastern California. Basaltic eruptions began around Long Valley about 4 Ma, coinciding with fault subsidence of Panamint Valley, Death Valley, Owens Valley, Saline Valley, and many other valleys in southeastern California. Volcanism began in the Glass Mountains about 2 Ma, and peaked in a cataclysmic eruption of 600 km^3 of high-silica rhyolite at 760 ka. This massive eruption resulted in ash clouds extending as far as Nebraska, and widespread deposition in California of the Bishop Tuff. Simultaneous 2–3 km subsidence of the magma chamber roof formed the present Long Valley Caldera, the western-most portion of which approaches the modern Sierra Nevada crest near Mammoth Lakes. Subsequent volcanism in this region shaped much of the current landscape, including, for example, Mammoth Mountain, which erupted as a series of small extrusions over a period from 110 ka to 50 ka. Volcanism shifted north, first forming the Mono-Inyo Craters chain (50 ka to 650 years before present) and then farther northward to form the islands of Mono Lake, where volcanism continued to just before the historic period (~200 years ago) and is still active, as attested by hot springs on the islands.

Vegetation. California plant species and communities were significantly influenced by climatic and geologic events of the Quaternary and responded to both major and minor climate cycles. Relatively few plant speciation or extinction events (contrasting with abundant animal extinctions) are documented at this time in California, although evidence points to significant genetic adaptation at population levels. A significant new factor influencing vegetation patterns in California during the past 10,000 years is the presence of humans. In the California region, Native American activity likely had its greatest effect on vegetation in the past 6,000 to 4,000 years, as migrations of people into California took place, populations grew, and sophisticated methods of plant use and vegetation control developed. Invasion of modern Eurasians starting in the 1700s and increasing greatly from the middle 1800s vastly altered the scope, rate, and nature of vegetation change in the region.

Several categories of vegetation response to Quaternary glacial-interglacial climatic change (and later human manipulation) occurred in the greater California region. These include:

1. *North-south shifts of distribution ranges, primarily in low-relief areas.* An example is singleleaf pinyon pine (*Pinus monophylla*) during the last glacial cycle. Pollen and woodrat-midden records document that singleleaf pinyon pine distribution was widespread in the late Pleistocene south of its current range and in the current range of the Mojave Desert. As climates warmed during the early Holocene, singleleaf pinyon pine moved gradually northward, reaching central Nevada about 5 ka, near Monitor Pass in eastern California 1.4 ka, the Reno area 400 years ago, and its current northern limit on the west side of the Great Basin near Pyramid Lake in western Nevada 200 years ago. Similar shifts appear for species of California's Great Central Valley.

2. *Vertical shifts in elevation in mountainous areas*. Elevational shifts that correspond to glacial-interglacial climatic phases are documented for many California species. In the Sierra Nevada, for example, during coldest glacial periods when an ice cap covered the range, montane conifer ranges shifted downslope by as much as 1000 m relative to their present elevations.

3. *Population contractions (refugia and extirpations) and expansions (colonizations).* Contractions and expansions were common for many California plant species in response to glacial-interglacial climate dynamics. These shifts occurred sometimes with little significant effect on elevational limits of species ranges. For example, coast redwood, the California closed-cone pines, coastal cypresses, and many of California's oak species followed this pattern, contracting to fewer populations of smaller size during unfavorable periods. Such contractions rarely amounted to significant directional shift in the overall species range; rather to loss of connectivity and small population sizes. For example, California's oak populations expanded during

interglacials, becoming more connected and covering large areas of the California landscape. During unfavorable climate periods (glacial), populations contracted into disjunct, isolated locations, with many population extirpations. Similarly, during interglacials when the California Current was strongest and coastal fog belts extensive, coast redwood expanded; the converse occurred during glacial periods. The scattered distributions resulting from such contractions included important refugial populations for many species during unfavorable climatic periods. These were not only sources for rapid recolonization following return to favorable conditions but critical for conservation of population-level genetic diversity. Such refugial populations also existed throughout mountainous areas, where habitat heterogeneity afforded considerable opportunity for maintenance of small populations.

4. *Changes in community composition, including development of non-analog assemblages.* Plant communities at any time and place on the California landscape reflect to some degree the interaction of climate with individual species' ecologies. In some situations, especially for broadly adapted taxa, species responded synchronously to Quaternary climatic changes, and community compositions remained relatively similar as species shifted. In other situations, species responded individualistically, and community compositions changed over time. Unusual assemblages, such as combinations of species not found at present, resulted from unique combinations of climate, other environmental conditions, species adaptation, differential migration, and chance events.

Past, Present, and Future: 1,200 Years Ago and Forward

The last 1,200 years in California warrant special attention. Not only is this interval our immediate heritage where we have sufficient detail to illustrate key processes, but the period also provides context for the future. Further, this interval marks the beginning of a transition to human dominance and influence. The background for this 1,200 year period is a general cooling trend that began ~4 ka, which varied in timing regionally and distinguished the late Holocene from the warm middle Holocene (6–4 ka). Climate cycles paced by fluctuations in solar activity and in ocean cycling rendered significant climate variability at century and shorter scales within this time. The Medieval climatic anomaly, about 700 to 1,100 years ago (900–1350 CE), was a worldwide interval of temperature and precipitation divergence, varying in expression regionally. In California, abundant evidence documents two major droughts each lasting more than a century. These caused many currently large lakes and rivers to dry, and salinities to increase in those that remained. In mountain regions, evidence exists for increased warmth relative to present (as much as 3°C). Shifts occurred in response to this interval, with upslope movements of mountain taxa and considerable rearrangement of vegetation communities.

About 600 years ago (1400 CE), shifts in the solar cycle resulted in return to cooler conditions, with the advent of the global Little Ice Age. Cool temperatures for this period were intensified by the coincidence of several significant volcanic eruptions that injected abundant ash into the atmosphere and by the persistence of several anomalous sunspot events. In California, the Little Ice Age triggered the largest glacial advance in over 11,000 years, and cirque glaciers in the Sierra Nevada, Cascades, and Klamath Ranges formed. The coldest part of the Little Ice Age in California was during the late 1800s and into the early decades of the 20th century. The primary effect of this period on vegetation was to dampen productivity. Forests were sparse and growth rates low, whereas high water tables and cold soils maintained extensive mountain meadows. Relative to the Medieval climatic anomaly, forest fires were generally of low severity, long duration, and broad extent across the landscape, rather than the high-intensity crown fires of earlier. Fire patterns and their consequences to vegetation were influenced in many regions by activities of Native Californians as well as climate. Upper treeline in California's mountains was distinct, and persistent snowpacks maintained significant gaps in mountain vegetation. Lake and river waters were cool and riparian corridors extensive. Species such as aspen (*Populus tremuloides*) that thrive under high soil-water tables expanded on slopes as well as along rivers and streams (riparian habitats) and in meadows.

The Little Ice Age ended about 1925 CE in California as solar cycles shifted once again, triggering warming trends and drought that are known from the 1930s and 1940s. Temperatures plateaued in the mid 20th century and began to climb sharply in the early 1970s. The impact of anthropogenic greenhouse gases became significant during these decades, compounding climatic processes and forcing conditions beyond natural variability. Vegetation dynamics of recent decades are further influenced by short natural climate cycles such as the Pacific Decadal Oscillation (~40–60 years) and the El Niño/La Niña (~2–8 year) modes. These ocean circulation oscillations stimulate alternating periods of warm-wet years with cool-dry conditions, modulating forest and grassland cycles of fuel buildup followed by vegetation dry-down and heightened fire impact. Trends that began in response to natural warming after the Little Ice Age have accelerated in recent decades, including species range and elevation shifts, forest densification, forest mortality by insects and disease, and altered fire regimes.

The present condition of California's environment and the future that is unfolding are complex expressions of natural forces intertwined with increasing anthropogenic influences. A key lesson from history is to work with change and harness inherent capacities for adaptation. That plant species have been subject to continuous change over time highlights the value of understanding natural processes as we develop conservation strategies for an uncertain future.

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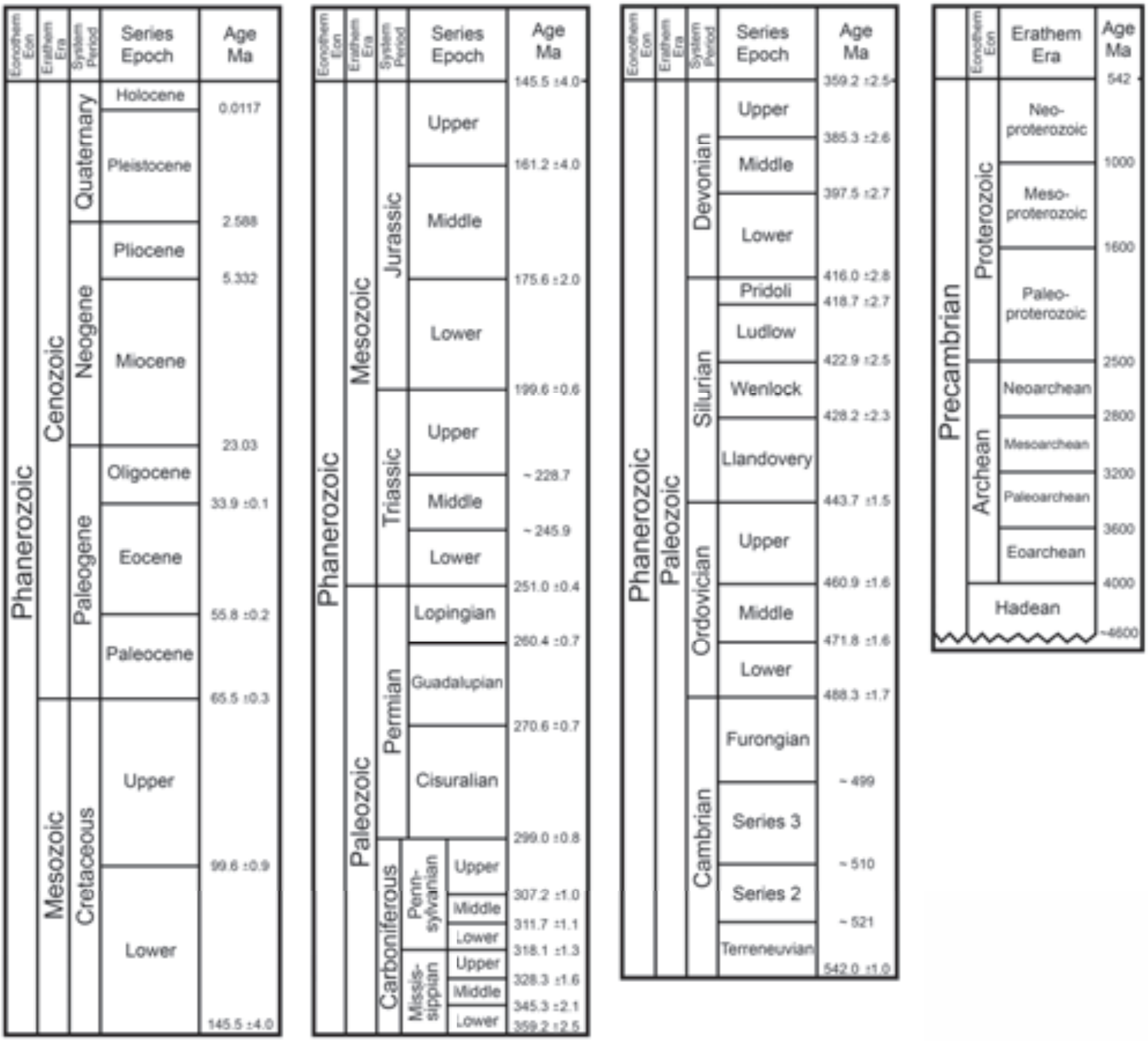
International Stratigraphic Chart

International Commission on Stratigraphy



Eonothem Eon	Erathem Era	System Period	Series Epoch	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene	0.0117
			Pleistocene	2.588
		Neogene	Pliocene	5.332
			Miocene	23.03
		Paleogene	Oligocene	33.9 ±0.1
			Eocene	55.8 ±0.2
			Paleocene	65.5 ±0.3
	Mesozoic	Cretaceous	Upper	99.6 ±0.9
			Lower	145.5 ±4.0

Eonothem Eon	Erathem Era	System Period		Series Epoch	Age Ma
					145.5 ±4.0
Phanerozoic	Mesozoic	Jurassic		Upper	161.2 ±4.0
				Middle	175.6 ±2.0
				Lower	199.6 ±0.6
		Triassic		Upper	~ 228.7
				Middle	~ 245.9
				Lower	251.0 ±0.4
	Paleozoic	Permian		Lopingian	260.4 ±0.7
				Guadalupian	270.6 ±0.7
				Cisuralian	299.0 ±0.8
		Carboniferous	Pennsylvanian	Upper	307.2 ±1.0
				Middle	311.7 ±1.1
				Lower	318.1 ±1.3
			Mississippian	Upper	328.3 ±1.6
				Middle	345.3 ±2.1
				Lower	359.2 ±2.5

Eonothem Eon	Erathem Era	System Period	Series Epoch	Age Ma
				359.2 ±2.5
Phanerozoic	Paleozoic	Devonian	Upper	385.3 ±2.6
			Middle	397.5 ±2.7
			Lower	416.0 ±2.8
		Silurian	Pridoli	418.7 ±2.7
			Ludlow	422.9 ±2.5
			Wenlock	428.2 ±2.3
			Llandovery	443.7 ±1.5
		Ordovician	Upper	460.9 ±1.6
			Middle	471.8 ±1.6
			Lower	488.3 ±1.7
		Cambrian	Furongian	~ 499
			Series 3	~ 510
			Series 2	~ 521
			Terreneuvian	542.0 ±1.0

	Eonothem Eon	Erathem Era	Age Ma
			542
Precambrian	Proterozoic	Neoproterozoic	1000
		Mesoproterozoic	1600
		Paleoproterozoic	2500
	Archean	Neoarchean	2800
		Mesoarchean	3200
		Paleoarchean	3600
		Eoarchean	4000
	Hadean		~4600

Stratigraphic Time Chart, from the International Commission on Stratigraphy (IUGS), 2009 revision