he Geologic Story of Yosemite National Park (1987) by N. King I

N. King Huber
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About the Author

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r *N. King Huber, 2004*r
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r N. King Huber was born January 14, 1926 in Duluth, Minnesota.r His interest in geology started when he hunted for agates along the Lake Superior shorline.r He served in the U.S. Army from 1944 to 1946 in Europe and Japan.r Huber married Martha Ann Barr June 2, 1951 and they had two sons.r He received a BS from Franklin and Marshall College in 1953,r and MS and Ph.D. from Northwestern University in 1952 and 1956, respectively.r In 1953 he was elected fellow of The Geological Society of America.r

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r In 1954 King Huber joined the U.S. Geological Survey in Menlo Park, Californiar as a geologist and worked there for his entire career.r Huber first visited Yosemite with his wife in 1955.r His specialties were in Yosemite National Park andr Sierra Nevada geology, geomorphology, and glacial geology.r Dr. Huber has written many professional papers on geology,r has authored several geologic maps of the Sierra Nevada,r and written books onr Isle Royale National Parkr andr r Devils Postpile National Monument geology.r

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r King Huber and his wife Martha Ann had two sons, Steven King and Richard Norman Huber.r

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r After retirement, Dr. Huber was Geologist Emeritus with the USGS,r contributed several geology-related articles to ther Yosemite Association's member publicationr *Yosemite,*r and was the *de facto* geologist for Yosemite National Park,r providing geological training for Park Service interpretive staff.r Dr. Huber died February 24, 2007.r Before his death, he completed a book,r *Geological Ramblings in Yosemite* (2007),r a collection of articles published in *Yosemite*.r

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- r N. King Huber and James B. Snyder,r "A History of the El Capitan Moraine,"r *Yosemite* 64(1):2-6 (Winter 2002).r (Yosemite: Yosemite Association, 2002)r

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- r N. King Huber,r "Yosemite Falls—A New Perspective,"r *Yosemite* 65(1):10-14 (Winter 2003).r Available online atr r *Sierra Nature Notes* 3 (March 2003)r

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Bibliographical Information

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r Norman King Huber (1926 - 2007),r *The Geologic Story of Yosemite National Park*r (Washington: Government Printing Office, 1987).r USGS Bulletin 1595.r LCCN 86600008.r Sup. of Docs no.:I 19.3:1595.r xi+64 pages. Illustrated (some color), color maps. 28 cm.r Perfect bound in paper wrappers with front color photograph.r Illustrated by Tau Rho Alpha and Susan Mayfield.r Library of Congress call number QE75.B9 no. 1595.r

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r The 1987 printing is no longer available from the USGS.r However, it wasr r reprinted in 1989 and later by the Yosemite Association.r The only changes were to the title pages and cover.r Most of the photographs in the book are available online from ther USGS library'sr photo archive.r

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r *r A comprehensiver r geologic view ofr r the natural processesr r that have created—r r and are still creating—r r the stunning terrainr r we know as Yosemite*r

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*The Geologic Story of*r r
YOSEMITE
r NATIONAL PARKr

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By N. King Huber

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U.S. GEOLOGICAL SURVEY BULLETIN 1595

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r DEPARTMENT OF THE INTERIORr
r DONALD PAUL HODEL, Secretaryr

r r

r U.S. GEOLOGICAL SURVEYr
r Dallas L. Peck, Directorr

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r **r HALF DOME AT SUNSETr** r

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r **r** ***r "On the south-east stands the majestic Mount Tis-sa-ack, or "South Dome" * * *. Almost one-half of thisr immense mass, either from some convulsion of nature, or "Time's effacing fingers,' has fallen over * * *.r Yet proudly, aye, defiantly erect, it still holds its noble head, and is not only the highest of all those around,r but is the greatest attraction of the valley."r —J. M. Hutchings, "Scenes of Wonder and Curiosity in California," 1870.r*** **r** r

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FOREWORD

Within 150 years, Yosemite has moved from great obscurity to worldwide fame as one of the most visited of our national parks. As a remarkable place where people can enjoy unparalleled scenes of natural beauty and where many easily observed geologic features are concentrated, the park is rivaled by few other areas on the planet. The majesty and immense variety of these features have inspired artists and photographers, intrigued tourists, and stirred controversy among geologists.

Field studies in the Yosemite area have contributed to the development of our ideas about geologic processes, including the different actions of streams and glaciers in the evolution of the landscape, and the formation of granite, the basic bedrock of much of the Earth's continents. The park's role as a natural laboratory for geologic research cannot be overemphasized, and its investigation has led to many landmark studies by U.S. Geological Survey geologists over the past 70 years. In 1913, the first detailed program of research on the geology of the park and the origin of Yosemite Valley was begun by François Matthes and Frank Calkins. Their work, along with that of later generations of Survey geologists, myself included, serves as the basis for our present understanding of the geologic history of Yosemite and of the processes that formed and continue to mold its landscape.

This book, which makes available in one volume a comprehensive summary of the current geologic knowledge of Yosemite National Park, is an excellent example of the Survey's continuing effort to provide earth-science information in the public service.

Dallas L. Peck
Director, U.S. Geological Survey

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YOSEMITE COUNTRY

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Creation of a park

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r For its towering cliffs, spectacular waterfalls, graniter domes and spires, glacially polished rock, and groves ofr Big Trees, Yosemite is world famous. Nowhere else arer all these exceptional features so well displayed and sor easily accessible. Artists, writers, tourists, andr geologists have flocked to Yosemite—and marveled.r
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r **r YOSEMITE NATIONAL PARK and the original grants to the State of California. (Fig. 1)r** r

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r r Although there are other valleys with similarities tor Yosemite, there is but one Yosemite Valley, the "Incomparabler Valley" of John Muir. Appreciation of Yosemiter Valley came early, and in 1864, less than 15 years afterr the general public became aware of the area's existence,r President Abraham Lincoln signed a bill that grantedr Yosemite Valley—"the 'Cleft' or 'Gorge' in the graniter peak of the Sierra Nevada"—to the State of California.r The act stipulated that "the premises shall be held forr public use, resort, and recreation; shall be inalienabler for all time." Also included in the grant was ther "Mariposa Big Tree Grove." Though not the firstr official national park, Yosemite established ther national-park concept and eventually evolved into ar national park itself. An area larger than the presentr park, surrounding but not including Yosemite Valley,r was set aside as a national park in 1890. In 1906, ther boundaries were adjusted, and Yosemite Valley and ther Mariposa Grove were re-ceded to the Federal Governmentr by California to create a unified national parkr (fig. 1).rr r

Years of Exploration

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r From the earliest days, the Sierra Nevada (Spanishr for "snowy mountain range") was a formidable barrierr to westward explorationr (fig. 2).r Running half ther length of California, it is the longest, the highest, andr the grandest continuous mountain range in the Unitedr r r r
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r **r THE SIERRA NEVADA, a strongly asymmetric mountain range with a deep east escarpment and a gentle westward slope toward the broad Central Valley of California. Physiography from landform map by Erwin Raisz: used with permission. (Fig. 2)r** r

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r r States, outside of Alaska. The central Sierra with itsr steep east escarpment is particularly awesome. Nevertheless,r in 1833, Joseph Walker led a party up ther east escarpment and westward across the range throughr Yosemite country. His route traversed the uplandr between the Tuolumne and Merced Rivers, a router later followed by the western part of the Tioga Road.r Walker and his men were probably the first of Europeanr descent to view Yosemite Valley and the Big Trees, nowr known as giant sequoias.rr r r r The Walker party's journal, recorded by Zenasr Leonard, refers to "many small streams which wouldr shoot out from under these high snow-banks, and afterr pinning a short distance in deep chasms which theyr have through ages cut in the rocks, precipitate themselvesr from one lofty precipice to another, until theyr are exhausted in rain below. Some of these precipicesr appear to be more than a mile high. * * * we foundr utterly impossible to descend, to say nothing of ther r horses. [Continuing westward] * * * we have foundr some trees of the redwood species, incredibly large—r some of which would measure from 16 to 18 fathomsr [96 to 108 ft] around the trunk at the height of a man'sr head from the ground." The trees Leonard describedr could he those either of the Tuolumne Grove or of ther Merced Grove, possibly both. The journal was printedr in Pennsylvania in 1839, but only a few copies survivedr a printshop fire, and so this account went unread tor many years.r [Editor's note:r today historians generally believe the Walker party looked down The Cascades,r which are just west of Yosemite Valley, instead of Yosemite Valley itself.—dea]r r

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r **r SUMMIT OF MOUNT HOFFMANN. Charles F. Hoffmann, cartographer with the Geological Survey of California, at the transit. Photograph by W. Harris, 1867, first published in J. D. Whitney's "The Yosemite Book" in 1868. (Fig. 3)r** r

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r Yosemite Valley and the giant sequoias remainedr unknown to the world at large for nearly another 20r years after the Walker party's discovery, until Maj.r James Savage and the Mariposa Battalion of militiar entered the valley in pursuit of Indians in 1851. Overwhelmedr by the majesty of the valley, one member ofr the battalion,r Dr. Lafayette Bunnell,r remarked that itr needed an appropriate name. He suggested Yo-sem-i-ty,r the name of the Indian tribe that inhabited it, and alsor r r r r the Indian word for grizzly bear.r r [Editor's note:r For the correct origin of the word *Yosemite* seer r "Origin of the Word Yosemite."—dea.]r r A year later, giantr sequoias were discovered anew in the Mariposa Grover and in the Calaveras Grove north of Yosemite.r

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r The history of further exploration of the Yosemiter area, and of the creation of the park itself, were wellr described byr Carl P. Russellr (1957). Of particularr geologic interest was the excursion of ther Geological Survey of Californiar to Yosemite in 1863. After visitingr Yosemite Valley, Josiah Whitney, the Director of ther Survey, accompanied by William Brewer and Charlesr Hoffmann, explored the headwaters of the Tuolumner River and named Mounts Dana, Lyell, and Maclure forr famous geologists and Mount Hoffmann for one of theirr own party. In 1867, another party from the Geologicalr Survey of California again ascended Mount Hoffmann,r accompanied by photographer W. Harris, who documentedr the scene with Hoffmann himself at the transitr (fig. 3).r Observations from these excursions, and additionalr topographic mapping by Geological Survey ofr California colleagues Clarence King and James Gardiner,r provided the first description of Yosemite Valleyr and the High Sierra that not only contained reasonablyr accurate topographic information but also was relativelyr tree from the romantic exaggeration characteristic ofr the times. The term "High Sierra," coined byr Whitneyr to include the higher region of the Sierra Nevada,r much of it above timberline, has been used by writersr and hikers ever since. Whitney and his party recognizedr abundant evidence for past glaciation in the Highr Sierra but failed to recognize the degree to whichr glaciers had modified the topography, and Whitneyr r ascribed the origin of Yosemite Valley to a "grandr cataclysm" in which the bottom simply dropped down.r

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r Indeed, most geologic processes were poorly understoodr in Whitney's day, and so numerous conflictingr interpretations soon developed regarding the origin ofr many of Yosemite's scenic features. The controversyr that arose between Josiah Whitney and John Muirr regarding the origin of Yosemite Valley reflects thisr situation. Muir's observations in the Yosemite Sierra ledr him to propose that Yosemite Valley was entirely carvedr by a glacier. However, he overestimated both the workr of glaciers and the extent of glaciation, because her believed that ice once completely covered the Sierra tor the Central Valley and beyond. Thus, Whitney andr Muir held opposing views that were both too extreme,r although Muir's ultimately proved more durable. Finally,r partly in response to this controversy, a study of ther geology of the Yosemite area was initiated in 1913 byr the U.S. Geological Survey, with François E. Matthesr studying the geomorphology and glacial geology andr Frank C. Calkins the bedrock geology. Matthes' conclusions,r particularly with respect to the relative rolesr of rivers and glaciers in sculpting the landscape, haver held up well, and his lucid descriptions and interpretationsr have enlightened many a park visitor. In the 50-oddr years since Matthes and Calkins completed theirr studies, we have gained considerably more geologicr knowledge of the Sierra Nevada; we have abandonedr some of their ideas, but we still build on their pioneeringr efforts.r

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A VIEW FROM THE TOP—MOUNT HOFFMANN

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r **VIEWS FROM MOUNT HOFFMANN.r *A*, Westerly view down wooded slopes toward California's Central Valley.r *B*, Northerly view including snow-patched Sawtooth Ridge andr Matterhorn Peak on Skyline at north edge of the park. Photographr by Tau Rho Alpha.r *C*, Easterly view, with May Lake in foreground and Tenaya Lake to right in middle distance.r Tuolumne Meadows is in wooded area to left, and Mount Dana isr highest summit on skyline beyond.r *D*, Southerly view towardr Clouds Rest in late spring, with Mount Clark on left skyline. Halfr Dome at far right center displays its northeast shoulder, in contrastr to its oft-pictured profile from Yosemite Valley's floor. Photographr from National Park Service collection.r (Fig. 4)r** r

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r Of Mount Hoffmann, William Brewer noted in hisr journal under the date June 24, 1863, that “It commandedr a sublime view and the scene is one to ber remembered for a lifetime.” In his turn, Josiah Whitneyr stated that “The view from the summit of Mountr Hoffmann is remarkably fine.”r

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r The view from Mount Hoffmann is, indeed,r remarkably fine. This peak is in almost the exact centerr of Yosemite Parkr (fig. 4),r and from its 10,850-ft summitr we can see much of the perimeter of the park, for muchr of that perimeter consists of high ridges.r

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r Looking westward from Mount Hoffmann, we seer timbered foothills disappearing into the haze of ther Central Valley of California. As we shift our viewr northward, we see the smooth contours of the foothillsr give way along the skyline to pointed and jagged peaksr of bare rock in shades of white, red, and gray. A lake-strewnr cirque, which fed the Hoffmann Glacier thatr moved down Yosemite Creek, forms the precipitousr north face of Mount Hoffmann itself.r

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r To the east, May Lake—named for Hoffmann’sr wife—is directly below and Tenaya Lake is in ther middle distance, surrounded by sheeted granite walls,r r

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r r r r which lead to a series of monolithic granite domesr between Tenaya Lake and Tuolumne Meadows—domesr that are among the most striking features of ther Yosemite landscape. On the eastern segment of ther skyline rise the highest peaks in the park: Conness,r Dana, Gibbs, Koip, and Lyell—all but Gibbs withr living glaciers. The vista to the south past Clouds Rest,r Half Dome, and Yosemite Valley has the Clark Ranger and Buena Vista Crest as the skyline backdrop. Fromr Mount Hoffmann we see the northeast shoulder of Halfr Dome, a striking contrast to the view from Yosemiter Valleyr (figs. 5, 6).rr r

r The scenic panorama from Mount Hoffmann is ar grand introduction to much of the geology of Yosemite.r The landforms of Yosemite, like landforms everywhere,r reflect the type, structure, and erosional history of ther underlying rocks. The different colors—white, red,r shades of gray—reflect different rock types. The differentr topographic shapes—spires, domes, cliffs—r reflect different rock structures and erosional histories,r especially erosion caused by glaciers. In discussing "howr best to spend one's Yosemite time,"r John Muir suggestedr "go straight to Mount Hoffmann. From the summitr r nearly all the Yosemite Park is displayed like a map."r For those who wish to take his advice, the summit isr about 3 mi from the trailhead south of May Lake, andr the elevation gain is about 2,000 ft.r

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r The landscape we see today is largely the result ofr geologic processes operating in the past few tens ofr millions of years on the parent rock. But to gain a fullr understanding of the present landscape, we must gor back many tens of millions of years more—to ther creation of the rocks themselves. Fragments of geologicr history going back hundreds of millions of years can ber read from the rocks of the park, and with additionalr data from elsewhere in the Sierra Nevada and beyond,r we can reconstruct much of the geologic story ofr Yosemite. After more than a hundred years of study,r the story is still incomplete. But then, geologic storiesr are seldom complete, and what we do know whets ourr curiosity about the missing pieces and allows a deeperr appreciation for one of our most spectacular nationalr parks. This volume is an attempt to describe ther geology of Yosemite and to explain how this splendidr landscape, centered on Mount Hoffmann, came intor being.r

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r **r Direction of view from Mount Hoffmannr**
r for panorama.r (Fig. 5)r r

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r r **r PANORAMA FROM MOUNT HOFFMANN, encompassing an easterly-facing arc between Whorl Mountain on left and Halfr Dome on right.r (Fig. 5)r** r r

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YSIOGRAPHIC GRAM ofr emite National k and vicinity. r dot, centrally ted Mount fmann.r (Fig. 6)r

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GEOLOGIC OVERVIEW

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r **r THE GEOLOGIC TIME SCALE—the "calendar" used byr geologists in interpreting Earth history. Column A, graduated inr billions of years (b.y.) and subdivided into the four major geologicr eras (Precambrian, for example), represents the time elapsed sincer the beginning of the Earth, which is believed to have been aboutr 4.5 b.y. ago. Column B is an expansion of part of the time scale inr millions of years (m.y.), to show the subdivisions (periods—r Cambrian, for example) of the Paleozoic, Mesozoic, andr Cenozoic Eras; column C is a further expansion to show particularlyr the subdivisions (epochs—Paleocene, for example) of ther Tertiary and Quaternary Periods. Some key events in the**

geologicr history of Yosemite National Park are listed alongside the columns,r opposite the time intervals in which they occurred.r r

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r **r The subdivisions of geologic time are based largely on the fossilr record; rocks of the Cambrian Period contain the earliest evidencer of complex forms of life, which evolved through subsequent periodsr into the life of the modern world. The ages (in years) are based onr radiometric dating. Many rocks contain radioactive elements thatr begin to decay at a very slow but measurable rate as soon as ther parent rock is formed. The most common radioactive elements arer uranium, rubidium, and potassium, and their decay ("daughter")r products are lead, strontium, and argon, respectively. By measuringr both the amount of a given daughter product and the amount ofr the original radioactive element still remaining in the parent rock,r and then relating these measurements to the known rates of radioactiver decay, the age of the rock in actual numbers of years can ber calculated.r (Fig. 7)r** r

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r Topographically, the Sierra Nevada is an asymmetricr mountain range with a long, gentle west slope and ar short, steep east escarpment that culminates in ther highest peaksr (fig. 2).r It is 50 to 80 mi wide andr extends in altitude from near sea level along its westr edge to more than 13,000 ft along the crest in ther Yosemite area. Geologically, the Sierra Nevada is ar huge block of the Earth's crust that has broken free onr the east along a bounding fault system and has beenr uplifted and tilted westward. This combination of upliftr and tilt, which is the underlying geologic process thatr created the present range, is still going on today.r

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r Massive granite dominates the Yosemite area andr much of the Sierra Nevada as well. Mount Hoffmannr and most of the terrane visible from it are composed ofr granite, formed deep within the Earth by solidificationr of formerly molten rock material and subsequentlyr exposed by erosion of the overlying rocks. Because of itsr massiveness and durability, granite is shaped into boldr forms: the cliffs of Yosemite and Hetch Hetchy Valleys,r r r many of the higher peaks in the park, and the strikingr sheeted domes that can form only in massive, unlayeredr rock. Although granite dominates nearly the entirer length of the Sierra, the granite is not monolithic.r Instead, it is a composite of hundreds of smaller bodiesr of granitic rock that, as magma (molten material),r individually intruded one another over a timespan ofr more than 100 million yearsr (fig. 7).r This multiplicityr of intrusions is one of the reasons why there are sor many varieties of granitic rock in Yosemite and the restr of the Sierra. The differences are not always apparentr to the casual observer, but they are reflected in sometimesr subtle differences in appearance and in differencesr in response to weathering and erosion actingr on the rocks.r

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r Layered metamorphic rocks in the foothills at ther west edge of the park and along the eastern margin inr the summit area are remnants of ancient sedimentaryr and volcanic rocks that were deformed and metamorphosedr in part by the invading granitic intrusions.r Other metamorphic rocks that once formed the roofr beneath which the granitic rocks solidified were longr ago eroded away to expose the granitic core of ther range, and only small isolated remnants are left.r r Because Yosemite is centered on this deeply dissectedr body of granite, metamorphic rocks are sparse; theyr occupy less than 5 percent of the area of the park.r

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COMMON MINERALSr IN GRANITE

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r Five minerals compose the bulk of the plutonicr rocks of Yosemite: quartz, potassium feldspar, plagioclase feldspar,r biotite, and hornblende. Quartzr and both varieties of feldspar are translucent andr appear light gray on fresh surfaces. On a weatheredr surface, the feldspars turn chalky white, whereasr the quartz remains clear gray. Feldspar crystals haver good cleavage, a property of breaking along planarr surfaces that reflect sunlight when properly oriented;r quartz has no cleavage but breaks randomlyr along curved surfaces. Biotite crystals commonlyr appear hexagonal, and their dark, brown to blackr plates can be split with a knife into thin flakes alongr one perfect cleavage directionr (fig. 8).r Hornblende isr much harder than biotite, appears very dark green tor almost black, and commonly occurs as elongate,r rod-shaped crystals. It has good cleavages in twor directions that intersect to form fine striations alongr the length of the rods, making them look like bits ofr charcoal. Other minerals are present in smallr amounts; the most distinctive is sphene (calcium andr titanium silicate), which occurs in small, amber,r wedge-shaped crystals. With a little practice, allr these minerals can be identified with a small magnifying glass.r

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r **r HORNBLENDE AND BIOTITE. Rod-shaped crystals ofr hornblende and hexagonal crystals of biotite. These large andr exceptionally well formed crystals are fromr Half Dome Granodiorite.r (Fig. 8)r** r

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r Evolution of the landscape is as much a part of ther geologic story as the rocks themselves, and Yosemite isr a place where the dynamism of geologic processes isr well displayed. By the end of Cretaceous timer (see fig. 7),r about 65 million years ago, after the granite core ofr the range had been exposed, the area had a low reliefr in comparison with the mountains of today. Then,r about 25 million years ago, this lowland area began tor be uplifted and tilted toward the southwest, a constructionr that would eventually lead to the presentr Sierra Nevada. As the rate and degree of southwestwardr tilt increased, the gradients of streams flowingr southwestward to California's Central Valley alsor increased, and the faster flowing streams cut deeper andr deeper canyons into the mountain block. About 10r million years ago, from the Tuolumne River northward,r these canyons were inundated and buried by volcanicr lava flows and mudflows, and the streams were forced tor begin their downcutting anew, in many places shiftingr laterally to find a new route to the Central Valley. Ther streams were equal to the task, however, and ther present river courses and drainage patterns throughoutr the Sierra became well established.r

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r As the world grew colder, beginning about 2 or 3r million years ago, the Sierra Nevada had risen highr enough for glaciers and a mountain icefield to formr periodically along the range crest. When extensive, ther icefield covered much of the higher Yosemite area andr sent glaciers down many of the valleys. Glacial icer quarried loose and transported vast volumes of rubble,r and used it to help scour and modify the landscape.r Much of this debris eventually accumulated along ther margins of the glaciers and in widely distributed, hummocky piles.r The greatest bulk of this debris, however,r was flushed out of the Sierra to the Central Valley byr streams swollen with meltwater formerly stored in ther glaciers as ice and released as the glaciers melted away.r

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r Although many of today's general landforms existedr before modification by glacial action, some of themr surely did not. Can you imagine the Yosemite landscaper with no lakes? Virtually all the innumerabler natural lakes in the park are the result of glacialr activity. But even these lakes are transitory, doomed tor be filled with sediment and become meadows; manyr lakes already have undergone this transformation.r Yosemite Valley itself once contained a lake.r

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r The geologic story of Yosemite National Park can ber considered in two parts: (1) deposition and deformationr of the metamorphic rocks and emplacement of ther granitic rocks during the Paleozoic and Mesozoic; andr (2) later uplift, erosion, and glaciation of the rocksr during the Cenozoic to form today's landscape.r

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r The paragraphs that follow start with a description ofr the rocks—what can be seen on excursions through ther park—granite first and in the most detail, because itr dominates the Yosemite scene. The rocks will then ber fitted into the context of a geologic history throughr which today's Yosemite evolved.r

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r **r Next: Rocksr •r Contentsr •r Previous: Mount Hoffmannr** r

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r Yosemite > Library >r Geologic Story of Yosemite >r Rocks, the building materials >r

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r **Next: Genesis of Yosemite’s rocksr •r Contentsr •r Previous: Geologic overviewr** r

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The Geologic Story of Yosemite National Park (1987) by N. King Huber

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ROCKS, THE BUILDING MATERIALS

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r Yosemite is renowned for its magnificent rockr exposures. Although granitic rocks dominate ther Yosemite scene, various metamorphic and volcanicr rocks are also present. Together, these rocks formr Yosemite's foundation.r

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Granite, Granite Everywhere

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r Granite, in the broad sense of the term, is a massiver rock with a salt-and-pepper appearance due to randomr distribution of light and dark minerals. The mineralr grains are coarse enough to be individually visible tor the naked eye.r

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r Granite is a plutonic igneous rock. There are twor types of igneous rock—plutonic and volcanic. Bothr types result from the cooling and solidification of moltenr rock, or magma. Magma originates deep withinr the Earth and rises toward the Earth's surface atr temperatures of about 1,000 °C if granitic in compositionr and of as high as 1,200 °C if basaltic—byr comparison, steel melts at about 1,430 °C. Magmar that cools and solidifies within the Earth's crust formsr plutonic rock (named for Pluto, the Roman god ofr the underworld). The slow cooling of plutonicr magma fosters the growth of individual crystals visibler to the naked eye. In contrast, magma that eruptsr at the Earth's surface, where it is known as lava,r quickly cools into volcanic rock. Thus, having insufficientr time to grow, most mineral grains in volcanicr rock are so small that a microscope is needed tor distinguish them.r

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r The plutonic terrane in the Sierra, once thoughtr simply to represent local variations in one huge massr r r r of granite, is actually made up of many individualr bodies of plutonic rock—*plutons*—that formed fromr repeated intrusions of magma into older host rocksr beneath the surface of the Earth. These plutonicr rocks, formerly deep within the Earth, are nowr exposed at the surface, owing to deep erosion andr removal of the formerly overlying rocks; they formr the monoliths and domes of Yosemite within ther lofty Sierra Nevada.r

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r **r PLUTONIC-ROCK CLASSIFICATION, showing classificationr components, the formerly used system, and the one nowr used worldwide. Red area indicates general range in compositionr of plutonic rocks, exclusive of dikes and other small bodies, in ther Yosemite area; names for rock types not occurring in the area arer omitted. Star in center of triangle indicates composition of a rockr containing equal proportions of quartz, potassium feldspar, andr plagioclase.r (Fig. 9)r** r

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–CLASSIFICATION OF PLUTONIC ROCKS–

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r Names for the more common varieties of plutonicr rocks are based on the relative proportions of quartz,r potassium feldspar, and plagioclase, as plotted on ar triangular diagram, with each corner representingr 100 percent of that constituentr (fig. 9);r other mineralsr present are ignored. The greater the percentage ofr any one of these three minerals in the rock, ther closer the rock's composition would plot to the cornerr for that mineral. A rock with equal percentages ofr the three minerals would plot in the center of ther diagram (*), and the rock would be called a granite.r Increasing the percentage of plagioclase at ther expense of potassium feldspar would move the compositionr toward the granodiorite compartment on ther triangular diagram. "Granitic rocks" are those thatr lie within the heavy-lined boundary.r

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r The rock classification used in this volume wasr adopted by an international commission in 1972 andr is now used worldwide. This classification differsr from the one previously in use and thus results inr many contradictions with the rock names in earlierr geologic writings on the Sierra Nevada. Nearly allr the granitic rocks in the Sierra previously calledr quartz monzonite fall within the granite classificationr of the present system, and quartz monzonite isr relegated to a small compartment below granite onr the triangular diagram; the old system is shown forr comparison. In some cases, rocks previously calledr quartz monzonite are now called granodioriter because of better knowledge of their actual mineralr composition.r

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r The collection of plutons in the park is part of ar larger mass of plutonic rock called the Sierra Nevadar batholith (from the Greek words *bathos,* deep, andr *lithos,* rock). Although this large mass of graniter forms the bedrock of much of the Sierra Nevada, it isr different from the range itself and originated manyr tens of millions of years before uplift, weathering,r and erosion shaped the present range. It needs to ber emphasized that the batholith is composite, a factr not perceived by the earliest geologic studies. Distinguishingr between individual plutons that representr separate episodes of intrusion and solidification ofr magma is the key to understanding the origin andr complex geologic history of the batholith. Geologistsr have mapped more than a hundred discrete masses ofr plutonic rock in the vicinity of Yosemite Nationalr Park alone, attesting to the complexity of what wasr once thought to be a relatively simple batholithicr setting. Emplacement of the Sierra Nevada batholithr at depth may have taken as long as 130 million years.r

r r

r Five minerals compose the bulk of the plutonicr rocks of the batholith: quartz, two varieties ofr feldspar (potassium feldspar and plagioclase), biotite, andr hornblende. All contain the elements silicon andr oxygen, and all except quartz contain aluminum asr well. Other constituents of the feldspars includer potassium, sodium, and calcium; greenish-blackr hornblende and the black mica, biotite, also containr magnesium and iron. Ther section on common minerals in graniter provides clues on how to identifyr these minerals.r

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r Plutonic rocks consisting chiefly of quartz and feldspar,r with only a minor amount of dark minerals, arer loosely called granitic rocks. Granitic rocks, such asr granite, granodiorite, and tonalite, differ primarily inr the relative proportions of these mineralsr (fig. 9).r Forr example, granite, in the technical sense of the term,r contains much quartz and both potassium feldspar andr calcium-rich feldspar (plagioclase). In outcrop, it isr generally difficult to distinguish the relative percentagesr t potassium feldspar and plagioclase. In the laboratory,r the feldspars can be distinguished by applying chemicalsr that stain potassium feldspar yellow, plagioclase red,r and leave quartz uncoloredr (fig. 10).r By this means, ther relative percentages of the three minerals can be determinedr easily.r

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r **r EL CAPITAN GRANITE. A, Freshly broken surface of ther rock. B, Rock surface chemically etched and stained to differentiater potassium feldspar (orange yellow), plagioclase (red), andr quartz (uncolored).r (Fig. 10)r** r

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r Granodioriter (fig. 11)r is similar to granite but containsr about twice as much plagioclase as potassiumr feldspar. Tonalite contains even less potassium feldspar.r In addition to quartz and feldspar, dark minerals, suchr as hornblende and biotite, further characterize individualr plutonic-rock types, as is commonly indicated withr modified names, such as hornblende granodiorite andr biotite granodiorite. Dark minerals are generally morer abundant where potassium feldspar is scarce, and thusr granodiorite tends to be darker than granite, and mostr tonalite even darker.r

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r **r VARIETIES OF GRANODIORITE. All these granodioritesr have about the same mineral composition but differ in texture:r Half Dome Granodiorite (A) contains large, well-formedr hornblende crystals; Sentinel Granodiorite (B) contains bothr biotite and hornblende in poorly formed crystals; Leaning Towerr Granodiorite (C) has a spotted appearance from rounded clots ofr dark minerals; and Bridalveil Granodiorite (D) has a salt-and-pepperr appearance from fine, evenly distributed light and darkr minerals.r (Fig. 11)r** r

r r

r In contrast to granitic rocks, quartz diorite, diorite,r and gabbro contain mostly plagioclase and dark minerals,r with little or no quartz or potassium feldsparr (figs.r 9, 12).r In addition, the plagioclase in gabbro containsr more calcium than the plagioclase in diorite. Suchr plutonic rocks poor in quartz are sparse in the Yosemiter area and generally occur as small, irregular masses andr dikes—sheetlike masses—of quartz diorite or diorite;r they generally are dark gray and commonly are finer grained, with few minerals readily recognizable to ther naked eye.r

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r **r DIORITE is mostly plagioclase and dark minerals, with littler**
r quartz and potassium feldspar.r (Fig. 12)r r

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r Light-colored rock, composed chiefly of quartz andr potassium feldspar, also forms irregular masses andr dikes. This rock occurs both with a fine-grained texture—*aplite*r (fig. 13)r —and with a very coarse grainedr texture—*pegmatite*—displaying large, intergrownr r r quartz and potassium feldspar crystals. A fine exampler of pegmatite is visible a short distance down ther Pohono Trail to Taft Point from the Glacier Pointr Road.r

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r **r DIKE of light-colored, fine-grained aplite crosscutting granodiorite.r**
r Aplite is a silica-rich rock composed chiefly of quartz andr
r potassium feldspar.r (Fig. 13)r r

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r Most granitic rocks contain mineral grains ofr about equal size and are said to have a granularr texture. Some granites, however, and many volcanicr rocks have crystals of one mineral considerably largerr than the others; these oversized crystals are calledr *phenocrysts* (from the Greek words meaning “tor appear” and “crystal”), and the texture of such a rockr is described as *porphyritic.* In Sierran granites, ther most common mineral to occur as phenocrysts isr potassium feldspar, in crystals commonly as much asr 2 to 3 in. longr (fig. 14).r

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r **r PORPHYRITIC TEXTURE in Cathedral Peak Granodiorite,r**
r with potassium feldspar phenocrysts much larger than ther
r other minerals in the rock matrix.r (Fig. 14)r r

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r Rounded inclusions of dark, fine-grained dioriticr material are common in granitic rocks, most commonlyr in granodiorites and tonalites. Generally pancaker or football shaped, the inclusions range in sizer from a few inches to many feet across. It is notr uncommon for all the inclusions within an area tor have their long dimensions arranged in the samer direction, like a school of fishr (fig. 15).r An excellentr example occurs at the Yosemite Falls overlook on ther north rim of the valley. The origin of these inclusionsr is uncertain. Some probably were derived fromr preexisting rock; others may be derived from globulesr of darker magma that because of their high meltingr temperature were chilled by the granitic magmar rather than being digested into it. However, ther shape of the inclusions suggests that, whatever theirr origin, they were at least partially plastic while suspendedr in the magma and that they were stretchedr and given their parallelism by movement within ther magma.r

r r

r Concentrations of dark minerals sometimes formr wavy, discontinuous streaks and layers, especiallyr near the outer margins of individual plutons. Theser layers, called *schlieren* (German for streaks), probablyr represent clustering of dark minerals early during ther crystallization of the magma, with alignment inr streaks caused by movement within the partiallyr solidified magmar (fig. 16).r The commonly abruptr termination of one set of layers by another set suggestsr repeated pulses of movement in a magma mush.r

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r **r ALIGNED DARK DIORITICr**
r INCLUSIONS in granodiorite.r
r Photograph by Dallas L. Peck.r
r (Fig. 15)r r

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r **r SCHLIEREN—streaks or layersr r formed by clustering of dark mineralsr r during differential flow within ther r partially solidified magma. Noter r parallel alignment of potassium feldsparr r phenocrysts by the same process;r r larger phenocrysts are about 2r r in. long.r (Fig. 16)r** r

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r Individual bodies of granitic rock, particularly larger ones, generally vary in mineral makeup and commonlyr overlap the boundaries between specific rock classifications.r Bodies of granitic rock may also overlap eachr ocher's compositional ranges, and so composition isr only one factor in the recognition of separate rockr r r r bodies. The chief distinguishing property may be ther presence or absence of specific minerals, such as biotite,r hornblende, or sphene. Or it may be the generalr physical appearance defined by the texture of ther rock—the size, shape, and arrangement (random orr oriented) of the mineralsr (fig. 11).r A porphyritic texturer is particularly useful because it is prevalent in onlyr a few plutons in the Yosemite area. The presence orr absence of dark inclusions may also characterize a rockr body.r

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r Knowledge of the age relations among plutons isr essential to understanding the geologic history of ther r Sierra Nevada batholith. Certain features observed inr outcrop help determine the relative ages of individualr rock bodies. For example, younger magma commonlyr shoots thin sheets, or dikes, into cracks in the olderr rocksr (fig. 17*A*).r Additionally, some of the youngerr plutons contain inclusions, or fragments of olderr rock, which were embedded in the younger rockr while it was still moltenr (fig. 17*B*).r Where darkr inclusions or other oriented structures are present,r the contact between two rock bodies may truncater structures in the older body, while similar features inr the younger rock may parallel the contactr (fig. 17*C*).r r r r Determining the absolute age of a given graniticr rock, in millions of years, requires measurement ofr the extent of radioactive decay of certain elements,r such as uranium, potassium, and rubidium. Fromr such measurements and the known rates of decay, wer can approximately determine the time elapsed sincer the rock crystallized or cooled enough to stop escaper of the daughter decay products from the rockr (see fig. 7).r

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r In their studies of plutonic rocks, geologists haver devised ways to separate individual bodies of suchr rock and to depict them on geologic maps so as tor show their relations to each other and to nonplutonicr rocks with which they are in contact. Once establishedr by field study, the boundaries of these individualr plutonic-rock bodies—plutons—can be plottedr on a map, and these rock bodies become geologicr map units. After further study, the geologist mayr decide that two or more nearby bodies of plutonicr rock exposed on the Earth's surface are similar in allr essential respects, including known or inferred age.r Even though they may not be connected at ther Earth's surface, the geologist may thus combine severalr masses of similar plutonic rock into a singler geologic map unit, inferring that they are somehowr connected below the surface and represent a singler intrusive episode. This grouping of isolated bodies ofr related plutonic rock into a single geologic map unitr is analogous to the grouping of discontinuousr exposures of similar sedimentary rock into formations,r such as the Coconino Sandstone and ther Kaibab Limestone, which are well exposed in ther Grand Canyon region. For ease of reference, ther plutonic-rock units likewise are generally named forr an appropriate geographic feature, plus a compositionalr term: for example, the El Capitan Granite, ther Half Dome Granodiorite, and the granodiorite ofr Kuna Crest.r

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r **r FEATURES SEEN IN OUTCROP that help determine ther**
r relative ages of plutonic rocks: 0, older pluton; Y, younger pluton.r
r (Fig. 17)r r

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Granitic Rocks of Yosemite

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r The plutonic rocks of Yosemite have been mappedr and studied in considerable detail. Few of those detailsr can be shown on the generalized geologic map in thisr volume (pl. 1), but ar r geologic map at a much largerr scale is availabler (Huber and others, in pressr [Editor's note:r 1989—dea]).r On thatr map, the granitic rocks of the Yosemite area are separatedr into nearly 50 different plutonic-rock units, eachr consisting of one or more individual bodies of rock. Anr even larger scale geologic map is available for Yosemiter Valley (Calkins, 1985; see section above entitledr "Geologic Maps of Yosemite").r

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r Some plutonic-rock units are further grouped intor intrusive suites. The concept underlying an intrusiver suite is that all the rocks in the suite resulted from ther same magma-producing event. Geologists are most surer of a common ancestry if the rocks in a suite grade intor each other. Such suites commonly are zoned, bothr compositionally and texturally, and generally exhibitr partial or complete nested patterns in which relativelyr dark rock in the margins gives way inward to younger,r lighter colored rock in the interior. The units thatr compose this ideal kind of intrusive suite are believed tor result from modifications of a common parent magma.r Examples include the Tuolumne Intrusive Suite, ther first intrusive suite to be identified in the Sierrar Nevada, and the intrusive suite of Buena Vista Crest.r The geologic map (pl. 1) groups most plutonic-rockr units into intrusive suites and thus provides a broaderr picture of the major pulses of plutonic activity thatr contributed to the construction of the Sierra Nevadar batholith. The more detailed geologic map of Yosemiter Valley (pl. 2) delineates not only intrusive suites butr also component units of the suites.r

r r

r All the plutonic rocks within Yosemite Nationalr Park proper are believed to be of Cretaceous age, withr the possible exception of some small bodies of dioriter and gabbro that may be somewhat older. Some Jurassicr plutonic rock does occur just west of the park, west ofr the Big Oak Flat entrance, and some Triassic plutonicr rock occurs east of the park in Lee Vining and Lundyr Canyons. These rocks are included with “Plutonicr rocks, unassigned to suites” on plate 1 and are shownr individually only on ther r larger scale geologic mapr published separatelyr (Huber and others, in pressr [Editor’s note:r 1989—dea]).r

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r Examples of many of the named rock types inr Yosemite are displayed at the Valley Visitor Center,r where they may easily be compared; they are nextr described for two readily accessible areas in the park,r Yosemite Valley and the Tuolumne Meadows area.r

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r **r BIRD’S-EYE VIEWr**
r OF YOSEMITEr
r VALLEY, with selectedr
r landforms identified.r
r (Fig. 18)r r

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YOSEMITE VALLEY AREA

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r The oldest plutonic rocks of the Yosemite Valley arear compose the walls of Merced Gorge and the west endr of the valley. They include the diorite of the Rockslides,r the granodiorite of Arch Rock, and the tonaliter of the Gateway (pl. 2). The largest outcrop of diorite isr just west of the Rockslidesr (fig. 18),r but the talus slopesr below, composed of broken blocks of diorite, are morer accessible. A good exposure of the granodiorite of Archr Rock can be seen immediately east of the Arch Rockr Entrance Station on the El Portal Road (Route 140),r where the road passes under two large fallen blocks ofr the granodiorite (park vehicles near the entrance station).r The tonalite of the Gateway can be seen alongr the El Portal Road across from the first turnout after ther road starts climbing up the Merced Gorge eastwardr from El Portal; these last two locations are west of ther map area shown in plate 2. Studies of radiometric decayr indicate that the tonalite of the Gateway is about 114r million years old. The radiometric age of the granodioriter of Arch Rock has not been determined, but itr probably is only a little younger than that of ther Gateway.r

r r

r The El Capitan Granite subsequently intruded theser older plutonic rocks about 108 million years ago andr r now makes up the bulk of the west half of the valleyr area. About 4 km east of the Arch Rock Entrancer Station, the El Portal Road cuts through blocks of Elr Capitan Granite dislodged in a 1982 rockfall. Theser blocks, some the size of a small house, display freshr surfaces of the graniter (fig. 10;r seer fig. 48),r as well asr numerous inclusions of dark-colored rock. The imposingr monoliths of Turtleback Dome, El Capitan, Threer Brothers, and Cathedral Rocks also are hewn chieflyr from massive El Capitan Granite.r

r r

r After the El Capitan Granite was emplaced, the Taftr Granite welled up and intruded the El Capitan. Dikesr of Taft Granite invading El Capitan Granite and inclusionsr of El Capitan in Taft establish the Taft asr younger. The two rocks are similar, but Taft Granite isr lighter in color and commonly finer grained than Elr Capitan Granite and, unlike El Capitan Granite, generallyr does not contain phenocrysts. Taft Granite formsr the brow of El Capitan and part of the upland betweenr El Capitan and Fireplace Bluffs. On the south side ofr the valley, Taft Granite can be seen at Dewey Point andr near The Fissures, just east of Taft Point.r

r r

r In the vicinity of Leaning Tower and Cathedralr Rocks, dikes and irregular masses of several fine-grainedr rocks cut the Taft and El Capitan Granites. Examplesr of these fine-grained rocks can be seen in blocky rubbler r r r near the base of Bridalveil Fall. The Leaning Towerr Granodiorite characteristically contains rounded clotsr of dark minerals that give it a spotted appearancer (fig. 11*C*).r The Bridalveil Granodiorite, which containsr fine, evenly distributed, light and dark minerals, hasr a salt-and-pepper appearancer (fig. 11*D*);r features seenr in outcrop show that it intruded nearly all the rocksr which it now contacts.r

r r

r Dark, fine-grained diorite also intrudes the Elr Capitan and Taft Granites. A striking example isr exposed on the east face of El Capitan, where dikesr of diorite form an irregular pattern that, in part, veryr crudely resembles a map of North Americar (fig. 19).r

r r

r The Sentinel Granodiorite forms a north-south bandr that crosses the valley between Taft Point and Glacierr Point. The rock varies in appearance but is generallyr medium gray and medium grainedr (fig. 11*B*).r Giantr inclusions of El Capitan Granite are embeddedr within Sentinel Granodiorite in a zone that extendsr along Yosemite Creek and down the face of the cliffr near Yosemite Falls. The Sentinel Granodiorite reappearsr on the south valley wall west of Union Pointr and then extends southward through Sentinel Domer to Illilouette Ridge. Dikes of Sentinel Granodioriter r r

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r **r DIORITE DIKES on the face of El Capitan; dark patch isr**
r thought by some to resemble a crude map of North America.r
r Some lighter colored dikes are also present.r
r (Fig. 19)r r

r r r r that cut inclusions of El Capitan Granite can be seenr in the roadcut along the Glacier Point Road near ther trailhead to Taft Point.rr r

r The rock at Glacier and Washburn Points is darkerr than Sentinel Granodiorite and has a streakyr appearance from parallel-oriented flakes of biotiter and rods of hornblende. This darker rock, oncer thought to be part of the Sentinel and shown as suchr on earlier geologic maps, is now assigned to ther granodiorite of Kuna Crest.r

r r

r The Half Dome Granodiorite dominates the valleyr area east of Royal Arches and Glacier Point. It isr medium to coarse grained and contains well-formedr plates of biotite and rods of hornblender (fig. 11*A*).r At

Church Bowl and in the cliff west of Royalr Arches, horizontal dikes of Half Dome Granodioriter cut the older granodiorite of Kuna Crest. Half Domer Granodiorite forms the sheer cliffs to the north ofr the trail between the Ahwahnee Hotel and Mirrorr Lake. The trail to Vernal and Nevada Falls alsor crosses through Half Dome Granodiorite. Except forr minor dikes, the Half Dome Granodiorite, about 87r million years old, is the youngest plutonic rock inr the valley area.r

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TUOLUMNE MEADOWS AREA

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r The granodiorite of Kuna Crest and the Half Domer Granodiorite exposed at the east end of Yosemite Valleyr are two plutonic-rock units that make up the westernr margin of the Tuolumne Intrusive Suite. This suiter underlies a large part of eastern Yosemite National Parkr from upper Yosemite Valley, across Tuolumne Meadowsr eastward to the crest of the Sierra, and northwardr beyond the park boundary (pl. 1). The Tuolumner Intrusive Suite, one of the best studied groups ofr granitic rocks in the Sierra, consists of four bodies ofr plutonic rock, sequentially emplaced and partly nestedr one within the otherr (fig. 20).r The suite is well exposedr in the area centered on Tuolumne Meadows, and ther Tioga Road (Route 120) provides access to many conspicuousr outcrops of the suite's components.r

r r

r The oldest and darkest plutonic rock generally formsr the margin of the suite, and the youngest rock is in itsr core. The rocks are, from oldest to youngest: ther granodiorite of Kuna Crest (about 91 million years old),r the Half Dome Granodiorite, the Cathedral Peakr Granodiorite (about 86 million years old), and ther Johnson Granite Porphyry. Field relations indicate thatr the Johnson Granite Porphyry is the youngest graniticr rock in the park, although a radiometric age has notr r r r yet been determined. The granodiorite of Kuna Crestr normally occupies the margin of the suite, but on muchr of the perimeter the Half Dome Granodiorite and ther Cathedral Peak Granodiorite have broken through ther granodiorite of Kuna Crest to form the marginal unitsr (fig. 20).r

r r

r The overall concentric zonation of rock bodiesr within the suite, as well as the overall chemical similaritiesr among the rocks, suggests that these rocksr originated from the same magma chamber. This inferredr common parentage provides the rationale for groupingr these rocks into an intrusive suite. The compositionr of the magma, however, changed over time: the older,r hornblende- and biotite-rich rocks at the margins giver way to quartz- and potassium feldspar-rich rocks towardr the center. Hornblende and biotite crystallize at higherr temperatures than quartz and feldspar, and so duringr cooling of a magma, these dark minerals generallyr crystallize earlier than the light-colored ones. Thisr relation suggests that cooling of the magma started atr the margins and progressed inward over time.r

r r

r North of the Tioga Pass Entrance Station, the trailr to Gaylor Lakes crosses over the granodiorite of Kunar Crest, the oldest and darkest rock in the Tuolumner Intrusive Suite. This trail weaves back and forth nearr the contact between the granodiorite and the metamorphicr rocks that it intruded. The granodiorite alsor contains many disc-shaped inclusions that are orientedr parallel to its contact with the older metamorphicr rocks. These inclusions were probably stretched andr oriented by movement within the magma during intrusionr and cooling.r

r r

r The Half Dome Granodiorite, the next youngestr rock in the suite, is in contact with the granodiorite ofr Kuna Crest to the west along the ridge crossed by ther Gaylor Lakes Trail. The best exposures of the Halfr Dome, however, are surrounding the turnout atr Olmsted Point west of Tenaya Lake. Fresh, clean outcropsr of the rock abound at and across from ther turnout. Half Dome Granodiorite makes up much ofr the southwestern part of the Tuolumne Intrusive Suiter and in several areas is the marginal rock.r

r r

r Heading east toward Tuolumne Meadows, the Tiogar Road crosses the contact between the Half Domer Granodiorite and the Cathedral Peak Granodiorite justr east of Tenaya Lake. The contact is obscure, however,r because here the Half Dome contains nearly as manyr potassium feldspar phenocrysts as does the youngerr r r r

r r r

r **r EVOLUTION OF THE TUOLUMNE INTRUSIVEr**
r SUITE—a map view.r
r (Fig. 20)r r

r r r r r r Cathedral Peak. Pothole and Lembert Domes, bothr marginal to the meadows, are composed entirely ofr Cathedral Peak Granodiorite. The rock of these domesr clearly displays potassium feldspar phenocrysts, commonlyr as much as 2 to 3 in. longr (fig. 14).r Theser impressive crystals stand out against a medium-grainedr background. The Cathedral Peak Granodiorite formsr the largest pluton of the Tuolumne Intrusive Suite,r extending long distances to the north and south ofr Tuolumne Meadows.rr r

r The youngest, smallest, and most central rock bodyr if the suite is composed of the Johnson Granite Porphyry.r In a *porphyry,* the conspicuous phenocrysts arer set in a finer grained matrix than in such porphyriticr rocks as the Cathedral Peak Granodiorite, and sor individual mineral grains in the matrix are difficult tor identify without a microscope. Low outcrops of ther porphyry can be seen in Tuolumne Meadows alongr the Tuolumne River, across from the store, and eastr of Soda Springs on the north side of the river. Ther rock is very light colored, with only a few scatteredr potassium feldspar phenocrysts within a fine-grainedr matrixr (fig. 21).r Dikes of Johnson Granite Porphyryr intrude Cathedral Peak Granodiorite, and the porphyryr itself is cut by light, fine-grained aplite dikes.r

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r **r JOHNSON GRANITE PORPHYRY, showing potassiumr**
r feldspar phenocrysts set in a fine-grained matrix.r
r (Fig. 21)r r

r r

r The fine-grained matrix of a porphyry requires thatr r partially crystallized magma be quenched or cool relativelyr quickly. Such conditions would result from ar sudden release of pressure, as would occur if some ofr the magma were erupted at the Earth's surface. Thus,r volcanic eruptions probably accompanied finalr emplacement of the Tuolumne Intrusive Suite—a volcanicr caldera may once have existed far above what isr now Johnson Peakr (fig. 22).r r r
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r **r FINAL STAGESr IN THE EVOLUTIONr OF THEr TUOLUMNE INTRUSIVEr SUITE.r The Johnson Granite Porphyryr intrudes the Cathedralr Peak Granodioriter and erupts through a volcanicr caldera, spewingr volcanic ash and debrisr onto the Earth's surface.r The volcanic deposit andr much of the underlyingr rock are subsequentlyr removed by erosion tor create today's land surface.r (Fig. 22)r**
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METAMORPHIC ROCKS—ANCIENTr SEDIMENT AND LAVAS

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r Metamorphic rocks are derived from preexistingr rocks by mineralogic and structural changes in responser to increases in temperature, pressure, and shearingr stress at depth within the Earth's crust. In the Sierrar Nevada, some of this heat and pressure was supplied byr the intruding granitic rocks, but much of it wasr imposed simply by depressing sedimentary and volcanicr rocks once exposed at the Earth's surface downward tor depths where higher temperature and pressure are ther normal environment. The metamorphic rocks in ther Yosemite area were derived from a great variety ofr sedimentary and volcanic rocks and thus exhibit a greatr variety in themselves. Some rocks have been onlyr mildly metamorphosed and still retain original structures,r such as sedimentary layering, that help to identifyr the nature of the original rock. Others have beenr so strongly deformed and recrystallized that originalr textures and structures have been destroyed, and determinationr of the original rock type is difficult.r

r r

r Metamorphosed sedimentary rocks in the Yosemiter area include rocks that were originally sandstone andr siltstone, conglomerate, limestone, shale, and chert.r Metamorphosed volcanic rocks in the Yosemite arear include those derived from lava flows and various typesr of pyroclastic rocks—those formed from violentlyr erupted volcanic debris.r

r r

r The rocks into which the Sierra Nevada batholithr was emplaced are weakly to strongly metamorphosed,r mildly to complexly deformed strata of probable Paleozoicr and Mesozoic age. In the Yosemite area theser metamorphic rocks occur in two northwest-trendingr belts situated largely east and west of the park properr and in small isolated bodies scattered throughout ther park. Fossils are scarce, and the radiometric ages ofr most of these rocks are poorly known.r

r r

r Rocks of the western metamorphic belt underlier much of the foothills of the western Sierra between ther San Joaquin and Feather Rivers, and form the westernr wallrocks of the Sierra Nevada batholith. In the canyonr of the Merced River approaching Yosemite onr Route 140, strikingly banded chert is exposed in ther vicinity of the “geological exhibit” and eastward forr several milesr (fig. 23).r This banded chert was formedr from the skeletons of very tiny, silica-secreting mariner animals called radiolarians; upon the death of suchr animals, their skeletons settle to the ocean bottom,r where they collect in enormous numbers. Although ther chert beds are moderately to strongly deformed, ther r r
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r **r CONTORTED CHERT BEDS along the Merced River westr r of El Portal are ancient marine sediment that has beenr r metamorphosed.r (Fig. 23)r** r

r r r r r rock is easily recognizable as of sedimentary origin. Inr contrast, metamorphic rocks just west of El Portal andr just west of Crane Flat along the Big Oak Flat Roadr (Route 120) have a metamorphic layering that largelyr destroys original bedding, and the origin of these rocksr as sediment is less obvious. Fossils in a limestone bedr just west of the “geological exhibit” on Route 140r indicate a Triassic age for at least some of the rocksr exposed along this part of the Merced River canyon.rr r

r The eastern belt of metamorphic rocks extends forr about 50 mi from south of Mammoth Lakes to north ofr Twin Lakes (pl. 1). Furthermore, rather than boundingr the batholith, this belt is a giant septum of metamorphicr rocks separating plutonic rocks on either side.r

r r

r This eastern belt includes rocks of both sedimentaryr and volcanic origin, which range in age from earlyr Paleozoic to late Mesozoic. The Paleozoic rocks arer metasedimentary and include such varieties asr quartzite, metaconglomerate, and marble. The commonestr rock, however, is homfels—a catchall term forr a fine-grained metamorphic rock composed of a mosaicr of equidimensional grains formed by recrystallization ofr sedimentary and volcanic rocks of various compositions.r These Paleozoic rocks are well exposed alongr Route 120 near Ellery Lake east of Tioga Pass.r

r r

r The Mesozoic rocks of the eastern metamorphic beltr are chiefly of volcanic origin—tuff and otherr explosively ejected fragmental volcanic rock—withr lesser amounts of sedimentary rock. These Mesozoicr rocks, which lie generally west of the Paleozoic rocks inr the eastern metamorphic belt, make up the Ritterr Range and the southeastern margin of the park, andr r r r much of the Sierran Crest northward through Kunar Peak, Mount Dana, Gaylor Peak, and continuing northr of the park beyond Twin Lakes (pl. 1). Relict sedimentaryr bedding is commonly preserved—steeply dipping,r as west of Saddlebag Lake, or highly contorted, as nearr Spotted Lakes at the south end of the parkr (fig. 24).r

r r

r Of particular interest are the little-deformed metamorphicr rocks of Cretaceous age. Metamorphosed volcanicr rocks near the summit of Mount Dana have ar radiometric age of about 118 million years, and thoser from the Ritter Range of about 100 million years,r which means that their eruption from volcanoesr occurred at the same time that some of the smallerr plutonic-rock suites were emplaced at depth. In ther Ritter Range, a thick deposit of volcanic breccia hasr been interpreted as resulting from collapse of anr ancient volcanic caldera.r

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r **r METAMORPHIC ROCKS with relict sedimentary bedding.r A, Steeply dipping, as northwest of Saddlebag Lake. B, Highlyr contorted, as near Spotted Lakes. Photograph by John P. Lockwood.r (Fig. 24)r** r
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Late Cenozoic Volcanic Rocks—r Born of Fire

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r Volcanic rocks, like their plutonic counterparts, arer also classified on the basis of composition. Becauser volcanic rocks erupted onto the Earth's surface cool andr solidify more quickly than plutonic rocks, they tend tor be finer grained or even glassy, with few mineralsr identifiable to the eye. Those few visible minerals,r however, are guides to the rock's composition. Later Cenozoic volcanic rocks in Yosemite have a very limitedr range in composition; they generally contain littler or no quartz and range from basalt and andesite (containingr little or no potassium feldspar) to latite (containingr both potassium and plagioclase feldspar). Ar volcanic rock containing quartz—rhyolite—does occurr just east of Yosemite at the Mono Craters.r

r r

r Late Cenozoic volcanic rocks of the Yosemite arear formed both by the eruption of vast volumes of lavar and by much smaller eruptions. The products of greatr eruptions extend into the northern part of the park butr are much more extensive in the northern Sierra; theyr include lava flows, tuff, and volcanic mudflows. Detailsr of the nature and distribution of all these volcanicr rocks are deferred to ther <u>section dealing with the later Cenozoic</u>.r

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PLATE TECTONICSr A DYNAMIC GLOBE

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r **r The Earth is generally depicted as consisting of ar series of concentric shells—a relatively thin outerr *crust,* an intermediate *mantle,* and an interior corer (<u>fig. 25</u>).r The Earth's crust and uppermost part of ther upper mantle together form the rigid outer part of ther Earth—the *lithosphere*—which is broken into platesr that ride over a less rigid, viscous layer within ther upper mantle that yields plastically. There are sevenr very large plates, and a dozen or so small onesr (not all of which are shown in <u>fig. 26</u>.)r The large platesr consist of both oceanic and continental portions; ther present North American plate, for example, includesr not only the North American Continent but Greenlandr and the west half of the North Atlantic Oceanr as well. The crust beneath continents is typically 20r to 34 mi thick and is less dense than the crustr beneath oceans, which typically is only 4 to 5 mir thick. The plates generally are internally rigid, andr most dynamic geologic activity is concentratedr along the plate boundaries; these boundaries arer marked by long, narrow belts of earthquake andr volcanic activity.r** r

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r **r Each of the plates is moving relative to all ther others. In the simplest mode, two plates slide pastr each other along a**

r **r INTERIOR OF THE EARTH, showing relation ofr r crust andr mantle to the rigid lithosphere—the stuff**

strike-slip faultr (fig. *27A*).r The Sanr Andreas fault, running much the length of Californiar and forming part of the present boundary betweenr the North American and Pacific plates, is an example.r Where plates move away from each other, primarilyr along the system of great submarine ridgesr in the world's oceans, hot material wells up fromr below to fill the gapr (fig. *27B*).r As this hot materialr cools to form basalt, it becomes attached to ther plates on either side of the spreading zone, and newr crust is created. Where plates converge, one tipsr downward and slides beneath the other—a processr called *subduction*r (fig. *27C*).r Generally, a plate withr dense oceanic crust slides beneath one with morer bouyant continental crust. Thus, new oceanic crustr created at spreading centers is recycled back intor the Earth's interior through subduction, and and ther total surface area of the Earth remains unchanged.r r

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r which the mobiler plates are made.r (Fig. 25)r r

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r **r MAJOR LITHOSPHERE PLATES OF THEr WORLD, showing boundaries that are presently active. Doubler One, zone of spreading, from which plates are moving apart;r barbed line, zone of underthrusting (subduction), where one plater s sliding beneath another—barbs on overriding plate; single line,r strike-slip fault, along which plates are sliding past one another.r Seer figure 27r for examples of plate motions.r (Fig. 26)r** r

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r **r THREE PRINCIPLE KINDS OF PLATE MOTION.r A, The plates slide past each other along a strike-slip fault. B,r The plates move away from each other at a divergent boundary. C,r The plates move toward each other at a convergent boundary; ther process of subduction consumes crust at convergent plate boundaries.r (Fig. 27)r** r

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r **r Next: Genesis of Yosemite’s rocksr •r Contentsr •r Previous: Geologic overviewr** r

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r http://www.yosemite.ca.us/library/geologic_story_of_yosemite/rocks.htmlr

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GENESIS OF YOSEMITE’S ROCKS

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r The geologic story of Yosemite as presented up tor this point has been largely a description of the rocks asr we see them now. But how did they get this way? Andr when? The search for answers to these questionsr involves interpretation of geologic observations made inr Yosemite and elsewhere in the Sierra Nevada, togetherr with numerous inferences based on accumulated geologicr knowledge and on theoretical concepts. Somer parts of the geologic history can be deciphered withr confidence and in considerable detail, but other partsr are less complete because the geologic data are veryr spotty.r

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A Single Quiet Plate—r The Paleozoicr

r r

r The framework within which most geologists todayr view geologic processes, such as the creation ofr batholiths and the building of mountains, is that of ther theory of *plate tectonics* (see section above entitledr “Plate Tectonics — * * *”). Tectonics is the study ofr the deformation of earth materials and the structuresr resulting from that deformation. The “tectonics” inr plate tectonics refers to deformation and structure onr a global scale.r

r r

r The oldest rocks in the Yosemite area were derivedr from sediment deposited during early Paleozoic time,r beginning about 500 million years ago. During ther Paleozoic, the area that was to become Yosemite wasr near the west edge of the growing North Americanr Continent. The setting, for the most part, was ar relatively passive one. Paleozoic sediment derived byr erosion of still older rocks to the east was deliveredr by ancient streams flowing westward to a sea alongr the continental margin. Deposition of such sedimentr throughout most of the Paleozoic, though not necessarilyr continuous, resulted in the accumulation ofr thousands of feet of mud and sand, which eventuallyr consolidated into shale and sandstone. Plant andr animal life in the sea contributed their part byr depositing calcium carbonate and silica, later tor become beds of limestone and chert.r

r r

r During the Paleozoic, the continent and its adjacentr sea appear to have been traveling together on ar single plate. All was not totally passive, however,r because there is evidence for folding and deformationr r of some early Paleozoic strata during the late Paleozoic.r It is not possible to relate such deformationr to specific plate-margin tectonics because of severer overprinting by later tectonic events. By the end ofr the Paleozoic the geometry at the west edge of ther North American plate had changed, and an oceanicr plate was now underriding, or being subductedr beneath, the North American plate.r

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r A Time of Fire and Upheaval—r The Mesozoicr

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r The presence of a subduction zone along the westr margin of the North American plate had profoundr effects on that plate. As the cool oceanic plate wasr subducted, the overriding continental plate wasr deformed. But more important to the Yosemite storyr were the igneous effects of subduction. Wherever convergentr plate margins and subduction zones are presentr today, magma is generated at depth, and linear belts ofr volcanoes form atop the overriding plate, parallel to ther subduction zone. Mount St. Helens, for example, andr other volcanoes of the Cascade Range lie parallel to anr active subduction zone that extends from northernr California to Canada, and we infer that ancient subductionr zones produced similar belts of igneous activity.r

r r

r We can only speculate as to the nature of ther physical and chemical processes that take place withinr a subduction zone. A prevalent theory is based onr experiments indicating that the presence of waterr lowers the melting temperature of rock materials. Thisr theory holds that water entrapped in the descendingr slab of oceanic crust is driven out as the slab reachesr higher temperatures and leaks upward into the overridingr lithosphere, where partial melting resultsr (fig. 28).r r Magma generated in the mantle part of the lithospherer has the composition of basalt or andesite, but as ther magma rises into the continental crust, a more silicicr magma may be generated—one with the compositionr of rhyolite or granite. After rising toward the Earth'sr surface, this silicic magma may erupt as rhyolite volcanoes,r or cool and come to rest as great bodies ofr granitic rock within the upper crust. Most geologistsr now believe that this is the mechanism—greatly simplifiedr here — through which the Sierra Nevadar batholith was generated and emplaced.r

r r

r By early Mesozoic time, more than 200 million yearsr ago, magma reached the Earth's surface in a belt ofr volcanoes and spewed forth to form great volumes ofr volcanic rock, metamorphosed remnants of which arer now exposed in the area of the Sierran crestr (pl. 1).r Byr r r r this time, silicic magma had also formed, some ofr which cooled and solidified below the Earth's surface tor form bodies of granitic rock; one such body is nowr exposed in Lee Vining Canyon (intrusive suite ofr Sheelite,r pl. 1).r Subduction along the margin of ther North American plate was not continuous during ther Mesozoic, and subsequent movement of granitic magmar into the upper crust was somewhat episodic; the greatestr volumes were emplaced during the middle Jurassicr and Late Cretaceous. By the beginning of ther Cenozoic, the magmatic system in the Sierran regionr shut off, leaving behind the mass of granitic rock wer now call the Sierra Nevada batholith.r

r r

r Emplacement of plutonic rocks within the upperr crust was probably accompanied by many contemporaneousr volcanic eruptions at the Earth's surface. Evidencer in the Yosemite area for such eruptions includesr the texture of the Johnson Granite Porphyryr (fig. 21)r and similar porphyries in other intrusive suites, and ther 100- to 118-million-year ages of the volcanic rocks nearr Mount Dana and in the Ritter Range. In addition,r volcanic eruptions associated with emplacement of ther Sierra Nevada batholith and other contemporaneousr batholithic complexes - now exposed along the westernr margin of the North American

Continent provide ther only apparent source for the extremely voluminousr deposits of Cretaceous volcanic ash to the east in ther continental interior.r

r r

r Not all of the oceanic plate was being subductedr during that time, however. Parts of that plate, particularlyr the upper layer of marine sedimentary rocks onr the oceanic crust, were added, or accreted, to ther leading margin of the overriding continental crust. Ther handed chert in the Merced River canyon west of Elr Portal, once part of an ocean floor, was added to ther North American plate by such a process.r

r r

r The end result of the intrusion of the batholith, ther construction of volcanoes, and the deformation of ther metamorphic rocks was a linear mountain range parallelr to and inboard of the continental margin. Thisr r range has been referred to as the ancestral Sierrar Nevada. Mountains are born, only to be worn down byr erosion; and erosive forces begin to act even as ther mountains are being upraised. Nevertheless, ther ancestral Sierra probably reached elevations abover 13,000 ft, similar to those in the Cascade Range inr western Washington and Oregon, a range being constructedr over an active subduction zone today.r

r r

r What caused magmatism in the Sierra to ceaser during the late Mesozoic? Many geologists speculater that the subducting oceanic slab speeded up and flattenedr out, so that the zone of magma generationr shifted eastward. Although there are no giantr batholiths in Nevada, many bodies of granitic andr volcanic rock occur there that are chiefly of Cenozoicr age, younger than the Sierra Nevada batholith.r

r r

r Once the magmatic construction of the ancestralr Sierra Nevada ceased, erosion became the dominantr force in shaping the range, mostly by removing it.r Before the end of the Mesozoic, some 63 million yearsr ago, the volcanoes had largely been removed, and ther batholith itself was exposed and being eroded. Sedimentr derived from this erosion was transported byr streams coursing down the slope of the range to ther Central Valley, where it now forms deposits as much asr tens of thousands of feet thick. By middle Cenozoicr time, so much of the range had been removed that itr had a relief of only a few thousand feet or so.r

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r **r SUBDUCTION OF AN OCEANIC PLATEr during convergence with a continental plate.r Magma, formed by partial melting of overridingr continental plate, rises into continental plate to formr volcanoes and plutons along a mountain chain.r (Fig. 28)r** r

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r The Sierra Grows Again—r The Late Cenozoicr

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r During early Cenozoic time the Sierra Nevadar region was relatively stable, and the range continued tor be worn down faster than it was rising. But during ther late Cenozoic, from about 25 to 15 million years ago, ar dramatic change in plate motion along the edge of ther North American plate occurred, with far-reachingr effects. The oceanic plate that was being subductedr beneath the Sierra Nevada was totally consumed intor r r r r the subduction zone, and the plate that replaced it wasr moving in a different direction—northwesterly. Ther boundary between the North American plate and thisr northwesterly-moving plate, called the Pacific plate,r became a strike-slip fault along this segment of California—r the San Andreas faultr (fig. 26).r

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r This change in plate-boundary motion, from convergencer to lateral motion, caused a change in ther pattern of stresses imposed on the Sierran region. Ther continental crust east of the Sierra began to expand inr an east-west direction, and the thick, light-weightr Sierran crust began to rise again. The exact mechanismr of this uplift is not understood, but the results are therer to see. In the Yosemite area, the Sierra is clearly anr uptilted block of the Earth's crust, with a long sloper westward to the Central Valley and a steep escarpmentr separating it from the country to the eastr (fig. 29).r Total uplift in the vicinity of Mount Dana during later Cenozoic time to the present is estimated at aboutr 11,000 ft.r

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r The uplift began slowly and accelerated over time.r The range certainly is still rising—and the rate mayr still be accelerating. The estimated current rate of upliftr at Mount Dana, less than 1 1/2 inches per 100 years, mayr appear small, but it is greater than the overall rate ofr smoothing off and lowering of the range by erosion.r Thus, there is a net increase in elevation. Estimates ofr uplift amount and rate are based on studies of lava flowsr and stream deposits thought to be nearly horizontalr when formed, but which are now tilted westwardr toward the Central Valley. Progressive tilt is indicatedr by older deposits with greater inclinations than youngerr ones.r

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r François Matthes inferred from his studies that ther late Cenozoic uplift occurred in a series of three pulses,r interrupted by pauses in uplift. In his view, each pulser initiated a new cycle of erosion and thus produced ar stage of landscape incision characterized by successivelyr greater relief: Matthes' broad-valley, mountain-valley,r and canyon stages. More recent studies show thatr r

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r **r UPLIFT AND TILT of the Sierran block, with eastr r escarpment formed along fault. Arrows show direction ofr r movement on fault.r (Fig. 29)r** r

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r r fortuitous correlation and the commonly local controlr of erosion weaken Matthes' case for three distinct pulsesr of uplift. This does not mean that the uplift wasr entirely uniform—few things in geology are—butr rather that uplift, once initiated, was more nearlyr continuous than he envisioned.rr r

r At the same time that the Sierra was undergoingr uplift and erosion and incision by streams, volcanoesr again became active in parts of the range, particularlyr north of Yosemite. During the interval from about 20r million years ago to about 5 million years ago, vastr volumes of volcanic material were erupted from a beltr of volcanoes extending along what is now the Sierranr crest north of Yosemite. These volcanoes were ther southward extension of the Cascade Range of volcanoesr still active in northern California, Oregon, and Washington.r With the advent of the San Andreas strike-slipr fault, the subduction complex associated with Cascader volcanism migrated northward, and the Sierran volcanoesr turned off. Lassen Peak in northern California isr the southernmost volcano of this chain that is stillr active.r

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r During this late Cenozoic volcanism, the Sierrar Nevada north of Yosemite was virtually buried by lavar flows, volcanic tuff, and volcanic mudflows. The volcanicr material traveled great distances. Much of itr reached the margin of the Central Valley, and some ofr it traveled as far south as the northern part of Yosemite.r Three separate units of this volcanic extravaganza—ar mudflow, a lava flow, and a volcanic tuff—successivelyr flowed down the valley of a south-flowing tributary ofr the ancestral Tuolumne River and into the main channelr in the vicinity of Rancheria Mountain northeast ofr Hetch Hetchyr (figs. 30, 31).r Erosional remnants of ther volcanic mudflow indicate that it flowed almost as farr west as Groveland, some 20 mi west of the park. Otherr erosional remnants of this mudflow indicate that it wasr so thick that it actually flowed upstream along ther ancestral Tuolumne River at least 5 mi above ther junction of the south-flowing tributary.r

r r

r Other volcanic rocks in Yosemite represent localr eruptive events. One such event is recorded by a basaltr plug—a solidified remnant of lava in a volcanic conduit—r locally known as "Little Devils Postpile" andr located on the south side of the Tuolumne River severalr miles west of Tuolumne Meadows. The outcrop, easilyr reached by the Glen Aulin trail, exhibits crudelyr developed columnar jointsr (fig. 32).r This basalt is aboutr 9 million years old.r

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r **r ANCIENT CHANNEL OF THE TUOLUMNEr RIVER on Rancheria Mountain northeast of Hetchr Hetchy. The river flowed westward away from the viewerr into the V-shaped notch cut into granite in the center of ther photograph. About 10 million years ago, the channel andr about 50 ft of river gravel were buried beneath a volcanicr mudflow, the material seen on the slope above the "V". Itsr cross section now exposed by erosion, this ancient channelr was first described as such by Henry W. Turner, who tookr this photograph about 1900.r (Fig. 30)r** rr

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r **r VOLCANIC MUDFLOW DEPOSIT onr Rancheria Mountain. Brown, smooth-appearingr slope to the right, at middle distance, is underlain byr a volcanic mudflow deposit filling an ancient streamr channel. This photograph, which is another view ofr the channel inr figure 30,r shows its position on ther slope above Piute Creek, which drains away from ther viewer to the present canyon of the Tuolumne Riverr in the background. The former Tuolumne Riverr flowed from left to right into the base of the brownr area, concealed by trees in the center of the photograph,r and at** r **this point was more than 1,500 ftr above the present canyon of the Tuolumne. Thisr difference in elevation indicates the amount of streamr incision by the Tuolumne River since its former channelr was filled and abandoned and the river wasr forced to cut a new one. Photograph by Clyder Wahrhaftig.r (Fig. 31)r** r

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r **r COLUMNAR JOINTS in a basalt plug—a remnant of ar r volcanic conduit—at “Little Devils Postpile,” adjacent to ther r Tuolumne River west of Tuolumne Meadows.r (Fig. 32)r** r

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r One small lava flow of basalt, about 3 1/2 million yearsr old, was erupted just south of Merced Pass, and a fewr r scattered flows of similar age lie just south and southeastr of the park. These flows record the most recent igneousr activity in Yosemite.r

r r

r Things have not remained quiet east of Yosemite,r however. A cataclysmic eruption about 700,000 yearsr ago created 10- by 20-mi-wide Long Valley caldera,r within which now sits the town of Mammoth Lakes.r This eruption spewed forth 2,500 times as much ash asr the 1980 Mount St. Helens eruption; layers of the ashr from Long Valley caldera have been found as far east asr Nebraska. Volcanic rocks of Mammoth Mountain andr the basalt at the Devils Postpile were erupted subsequently.r The Mono Craters and Inyo domes betweenr Mono Lake and Mammoth Lakes have been eruptingr episodically during the past few thousand years, and ther most recent domes were formed only about 600 yearsr ago. Such activity is almost certainly not yet finished.r r r r

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r **r Next: Final evolutionr •r Contentsr •r Previous: Rocksr** r

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FINAL EVOLUTION OF THE LANDSCAPE

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r The Role of Jointsr

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r The bedrock structures having the greatest effects onr Yosemite's landform development are joints. Joints arer more or less planar cracks commonly found as sets ofr parallel fractures in the rock. Regional-scale jointsr commonly determine the orientation of major featuresr of the landscape, whereas outcrop-scale jointsr determine the ease with which rock erodes. Jointsr are of overwhelming influence on landform developmentr in granitic terrane because they form greatlyr contrasting zones of weakness in otherwise homogeneous,r erosion-resistant rock and are avenues ofr r access of water and air for weathering. In metamorphicr rocks, such planar structures as bedding orr aligned minerals commonly determine the orientationr of fractures.r

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r **r REGIONAL JOINTSr emphasized by vegetation, asr seen on an aerial photograph—r Yosemite Creekr basin north of Yosemite Valley.r Northeast-trending jointr set is more closely spacedr than northwest-trending set.r Sparser, east-west-trendingr set is also present. Accompanyingr sketch map showsr orientation of major jointsr and illustrates the significantr control of stream courses byr joints.r (Fig. 33)r** r r r

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r A regional system of widely spaced master joints isr conspicuous throughout the granitic terrane, particularlyr in the High Sierra where rock exposures arer extensive. These joints generally are nearly verticalr and are not to be confused with the gently dippingr sheet joints that are subparallel to topographic surfaces.r Linear depressions commonly follow the masterr joints, and even in highly dissected regions, straightr segments of streams are joint controlled. Generally,r two principle sets of joints can be identified nearly atr right angles, one set commonly trending northeastr and the other northwestr (fig. 33).r The orientationr changes from place to place, but most joints arer straight or only gently curved. Some individual jointsr can be traced for many miles. The continuity of jointr sets across the boundaries between individual graniticr plutons indicates that the joints formed after consolidationr of the entire batholith and thus are notr cooling fractures of the individual bodies. Ther regional joint system evidently resulted from stressesr imposed on the batholith during later tectonicr events, such as tilting of the Sierra region.r

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r Some movement other than simple opening alongr the joint planes has probably taken place along most ofr the master joints. Such lateral, or fault, movement,r even though slight, would crush or break rock alongr the joint. Deep weathering and erosion along theser Danes of broken rock form long, linear depressions,r many of them now channels for streams. Areas ofr granite within blocks bounded by master joints arer themselves jointed to a lesser degree hut remain morer r cohesive and form the bolder areas between masterr joints.r

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r **r INCLINED JOINTS determine westward slope of upper surfacesr**
r of the Three Brothers. Photograph from National Parkr
r Service collection.r (Fig. 34)r r

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r **r STAIRCASE FALLS. Stairtreads follow joints inclinedr**
r eastward.r Photograph by Tau Rho Alpha.r (Fig. 35)r r

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r On a more local scale, vertical joint sets are responsibler for the orientation of major features, such as ther planar face of Half Dome and the series of parallel cliffsr at Cathedral Rocks. An individual cliff face itself mayr not be the original controlling joint surface, becauser material is continually spalling off, but its orientation isr controlled by a preexisting joint.r

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r Although vertical master joints prevail, inclinedr joint sets have added to the diversity of Yosemite'sr landforms. The west faces of the Three Brothers inr Yosemite Valley were largely determined by a set ofr master joints that slope about 45° westwardr (fig. 34).r The slope between Cathedral Rocks and Bridalveilr Creek also follows a set of westward-inclined joints.r The stairtreads of Staircase Falls follow east-dippingr jointsr (fig. 35).r

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r **r RECTANGULAR BLOCKS formed in El Capitan Graniter**
r by intersecting joints.r (Fig. 36)r r
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r At outcrop scale, two nearly vertical joint sets,r perpendicular to each other, combine with nearly horizontalr r r r r joints to create approximately rectangular blocksr (fig. 36).r Generally, the more siliceous, or quartz-rich,r rocks (granite and granodiorite) have more widelyr spaced joints than the less siliceous rocks (tonalite andr diorite). Also, the finer grained rocks generally haver more closely spaced joints than the coarser grainedr ones. Thus, both composition and texture influencer the spacing of joints in a given rock mass.r

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r The least siliceous of the plutonic rocks in Yosemiter Valley, for example, is the diorite that occurs at ther Rockslides; this rock is also generally finer grained thanr most of the granitic rocks. The diorite is the mostr closely jointed rock in the valley, and enormous piles ofr joint-derived blocks of diorite have accumulatedr throughout the area of the Rockslidesr (fig. 37).r

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r **r THE ROCKSLIDES AND EL CAPITAN. The Rockslides (left) is a jumbled collection of talusr blocks of diorite, the most closely jointed rock in Yosemite Valley. In contrast, El Capitan (right) is largelyr unjointed granite, and the pile of debris at its foot, though concealed in this photograph, is comparativelyr small.r (Fig. 37)r** r

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r In a particularly striking contrast to the jumbledr piles of debris at the Rockslides is the largely unbrokenr face of El Capitan, a short distance to the east—one ofr the sheerest cliffs in the world. It consists chiefly of Elr Capitan and Taft Granites, two of the most siliceousr plutonic rocks in this area. The composition of theser rocks determines the characteristics of El Capitanr itself—massiveness and resistance. Because El Capitanr is largely unjointed, the talus pile at its foot is small.r Cathedral Rocks and the Leaning Tower are composedr of El Capitan Granite, complexly intruded by Bridalveilr r r r Granodiorite; these pinnacles stand out as they dor because of their siliceous composition.r

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r The apron or lower part of the cliff east of Glacierr Point consists of unjointed Half Dome Granodioriter capped by well-jointed tonalite; from a viewpoint inr Stoneman Meadow, an observer, by noting this differencer in structure, can trace the contact between ther two rock types quite closelyr (fig. 38).r

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r **r BOLD EXPOSURE of unjointed Half Dome Granodiorite (in sun) capped byr mostly well-jointed tonalite (in shade) making up Glacier Point. The contact betweenr the two rock types angles upward to left.r** (Fig. 38)**r** r

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r So mammoth a feature as Half Dome could onlyr have been carved from a sparsely jointed rock. In spiter of James Hutchings' eloquent statement accompanyingr ther frontispiecer to this volume, Half Dome is nearly asr whole as it ever was. The impression from the valleyr floor that this is a round dome which has lost itsr northwest half is an illusion. From Glacier Point or,r even better, from Washburn Point, we can see that it isr actually a thin ridge of rock oriented northeast-southwest,r with its southeast side almost as steep as itsr northwest side except for the very top. Although ther trend of this ridge, as well as that of Tenaya Canyon, isr probably controlled by master joints, 80 percent of ther northwest "half" of the original dome may well still ber there. What probably happened is that frost splitting ofr the rock at the back of a tiny glacier against Half Domer above Mirror Lake gradually quarried back the steepr northwest face. As the base of the cliff was hewn away,r ultimately parts of the sheets parallel to the originalr upper surface of Half Dome were left projecting outwardr at the crest of the vertical cliff. Sharp angularr bends in the gross form of Yosemite Valley suggest thatr the entire valley, as well as Tenaya Valley, may haver been eroded along a complex joint system now concealedr by stream deposits on the valley floor.r

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r **r PROGRESSIVE ROUNDING OF MASSIVE GRANITEr**
r as successive sheets (dashed lines) are formed and spalled offr
r in response to unloading, or release of the confining pressure underr
r which the granite crystallized deep within the Earth. This is a formr
r of exfoliation.r (Fig. 39)**r** r

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r The type of jointing that has most influenced ther form of Yosemite's landmarks, however, is the broad,r shell-like unloading joints or sheeting, also commonlyr referred to as exfoliation. Granitic rocks crystallize atr considerable depth within the Earth while underr great pressure from miles of overlying rock. As ther still-buried plutonic rocks are uplifted into mountainsr and the overlying rock is eroded, the unloading,r or release of the previously confining pressure,r causes the rock to expand toward the Earth's surface.r In jointed rocks, such expansion is taken up byr adjustments along the numerous partings; but in ar massive monolith, the stresses accumulate until theyr exceed the tensile strength of the rock, and the outerr and more rapidly expanding layer bursts loose. Overr time, the process is repeated, and the monolithr becomes covered with several layers of shells. Ther outermost layer, exposed to the weather, graduallyr disintegrates, and the pieces fall off. The process ofr r r r r sheeting eliminates projecting corners and angles andr replaces them with curvesr (fig. 39).r As succeedingr shells drop off, these curves become more and morer gentle, and thus a smoothly rounded surface evolves.r

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r **r SHEET JOINTS FOLLOW TOPOGRAPHIC SURFACES.r *A,* Horizontal sheeting exposed on quarry face, cut intor broad, level surface. *B,* Convex sheeting on granite dome. *C,*r Concave sheeting on valley floor. *D,* Near-vertical sheeting onr Matthes Crest. Unloading has taken place from both sides of ar steep linear ridge. Photograph from National Park Servicer collection.r (Fig. 40)r** r

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r Because the expansion that forms sheet jointsr takes place perpendicular to the Earth's surface, ther shape of sheets generally reflects the topography,r although their formation subtly modifies the topographyr at the same time. If the ground surface is level,r the sheets will be horizontalr (fig. 40*A*).r If the graniter underlies a hill, the sheets will curve accordingly,r convex upwardr (fig. 40*B*);r and if beneath a valley,r concave upwardr (fig. 40*C*).r Sheeting also tends tor parallel the walls of canyons. If the canyon wallr slopes toward the river, the sheets do also. If ther walls are vertical, the sheets are also verticalr (fig.r 40*D*);r thus, the vertical cliffs of Yosemite that appearr to be unbroken monoliths may have hidden verticalr fractures behind and parallel to the cliff face. Ther undulating surface of the wall below Clouds Rest isr an outstanding example of sheeting that parallels ther topographic surface; the sheets are concave in ther bowl-shaped basins high on the cliff face and convexr on the intervening spursr (fig. 41).r

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r **r UNDULATING SURFACE belowr Clouds Rest. The sheet joints are concave inr the bowl-shaped basins high on the cliff face,r and convex on the intervening spurs.r (Fig. 41)r** r

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r The Royal Arches is a gigantic expression of sheetr jointing, with sheets as much as 200 ft thickr (fig.r 42).r Too far below the surface to form the tops ofr domes, the arches reveal a cross- sectional view ofr sheet jointing in Half Dome Granodiorite that hasr been truncated by the north wall of Yosemite Valley.r Similar features can also be seen on the walls behindr Upper Yosemite Fall and at the head of Ribbon Fallr alcove.r

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r **r ROYAL ARCHES, in left center of photograph and topped by North Dome, is a gigantic expression of sheet joints, withr sheets truncated by north wall of Yosemite Valley. Photograph by Eadweard Muybridge, about 1872.r (Fig. 42)r** r

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r **r WEATHERING OF JOINT BLOCKS and stages in ther formationr**
r of corestones. Corners and edges of granite blocks arer attackedr
r more readily by weathering along joints, and roundedr
r corestones result.r (Fig. 43)r r

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r r SPHEROIDAL WEATHERING around corestones. Rectangularr r pattern of sheets reflects horizontal and vertical orientationr r of joints originally bounding the disintegrating blocksr r Roadcut at Big Meadow overlook, Big Oak Flat Roadr (Fig. 44)r r

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r Weathering and Erosionr

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r INFLUENCE OF THE ROCKSr ON WEATHERINGr

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r Unfractured granite is impermeable, and becauser weathering processes depend on the presence ofr moisture, exposed granite surfaces weather slowly.r However, where buried by soil and in contact with ar chemically reactive mixture of water, atmosphericr gases, and organic decay products, granite weathersr much more readily. Joints in the granite that provider avenues for deep circulation of ground water permitr weathering to proceed well below the buried bedrockr surface. As weathering penetrates the rock from jointr surfaces, the edges and corners of the joint blocks arer affected more rapidly than the sides, because they arer attacked from two or three directions at oncer (fig. 43).r The unweathered remnant of granite in the center ofr the joint block becomes a rounded boulder, called ar *corestone,* and the process of its formation is a form ofr exfoliation called *spheroidal weathering*r (fig. 44).r

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r Where water collects in small natural depressionsr on granitic-rock surfaces, the weathering processr commonly enlarges the depressions to form weatherr pits, or pansr (fig. 45).r The pans are typically flatr bottomed, a fact that has not yet been completelyr explained. A possible explanation is based on ther proposition that the most active environment forr weathering is the zone of alternate wetting and dryingr along the margins of the pools that collect in ther pans. The margins tend to deepen and enlarge untilr all points of the bottom of the pan are equally wet orr dry at the same time. Thereafter, they weather downwardr at a rate that is constant over all of the panr surface. This explanation also accounts for the overhangingr rims, which are very common, and forr coalescing pans, which also are common. The flatr floors of the pans are horizontal even where the pansr occur on the sides of boulders. The weathered materialr in the pans is removed by wind, although inr deeper ones a granite sand remains. The process is ar slow one—such pans normally are not found onr surfaces scraped smooth during the last major glaciation,r which ended some 10,000 years ago.r

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r **r WEATHER PANS formedr on summit of North Dome, highr above Yosemite Valley. Neighboringr pans coalesce as a resultr of progressive expansion at ther expense of intermediate partitions.r Photograph fromr National Park Service collection.r (Fig. 45)r** r

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r **r RESISTANT POTASSIUM FELDSPAR PHENOCRYSTSr r protrude from weathered surface of Cathedralr r Peakr Granodiorite. Matrix minerals formerlyr r enclosing the phenocrystsr have been weatheredr r to grus (granite sand) and washed away.r r (Fig. 46)r** r

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r The weathering and disintegration of rock, makingr it susceptible to erosion, depend on both rockr composition and rock texture. The darker varieties ofr medium-grained granitic rocks, particularly thoser rich in biotite, weather more readily than the lighterr colored varieties. Expansion of the biotite by absorptionr of water helps free the crystal from surroundingr r mineral grains and thus leads to disaggregation of ther rock. The resulting granular product, a granitic sandr called *grus,* is easily erodedr (fig. 46).r For this reason,r many topographic basins in granitic terrane are inr areas underlain by biotite granodiorite, and ridges arer held up by granites that contain less biotite. Finerr grained plutonic rocks (both light and dark colored)r are generally more resistant to formation of grus thanr coarser grained ones. Because the fine-grained rocksr occur mostly as dikes and other small bodies, theyr have less effect on major landforms, although theyr sometimes create rather spectacular featuresr (figs. 47,r 48).r

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r The composition and texture of metamorphic rocksr also affect their weathering and erosion. Again, ther presence of mica facilitates breakup of the rock duringr weathering. The most resistant metamorphic rocks arer those containing abundant quartz, such as metamorphosedr sandstone, and those made dense and hardr from baking by magma. Many metamorphic rocks arer more resistant than plutonic rocks; metamorphic rocksr hold up much of the Sierran crest along the east edger of the park, as well as the Ritter Range southeast of ther park.r

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r **r KNOBS of resistant fine-grainedr diorite protrude fromr weathered outcrop surface ofr El Capitan Granite.r (Fig. 47)r** r

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r **r NATURAL BRIDGE formed where weather-resistantr r apliter bridges an opening eroded in underlying,r r less resistant Half Domer Granodiorite.r (Fig. 48)r** r

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r AGENTS OF EROSIONr

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r Erosion, simply stated, is the removal of earth materialsr from high areas to low areas. Erosion thus tends tor level a high area.r

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r Two agents of erosion are chiefly responsible forr sculpting the present Yosemite landscape—flowingr water and glacial ice. Flowing water had the major role,r and glaciers added the final touches. The major drainages,r the intervening divides, and the general landformsr were all established before glaciation. Some ofr the glacial modifications were profound: the creation ofr alpine topography full of cirques and arêtes along ther higher divides, the rounding of many valleys from V-shapedr to U-shaped and their straightening in ther process, and the creation of hundreds of lakes andr ponds where formerly there were none.r

r r

r Still another agent of erosion is simply gravity. Ther downslope movement of rock materials without the aidr of a transport medium produces landslides and rockfalls.r Although generally of local extent, such movementr is important, particularly in mountainous terrain.r In the winter of 1982, a rockfall dropped huge blocks ofr granite on Route 140 near the junction of the Oldr Coulterville Road, about 2 mi east of the Arch Rockr Entrance Stationr (fig. 49).r The highway remainedr closed until a way could be blasted through the debris,r and the little-used Old Coulterville Road on the sloper above was blocked severely enough to be abandoned.r

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r **r ROCKFALL of blocks the size of small houses temporarilyr**
r closed the El Portal Road east of Arch Rock Entrance Stationr
r inr 1982 until a way could be blasted through the debris.r
r [Editor's note:r This boulder was demolished by road crews after the 1997r
r flood—dea.]r (Fig. 49)r r

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r THE ROLE OF FLOWING WATERr

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r The work of flowing water can be seen at all scales,r from that of tiny rivulets cascading down a slope after ar rain and transporting soil-size particles, to raging floodr torrents with streams using stones as hammers to breakr up material in their beds. But flowing water can transportr cobbles and boulders only during the high-energy,r turbulent flow of floods. Thus, the effectiveness ofr erosion by flowing water depends largely on processes ofr weathering, the breakdown of parent rock into moleculesr and rock or mineral fragments that the streamsr can transport easily.r

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r With the onset of late Cenozoic uplift of the range,r the major streams were rejuvenated and made morer vigorous by their increased gradients. In a mountainr range that is rising faster than upland material can ber removed, the tendency is for major streams to cut deepr canyons, with both the local topographic relief and ther maximum elevation of the range increasing. This canyonr cutting requires that river-channel incision be fasterr than hillslope erosion. If river-channel incision canr keep up with uplift but hillside erosion cannot, thenr stream channels become progressively deepened relativer to areas between streams. In particular, for rocks resistantr to weathering, channel incision will be relativelyr much faster than hillslope erosion, and a canyon isr formed. Yosemite has superb examples in the canyonsr of the Tuolumne River, the Merced Riverr (fig. 50),r andr the South Fork of the Merced River. The upper basinsr of these rivers were later modified by glacial erosion,r but the fact that the rivers flow in deep canyons beyondr the western reach of past glaciers shows that canyonr rutting was accomplished solely by the action ofr streams.r

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r **r DEEPLY INCISED, UNGLACIATED CANYON of ther**
r Merced River about 7 mi west of El Portal.r
r Photograph byr Dallas L. Peck.r (Fig. 50)r r

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r The general courses of the major streams inr Yosemite, with few exceptions, were probably inheritedr from the preuplift drainage pattern and depend mainlyr an the westerly slope of the range. The courses of ther tributaries to the trunk streams and the shapes of theirr drainage basins depend more on granite compositionr and joints, as discussed in previous sections.r The results of stream incision are depicted in a seriesr of sketches that interpret landscape development from ar region of gently rolling hills with meandering streamsr to one of canyonlands cut into the upland surfacer (fig.r 51).r These scenes should be viewed as snapshots in ar continuing process, rather than as distinct stages inr landscape evolution. Note that granite domes form asr the relief increases. The final scene is one conceptionr of what Yosemite looked like about 2 or 3 million yearsr ago, before the onset of glaciation.r

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r **r UPLIFT AND STREAM INCISION. A, About 15 million years ago, the Yosemite area was a rolling surface ofr rounded hills and broad valleys with meandering streams. B, By 10 million years ago, uplift of the range was sufficient tor steepen stream gradients, and the valleys deepened. C, Before the onset of glaciation possibly some 2 million years ago,r streams had incised deep canyons into the west flank of the range.r (Fig. 51)r** r r r r r

r THE ROLE OF GLACIERSr

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r The Yosemite landscape as we see it today stronglyr reflects the dynamic influence of moving ice that longr ago covered much of it several times. We are stillr uncertain as to how many times ice mantled Yosemite,r but at least three major glaciations have been wellr documented in the Sierra Nevada, and other evidencer suggests additional glacial episodes.r

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r Formation of glaciers requires that some of the snowr that falls each winter persist through the followingr summer into the next winter's accumulation season.r r Thus, heavy winter snowfall or cool summer temperatures,r or both, favor the growth of glaciers. If theser conditions persist for a few centuries, possibly less, ther layers of accumulating snow form a deposit thickr enough for the snow in the lower part of the deposit tor be compacted into icer (fig. 52).r At a thickness of aboutr 100 ft, ice begins to flow outward under its own weight,r and on slopes will begin to flow downhill at lesserr thicknesses; when it flows, a glacier is born.r

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r **r MACLURE GLACIER, showing annual layers of icer accumulation exposed after melting of seasonal snow. Note peopler for scale in lower right. The layers slant upward into the glacier;r the youngest layers are highest up the slope. Photograph fromr National Park Service collection.r (Fig. 52)r** r

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r As the glacier flows downhill, it enters regions ofr warmer climate, where the snow does not persist fromr year to year. The boundary where loss from melting andr evaporation equals accumulation from snowfall is calledr the *annual snowline or firn limit*— "firn" being ther term for partially compacted snow carried over fromr previous seasonsr (fig. 53).r The firn limit fluctuatesr from year to year in response to changes in precipitationr and temperature. The firn limit can be as muchr as 1,000 ft lower in elevation on the shaded northr sides of mountain peaks than on their sunny southr sides. For this reason, nearly all of the small present-dayr glaciers in the Sierra are on north-facing slopes.r

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r **VALLEY GLACIER sectionedr to show relation between accumulationr and wastage areas. Annualr snowline, or fern limit, is the boundaryr where accumulation from seasonalr snowfall equals loss fromr melting and evaporation.r (Fig. 53)r** r

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r The section of the glacier through which ther maximum amount of ice flows coincides with the firnr r r r limit, because as the glacier flows toward the firnr limit, it is continually augmented by new net snowfall;r and downvalley from the fim limit, more ice isr lost by melting and evaporation—together calledr *ablation*—each year than is added by snowfall. As ther glacier flows downvalley from the firn limit, more andr more of the ice ablates, and the glacier grows thinnerr or narrower, or both. Ultimately a point is reachedr where the ice front can advance no farther becauser the ice melts there as rapidly as it is provided byr inflow from upglacier. If the yearly rates of accumulationr and ablation were constant, this point would ber fixed. However, they vary, and for that reason aloner the terminus of the glacier is not likely to be fixed inr position. As the climate turns warmer or drier, ar glacier will gradually waste away, rather than meltingr catastrophically.r

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r *Glacial erosion*r

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r **r ROCHE MOUTONNÉE, sectioned to show the influence ofr r jointing on its development. The ice moves upward over unjointedr r rock, smoothing it off, and plucks up and carries away blocks ofr r jointed rock.r (Fig. 54)r** r

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r The velocity at which a glacier slips over its bed isr only about half the ice velocity measured at its surface;r the difference is taken up by deformation within ther moving ice. But it is the slippage over the bed that isr responsible for glacial erosion. Wherever basal flow isr especially strong, or the rock easily removed, bedrockr basins are carved, which eventually hold lakes. Ther glaciers widen and deepen valley bottoms to give ar characteristic U-shaped profile. On the leesides of bedrockr projections into the ice are regions of low pressurer where meltwater refreezes in cracks in the rock, pryingr loose blocks of bedrock that are then incorporated intor the glacial ice and quarried away. Asymmetric rockr knobs with smoothly abraded stoss, or upstream, sidesr and jagged and quarried leesides are calledr *roches moutonnées* and record the direction of glacier flowr (fig. 54).r Commonly translated as “sheep,” moutonnéer is actually a French adjective meaning “fleecy”;r the term was introduced into geology in 1786 tor describe rounded Alpine hills whose repeated curves,r taken as a whole and as seen from a distance,r resemble a thick fleece. As rock fragments embeddedr in the basal ice are dragged across the bedrockr surface, they impart scratches, grooves, crescenticr gouges, and a shining polishr (fig. 55).r

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r **r IMPRINTS ON THE ROCK left by passing debris-ladenr ice.r *A,* Glacial polish and striations (lower right). Crescenticr gouges, or percussion marks, are visible in center; horns of ther crescents point upglacier. Chatter marks (not illustrated) consist ofr a group of crescent-shaped cracks pointing downglacier, butr generally they do not form gouges. Photograph by John P. Lockwood.r *B,* Glacial polish and striations. Polished surface layerr flakes off, and this evidence of glaciation gradually disappears.r This excellent and accessible exposure is at the foot of Polly Domer along the Tioga Road on the north side of Tenaya Lake.r (Fig. 55)r** r

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r Another feature of glacial erosion is the bowl-shaped,r theaterlike valley head called a cirquer (fig.r 56).r During the summer season, when no new snowr is accumulating and the ice pulls away from the rockr face at the head of the glacier, a great crevice, calledr a *bergschrund,* opens. This opening exposes the rockr at the head of the cirque to freezing and thawing,r r r r
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r **r MOUNTAIN CREST, showing valley glacier and glacialr r sculpture.r (Fig. 56)r** r r r which wedges blocks of rock free from the base of ther cliff. The freed blocks, frozen into the main mass ofr ice during the winter season, are then transportedr out of tie cirque by the glacier; retreat of ther headwall thus enlarges the cirque.rr r

r The cliffs behind the cirques and above the glacierr surface elsewhere are also sculpted by the freezing ofr water in cracks in the rock. Expansion of water whenr it freezes to ice breaks and wedges out blocks, whichr then avalanche onto the glacier's surface below. Ther falling blocks knock loose any projecting rock inr their paths, and chip away fragments as they bouncer r down the cliff face. The hollows created by ther detachment of these blocks and by the erosion theyr cause on their fall collect and hold more moisturer than do the projecting ribs between them; they thusr retreat more rapidly by frost wedging than do ther ribs, so that even if initially smooth, a cliff face,r given enough time, can become intricatelyr sculptured.r

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r As the cliffs on opposite sides of a ridge arer quarried back by frost action above the active cirquer glaciers, they eventually intersect to form a sharp,r jagged rock crest called an *arête,* with sharp peaks,r called *horns,* where the ridges branchr (fig. 56).r Ther sharp change in character of the walls of glaciatedr valleys—from intricate and jagged sculpturing above,r to smooth sculpturing below—marks the edge, orr trimline, of the former glacier and makes it possible tor reconstruct the former margin of the mountainr icefieldr (fig. 57).r

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r **r JAGGED UNGLACIATED SPIRES of Unicorn Peak risingr r above smooth shoulders of glacially scoured granite. Boundaryr r between jagged sculpture above and smooth below, called the trimline,r r marks upper limit of a former glacier along the valley wall.r (Fig. 57)r** r

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r Glaciated valleys are nearly straight and have U-shapedr crossprofiles, in contrast to the sinuous V-shapedr valleys of normal stream erosion (figs. 50,r 58).r At the high velocities of running water, inertia throwsr the fastest current against the outside of a bend. At ther much slower velocities of glacial ice, the fastest flow isr on the insides of bends, where the distance is shorterr and the ice surface is steepest. Thus, whereas a streamr erodes the outsides of bends preferentially and makes itsr course more sinuous, glacial erosion is concentrated onr the insides of bends, removing the overlapping spurs ofr r r r the original stream-eroded valley and leaving a wide,r straight valley floor in place of the sinuous one. Ar major factor leading to the U-shaped crossprofile ofr glacial valleys is the ability of a glacier to erode far upr the valley walls. The entire glaciated valley was oncer occupied by the former glacier that carved it, whereas ar stream occupies only the very bottom of its valley.r

r r

r In addition to truncated spurs, hanging tributaryr valleys are formed on the sides of glaciated valleys. In ar landscape developed by stream erosion, tributaryr streams normally join the main-think river at the samer level. During glaciation, the upper surfaces of ther glaciers occupying the tributary valleys join at the levelr of the surface of the ice filling the main channel; butr beneath the ice the trunk glacier, with its greaterr thickness and erosive power, carves much more deeplyr into the bedrock than the tributary glaciers can. Whenr the glacier wastes away and the ice is all gone, ther tributary valleys are left hanging high up on the sides ofr the trunk valley, and their streams cascade or fall tor join the main river belowr (fig. 58).r During the timer since the pre-Tahoe glaciation, when Yosemite Valleyr acquired nearly its present form, spray from the waterfallsr freezing in cracks ib the rock at the base of the cliffr promoted spalling of rock slabs there and formed ther recessed alcoves into which the falls now leap. Most ofr the waterfalls in Yosemite Valley formed in this mannerr and, indeed, are the finest examples anywherer (fig. 59).r Thus, throughout the world the name “Yosemite” hasr come to spell “waterfalls.”r

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r **r VALLEY MODIFICATION by glacial erosion, showingr stages in the conversion of a meandering V-shaped valley into ar straightened U-shaped valley.r (Fig. 58)r** r

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r **r BRIDALVEIL FALL, an outstanding example of a waterfallr r issuing from a hanging valley far above Yosemite Valleyr r floor.r Photograph by Julia A. Thomas.r (Fig. 59)r** r

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r *Glacial deposition*r

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r Glacially carved landforms are the most strikingr evidence of the passage of long-gone ice masses. Butr glaciers must eventually deposit the materials they arer transporting, and in the process they also build upr characteristic landforms. The material deposited byr glaciers is an unsorted mixture of boulders, sand, andr clay called *till*r (fig. 60).r Till may be deposited by ther glacier on its bed as it is actively flowing, or the tillr may be left behind as the ice melts away, generallyr beginning as an accumulation of rock debris on ther ice surface. Other depositional evidence of icer includes *glacial erratics,* boulders left behind as ther ice meltedr (fig. 61).r Direction of glacial transport isr commonly indicated by boulders of rock types differentr from the bedrock on which they rest, but thatr can be traced back upglacier to a source area.r Whereas till is the unsorted material deposited by ar glacier, the deposit itself is known as moraine, andr such moraine takes different topographic forms,r depending on how the till was deposited.r

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r **r GLACIAL TILL, an unsorted mixture of boulders, sand, andr r clay, exposed along the Tioga Road at Siesta Lake.r (Fig. 60)r** r

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r **r GLACIAL ERRATIC transported by a glacier and leftr r precariouslyr balanced near Olmsted Point as the ice melted.r r (Fig. 61)r** r

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r The most distinctive morainal features in the Sierrar Nevada are *lateral moraines,* linear ridges of till thatr rest on the sides of the glaciated valley and extendr parallel to the valley axisr (fig. 62).r These ridgesr generally define the maximum height and width ofr the glacier that deposited them. Commonly, lateralr moraines curve around at their lower ends to formr *terminal moraines,* ridges of till deposited at the terminusr of a glacier. When a glacial cycle ends, glaciersr do not always melt back uniformly; instead, theyr commonly pause periodically in their retreat, constructingr a series of *recessional moraines.* Excellentr examples of all these varieties of moraines can ber seen in Lee Vining Canyon just east of the parkr (fig.r 63).r

r r

r Most of the terminal and recessional moraines onr the west side of the Sierra Nevada have beenr breached or removed by swift meltwater streams, andr it is doubtful whether they were even deposited inr the steep narrow canyons of most of the west-flowingr streams, such as the Merced River west of Yosemiter Valley. The glaciers that debouched onto ther lowlands along the east base of the Sierra Nevada,r however, left distinct terminal moraines, some ofr which presently enclose lakes.r

r r

r Where two glaciers join to form a single trunkr glacier, the lateral moraines being formed on theirr adjoining sides will continue as a linear train ofr debris outward onto the surface of the trunk glacier.r r This train is called a *medial moraine,* and when ther glacier melts, the debris will form a linear ridger parallel to the axis of the glacial valley. Such ar medial moraine can be seen where the Merced andr Tenaya Glaciers once joined at the east end ofr Yosemite Valley.r

r r

r The total amount of till left as moraine inr Yosemite and elsewhere on the west slope of ther Sierra Nevada is small, however, in comparison withr the amount of glacially derived debris that wasr flushed out of the mountains by streams swollen withr glacial meltwater. Most of that debris was thenr deposited as alluvial fans and valley fill in ther Central Valley, and some of the finer material traveledr even farther, finally coming to rest in the San Francisco Bayr and the Pacific Ocean.r

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r **r MORAINES formed by a valley glacier.r Lateral moraine formed along side marginr of glacier; terminal moraine formed at pointr of farthest glacial advance; and recessionalr moraine formed during pause in retreat ofr glacier. Ground moraine is a rather shapeless,r hummocky till deposited beneath ar glacier or simply left behind as the glacierr retreats or wastes away.r (Fig. 62)r** r

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r **r MORAINES IN LEE VINING CANYON east of Tiogar r Pass, looking westward toward crest of the Sierra. Paired lateralr r moraines on both sides of the canyon extend toward the viewer; ther r outer pair (O) represent the Tahoe glaciation, and the inner pairr**

r (I) the Tioga glaciation. The inner pair of moraines coalesce tor r form a terminal moraine (T) at lower left. A recessional morainer r (R) crosses the valley as a low, tree-lined ridge. Photograph byr r Clyde Wahrhaftig.r (Fig. 63)r r
r r

r The Record ofr Pleistocene Glaciationsr

r r

r The record of glaciation in Yosemite National Park isr very incomplete. Only for the last two major glaciationsr can the extent of the ice be reconstructed with anyr confidence. Older glacial deposits, if preserved at all,r are so fragmentary that it is generally impossible tor distinguish the separate ice advances that may haver deposited them. The glaciers grew and melted away inr response to climatic changes of long duration that werer probably worldwide, and so a record of all the glaciationsr that might have affected Yosemite must be soughtr elsewhere.r

r r

r During worldwide glacial cycles, large volumes ofr water evaporated from the oceans arc stored on land asr ice; this storage causes a decrease in the volume ofr water remaining in the oceans. During evaporation ofr seawater, the light isotope of oxygen—oxygen-16—isr more easily lost to atmospheric vapor than is the heavyr isotope-oxygen-18. When this vapor precipitates onr land and is stored as ice, rather than returning to ther oceans, the ratio of these two isotopes of oxygenr remaining in the ocean will change. Organisms livingr in the oceans at any given time secrete calcareous shellsr whose ratio of oxygen isotopes is comparable to that ofr the water in which the organisms lived. Measurementsr of fluctuations in this ratio provide indirect measurementsr of ice volume, with times of large ice volumer interpreted as glacial episodes. Isotopic measurementsr on such shells extracted from deep-sea sediment samplesr indicate about 10 major glacial episodes during ther past 1 million years. Normally, evidence for only ar small fraction of these glaciations can be found in ar r r r given area on land, because the more extensive glaciersr destroy the moraines of earlier, less extensive ones.r Only if older glaciers extended beyond the limits ofr younger glaciers will the older deposits remain to documentr the earlier glacier's existence, and so the glaciationsr now recognized in Yosemite may be only ar fraction of those that actually occurred.r

r r

r François Matthes presented evidence for three majorr glaciations in Yosemite, which he called, from youngestr to oldest, Wisconsin, El Portal, and Glacier Point.r Working on the east side of the Sierra about the samer time, Eliot Blackwelder recognized four major glaciations:r Tioga, Tahoe, Sherwin, and McGee; these latterr terms have become firmly established and have largelyr replaced those of Matthes. His Wisconsin is nowr thought to include equivalents of both the Tioga andr Tahoe glaciations, and his El Portal is probably equivalentr r
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r **r TIOGA MORAINE in Harden Lake area, showing sharpr**
r crest and abundant boulders exposed on surface.r (Fig. 64)r r

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r **r TAHOE MORAINE in Harden Lake area, showing subduedr**
r crest and only scattered boulders exposed on surface.r (Fig. 65)r r

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r **r PERCHED ERRATIC deposited on ridge west of Upperr**
r Yosemite Fall during a pre-Tahoe glaciation. Pedestal height of 5r
r ft indicates amount of rock weathered away since boulder wasr
r dropped by the ice. Photograph from National Park Servicer
r collection.r (Fig. 66)r r

r r to the Sherwin. The evidence for Matthes' separater Glacier Point glaciation is unconvincing, and therer may not be an equivalent of the McGee in Yosemite.r Many additional glacial episodes have been proposed tor account for the diverse deposits of till, out-wash, andr glacial-lake sediment on the east side of the Sierrar Nevada. There is disagreement, however, as to whetherr each of these deposits represents separate glaciations orr pulses within major glaciations, and they have not beenr recognized in Yosemite.rr r

r In Yosemite, deposits of three separate glacial episodesr are now distinguished on the following basis:r

r r

r 1. Tioga (youngest): Unweathered till consisting ofr fresh granitic boulders and loose, porous gravel andr sand, making sharp-crested moraines that haver closely spaced boulders on their upper surfacesr (fig.r 64).r

r r

r 2. Tahoe (intermediate): Subdued moraines whose buriedr granodiorite boulders have commonly disintegratedr at least partly to gnus. The summits of theser moraines tend to be rounded, and exposed bouldersr along their crests are generally sparser (fig. 65).r

r r

r 3. Pre-Tahoe (oldest): Outside the ice limits defined byr the intermediate moraines, a few glacial erratics,r commonly perchedr (fig. 66),r and patches of formlessr glacial till give evidence of at least one earlier icer advance more extensive than the glaciers thatr deposited the intermediate moraines.r

r r

r By recognizing these distinctions, we can at leastr partly reconstruct the glacial geology of Yosemite.r

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r The Glacial Geology of Yosemiter

r r

r The glacially related features of today's landscape,r both erosional and depositional, largely reflect ther latest major glaciation, the Tioga. The effects of multipler glaciations are cumulative, however, and the effectsr of earlier glaciations must have been substantial,r although we can only gauge them by inference. Wer shall examine the end results of these episodic glaciationsr culminating with the Tioga, and then examiner the evidence for the work of earlier glaciations.r

r r

r The Tioga glaciation began about 30,000 to 60,000r years ago, when a cooling climate permitted smallr glaciers to develop in high cirques originally formed andr then abandoned by earlier glaciers. With continuedr cooling, these glaciers grew and moved outward andr downward to coalesce into a mountain icefield, withr only the higher peaks and divides projecting through asr arêtes and horns. With further growth, the icefield fedr fingers of ice into the major drainages on the west sloper r r r of the Sierra, until the ice reached its maximum extentr about 15,000 to 20,000 years agor (fig. 67).r

r r r

r The icefield in the upper Tuolumne River basin, andr in the tributary basins to the north, fed the glacier thatr moved down the canyon of the Tuolumne Riverr through Hetch Hetchy Valley. Some of the ice fillingr the basin of the Lyell Fork of the Tuolumne spilled overr low passes to augment ice in the Merced River basinr that flowed down through Little Yosemite Valley.r Tuolumne ice also flowed over a pass into the Tenayar Lake basin and down Tenaya Canyon to join the mainr Merced Glacier in Yosemite Valley. During the Tiogar glaciation, the glacier in Yosemite Valley reached onlyr as far as Bridalveil Meadow.r

r r r r

r **r TIOGA ICEFIELD AND VALLEY GLACIERS, showingr maximum extent during the Tioga glaciation, the last majorr glaciation in the Sierra Nevada, which peaked about 20,000 tor 15,000 years ago.r (Fig. 67)r** r

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r Tioga ice also flowed eastward from the summitr region to cascade down canyons cut into the eastr r r r r escarpment of the Sierra. Southeast of the park, icer from the Mount Lyell area flowed eastward onto ther

Mono lowland and southeastward and southward downr the Middle and North Forks of the San Joaquin River.r In the southern part of the park, ice in the South Forkr of the Merced River reached nearly to the present siter of Wawona.r

r r

r In addition to the major icefields in the headwatersr of the Tuolumne and Merced Rivers and the majorr valley glaciers they fed, smaller, isolated glaciers formedr in favorable localities, as on Buena Vista Crest, Horser Ridge, and above Siesta Lake near the Tioga Road.r Each played a part in creating today's landscape.r

r r

r At the time of the Tioga glacial maximum, glacialr Lake Russell was much larger than the present-dayr Mono Laker (fig. 67).r The surface elevation of Laker Russell at that time was about 6,800 ft, 425 ft higherr than the 1980 elevation of Mono Lake of about 6,375r r ft. The increased volume of Lake Russell was probablyr due to a much lower rate of evaporation of water fromr the lake during Tioga time, partly because of ther prevailing cooler climate and partly because the laker probably was covered by ice much of the time.r

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r **r U-SHAPED GLACIATED VALLEY, the Lyell Fork of the Tuolumne River, looking southward.r Photograph by Robert W. Cameron. © Cameron and Company; used with permission.r (Fig. 68)r** r
r r

r The Tuolumne Meadows area is one of the mostr accessible, as well as one of the best, places to see howr glaciers modified the landscape by both erosion andr deposition. The Lyell Fork of the Tuolumne River flowsr to the meadows through one of the park's finest examplesr of a U-shaped valleyr (fig. 68).r The frost-rivenr spires of Unicorn and Cathedral Peaks standing abover smoothly rounded granite shoulders graphically indicater the height to which Tioga ice reachedr (fig. 57).r Glacialr polish high on Fairview Dome indicates that it wasr overtopped by icer (fig. 69).r Lembert Dome, on ther northeast side of the meadows, is a roche moutonnéer that records stoss-side smoothing and leeside pluckingr r r r on a grand scale, as does the smaller but easilyr ascended Pothole Dome at the meadow's west endr (fig.r 70).r Glacial polish and striations can be seen on manyr outcrops, and erratic boulders abound.r

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r **r GLACIAL POLISH high on east shoulder of Fairview Dome.r r It and similar polish and erratics on the summit indicater r that ther dome was once overtopped by ice.r (Fig. 69)r** r

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r A series of potholes angles diagonally from levelr ground up the south side of Pothole Domer (fig. 71).r The rock polish near these potholes can easily ber mistaken for glacial polish, but it has a different origin.r Unlike glacially polished surfaces, which are generallyr planar, these surfaces are flutedr (fig. 72),r like thoser forming on bedrock today by flowing water of ther Tuolumne River. Both the polish on this part ofr Pothole Dome, and the potholes themselves, were createdr by water in a subglacial stream that flowed upward overr the dome in a tunnel beneath ice of the Tioga glacier.r Glacial polish can, indeed, be seen on the gentle east-facingr slope of the dome, the stoss side of this rocher moutonnée.r

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r **r POTHOLE DOME, a larger roche moutonnée on the west sider of Tuolumne Meadows, wasr shaped by glacial smoothing andr plucking. Ice moved from rightr (stoss side) to left (beside).r Fluted surface was shaped byr subglacial water scour (seer fig.**

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72).r (Fig. 70)r r

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r **r POTHOLES angling up side of Pothole Dome, west side ofr Tuolumne Meadows. Bowl-shaped potholes are carved into ther rock by the grinding action of stones whirled around and kept inr motion by the force of a stream in a given spot. Here, the streamr flowed in a tunnel beneath the ice that covered this area during ther Tioga glaciation.r (Fig. 71)r** r

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r **r SUBGLACIAL WATER POLISH on Pothole Dome,r formed by water flowing beneath the glacier. Surface is flutedr rather than flat, as with glacial polishr (compare with fig. 55).r Polished surface layer is flaking off, similar to the glacial polishr shown inr figure 55*B*.r (Fig. 72)r** r

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r **r KETTLES (small lakes) nearr Tioga Pass, filling depressionsr left by the final melting of blocksr of glacial ice. View eastwardr across Dana Meadows towardr Mount Dana.r (Fig. 73)r** r

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r Most of the till in the Tuolumne Meadows area wasr deposited as hummocky ground moraine beneath ther glacier, or left behind as the glacier wasted away. Ther small lakes in ground moraine southeast of ther entrance station at Tioga Pass appear to be kettles,r depressions left by the final melting of blocks of icer buried in tillr (fig. 73).r Elongate ridges of morainer flank the roadway between Tioga Pass and Tuolumner Meadows, and a cross section through such till isr exposed in a roadcut about 11 mi east of ther Tuolumne River bridge. Lateral and recessional morainesr are inconspicuous and may be absent in ther Tuolumne Meadows area, but magnificent examplesr of both are in lower Lee Vining Canyon along ther Tioga Road east of the parkr (fig. 63).r

r r

r Yosemite Valley, in spite of its profound glacialr modification, is not a good place to see much directr evidence of glaciation. The Tioga glacier onlyr reached as far as Bridalveil Meadow, where its terminalr moraine, although well exposed in a roadcutr (fig.r 74),r is relatively inconspicuous, and lateral morainesr are absent. Glacial polish and striations are scarce,r but they can be seen on a low, flat shelf of rock nearr the base of the north valley wall opposite the westr end of the Yosemite Lodge, and along the base of ther cliffs on the north side of the Tenaya Lake Trail,r about 500 to 1,000 ft east of Mirror Lake. Glacialr polish also occurs in such places as on the slope ofr the Glacier Point apron, but these localities arer r accessible only to the experienced climber. Thisr paucity of direct evidence is probably the basis forr Josiah Whitney's stand against the glacial origin ofr Yosemite Valley, noting as he did the glaciation ofr Hetch Hetchy Valley, where he described glacialr polish at least 800 ft and a glacial moraine 1,200 ftr above the valley floor.r

r r

r The Tahoe glaciation was almost everywhere somewhatr more extensive than the Tioga, and so its morainesr lie outboard of Tioga moraines. Recent studiesr suggest that Yosemite Valley was an exception: ar Tahoe-age glacier reached Yosemite Valley but was smaller andr thinner, and did not extend as far into the valley asr Tioga ice did. If both the Tioga and Tahoe glaciers hadr limited erosive power in Yosemite Valley because theyr both were relatively thin, then the valley must haver attained nearly its present shape during one or morer pre-Tahoe glaciations.r

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r **r GLACIAL MORAINES IN YOSEMITE VALLEY.r**
r *A,* Tioga-age terminal moraine exposed in roadcut just east ofr
r Bridalveil Meadow. This moraine contains large boulders ofr
r Cathedral Peak Granodiorite, clear evidence of glacial transportr
r from Tuolumne Meadows via Tenaya Canyon or from ther
r upper Merced River basin via Little Yosemite Valley.r *B,* Tioga-ager
r recessional moraine exposed in roadcut below Cathedralr
r Rock. Large boulder in center is of Cathedral Peakr
r Granodiorite.r (Fig. 74)r r

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r ***A***r

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r ***B***r

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r Direct evidence for pre-Tahoe glaciation in Yosemiter Valley is also elusive. It consists mostly of scattered,r commonly perched erratics on upland areas adjacent tor the valleyr (fig. 66).r These perched erratics rest onr pillars of rock protected from weathering and erosion byr the erratic itself. The surrounding area commonly hasr been lowered several feet or more by erosion since ther erratics were left as the ice melted. This amount ofr erosion, which is not seen in areas overridden andr scoured by Tahoe ice, is the main argument forr attributing these erratics to a much earlier glaciation.r r r r Readily accessible examples of pre-Tahoe erratics,r though not perched, occur near the radio-relay towerr on Turtleback Dome above the Wawona Road. A smallr patch of old, deeply weathered till is exposed in ar roadcut on the Big Oak Flat Road just east of ther bridge crossing Cascade Creek. This till, about 1,000 ftr above the valley floor, would hardly be recognized asr such without the artificial cut. These erratics and tillr are assigned to one or more pre-Tahoe glaciers thatr filled Yosemite Valleyr (fig. 75).r No terminal moraine forr this glaciation remains in the Merced River canyon,r but the glacier could not have extended more than ar short distance below the town of El Portal, where ther canyon abruptly starts to meander and has a V shaper (fig. 76).r

r r

r Evidence for three separate glaciations in Yosemite isr most readily seen at Harden Lake, about 3 mi down ther Old Tioga Road from White Wolf. Harden Lake sits onr the edge of the upland bordering the Grand Canyon ofr the Tuolumne River, which was completely filled withr ice during each of the three recognized glaciations.r Harden Lake is sandwiched between fresh, boulderyr lateral moraines reflecting pulses of Tioga icer (fig. 64).r Outside of these moraines, farther from the canyon, arer Tahoe moraines, still-linear but subdued ridges, withr extensive soil cover and only scattered boulders on ther surfacer (fig. 65).r Farthest from the canyon, outside ofr the Tahoe moraines, are pre-Tahoe erratics and highlyr dissected till whose original morainal form has beenr destroyed by erosion.r

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r **r GLACIERS COME AND GO. Sketches of Yosemite Valley area, showing extent of pre-Tahoe glacier (*A*), extent of Tioga glacierr (*B*), and glacial Lake Yosemite after retreat of Tioga ice (*C*).r (Fig. 75)r** r

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r **r PRE-TAHOE GLACIATION—its extent in the Yosemite Valley area in comparison with that of the Tioga glaciation.r (Fig. 76)r** r

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r What the Glaciers Missedr

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r Among the arêtes and cols of the Sierran crest andr adjacent spurs are anomalous areas with gently rollingr surfaces that escaped glacial sculpting; the Dana Plateau is an outstanding exampler (fig. 77).r These areas apparentlyr never accumulated enough snow to generater glaciers on their upland surfaces. Not only is ther Sierran crest swept by strong winds, but it also receivesr less snowfall than areas farther west because most of ther moisture is wrung out of the upwelling stormcloudsr before they reach the crest. Glaciers did form in cirquesr on the lower protected slopes of these plateaus, particularlyr on northerly slopes, where sufficient snowr could accumulate by wind drift from the plateaus to ther windward and remain through the summer. But theser glaciers never succeeded in cutting cirques far enoughr back into the plateaus to entirely destroy them.r

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r **r DANA PLATEAU, unglaciated remnant of an ancient landr surface sharply truncated by glacial cirques. Ellery Lake and ther Toga Road lie 2,000 ft below. At upper** r

right is Mount Dana,r with an unglaciated surface sloping downward to right. These twor remnant surfaces are parts of a once-continuous surface breachedr by a glacial cirque excavated by past glaciers and now containingr the present-day Dana Glacier, seen as the gray, oval-shaped spotr on the snow below Mount Dana (see fig. 82).r Photograph by Robert W. Cameron. © Cameron and Co.; used with permission.r (Fig. 77)r rr

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r r **BOULDER-STREWN UPLAND SURFACE on ther Dana Plateau. Frost-heaved joint blocks have been rounded byr sand-blasting action of wind-driven grit. Snow chute on Mountr Dana near right margin leads down to the Dana Glacier acrossr Glacier Canyon from the plateau. View southeastward. Width ofr view in middle distance is about 1/2 mi; southeast edge of plateau isr about 1 1/2 mi away.r**

(Fig. 78)r r
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r These upland surfaces did not totally escape ther effects of glacial climate. Cycles of freezing and thawingr broke the bedrock along fractures and heaved it into ar mass of jumbled blocks. Such rubble-covered surfacesr are scattered along the Sierran crest, as at Dana Plateaur (fig. 78),r and include the summit of Mount Whitneyr 50 mi to the south. The south-facing slope of Mountr Hoffmann, our original vantage point in the park, is ar somewhat similar upland surface, although slow disintegrationr and spalling of granite sheets has created anr r r r r r r r irregular, flaggy surface. This unglaciated surface isr abruptly truncated by a glacial cirque cut deeply intor the north face of Hoffmann—a striking contrast inr erosional processesr (fig. 79).r

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r **r WEST SHOULDER OF MOUNT HOFFMANN.r**
r Smooth, unglaciated south-facing slope (to left)r
r is abruptly truncatedr by a north-facing glacialr
r cirque—a strikingr contrast in erosionalr
r processes.r (Fig. 79)r r
r r

r These upland surfaces have a significance far beyondr being unglaciated, because they are very ancient. Theyr are remnants of the gently rolling terrain that existedr here before the late Cenozoic uplift and incision of ther Sierra that began about 25 million years ago. As ther range was uplifted and tilted, the major westward-flowingr streams incised deeper and deeper canyons,r cutting headward into the range. The upland areasr near the stream headwaters were the last to ber affected some remnants still remain undissected.r

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r Modern Glaciersr

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r Although Tioga glaciers were the last to cap larger parts of the Sierra Nevada, the modern Sierran glaciersr are not remnants of Tioga ice. Instead, they formedr during one or more post-Pleistocene cool cycles thatr François Matthes collectively called the "Little Icer Age." Because of ambiguity in its definition and wider variation in its application, students of glacial geologyr have generally abandoned the term, and post-Pleistocener glaciations are referred to as Neoglacialr events. The latest of these Neoglacial events in ther Sierra Nevada, to which the present-day glaciersr belong, has been called the Matthes glaciation inr honor of his pioneering studies.r

r r

r After the end of the Pleistocene (10,000 years ago),r temperatures in many parts of the world rose, reachingr r a maximum about 5,000 years ago. By that time,r probably no glaciers survived in the Sierra Nevada.r Temperatures then dropped, first slowly, then morer rapidly; and small glaciers began to form in the Sierrar once again by about 2,500 years ago.r

r r

r World climate has continued to fluctuate throughr warming and cooling cycles up to the present. Historicalr records in the Alps indicate a major glacialr advance about A. D. 1600, when glaciers descendedr into valleys and overwhelmed pastureland and villages.r The most recent major advance there occurred aboutr 1850. If Sierran glaciation was synchronous, Yosemite'sr modern glaciers would have been near their most recentr maximum about the same time that John Muir wasr making his studies. We do know that Sierran glaciersr have been receding rather rapidly since Muir's day: Ther first "living glacier" discovered by Muir in 1871, onr Merced Peak, no longer exists.r

r r

r As of 1980, there were nearly 500 glaciers remainingr in the Sierra Nevada, most of them so small as tor barely show evidence of iceflow, such as a bergschrund.r The largest glacier left in the Sierra, the Palisader Glacier in the John Muir Wilderness, covers little morer than 1/2 mi^2; and the largest in Yosemite, the Lyellr Glacier, less than 1/4 mi^2r (figs. 80,r 81).r

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r **r LYELL AND MACLURE GLACIERS. Lyell Glacier (onr left) is divided into two parts by an intervening ridge. Lobater terminal moraine below indicates that at the maximum extent of ther glacier, the**

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two parts joined at the base of that ridge. Gray areasr are ice exposed after melting of seasonal snow. Crevasses arer especially well displayed in the ice exposed on the Maclure Glacierr (on right). View southward. Photograph by Austin Post, Augustr 1972.r (Fig. 80)r r

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r **r LYELL AND MACLUREr GLACIERS, as they were mapped inr 1883 by Willard D. Johnson of the U.S.r Geological Survey. Comparison with ther present-day glaciers inr figure 80r indicatesr their much greater extent at that earlierr date. Mount Maclure, named by Josiahr Whitney for an early American geologist,r is here mistakenly labeled "McClure."r This error may be the source of occasionalr confusion in associating the mountain withr Lt. N.F. McClure, who, however, wasr not on the scene as a guardian of Yosemiter National Park until after 1890.r (Fig. 81)r** r

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r **r DANA GLACIER, 1975. Crevassed ice of the Dana Glacierr**
r is exposed in left center of photograph, and the glacier'sr
r bergschrund is barely visible in shadowed area above. Since ther
r early part of the 20th century, the glacier has retreated headwardr
r from its terminal moraine, visible in lower rightr (compare fig. 83).r
r View southwestward. Photograph by Malcolm M. Clark, Septemberr

r 1975.r (Fig. 82)r r
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r r **r DANA GLACIER, 1908. When this photograph was takenr**
r early in the 20th century, ice of the Dana Glacier abutted ther
r terminal moraine, visible in center. Note bergschrund near glacierr
r head below cirque headwall. View southeastward. Photographr
r by G.K. Gilbert, August 1908.r (Fig. 83)r r

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r Few of the modern glaciers extended very far fromr their cirques, but many left rather impressive arcuater piles of moraine, considering their small size. Danar Glacier and its moraines are the most readily accessibler of those remaining in the parkr (fig. 82);r it is about a 3-hourr hike upcanyon from the south shore of Tiogar Lake east of Tioga Pass, but does require scramblingr over large boulder piles. The glacier is now but a merer shadow of its former self as shown in a photographr taken early in the 20th centuryr (fig. 83).r This 1908r photograph shows Dana Glacier nestled up against itsr terminal moraine, and so it had not receded much, ifr any, from its latest advance. In the 67 years betweenr the two photographs, the glacier lost about three-fourthsr of its area and a much larger fraction of itsr volume.r

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r After the Glaciersr

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r The cold cycle that brought about the Tioga glaciationr ended about 10,000 years ago. Because glaciersr during Neoglacial episodes were so small, runningr water, along with gravity, has dominated further shapingr of the Yosemite landscape since Tioga time. Ther principal changes in landscape have been the filling ofr lakes with rehandled Tioga till; meadows have formedr as a result.r

r r

r One lake to be converted to meadows was ancientr Lake Yosemite, which occupied Yosemite Valleyr upstream from a moraine dam near the foot ofr Cathedral Rocksr (fig. 75).r This was only the last of manyr “Lake Yosemites” that probably followed each glaciation.r The deep excavation created by earlier glaciers, asr much as 2,000 ft into bedrock beneath Yosemite Valley,r was already filled with glacial till and sediment longr before Tioga time, and the Tioga ice had insufficientr erosive power to reexcavate the valley to any appreciabler depth. Lake Yosemite eventually filled in with silt,r leaving today’s level valley floor.r

r r

r Gravity, commonly aided by water and ice, actingr on slopes oversteepened by glacial undercutting, modifiesr the landscape most visibly. Canyon walls are constantlyr shedding rock fragments, and tremendous conesr of debris accumulate in winter below avalanche chutesr (fig. 84).r

r r

r Rockfalls, the largest probably triggered by earthquakes,r can catastrophically move large volumes ofr materialr (fig. 85).r One rockfall,r r graphically described by John Muir,r occurred in Yosemite Valley during ther great Owens Valley earthquake of 1872: “The Eagler Rock on the south wall, about a half mile up ther Valley, gave way and I saw it falling in thousands of ther great boulders I had so long been studying, pouring tor the Valley floor in a free curve luminous from friction,r making a terribly sublime spectacle—an arc of glowing,r passionate fire, fifteen hundred feet span, as true inr form and as serene in beauty as a rainbow in the midstr of the stupendous, roaring rock-storm.” In May 1980,r two people were critically injured on the Sierra Pointr Trail east of Happy Isles by rocks dislodged during ar much smaller earthquake whose epicenter was nearr Mammoth Lakes, over 35 mi to the east. Ironically,r this trail had been officially closed some years earlier,r owing to the danger of loose rock. Another rockfallr that killed three hikers on the Yosemite Falls Trail 6r months later may have been a delayed result of rockr loosened during that same earthquake. A rockfall createdr the dam that formed Mirror Lake, which, in turn,r r r r is being filled by sediment carried by Tenaya Creek.r Dynamic change is indeed taking place, though slowly.r One lifetime is not enough to see dramatic changes.r

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r **r AVALANCHE CHUTES AND TALUS CONES in Leer r Vining Canyon east of Tioga Pass.r (Fig. 84)r** r

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r No sooner had the glaciers departed than weatheringr processes began to attack the freshly scoured rockr surfaces left behind. Surface spalling leaves only remnantsr of once-extensive glacial polish. When the polishr and glacial striations are all gone, some of the mostr striking evidence for past glaciation will be lost.r

r r

r The landscape is slowly but continually being modified.r The Sierra Nevada continues to rise—and continuesr to be eroded. Lakes are being filled with sediment.r When erosion outpaces uplift, as it eventuallyr will, the range will be reduced to rolling upland, muchr as it was tens of millions of years ago. In the meantime,r Yosemite remains a delight to the visitor, especially tor those who learn to read the story its rocks and landscaper have to tell.r

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r **r THE SLIDE on Slide Mountain west of Matterhorn Peak, near north boundary of the park. This giant rockslide, more than 1/2 mi longr and 1/4 mi wide, roared down with such energy that it climbed almost 200 vertical feet up the opposite side of the canyon.r Photograph by Robert W. Cameron. © Cameron and Co.; used with permission.r (Fig. 85)r** r

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r http://www.yosemite.ca.us/library/geologic_story_of_yosemite/final_evolution.htmlr

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DEFINITON OF TERMS

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r I have tried to minimize the use of technical terms inr this volume, but some jargon is inevitable in anyr discussion of technical matters. Most of the strictlyr geologic terms that are apt to be stumbling blocks arer defined where they first appear in the text; for case ofr reference, some of them are summarized here in thisr short glossary. Geologic time terms are not includedr (see fig. 7).r

r r

Alluvial fan. A sloping, fan-shaped mass of looser rock material deposited by a stream where it emergesr from a canyon onto a broad valley or plain.r

r r

Alluvium. A general term for clay, silt, sand, andr gravel deposited by running water, such as a stream.r

r r

Andesite. A volcanic rock of intermediate composition,r with a silica (SiO_2) content generally of fromr 50 to 60 percent.r

r r

Arête. A narrow, serrate mountain ridger (fig. 56).r

r r

Basalt. The most common type of volcanic rock,r generally fine grained, dark, and heavy, with a silicar (SiO_2) content of no more than about 50 percent.r

r r

Batholith. A very large body of plutonic rock. Ther Sierra Nevada batholith is a composite of numerousr smaller bodies (plutons) that represent repeatedr intrusions of granitic magma.r

r r

Bedding. The arrangement of sedimentary rock inr beds or layers, reflecting the fact that water or windr spread sediment they deposit in thin sheets. Ther beds of sedimentary rock are these successively accumulatedr sheets.r

r r

Bergschrund. A deep crevice near the head of anr alpine glacier that separates moving ice from ther headwall of the cirque. It may be covered by or filledr with snow during the winter, but visible andr reopened in the summerr (fig. 56).r

r r

Breccia. A consolidated rock composed of angularr rock fragments.r

r r

Cirque. A bowl-shaped, theaterlike basin at the headr of a glacial valleyr (fig. 56).r

r r

Cleavage. The tendency of a mineral to break alongr definite planes controlled by its molecular structurer and producing smooth surfaces.r

r r

Columnar jointing. Joints that bound parallel prismaticr columns, polygonal in cross section, formed byr contraction during cooling in some lava flows, dikes,r and volcanic plugs (a plug consists of solidified lavar in an old volcanic conduit)r (fig. 32).r

r r

Conglomerate. A rock, the consolidated equivalentr of gravel.r

r r

Crust (of the Earth). The outermost of the concentricr shells that make up the Earth. The crust is 4r to 5 mi thick beneath oceans and 20 to 35 mi thickr beneath continentsr (fig. 25).r

r r

Dike. A sheetlike body of igneous rock that wasr intruded while molten into cracks in older rocksr (figs. 13,r 17).r

r r

Diorite. A plutonic rock composed primarily of plagioclaser and dark minerals; generally fine grainedr (figs. 9,r 12).r

r r

Erratic (glacial). A rock fragment, generally large,r that has been transported from a distant source byr the action of glacial icer (fig. 61).r

r r

Exfoliation. Any process by which concentricr scales, plates, or shells of rock are successivelyr spalled or stripped from the surface of a rock mass. Itr produces such diverse results as the spalling off ofr glacial polish a fraction of an inch thick and ther formation of sheet joints many feet thickr (figs. 39,r 55).r

r r

Fault. A fracture in the Earth’s crust along whichr there has been movement parallel to the fracturer plane.r

r r

Gradient. As applied to streams, the inclination ofr the bed.r

r r

Granitic rocks. Includes granite (in the technicalr sense), granodiorite, and tonaliter (seer fig. 9r forr classification of plutonic rocks).r

r r

Grus. The fragmental products of granular disintegrationr of granitic rocks in place; granitic sandr (fig. 45).r

r r

High Sierra. A term coined byr r J.D. Whitneyr (1868)r to describe the higher region of the Sierra Nevada,r much of it above timberline.r

r r

Igneous Rock. A rock formed by solidification of hotr molten material, either at depth in the Earth’s crustr (plutonic) or erupted at the Earth’s surface (volcanic).r

r r

Intrude, intruded, intrusion. Process by whichr magma invades or is injected into preexisting rockr bodies.r

r r

Intrusive suite. A grouping of individual plutons orr plutonic rock units having significant features inr common and thought to have formed from the samer parent magma.r

r r

Isotope. Any of two or more forms of an elementr with the same or very closely related properties andr the same atomic number but different atomicr weights. Some isotopes are radioactive and changer to different isotopes at a constant rater (fig. 7).r

r r

Joint. A fracture along which there has been little orr no movement parallel to the fracture plane.r

r r r r

Lithosphere. The rigid outer portion of the Earthr comprising the Earth's crust and the uppermost partr of the upper mantler (fig. 25).r

r r

Magma. Naturally occuring molten rock generatedr within the Earth. Magma may intrude to formr plutonic rock or be extruded to form volcanic rock.r

r r

Mantle (of the Earth). The intermediate of ther concentric shells that make up the Earth; it liesr beneath the crust.r (fig. 25).r

r r

Metamorphic rock. Rock changed materially inr composition or appearance by heat, pressure, orr infiltrations at depth in the Earth's crust.r

r r

Mineral. A naturally occurring, inanimate substancer of definite chemical composition and distinctiver physical and molecular properties. Minerals make upr rocks.r

r r

Moraine. An accumulation of glacial till with anr initial topographic expression of its own, commonlyr a ridge. Several varieties are described in the textr (fig. 62).r

r r

Pegmatite. An exceedingly coarsely crystalline plutonic rock,r commonly in dikes or pods a few feetr across. Individual crystals are several inches to a footr or more across.r

r r

Phenocryst. A large crystal in an igneous rock,r embedded in a finer grained matrix.r

r r

Plate (tectonic). A segment of the Earth's crust inr constant motion relative to other segmentsr (fig. 26).r

r r

Pluton. A general term applied to any body ofr intrusive igneous rock of deep-seated origin, regardless ofr shape or size.r

r r

Plutonic rock. Igneous rock formed by solidificationr of magma deep within the Earth's crust.r

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Porphyritic. Said of an igneous-rock texture withr larger crystals scattered through a finer grainedr matrix.r

r r

Porphyry. A porphyritic rock with conspicuous phenocrystsr in a very fine grained matrixr (fig. 21).r

r r

Pre-Tahoe glaciation. Composite of the one orr more major glaciations in Yosemite that preceded ther Tahoe glaciation. Supersedes the El Portal andr Glacier Point glaciations of Matthes' usage inr Yosemite.r

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Ptroclastic rock. Rock formed of ash or otherr fragmental material explosively ejected from a volcano.r

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Quartz monzonite. A granitelike plutonic rockr containing about equal proportions of potassiumr feldspar and plagioclase and less than 20 percentr quartz under the classification system now in use.r Rocks in the Yosemite area containing more than 20r percent quartz that were previously called quartzr monzonite are now classified as graniter (fig. 9).r

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Rhyolite. A light-colored volcanic rock with a highr silica (SiO_2) content of at least 70 percent.r

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Roche Moutonnée. A protruding knob of bedrockr glacially eroded to have a gently inclined, striatedr upstream slope and a steep, rough, and hackly downstreamr side. Commonly translated as "sheep,"r moutonnée is actually a French adjective meaningr "fleecy"; the term was introduced into geology inr 1786 in describing rounded Alpine hills whoser repeated curves, taken as a whole and as seen from ar distance, resemble a thick fleecer (figs. 54,r 70).r

r r

Schist. A crystalline metamorphic rock composedr chiefly of platy mineral grains, such as mica, orientedr so that the rock tends to split into layers orr slabs.r

r r

Schlieren. Streaky concentrations of dark mineralsr in a granitic rock, caused by movement within ther partially solidified magmar (fig. 16).r

r r

Sedimentary rock. Rock formed by consolidation ofr sediment (gravel, sand, mud) deposited at the surfacer of the Earth.r

r r

Silica (SiO_2). Occurs as the natural mineral quartz,r including various fine-grained varieties, such asr chert. The element silicon (Si) also occurs in mostr rock-forming minerals (silicates), such as feldspars.r

r r

Subduction. The process wherein an oceanic plater converging with a continental plate is deflectedr downward and consumed into the mantle beneathr the continental plater (fig. 28).r

r r

Tahoe glaciation. The intermediate of the threer major glaciations recognized in Yosemite. Approximatelyr equivalent to the earlier part of the Wisconsinr glaciation of Matthes.r

r r

Talus. An accumulation of coarse, angular rock fragmentsr derived from and resting at the base of a cliffr or very steep slope.r

r r

Till. Glacially transported material deposited directlyr by ice, without transportation or sorting by waterr (fig. 60).r

r r

Tioga glaciation. The latest of the three majorr glaciations recognized in Yosemite. Approximatelyr equivalent to the younger part of the Wisconsinr glaciation of Matthes.r

r r

Trimline. A sharp boundary line marking the maximumr upper level of the margins of a glacier. Itr commonly separates jagged cliffs above from glaciallyr smoothed rock surfaces belowr (figs. 56,r 57).r

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Tuff. Rock formed from consolidation of volcanic ash.r

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r *r This map depicts the Tioga icefield and associated valleyr glaciers as viewed looking down toward the northeast atr an angle of 30°. It is an enlarged and more detailedr version ofr* figure 67*r in this volume.r* r

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r *r Map showing the maximum extent of Tioga-age glaciersr and the distribution of glacial moraines of various ages. Itr provides the technical background forr figure 67r in this volume (Tioga icefield and valley glaciers).r* r

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A WORD OF THANKS

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r Geologist Alfred C. Lane once wrote,r “The progressr of knowledge is like the growth of a coral reef; eachr generation builds upon that which has been left behindr by those who have gone before.”r So it is with thisr volume. I have drawn upon so many sources of informationr in presenting this geologic story of Yosemite that itr is impossible to acknowledge the individual contributionsr of each. This is especially true of the historicalr material and of the numerous works that have delineatedr the regional geologic framework within which Ir have placed Yosemite. For those who wish to delver further into various aspects of Yosemite history andr geology, several pertinent references, briefly annotated,r are listed in the bibliography; these, in turn, will leadr to additional source materials.r

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r I must, however, specifically acknowledge the modernr geologic mapping and detailed studies by my U.S.r Geological Survey colleagues that made possible ther present volume, as well as the newr r geologic map ofr Yosemite National Park published separatelyr (Huberr and others, in press). For that foundation and for theirr continuing support and contributions, I thank Paul Bateman,r Lew Calk, Frank Dodge, Bill Keith, Ron Kistler,r Dallas Peck, Dean Rinehart, Jim Seitz, andr Clyde Wahrhaftig. Clyde Wahrhaftig also developedr the explanation for the formation of weather pans,r described on page 36.r

r Julie Roller assisted me in the field and in the earlyr stages of writing this volume and compiling the geologicr map. Thoughtful manuscript reviews werer provided by many of my colleagues, as well as byr Genny Smith of Palo Alto and Mammoth Lakes,r Calif., and Jim Sano of the National Park Service.r Finally, during excursions to Yosemite, the hospitalityr and enthusiastic support of every member of the Parkr Service staff there contributed significantly to the successr of the project. Jan van Wagtendonk was particularlyr helpful in assisting with logistic support.r Thanks are also due to the individuals and organizationsr permitting use of their photographs; those not byr myself are credited in the captions, except for ther frontispiece, which was contributed by Dallas Peck.r Throughout the process of illustrating this volume, Ir have had the distinct pleasure of drawing upon andr working with the artistic talents of cartographer Tau Rho Alphar and illustrator Susan Mayfield. In particular,r Tau created the oblique views of Yosemite’sr physiographyr (fig. 6)r and the Tioga glaciationr (fig. 67),r and the panorama from Mount Hoffmanr (fig. 5).r The oblique viewsr (figs.r 6,r 67)r have been published inr much-enlarged, more detailed versions asr U.S. Geological Survey Miscellaneous Investigations Series Mapsr I-1776 and I-1885, respectively.rr r r r
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Geologic Maps

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GEOLOGIC MAP OF YOSEMITE NATIONAL PARK AND VICINITY — PLATE 1

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GEOLOGIC MAPS OF YOSEMITE

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r **r A geologic map shows the distribution of differentr types of rocks at the Earth's surface. Construction ofr such a map is usually prerequisite to understandingr the geology of any given area. Geologic quadrangler maps at the same scale as topographic quadrangler maps of the U.S. Geological Survey's 15-minuter series (1 in. to 1 mi) currently are available for only ar little more than half of the park area. Two otherr geologic maps are especially suitable to this volumer because they show details of Yosemite geology notr possible to show at the small scale of the geologicr maps herein. A newr r geologic map of Yosemiter National Park and vicinity, at a scale of 1 in. to aboutr 2 mi, has recently been compiled from both publishedr and unpublished geologic mapping by manyr individuals (Huber and others, in pressr [Editor's note:r 1989—dea]).r A morer detailed geologic map of Yosemite Valley is alsor available (Calkins and others, 1985). The fieldworkr for this latter map was carried out by Frank Calkinsr between 1913 and 1916, but Calkins, the consummater perfectionist, was never completely satisfied withr his map and would not let it be published during hisr lifetime. Though now belatedly published as a historicalr document, it is still the best geologic map ofr Yosemite Valley available. These two geologic maps,r reduced and generalized, are the basis for the geologicr maps in this volumer (pls. 1, 2).r** r

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GEOLOGIC MAP OF THEr r YOSEMITE VALLEY AREAr r PLATE 2

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r **r YOSEMITE NATIONAL PARK AND VICINITY —r index map showing key localities and geographic features.r** r

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r **r INDEX MAP for topographic and geologic maps of ther**
r Yosemite area. In addition to geologic maps of Yosemite Valleyr
r and Yosemite National Park and vicinity, geologic maps of the 15-minuter
r quadrangles with underlined names are available.r r

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r **r INDEX MAP for 7.5' topographic maps of ther**
r Yosemite area.r [Editor's note:r not in original book—dea].r r

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About the Author

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r *N. King Huber, 2004*r

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r N. King Huber was born January 14, 1926 in Duluth, Minnesota.r His interest in geology started when he hunted for agates along the Lake Superior shorline.r He served in the U.S. Army from 1944 to 1946 in Europe and Japan.r Huber married Martha Ann Barr June 2, 1951 and they had two sons.r He received a BS from Franklin and Marshall College in 1953,r and MS and Ph.D. from Northwestern University in 1952 and 1956, respectively.r In 1953 he was elected fellow of The Geological Society of America.r

r r

r In 1954 King Huber joined the U.S. Geological Survey in Menlo Park, Californiar as a geologist and worked there for his entire career.r Huber first visited Yosemite with his wife in 1955.r His specialties were in Yosemite National Park andr Sierra Nevada geology, geomorphology, and glacial geology.r Dr. Huber has written many professional papers on geology,r has authored several geologic maps of the Sierra Nevada,r and written books onr Isle Royale National Parkr andr r Devils Postpile National Monument geology.r

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r King Huber and his wife Martha Ann had two sons, Steven King and Richard Norman Huber.r

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r After retirement, Dr. Huber was Geologist Emeritus with the USGS,r contributed several geology-related articles to ther Yosemite Association's member publicationr *Yosemite,*r and was the *de facto* geologist for Yosemite National Park,r providing geological training for Park Service interpretive staff.r Dr. Huber died February 24, 2007.r Before his death, he completed a book,r *Geological Ramblings in Yosemite* (2007),r a collection of articles published in *Yosemite*.r

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r Norman King Huber (1926 - 2007),r *The Geologic Story of Yosemite National Park*r (Washington: Government Printing Office, 1987).r USGS Bulletin 1595.r LCCN 86600008.r Sup. of Docs no.:I 19.3:1595.r xi+64 pages. Illustrated (some color), color maps. 28 cm.r Perfect bound in paper wrappers with front color photograph.r Illustrated by Tau Rho Alpha and Susan Mayfield.r Library of Congress call number QE75.B9 no. 1595.r

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r The 1987 printing is no longer available from the USGS.r However, it wasr r reprinted in 1989 and later by the Yosemite Association.r The only changes were to the title pages and cover.r Most of the photographs in the book are available online from ther USGS library'sr photo archive.r

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