Yosemite

1. John Muir described Yosemite Valley as “by far the grandest of all the special temples of Nature I was ever permitted to enter.” Coming from the “Father of America’s National Parks”, that’s saying a lot.
2. The famed naturalist and ecologist had a decent understanding of geology and was perhaps the first to propose that this magnificent valley was carved by glaciers. Indeed there is perhaps no finer place in the world to see the artistry that glaciers have worked on granite.
3. We’ll cover Yosemite’s glacial processes in due time, but first let’s have a look at where all that beautiful granite came from.
4. The parks we studied in the Cascades and in Southern Alaska are in active subduction zones…
5. … but the granitic rocks of Yosemite and the rest of the Sierra Nevada formed in an ancient subduction zone…
6. … about 100 million years ago. Like the modern Cascadian subduction zone, the ancient one involved the subduction of the Farallon Plate under the North American Plate and the development of a chain of volcanoes; only this one was much longer than the Cascades. It involved the entire west coast of North America, all the way from Northern Canada to Central Mexico.
7. The granitic rocks of the Sierra Nevada, as well as several other western North American mountain ranges, represent the eroded remnants of magma chambers that fed the ancient volcanoes. These massive complexes of plutonic igneous rock are called batholiths. Today the Coast Ranges, Idaho, Sierra Nevada and Peninsular Ranges Batholiths are discontinuous, …
8. … but before the Pacific Plate encountered the edge of the North American Plate, all four batholiths may have formed a continuous plutonic root beneath the once great chain of volcanoes.
9. The meeting of the Pacific and North American Plates broke the chain as subduction of the Farallon Plate ended and a transform plate boundary developed. Subduction continued where fragments of the old Farallon Plate remained, now known as the Juan de Fuca and Cocos plates.
10. The once continuous volcanic /plutonic arc was further segmented by Basin and Range extension and San Andreas transform motion.
11. So the massive granite edifices in Yosemite are the erosion-exposed magma chambers of former volcanoes …
12. …and towering composite volcanoes like Mt. Rainier stood above those magma chambers 100 million years ago.
13. Like Mt. Rainier those volcanoes would have been comprised mainly of andesite – a rapidly cooled, fine-grained volcanic rock of intermediate composition.
14. Several kilometers beneath them, where their magma chambers cooled much more slowly - coarse grained granodiorite formed.
15. As uplift occurred …
16. … the volcanic rocks where eroded…
17. …
18. …
19. … eventually exposing the once deeply buried plutonic rocks.
20. But plutons had to intrude into something. What were those rocks like that existed before the plutons?
21. The oldest rocks in the Yosemite region are exposed as discontinuous patches of mostly metamorphosed, folded …
22. … and tilted strata.
23. Since these rocks are older than the plutons and the Sierra Nevada batholith is made of these plutons, we will refer to them as the pre-batholithic rocks. In Yosemite National Park, pre-batholithic rocks fall into three general types.
24. The oldest of these includes quartzite, schist and marble, which are the metamorphic equivalents of quartz sandstone, shale and limestone. By now you should recognize that as a typical divergent continental margin assemblage and it shouldn’t surprise you therefore that these rocks are late Proterozoic to early Cambrian in age, which is the same age as the Grand Canyon strata laid down during the first great transgression.
25. Like most of the pre-batholithic rocks in the Yosemite area, these rocks outcrop mostly on the western and eastern margins of the park. Shown in green and blue in this geologic map, the pre-batholithic rocks represent “roof pendants” – meaning portions of the roof of the old magma chamber that sagged-down like pendants into the magma.
26. In addition to the afore mentioned DCM sediments, two other pre-batholithic rock groups exist in the Yosemite area. The first of these, the “Shoofly Complex” suggests that west coast orogeny started early in the Paleozoic and perhaps even as far back as the late Proterozoic, because its schists and gneisses are derived from the erosion of continental sources (implying mountain building) and are intruded by Paleozoic granites.
27. Where the Shoofly Complex is not severely metamorphosed …
28. … it is reminiscent of the flysch deposits of the Valdez Group in Kenai Fjords National Park. Recall that flysch is a syn-orogenic sediment - meaning that it deposits at the same time as orogeny.
29. In most places the Shoo Fly Complex is folded and metamorphosed with a strong foliation developed perpendicular to the direction of compression.
30. It is also typically refolded, indicating that it was affected by more than one orogeny.
31. Such would be the case if the Shoo Fly Complex originated from the Paleozoic collision and amalgamation of rifted continental fragments …
32. …and island arc material …
33. … that were re-compressed during the Mesozoic as various other terranes accreted to the western edge of North America. Anyway, that’s one interpretation. With all those terranes moving about off western North America, there’s a lot of room for interpretation.
34. With all that Paleozoic orogeny, it follows that somewhere subduction was busy making mélange. The Calaveras Complex represents that mélange. The mid to late Paleozoic Calaveras Complex …
35. … highlighted here is thrust under the older Shoo Fly Complex along the Calaveras - Shoo Fly Thrust (CSFT) in typical mélange fashion.
36. Here we see the banded chert and phyllite (metamorphosed mud) of the Calaveras Complex exposed along the Merced River that flows through Yosemite. Note the contorted folding typical of mélange rocks …
37. … and reminiscent of the McHugh Complex in Kenai Fjords National Park …
38. … and the Franciscan Complex in Redwoods National Park.
39. OK, I know you’re anxious to get to the main event, the formation of the Sierra Nevada Batholith, but we have one more stop to make first. There’s a significant amount of rock in and around the park that formed at about the same time as the batholith. These “syn-batholithic rocks are…
40. …Triassic to Jurassic in age, …
41. … generally volcanic and sedimentary rocks derived form volcanic rocks, …
42. … and represent volcanic activity taking place above the plutons which comprise the batholith.
43. Shown in various shades of green on this geologic map, like the pre-batholithic rocks, the syn-batholithic rock’s outcrops are discontinuous and occur mainly as roof pendants.
44. This interpretation of Mesozoic paleogeography suggests that the syn-batholithic volcanic rocks in Yosemite represent the southern portion of an extensive volcanic arc that existed well westward of the continent’s western margin.
45. By Jurassic time a second volcanic arc existed between the main Sierran arc and the continent’s edge.
46. As subduction progressed, compression and associated thrust faulting brought the two arcs closer …
47. .. .fused them together …
48. … and accreted them to the North American Plate.
49. By Cretaceous time, subduction had changed from ocean-ocean to ocean-continent.
50. Continued compression tightened up the newly accreted continental margin while a shallowing subduction angle caused arc magmatism to migrate eastward…
51. … along with associated foreland folding …
52. … and thrust faulting.
53. By the early Cenozoic, active arc magmatism had completely left the Yosemite area.
54. The batholithic rocks that formed beneath the volcanic arcs have ages that cluster into three distinct groups. The oldest group is about 210 to 150 million years old, or late Triassic to Jurassic.
55. These oldest of the batholithic rocks are shown in purple here and tend to be mostly diorite and gabbro.
56. They are intruded by the younger and generally more felsic plutonic rocks shown in the darker pink here…
57. … which belong to the second group of batholithic rocks, mostly represented by the Western Intrusive Suite. At 120 to 100 million years old, the Western Intrusive Suite is Cretaceous in age.
58. The massive granite monolith of El Capitan is representative of the Western Intrusive Suite.
59. The El Capitan Granite is a beautiful rock comprised of slow-cooled, clearly visible crystals.
60. Typical of granitic rocks, it contains few dark minerals and is mostly quartz (gray glassy looking grains), ….
61. … and alkali feldspar (white grains).
62. The few ferromagnesian minerals here are mostly biotite mica (black grains).
63. The same period of magmatism also produced a few relatively mafic rocks most notably represented by the so-called “Map of North America”…
64. … which is a diorite intrusion on the east face of El Capitan.
65. Viewed from the right angle and degree of tolerance …
66. … the resemblance, albeit crude, is obvious. Given the position of Baja California, perhaps this is a version of what North America will look like in the geologic future.
67. The Western and Minor Intrusive Suites were emplaced early in the ocean-continent collision known as the Nevadan Orogeny. Since the accretionary wedge was relatively small and the angle of subduction relatively steep at the time, subduction-generated magmatism occurred fairly close to the trench.
68. But the accelerating westward motion of the North American plate, combined with a growing accretionary wedge, flattened the subduction angle …
69. … such that by the late Cretaceous, arc magmatism had shifted eastward and emplaced the “Tuolumne Intrusive Suite”.
70. This suite of plutonic igneous rocks is about 95 to 80 million years old and is geologically well known as the rock of which Half Dome is made.
71. If we superimpose the geologic map onto Yosemite’s topography in Google Earth …
72. … we can see the pink, dashed-pattern of the Tuolumne Intrusive Suite covering the eastern part of the park in the background, while the Western Intrusive Suite (solid colors) covers the foreground.
73. The contact between the two intrusive suites is complex and includes syn-batholithic roof pendants as well as a spectrum of various plutonic rocks genetically related to the emplacement of the Tuolumne Intrusive Suite.
74. If we expand the previous map area several times we can see the vast Tuolumne Intrusive Suite in its entirety, covering almost the entire eastern portion of the park.
75. Shaped something like a horse sitting on its rear, the Tuolumne Intrusive Suite is a world-class example of a “nested” pluton.
76. Like nested bowls, the term implies that progressively smaller plutons are concentrically “stacked” inside larger plutons.
77. As is typically the case for nested plutons, the Tuolumne Intrusive Suite is more mafic on the outside and felsic on the inside. Less common in nested plutons (but certainly not rare) are Tuolumne’s textural differences, which vary from equigranular on the outside, to commonly porphyritic textures on the inside.
78. We can see this pattern in the Half Dome Granodiorite. This piece is near the outside edge of the Tuolumne Intrusive Suite. Notice that all of its crystals are about the same size.
79. In this specimen taken from further inside the suite, notice that some of the crystals are much larger than others and thus the texture is porphyritic.
80. Towards the center of the suite the composition and texture is so much different than the edge, that a different formation name is given. The Cathedral Peak Granodiorite is blatantly porphyritic, with huge alkali feldspar crystals (phenocrysts).
81. Porphyries always indicate two different cooling rates – very slow cooling for the large phenocrysts and more rapid cooling for the finer matrix crystals. As we will see, the models for producing nested plutons not only account for the silica variations seen, but also explain the formation of porphyritic textures.
82. One model works something like this: Since the lower part of the crust is ductile …
83. … plutons, driven by their relative buoyancy, will rise from subduction zones and work their way into the pliable lower crust ...
84. … until they encounter crust equal to their own density.
85. Since this takes place near the bottom of the crust, the cooling rate is very slow, which gives ample time for fractionation of the magma to occur. Like an ice cube freezing, cooling progresses inward such that at some point the outside of the pluton will be solidified while the inside is still magma. Because low silica (mafic) minerals are the first to crystallize from a cooling silicate magma (remember Bowen’s Reaction Series?), the solidified margin of the pluton will be lower in silica than the interior. The magma has now separated, (fractionated) into different components based on silica content. Any crystals growing in the magma at this time will be relatively large because the cooling rate is so slow.
86. Because magma density decreases as silica increases, the residual, silica-rich magma will be buoyed upwards until again it encounters crust equal to its own density.
87. As this magma cools, the faster cooling rate near the surface causes the upper portion of the magma to solidify without fractionation while the lower portion continues to undergo fractionation, producing further silica enrichment in the residual magma.
88. The buoyancy of that silica-enriched magma will cause it to rise as a second pulse of magma forced into the center of the first pulse.
89. When this second batch of magma crystallizes, not only will it have more silica than the first batch, but it is likely to be porphyritic as well. That’s because it began crystallizing at depth where cooling is slow and large crystals form, but it competed crystallization nearer to the surface, where cooling is faster and smaller crystals form.
90. An alternate model for nested plutons relies on deferent degrees of partial melting to achieve the silica variations, but again could produce the porphyritic textures through crystallization at different depths. Here, a pluton gets stuck at the base of the continental crust …
91. … where it generates a more silica-rich magma by partially melting the base of the continental crust. Silica enrichment buoys the partial melt further upward into the continental crust while the original pluton and residual solids from partial melting become part of the lower crust and upper mantle.
92. If a smaller pluton gets trapped at the base of the crust, …
93. … only a small portion of the crust will melt, which will be only the very most silica-rich minerals. Thus this partial melt will be smaller in volume but greater in silica concentration.
94. Again a nested pluton is produced with a more silica-rich center, but this model may not produce as distinctly porphyritic rocks as the first.
95. The development of the Tuolumne Intrusive Suite probably involved one or both of these mechanisms. Detailed field study of the suite indicates that the first pulse of magma solidified to produce the relatively mafic-rich granodiorite of Kuna Crest. Before this magma had completely solidified …
96. … a surge of fresh magma locally breached the Kuna Crest and solidified as the equigranular phase of the Half Dome Granodiorite. Before this magma completely solidified …
97. … a new pulse of magma intruded and formed the porphyritic phase of the Half Dome Granodiorite.
98. The third surge of magma was followed by the solidification of the Cathedral Peak Granodiorite and emplacement of the Johnson Granite Porphyry.
99. Well if your head hasn’t exploded with all those magma surges, you might think you have a pretty good understanding of magmatic processes now.
100. Well think again!
101. The Tuolumne Intrusive Suite is notorious for boggling geologists with fiendish textures and bizarre structural relationships.
102. There are places where these plutonic rocks take on down-right sedimentary textures.
103. Yet layers can be abruptly juxtaposed against perfectly ordinary crystalline textures.
104. I’ll not explain these …
105. … because I can’t!
106. There even are textures that resemble turbidites!
107. But my favorites are the magma worms!
108. Mesozoic magmatic madness ends in the Cenozoic.
109. As it did during the Nevadan Orogeny, the Farallon Plate continued to subduct under North America …
110. … but the accelerating westward motion of the North American Plate ….
111. … combined with ever younger and more buoyant crust arriving at the subduction zone…
112. … caused the uplift and erosion of the leading edge of the North American Plate. By the Mid-Cenozoic erosion had exposed the Sierra Nevada Batholith and a vast peneplain sloped towards the ocean.
113. Across this peneplain the Merced and several other Sierra Nevada rivers flowed. Because the gradient was very low, these rivers did little down-cutting.
114. But that will change considerably when the arrival of the Pacific Plate at the trench changes stress patterns from compression to shear stress and extension. Not only did this event initiate the formation of the Basin and Range Province …
115. … but at the same time the entire Sierra Block uplifts along a regional-scale normal fault.
116. That creates a steep fault escarpment bordering the Basin and Range Province on the east side of the Sierra Nevada, …
117. … and an arrangement similar in appearance to the Grand Tetons.
118. At 11,000 meters, displacement on the Sierra fault is much less than on the Teton Fault, but that uplift is very young and it has been accelerating. Uplift tilted the Sierran Block to the west, greatly increasing stream gradient for the main east-west flowing streams like the Merced, but it had much less effect on the more north-south oriented tributaries.
119. This caused the old, relatively stable Merced River …
120. … to down-cut into its canyon…
121. … and to a much lower elevation along the high gradient main channel relative to its low gradient tributaries. The smaller, less down-cut tributaries dropped-off steeply where they entered the main canyon, forming “hanging valleys”.
122. Pleistocene glaciation will accentuate this relationship …
123. … as large glaciers have far more erosive power than small glaciers.
124. Although hanging valleys are certainly a characteristic feature of glaciated landscapes, the exceptional drop-offs of Yosemite’s are in part due to pre-existing hanging valleys created by river erosion.
125. All that uplift and erosion unloaded the weight of 1000’s of meters of rock overlying the plutons.
126. The resultant reduction in pressure was one of the main reasons for the formation of joints within the plutonic rocks. Joints are rock fractures along which no displacement has taken place. Three joint types occur in Yosemite National Park and they play a major role in the development of many of the park’s landforms. Master joints are regional in extent, but widely spaced.
127. Half Dome’s near-vertical north face is a prime example of a master joint. Such joints probably are related to regional tectonic stress.
128. From this rarely seen aerial perspective of Half Dome you can see a second master joint shaping its back side.
129. Looking straight down Half Dome you can see how its shape is not truly dome-like but, rather, is distinctly elongated parallel to the master joints.
130. A complex system of more closely-spaced, “lesser joints” lie buried beneath the valley’s sediments, weakening the rock and facilitating both stream and glacial erosion. Such joints can form by contraction associated with pluton cooling.
131. The third type of joint, the skin-like “sheet joints” are most obvious on the top of Half Dome, …
132. … which can be accessed via the infamous cable route. From this perspective you can see that Half Dome is more of a rounded-off vertical slab rather than a semi-circular dome.
133. The rounding is due to the action of sheet joints which are prominent on the top of Half Dome. Sheet Joints form from expansion due to pressure release as erosion removes the massive weight of rock that once sat on top of the plutons.
134. Because the pressure reduction on the top of the pluton is greater than in the pluton’s interior, …
135. … the amount of expansion is greatest near the surface. To accommodate the differential expansion, sheet joints therefore form parallel to the surface in a concentric onion-like arrangement.
136. Frost wedging and other processes widen and loosen the joint-bounded slabs until they eventually slide off …
137. …
138. … in a process called exfoliation. Exfoliation ultimately smoothes and rounds the exposed plutons ….
139. … forming exfoliation domes.
140. These lie just north of Half Dome hence the name “North Dome”.
141. Below North Dome lie the great sheet joints known as the Royal Arches. These are somewhat special sheet joints in that they formed in response to the release of pressure on the *wall* of the valley as glacial erosion of the valley removed the confining pressure on these rocks. Nonetheless, they ultimately have the same rounding affect as all sheet joints. As these great slabs spall off, North Dome will widen and blend more seamlessly into the valley slopes.
142. The absence of jointing also controls topography. The massive, non-jointed El Capitan granite was strong enough to resist glacial erosion and support some of the highest vertical cliffs in the world.
143. No study of the geology of Yosemite National Park is complete without a thorough discussion of the affects of Pleistocene glaciation.
144. During numerous times in the Pleistocene the entire Yosemite Valley …
145. …was covered with glacial ice.
146. Glacial Polish on the walls of the valley …
147. … and importantly, above the valley rim…
148. .. where random, ice-deposited boulders called glacial erratics rest, attest to the erosion of glaciers …
149. … and that they spilled out from the confines of the valley on to the surrounding terrain. Ice thickness was not enough to cover the entire land surface around Yosemite and so, like this ice field in Greenland, numerous rocky peaks called Nunataks were exposed above the ice.
150. Half Dome was once a Nunatak.
151. Roches Moutonnees are of particular interest in Yosemite.
152. You should remember them from our study of Isle Royale. Remember that the steep side forms as glacial ice freezes to jointed rock and “plucks” it away as the ice moves.
153. Lembert Dome in Tuolumne Meadows is a beautiful (and huge!) example of a roche moutonnée. Can you tell which direction the glacier moved?
154. Right to left is correct.
155. Just below Half Dome lie two other good examples of roche moutonnées - Mt Broderick and Liberty Cap.
156. From the right angle the characteristic roche moutonnée asymmetry is apparent.
157. Glacial plucking on the down flow side of Liberty Cap formed the steep drop-off down which Nevada Falls cascades.
158. Nevada Falls belongs to a type of waterfall called a glacial “staircase” fall.
159. Vernal Falls is part of this same “staircase”.
160. If you look closely at this Google Earth view you can see that the steps that create Vernal and Nevada falls are aligned parallel to the system of master joints that were so influential in the formation of Half Dome.
161. This suicide view of Nevada Falls clearly shows the master joint surface exposed by glacial plucking.
162. The half-mile distance between Nevada Falls …
163. … and Vernal Falls provides some perspective …
164. …on the spacing of the master joints.
165. Yosemite’s second type of waterfall issues from the much higher hanging valleys.
166. Remember that hanging valleys form where a small glacier joins the far deeper trough of a much larger glacier.
167. Bridal Veil Falls issues from this hanging valley and is a classic example.
168. Although one of the most popular waterfalls in the park, at 620 feet Bridal Veil is nowhere near the highest.
169. Ribbon Falls comes in at 1,612 feet …
170. … and Yosemite Falls at 2,425 feet – making it the 7th highest in world. Both exemplify the terrific heights typical of hanging valley water falls.
171. For nearly a hundred years there was another type of fall in Yosemite. Back in the day, a great pile of embers would be pushed nightly from the top of glacier point …
172. … towards great crowds of onlookers below. Congestion and heightened environmental consciousness led to the popular attraction’s termination in 1968.
173. The final geologic touches on the park were applied by glacial deposition.
174. Although touted as a classic example of a U-shaped glacial trough, you can see that the valley is actually quite flat from side to side.
175. That’s because of the sediment that accumulated in Lake Yosemite – a large lake that formed behind a recessional moraine located below Bridal Veil Falls.
176. Because lake sediments are more permeable than the unsorted till that makes up moraines, the water table is lower in areas where the lake sediments deposited. Lower water tables and periodic natural wildfires combine to inhibit tree growth such that only grasses survive and thus meadows form. Note that trees only grow next to the Merced River here.
177. Meadows used to cover much more of the valley but by one estimate, they only cover 6.8% of their 1866 area.
178. Meadow size reduction in Yosemite Valley is largely a result of human fire-suppression, which has allowed tree seedlings to gain a foot hold.