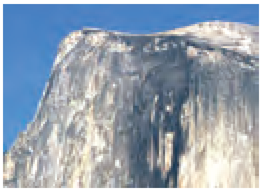
Classic localities explained 8



Yosemite—the Incomparable Valley

Cut deep into the heart of California's Sierra Nevada, the Yosemite Valley has been dubbed the Incomparable Valley, because it is so seriously spectacular. And it is. It has also been called the finest example of a deep glaciated trough. But it's not. Yosemite is more than that, and the glaciation is only part of its splendid geological story.

Tony Waltham
Nottingham, UK
tony@geophotos.co.uk

It was only in 1833 that a party crossed the granite country of the High Sierra westward and became the first modern Americans to glimpse from afar the awesome granite cliffs that plunge into the Yosemite Valley. And it was not until twenty years later that first a military party and then a team from the Geological Survey of California rode their horses along the floor of the valley. They named the site after an Indian tribe that periodically lived in the valley, and recognized it as a truly remarkable landscape (Fig. 1). It was soon protected by national park status.

This all happened when California was still a very new land, kick-started by the forty-niners, the hordes of incomers who came to dig gold from the rich placer deposits and mother lodes along the western margin of the Sierra Nevada granite. When the gold rush had faded away, Yosemite became the Sierra's honey-pot of the new age, and it remains today a huge tourist attraction; it lies only four hours' drive east of San Francisco. Family visitors flock to the valley floor to be enthralled by the towering cliffs and plunging waterfalls, while hikers head for the dramatic rock landscapes of the high country, climbers take to the near-vertical cliffs, and geologists are drawn to both the splendid granite and the spectacular geomorphology (Fig. 2).

The first part of the Yosemite story is its granite, where a huge batholith is no simple feature because it was formed by a very long sequence of intrusions of distinctly different magmas. Then there is the magnificent granite terrain on this great batholith, with the beautiful domes and enormous cliffs that are all so strongly controlled by the joints within the host granite. The third aspect is the glacial story that evolved through the Pleistocene. But this was no normal glaciation, because the ice erosion was superimposed on, and was so much controlled by, those structures within the granite. And it is the combination of these three factors that really has produced a classic landscape at Yosemite, perhaps even an incomparable one.

Fig. 1. The classic view of Yosemite from Glacier Pont, with Half Dome's vertical face overlooking the deep glaciated trough of the Tenaya Valley, and Nevada and Vernal Falls cascading over the rock steps in the Merced Valley to the right.

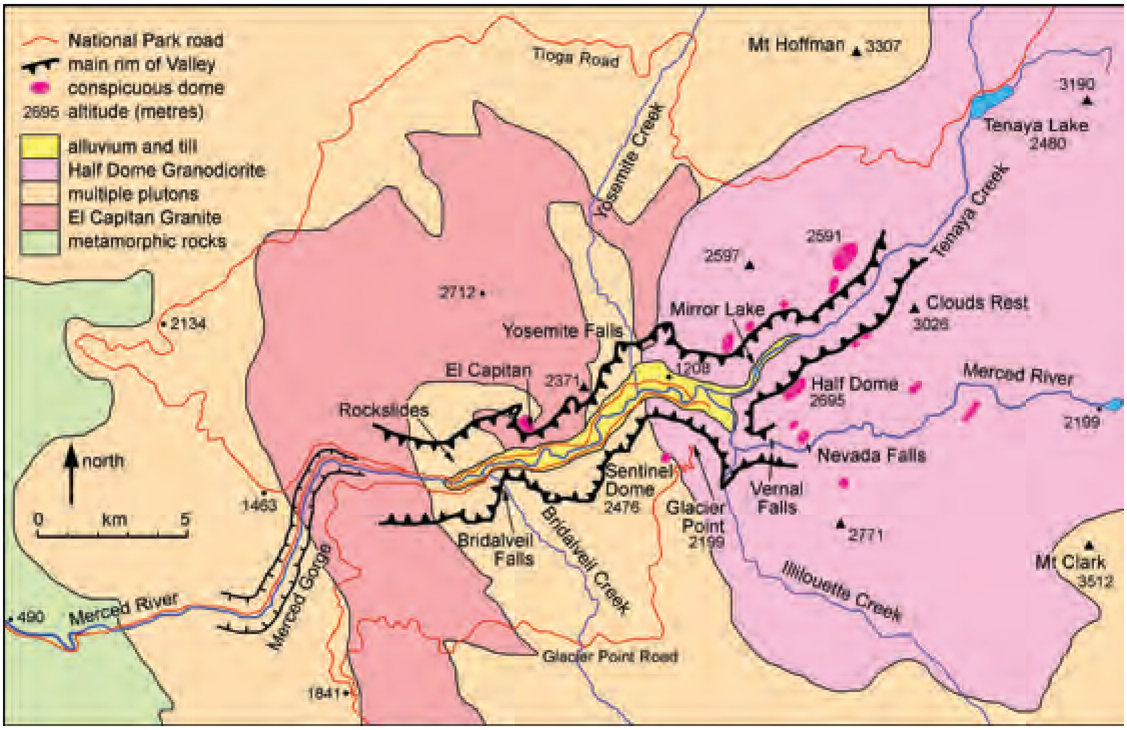


Fig. 2. Simplified bedrock geology and major topographical features of the Yosemite Valley; alluvium and till are only shown along the flat floor of the Valley (map compiled from various USGS sources)

Yosemite's granite

California's geology is dominated by the Sierra Nevada batholith, more than 600 km long and up to 80 km wide, which now forms most of the mountain chain between the state's Central Valley and the Nevada deserts. It was created by a succession of intrusions that lasted through most of the Mesozoic while the Farallon plate was subducted (and finally disappeared) beneath the advancing North America plate. Magma was generated deep within the continuously active orogenic belt, and a long series of pulses saw it move upwards to intrude the cover rocks. Each pulse created its own pluton, largely intruding its predecessors, and there are hundreds of individual plutons within the one batholith.

At Yosemite, and along most of the Sierra southwards, almost all the magma remained underground to form those plutons. To the north, much of the magma did reach the surface, so the mountains from Yosemite north to Tahoe and beyond, ultimately along the Cascades, are dominated by lavas and pyroclastics overlying a core of metamorphic rocks. All this activity reached a crescendo in the Cretaceous, and the plutons now exposed in Yosemite Valley range from 114 to 87 million years old.

Each pulse of magma originated from a slightly different source at depth, so the composition of each pluton differs from that of its neighbours. Called granite only in the broadest sense, these include granodiorites, diorites and a tonalite (all with less potassium feldspar than the true granites) within the ten separate plutons that are exposed just in the walls of the Yosemite Valley. Forming most of the walls along the downstream half of the main valley, and named after the enormous cliff in the north side (Fig. 3), the homogeneous and very strong El Capitan Granite is one of the older units, about 108 million years old. In contrast, the top end of the main valley is cut in the

Fig. 3. The huge granite cliff of El Capitan, with 900 m of nearly vertical rock that is a major challenge to climbers.

Fig. 4. Yosemite Valley looking upstream, with Bridalveil Fall in low flow condition on the right wall.

equally strong Half Dome Granodiorite, formed about 87 million years ago, therefore the youngest pluton exposed within the Valley; it is distinguished by its large black hornblende crystals, and parts of it also have phenocrysts of white orthoclase. Between the two big plutons, a series of smaller intrusions, mainly of granodiorite, form the high cliffs between Glacier Point and the Bridalveil waterfall; a slight colour contrast picks out two of the granodiorites forming horizontal bands across the cliff left of the waterfall (Fig. 4). An even darker diorite is distinguished by much more jointing, and therefore forms the huge debris ramps of the Rockslides on the opposite side of the main valley. Palest of all the rocks are the mafic-free aplites forming thin, late-stage dykes scattered through the plutons. Both aplites and pegmatites are exposed in the face of El Capitan.

The Sierra Nevada batholith cooled down to form solid rock when it was between 3 and 6 km below the contemporary ground surface. This is known from studies of pressure-sensitive mineral assemblages within the granite, and also from the lack of high-pressure minerals within the adjacent metamorphic rocks. However, the Cretaceous emplacement of most of the batholith was soon followed by uplift of the entire mountain chain, and the consequent erosion and removal of the covering rocks. Sediments within the Central Valley of California are largely derived from the Sierra, and their mineralogy indicates that part of the granite was already exposed by the end of the Cretaceous.

Batholiths do have a certain space problem, with the question of what was there before the granite came in. This was once known as the 'granite problem', though the problem ameliorated with the recognition of a non-rigid crust that came with the understanding of plate tectonics. The lenticular shape of most of the plutons, and the structures of adjacent metamorphic rocks, show that forceful intrusions of the viscous magmas did dominate the emplacement processes of the Sierra Nevada batholith. Some older rock was displaced downwards within the orogenic belt, but there was also room for expansion of the continental crust above the subduction zone. However, metamorphic granitisation and magmatic stoping have also played their parts, though granitised migmatites are very localized in the Sierra Nevada. Stoping was widespread around the batholith margins. Among the most spectacular products of this are the agmatites now exposed in road cuts along the approaches to Yosemite (Fig. 5); this term describes rocks that occupy the intermediate stages between

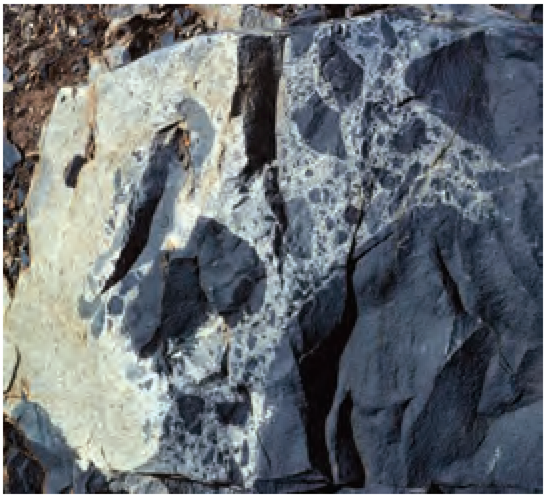


Fig. 5. Agmatite; a mixture of light granite and dark country rock close to the western edge of the batholith.

Fig. 6. Clean granite surfaces dictated by exfoliation joints that are both convex and concave in the upper Tenaya Valley; the view is to the northeast from the top of Half Dome.

scattered xenoliths in the granite and isolated igneous veins in the country rocks.

Yosemite's domes

One of the great features of Yosemite's landscape is the huge extent of bare granite. This is not only in the tall cliffs of the glaciated valley, but also in the sweeping curved slopes, ramparts and domes of the uplands on either side (Fig. 6). The natural vegetation on the high ground is a forest of pines and hemlock (the giant sequoia redwoods only grow in isolated groves on the western slopes). But plants cannot establish where the surface is formed by sheets of solid granite, each a metre and more thick, that are unbroken by cross-joints and lack any soil cover. The sheet structure is due to exfoliation on a grand scale.

Exfoliation is essentially a feature of stress relief. This is simply the expansion of the rock when its confining pressure is removed, and it is also known as unloading. The expansion may be minute, but erosion of the cover rocks produced massive unloading when the Yosemite granite was transferred from a depth of a few kilometres to a near-surface situation. Unloading joints should develop in tension parallel to the ground surface and therefore perpendicular to the direction of possible expansion. Hence are developed the curved joints of Yosemite, convex over the hills and concave across the valleys. As erosion removes successive sheets or shells of exfoliated granite, new joints are developed, and they become progressively more rounded. The end results are the great domes for which Yosemite is famous. The taller granite domes survived the Pleistocene glaciations because the ice sheets were diverted around them; some of the lower domes were overrun, but only by slow-moving ice without the power to significantly erode them. Only the tallest and most conspicuous of the domes are marked on Figs 2 and 11; there are many more domes with lower but equally well-rounded profiles in the high country east of the valley. Some of the domed exfoliated surfaces around Lake Tenaya are known for the large glacial erratics scattered across them. Exfoliation is slow, taking perhaps millions of years, and Yosemite's great bare domes largely predate the incursions of Pleistocene ice.

There is still debate on exactly how, where and when the domed exfoliation joints originated. It appears that they can be initiated very close to the surface, when an outer sheet of rock expands away from a core. This could be an almost explosive process, comparable to rock bursts experienced in some deep mines (soon after excavation of a passage removes the confining pressure within its walls). But the question is whether or not there was some older, guiding, structural weakness within the rock. Back in the 1860s, the first geologists into Yosemite thought that the curved joints were a feature of shrinkage when the granite first cooled down. Cooling shrinkage there must have been, but there is no real evidence for this concept. Domes do not relate to the shapes of the multiple plutons, though most of Yosemite's finest domes do lie within the very homogeneous Half Dome Granodiorite. The cooling theory was overtaken by the unloading theory in the early 1900s, and the question then concerned the depth at which these curved fractures start to develop. A cliff exposure of a great pile of concentric fractures shows that exfoliation processes are not restricted to the immediate surface zone (Fig. 7).

Fig. 7. Multiple, concentric exfoliation joints exposed in a cliff in the upper Tenaya Valley.

Though Yosemite is renowned for its granite domes, few have the symmetry of true domes. Nearly all are either broken by, or are elongated between, major sub-vertical joints. These cut right across the otherwise structureless granite and must have had some influence on the early drainage patterns that cut into the exposed batholith. Hence the residual hills left between the major joints became ideal sites for dome development in homogeneous rock.

The most conspicuous of these major joints dictates the position of the great wall on one side of Half

Fig. 8. The northwest side of Half Dome, with its unbroken wall rising 700 m on a major joint.

Dome (Fig. 8), and belongs to a set aligned NE–SW. Half Dome never was a whole dome. It is anyway a very elongate hill, and its curved exfoliation joints fit in between major vertical joints on its two long sides. On the southeast side, and over the summit, exfoliation has dominated to develop the rounded dome profile, though the main part of its wall is at a very steep angle. On the north-west side, the vertical joints dominate, and so create the huge vertical face. This itself has been subject to stress relief, with vertical sheets coming away from planar varieties of exfoliation fractures that follow the line of the earlier sub-vertical joints. This maintains its steep and fresh profile, and great slabs of granite project over the wall where they have been undermined by the vertical slab failures (Fig. 9). The long-term process of selective denudation picking out the two different joint sets has created a remarkable mountain profile, one that has become the iconic symbol of Yosemite.

Yosemite's glaciation

A truly spectacular rock landscape nearly always benefits from glaciation. In hot and wet climates, even the strongest of granites weathers to a thick soil and is then submerged beneath lush greenery. But weathering is slower in cold climates, and glaciers are also the best way of removing any cover. Today, the Sierra Nevada has only small cirque glaciers around the highest summits; there are many of them, but they all date only from the Little Ice Age, and there was none through the warmer climes of the mid-Holocene. But the Pleistocene ice cover was extensive. Not only did it scrape clean so many of the high outcrops of granite, but it also produced powerful valley glaciers, one of which flowed down Yosemite's Incomparable Valley. But that is only part of the valley's story.

As is the case at many other sites, including Britain, there is still debate over the glacial history of

Fig. 9. Exfoliation sheets of the dome structure overhang the great wall of Half Dome that has retreated beneath due to failures on the sub-vertical joints.

Yosemite. Pleistocene ice reached its greatest extent during an early cold stage, when it covered most of the Sierra Nevada. This is known across the Sierra as the Sherwin Glaciation (previously referred to as the El Portal in Yosemite), and is confirmed as at least 800 000 years old, because its weathered sur-

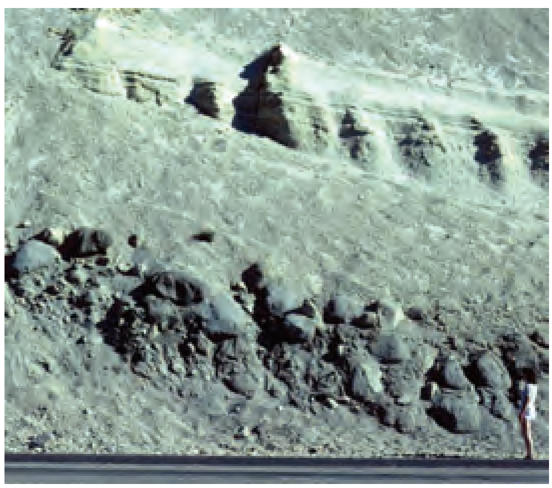


Fig. 10. Sherwin Till overlain by Bishop Tuff in a renowned cutting on Highway 395, beside the eastern edge of the Sierra Nevada.

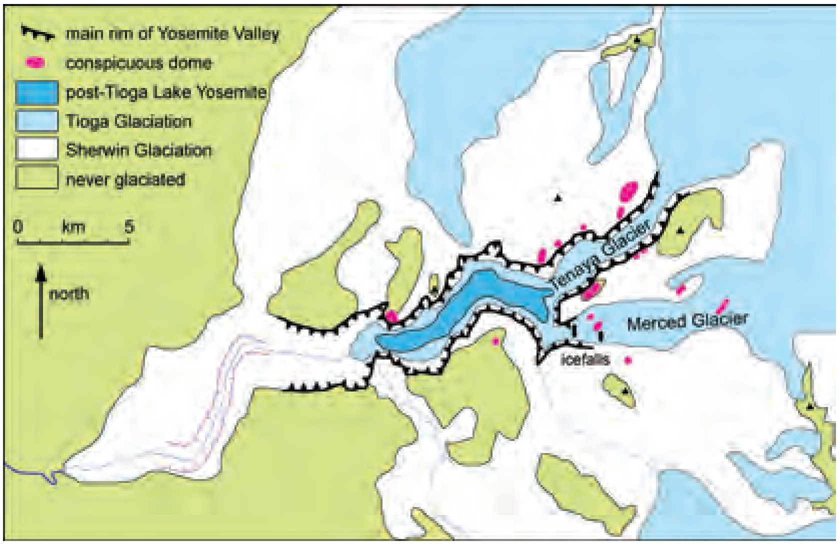


Fig. 11. The extent of ice cover and the glaciers in Yosemite Valley during the Sherwin and Tioga glaciations; this map covers the same area as Fig. 2 (compiled largely from USGS sources).

face is overlain by the well-dated Bishop Tuff along the eastern flanks of the range (Fig. 10). The last ice into the Yosemite Valley was the Tioga Glaciation, dating from about 26 to 14 thousand years ago in the Late Devensian, and this had a much smaller extent. Between the Sherwin and the Tioga there are at least five stages within the Greenland icecap oxygen isotope record when world climates were as cold. Widespread glaciations did occur then, but almost nothing is known about these events at Yosemite.

The real ancestor of the Yosemite Valley is a fluvial feature that was well established on the uplifted Sierra by about 15 million years ago. River erosion deepened this into a substantial canyon when renewed uplift raised the Sierra well above the lowlands to the west. Only in the early Pleistocene did ice begin to play its role. During the Sherwin maximum, ice covered most of the high granite country, and the ancestral river valley guided a powerful ice stream out to the west (Fig. 11). This and probably many other glacial incursions scoured the Yosemite Valley to impressive depths. Away from the erosive ice stream, ice moving more slowly spread over the granite highlands and had little impact on the landscape. The ice was deflected around the tallest of the great granite domes, and the glacier surface stood about 300 m below the top of Half Dome. The Valley was hugely over-deepened by the powerful ice stream constrained between the high granite walls inherited from the river erosion. Well logs have revealed sediments 300 m deep beneath the Valley floor just below Glacier Point, and seismic surveys have shown that the rock floor is about 600 m down. These figures put the main Sherwin-age glacier as about 1800 m thick through the heart of the valley.

In contrast to that great early event, the Tioga Glaciation produced little more than a trickle of ice along the floor of the valley. It reached only as far as a terminal moraine below the Bridalveil waterfall (Fig. 11). Further downstream, meltwater cut the Merced Gorge deep into the floor of the older glaciated valley, through what are now forested foothills almost devoid of glacial features. Because the Tioga ice was so recent, its features are still conspicuous, though it really only trimmed the edges of the landscape. It polished the granite on the high country (Fig. 12), and it trimmed the highest peaks (Mt Clark and others further east) into glaciated horns, but it skirted round the big granite domes, and it did little to the Yosemite Valley. The Tenaya Glacier, the northern arm of the valley glacier, swept fallen rock away from the foot of Half Dome, but the Tioga-age glacier in the main valley did not even scour down through the Sherwin till to reach bedrock. The conspicuously flat valley floor was created by sediments that filled a short-lived lake, ponded behind the Bridalveil terminal moraine (Fig. 11).

Tioga ice never reached high on the walls of Yosemite Valley, and the classic hanging valleys are much as they were after the Sherwin Glaciation. Their finest features are the great waterfalls that drop from them into the valley. Yosemite Falls, on the north side, claim various records as they drop 740 m in three great steps, where the Upper Fall take a clear leap of 435 m (Fig. 13); sadly, these dry to nothing in the summer, after an impressive snow-melt peak in June. Bridalveil Fall does maintain some flow in the dry summer, where it descends nearly 200 m down the south wall of the valley. The two more powerful waterfalls are Nevada and Vernal (Fig. 14), respectively nearing 200 and 100 m high, which take the Merced River down two great glacial steps cut into the granite; these were the sites of dramatic ice falls along the Tioga-age Merced Glacier (and perhaps some of its predecessors).

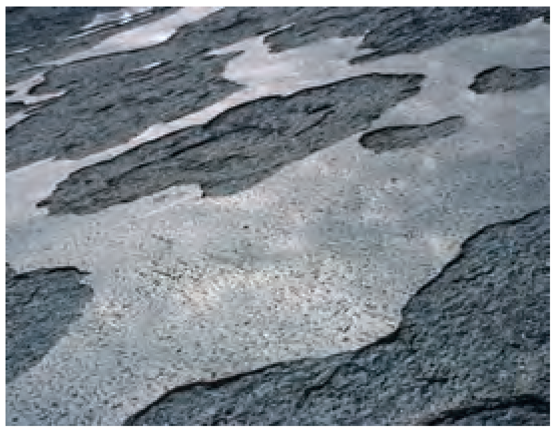


Fig. 12. Granite polished by debris-laden ice during the Tioga Glaciation, with the polished crust steadily flaking away; near Lake Tenaya on the high Sierra.

The first geologists into the Valley, in the 1860s, thought the sides so steep that they had to be left along faults where the bottom had dropped down, in the manner of a graben. But soon after, John Muir, that great Sierran conservationist of Scottish ances-

Fig. 13. Yosemite Falls at full flow charged by snow melt in June, with the Middle Fall out of sight behind the pale rock buttress.

try, argued for a glacial origin, and this was finally supported by the US Geological Survey in 1930. But it is not a characteristic U-shaped glaciated valley. A far better example of glacial erosion is the Grand Canyon of the Tuolumne, the next valley to the north, also in the Yosemite National Park, but road-less and therefore requiring a hike to see its textbook U-shape.

In the Yosemite Valley itself the floor is too flat and the walls are too steep for pure glacier erosion. The floor is alluviated, and indeed may have a U-shaped bedrock profile beneath its sediment. It's the walls that are the real anomaly. And here the story returns to exfoliation. Since the main valley excavation by the Sherwin-age glacier nearly a million years ago, the strong granite has not just weathered, crumbled and degraded, as would a weaker rock. Instead, it has exfoliated, with stress relief out towards the valley walls. This has created steeply inclined unloading joints, and the consequent spalling of huge slabs of rock. Many of these unloading joints appear to have taken some guidance from the earlier sub-vertical fractures through the granite, so the unloading slab failures actually steepened the valley walls, most conspicuously to form the great face of Half Dome. Control by geological structures is shown not only by the great faces of Half Dome and El Capitan, but also by the great embayments that break the smooth line of the valley in plan view (Fig. 11), so unlike a feature trimmed by an all-powerful glacier.

Rock failures in the great walls of Yosemite are an ongoing process; a significant rockfall involving 100 000 tonnes of rock or more occurs on average about once every decade. In prehistoric times a

Fig. 14. Vernal Fall drops 97 m over a glacial step plucked out of the Half Dome Granodiorite largely by the Tioga-age glacier squeezing down the Merced Valley.

rockfall a hundred times that size created the pile of granodiorite blocks that impounds Mirror Lake on the floor of the Tenaya Valley, though the lake is steadily

Fig. 15. The distinctive profile of Half Dome seen in early morning light from the top of Clouds Rest, with the cliff-lined Yosemite Valley heading away to the right and hazy with smoke from a small forest fire.

Fig. 16. On the Half Dome cable ladder.

filling with river sediment. The aptly named Rockslides, the great ramp of debris opposite the Bridalveil waterfall, is the product of multiple rockfalls from the cliffs of diorite, which is so much more closely jointed and hence weaker than the surrounding granites. Opening of its close-set fractures was also aided by unloading in the rock face, but it is the huge slab failures in the stronger rocks that have contributed so much to the profile of Yosemite Valley (Fig. 15).

So structures and processes do provide good reason to explain the spectacularly steep profiles of the huge granite walls along the Yosemite Valley. True, the valley has been glaciated, but its flat alluviated floor and its steep exfoliated granite walls make it more of a box canyon than a glaciated trough. Perhaps it really is an Incomparable Valley.

Visiting Yosemite

More than five million visitors every year constitute a veritable invasion of Yosemite. Most come in the summer, and most stay on the valley floor, which is a mass of cabins, lodges and campgrounds at its upper end. But the Incomparable Valley is best seen from above, and there are two great options. The easy one is a road that winds up to Glacier Point. More exhilarating is the walk up Half Dome, though this is a major full-day epic, climbing 1500 m from the valley floor, up past Vernal and Nevada Falls; its last 200 m up the cable ladder on the northeast flank is unforgettable (Fig. 16). The Glacier Point road (and the Tioga Road that offers the only route over the high Sierra to the Nevada desert) is normally closed by snow from early November to late May, while the cables are only in place on Half Dome from late May to mid-October. All accommodation in Yosemite (including campsites), together with permits for back-country camping or a weekend walk up Half Dome, must be booked ahead on the National Park website, and there is little available just outside the Park. Simple pressures of numbers mean that a visit to Yosemite must be planned ahead, but it is well worth some effort to go and see this classic piece of geomorphology.

Suggestions for further reading

Bateman, P.C., 1992. Plutonism in the central part of the Sierra Nevada Batholith, California. *US Geological Survey Professional Paper*, v.1483, 186pp.

Huber, N.K., 1987. The geologic story of Yosemite National Park. *US Geological Survey Bulletin*, v.1595, 80pp.

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Moore, J.G., 2000. *Exploring the Highest Sierra*. Stanford University Press, 428pp.