Geologic Map of the Guadalupe Mountains National Park, Culberson and Hudspeth Counties, Texas

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Scale 1:24:000

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Figure 1. The view northwestward towards El Capitan from the northeast side of Guadalupe Pass.

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INTRODUCTION

The Guadalupe Mountains National Park covers the southernmost exposures of the Guadalupe Mountains, in western Texas. Elevations in the quadrangle range from approximately 3,630 feet above sea level in the at the entrance to the western sand dunes to 8,751 feet at Guadalupe Peak, the highest elevation in the State of Texas.

U.S. Highways 62/180 cut through the very southeast edge of the Park, connecting El Paso approximately 100 miles to the west with Carlsbad, New Mexico, approximately 50 miles to the northeast. A 70-mile drive west and south along Route 137 from Carlsbad provides the only vehicle access to the high country into Upper Dog Canyon, near the northern boundary of the map.

Pine Spring Canyon is the gateway to the Guadalupe Mountains National Park. The canyon contains the National Park Visitor Center and Pine Spring Campground, and is the trailhead for several of the Park's extensive and well-maintained trails. U.S. Highways 62/180 reach their highest elevation at the 5,424-foot-high divide located approximately 3,000 feet directly south of the Visitor Center. This divide has been a nexus for travelers for hundreds and possibly for thousands of years, the nearby thousand-foot-high spire of El Capitan providing a landmark visible from far away.

The rocks of the Guadalupe Mountains are some of the most studied rocks on Earth and much has been written about their geologic history (see the webpage of the National Park Service for a good introduction and their Geodiversity Atlas for links to more geologic resources: https://www.nps.gov/articles/nps-geodiversity-atlas-guadalupe-mountains-national-park-texas.htm. Also, Peter Scholle's website provides a great introduction to the geologic history of the Guadalupe Mountains with numerous illustrations and referenced sources for further reading: https://geoinfo.nmt.edu/tour/federal/parks/PermianReef/home.html. The current report does not attempt to reproduce or assimilate this large body of research. Instead, this report simply adds some new observations gleaned during the recent geologic mapping of the area and relates them to a small selection of some the previous work that has been done. This study also discusses some of the challenges that remain.

The first portion of this study was carried out during 2015 and 2016, which involved detailed mapping of mostly the lower elevations in the Guadalupe Mountains National Park from McKittrick Canyon in the northeast to the even lower elevations west and southwest of Guadalupe Pass. The second portion of the field work was performed in 2019, which mostly involved detailed mapping of the higher elevations. The third portion of the field work was carried out in 2020 and 2021 along the northwest escarpment, on the western alluvial fans, the Patterson Hills, and on a portion of the gypsum salt flats near the western entrance to the Park.

During the field work, sustained 20-30 mph winds, often with gusts exceeding 50 mph, were a constant companion. Because of the ubiquity of sharp, spiny *Agave Lechugilla* on the landscape, several times, after hiking to the top of a ridge only to be met by driving winds, the author turned around and went back down, rather than risk being blown over and impaled. Wearing a hat in these conditions is almost impossible.

Relevant photographs are included throughout the text of this report. More photos are included at the end of the text, after the references section, to help future researchers compare changes in the landscape.

METHODS

Field work was augmented with 9 x 9-inch color stereo aerial photos (dated October 19, 1973, November 11, 1974, and October 11, 1990), provided by the National Park Service, originally obtained from the U.S.G.S National Aerial Photography Program (NAPP). These photos were used in conjunction with field work to more accurately, and efficiently, map the Tertiary and Quaternary deposits along he mountain front and southwest of Guadalupe Pass. In the higher elevations, a computer application known as Stereo Analyst was used, linked to ArcGIS (created by ESRI) (see Figure 2). Stereo Analyst uses nearby digital stereo aerial image pairs that are rectified and alternately turned on and off at a rate of 125 times per second. At this rate, the flicker is imperceptible to the human eye. The user wears special glasses equipped with liquid-crystal-display lenses that are synced wirelessly to Stereo Analyst. The left and right lenses are alternately turned opaque and clear in sync with the computer. Looking through the classes gives the illusion of 3D at the resolution of up to about 1 meter. Linked to ArcGIS (ArcMap), it is possible to trace contacts on the stereo image (on one computer monitor) while at the same time those contacts are drawn in the georeferenced space within ArcMap. Photographic coverage of Stereo Analyst existed only in the higher elevations of the quadrangle.

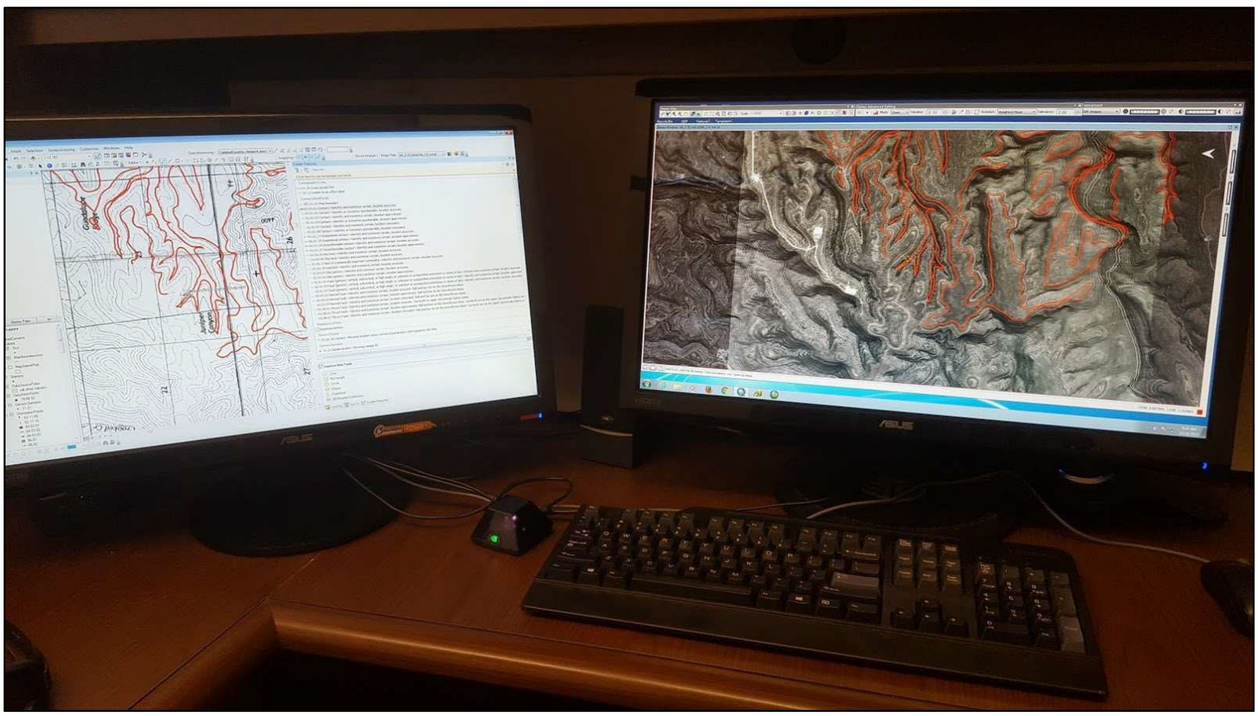

Figure 2. Workstation for Stereo Analyst. Digitally overlain rectified aerial images (on the right) blinked on and off consecutively and were synced, wirelessly, with liquid-crystal blink glasses that allowed viewing of the landscape in 3D. This allowed digitization of contacts and features directly on the stereo aerial images, at any scale. The digitized features were linked to ArcGIS (on the left) where they could be further edited.

The western escarpment south of Shumard Peak was one of the most challenging areas to map, not just because of the 3,000+ feet of relief, but because the contour lines on the U.S. G.S. topographic quadrangle are not accurate. Large portions of the steep sloping terrain below the cliffs in the southwest corner of the map are portrayed as smooth whereas, in reality, the slope here contains tall ridges separated by deep incised canyons. The existing aerial photos that covered this slope were digitized and stretched (rectified) to provide a reference for mapping more accurate geologic contacts. However, the steep topography led to excessive distortion in the stretching in some areas. The rectified U.S.G.S. orthophoto quadrangle turned out to provide a more accurate base (even though it is not in 3D) and much of the surficial deposits on the slope here were mapped in this way, in conjunction with mapping on the ground.

Thirty-four stratigraphic sections were measured throughout the quadrangle. As King (1948) no doubt also discovered, many of the mapped formations are really composed of intercalated carbonate and sandstone layers that cannot be shown accurately at the scale of the map. The stratigraphic sections provide a more accurate representation of the composition and thickness of these units. The sections measured during the present study were drafted using Adobe Illustrator.

The small southeastern portion of the map was, unfortunately, not mapped. This area is private property and no stereo aerial photos were available that covered this area.

PREVIOUS GEOLOGIC MAPPING

King (1948) performed a large amount of research and field work that resulted in the first published geologic map of the portion of the Guadalupe Mountains south of the New Mexico/Texas border. He measured 67 stratigraphic sections (in the Guadalupe Mountains, the Delaware Mountains, and in some of the isolated hills to the west) and interpreted correlations between these sections. Because of his detailed mapping, he was one of the first to understand that the rocks here represented the various facies of an ancient reef. The map technology of the day allowed him to produce a color 1:48,000-scale map that has a fairly wide contour interval of 250 feet. Hayes (1964) mapped most of the Guadalupe Mountains north of the New Mexico/Texas border, including the portion that was to become Carlsbad Caverns National Park.

The National Park Service compiled this existing geologic mapping into one of the first digital geologic maps of the Guadalupe Mountains National Park and vicinity (NPS, 2007). The most recent geologic map of the Park and vicinity by the National Park Service (2017) is based, in large part, on King's map.

WESTERN ESCARPMENT

The western escarpment of the Guadalupe Mountains is a unique location for several reasons. It contains one of the thickest stratigraphic sections exposed at the surface in Texas, and includes the highest mountain in Texas (8,751 feet above sea level). The structural and topographic relief exposed in Shumard Canyon is approximately 3,600 feet. It also contains one of the thickest exposed sequences of middle Permian Guadalupian-age strata on Earth (270 to 260 million years ago). Many of these strata are continuous in the subsurface so they provide some of the best, and most easily accessible, information about what lies beneath the mountain range. Some observations of these strata and their relationships are described below.

Figure 3. Williams Ranch cabin sits near 5,000 feet elevation, just west of the basin-bounding fault at the base of the western escarpment. At an elevation of 8,617 feet, Shumard Peak (directly behind the cabin) caps 3,600 feet of relief on the western escarpment.

Bone Spring Formation and Victorio Peak Formation

The Bone Spring and Victorio Peak Formations are well exposed on the western escarpment west of Guadalupe Peak. The Bone Spring Formation is the stratigraphically lowest unit exposed. Apparently, only an uppermost portion of the unit is exposed on the western side of the Guadalupe Mountains. Hayes (1964) reports that several wells penetrated more than 3,000 feet of the formation. The remainder of the formation is exposed in Diablo Plateau, across the Salt Basin. The Bone Spring Formation (Pbs) is composed of thinly bedded limestone that, from a distance, appears very regularly bedded. Early diagenetic chert is abundant and commonly occurs as thin bedding-parallel sheets and as discrete elongated nodules. On fresh surfaces the chert is very dark gray, but weathers lighter tan. Limestone beds are commonly partly laminated and locally massive (Figure 4).

The Bone Spring Formation contains abundant intraformational angular unconformities, beautifully exposed on the north wall of Shumard Canyon and its upstream tributaries. King (1948, p. 15-18) also recognized these features but did not include an interpretation of how they may have formed. None of the beds either below or above these unconformities appear to exhibit any deformation. Instead, the overlying beds immediately above an unconformity are parallel with the plane of the unconformity and neatly truncate the beds below. Some of the unconformities appear to pinch out laterally where beds both below and above appear conformable. The beds below each of the unconformities do not exhibit any obvious evidence of emergence and erosion above sea level (no obvious dissolution, karsting, or pedogenic features). If the unconformities were created by slumping one might expect to see deposits of deformed or otherwise disturbed beds downslope. Also, there does not seem to be any preferred direction to the slope direction of the angular unconformities.

Figure 4. Outcrop view of the Bone Spring Formation (Pbs) exposed near the trail on the south side of Shumard Canyon showing laminated lime mudstone and abundant interbedded bedding-parallel chert (dark).

Interestingly, Boyd (1958, p. 53) described somewhat similar features in the El Paso gap quadrangle to the north. There, he described discordant dips in the upper San Andres Formation that he described as being located either in or near the transition between the San Andres Formation and the Cherry Canyon tongue. His figure 6 shows an angular unconformity. He recognized four different types of discordant dips and interpreted them as the result of (1) more deposition in one area than in another, (2) deposition on an uneven surface, (3) penecontemporaneous tilting of the surface of deposition, and (4) deposition of truncated compaction folds. Of these, penecontemporaneous tilting best fits the presence of angular unconformities exposed in Shumard Canyon, yet doesn't adequately explain the lack of deformed beds or debris that must have resulted if the truncation of the beds was the result of erosion. Could it be possible that these features formed as the result of seismic activity within an actively asymmetrically subsiding basin? In this scenario the limestone beds locally underwent subsidence and tilting. Subsequent slumping of the topographically higher portions removed some of the layers creating the unconformities, upon which additional limestone precipitated. This scenario still doesn't adequately explain the absence of any visible slumped or eroded debris.

Conformably overlying the thin-bedded Bone Spring Formation are much thicker slightly lighter gray limestone beds that forms high ledges and small cliffs (Figure 5). Although subtle, from a distance these beds tend to form a discrete unit. These thick beds are overlain by more massive limestone outcrops of the Victorio Peak Formation that are only faintly bedded and mostly form steep rounded outcrops above the thick beds. The thick beds may be equivalent to what King (1948, p. 17) described as his "lower division" of the Victorio Peak Formation, composed of "350 feet of gray-brown, fine-grained, dolomitic limestone in beds several feet thick" in gradational contact with the thinner beds below. The thick beds of this 'middle' unit wrap around the east side of Shumard Canyon where the trail first climbs up out of the canyon bottom

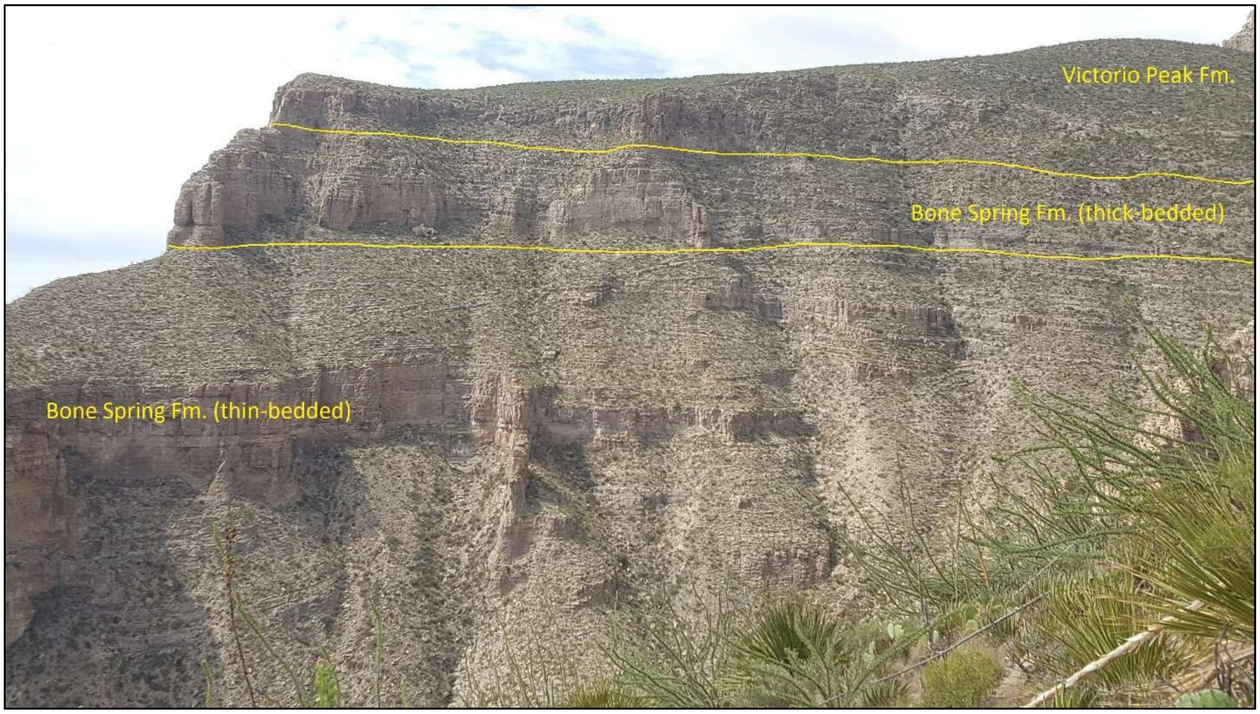

Figure 5. View northward of the north side of Shumard Canyon shows the lower thin-bedded portion of the Bone Spring Formation (Pbs1) overlain by the upper cliff-forming portion Bone Spring Formation (Pbs2), in turn overlain by the massive limestone of the Victorio Peak Formation (Pvp). As drawn here, the contacts are gradational and somewhat arbitrary.

and traverses over the unit. One of the best locations from which to view this unit is looking north from where the trail traverses across the small north-facing cliff near where it crosses the 5,520-foot elevation contour. King (1948, p. 17-18, 164) described three informal units within the Victorio Peak Formation further north near Cutoff Mountain: (1) a lower fine-grained partially dolomitic limestone in 1-6 foot thick beds, (2) a thin-bedded slope-forming middle unit composed of light gray to white limestone interbedded with calcareous sandstone, and (3) an upper unit composed of fine-grained thick-bedded limestone capped by an upper portion of thin-bedded limestone. The description of the lower unit sounds similar to the thick-bedded ‘middle’ unit described above, but the two overlying units do not sound similar to the massive unit seen on the north side of Shumard Canyon.

Cutoff Formation

As was recognized and described by King (1948), the Cutoff Formation obliquely truncates bedding in the underlying Bone Spring Formation, cutting down-section to the south. The unit is exposed between Shumard Canyon in the north all the way to U.S. Highway 62/180 six miles to the south, and beyond, but the formation shows the most variability in a small area extending from Shumard Canyon in the north to approximately 4,000 feet southward. Harris (1982, 2000) created 13 detailed stratigraphic sections. He subdivided the Cutoff Formation into upper and lower portions (following King, 1948) and subdivided each into distinct lithofacies. See also the more recent detailed mapping and subdivisions of Amerman and others (2011). This previous detailed work was necessarily generalized during the current study and only five general lithofacies were mapped: (1limestone breccia , (2) thin-bedded limestone [roughly equivalent to the Shumard Member of Harris, 2000], (3) lime mudstone, sandstone and shale, (4) fetid dark gray limestone, and (5)) thick-bedded tan limestone. It is unclear how lithofacies 3, 4, and 5 correlate with Harris’ (2000) members. These units occur only in the very far southwestern corner of the map which has very limited exposure of the Cutoff Formation. This is a work in progress and these distinctions will probably change once the region to the west and south has been mapped in detail.

The greatest truncation of the underlying Bone Spring Formation occurs from the north side of Shumard Canyon to the south side of Shumard Canyon. Here, in a horizontal north-south distance of approximately 2,000 feet, the Cutoff Formation cuts down across more than 200 feet of older rocks, including the lowermost portion of the Victorio Peak Formation, the thick-bedded interval between the Victorio Peak and Bone Spring Formations, and the upper portion of the thin-bedded Bone Spring Formation.

Probably the most extensive mappable facies recognized here is informally named the fetid member (Pcf). It forms most of the linear escarpment south of Bone Spring Canyon southward to the highway. This unit is thin- to medium-bedded containing faint lightly wavy laminations and contains abundant bedded chert in sheets 1-2 cm thick. Fresh surfaces are very dark gray and characteristically exude a weak fetid to strong petroliferous odor from broken surfaces. From a distance the bedding appears very regular. This is the unit that contains the enigmatic intraformational folds that are best exposed southwest of El Capitan (see Amerman and others, 2011, for a discussion and photos of these features).

Figure 6. This exposure on the east side of Shumard Canyon, looking north, shows southwest-dipping limestone beds of the Cutoff Formation (Pcd) truncating thick-bedded south-dipping limestone beds of the upper portion of the Bone Spring Formation.

In eastern Shumard Canyon thinly bedded limestone of the Cutoff Formation (Pcd) forms localized deposits that truncate bedding in the underlying Bone Spring Formation (Pbs)(Figure 6). The three dimensional shape of these deposits suggests they fill channels eroded into the underlying Bone Spring Formation (Harris, 1982). Harris (1982) goes into much more detail about the petrology and sedimentology of these rocks, and mapped more varied and individual facies throughout Shumard Canyon.

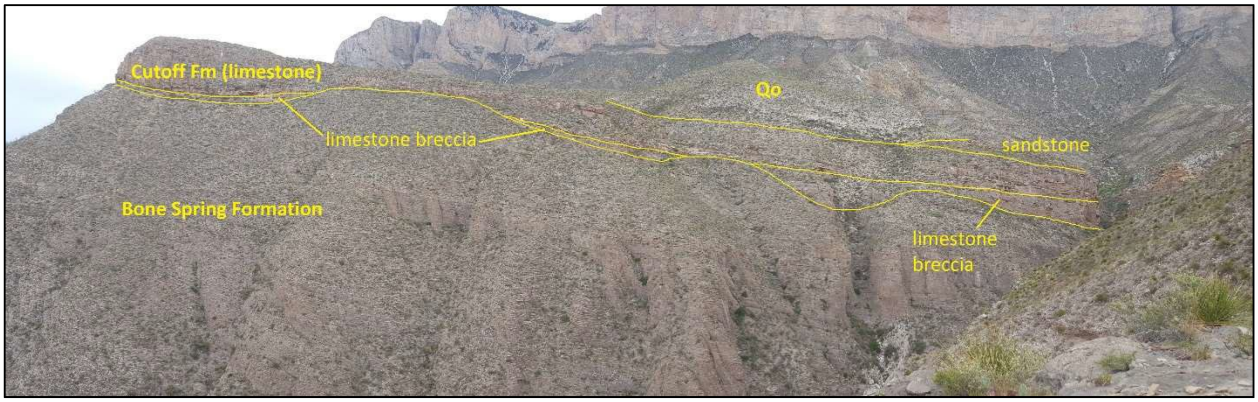

Figure 7. View northward of the north side of Bone Spring Canyon. Note the unconformable contact at the base of the Cutoff Formation that truncates bedding in the underlying Bone Spring Formation.

The fetid member is very locally overlain by a thin discontinuous horizon of breccia, here informally called the breccia member. The breccia is composed of poorly sorted subangular blocks of limestone from less than 1 cm to boulders, surrounded by a carbonate and locally sandy matrix. The unit appears to have filled small to broad channels up to several tens of meters across. The best exposures of the breccia are visible on the north side of Bone Spring Canyon (Figure 7). Here, the breccia is exposed in depressions cut into the underlying Bone Spring Formation and occur below the thick-bedded, tan-colored limestone beds (Pct) of the Cutoff Formation. On the top of the plateau on the south side of Bone Spring Canyon, the upper portion of the thick-bedded tan limestone is interbedded with brown-weathering ledges of sandstone that appear very similar to the sandstone within the overlying Brushy Canyon Formation. The contact between the Cutoff and Brushy Canyon Formations here was drawn at the top of the uppermost limestone bed.

The Cherry Canyon Tongue—Limestone layers below the Capitan Formation

Below the cliff formed by the Capitan Formation is a layer of bedded limestones that forms the base of the cliff itself (Figure 8). They are composed of multiple layers of thin- to thick-bedded limestone intercalated with abundant thinner layers of fine-grained sandstone/siltstone. These exposures form an almost continuous ribbon that wraps along the base of the cliff from Guadalupe Canyon and El Capitan, to the base of Shumard Peak. This continuous layer is most easily seen from a distance, but its position 3,000 feet above the valley floor at Williams Ranch requires a long and arduous climb to see it more closely. Probably the most accessible exposures are on the southern base of El Capitan, which is within 1,000 horizontal feet or so of the Williams Ranch Trail where it crosses the ridge immediately to the south of El Capitan.

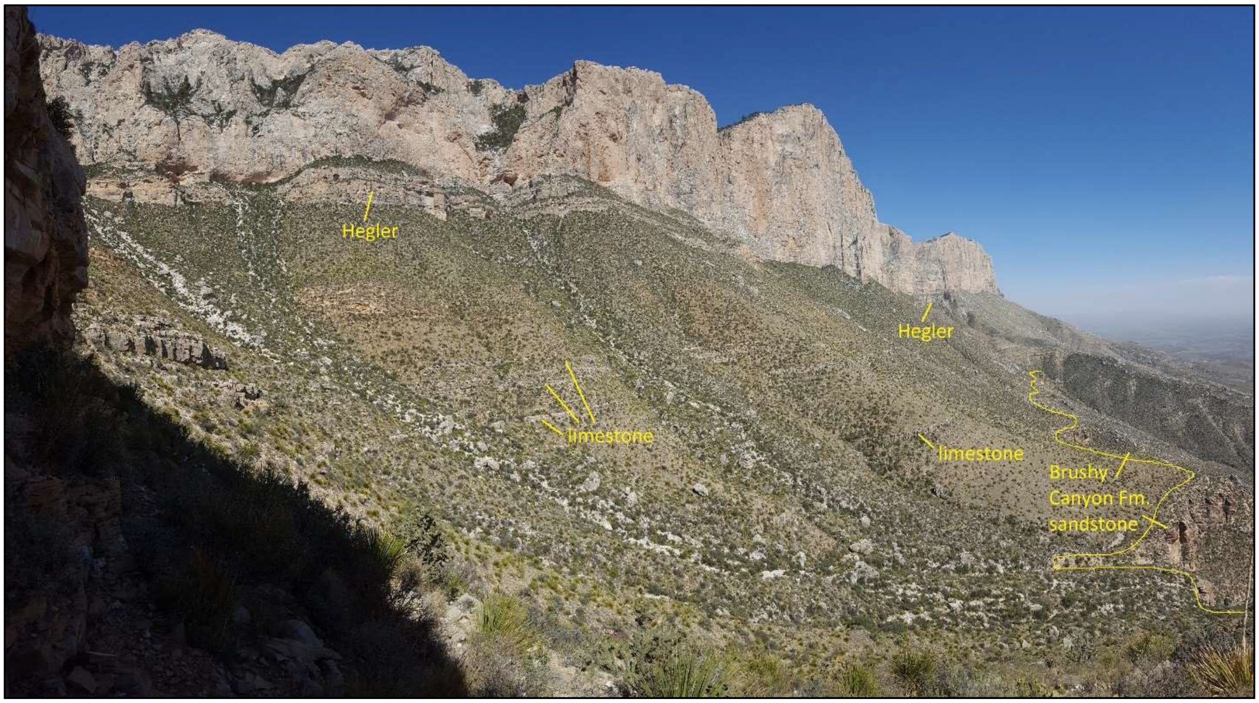

Figure 8. View of the western escarpment, looking southeast from just above the sandstone ledges of the Brushy Canyon Formation. The Cherry Canyon tongue forms the slope between the Brushy Canyon Formation and the Hegler Limestone Member at the base of the cliffs composed of the Capitan Formation.

King (1948, plate 6) mapped two separate units within this band of bedded rocks: a lower Hegler Limestone Member and an upper Pinery Limestone Member of the Bell Canyon Formation. He shows a major discontinuity between the two between the north and south sides of Bone Canyon. South of Bone Canyon the Pinery Limestone Member occupies the majority of exposures and overlies a very thin layer of the Hegler Limestone Member, separated by a thick sandstone layer. The apparent absence of this sandstone layer north of Bone Canyon may have been the reason for this subdivision. Within Bone Canyon he drew the Pinery Limestone Member as merging upward with the Capitan Formation, while north of Bone Canyon the Hegler Limestone Member is the only unit within this band. Detailed mapping between Pine Spring Canyon and Guadalupe Pass during the current study appears to show limestone beds of the Pinery Limestone Member thinning southward and pinching out as they merge with the Capitan Formation immediately north of Guadalupe Pass. Because of this observation, the Pinery Limestone Member was not mapped further west in Guadalupe Canyon or at El Capitan. Instead, all of the limestone beds at the base of the Capitan Formation from El Capitan to at least Shumard Peak were assigned to the Hegler Limestone Member (see Figure 9).

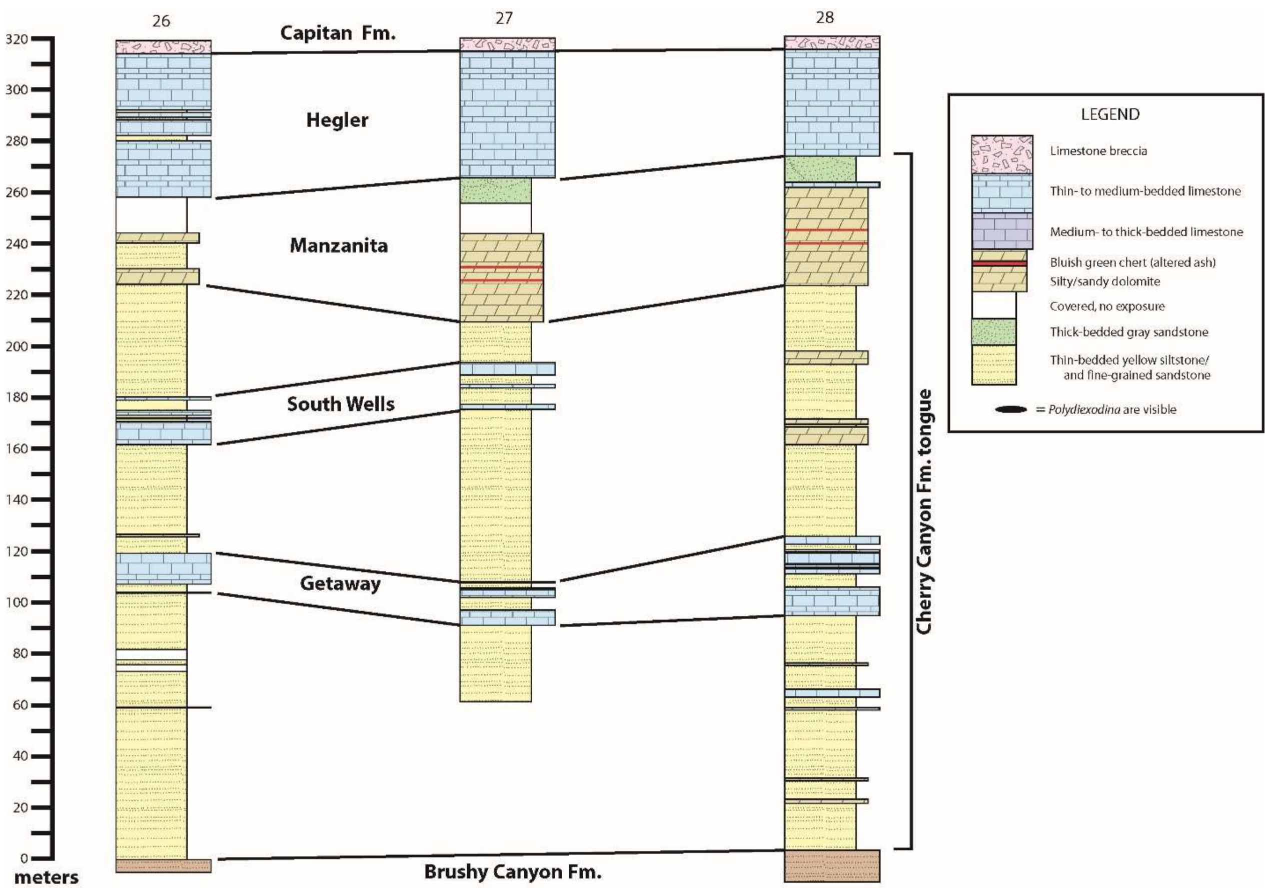

Figure 9. Fence diagram showing the relationship between the three measured sections on the western escarpment. No datum used, best fit only.

Lower in the stratigraphy, Between Guadalupe Peak and Shumard Peak, several thick limestone beds can be traced across the slope where they are intercalated with slope-forming fine-grained sandstone/siltstone. King (1948) named the lower few limestone beds the Getaway Limestone Member and the upper few limestone beds the South Wells Limestone Member of the Cherry Canyon Formation. According to King (1948, p. 35) the Getaway Limestone Member of the Cherry Canyon Formation was named after a 107-foot-thick exposure of limestone in Getaway Gap, six miles southeast of El Capitan. He also said that it is well exposed on the south side of Guadalupe Pass below the "Guadalupe Summit radio station." Mapping during the current study confirms that the limestone exposed at the radio tower on the south side of the pass is stratigraphically below the Hegler Limestone Member. The hill immediately to the north of Guadalupe Pass is also capped by a limestone unit. Although difficult to determine for certain, it appears that this unit is slightly stratigraphically higher than the limestone on the south side of Guadalupe Pass. If so, this may be equivalent to the South Wells Limestone Member of the Cherry Canyon Formation, which King (1948) described as thin limestone layers interbedded with mostly sandstone and occurring above the Getaway Limestone Member (see measured sections in Figure 10). Northward, immediately southwest of Shumard Peak, most of these individual limestone layers (probably of both members) thicken and merge together to form a resistant knob. Further to the northwest, across Shirttail Canyon, the limestone thickens at the expense of the fine-grained sandstone/siltstone. King (1948) correlated these thickened, merged outcrops with the Goat Seep Formation. Alternatively, Franseen and others (1989) interpreted this thickening of limestone beds northward to be equivalent to the Grayburg

Formation. Because this area was very difficult to access, the differences between these interpretations remain temporarily unresolved. It is here mapped as the South Wells Limestone Member. Figure 11 shows the position of the Cherry Canyon tongue with respect to the other formations exposed on the western escarpment.

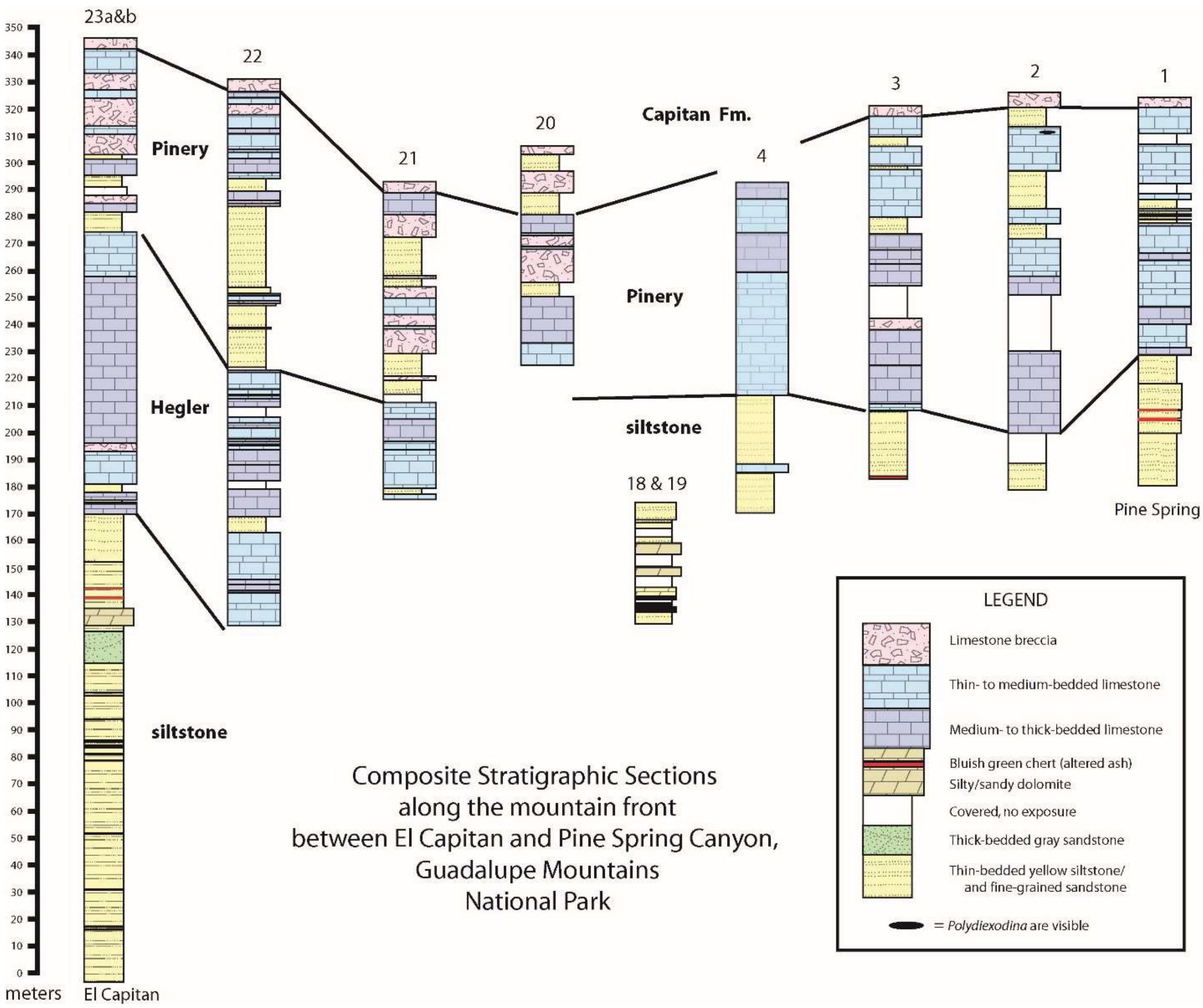

Figure 10. Composite stratigraphic sections between El Capitan and Pine Spring Canyon.

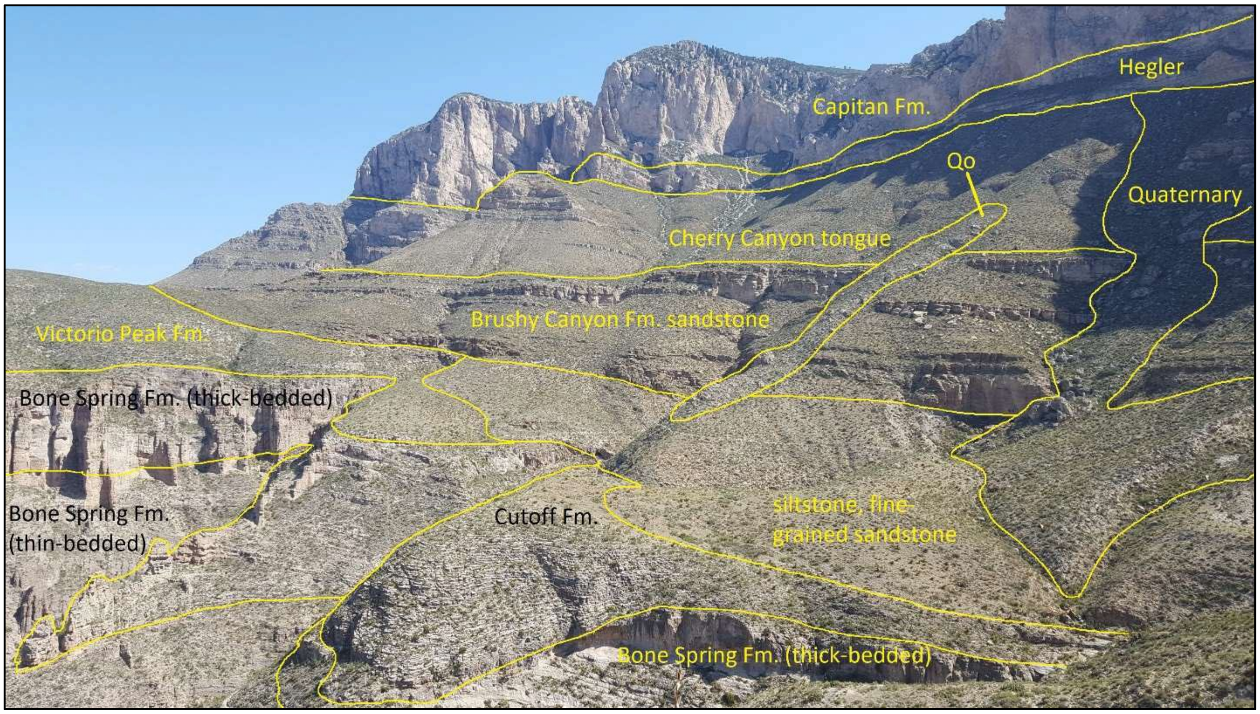

Figure 11. View of the western escarpment, from the south side of Shumard Canyon looking north toward Shumard Peak. Note how the Cutoff Formation and the Brushy Canyon Formation truncate the Victorio Peak Formation and the thick-bedded upper portion of the Bone Spring Formation. Slope-forming siltstones and fine-grained sandstones of the Cherry Canyon Tongue interfinger northward into more abundant limestone beds exposed on the left skyline immediately below the cliffs. Compare this figure to Plate 12B of King (1948).

THE ARTESIA GROUP

One of the major goals of this study was to attempt to delineate and distinguish the different formations that comprise the bedded lagoonal formations of the Artesia Group within the Park. This is not a new goal. As Boyd (1958) pointed out, this has been the goal of many studies since the early part of the Twentieth Century. Unfortunately, many of these rocks lose their individual characteristics as they merge with the reef deposits of the Capitan Formation. Much of the remainder of these rocks away from the reef occur at high elevations that are either covered with thick vegetation and soil or are exposed in precipitous and inaccessible cliff exposures. It was initially thought that measuring several detailed stratigraphic sections along the cliffs might reveal patterns in the stratigraphy, but some of the larger the canyons cut obliquely across the reef front and, hence, reveal different facies that are not easily correlateable. In addition, thick fine-grained sandstone and siltstone beds that could be used as marker beds pinch out and disappear entirely against the Capitan Formation. Although fossils are visible to the trained eye, they are not obvious to a non-expert. Many of the same fossils are found within different formations, such that they are non-diagnostic of any particular unit. Probably a better way to distinguish the formations of the Artesia Group within the Park is to first map them outside the Park to the north and follow those contacts southward. Another possible method, which has had success in other areas of the Guadalupe Mountains, is to rely the biostratigraphy of fusulinids and/or conodonts.

Probably the best exposure of the Artesia Group in the study area, and certainly the thickest exposure, is in the northwest corner of the map in West Dog Canyon. The cliff face on the west side of Lost Peak is the best exposure, revealing 1,000 feet of bedded dolomite and interbedded fine-grained sandstone (Figure

12). A steep west-dipping normal fault cutting north-northwest across the foot of this cliff forms the east side of a graben. Lost Peak is in the eastern foot-wall of this graben.

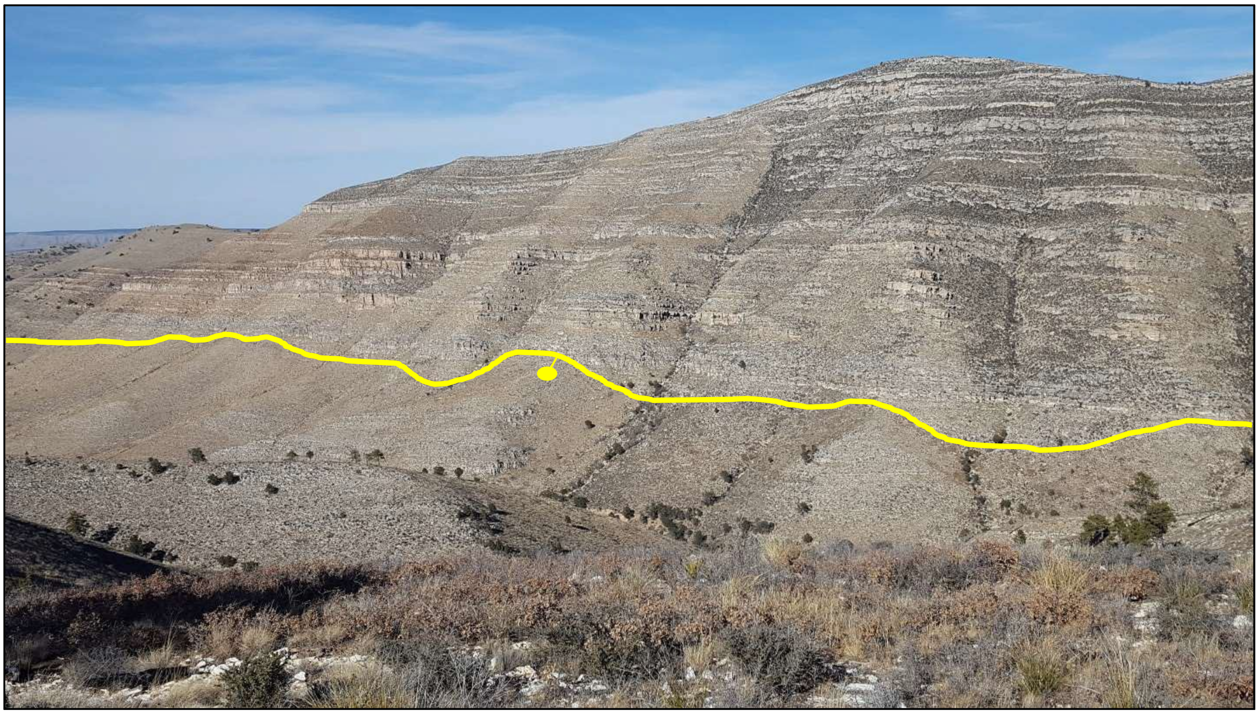

Figure 12. Looking northeast towards Lost Peak. The west-facing cliff forms the eastern structural boundary of West Dog Canyon and reveals one of the thickest exposures of Artesia Group strata in the Park. Most of the darker layers are slope-forming siltstone/sandstone. The yellow line represents a down-to-the-west normal fault.

A detailed stratigraphic section that was measured on the west side of Lost Peak is shown in Appendix A. In general, the dolomite beds from top to bottom look very similar and are mostly massive. Near the base, and truncated by the fault, is a section of dolomite that is slightly more bluish gray and is thicker than most of the beds above. This section was tentatively mapped as a distinct unit, though which unit it may be is unclear. King (1948, plate 3) mapped it as the Goat Seep Limestone ("thick-bedded to massive, in part sandy").

In the high area between Upper Dog Canyon and McKittrick Canyon, both King (1948) and Hayes (1964) mapped different formations which, in the present study, are lumped into the Artesia Group (Pa). King (1948) distinguished the Goat Seep limestone and, overlying, what he called the Capitan limestone which, as he described it, was thin-bedded and contained sandstone layers. North of the state line, Hayes (1964) also distinguished the Goat Seep dolomite and subdivided King's (1948) Carlsbad limestone into (in ascending order) the Grayburg Formation, the Queen Formation, and the carbonate facies of the Seven Rivers Formation. He also added the younger Yates and Tansill Formations. It is possible that several of these formations are exposed at Lost Peak, but in the absence of confident correlation with previous work, these layers were lumped together.

This area, in particular the rocks immediately south of the state line, were examined again during this study. Some of the best, and most accessible, outcrops are exposed on the west-facing fault scarp that forms the eastern edge of Upper Dog Canyon. Measured section 29 was measured here (Appendix A). Compare this to the measured section by King (1948) at nearly the same location. The mostly thick-bedded and massive light gray dolomite layers are intercalated with abundant thin to thick layers of fine-grained sandstone/siltstone. Three more stratigraphic sections were measured on the east side of North McKittrick Canyon (Appendix A). The dolomite layers in these sections are all very similar in appearance. During the current field work there did not appear to be any obvious criteria for subdividing the formations of the Artesia group here based on these layers alone. The sandstone layers may provide the key marker beds for distinguishing the different formations mapped by Hayes (1964). However, the paucity of good and accessible exposures in the higher elevations and the rapid loss of sandstone beds towards the southeast, as these lagoonal layers merge with the Capitan Formation, did not lend enough confidence to distinguish individual formations here. It would probably be easier to do so by beginning in a location further north that is well exposed and well understood and then tracing those contacts southward across the state line.

Figure 13. Looking north from the Permian Reef Trail, on the north side of McKittrick Canyon. The layered rocks of the Artesia Group dip gently eastward and rest on top of the massive rocks of the Capitan Formation. Both rocks extend along the cliff face into the far distance. Researchers in Bebout and Keran (1993) described many subunits within the Capitan Formation here.

CAPITAN FORMATION

As mentioned above, both King (1948) and Hayes (1964) mapped rocks of the Goat Seep limestone/formation in North McKittrick Canyon and distinguished them from the rocks of the Capitan Formation, based on relations exposed on the western escarpment north of Shumard Peak. Although these outcrops were not examined up close during the current mapping, through binoculars the two units are indistinguishable from one another in the Guadalupe Peak quadrangle. Additionally, both researchers subdivided the Capitan Limestone/Formation into an upper ‘massive’ unit and a lower ‘breccia’ unit, equivalent to Newell and others’ (1953) “reef” and “reef talus”. Within the study area, this relationship is probably most obvious on the northeast side of McKittrick Canyon near its mouth. Here, most visible in particular from half way up the Permian Reef Trail, the upper portion forms a steep featureless cliff, while the lower portion contains week, local layering that dips to the southeast between 15 and 30 degrees. In most areas, however, this relationship is not immediately obvious, and because of the extremely steep topography, and time constraints, no attempt was made to subdivide the Capitan Formation into these two units (see photo of this unit in Figure 13). Researchers who closely studied the Capitan Formation along the Permian Reef Trail (Bebout and Kerans, eds., 1993) were able to identify and describe many different subunits. Their color guidebook contains many photographs and illustrations. Probably the most spectacular exposure of the Capitan Formation anywhere is on the western escarpment from El Capitan northward. Where discernable, faint bedding within the unit dips up to ~25 degrees south-southeastward and has been interpreted to represent the talus of the reef front shed from the reef into the Delaware basin. Figure 14 shows some of these beds in McKittrick Canyon, while they are not so visible in Figure 15.

Figure 14. View from the Permian Reef Trail looking south-southwest along McKittrick Canyon in the foreground and South McKittrick Canyon in the distance. Bedding within the Lamar Limestone Member of the Bell Canyon Formation (on the left) steepens westward (to the right) where it merges with the steeper crudely bedded Capitan Formation.

Figure 15. View looking south into McKittrick Canyon from just south of the State line. Most of the mountains here are composed of the Capitan Formation, capped at the top of the ridges by the layered rocks of the Artesia Group.

THE DELAWARE MOUNTAIN GROUP

The formations of the Delaware Mountain Group are comprised of the Brushy Canyon Formation, the overlying Cherry Canyon Formation, and the youngest unit the Bell Canyon Formation. Within the current map area these formations underlie all of the lowlands beneath, and interfingering with, the Capitan Formation, and all of the rocks above the older limestones of the Cutoff, Bone Spring, and Victorio Peak Formations. Volumetrically, the Delaware Mountain Group is dominated by fine-grained siliciclastic deposits thought to have been deposited southward into the subsiding Delaware basin during the Guadalupian (see P. Scholle's website for references). Less abundant by volume, but still important, are several discrete and mappable limestone units. Detailed stratigraphic sections were measured along the base of the reef escarpment during this study. Close to the escarpment, all of these limestone units lose their character as they merge with the Capitan Formation.

Difficulties in Mapping the Delaware Mountain Group

From a distance, the rusty tan sandstone ledges of the Brushy Canyon Formation appear to form obvious marker beds and horizons. Viewed from a distance, most, if not all, of the sandstone ledges appear to be confined below a particular horizon. However, south of the Guadalupe Pass careful observation reveals that several light colored sandstone beds occur above this general horizon while other darker sandstone beds also occur above but are similar in color and erosional style to the neighboring fine-grained sandstone and siltstone within what is mapped as the Cherry Canyon Formation, making them invisible from a distance. Even closer observation reveals that some of the thicker layers that at first appear relatively horizontal are instead comprised of two or more inclined sets of dipping beds above inclined surfaces that truncate the beds below (Figure 16). These inclined surfaces have been interpreted as sequence boundaries. If so, they reflect local subaqueous unconformities that separate sequences of rock deposited at different times. Many researchers have recognized and drawn many such sequence boundaries on photographs of the west-facing escarpment. There is great difficulty, however, in transferring this detailed information to the horizontal projection of a map. In general, and certainly at the scale of this map, it is not possible to draw sequence-stratigraphic boundaries on a map view.

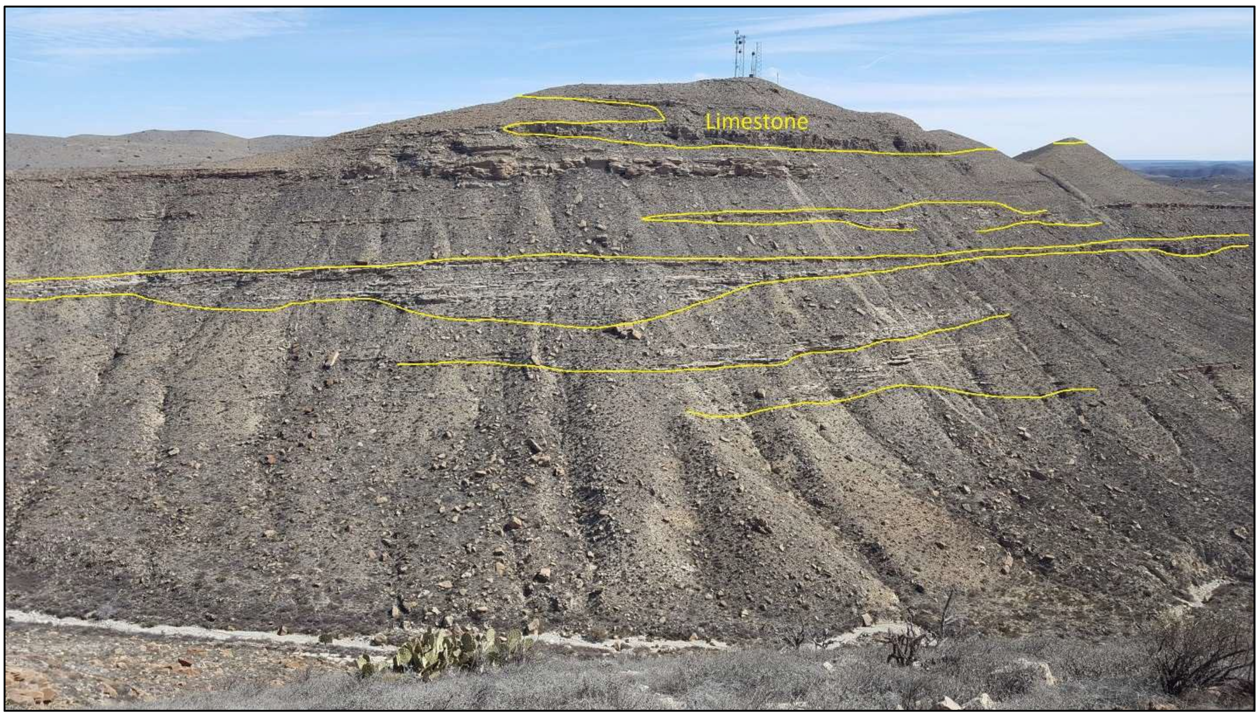

Figure 16. Slightly more resistant sandstone ledges of the Brushy Canyon Formation show channel-like lower contacts immediately south of Guadalupe Pass.

A similar relationship is exposed in some of the limestone exposures within the Bell Canyon Formation. Immediately south of the highway at Guadalupe Pass, the limestone capping the ridge below the communications towers interfingers with the fine-grained sandstone and siltstone of the Cherry Canyon Formation. This relationship is well exposed on the northwest side of the exposure along the cliff face. On the south side of the exposure the contact climbs and may pinch out. Immediately west of the communication towers, the prominent hill that dominates the curve in the highway is capped by limestone and flanked by resistant tan beds of sandstone. The basal contact of the limestone dips southward and truncates the underlying sandstone beds. No breccias or other deformed deposits are obvious along this contact, and tan dolomite beds take the place of the sandstone beds on the south side of the hill. Further to the northeast, immediately south of the Pine Spring Campground, the limestone capping the hill here shows an interbedded relationship with the adjacent fine-grained sandstone and siltstone of the Cherry Canyon Formation, and the limestone also appears to pinch out southward into the clastic rocks.

Some relationships make it difficult to draw the contact between the Brushy Canyon Formation and the Cherry Canyon Formation with much accuracy. For example, refer to plate 9 of King (1948) showing his geologic map of the western escarpment. The contact between Brushy Canyon Formation and the overlying Cherry Canyon Formation is drawn, quite reasonably, above the thick prominent sandstone ledge a little more than ½ mile directly south of El Capitan. This sandstone ledge pinches out about ½ mile to the northwest, forcing King (1948) to extend this contact through a very thick interval of nondescript slope-forming fine-grained sandstone/siltstone. He projected this contact more than one mile northward, apparently closely following a similar topographic contour, which is mostly obscured by much younger slope deposits, and then drawing the contact again at the top of a sandstone ledge that thickens to the north. While reasonable from the perspective of drawing contacts, its location is necessarily arbitrary. So although researchers have been able to subdivide the Brushy Canyon and Cherry Canyon Formations into multiple individual sequences and members, from a lithostratigraphic point of view these units have blurry boundaries that are not easy to define.

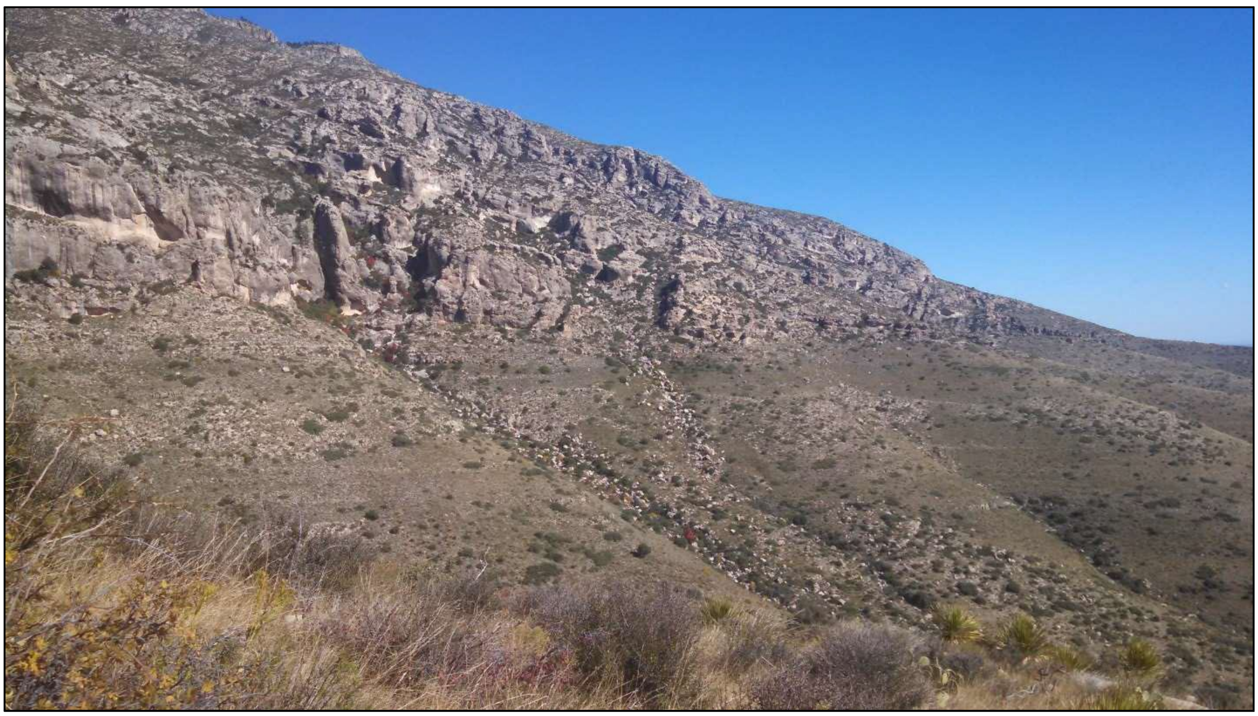

Figure 17. Looking north from somewhere east of Pine Spring. Gently southeast dipping limestone and siltstone of the slope-forming Delaware Mountain Group are overlain and intercalated with massive and crudely bedded fore reef deposits of the Capitan Formation that dip up to ~30 degrees to the southeast. Formations of the Artesia Group, assumed to be time-equivalent to members of the Delaware Group, are separated by 2,000 vertical feet of the Capitan Formation. Photo taken November 5, 2015.

Another goal of the current study was to try to correlate the limestone members within the Delaware Mountains Group with the lagoonal formations within the Artesia Group. Presumably, the basinal and lagoonal formations existed at the same time but were deposited in much different depositional environments, separated by 2,000 vertical feet of the reef front (Figure 17). Most of the limestone beds of the Delaware Mountains Group are dominated by more-or-less massive beds that contain sparse to abundant small skeletal fossil fragments. Where visible, many of these fragments are composed of calcite spar. In many beds they are selectively partially silicified to gray chert. The matrix between the grains is commonly micrite. Lithologically, most of these rocks can be classified as wackestones and some as packstones. Limestone beds that are solely micrite, without any skeletal material, are relatively uncommon. Also, laminae are commonly weakly developed. The thinner beds typically show better developed laminae, whereas in the medium- to thick-bedded limestone it is poorly developed. These characteristics suggest that the more massive beds may have been subjected to bioturbation. Their proximity near the base of the reef slope also suggests that much of the sand-size skeletal material may have been emplaced by turbidity flows originating from up-slope (Figure 18). Because most of the limestone beds are so similar it was not possibly to find characteristics that uniquely identified each member unambiguously (with the possible exception of the Reef Trail Member which contains abundant dark organic-rich laminae).

Figure 18. This photo shows how obviously bedded limestone and sandstone of the Delaware Mountain Group (on the left) merge laterally over a very short distance into massive outcrops of the Capitan Formation (on the right). Some beds can be followed into the Capitan Formation further than others. The resulting contact drawn on the map is necessarily partly arbitrary.

Manzanita Limestone Member of the Cherry Canyon Formation

As used in this report the Manzanita Limestone Member of the Cherry Canyon Formation contains two sub-members—dolomite (Pmd) and thick-bedded light gray sandstone (Pms)—that were most easily distinguished at Nipple Hill and on Rader Ridge. King (1948) called this the Manzanita Limestone Member and recognized that, unlike the other carbonate formations within the Delaware Mountains Group, this member is composed of dolomite rather than limestone. It is characteristically sandy, containing abundant subrounded very fine-grained to medium-grained quartz grains. The layers are typically medium- to thick-bedded and massive, forming slightly lighter tan ledges that are similar in appearance to the neighboring fine-grained sandstone/siltstone. Along the western escarpment this member typically forms steep ledgy outcrops and small cliffs, making this unit stand out a little more readily from a distance. This member is important because it contains, as King (1948) recognized, very thin aqua-green colored siliceous layers (Figure 19) between 10 and 50 cm thick that may represent altered Guadalupian-age volcanic ash. These beds are marked with an asterisk in plate 6 of King (1948) and are shown as red lines in the measured stratigraphic sections within the current report in Appendix A.

Figure 19. An angular clast of aqua-green colored siliceous rock is probably altered ash. This clast eroded from thin beds within dolomite of the Manzanita Limestone Member (Pmd) of the Cherry Canyon Formation.

Along the western escarpment the dolomite beds form one or two thick sequences of beds. From the north side of Guadalupe Pass eastward, however, the dolomite occurs as several different layers separated by fine-grained sandstone/siltstone. Taken together, these dolomite layers appear to form a mappable horizon that occurs progressively up-section further east. On the western escarpment the dolomite occurs below the Hegler Limestone Member. In Pine Spring Canyon, at Nipple Hill, and on the south side of Rader Ridge the same horizon occurs below the Pinery Limestone Member. The dolomite horizon is everywhere underlain by a distinctive slope-forming thick-bedded gray sandstone unit (Pms, where identifiable and mapped), suggesting that the Manzanita Limestone Member is equivalent in each of these locations (Figure 20).

This suggests that the Hegler Limestone Member pinches out to the east, southwest of the campground in Pine Spring Canyon. Alternatively, it might merge with the base of the Pinery Limestone Member. Refer to the stratigraphic sections measured between El Capitan and Pine Spring Canyon (Appendix A). It appears that the Hegler Limestone Member, which is more than 100 meters thick below El Capitan, thins dramatically on the southwest side of Pine Spring Canyon (section 21). This is discernable on the geologic map. However, could the thin dark-colored limestone beds at the base of the Pinery Limestone Member (sections 4, 6, 8, and 9) represent the eastern extensions of the Hegler Limestone Member instead?

The possibility that the Manzanita Limestone Member might be time-transgressive also makes it a bit difficult to confidently place the boundary between the Cherry Canyon Formation and the overlying Bell Canyon Formation. On the map, the contact is placed at the top contact of the uppermost dolomite unit of the

Manzanita Limestone Member. Sandstones of the Cherry Canyon Formation below this contact are labeled Pcss, and sandstones above this contact within the Bell Canyon Formation are labeled Pbcs.

Figure 20. The Manzanita Limestone Member of the Cherry Canyon Formation is well exposed at Nipple Hill. Light gray, thick bedded, cross-bedded to massive sandstone (Pms) is overlain by tan, ledgy dolomite layers (Pmd).

PINE SPRING CANYON

Structurally, most of Pine Spring Canyon sits within a graben that, in the north, also contains Upper Dog Canyon and West Dog Canyon. The graben is a little more than one mile wide. From the Visitor Center, the Bear Canyon Trail follows the fault that forms the eastern side of the graben, though the fault itself is mostly covered by talus and is only exposed in a few small locations. The fault on the western side is also obscured by much younger talus almost everywhere. The fault was inferred based on the differences in the stratigraphy on either side of its inferred location.

The Pinery Limestone Member (Pp) wraps through the canyon and forms many of the layered deposits exposed high up on the slopes of the north wall of the canyon. Here the formation is both underlain and overlain by light yellowish gray slope-forming siltstone and fine-grained sandstone (Pbcs). Further up the canyon, the limestone becomes thicker and no sandstone beds are visible. The limestone here is beautifully exposed at Devil's Hall, a slot canyon carved into the layered rocks. Remnants of formerly more extensive stream and slope deposits (Qm) exposed as much as 40 feet or more above the modern stream bed suggests that the latest incision of the stream occurred relatively recently, possibly during the Pleistocene. Some of the Qm deposits exposed in stream cuts in the canyon reveal filled paleochannels suggesting a long history of erosion, back-filling, and exhumation. The Pinery Limestone Member exposed in Devil's Hall is characterized by mostly thin-bedded to medium-bedded outcrops that, from a distance, exhibit very flat and planar bedding planes and appear very regularly bedded. Up close, the upper surfaces are not perfectly planar but commonly show an undulatory structure reminiscent of subdued linguoid/lunate ripple marks. Early diagenetic chert is common and occurs as both thin, bedding-parallel layers 1-2 cm thick and as relatively isolated elongate nodules whose long axes are parallel to bedding. On weathered surfaces the chert is light tan and is obvious, but on freshly broken surfaces is darker gray and similar in color to the limestone such that it is much less obvious. Higher in the formation chert is less abundant and beds are thicker and more massive.

The low rounded hills immediately southwest of the Pine Spring Campground contain some of the most accessible exposures of bedded dolomite in the Park, probably belonging to the Manzanita Limestone Member of the Cherry Canyon Formation (Pmd). The dolomite here typically forms light yellowish gray planar beds that are mostly massive but locally exhibit thin laminae. The dolomite forms resistant layers and ledges and commonly contains fine to medium quartz sand. This unit is extensively interbedded with light yellowish gray sandstone beds. Because both the dolomite and sandstone commonly exhibit similar colors distinguishing the two can be difficult. As in most areas, however, the sandstone beds tend to form easily erodable slopes.

Further to the southwest, the limestone beds become thinner and are interbedded with volumetrically more abundant fine-grained sandstone. The uppermost limestone beds interfinger with breccias of the overlying Capitan Formation. Both the limestone and sandstone pinch out on the north wall of Guadalupe Canyon, immediately north of Guadalupe Spring. Also in this area, another limestone unit is exposed stratigraphically below the Pinery Limestone Member and its interbedded sandstone. In this area the lower limestone does not appears to contain any sandstone beds and thickens dramatically to the southwest towards Guadalupe Spring. Here it forms the prominent high flat ridge that is visible from where the highway drops westward off of Guadalupe Pass to the south. It is interpreted to be equivalent to the Hegler Limestone Member of the Cherry Canyon Formation. Southeast of the Pine Spring Campground, and southeast of the highway, a low mesa is capped by thin-bedded limestone here also here interpreted to be equivalent to the Hegler Limestone Member. The limestone pinches out southward into fine-grained sandstone and siltstone.

BETWEEN PINE SPRING CANYON AND McKITTRICK CANYON

Nine stratigraphic sections were measured between Pine Spring Canyon and McKittrick Canyon. The individual sections are shown in Appendix A. A composite fence diagram is shown in Figure 21. No datum was used, so these sections are shown together only as a best-fit. By looking at the geologic map along the mountain front there appear to be many different limestone layers. On the composite stratigraphic-section, however, several layers appear to form distinct groups. These groups were lumped together and given member names. These group/member names seem reasonable from the stratigraphy, but it should be noted, as King (1948) did, that each of the members (with the notable exception of the Lamar Limestone Member) is interbedded with a considerable volume of very fine-grained sandstone/siltstone. The reader should be aware that these groupings are a best-fit estimate based solely on lithostratigraphic criteria (rock types and associations). It bears repeating that subsequent researchers may find that other criteria (such as fossils, isotopes, etc.) may provide a more accurate means of grouping these members.

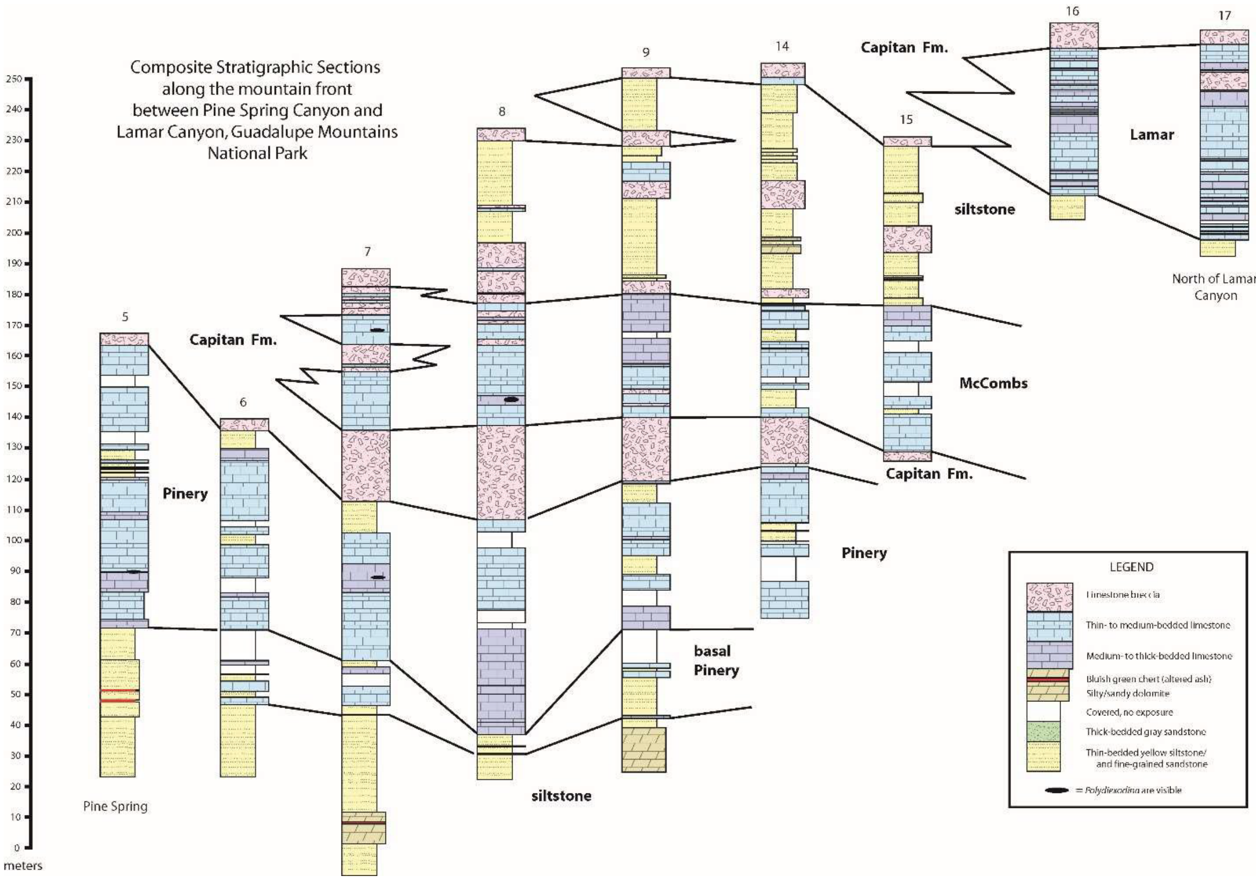

Figure 21. Composite stratigraphic sections between Pine Spring Canyon and Lamar Canyon showing rocks of the Bell Canyon Formation.

In any case, from the measured sections it appears that the Pinery Limestone Member, the McCombs Limestone Member, and the Lamar Limestone Member of the Cherry Canyon Formation can be distinguished across the mountain front. The detailed measured sections do not support the existence of the Rader Limestone Member as a separate unit. The pink fragmental pattern in the measured section represents extensions of the Capitan Formation that were deposited coevally within and between these limestone members. Notice how the Capitan Formation climbs in stratigraphic position from Pine Spring Canyon to McKittrick Canyon. This is probably in part the result of filling in of the Delaware basin with sediment and the migration of the reef seaward (southeastward). But the eastern escarpment also parallels the reef front from southwest to northeast, which is nearly perpendicular to the original depositional trend. This suggests that the reef may have also grown northeastward and younger portions of the reef may be exposed in that direction.

It has been the convention since King (1948) to call the limestone units of the Delaware Mountain Group "members" instead of formations. This is firmly entrenched in the literature. Although academic, a case could be made that each of the limestone units is itself a mappable formation. Also, in comparing the measured stratigraphic sections of King (1948, plates 6 and 15) with the sections measured during the current study, the reader will notice similarities, but also many differences. This is brought up to point out that even with excellent exposure, access, and decades of study, these rocks are not always easy to understand and subsequent studies will no doubt add even more to our understanding.

GUADALUPE PASS AREA

Guadalupe Pass is one of the most interesting areas in the study area, both historically and geologically. Historically, the pass has been a focal point for travelers. It is the only navigable pass within the more

Figure 22. A portion of the older paved road is overgrown but still visible immediately east of Guadalupe Pass.

than 100-mile barrier of the north-south trending Guadalupe and Delaware Mountains. In the mid to late 1800's it was the site of the snow-free southern transcontinental trail from St. Louis to San Francisco, during which time the pass saw thousands of would-be settlers travelling westward, and was the highest elevation crossed during that trip. According to King (1948, p. 5) the 'modern' road (of the 1940's) closely follows the course of an old caravan road that came into existence at the close of the Mexican-American War. This road, now abandoned, is still visible in sections, especially near Guadalupe Pass (Figures 22 and 23). Geologically, the pass sits near the easternmost structural boundary of the Basin and Range (or Rio Grande rift?) physiographic province. From Guadalupe Pass westward to the Sea of Cortez and the Pacific Ocean, Earth's crust is broken into a series of structural troughs and mountain ranges. East of the pass, there are only a few exposed faults with minor offset and, although buckled and folded into broad basins, the nearly horizontal layered formations have been relatively stable here since the end of the Paleozoic. A recent paper by Ricketts and others (2021) concludes that this area is really the eastern structural boundary of the Rio Grande rift, an entity that is structurally and temporally distinct from the Basin and Range province.

Figure 23. A portion of the older paved road, visible immediately west of Guadalupe Pass, is used to access the Salt Basin Trail.

Brushy Canyon Formation

The Brushy Canyon Formation (reference) is well exposed in the west-facing escarpment of the Delaware Mountains south of Guadalupe Pass. It is characterized by dark yellowish gray very-fine-grained sandstone and siltstone interbedded with more resistant lenticular beds of lighter gray fine- to medium-grained sandstone. From a distance, the color difference gives the formation a striped appearance. Some light gray sandstone beds can be followed for more than a mile along the escarpment while others are lens-shaped and pinch out rapidly. Some exhibit basal contacts that cut deeply down into the underlying sediments by up to several tens of meters and have been interpreted as sequence boundaries. Some of the thicker sandstone layers were mapped separately from the neighboring siltstone deposits, particularly north of Guadalupe Pass where the two are easily distinguished. South of the pass, however, this was not possible at the scale of the map. It was most convenient where sandstone layers capped small plateaus and/or were isolated enough to allow for an accurate portrayal of their extent.

West Dog Canyon and Upper Dog Canyon

Upper Dog Canyon can be accessed via Highway 137, a 70-mile drive west and south from Carlsbad. The valley is a half-graben formed by a normal fault on the east side that has down-dropped the valley and the western side. As a result, most of the bedding within the Artesia Group dips up to about 10 degrees to the east-northeast. The hills here are mostly mantled with a crumbly regolith so exposures are poor, except along steeper slopes and cliffs. Although difficult to measure, bedding within the hills immediately west of the fault, within the hanging wall appear to be moderately dipping to the west, suggesting that drag folding was the cause.

West Dog Canyon is more isolated and is best accessed from Upper Dog Canyon via the Bush Mountain Trail. This canyon resides within a graben (Figure 24). The fault that forms the eastern side of the graben has revealed a thick section of the Artesia Group layers (Figure 12) in the footwall there. The fault on the

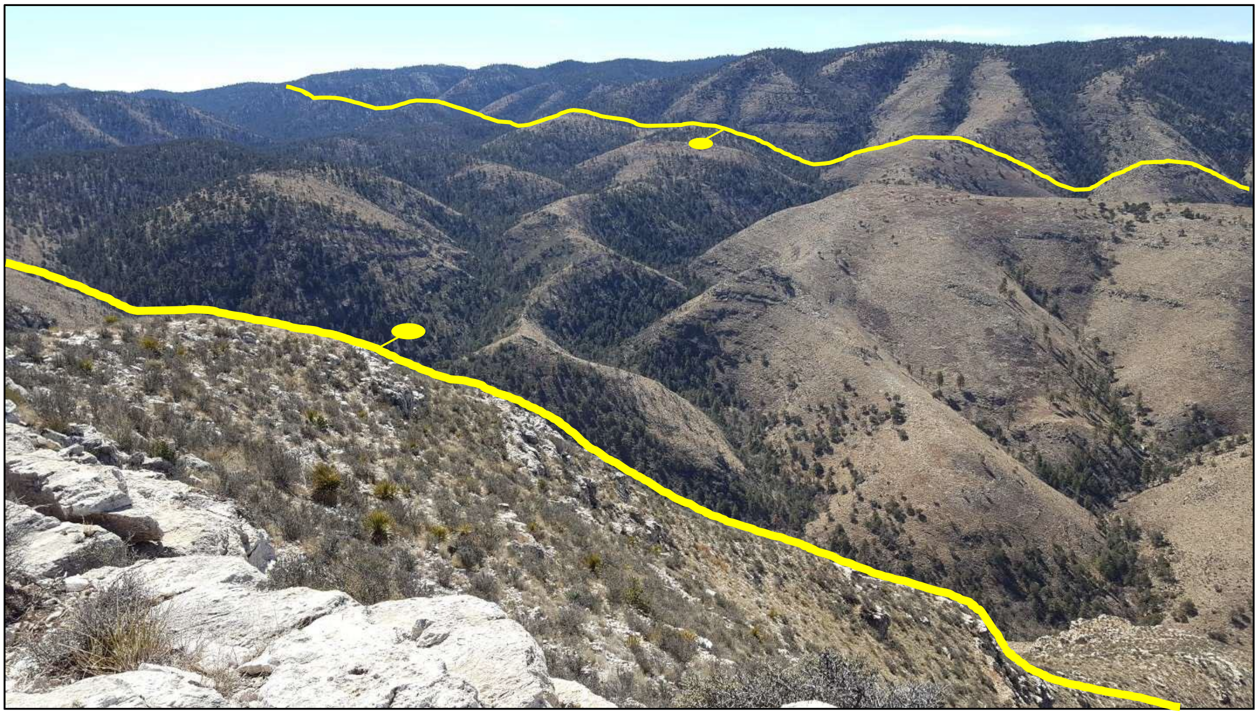

Figure 24. Looking south-southwest from Lost Peak across the graben that forms West Dog Canyon.

western side of the graben is not as easy to identify, in part because of the denser vegetation on the north-facing slopes. Offset on the western fault is presumably less than the offset on the eastern fault, resulting in most of the bedding of the Artesia Group sediments dipping to the northeast. As in Upper Dog Canyon, the bedding may dip to the west in the hills immediately adjacent to the fault, within the footwall, also suggesting they may have been formed by drag folding. Attitudes here are very difficult to measure with much confidence.

SUBSURFACE CROSS-SECTIONS

The discovery of oil in the Permian basin in 1920 led to numerous geologic studies in an effort to understand and correlate surface outcrops with a growing body of subsurface lithologic and geophysical logs obtained during the drilling of oil wells. So much detailed subsurface information was subsequently obtained that, ironically, the subsurface stratigraphy was better understood than the surface exposures themselves. Also ironically, as Boyd (1958) pointed out, the central Guadalupe Mountains were "a principal obstacle to all surface correlations between the pre-Capitanian basin and shelf units." Although many more wells have been drilled since then, to this day one of the least understood areas of the subsurface in the region lying beneath the southern Guadalupe Mountains.

Recognizing the geologic complexity of the mountains and long history of deciphering its history, much time was spent looking at the available subsurface information within this area. Because of the large number of studies, the limited amount of time, and the possibility that much better subsurface cross-sections already exist but may be proprietary, the following sources of subsurface information were relied upon the most: Plates 6 and 15 of King (1948), Plate 3 of Hayes (1964), cross-sections B-B' and C-C' of Standen and others (2009), and a sparse number of water-well logs obtained from the Texas Geological Survey/Bureau of Economic Geology.

NEOGENE AND QUATERNARY DEPOSITS

West of Guadalupe Pass

The Neogene and Quaternary sedimentary deposits west of Guadalupe Pass have been affected by long-lived tectonism, down-dropping of the basins to the west, and an overall steeper gradient. The oldest deposits are small remnants that cap steeply west-sloping ridges on the western escarpment west of El Capitan. On the map they are labeled as Tc for Tertiary deposits, because of their very high position in the landscape and their extensive degree of dissection. These characteristics suggest that they are older than Quaternary. Additionally, the slope of these deposits appears to intersect with isolated terrace remnants preserved high in the landscape further to the south of El Capitan mapped as Tc. Figures 25 and 26 show two of these remnants. Both are relatively thin deposits containing large boulders of the Capitan Formation (Pc) that must have originated from outcrops of the Capitan Formation. The flat upper surfaces appear to be original constructional surfaces. If so, these surfaces are likely quite old. These deposits might be good candidates for using cosmogenic dating to better constrain their ages. Since their deposition, they, and the underlying bedrock, have been extensively eroded.

Much of the younger Quaternary deposits (Qm) were deposited on the steep eastern slopes of El Capitan where they also contain large boulders of the Capitan Formation. Some of the boulders are house-sized and, like the Qo deposits, were probably emplaced as avalanche, debris flow, and rock fall deposits (Figure 27). Further away from the steep slopes the deposits still contain a large percentage of boulders of Pc, indicating that some of these debris flows travelled long distances. Good exposures can be seen in the road cuts near the rest area west of Guadalupe Pass. West of the western escarpment, Qm deposits form large alluvial fans incised by narrower younger drainages now 5-8 meters below the top of the fans.

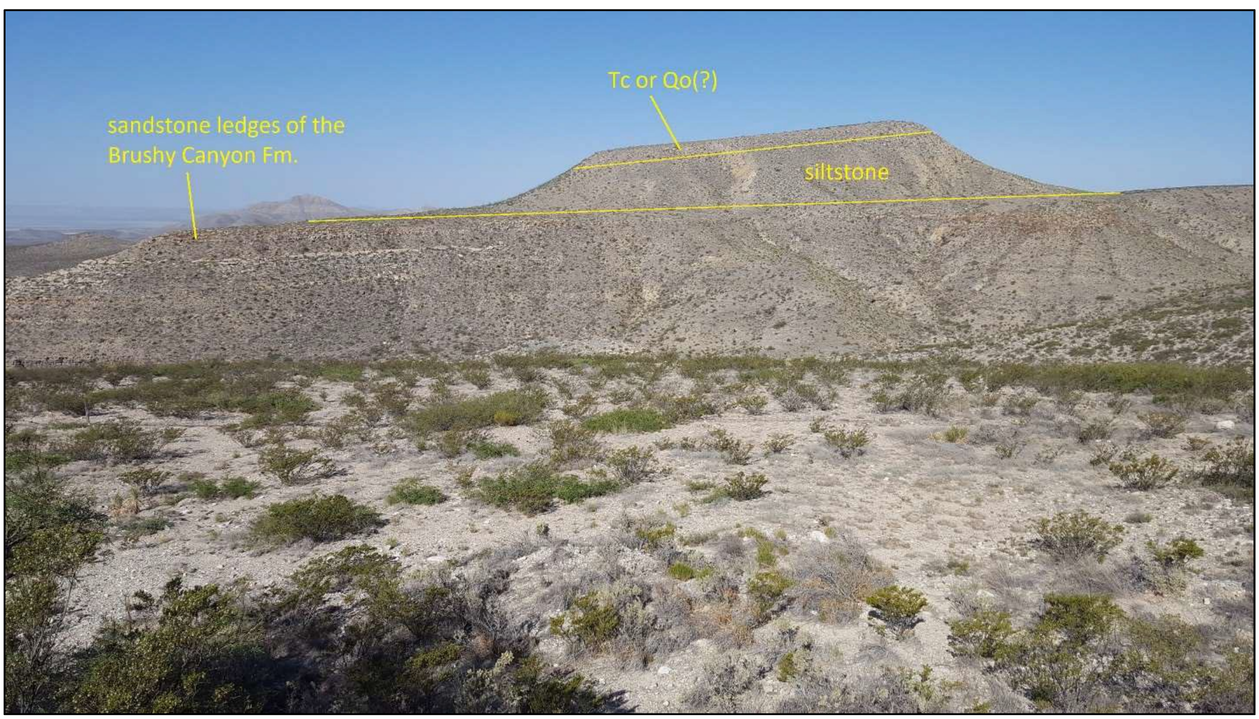

Figure 25. Looking west from the rest area west of Guadalupe Pass. A thin, high remnant of Neogene or earliest Quaternary sedimentary deposits caps the ridge. Notice how the erosional base of the remnant is discordant to bedding in the underlying sandstones of the Brushy Canyon Formation.

Figure 26. Looking south form the hill immediately east of the rest area west of Guadalupe Pass. A thin remnant of southwest-dipping Neogene or earliest Quaternary sedimentary deposits caps the ridge composed of the Brushy Canyon Formation.

Figure 27. Looking north-northeast towards El Capitan. Older Quaternary deposits containing huge boulders of the Capitan Formation mantle steep slopes and were probably deposited as avalanches, debris flows, and rock falls.

East of Guadalupe Pass

East of Guadalupe Pass, post-Cretaceous tectonism has been much less extensive. Most streams, therefore, are graded to a much shallower gradient. As a result, the difference in elevation in the landscape between the oldest and youngest deposits is not nearly as great as it is west of Guadalupe Pass. The oldest deposits, here labelled Tsy, form rounded dissected hills as shown in Figures 28 and 29. These hills characteristically no longer exhibit flat, constructional upper surfaces. These deposits have been eroded, revealing deposits of coarse, bouldery alluvium (Figure 30) strongly cemented with carbonate lithic grains and calcite cement. From the remnants of Tsy exposed between Guadalupe Pass and Rader

Figure 28. View from Nipple Hill looking north-northwest. Rounded hills of Tsy form the valley floor. All of these deposits have been incised by streams, probably in response to distant base-level drop and changes in climate.

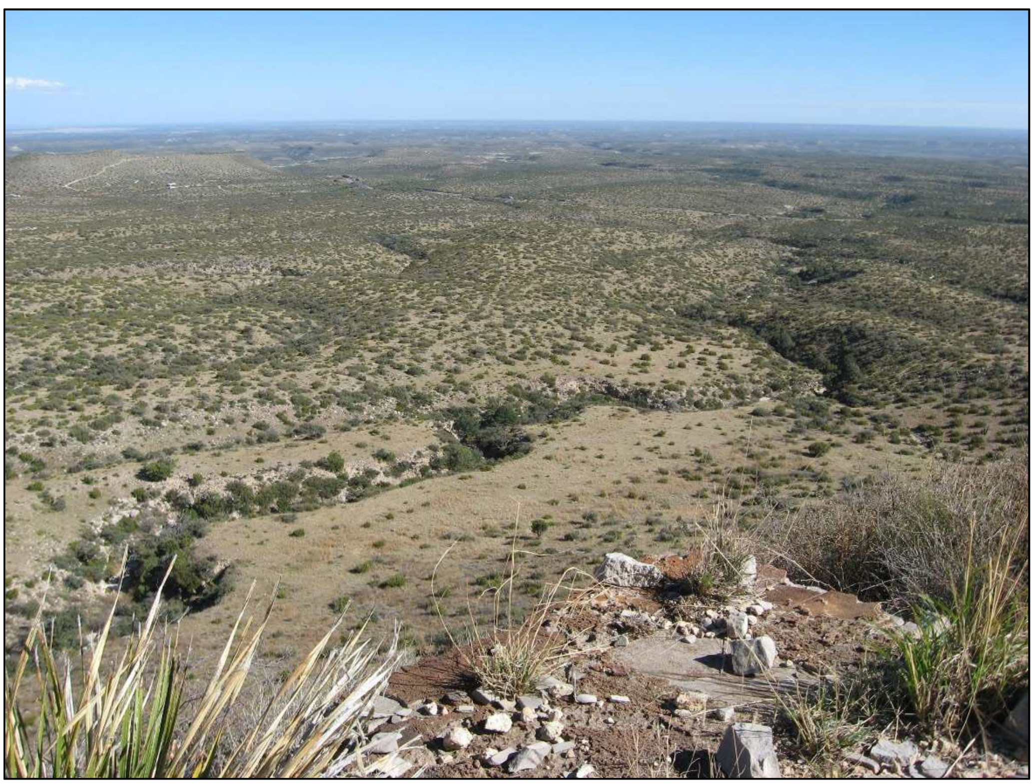

Figure 29. Looking east from northwest of Nipple Hill. This view contains Neogene and Quaternary deposits of different ages. Notice how steep-walled dissected streams are.

Ridge it is apparent that Tsy deposits were formerly much more extensive and probably covered much of this portion of the lowlands.

The Quaternary deposits are given labels that denote their relative age: Qo = older, Qm = middle, Ql = late, and Qy = younger. Deposits labeled Qo are slightly lower in the landscape than the upper portions of Tc. Qo deposits are also deeply dissected but contain relatively well preserved flat constructional surfaces. These deposits represent a period of stability where the landscape once again aggraded sediment after Tsy deposits had been partially eroded. Qm deposits represent another episode of erosion followed by stability and aggradation. Deposits of Qo and Qm dominate the Quaternary deposits along the mountain front (Figures 31 and 32). Slightly younger terraces (Ql1 and Qy2) are obvious in Pine Spring Canyon. The youngest deposits are related to the Holocene flood plains (Qy1) (Figure 33) and the modern stream beds (Qy2). Where these two units are not distinguished they are mapped as Qy. Notice in Figure 29 how the modern drainages have cut sharply downward into the Neogene and Quaternary deposits, creating steep-walled arroyos. The deposits of all ages contain a significant amount of carbonate cement that binds the grains together, allowing for vertical arroyo walls.

West Dog Canyon, near the very northwest corner of the quadrangle, contains Neogene deposits (Tc) in depositional contact with the underlying Artesia Group. Exposures are poor but the deposits appear to be comprised mostly of carbonate-cobble conglomerate. No bedding is visible but the visible relationships suggest that at least some of this material was shed into the graben during active faulting and has subsequently been tilted steeper and steep along the eastern fault. Because these deposits may be associated with tectonism they were given the label Tc to distinguish them from Tsy, deposits that are not obviously related to tectonism.

Figure 30. Typical stream-cut exposure of Tsy. Large boulder right of center is approximately 40 cm across.

Figure 31. Stream-cut cliff-face in Pine Spring Canyon exposes older Quaternary sedimentary deposits (Qm) that have partially filled the valley.

Figure 32. Closer view of Qm deposits in Pine Spring Canyon.

Figure 33. A stream-cut exposes Holocene alluvial deposits (Qy1) in McKittrick Canyon. Note the prominent dark brown organic horizon at the top.

McKittrick Canyon

At the mouth of McKittrick Canyon are exposures of Neogene conglomerates (Tsy) more than 100 feet thick on the north side of the canyon. The contact here cuts obliquely across the Paleozoic formations. This relationship indicates that the canyon was originally first scoured out by erosion, followed by a period of time when the canyon back-filled with coarse sediment, possibly due to either a temporary change in the down-stream base level or a change in climate. The canyon subsequently underwent another episode of down-cutting and erosion that removed all of Tsy from the interior canyons and much of it from the wider flood plain downstream from the mouth of the canyon. This same sequence of events may have occurred within all of the other smaller canyons along the mountain front but, because of the much larger drainage basin of McKittrick Canyon, these relationships are more obvious here and better preserved.

Sliding Boulder south of Guadalupe Pass

South of Guadalupe Pass, within a stone's throw of the old road sits a very large boulder that apparently slid down the hill relatively recently (Figures 34 and 35). The boulder is visible on Google Earth imagery as early as 1996 (the earliest available) and sits at 33º 51' 17.01", 104º 49' 57.65". The boulder apparently originated from a ledge of sandstone of the Brushy Canyon Formation exposed upslope. The linear path that the boulder followed is visible both in aerial imagery and on the ground as a lighter colored line. The fact that this path is still visible suggests this boulder did not slide very long ago (decades?).

Figure 34. Looking north from the old road south of Guadalupe Pass at the path of the large boulder. Lighter colored line down slope is presumably the path taken by the large boulder. February 20, 2019.

Figure 35. Another view of the large sliding boulder, looking west. Note the sediment pushed forward under the boulder.

Western Piedmont

In this report, the western Piedmont encompasses all areas west of the escarpment of the west side of the Guadalupe Mountains. This area has undergone much more extensive faulting and down-dropping than have other regions of the Park to the east. Because of this, the names and arrangement of the Quaternary units here are different from those used east of the escarpment. The western piedmont is here divided into three broad categories: (1) the escarpment, (2) alluvial fans and bajadas, and (3) salt flats. Each of these is briefly described below. Figure 36 shows the abrupt transition from the mountain front to the piedmont.

Figure 36. West-dipping beds of the Bone Spring Formation are well exposed along the northwestern portion of the escarpment of the Guadalupe Mountains.

Escarpment

The bedrock units of the western escarpment are described above. The units added here include colluvium and landslide deposits. Colluvium (Qc) represent material that was deposited on the flanks of steep slopes where sedimentation was driven mostly by gravity and mass-wasting processes. These deposits are poorly sorted and derived from the local bedrock upslope. Some deposits are strongly cemented by carbonate and form armored surfaces, while other deposits are only weakly cemented. Slopes show varying degrees of incision and gully formation. Because of this, the colluvium deposits may represent widely different ages from early Pleistocene to Holocene in age. No attempt was made to distinguish these different ages.

Landslide deposits (Qls) were mapped in only a few locations along the northwestern slope of the escarpment. Here, the rocks consist mostly of indistinguishable layers of the Artesia Group (interbedded dolomite and quartz siltstone/sandstone) that have been tilted and down-dropped to the west. The pervasive fracturing visible in these rocks, in addition to the tilting of these layers, made these rocks more susceptible to slumping. In fact, good exposures of the Artesia Group rocks along the northwestern portion of the escarpment are rare because of widespread slumping and sliding of boulder-size blocks of rock. Even the larger block tens of meters or more across are very difficult to define and seem to merge with the surrounding rocks. Some of these larger blocks appear to mantle and obscure the underlying layers, form hummocky to rather flat upper surfaces, and may have originated from somewhat cuspate scarps located uphill. Because of the difficulty in identifying these deposits, there may be more that exist but were not mapped, and those shown on the map should be viewed with some skepticism.

Alluvial fans and bajadas

As the name implies, the alluvial fans and bajadas form a relatively flat plain that slopes gently westward away from the mountain front. This area represents material that was eroded from the mountains and was deposited along the mountain front because of the marked change in gradient. Individual fan-shaped deposits are clearly visible where they emerge from the deep canyons along the mountain front. The individual fans locally merge downhill and westward where they become bajadas. As mapped, all of these deposits were deposited after tectonism and faulting had ceased and none of these deposits are obviously cross-cut by faults. These units were originally mapped using stereo photographic NAPP aerial images, printed as color photographs obtained from the Park Service, and drawing the geology on partially clear mylar overlays. However, the complexity of their patterns combined with the paucity of identifiable registration points on the existing topographic contour maps, led to many difficulties in georeferencing the overlays into ArcGISPro (the application used to digitize the map beginning in 2021). Therefore, the stereo-photo overlays were abandoned and the area was instead mapped using the georectified county aerial mosaic. This imagery, which shows differences in visible-light albedo, was very high-resolution and allowed mapping at a scale of 1:2,000 or better. Used in conjunction with the 3D topography feature of Google Earth, this proved to be a much more accurate method of mapping than the stereo photos alone.

Several different ages of alluvial fans were recognized. The oldest (Qco) has been almost completed eroded away. It currently forms small remnants along the base of the mountain front that are elevated approximately 5-10 meters or more above the next oldest fan deposits. Qco deposits are composed of poorly sorted boulders and cobbles of carbonate and sandstone that, where exposed, are cemented strongly together with sand, silt, silt and calcite cement. These deposits are mostly eroded and dissected such that the originally flat constructional surface on their upper surfaces has since mostly been removed. Qco deposits probably represent the uppermost level to which sediment accumulated in the valley, which was followed by episodes of periodic erosion, down-cutting, and deposition at lower levels in the landscape. This is a pattern that is widespread and visible across the Southwest.

The next oldest alluvial fan deposit (Qso) forms extensive deposits along the mountain front. They are characteristically the highest surficial deposits in the landscape (with the exception of Qco), are deeply dissected by ravines and streams, and are lighter in color than younger deposits as the result of the long-term accumulation of light tan-colored silt and the accumulation of light-colored carbonate cements in the soil. In most areas the contact between Qso and the younger Qsy deposits is obvious and sharp, where Qsy deposits are typically lower in the landscape. However, in some areas the distinction is not so clear, especially in areas where Qsy deposits accumulated above the top of the Qso deposits. As mapped, Qso deposits are shown as one unit, but in many areas long-term down-cutting by streams has formed several different intermediate terrace levels. However, the patterns of these terrace remnants are so complex that they were beyond the scope of this study to distinguish them all. Only one intermediate terrace was locally mapped as unit Qsyo.

Qsy deposits are characteristically darker in color than the older Qso deposits because of less accumulated silt and carbonate cement and because of the presence of more abundant darker vegetation (commonly creosote and cat claw). These deposits fill broad channels cut down into the older Qso deposits. They are typically composed of poorly sorted boulders, cobbles, and pebbles of carbonate and sandstone derived from the upstream mountains. These deposits are not as well lithified as Qso deposits and tend to exhibit upper surfaces composed of rather loose clasts. This property, together with the abundance of dense prickly shrubs, makes many of these surfaces difficult to walk across. In some areas, Qsy deposits typically show braided and anastomosing stream patters. In some upstream areas, Qsy deposits accumulated atop and locally buried the older Qso deposits, where they formed local alluvial fans. Because of their higher relief, these fans have subsequently undergone erosion, creating complex patterns with the underlying Qso deposits and making them very difficult to distinguish.

Although the downstream ends of the older Qso alluvial fan deposits are mostly sharp and well defined, the younger Qsy fans form continuous mappable units that extend beyond the toe of the Qso fans and out into the flatter portions of the basin. In these distal, downstream areas the grain size decreases and the fans merge into nearly flat deposits of silt covered in dense forests of creosote bushes (Figure 37).

Figure 37. The distal portions of the younger alluvial deposits (Qsyd) are dominated by silt and are characteristically covered by extensive low creosote bushes.

Both on the ground and in aerial imagery, the distinction between the coarse-grained upper portions of the fans and the distal fine-grained portions (Qsyd) is difficult to define. As such, the contact drawn on the map is rather arbitrary and is drawn near the location where the upstream fans converge into relatively narrow channels before diverging again downstream. This bottleneck probably represents a long-term response to changes in climate and/or gradient, and an adjustment of the sedimentation patterns accordingly.

The youngest mappable unit within the alluvial fans and bajadas are the youngest active channel deposits (Qsc). These are composed of accumulations of boulders, cobbles, gravel, sand, and silt that are weakly cemented by carbonate or not cemented at all. On the ground they are characterized by stream channels that have recently seen water flow and are, hence, mostly free of vegetation. Low terraces exposed along the main channel commonly collect silty over-bank deposits during times of flooding and contain more abundant vegetation (Figure 38). Qsc deposits characteristically form complex anastomosing and braided stream patterns composed of active channels and nearby channels that have not been active as recently. Because of this complexity, the contacts drawn on the map should be viewed with some caution, as there are probably other interpretations that are just as valid. Also, only the larger of these deposits was mapped separately from Qsy. There are many more active channels that exist but were deemed too small to be mapped.

Figure 38. A typical view of the active channel deposits (Qsc) showing the recently active stream channel that is relatively clear of vegetation bordered by low vegetated terraces.

Salt flats

As defined here, the "salt flats" form the far western portion of the map where they contain extensive deposits of gypsum and overlying eolian silt. Also lumped into this category are the extensive deposits of quartz sand dunes that, technically, also reside some distance up into the distal portions of the alluvial fans. Most of this area, as mapped, is outside the Park, but is included here to showcase its beauty and complexity, and to better show how these deposits relate to the surficial deposits to the east. Because only a very small portion of these deposits lie within the western road access to the Park, most of these observations are based on aerial imagery.

The most obvious feature of the salt flats are the extensive deposits of light gray gypsum (Qg). This material most likely precipitated out of a large fresh-water lake (or series of lakes) that existed here in the valley, probably during the Pliocene and Pleistocene. Gypsum (hydrated calcium sulfate) is a common evaporite mineral that precipitates within supersaturated freshwater and, probably more commonly, when temporary bodies of fresh water evaporate. The exact origin of the gypsum is enigmatic. Exposures near the park entrance form large, irregularly shaped elongated mounds and ridges covered by smaller mounds that are up to approximately 1 m in diameter and 0.5 m high (Figure 39). They are spaced more or less randomly across the surface. Up close there is no other layering, bedding, or any other obvious sedimentary structure visible. The features are amorphous both on the meter-scale and the larger tens-of-meters scale. It is only at the much larger scale that structure is visible. At this scale the mounds of gypsum are locally arranged into long winding ridges with similarly shaped winding depressions between them. Their shape and locations superficially resemble shorelines, yet they all appear to reside at similar elevations. Many of the more isolated mounds crudely resemble dunes and may be reworked or modified eolian deposits. Because of the uncertainty in their origin, all of these deposits were simply given the same unit label (Qg).

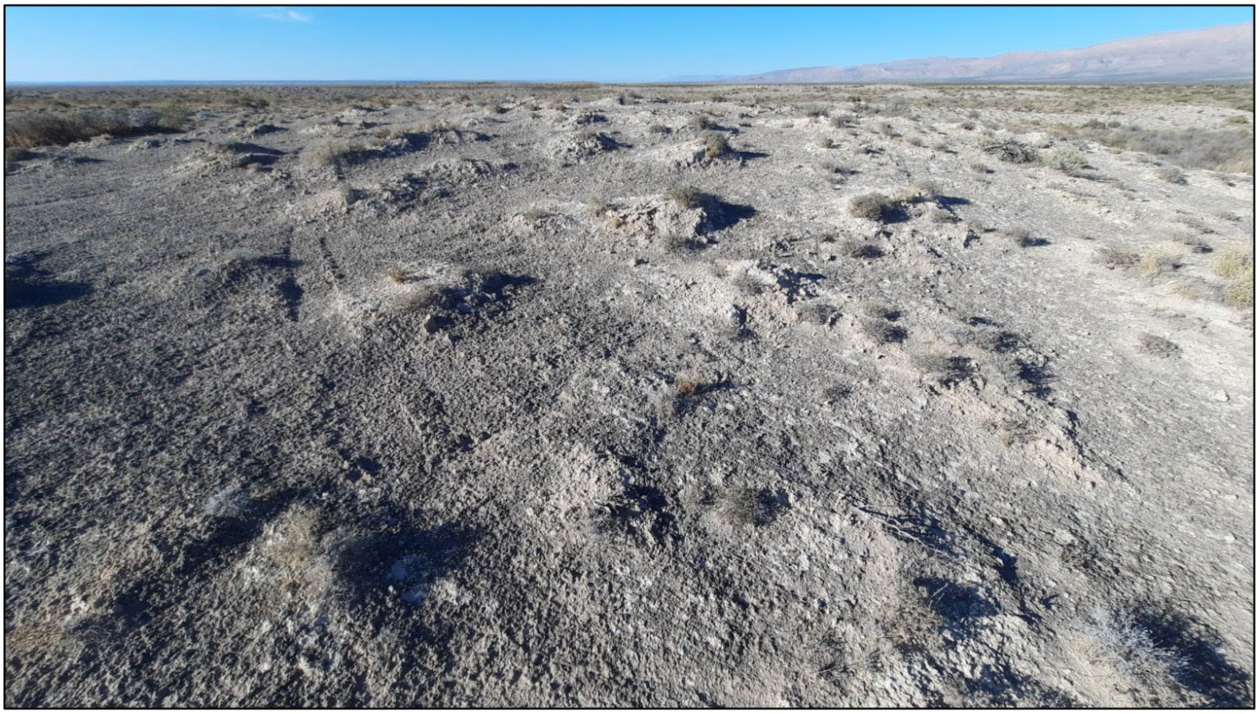

Figure 39. Many of the exposed gypsum deposits in the salt flats are covered with small mounds of unknown origin.

The gypsum deposits also contain a great abundance of shallow closed depressions of all sizes and shapes, from irregularly shaped to long sinuous forms, and from a few meters across to hundreds of meters across. The vast majority of these depressions are partially filled with quartz silt, interpreted to be wind-blown material. Where extensive enough, the silt is mapped as its own deposit (Qs).Upon close examination, small dunes are visible on the floors of many of the depressions. Several large depressions show evidence of lakes in the recent past. On aerial imagery, these depressions commonly show a much flatter floor, and are commonly darker in color (possible the result of the entrapment and accumulation of wind-blown clays and subsequent growth of vegetation in the clay-rich soil) or lighter in color (due to the presence of precipitated gypsum). All of these lake/playa features are mapped as Qp. Much larger lake depressions can be seen just outside the map area to the west were they form extremely flat surfaces floored, apparently, mostly by gypsum.

An extensive area of very light gray gypsum sand dunes (Qeg) is exposed on the west side of the map (Figure 40). The dunes are composed of fine to coarse platy and partially rounded frosted gypsum grains. Many of the dunes on the steep northeastern end of the dune field are still active and are slowly moving to the northeast (Figure 41). Many of the other dunes to the southwest are not as active and have been partially stabilized by low shrubs. An interesting and widespread feature of the gypsum dunes is the presence of deep circular closed depressions between the dune crests, visible both on aerial imagery and on the ground. The overall shape of the dune field, as well as the orientation of many of the steepest slip faces, indicates that the entire dune field has been transported to the northeast from grains of gypsum blown out of the gypsum deposits to the southwest.

Figure 40. The light gray active gypsum sand dunes of unit Qeg form an extensive deposit west of the Guadalupe Mountains escarpment. View is to the southeast.

The active dune field of Qeg overlies an older dune field to the south mapped as Qego. The older dunes are inactive and are mostly covered with small shrubs. To the south and west, it is difficult to distinguish between older dunes and in-place gypsum deposits, particularly on the north side of the active dune field as well.

East and northeast of the gypsum sand dunes is a much more extensive field of quartz sand dunes (Qes). Grain size varies from very fine to medium and marginally coarse, where grains are subangular to rounded and partially frosted. These quartz dunes are typically tan-colored and are slightly darker than the gypsum dunes, as can be seen in Figure 41. The quartz dunes are being over-ridden by the active gypsum dune field and are, thus, older that the gypsum dunes. Additionally, the quartz dunes are dissected by several large streams originate in the mountains to the east and have cut all of the way across the dune field. On the eastern side of the dune field the stream canyons are tens of meters deep and reveal nice layered exposures of quartz dune sand locally resting on older alluvial deposits. On the west side of the dune fields the streams disappear into younger flat-floored alluvial fans that have eroded the dunes nearby and have also filled some of the interdune areas with alluvial sediment, leaving some circular dunes protruding up out of the flat sediment sea as isolated islands of sand. The eastern contact of the dune fields is very difficult to define and probably thins/tapers eastward where it originally pinched out and has subsequently been reworked. Therefore, the contact on the eastern side should also be viewed as approximate.

Figure 41. The most active gypsum dunes (Qeg) are on the northeast side of the dune field and are being blown to the northeast. The quartz sand dunes (Qes) in the middle of the photo are darker tan.

Ancient Shorelines?

The southwest corner of the map contains two dark vegetation alignment that are most obvious beginning approximately 2.5 miles north of Highway 62 and continuing northward to the two prominent circular agricultural fields. Both alignments roughly parallel one another, even though they change direction. Both also appear to be parallel to the topographic contours. They also appear to be associated with very slight changes in elevation, rising a few feet eastward. These characteristics suggest that these alignments reflect ancient shorelines of the large, now dry, lake immediately to the west. Additionally, incised gullies within the alluvial fans of Qsy all terminate within approximately 600 feet of the easternmost vegetation alignment where the gullies become a narrow bajada of even younger alluvial fans. This band of younger fans may represent adjustment of the base level after the lake level had dropped slightly.

AKNOWLEDGEMENTS

This project was the idea of Jonena Hearst, of the National Park Service. It was her desire to update the geologic map of the park in order to catalog and place into context the large collection of paleontologic samples collected by previous researchers. She was the driving force behind this mapping effort.

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Figure 42. View of the upper portions of the Capitan Formation in South McKittrick Canyon from near the top of the trail, looking south. November 28, 2015.

Figure 43. View looking north-northeast along South McKittrick Canyon. Notice the subtle east-tilted crude bedding in the lower portions of the Capitan Formation. The bedded layers of the Artesia Group cap the ridge in the distance where they overlie massive non-bedded reef facies of the Capitan Formation.

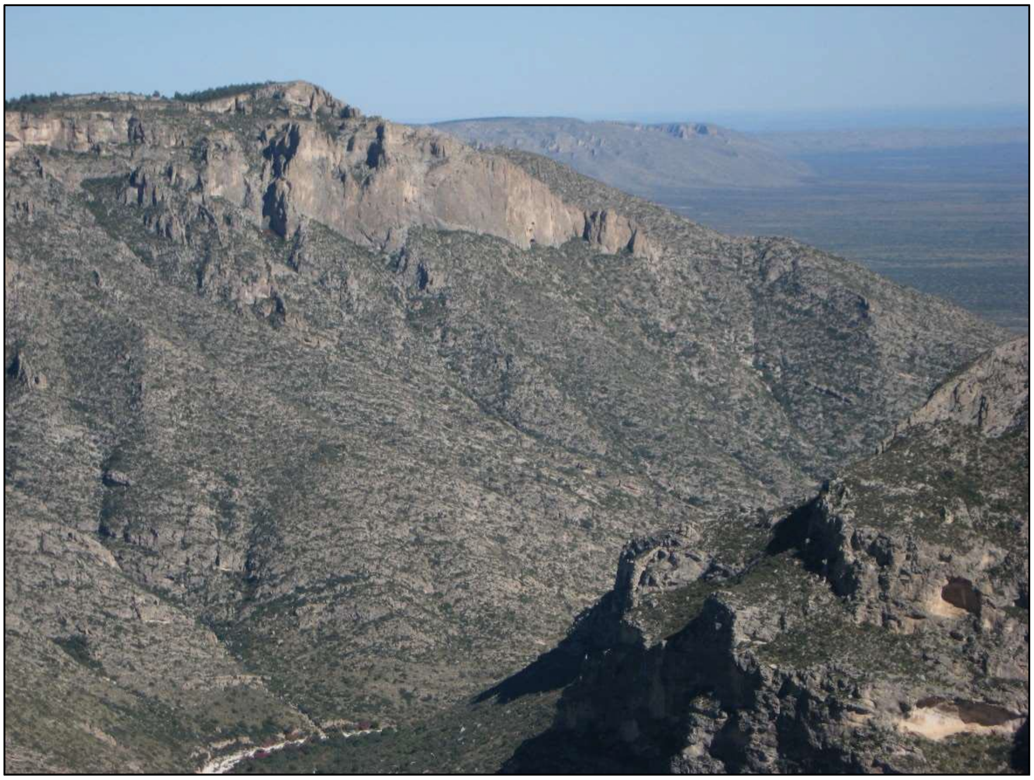


Figure 44. Taken from the same location as Figure 37. Looking northeast through South McKittrick Canyon. Notice the prominent crude east-dipping bedding within the steep slopes of the Capitan Formation. The reef front extends into the distance to Carlsbad Caverns. November 12, 2015.

Figure 45. View from the hills southwest of Pine Spring Campground, looking south to Guadalupe Pass and the Delaware Mountains in the distance. November 2, 2015.

Figure 46. Pine Spring Canyon, looking west from near Pine Spring. Tallest peak in the left distance is Guadalupe Peak. November 2, 2015.

Figure 47. Looking north across Pine Spring Canyon. Slope is composed mostly of the Pinery Limestone Member and thinly bedded siltstone and fine-grained sandstone of the Bell Canyon Formation. November 2, 2015.

Figure 48. Looking south to the Pine Spring Campground from the north side of Pine Spring Canyon. The Visitor Center is the large building on the far left. November 3, 2015.

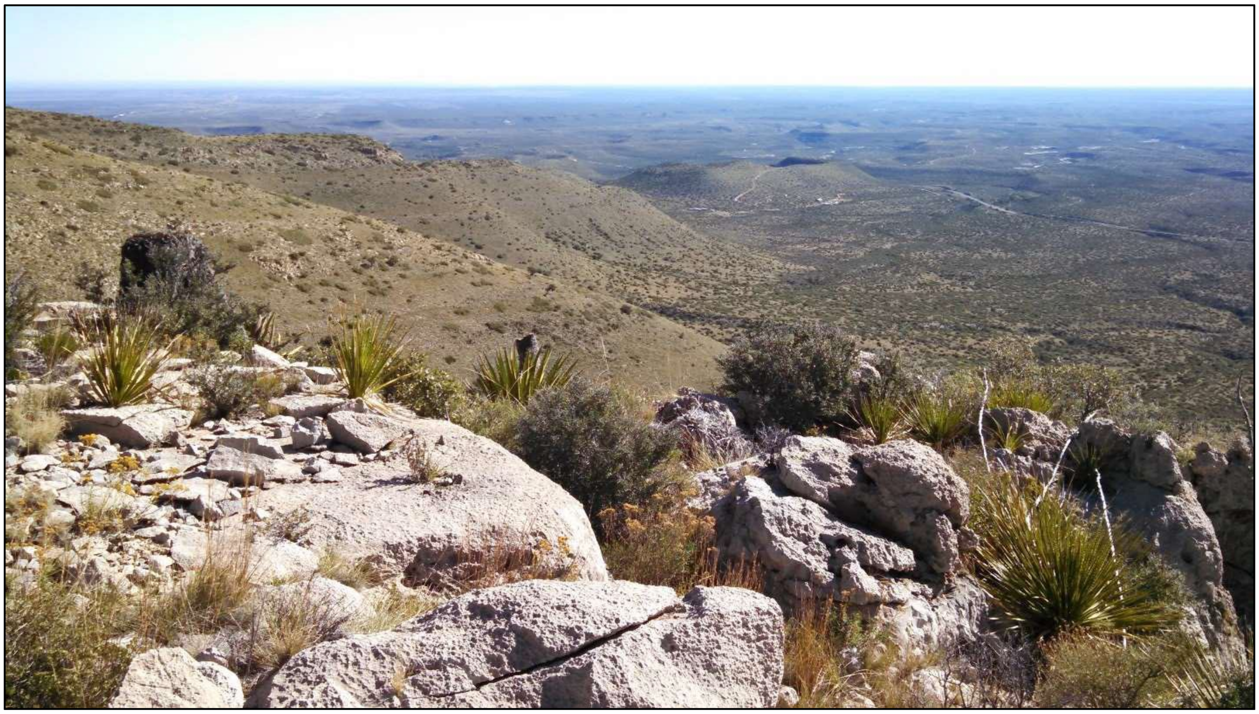


Figure 49. Looking eastward across the Delaware Basin from near the western side of Rader Ridge.

Figure 50. Looking southwest from Rader Ridge. Delaware Mountain Group sediments dip gently to the southeast and form the lower slopes of the mountain front. El Capitan is the steep knob on the left skyline. November 6, 2015.

Figure 51. View westward from the trail at the top of the first knob in South McKittrick Canyon. Notice how the rather massive cliffs of the Capitan Formation merge upward into well bedded layers of the Artesia Group. November 12, 2015.

Figure 52. Looking northeast through South McKittrick Canyon. November 12, 2015.

Figure 53. Looking west from about half way between Pine Spring Campground and Guadalupe Pass. September 29, 2015.

Figure 54. Large boulders of sandstone of the Brushy Canyon Formation litter the slopes south of Guadalupe Pass. View is to the north-northwest towards El Capitan. November 29, 2018.

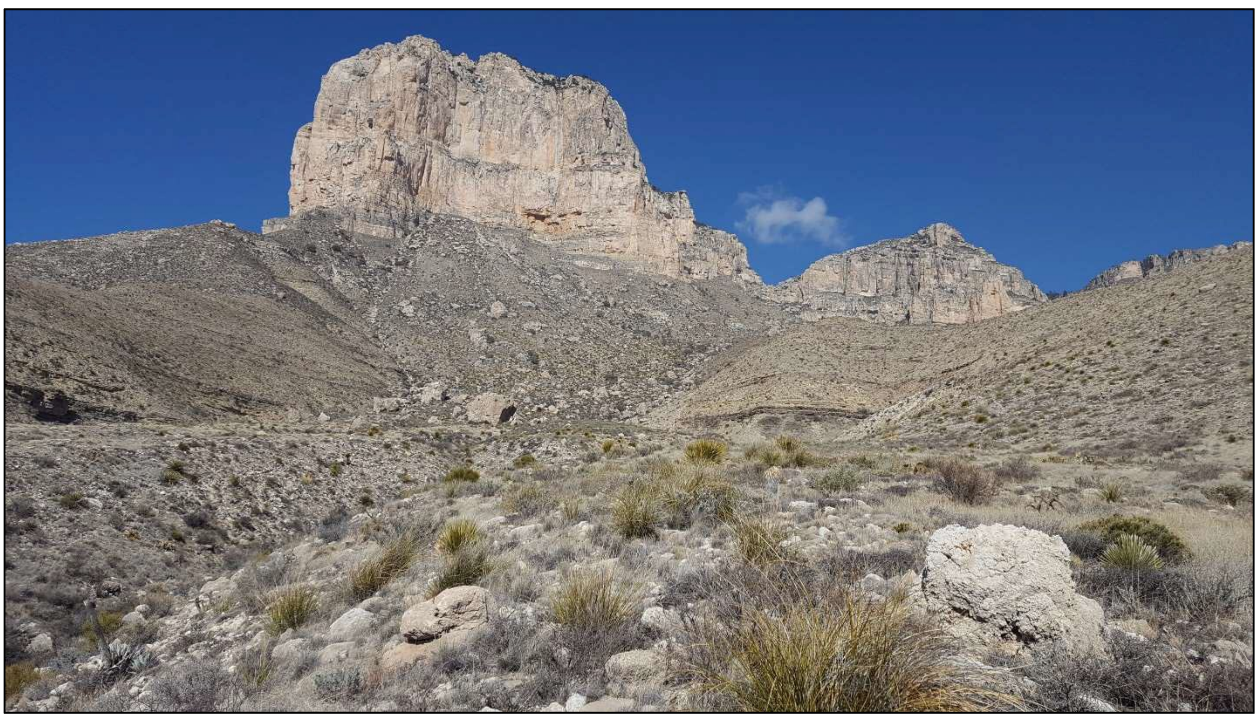


Figure 55. Looking northwest from near the Salt Basin Trail in Guadalupe Canyon. February 10, 2019.

Figure 56. View of Guadalupe Canyon from the Salt Basin Trail. February 19, 2019.

Figure 57. Looking east from the Salt Basin Trail. February 19, 2019.

Figure 58. Looking southeast towards Guadalupe Pass from the Salt Basin Trail. February 19, 2019.

Figure 59. Looking north up Guadalupe Canyon. February 20, 2019.

Figure 60. Looking south. Stream-cut exposure of resistant ledge of sandstone of the Brushy Canyon Formation offset about two meters. Note dark, organic-rich siltstone layers. February 19, 2019.

Figure 61. Looking south from near the base of El Capitan towards the Delaware Mountains.

Figure 62. Looking east from the north side of Guadalupe Pass. Much of the gentle dissected slopes are mantled with Quaternary sedimentary deposits (Qm). December, 2, 2015.

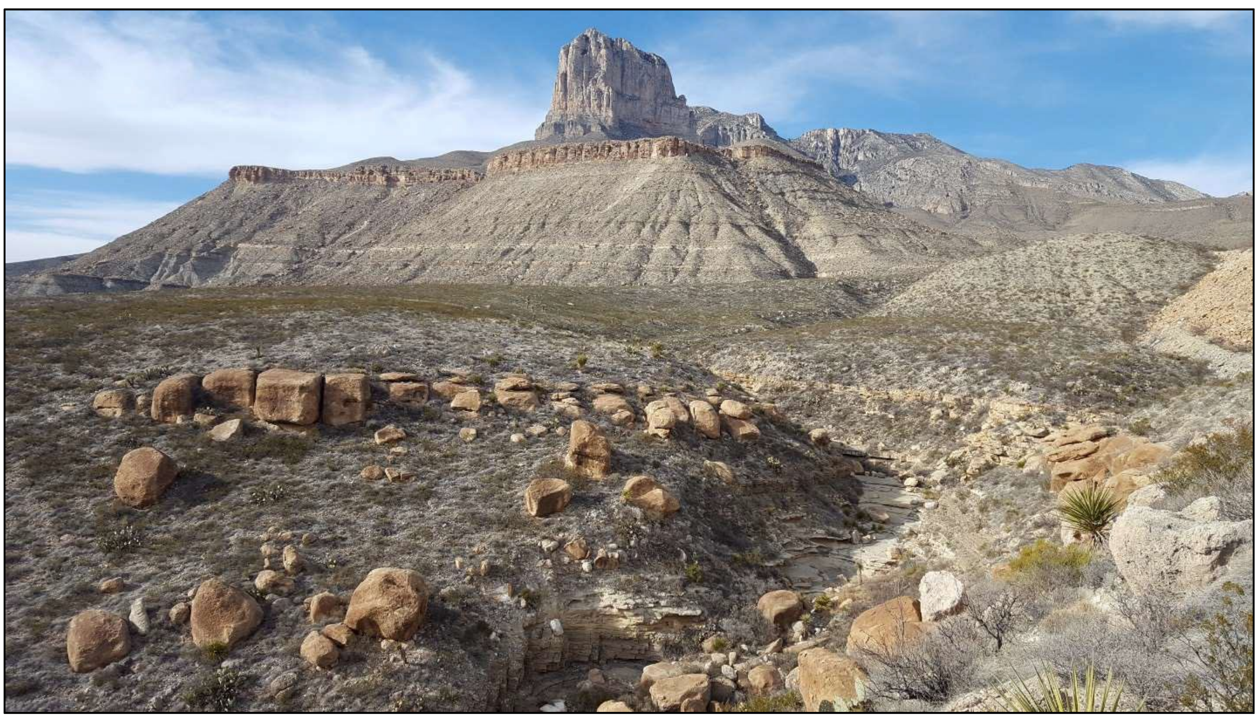


Figure 63. Looking north toward El Capitan from the west side of the rest stop, west of Guadalupe Pass, showing resistant sandstone ledges of the Brushy Canyon Formation. February 20, 2019.

Figure 64. Looking south from the Salt Basin Trail south of El Capitan. Several parallel north-trending normal faults cut though these hills and down-drop the blocks on the west (right). December 4, 2015.

Figure 65. Looking south from near the Salt Basin Trail, south of El Capitan. Note the steep angular contact between the cliff-forming sandstone ledge and fine-grained sandstone/siltstone near the base of the cliff. Also note the shallow dip of the Tertiary/Quaternary deposits capping the two prominent buttes west (right) of the highway. December 4, 2015.

Figure 66. Looking north-northwest across Manzanita Spring, near Frijole Ranch. Photo taken November 5, 2015.

Figure 67. Autumn colors in McKittrick Canyon.

Figure 68. Looking northeast from the beginning of the Bush Mountain Trail in Upper Dog Canyon. February 25, 2019.

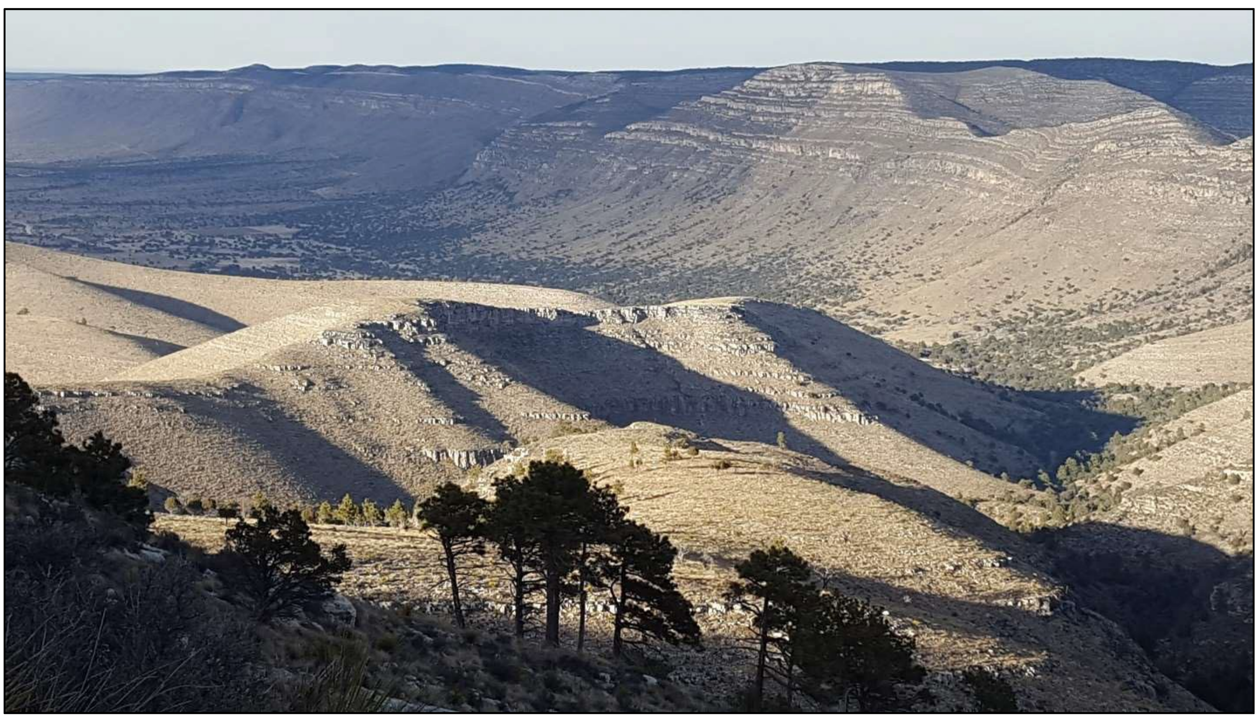


Figure 69. Looking northeast into Upper Dog Canyon from the Tejas Trail, northeast of Lost Peak. February 25, 2019. Compare this photo to Plate 14 of King (1948).

Figure 70. Looking southeast from near the intersection of the Tejas Trail and the McKittrick Canyon Trail. Prominent bedding in the Artesia Group grades abruptly downward into the more massive Capitan Formation. This valley follows the normal fault that projects through The Bowl and forms the easternmost structural boundary of the Rio Grande rift/Basin and Range province.

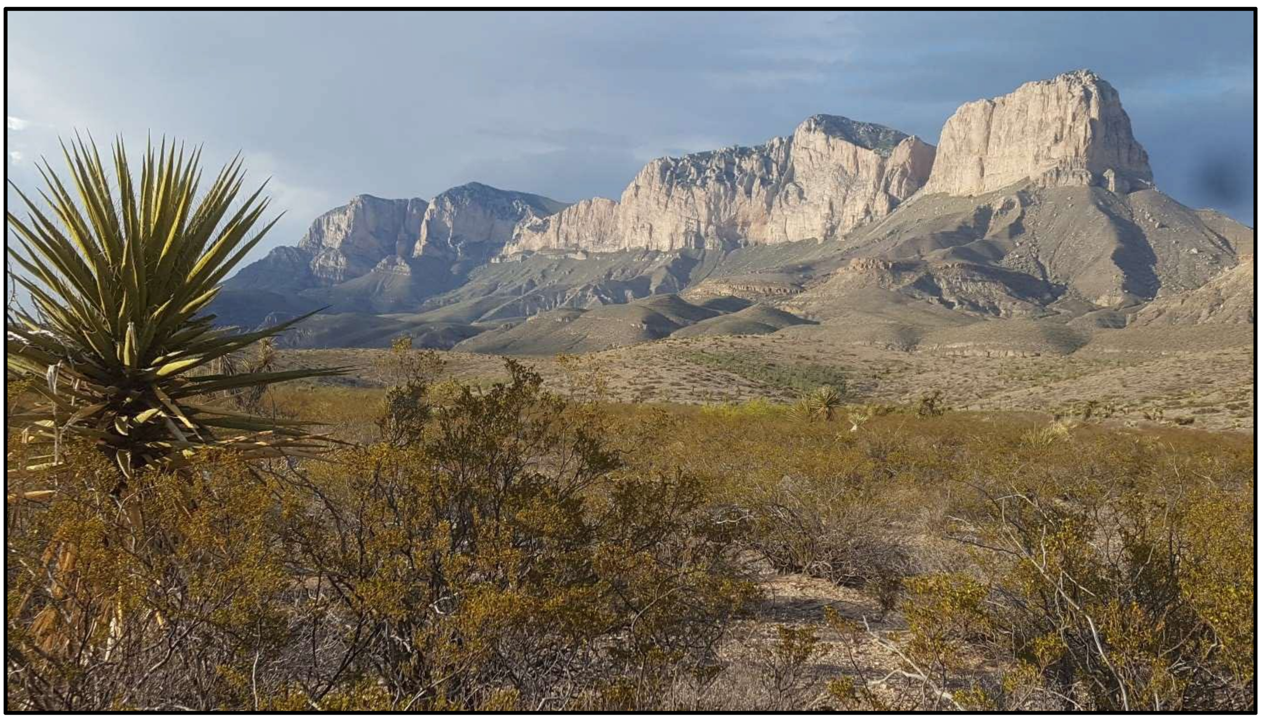


Figure 71. Looking northeast from the William's Ranch road across a sea of *creosote*. August 19, 2019.

Figure 72. The view of the western escarpment of the Guadalupe Mountains looking southeast from PX Well.

Figure 73. This view of the escarpment was taken from atop the shadowed slope seen in Figure 72 (immediately to the left of the well windmill tower). Looking southeast. January 12, 2021.

Figure 74. Panoramic view from the northwestern Patterson Hills, looking southwest, on a crystal clear winter day, January 26, 2021.

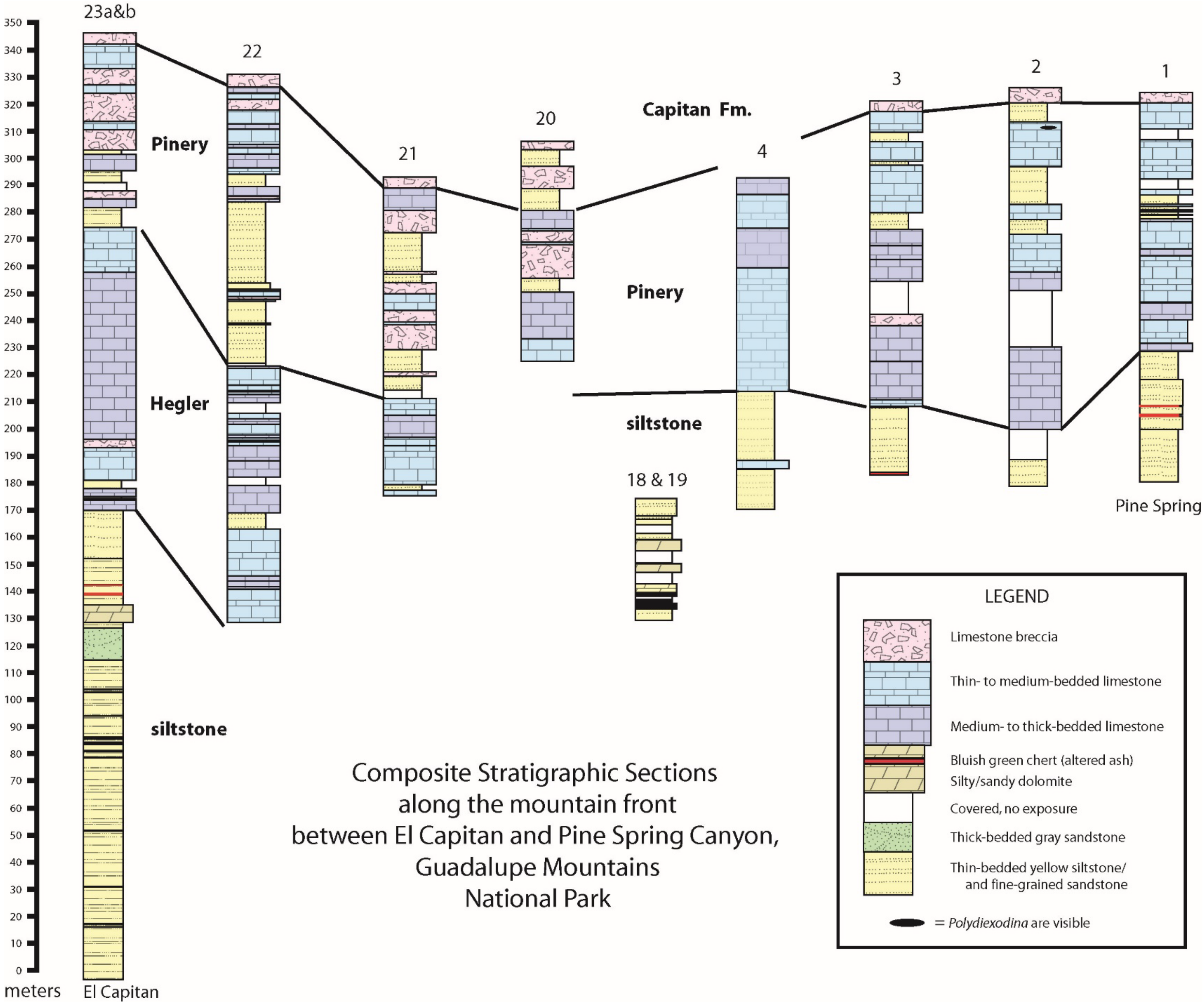
Figure 75. Panoramic view from the northwestern Patterson Hills, looking northeast, on a crystal clear winter day, January 26, 2021.

Figure 76. The entrance to McKittrick Canyon is mantled with snow the morning after a February 14, 2021 storm that brought rare snow and temperatures of minus 21^{o} F to the lower elevations of the Park.

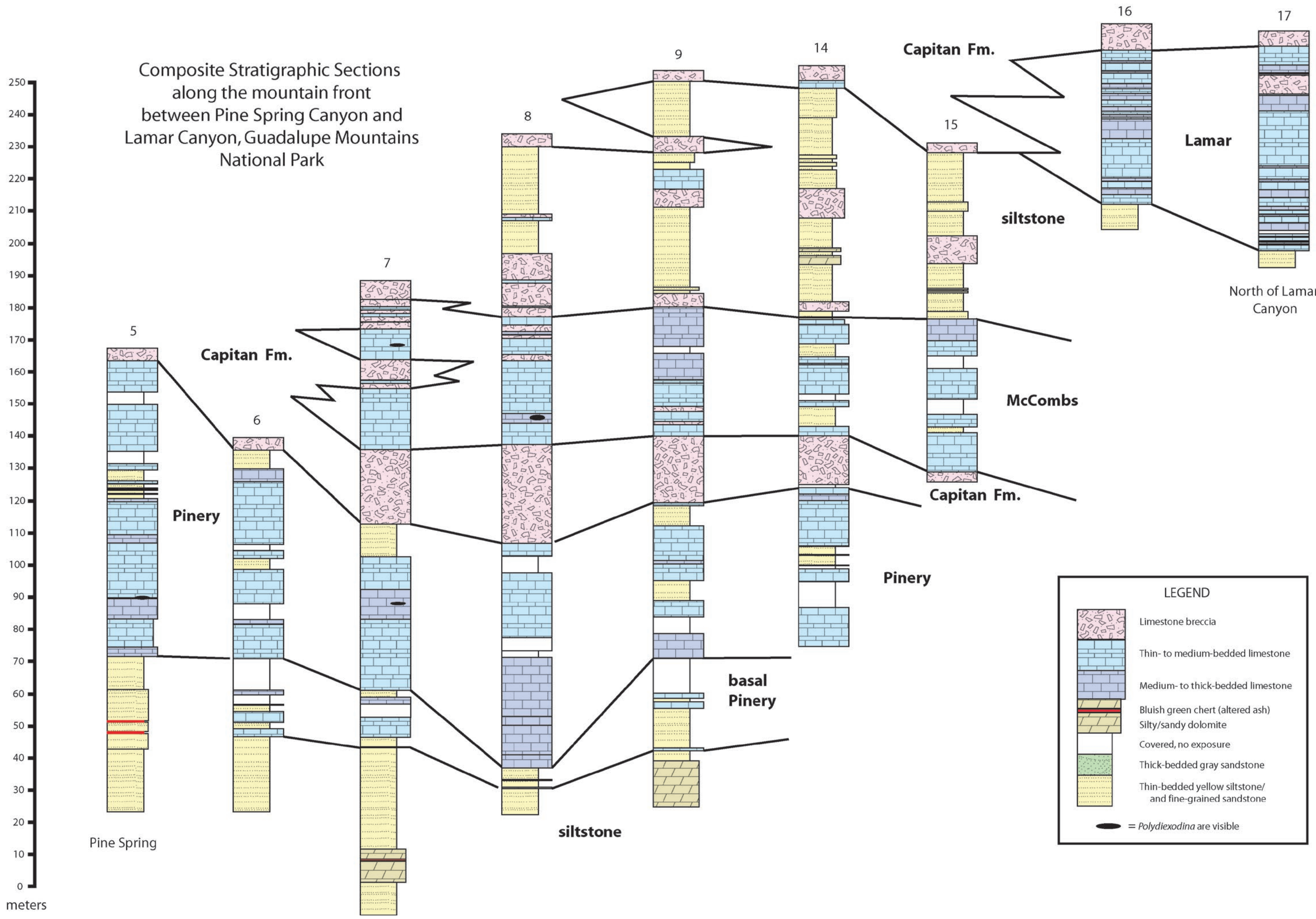
Figure 77. The snow provided stunning vistas around the low country of the Park, and closed the high country to access.

Appendix A

Measured Stratigraphic Sections



Composite Stratigraphic Sections along the mountain front between El Capitan and Pine Spring Canyon, Guadalupe Mountains National Park


Composite Stratigraphic Sections along the mountain front between Pine Spring Canyon and Lamar Canyon, Guadalupe Mountains National Park
meters
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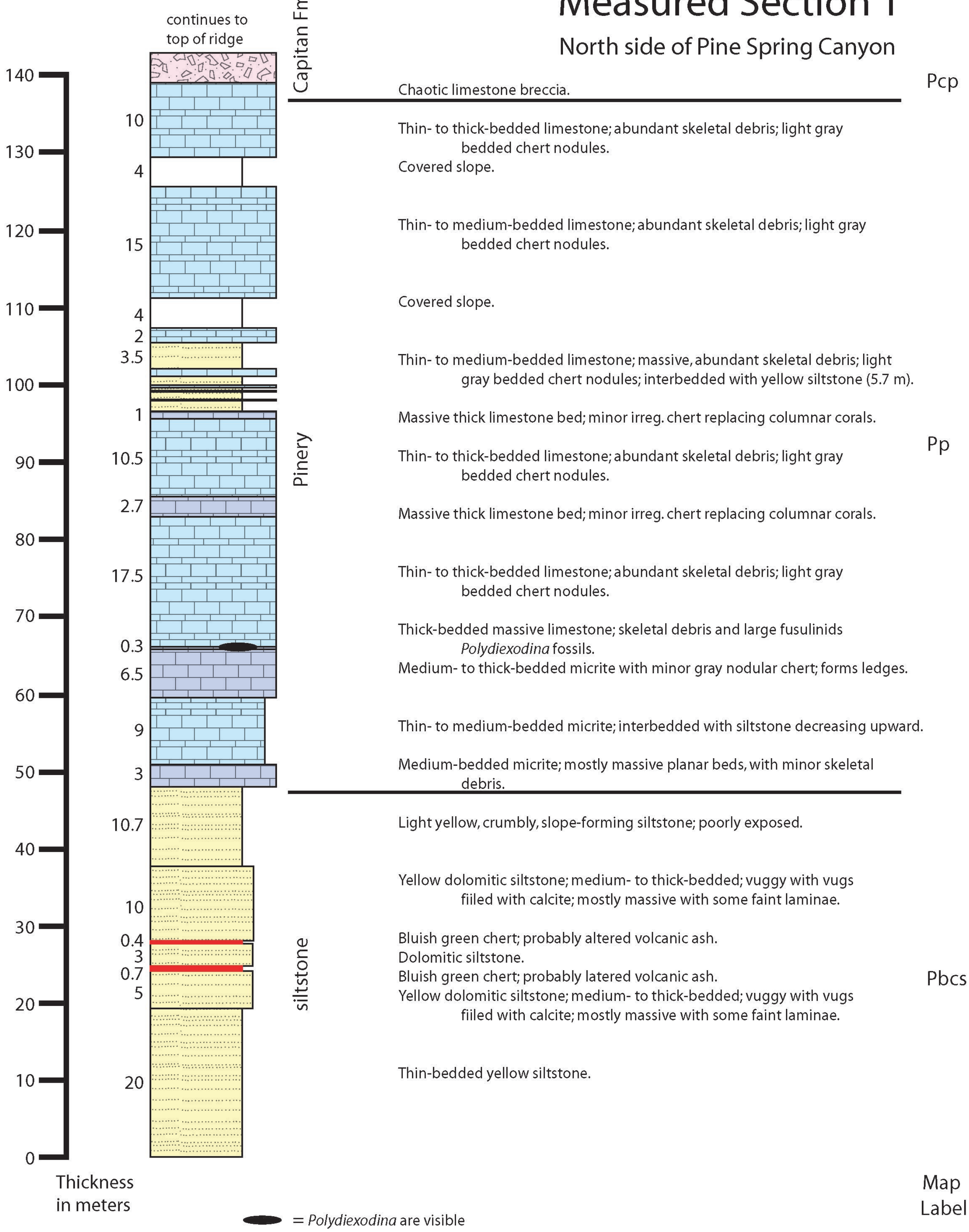
17
Pine Spring
North of Lamar Canyon
Capitan Fm.
Pinery
siltstone
basal Pinery
Pinery
Capitan Fm.
McCombs
siltstone
Capitan Fm.
Lamar
LEGEND
Limestone breccia
Thin- to medium-bedded limestone
Medium- to thick-bedded limestone
Bluish green chert (altered ash)
Silty/sandy dolomite
Covered, no exposure
Thick-bedded gray sandstone
Thin-bedded yellow siltstone/ and fine-grained sandstone
= Polydiexodina are visible

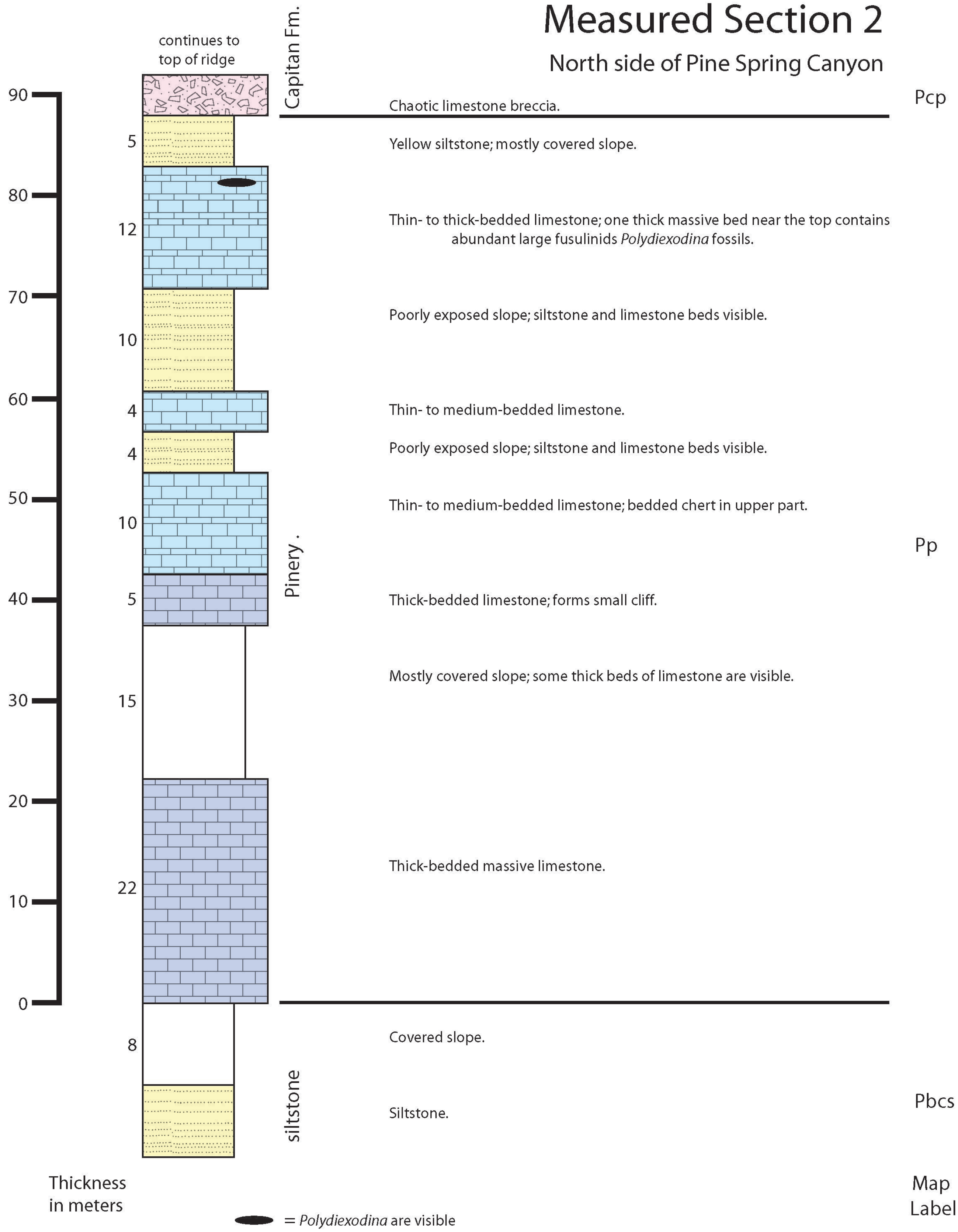
Measured Section 1

North side of Pine Spring Canyon



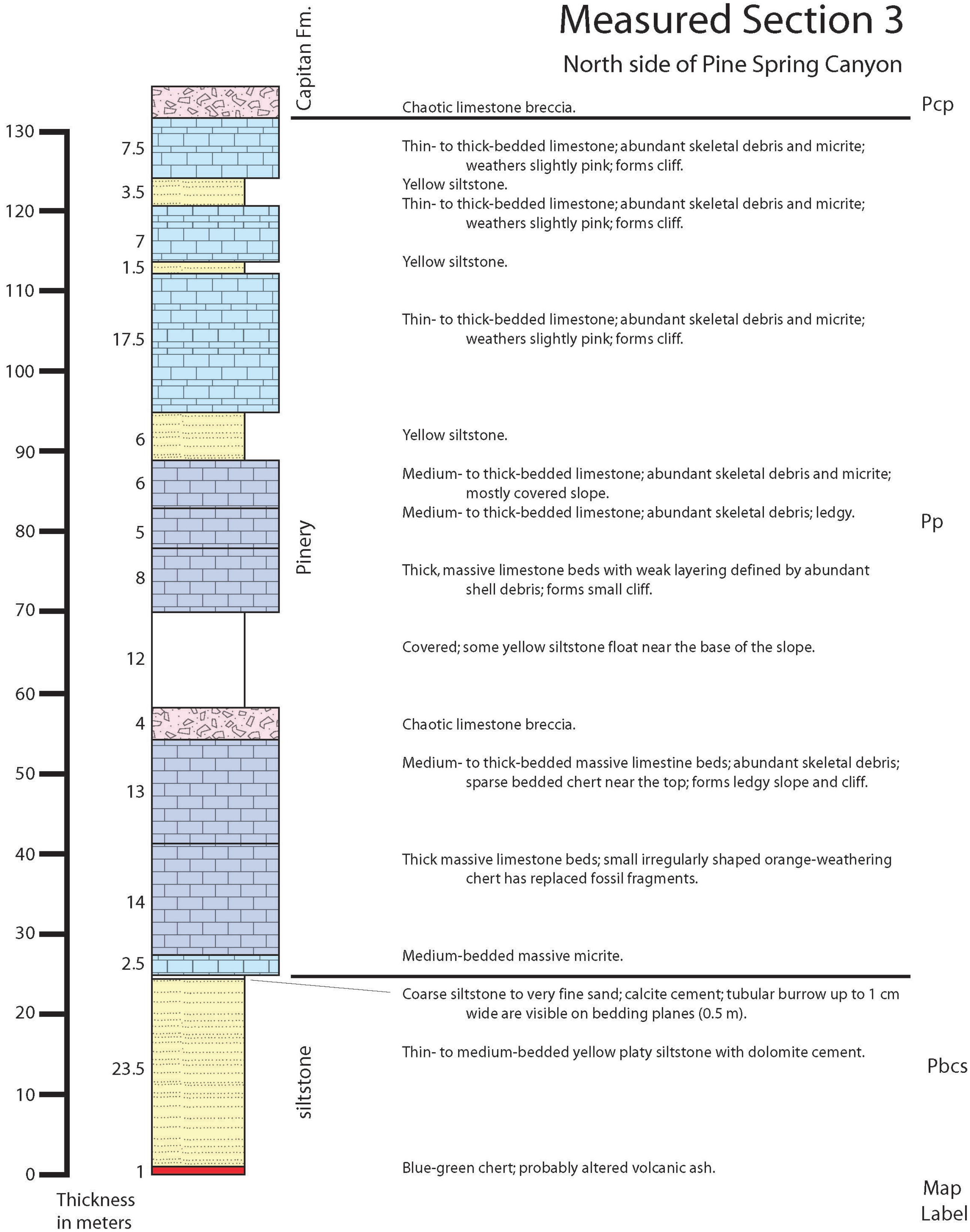
Measured Section 2

North side of Pine Spring Canyon



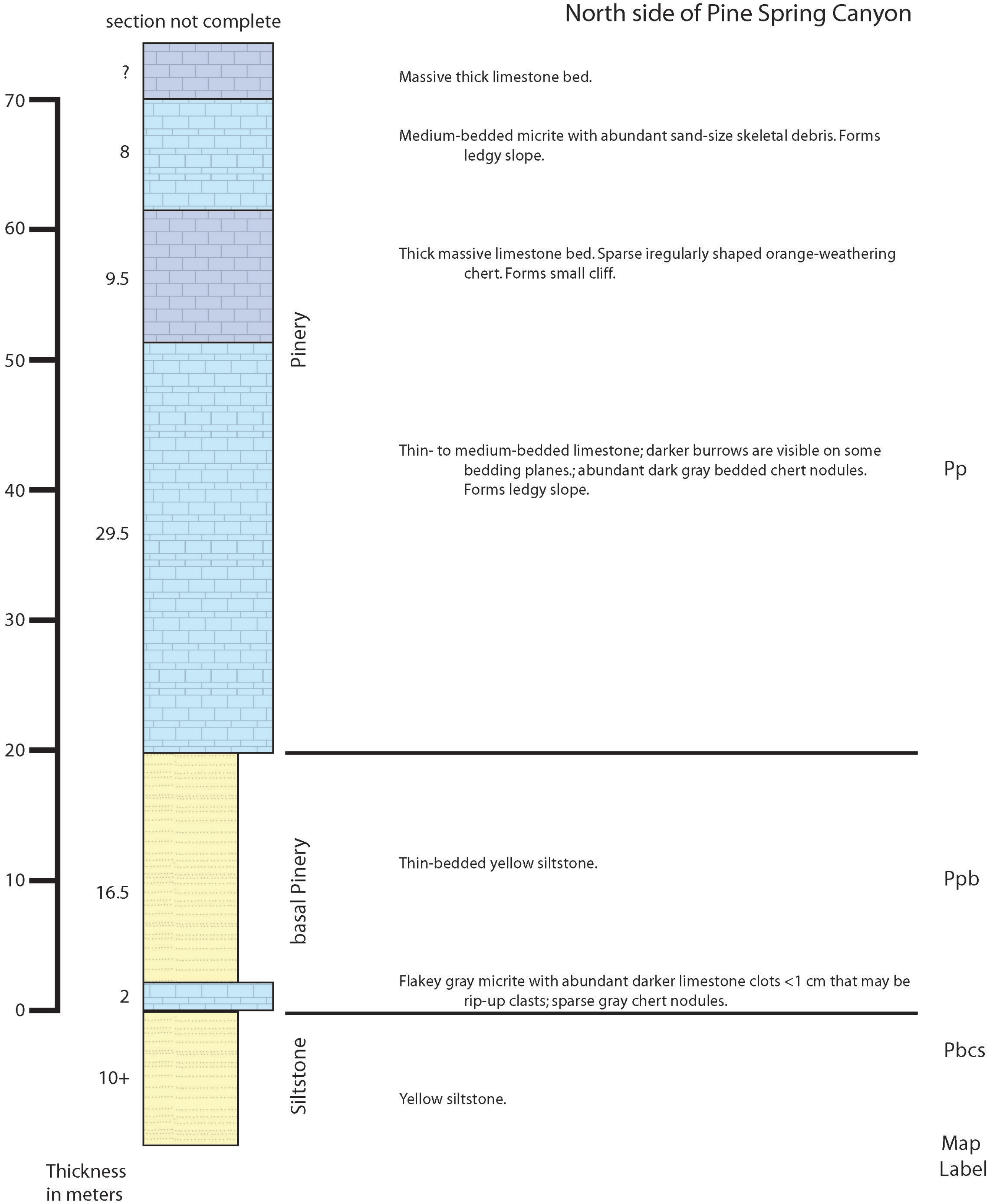
Measured Section 3

North side of Pine Spring Canyon

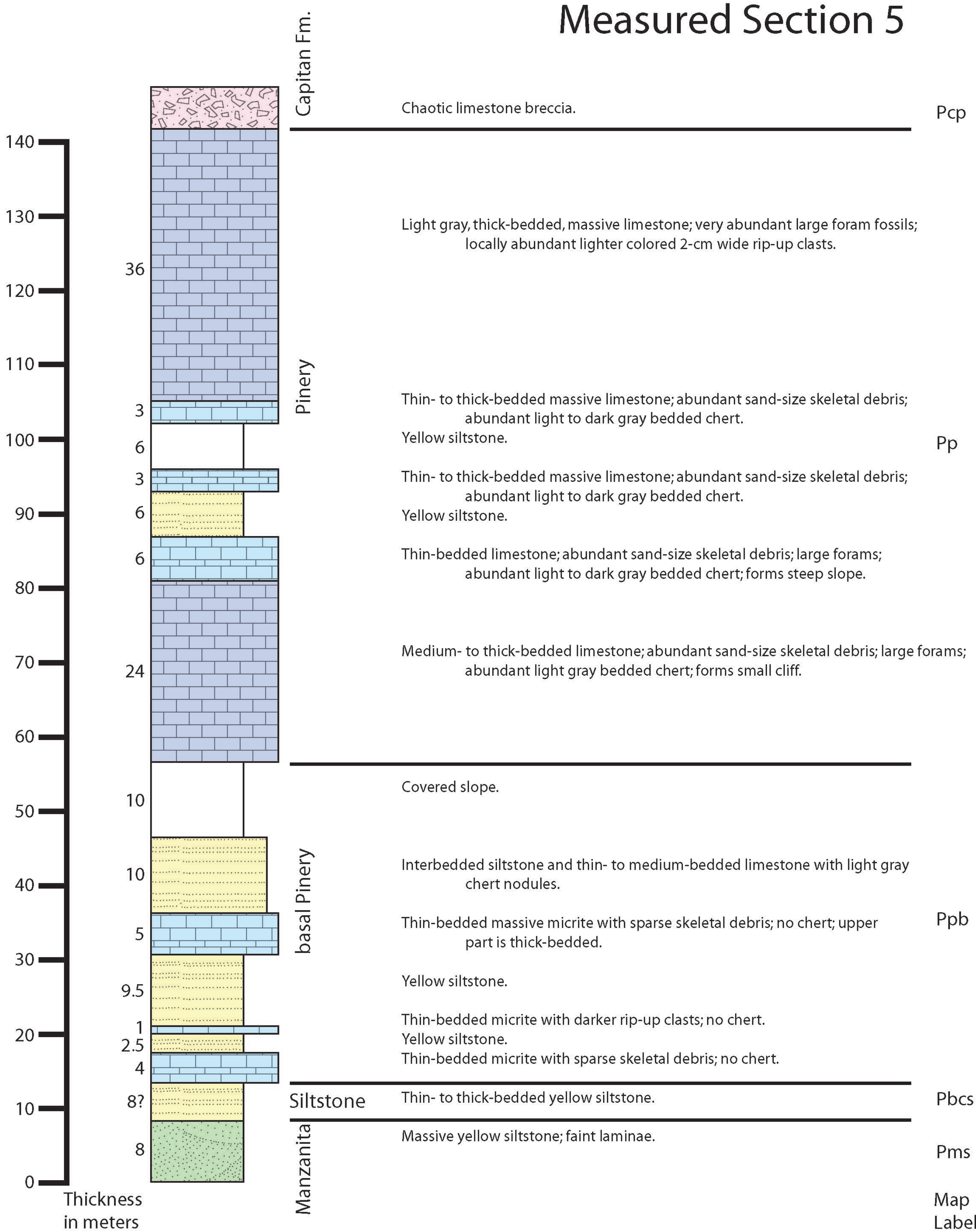


Measured Section 4

North side of Pine Spring Canyon

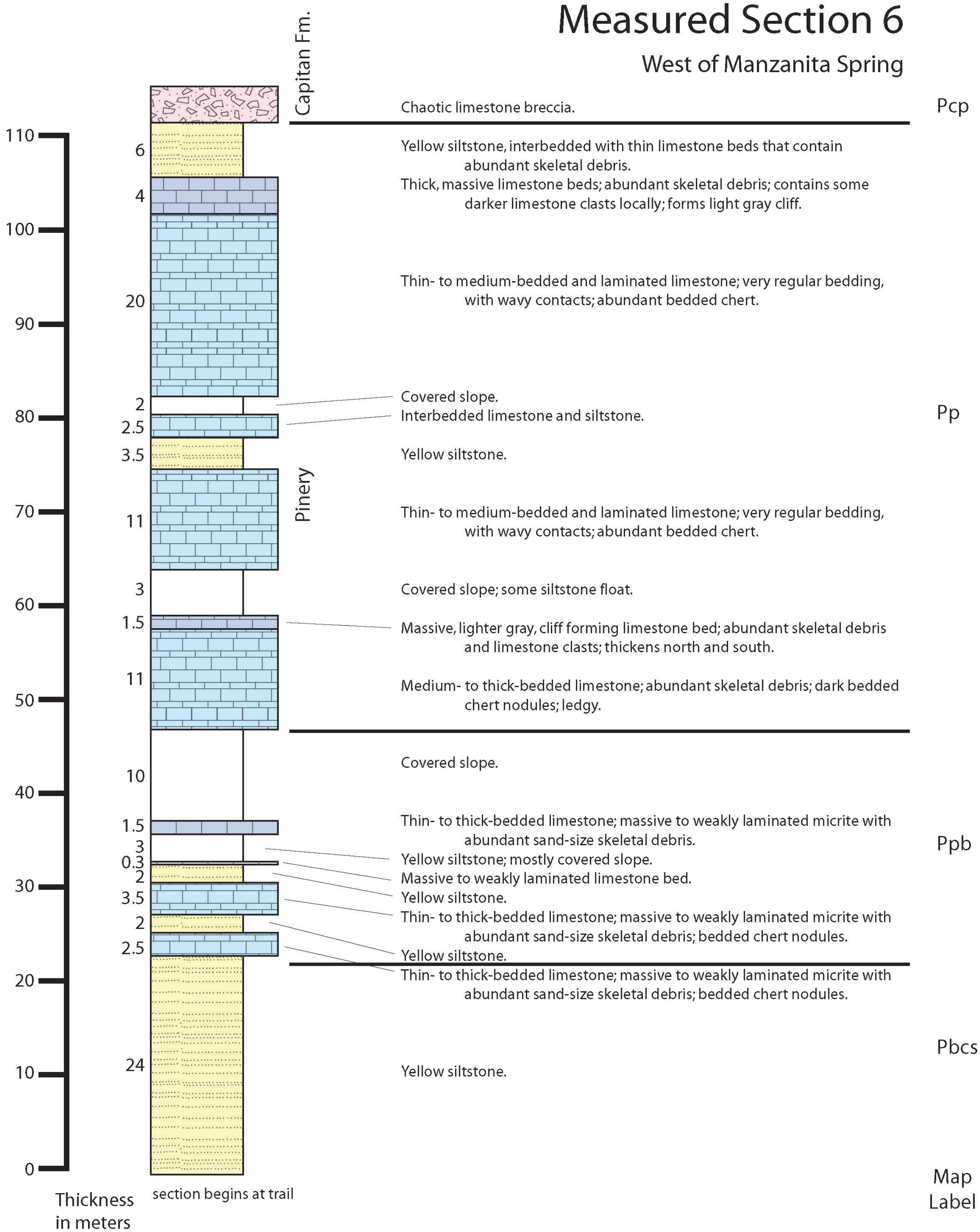


Measured Section 5



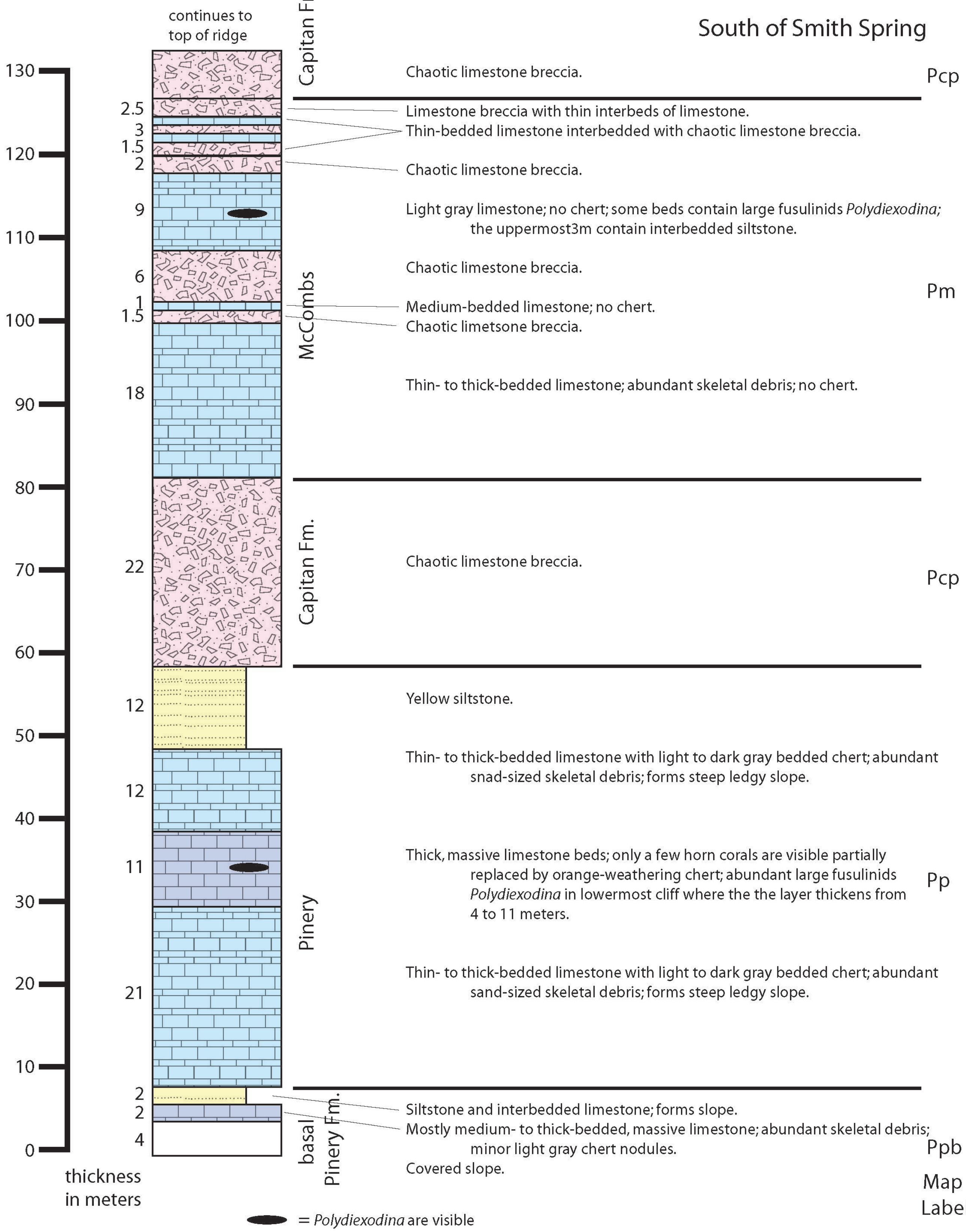
Measured Section 6

West of Manzanita Spring



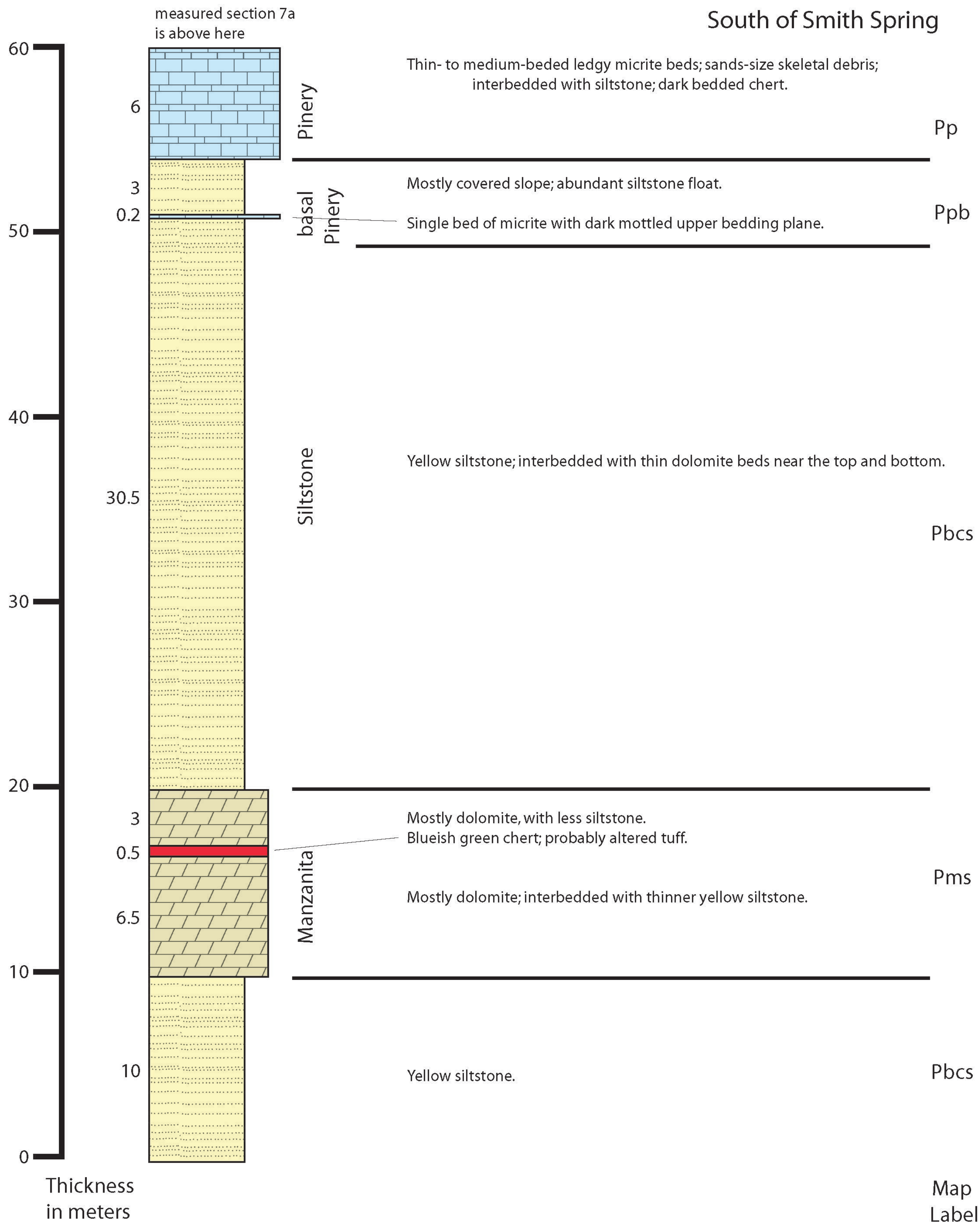
Measured Section 7a

South of Smith Spring



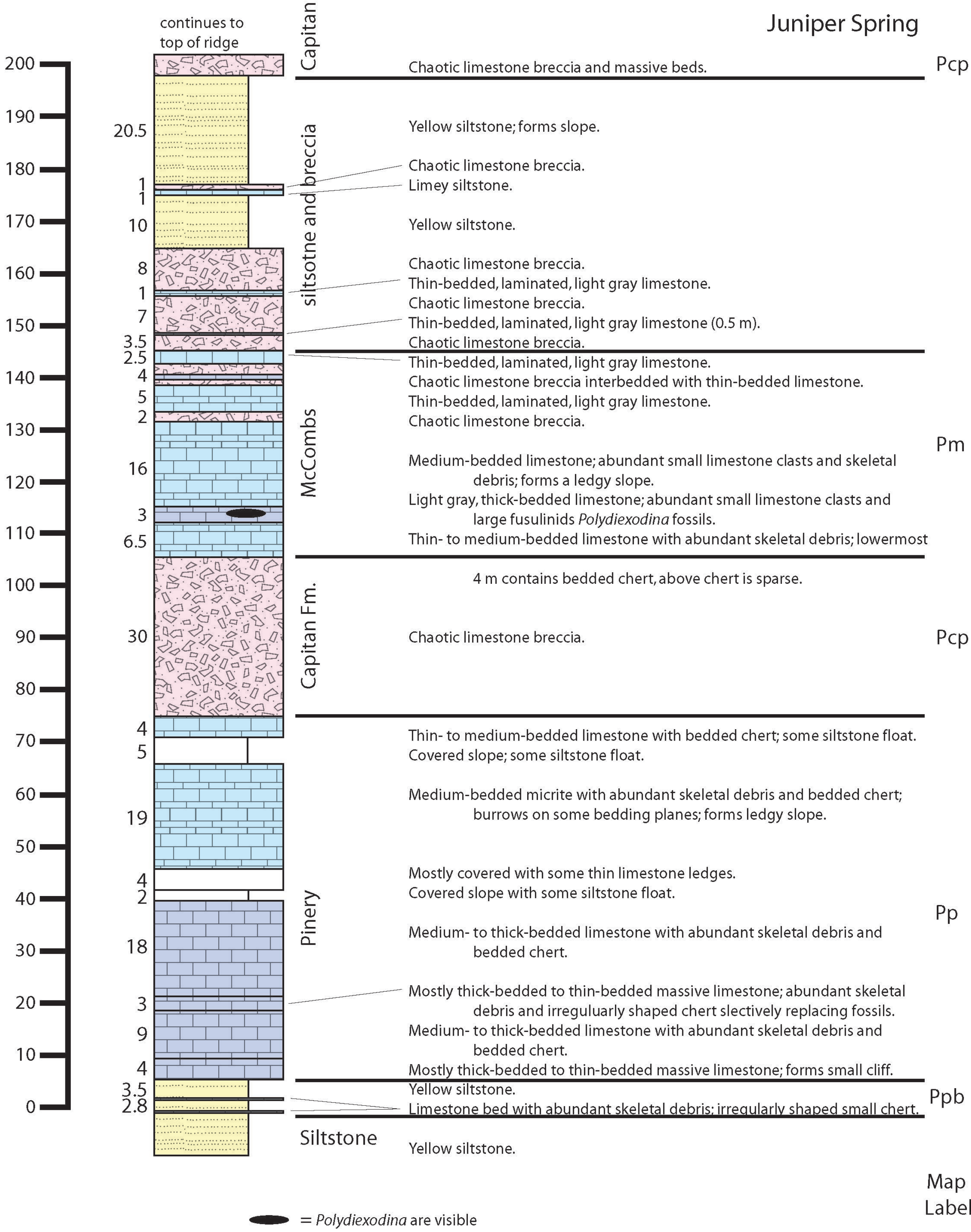
Measured Section 7b

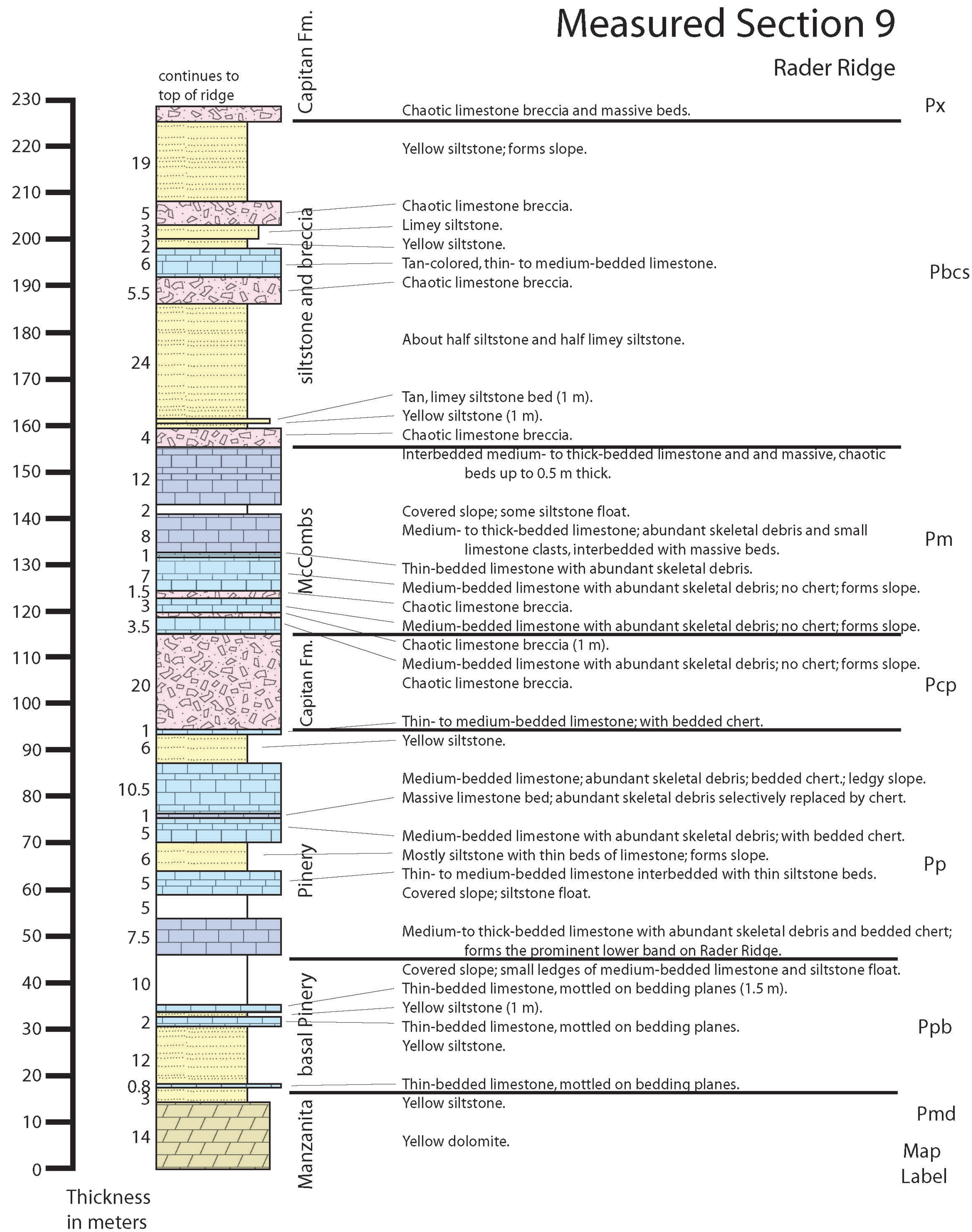
South of Smith Spring



Measured Section 8

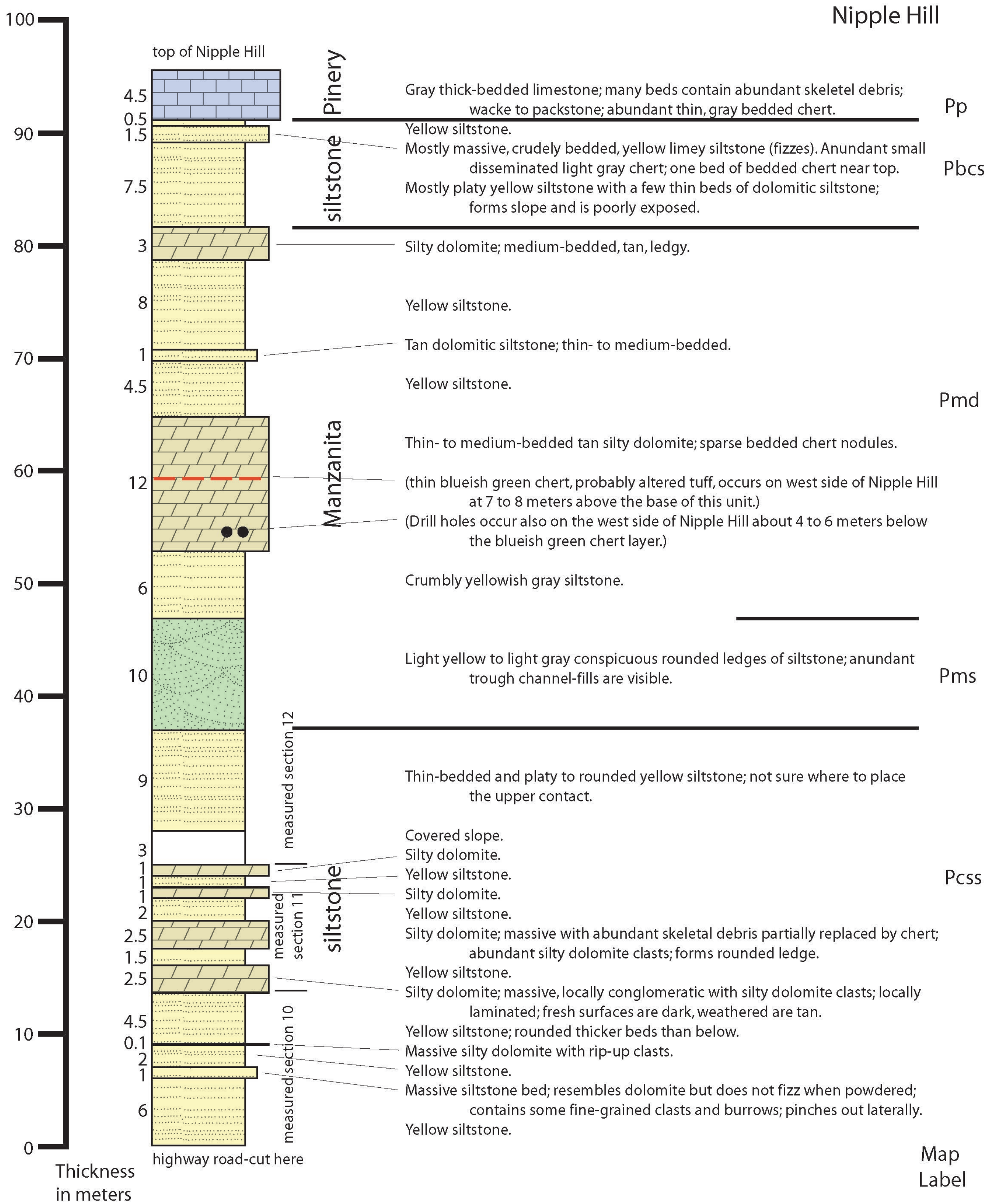
Juniper Spring





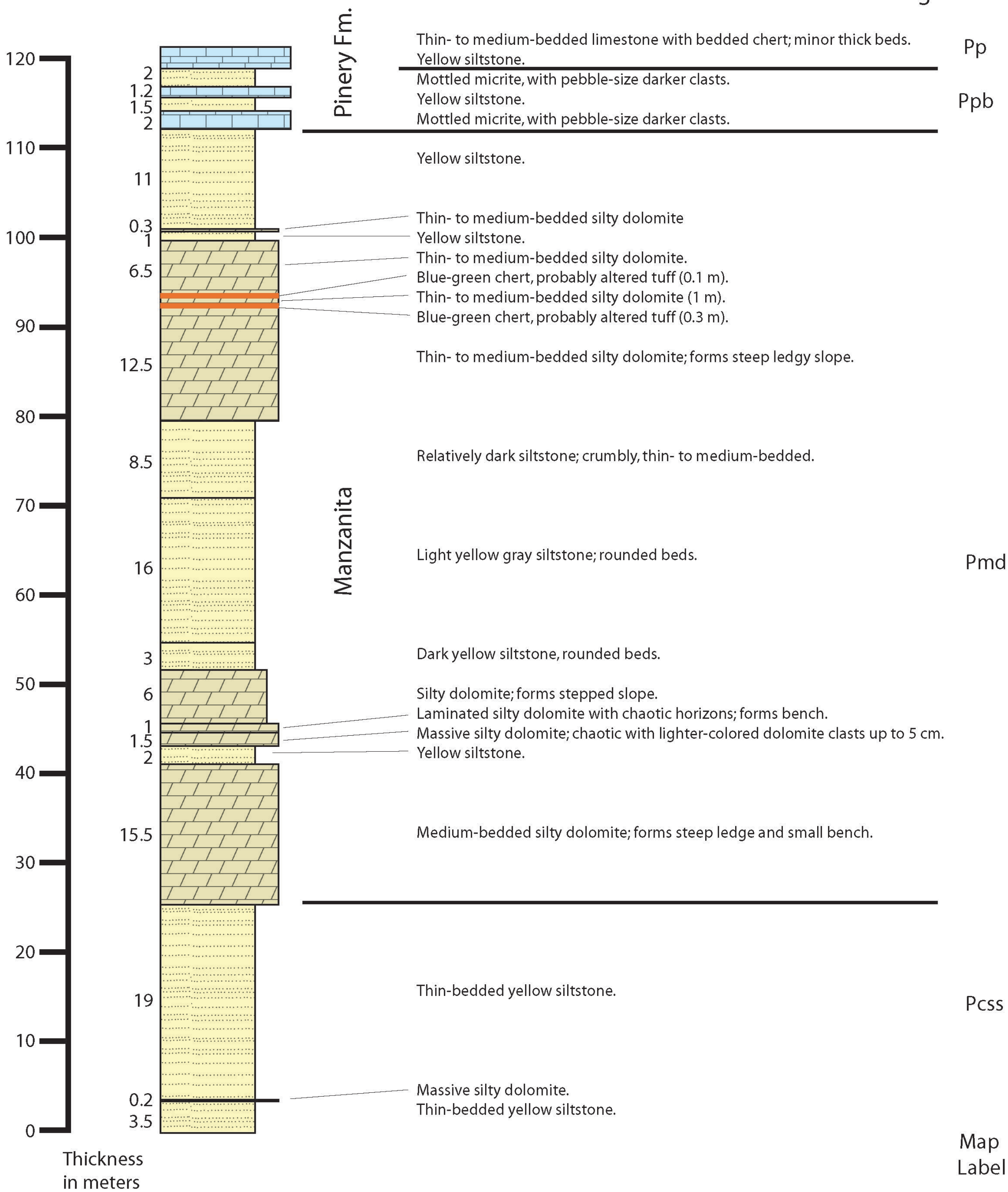
Measured Section 9
Rader Ridge
continues to top of ridge
Capitan Fm.
siltstone and breccia
McCombs
Capitan Fm.
Pinery
basal Pinery
Manzanita
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Thickness in meters
19
5
3
2
6
5.5
24
4
12
2
8
1
7
1.5
3
3.5
20
1
6
10.5
1
5
6
5
5
7.5
10
2
12
0.8
3
14
Chaotic limestone breccia and massive beds.
Px
Yellow siltstone; forms slope.
Chaotic limestone breccia.
Limey siltstone.
Yellow siltstone.
Tan-colored, thin- to medium-bedded limestone.
Chaotic limestone breccia.
Pbcs
About half siltstone and half limey siltstone.
Tan, limey siltstone bed (1 m).
Yellow siltstone (1 m).
Chaotic limestone breccia.
Interbedded medium- to thick-bedded limestone and and massive, chaotic beds up to 0.5 m thick.
Covered slope; some siltstone float.
Medium- to thick-bedded limestone; abundant skeletal debris and small limestone clasts, interbedded with massive beds.
Pm
Thin-bedded limestone with abundant skeletal debris.
Medium-bedded limestone with abundant skeletal debris; no chert; forms slope.
Chaotic limestone breccia.
Medium-bedded limestone with abundant skeletal debris; no chert; forms slope.
Chaotic limestone breccia (1 m).
Medium-bedded limestone with abundant skeletal debris; no chert; forms slope.
Chaotic limestone breccia.
Pcp
Thin- to medium-bedded limestone; with bedded chert.
Yellow siltstone.
Medium-bedded limestone; abundant skeletal debris; bedded chert.; ledgy slope.
Massive limestone bed; abundant skeletal debris selectively replaced by chert.
Medium-bedded limestone with abundant skeletal debris; with bedded chert.
Mostly siltstone with thin beds of limestone; forms slope.
Thin- to medium-bedded limestone interbedded with thin siltstone beds.
Pp
Covered slope; siltstone float.
Medium-to thick-bedded limestone with abundant skeletal debris and bedded chert; forms the prominent lower band on Rader Ridge.
Covered slope; small ledges of medium-bedded limestone and siltstone float.
Thin-bedded limestone, mottled on bedding planes (1.5 m).
Yellow siltstone (1 m).
Thin-bedded limestone, mottled on bedding planes.
Ppb
Yellow siltstone.
Thin-bedded limestone, mottled on bedding planes.
Yellow siltstone.
Pmd
Yellow dolomite.
Map Label

Measured Sections 10, 11, and 12



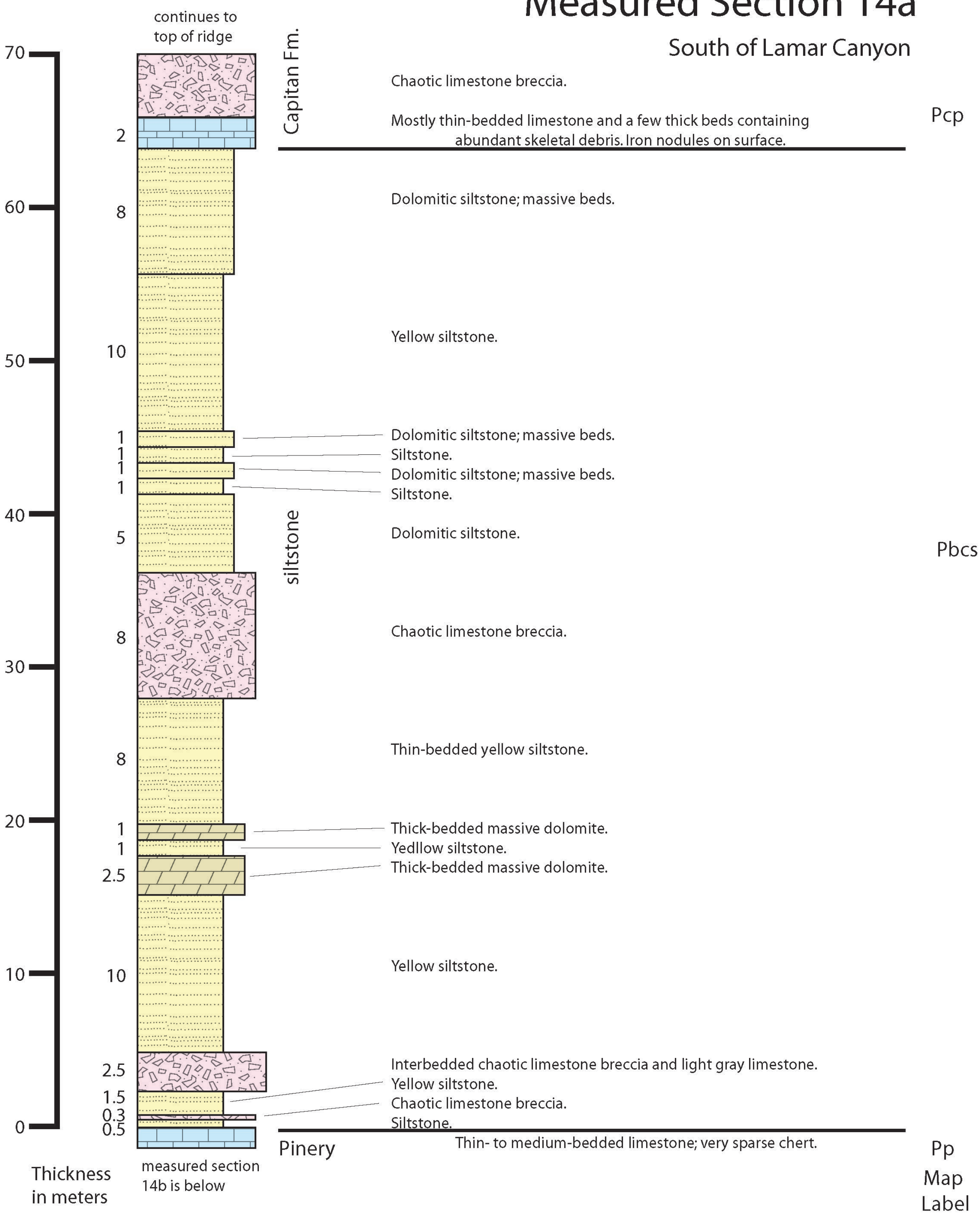
Measured Section 13

Rader Ridge



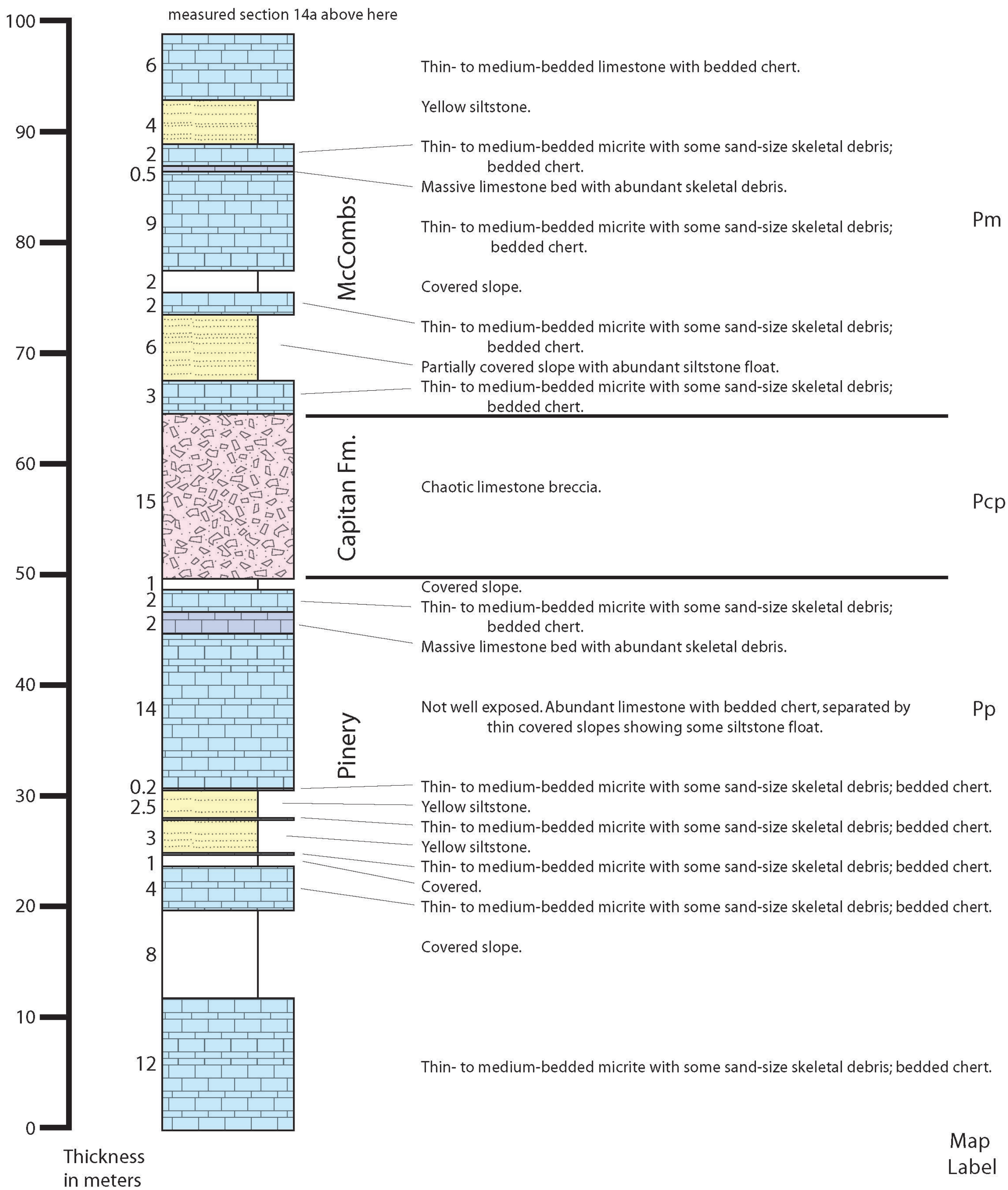
Measured Section 14a

South of Lamar Canyon



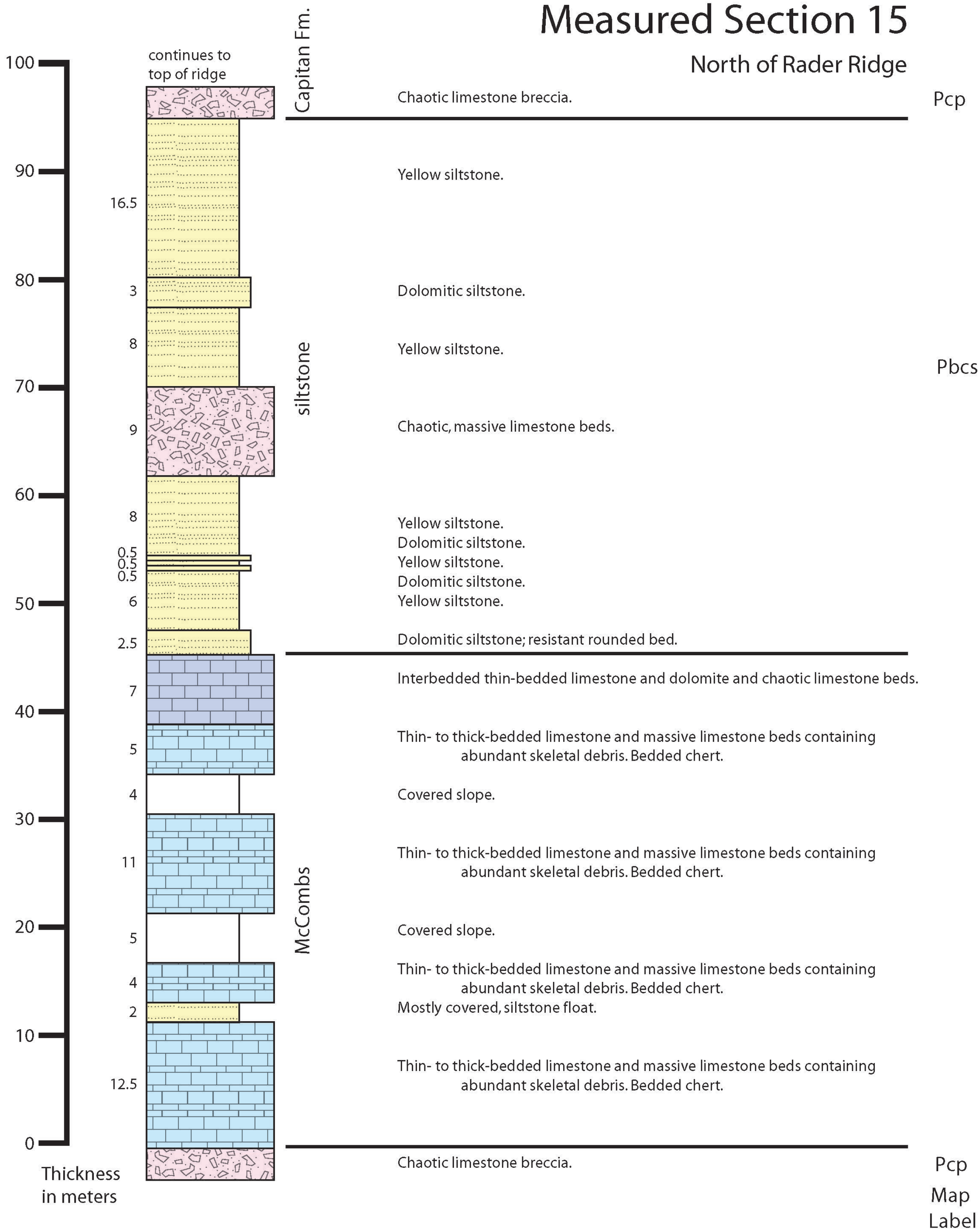
Measured Section 14b

North of Rader Ridge



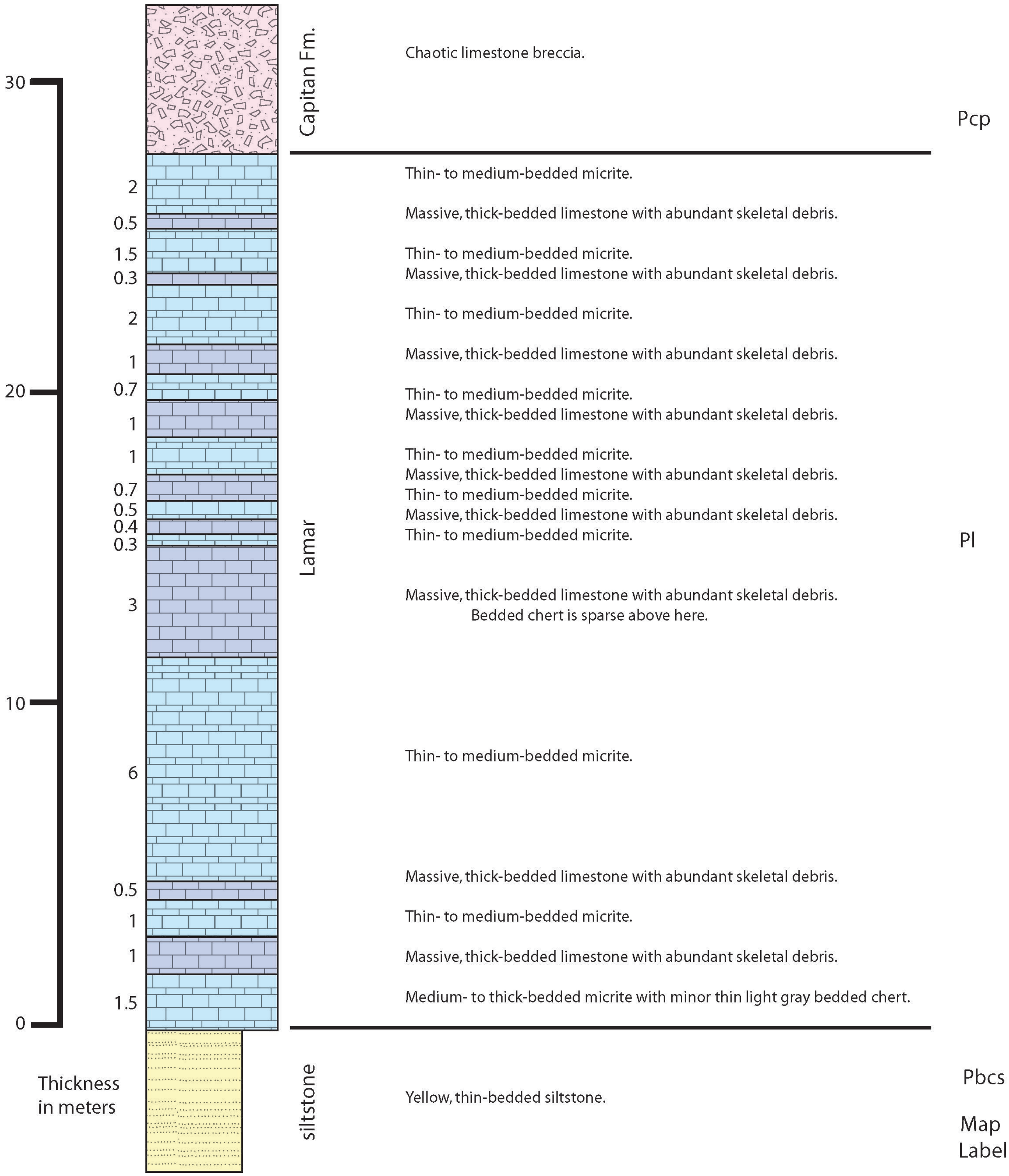
Measured Section 15

North of Rader Ridge



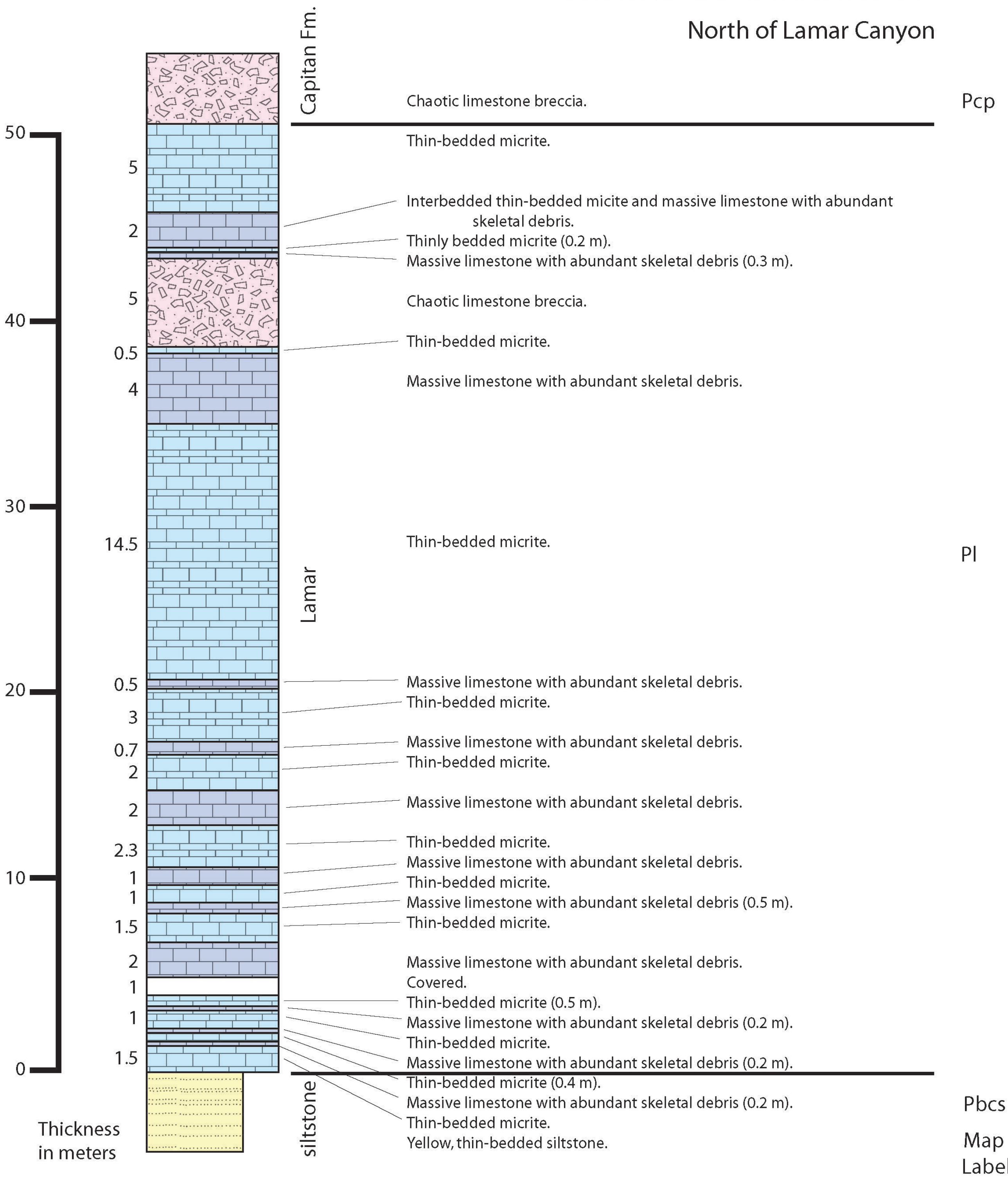
Measured Section 16

South of Lamar Canyon



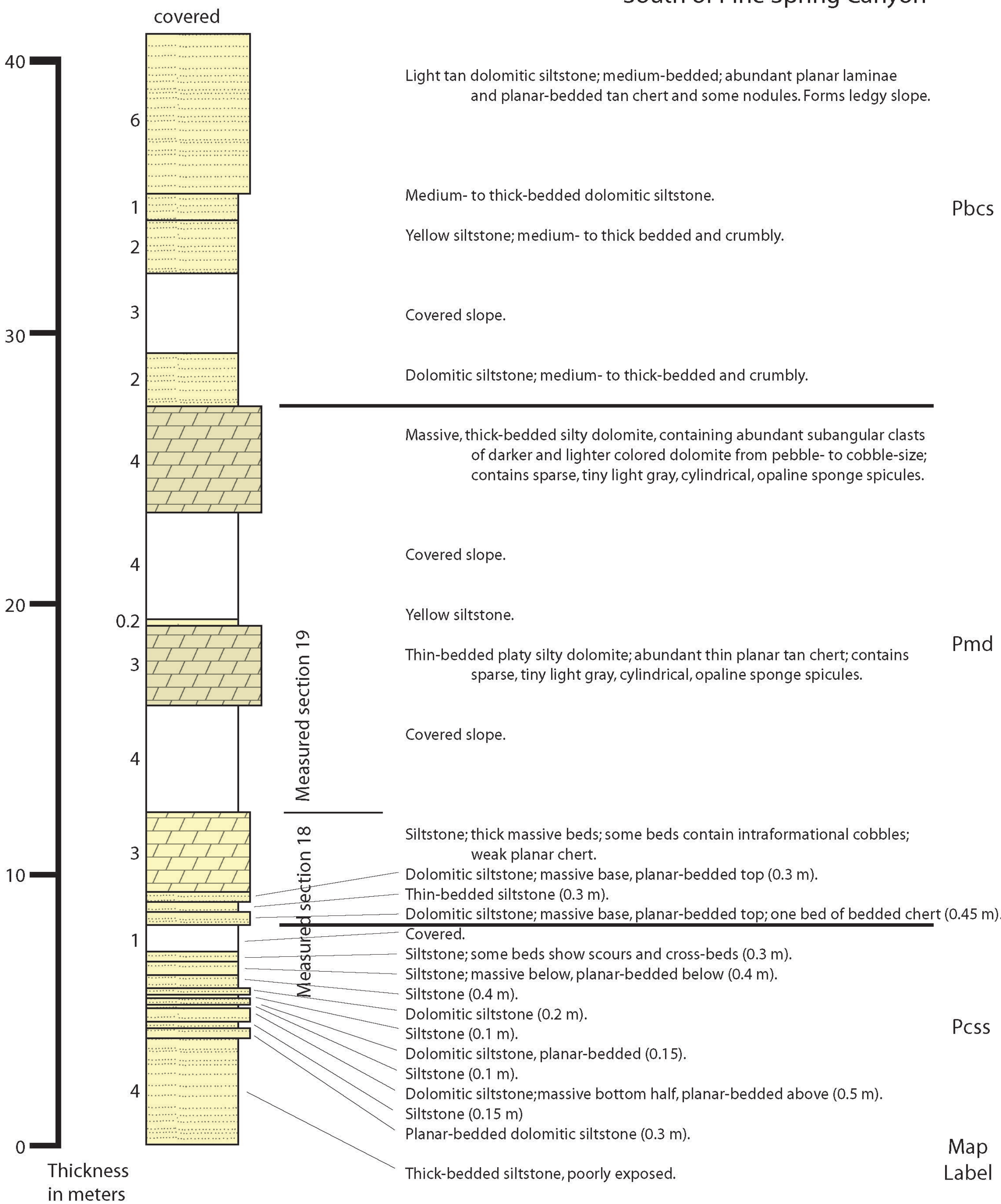
Measured Section 17

North of Lamar Canyon



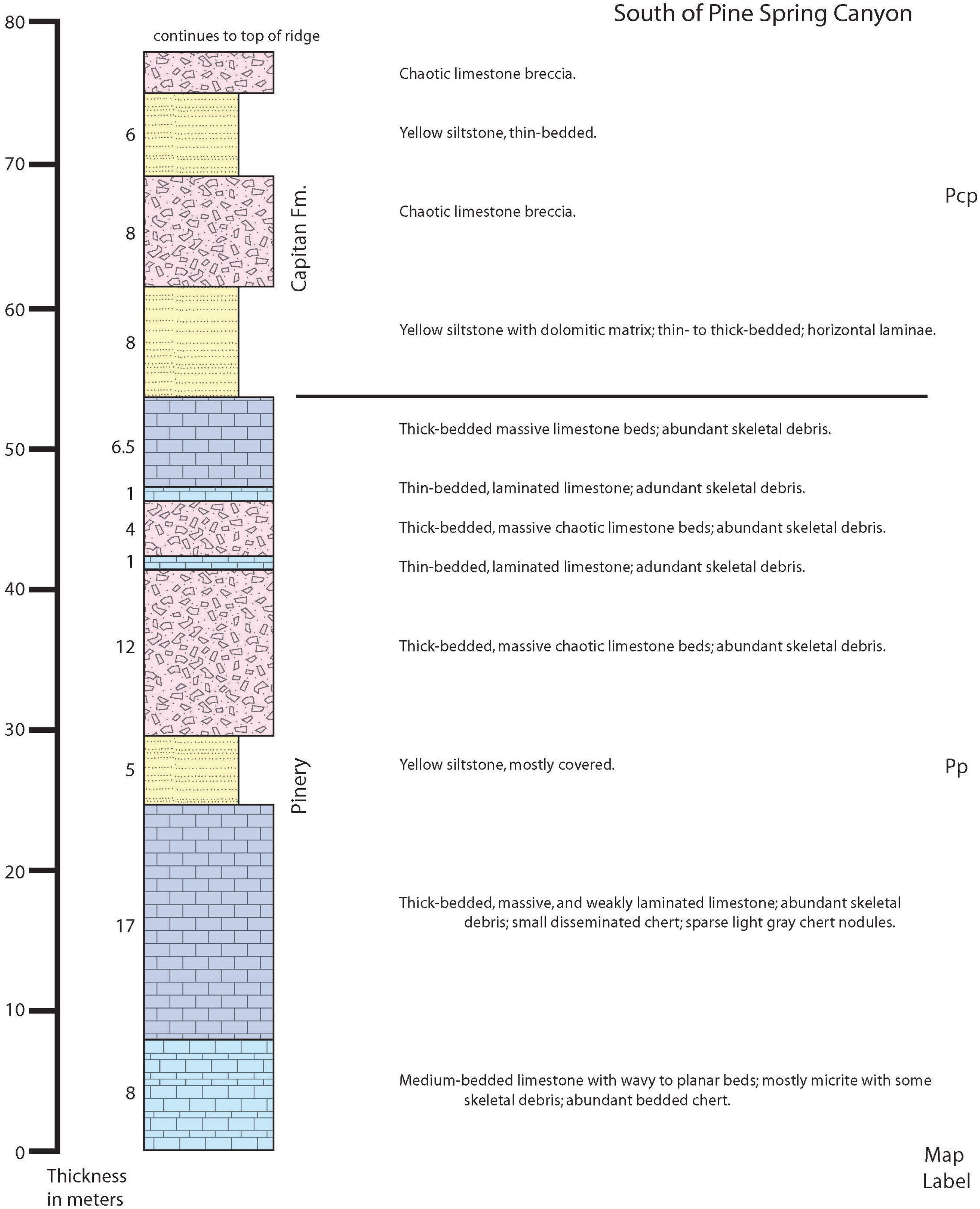
Measured Sections 18 and 19

South of Pine Spring Canyon



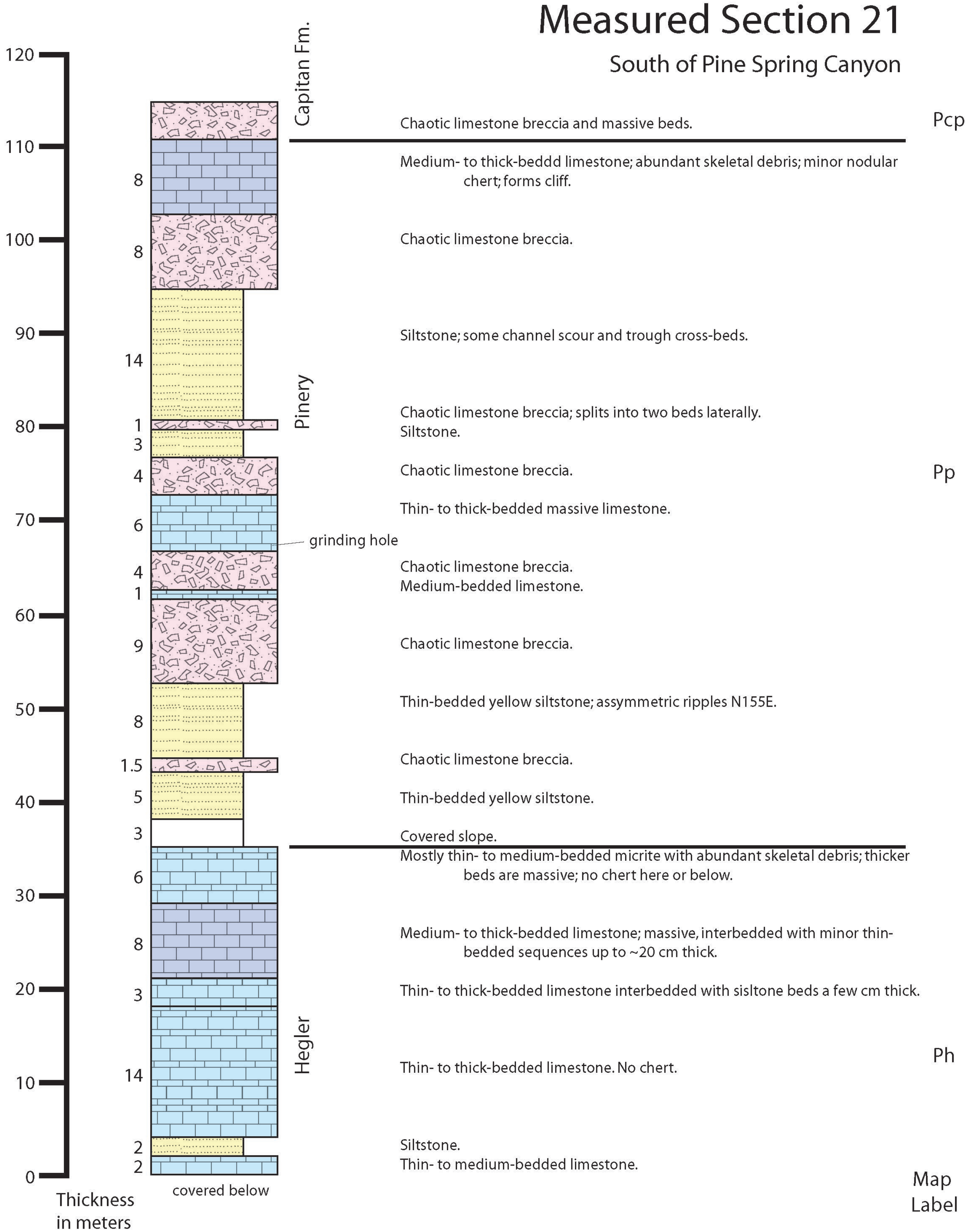
Measured Section 20

South of Pine Spring Canyon



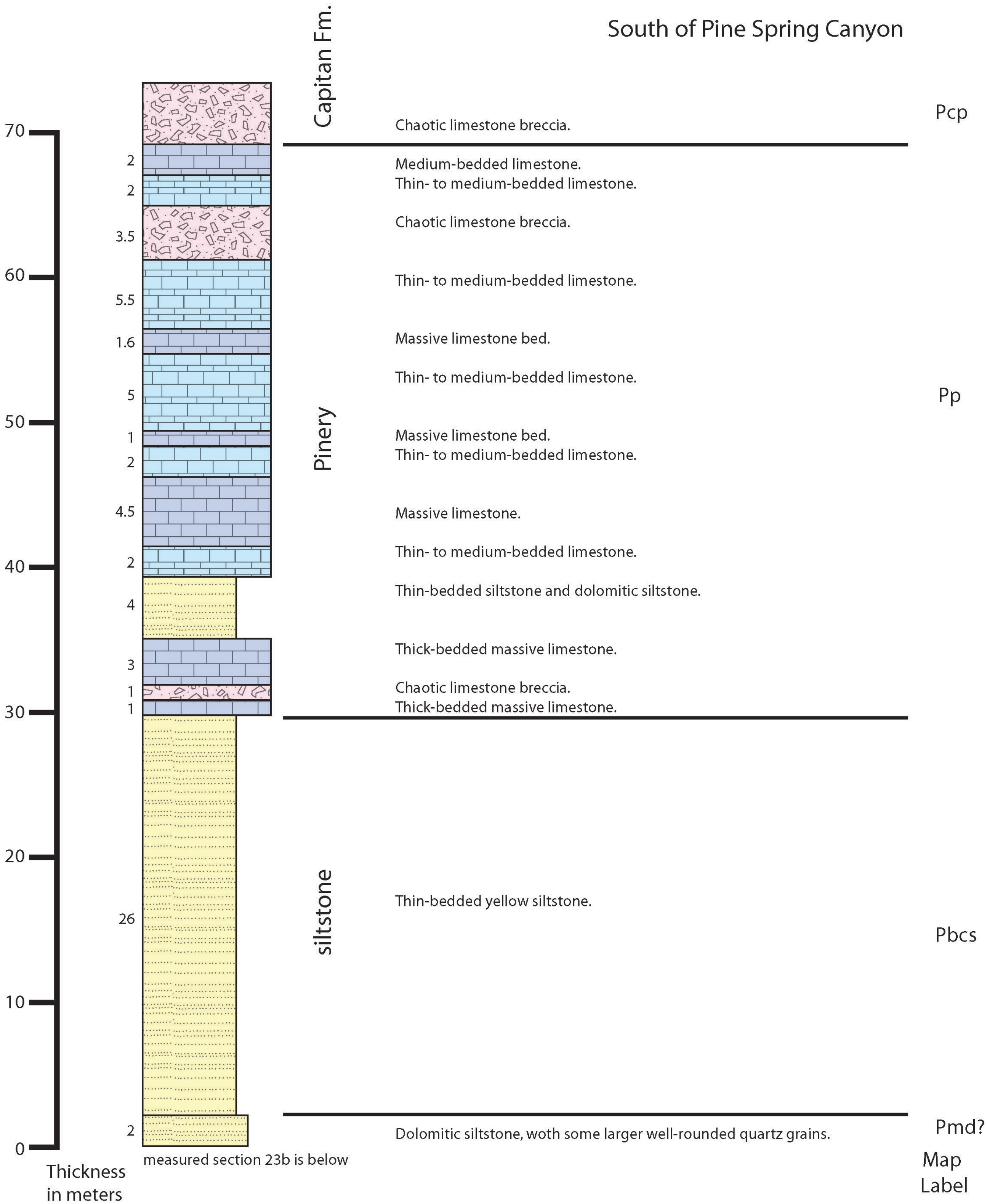
Measured Section 21

South of Pine Spring Canyon



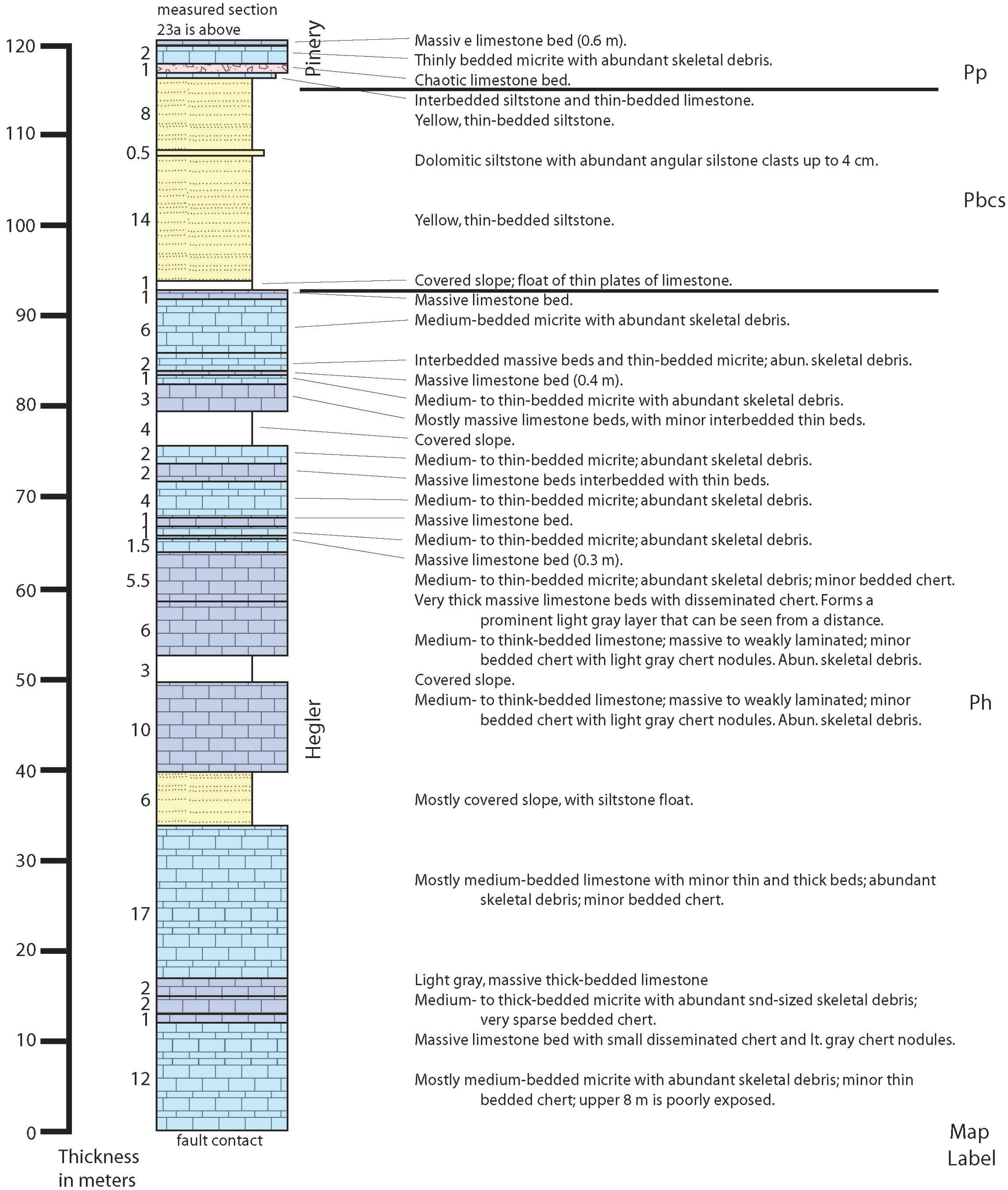
Measured Section 22a

South of Pine Spring Canyon



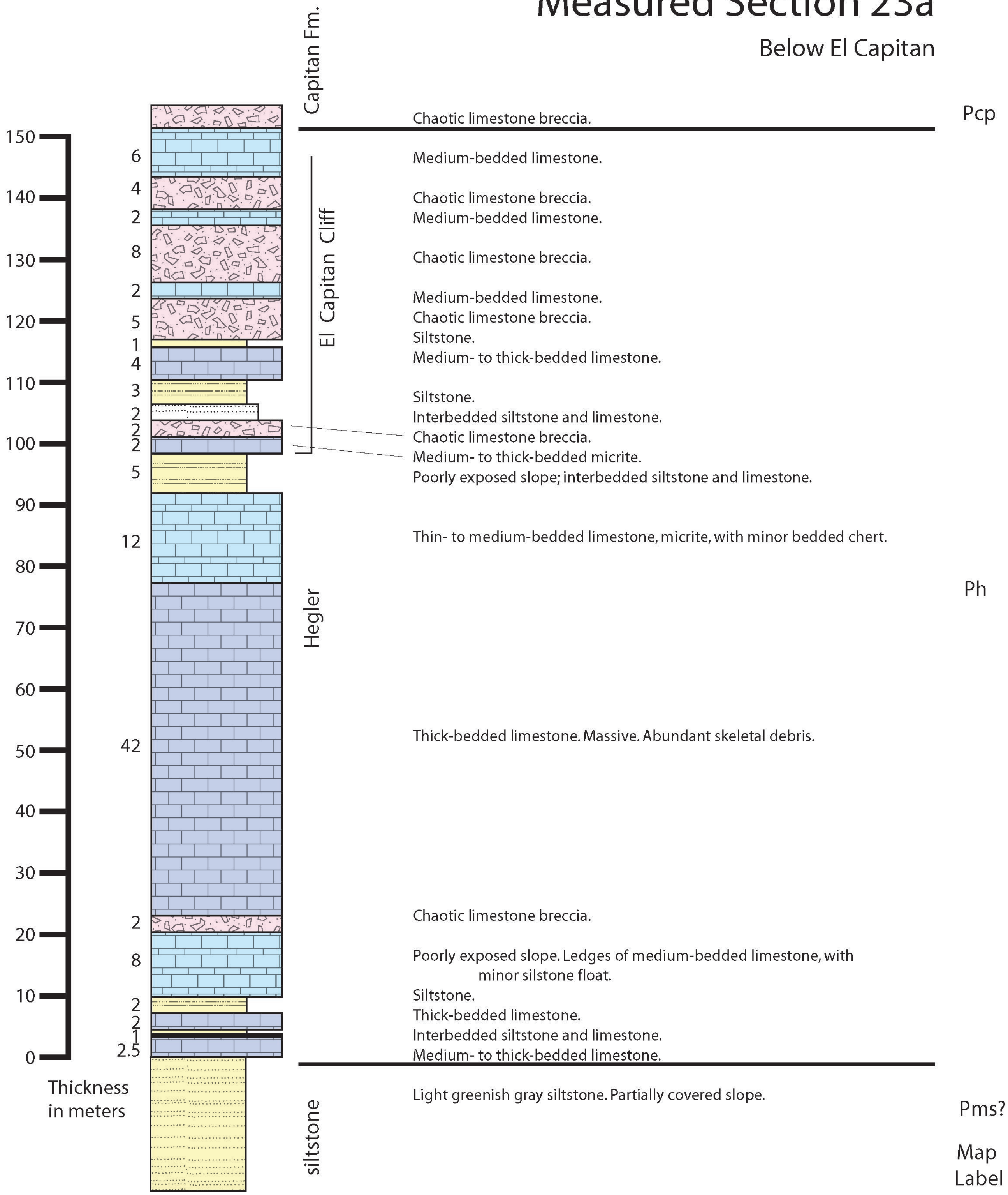
Measured Section 22b

South of Pine Spring Canyon



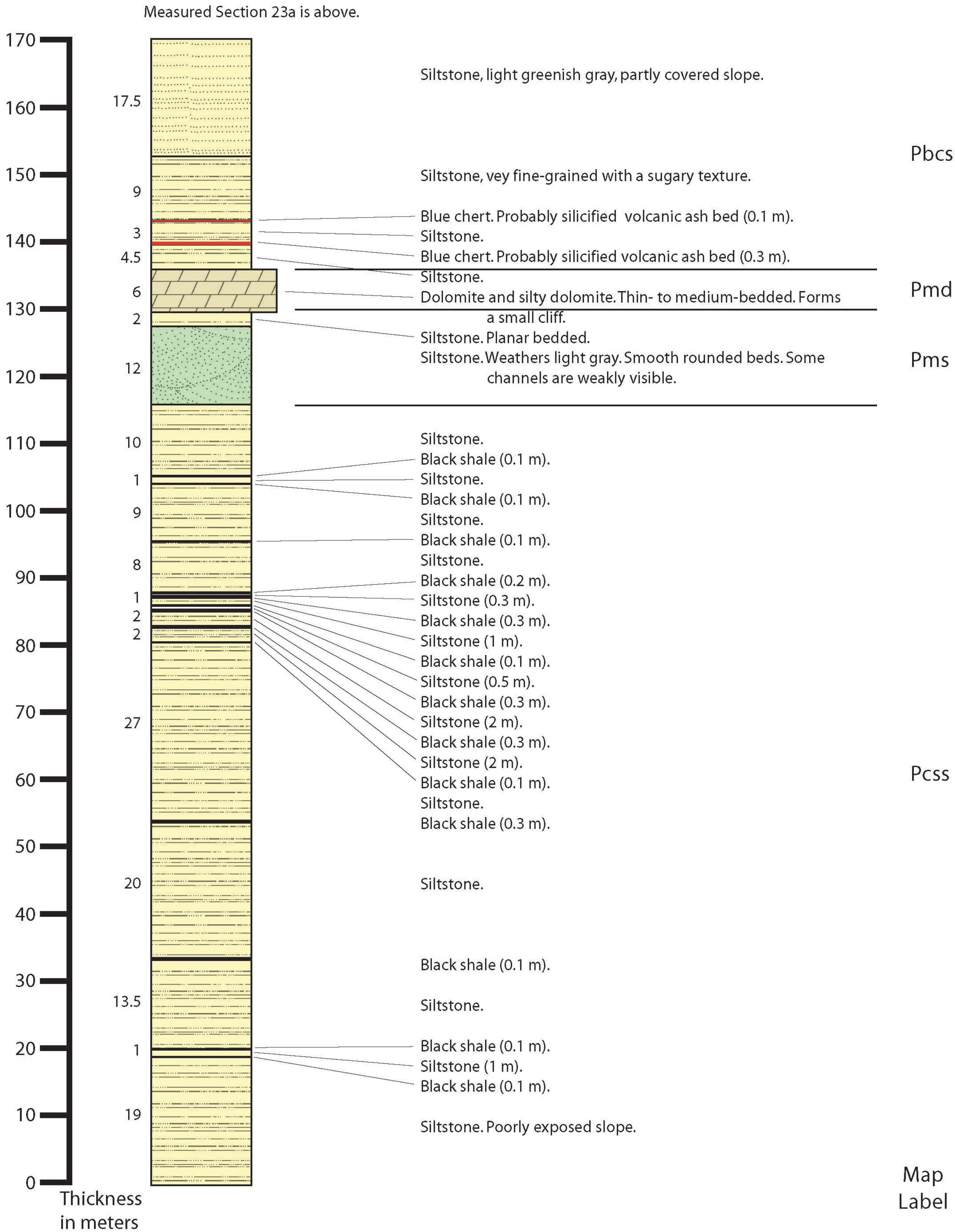
Measured Section 23a

Below El Capitan



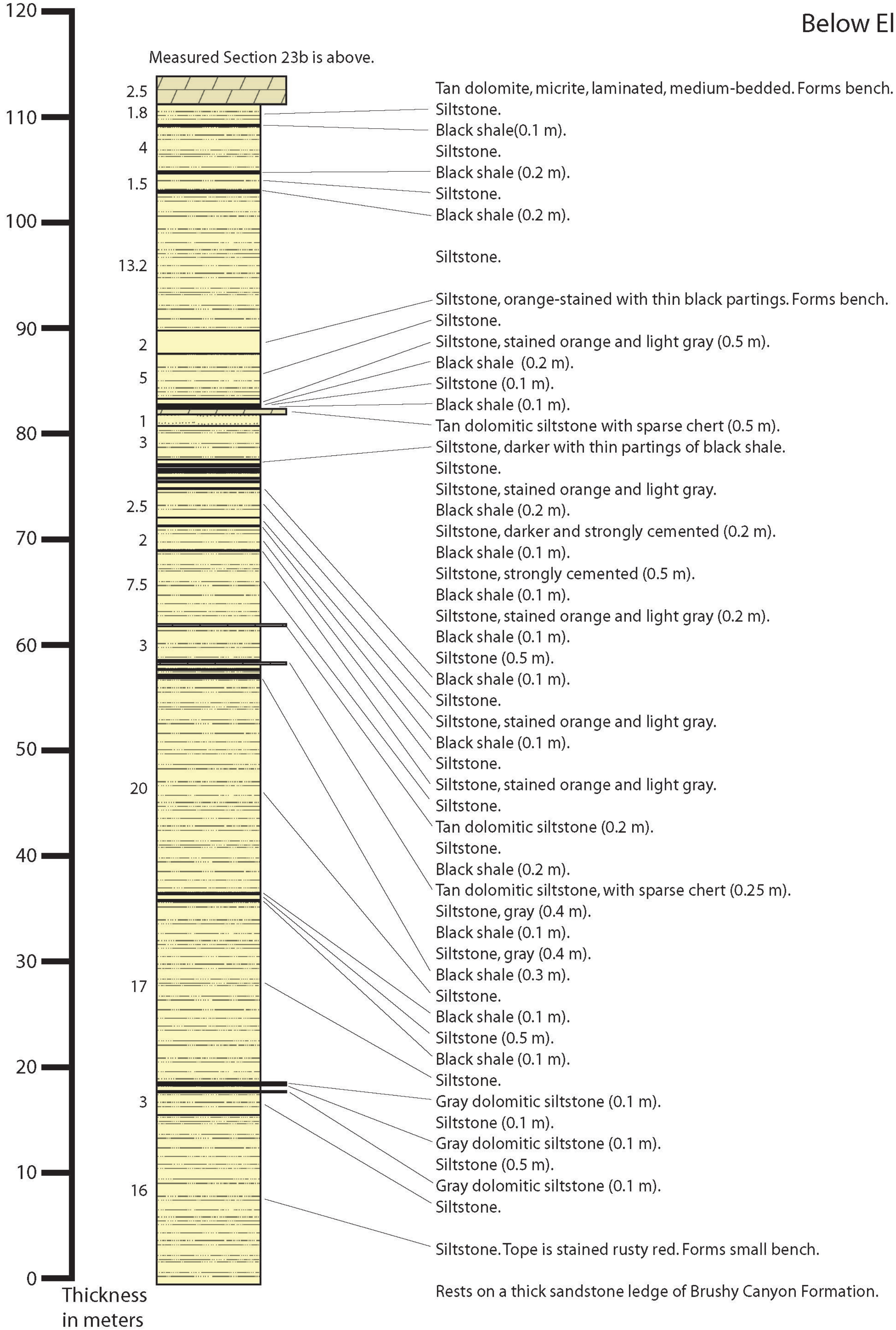
Measured Section 23b

Below El Capitan



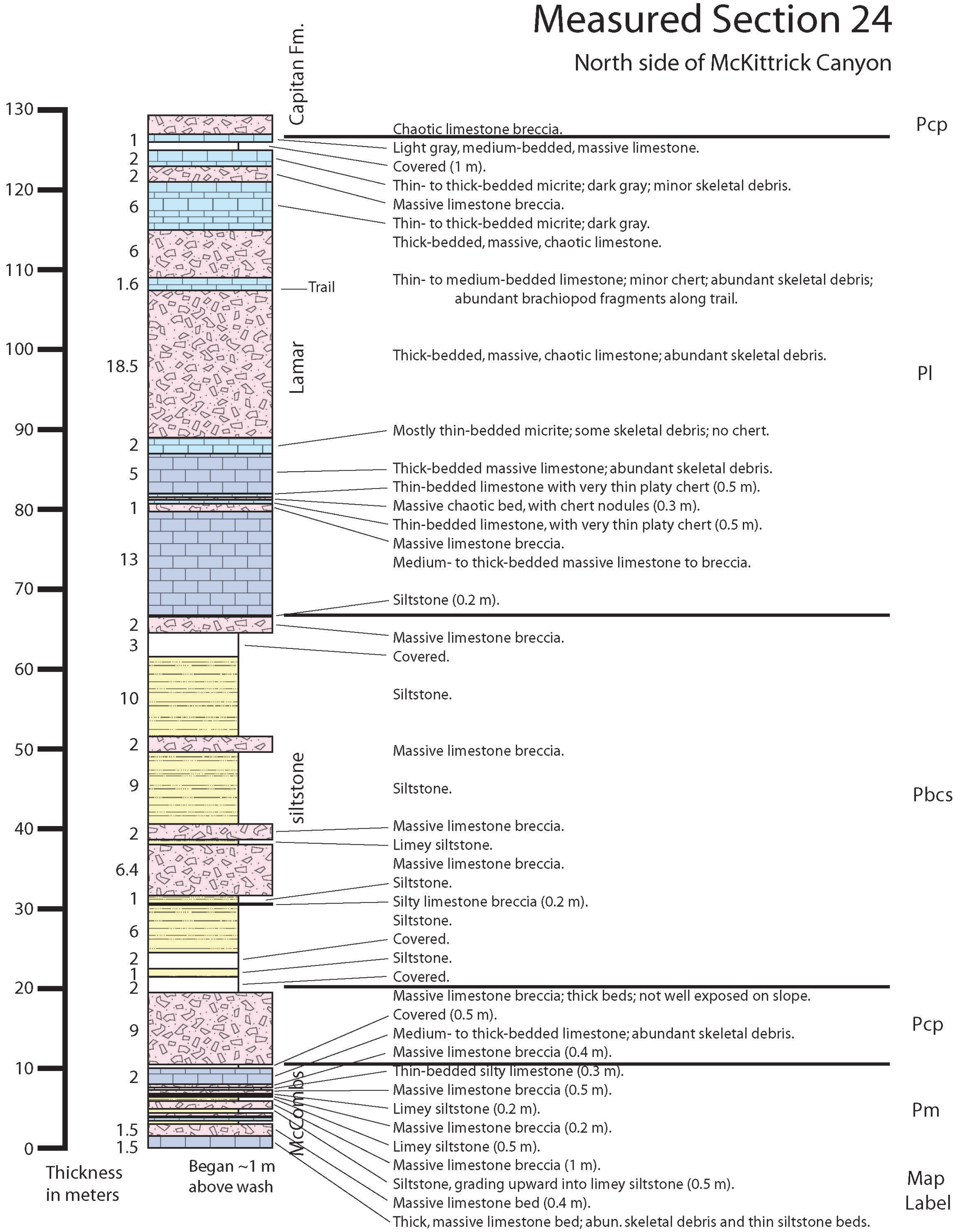
Measured Section 23c

Below El Capitan



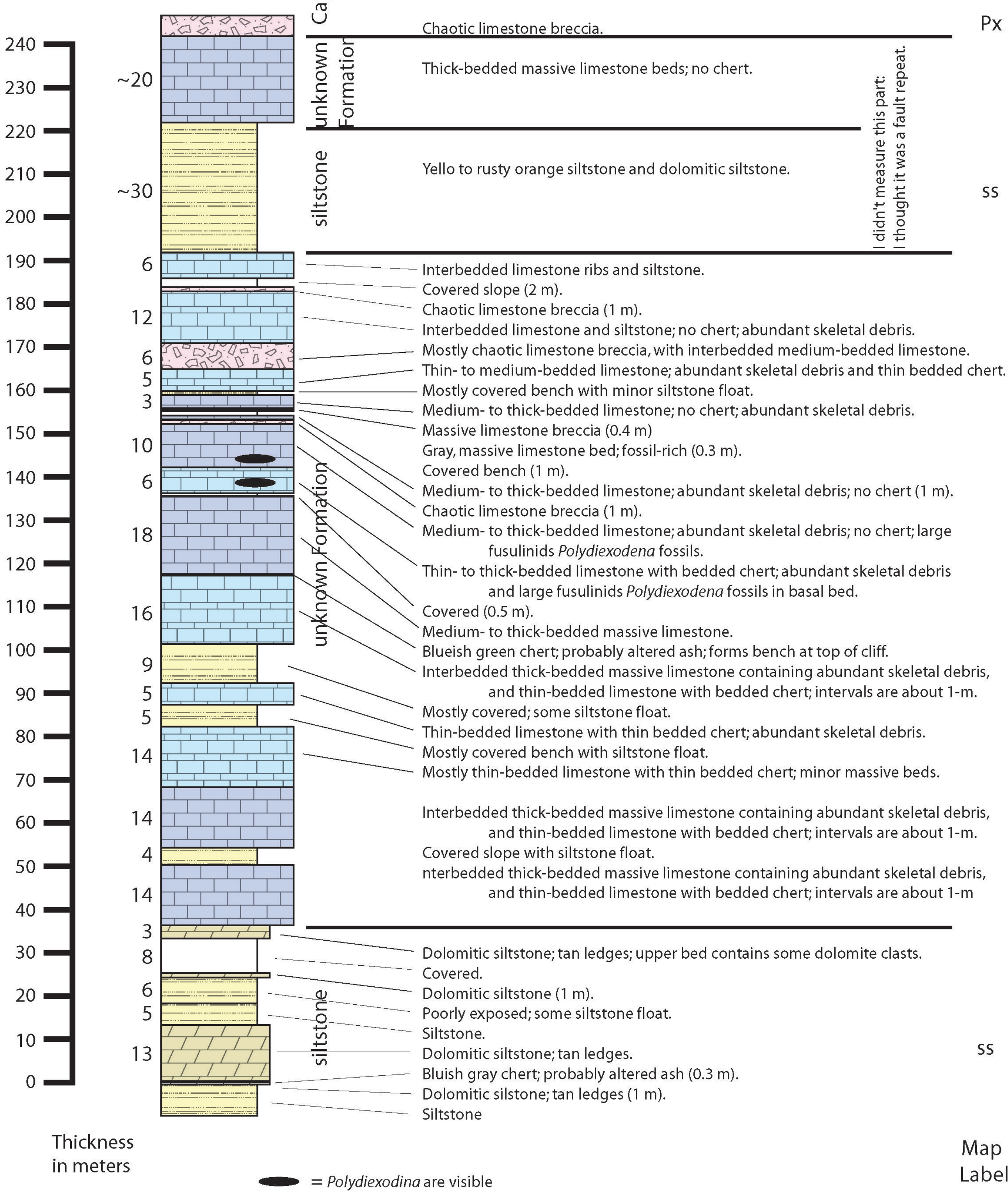
Measured Section 24

North side of McKittrick Canyon



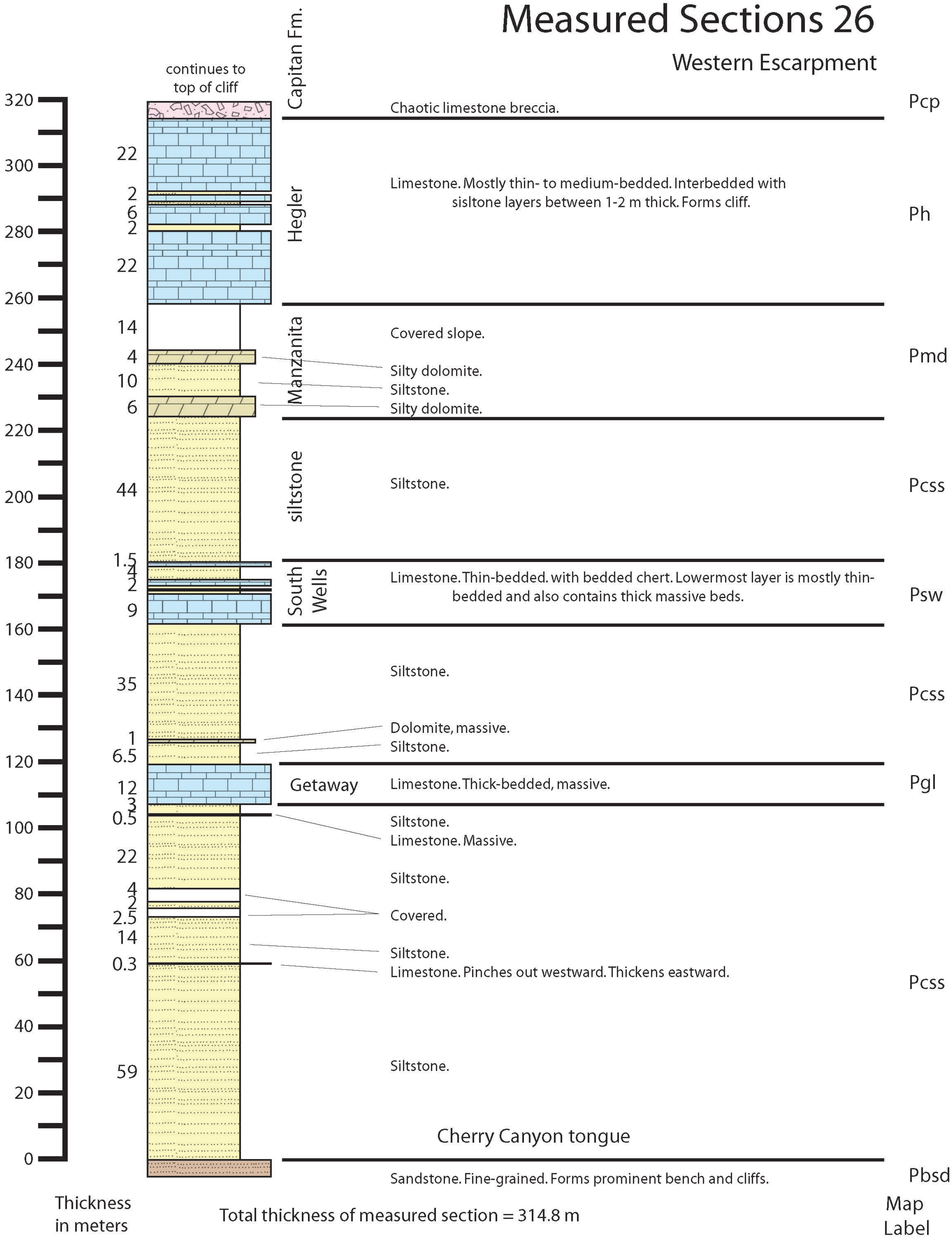
Measured Section 25

Patterson Hills



Measured Sections 26

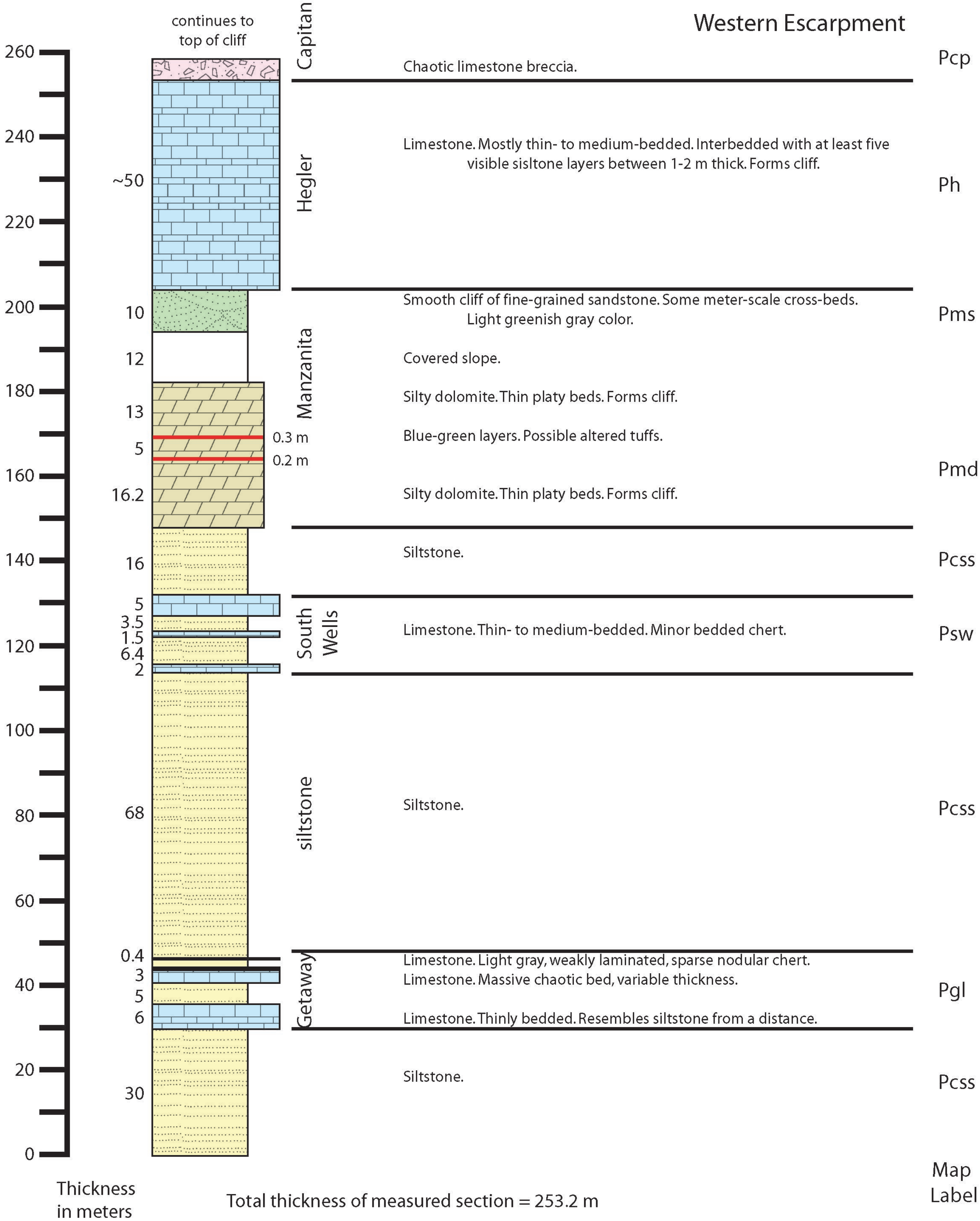
Western Escarpment



Total thickness of measured section = 314.8 m

Measured Section 27

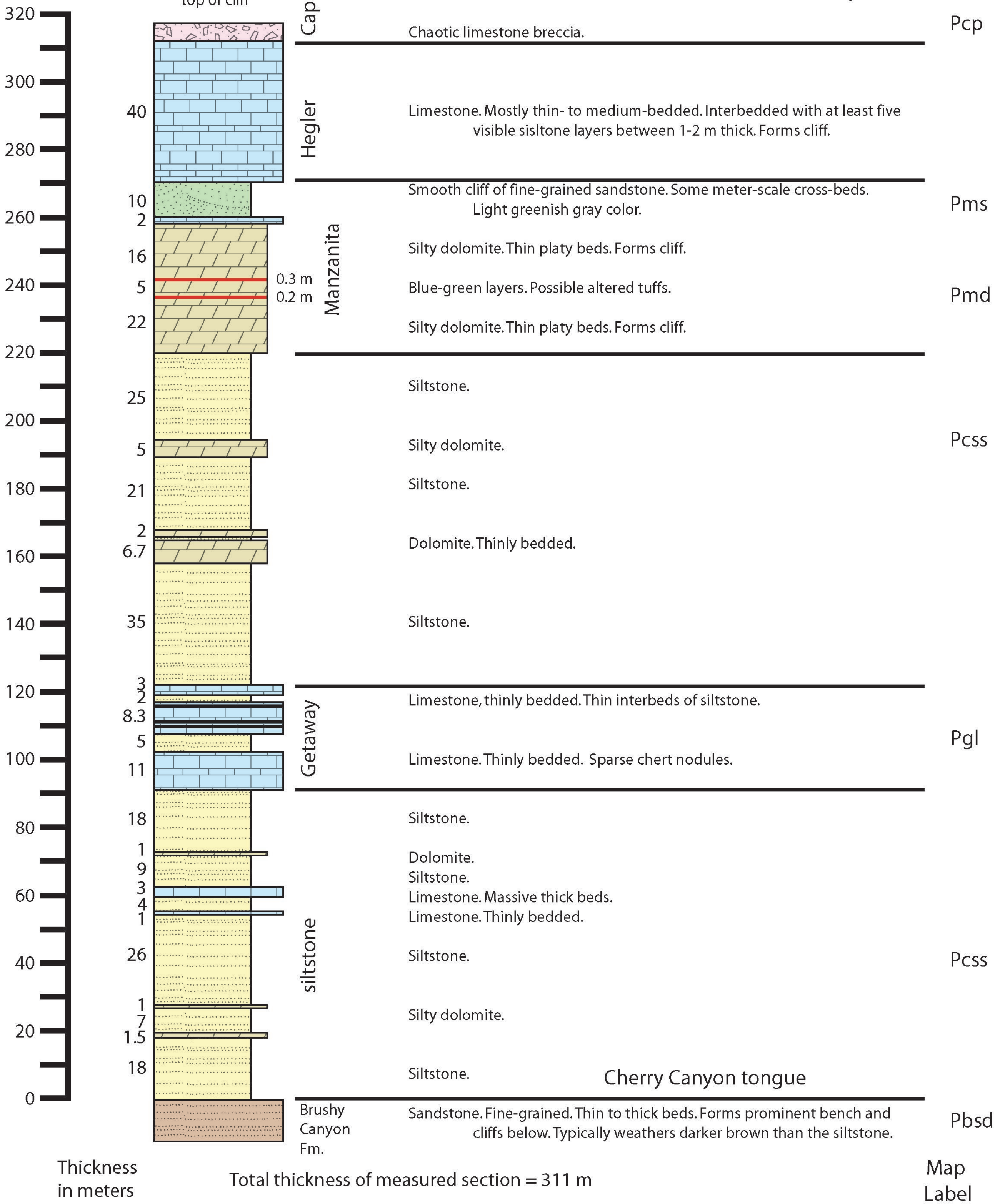
Western Escarpment



Total thickness of measured section = 253.2 m

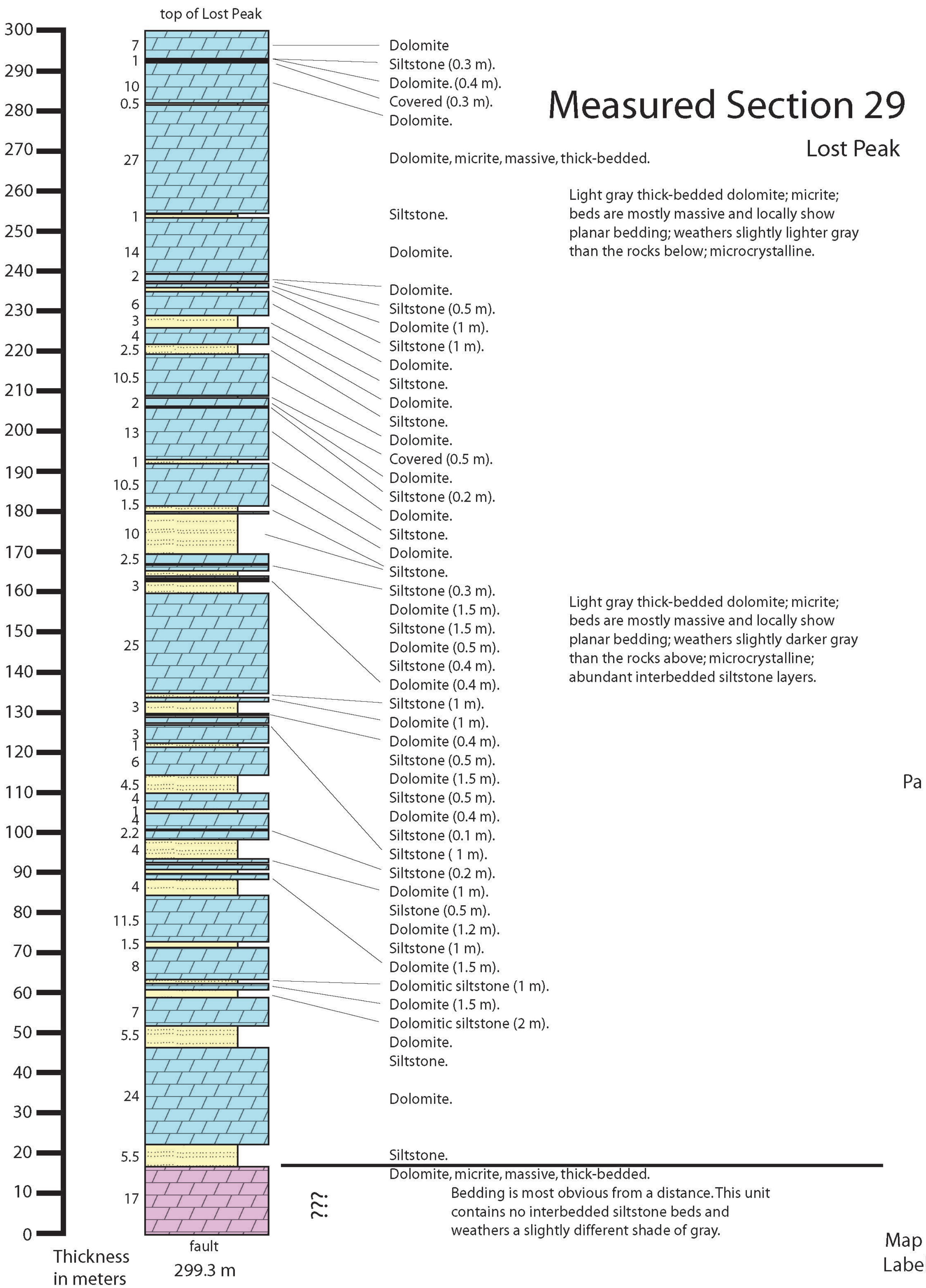
Measured Section 28

Western Escarpment



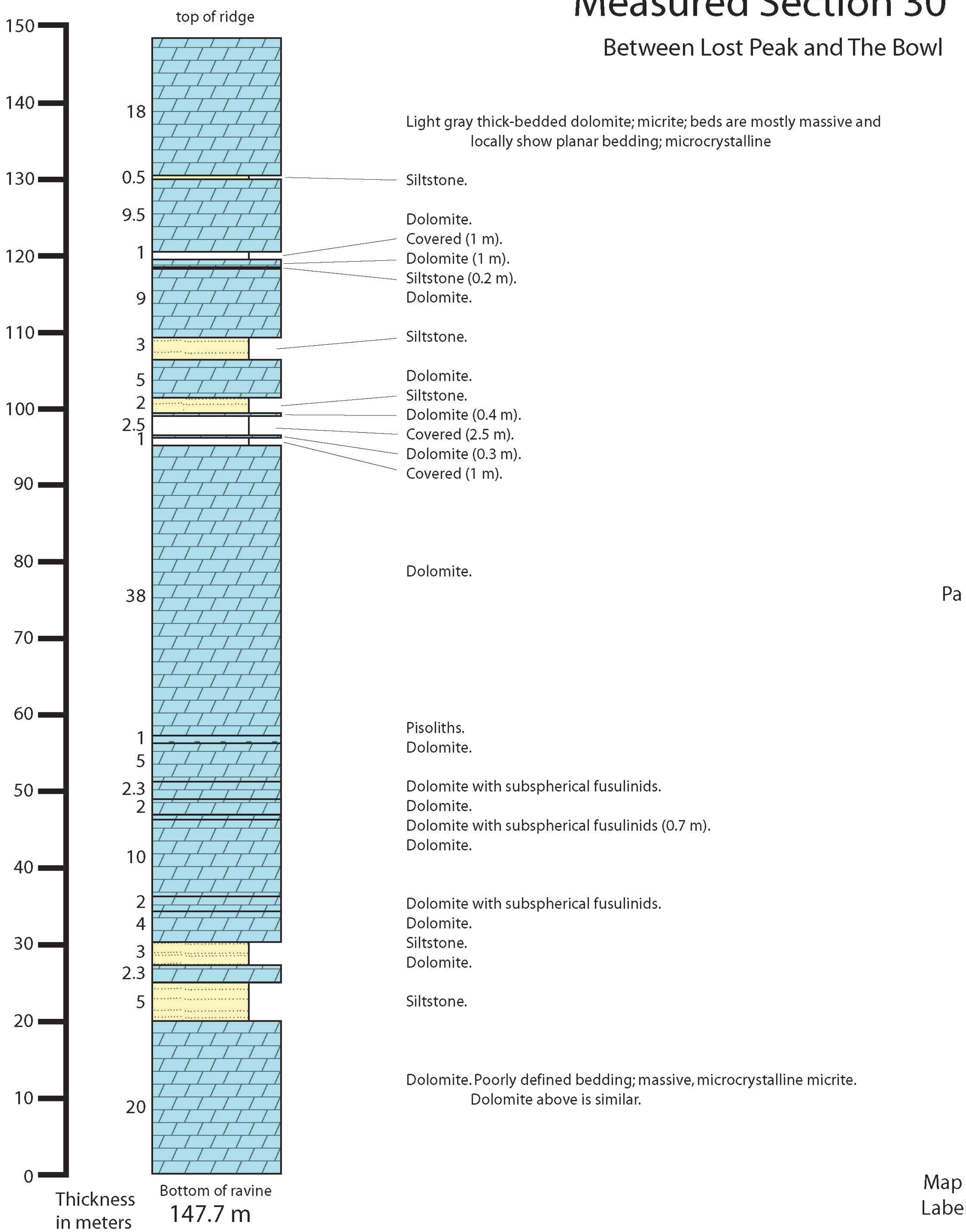
Measured Section 29

Lost Peak



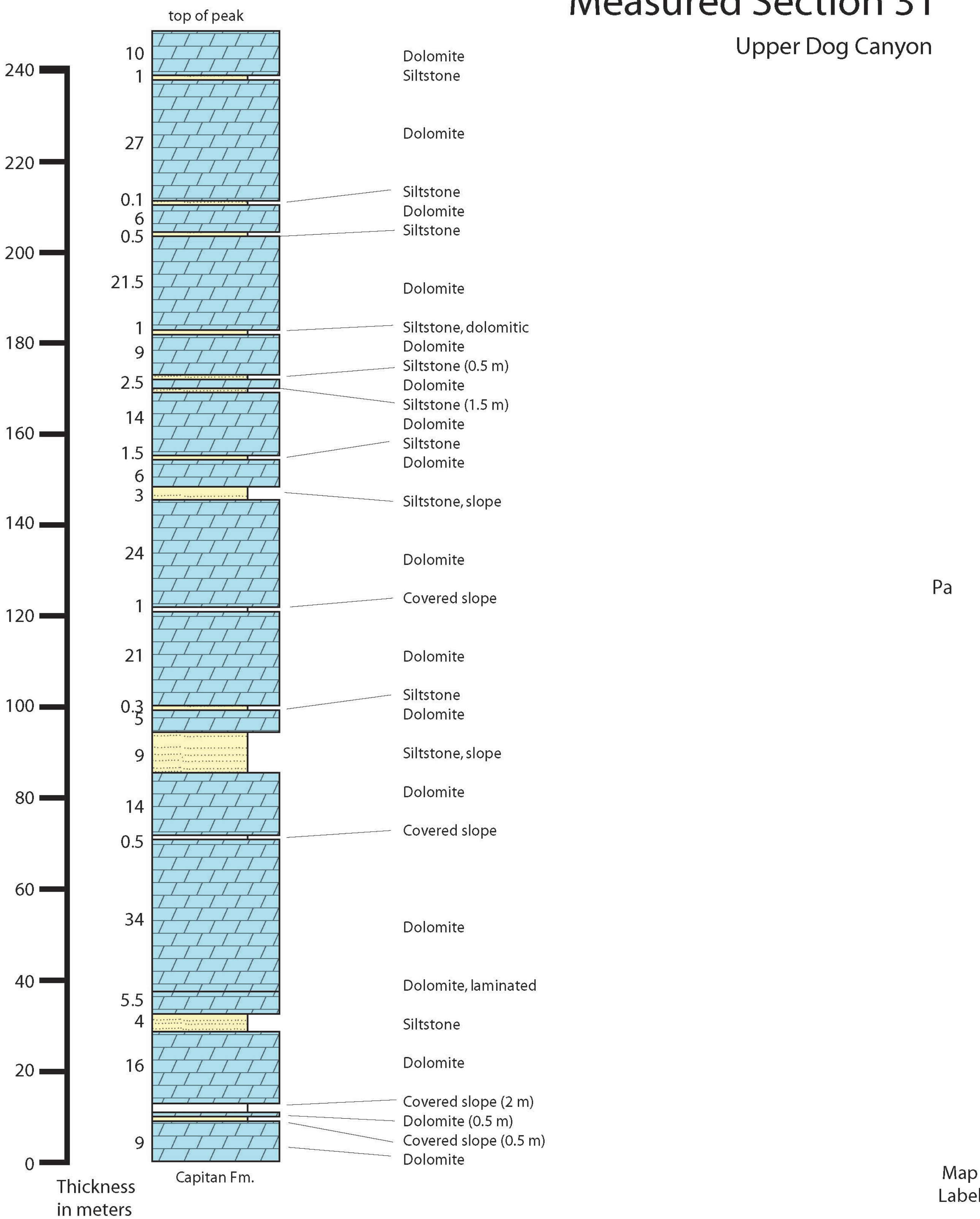
Measured Section 30

Between Lost Peak and The Bowl



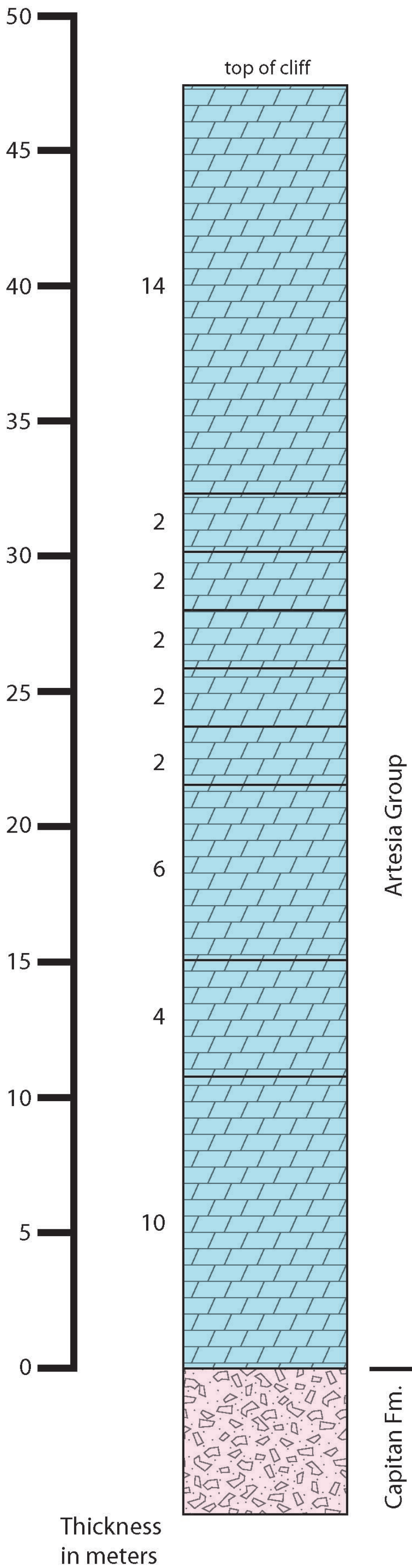
Measured Section 31

Upper Dog Canyon



Measured Section 32

Top of Permian Reef Trail



Crudely bedded to massive dolomite. Darker gray rock is limestone.

Laminated dolomite. Forms slope. Some pisoliths.

Massive thick dolomite. Flororms cliff.

Laminated dolomite. Forms slope.

Massive thick dolomite. Forms cliff.

Laminated dolomite. Forms slope. Abundant fossil fragments. — Pa

Thick bedded, massive dolomite. Forms cliff.

Thin-bedded to medium-bedded dolomite.

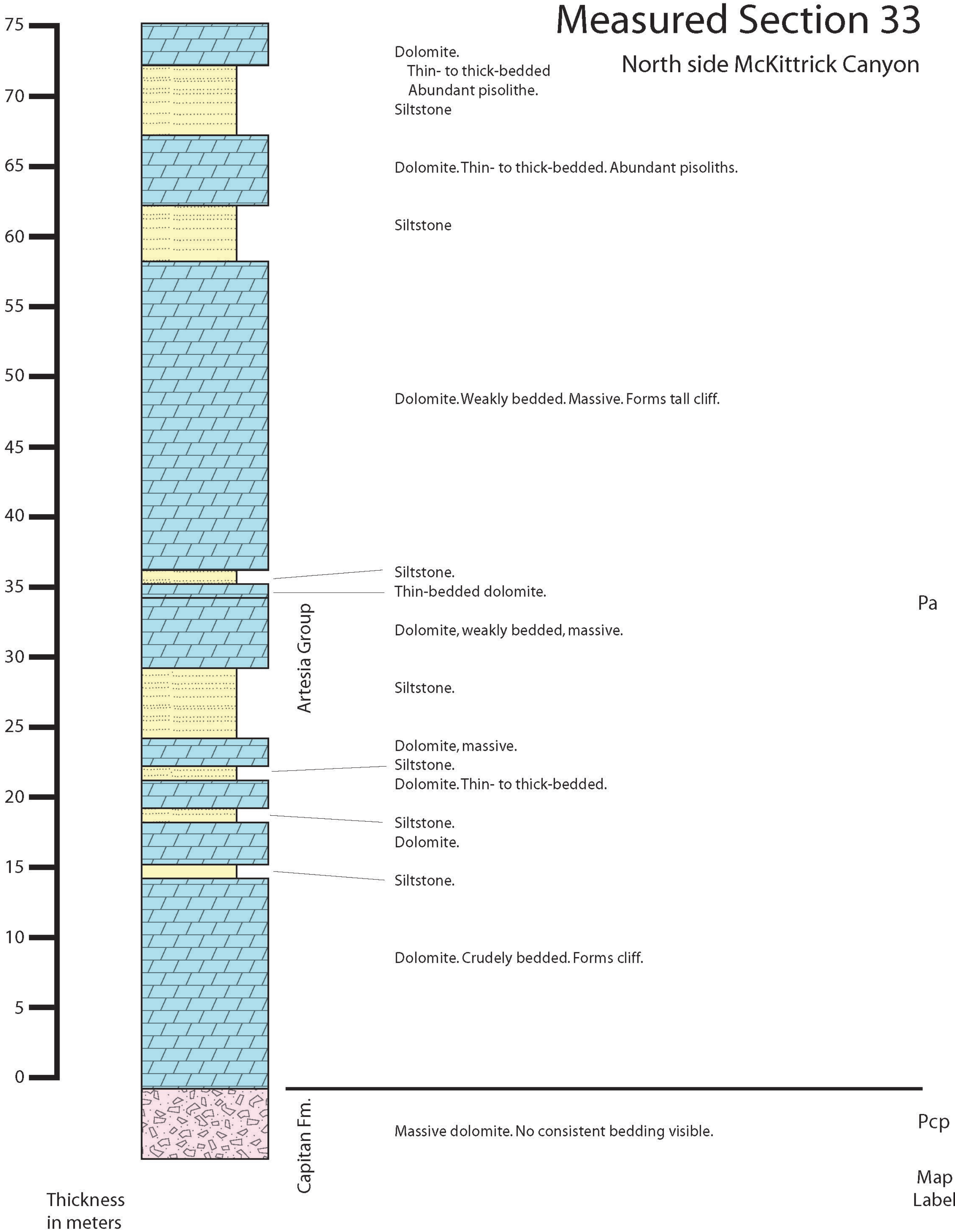
Thick massive dolomite. Prominently bedded from a distance.

Massive dolomite. No consistent bedding visible.

Map Label

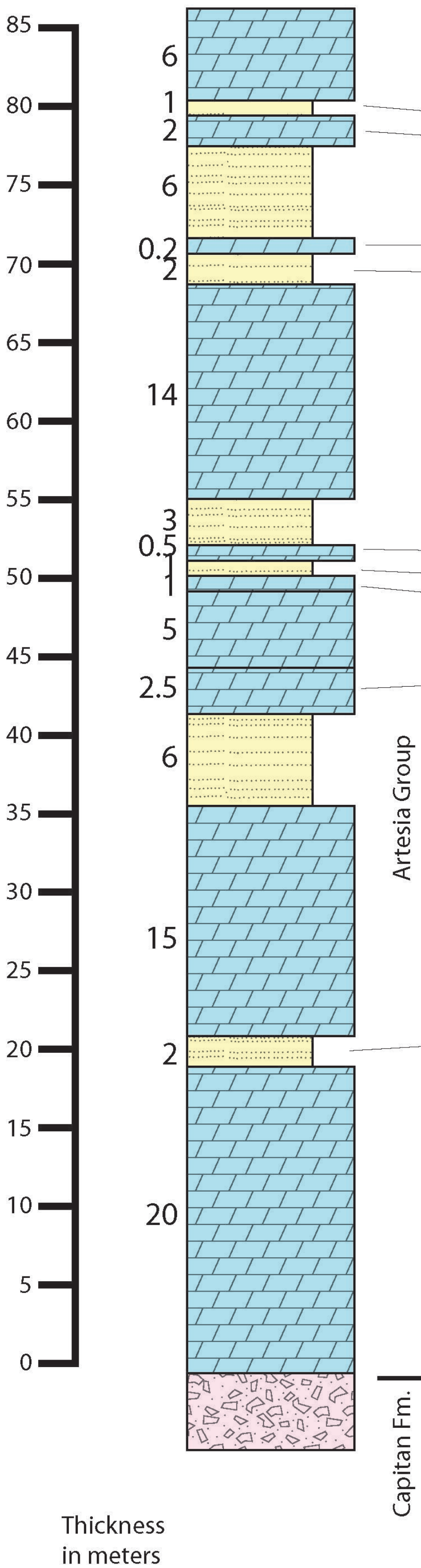
Measured Section 33

North side McKittrick Canyon



Measured Section 34

North side McKittrick Canyon



stoneDolomite.
Thin- to thick-bedded
Abundant pisolithe.

Siltstone.

Dolomite.

Siltstone.

Dolomite.

Siltstone.

Dolomite. Forms ledgy slope. No consistent bedding visible. Some beds contain abundant pisoliths. The uppermost 4 meters may contain very thin siltstone beds.

Siltstone.

Dolomite.

Siltstone.

Thin-bedded dolomite.

Dolomite. Thick-bedded and massive.

Dolomite. Thin-t to medium-bedded.

Siltstone.

Dolomite. Thick-bedded, massive. Forms cliff.

Siltstone.

Dolomite. Faintly thick-bedded and massive. Forms cliff.

Pa

Massive dolomite.

Pcp

Map Label