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STRATIGRAPHY, SEDIMENTOLOGY,
AND
SURFACE WATER QUALITY
AT
EL MORRO NATIONAL MONUMENT

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Executive Summary

El Morro is a large sandstone promontory that rises from a broad, linear valley on the southern margin of the Zuni Mountains. For centuries this valley has provided a corridor for east-west travel, and the perennial pool of water at the base of El Morro has made it a customary stop along the way. Many of these travelers left their marks carved on the bluff, and the historical inscriptions, the oldest dating back to 1605, are the *raison d'être* of El Morro National Monument. The inscriptions are weathering away at differential rates — some of the older inscriptions appear pristine while more recent inscriptions are visibly succumbing to erosion. Deterioration of these engravings is largely controlled by the interplay of extant geological conditions with fluctuating environmental conditions.

When designing an effective treatment program it is essential to acquire detailed baseline data concerning the characteristics of the rock that is to be treated. Mineralogy, permeability, porosity, texture of the rock, nature of cements, and weathering processes are all important considerations. The initial geological investigation for this program was performed by George Austin, Senior Geologist at the New Mexico Bureau of Mines and Mineral Resources. His report included data on bulk mineralogy, particle size analysis, mineralogy of the clay-size fraction, and leaching analysis. The sampling policy limited his study to grab samples and loose slabs. In order to further refine the understanding of the rock and its attendant modes of deterioration, it was necessary to develop a strategic sampling scheme with a spatial, stratigraphic framework on which to organize the data.

The promontory at El Morro is a landform known as a *cuesta*, a type of inclined mesa formed by the erosion of tilted strata — one flank is bounded by cliffs, the opposite flank dips gently into the subsurface. The northeast point of this *cuesta* forms the tallest cliff, and here is also the lowest exposed strata at the base of the outcrop. Moving away from this point, along either the northern wall or the eastern wall, the strata dip gently into the subsurface as the observer travels progressively upsection. By sampling from one wall or the other it was possible to construct a complete composite vertical succession of strata while avoiding areas near inscriptions. Samples were taken for permeability testing, detailed particle size analysis, and for cutting into petrographic

microscope slides to determine porosity, mineral arrangement, and cement characteristics. Maps of the cliff faces were constructed to organize sample locations, types of strata, and the bounding surfaces that delineate the various strata.

The El Morro cliffs are composed of the Jurassic Zuni Sandstone, which, like other sandstones, is made up of a framework of sand grains, the space between the grains, and any material that may occupy that space, such as fine-grained clay-sized particles (matrix) or crystalline cement that precipitates from pore fluids. Changes that occur in the character and composition of sediments after deposition and burial are known as diagenetic processes. Chemical diagenetic processes involve the mobilization and redistribution of ions in order to maintain equilibrium under shifting conditions. This results in the dissolution of pre-existing minerals that become unstable and the precipitation of minerals from solutions that become oversaturated. Precipitation of minerals into pores and onto the surfaces of framework grains results in cementation, which is the principal chemical process that causes unconsolidated sand to turn into stone.

The main constituents of the Zuni Sandstone at El Morro are sand grains, most of which are quartz, with a lesser component of feldspars. The grains are remarkably uniform in size and shape, and this provided high original porosity. Rearranging and deformation of grains appears to have been minimal and the intergranular space is largely preserved. However, most of this space is now occupied by either cement or fine-grained matrix, or has been incorporated into dissolution features.

Carbonate cements are usually the most common cements in sandstones, but carbonate was not found in the upper part of the Zuni Sandstone and occurs below only in a patchy distribution, either as isolated microscopic globs surrounding clusters of framework grains or as dense, meter-long concentrations located along bounding surfaces. Quartz cements are also common in sandstone, but none were found in the Zuni. Iron oxide cements occur exclusively in the upper layers of the Zuni, either disseminated in bands and nodules, as pore-filling cement along bounding surfaces, or as surface encrustations known as case hardening. Case hardening involves the formation of hard, limonitic crusts along well-established surfaces, and at El Morro it is closely associated with rock joints which apparently provided avenues for iron-rich waters. Chloritic cements occur in restricted stratigraphic horizons below the iron oxide. Throughout much of the Zuni, clay minerals are the only form of cement present, hence the general friability of the rock. These clay cements occur as coatings on framework grains which are aggregated by the surface

cohesion of the clay. The coatings are found beneath carbonate cement and iron oxide cement, indicating that coatings began forming early in the diagenetic history of the rock. The fine-grained particles in the matrix are mostly kaolinite clay, which is a product of the degradation of feldspars. Also present in the fine-grained fraction, in much smaller quantities, are chlorite, illite, vermiculite, and mixed-layer illite-smectite. Dissolution features observed in the Zuni Sandstone include oversized pores resulting from grain and cement dissolution, and "ghost grains", which are coatings that precipitated on a grain and were left behind when the grain dissolved.

Weathering is the process by which rocks are destroyed at or near the surface of the earth. Rock destruction is accomplished by chemical weathering, mechanical weathering, and the activities of organisms. Chemical weathering processes involve equilibrium reactions between rocks and the atmosphere and hydrosphere. Water and oxygen are abundant in the weathering environment and they drive several important reactions, including the oxidization of iron, the degradation of silicate minerals (such as feldspars) into hydrated minerals (such as clays), and the dissolution of cements. Mechanical weathering processes involve shrinking and swelling associated with freeze/thaw or wet/dry cycles. Also, when water percolates through permeable sandstone, it can become enriched in soluble salts that may concentrate and crystallize during dry periods. Then, after wet weather, rehydration of the salt causes volume expansion. Minerals that are brought to the rock surface accumulate and form a cap which is harder and less permeable than the underlying sandstone. Salts are repeatedly deposited behind this surface and can eventually cause spalling of the cap. Chemical weathering is generally much more important than mechanical weathering. Microflora (lichen, mosses and algae) can cause both physical and chemical damage to rock surfaces. Microflora roots penetrate into the rock surface and produce oxalic acid that can break down silicates in order to extract the mineral components. Microflora can also cause retention of moisture on the outcrop. Throughout all of these weathering processes water is the major player, either introduced into the rock as surface wetting, horizontal and vertical percolation, or rising damp.

A variety of weathering processes have been active at El Morro and they threaten the primary resource — the inscriptions. Material is removed from the outcrop in three principal ways: granular disintegration, wholesale wasting, and spalling (flaking of surface material). Granular disintegration occurs when material is separated as individual grains or small clumps of grains. Granular disintegration results from the loss of cementing agents within the sandstone. Wholesale wasting occurs when coherent blocks or chunks become detached from the outcrop.

greatly around the outcrop and therefore it would be expected that the effects of moisture and temperature fluctuation would also vary greatly. Characterizing the distribution and movement of moisture throughout the outcrop is crucial in developing a more complete understanding of weathering at El Morro.

Acknowledgements

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Particular thanks are due to all those people in the Park Service — Michele Pelletier, who got the project started; Ken Mabry and John Lujan, who kept it rolling; and especially Jake Barrow, who rode herd over the whole thing. And to Rangers Dorgan and Salas, SPMA Sandy and Rena Bob, and the many others who contributed to an enjoyable workplace.

All illustrations and photographs are by the author, who also needs to thank Becky Titus who taught me to draft on a computer.

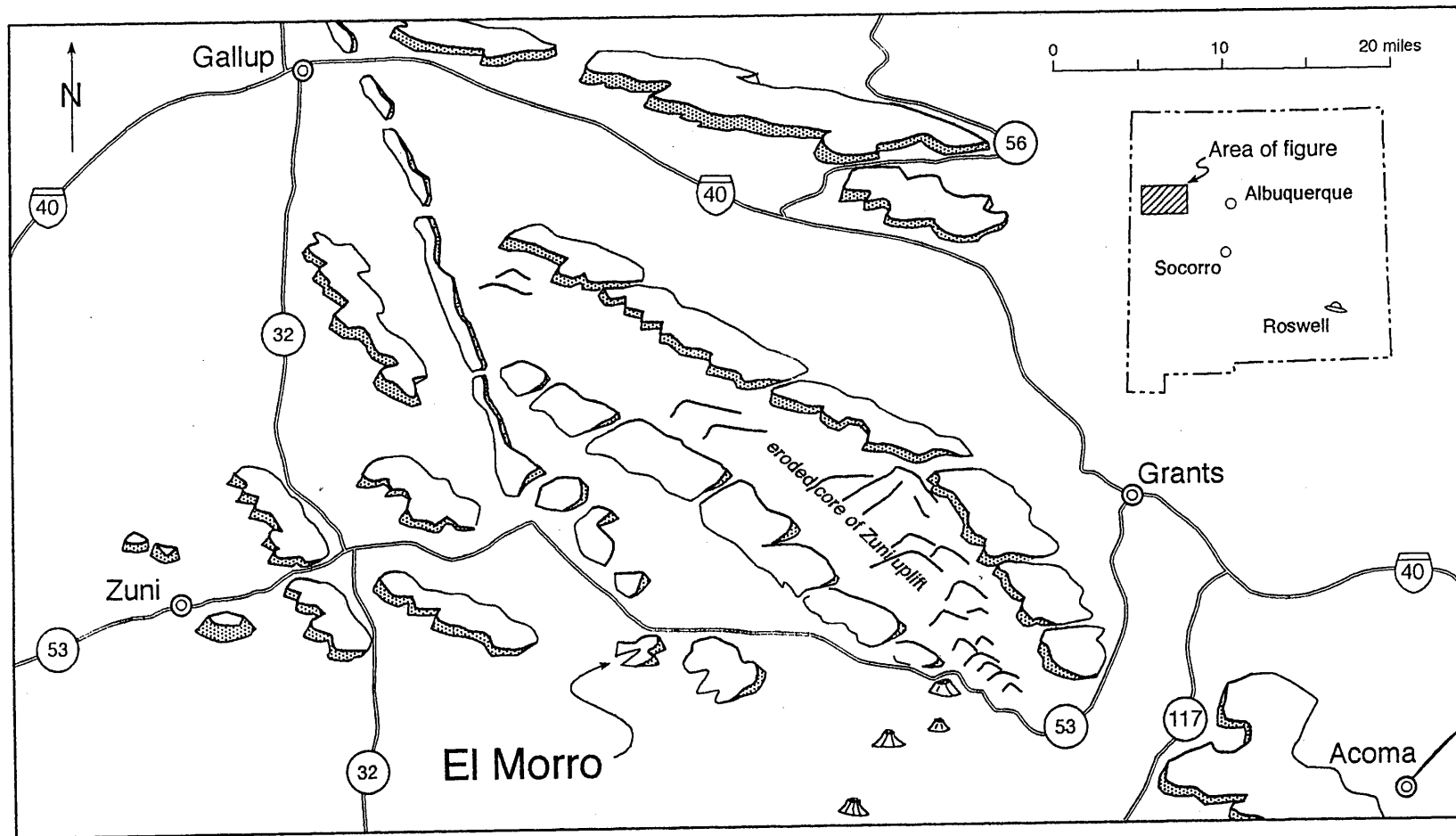


Figure 1. El Morro and vicinity

suggests that there may be east-west trending faults or folds in the valley to the north of El Morro that are now buried by Pleistocene basalt flows. Some faults further to the north are documented; all appear to be steeply dipping reverse faults, with the south side up 100 ft or more (Anderson and Maxwell, 1991). Polished grooves ("slickensides") in the Dakota Sandstone record microthrusting with a maximum compression in a N22°-47°E direction (Anderson and Maxwell, 1991). The outcrop at El Morro shows well-developed joint sets. Joints are planar rock fractures in which there has been no movement along the plane of the fracture (this lack of slippage distinguishes joints from faults). At El morro there are two sets of parallel joints, with the dominant set striking N65°E and another set striking N10°W. This jointing presumably results from stress imparted during burial and/or uplift.

Pertinent Geological Studies

Geological coverage of El Morro and the vicinity is fairly good. Early water reports which included geological information were supplied to the National Park Service by Rothrock and Hawkins, (1939), Maxwell (1940), West (1960), and West and Baldwin (1965). The geology of the Inscription Rock quadrangle was mapped by Smith *et al.* at 1:48,000 (1958) and more recently by Anderson and Maxwell at 1:24,000 (1991). The general geology of the Zuni Mountains is described by numerous papers in the New Mexico Geological Society Guidebooks for 1959 and 1989. These guidebooks, as well as Foster (1958), include road logs of the outlying areas. The most detailed report to date on the outcrop is supplied by Austin (1992). His report includes data on bulk mineralogy, particle size analysis, mineralogy of the clay-size fraction, and leaching analysis.

Other related works include descriptions of the Zuni Sandstone by Dutton (1885), Smith, (1959), and Anderson (1983, 1993). Discussions of the Jurassic system in the southwest are included in Harshbarger *et al.* (1957), Kocurek and Dott (1983), and Lucas *et al.* (1985).

availability, with most of the readily dissolved material having been already removed from the bare, exposed rock. Low conductivity values reflect low TDS values.

All samples showed low calcium and magnesium values, and hence low hardness values. Magnesium is usually supplied by the breakdown of rock materials, and the low values indicate that grains of magnesium-rich minerals are not a significant component of the rocks at El Morro. The spike in calcium readings from the cascade samples (and, for that matter, the magnesium readings also) are possibly the result of surface water moving through areas of soil. Although the top of El Morro is mostly barren rock, there are isolated areas of soil that are localized in shallow depressions and perched platforms along the top of the cliff face.

Testing for bicarbonate showed little variation among the nine samples. Chloride readings were typically low. Sulfate readings were also low but showed variability, especially among samples from the tinajas. One hypothesis to explain this variability might be the presence of sulfates such as gypsum which may have been preferentially concentrated by sedimentary processes into different stratigraphic layers.

All nine samples tested very low for potassium and sodium². These are highly mobile elements and presumably have been flushed from the system without replenishment. Phosphate tested below detectable limits. Fluorides tested very low, in all but one case being less than 0.20 ppm. This indicates that these two elements are not a significant component of this rock. Nitrate tested very low, except in the case of the samples from the two cascades. Nitrates are produced by animal urea. Bird droppings, as well as other animal waste, are a possible source of nitrate for these two samples.

Among the nine samples, the highest readings for magnesium, calcium, sodium, potassium, sulfate, and chloride came from the standing tinaja in the bleached zone of the Zuni Sandstone. High readings also came from the other standing tinaja, which is in the iron-stained part of the upper Zuni. Of the four samples taken from fresh tinajas, the one from the bleach zone did not show relative-elevated readings of these metals and salts. This would suggest that when it comes to TDS in the water at El Morro, time is more important than lithology.

² Except for the rainwater sample, which was contaminated for sodium.

STONE

Data Collection Scheme

The bluff at El Morro is a remnant form of a cuesta, one of a chain of such landforms. The steep cliffs of these cuestas face the broad valley that is carved into the Triassic section along the southwestern flank of the elongate Zuni Uplift (Figure 1). This retreating escarpment trends roughly NW-SE with the dip slopes grading into the Cretaceous valley floors to the southwest. Consequently, the northeast point at El Morro is the lowest available stratigraphic horizon of the outcrop. Moving away from this point, along the base of either the northern wall or the eastern wall, one travels progressively upsection. Samples were taken from the northeast point upward, but some areas of the outcrop are along the inscription trail and the sensitive nature of the resource restricted sampling here. Samples were taken for grain size analysis, permeability testing, and for cutting into thin slides for petrographic microscopic analysis. Locations of individual sample sites are described in Appendix B.

For purposes of developing a stratigraphic column, the outcrop has been divided into four primary types of strata: large-scale crossbedded units, small-scale crossbedded units, flat-bedded units, and undulatory-bedded units. Large-scale crossbedded units contain sets that are greater than 1 m thick, while small-scale crossbedded units contain sets that are less than 1 m thick. Flat-bedded units contain thin beds and laminations. Undulatory-bedded units contain thin laminations that are wavy parallel or discontinuous wavy parallel (Campbell, 1967). Contacts between these sedimentary packages are defined as either distinct, gradational, or incised. Thin (generally < 5 cm), laterally-pervasive silty/clayey seams often form bounding surfaces between sedimentary packages. Bounding surfaces are defined as either distinct or indistinct/inferred.

Sedimentology

Particle Size Analysis

Particle sizes are traditionally classified according to the Udden-Wentworth scale, which is a "grade scale" in that descriptive terms are used to refer to sizes intermediate between two defined

fraction was then washed through a series of 8 inch ASTM sieves. These were the 200 (.074 mm), 140 (.105 mm), 100 (.149 mm), 70 (.210 mm), 50 (.297 mm), and 40 mesh sizes (.420 mm). Results are accurate to $\pm 2\%$.

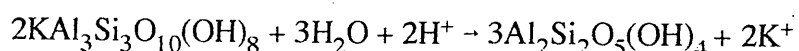
Clay content of the Zuni Sandstone ranged from 4 % to 11 % by weight, with the majority of the samples falling between 9 % and 11 %. Silt content ranged from 5 % to 18 % and was well distributed across the range. The sand fraction comprised 73 % to 86%. The only coarse material (> 0.5 mm) of any consequence from the entire suite of samples was found in the overlying Dakota Sandstone. Most of the sand grains are between 0.063 mm and 0.149 mm in diameter and are classified as fine to very fine sand. There is a slight coarsening upsection trend in the Zuni Sandstone. Percentages for individual samples are found in Appendix C.

Petrographic Microscope Slide Analysis

Thirty-eight rock samples were taken from the outcrop for cutting into petrographic microscope slides. These slides were vacuum impregnated with blue epoxy (to show porosity) and stained with a dye that detects potassium (to help identify feldspars). Slides were analyzed to characterize the nature of the framework grains, cement, matrix, and porosity. Individual descriptions of slides are included in Appendix D.

The Zuni Sandstone, like all other sandstones, is composed of framework grains, the space between the grains, and any material that may occupy that space, such as matrix or cement. Matrix is clay-sized interstitial material and can be either primary matrix (deposited with the framework grains), or secondary matrix (matrix formed after deposition). Cements are solids formed by chemical precipitation in pre-existing pore space from ions in aqueous solution in the pore fluid. Whereas matrix is comprised of a mixture of discrete fine particles, cement is a distinct crystalline mineral.

The main detrital constituents of the Zuni Sandstone at El Morro are framework grains of monocrystalline quartz (SiO_2) with a lesser component of potassic feldspars (KAlSi_3O_8) and a minor component of mudstone fragments. These framework grains are mostly between 0.05 mm and 0.15 mm in diameter. The grains are generally sub-rounded to rounded according to the Powers (1953) method, and were estimated to be well sorted to very well sorted by using a comparator such as provided by Anstey and Chase (1974) or Folk (1974). Grain-to-grain contacts are straight or tangential, with no observed concavo-convex or sutured contacts. Most of the rocks



Water carries away the soluble products and the reactions are forced to the right according to Le Chatelier's principle. Also present in the clay-sized fraction, in much smaller quantities, are chlorite, illite, vermiculite, and mixed-layer illite-smectite. For more information concerning the nature of clay in sandstone at El Morro, see Austin, 1992.

Permeability

Permeability measurements were obtained by using a computer controlled scanning minipermeameter (SMP). Like other permeameters, the SMP is built around a constant pressure air supply, a means to measure the air flow from the supply, and a soft silicon rubber tip which is pressed against the rock sample to achieve the seal. In SMP, both the air supply and the means for flow measurements are achieved by the use of a simple glass syringe. The gravitational force on a weight resting on a plunger produces a constant air pressure inside the syringe. An air pump is used to fill the syringe prior to each measurement. The total time interval required to inject the fixed volume of air from the syringe into the sample depends on the permeability of the portion of rock sample underneath the probe tip. Information of the position of the syringe plunger is obtained optically by means of commercial "edge detectors" that consists of a small light source (L.E.D.) and photodetectors. For details see Suboor and Heller (1995).

The permeability is calculated by a modified version of Darcy's Law:

$$K = \frac{\mu A \Delta x}{a G \Gamma P_g} \left[\frac{1}{T} - \frac{1}{t_{lk}} \right]$$

K = air permeability (Darcy)

μ = viscosity of air (Centipoise)

A = syringe area (centimeter squared)

Δx = distance traveled by the plunger (centimeters)

a = inner radius of the tip (centimeters)

G = geometrical factor

Γ = pressure correction factor

P_g = gauge pressure inside syringe (fractions of a standard atmosphere)

T = time interval for syringe plunger to sink (seconds)

t_{lk} = time interval in which syringe plunger will move downwards

by the distance Δx in the absence of flow into the rock (seconds)

There are four basic types of internal stratification present in the Zuni Sandstone at El Morro: (A) large-scale crossbedding with sets greater than 1 m thick (Photo 13), (B) small-scale crossbedding with sets less than 1 m thick, (C) undulatory bedding of low amplitude ripples (Photo 14), and (D) laminated flat bedding (Photos 15 and 16). Sedimentary packages are encompassed by laterally extensive bounding surfaces which generally form distinct contacts that truncate underlying cross sets, though local outcrop conditions can obscure these boundaries. Several of the bounding surfaces are formed by discrete seams that range from 2 cm to 10 cm in thickness. Bounding surfaces exhibit a planar parallel geometry, dip gently ($\approx 3^\circ$) to the southwest and are somewhat regularly spaced vertically (usually 2.5 m to 4 m, although less in several cases). Some bounding surfaces are associated with large (1-3 m), spheroidal, maroon-brown concretions and in some circumstances bounding surfaces delimit weathering features. No recognizable bedding plane markings were found on bounding surfaces. No soil zones were found, nor were any biological structures such as tracks or burrows.

Figure 3 is a topographic map of the El Morro which shows the location of cliff maps. Cliff maps (Figures 4-9) show physiographic features of the outcrop, upon which are superimposed bounding surfaces, stratification units, and sample sites, as well as diagenetic and weathering features (see sections on Diagenesis and Weathering).

Figure 10 shows a composite stratigraphic column from the northeast point (lowest stratigraphic exposure) to the top of the mesa (highest stratigraphic exposure). The lower strata are characterized by thick (≈ 4 m) layers of large-scale, southwesterly dipping crossbeds. Upsection, the large crossbeds are supplanted by thinner, somewhat regularly spaced units of undulatory bedded sandstone. Within the transition between the two are found layers of small-scale crossbedded sandstone. Many of these smaller crossbedded units contain laminae of preferential cementation (PC). These laminae are more resistant to weathering and stand out slightly from the cliff face. Further upsection is a very large package of crossbedded sandstone in which the curved bedding surfaces are frequently preferentially cemented. On top of this unit sits a relatively thin package of flat bedding that is well cemented with iron oxide. Above the flat bedding occurs more large-scale crossbeds which become progressively iron rich through a zone of iron-stained Liesegang banding (LBZ) and iron concretions (ICZ). Above this is a bleached zone (BZ) which has been scoured and upon which the Dakota Sandstone rests.

Stratigraphy

- Bounding surface, distinct
- Bounding surface, indistinct/inferred



Crossbeds, large scale



Crossbeds, small scale

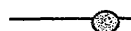


Sample sites

Diagenetic Effects



Case hardening



Concretions

BZ

Bleached zone

ICZ

Iron concretion zone

LBZ

Liesegang banding zone

PC

Preferential cementation

Weathering Features



Alveolar weathering



Spalling



Coves



Cascades

Human Features



Moqui steps



NPS steps

Trees



Pine (living)



Pine (deceased)



Oak thicket

Vertical exaggeration is 2:1

Letters across top of sections correspond to bend points
on Figure 3

Numbers next to stratigraphic columns correspond to
bounding surfaces

Stratigraphic columns are composited in Figure 10

Figure 4. Legend for Figures 5–9.

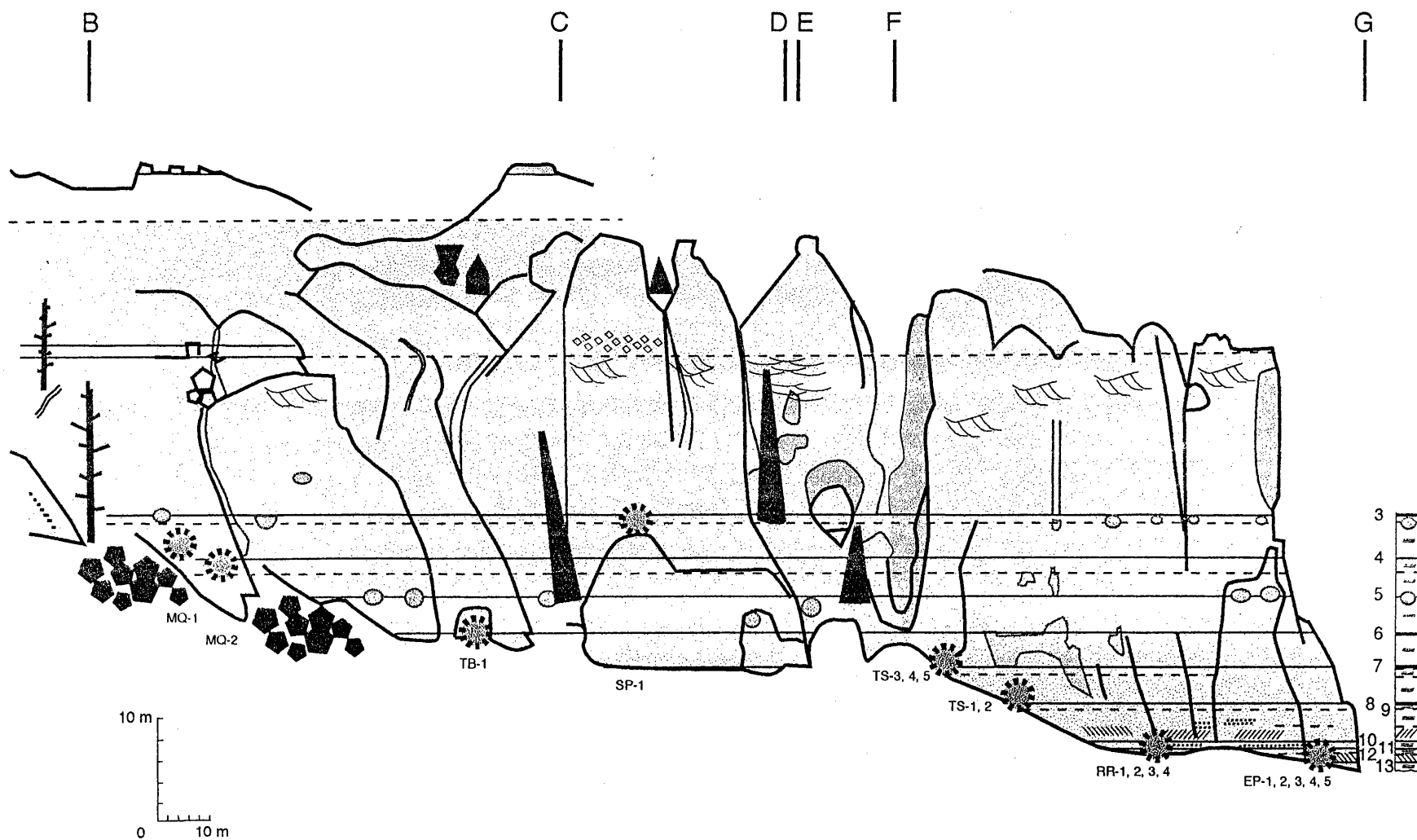


Figure 6. Nine Pine Cove area. See Figure 3 for location. See Figure 4 for description of symbols.

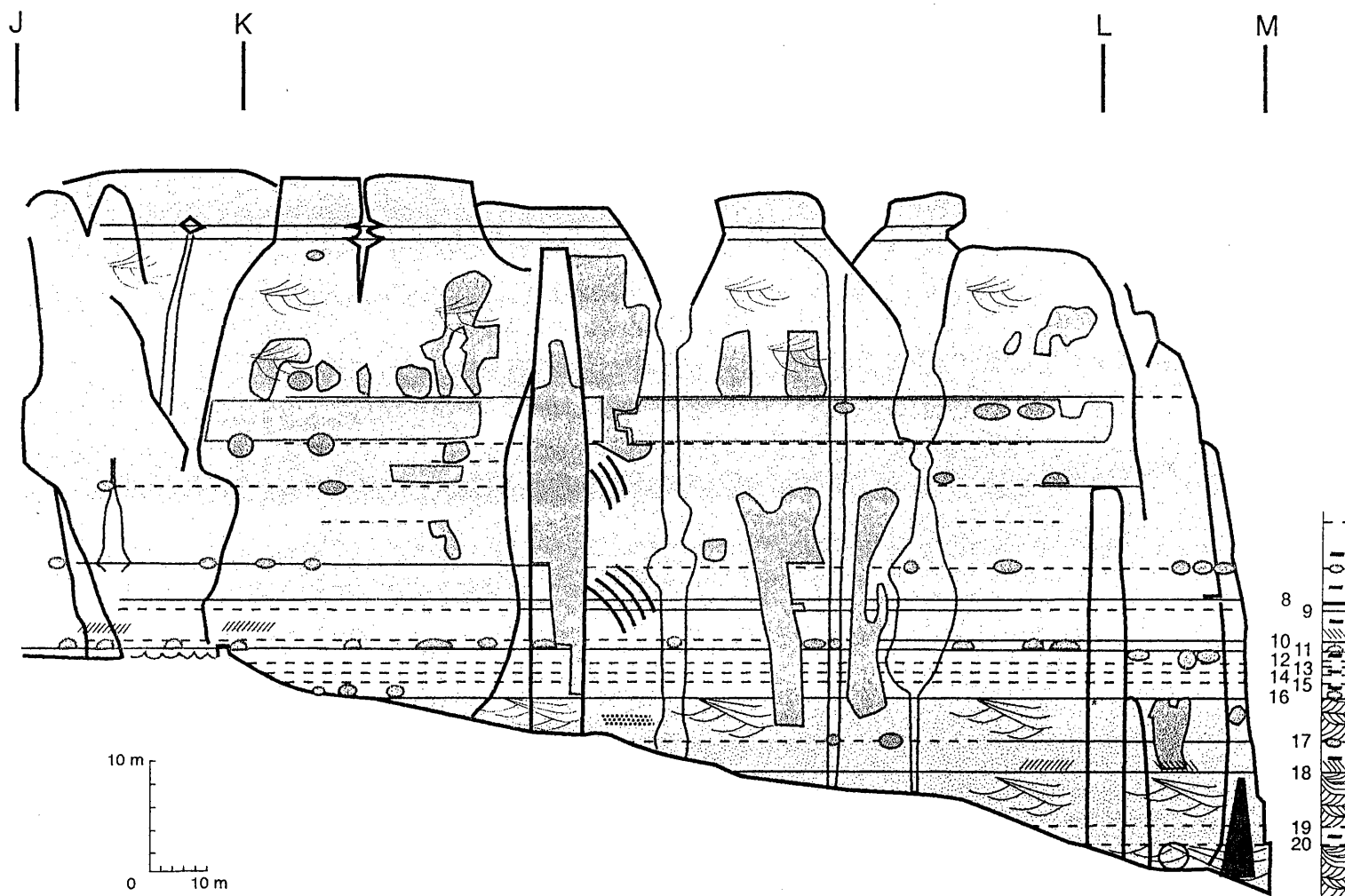


Figure 8. Inscription trail area. See Figure 3 for location. See Figure 4 for description of symbols.

