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Preliminary Geologic Survey of the Lost Dog Overlook Vicinity, McDowell Sonoran Preserve, Scottsdale, Arizona

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Editors Note (6.1.2010)

The contributed report, *Preliminary Geologic Survey of the Lostdog Overlook Vicinity, McDowell Sonoran Preserve, Scottsdale, Arizona*, is the product of a team of non-geologists –volunteers of the McDowell Sonoran Preserve -- working under the tutelage of a professional geoscientist. As such, it exemplifies "Citizen Science" contribution to the geology of Arizona.

The structure of this report differs somewhat from other contributed reports; the authors meticulously documented the evolution of their methods as they became increasingly familiar with how lithologic analyses drives geologic mapping. The result is a paper that improves our understanding of the lithologies and structures in the Lostdog Overlook area of the McDowell Sonoran Preserve.

PRELIMINARY GEOLOGIC SURVEY of the LOST DOG OVERLOOK VICINITY

McDowell Sonoran Preserve, Scottsdale, Arizona

Daniel G. Gruber, Larry S. Levy, Joni T. Millavec, William H. Ruppert
(McDowell Sonoran Conservancy: Project Leaders), and
Brian F. Gootee
(Arizona Geological Survey: Supervising Project Geologist)

Supervising Geologist Brian Gootee conducting a field review.

Please note that many of the features described in this article are not accessible on any trail in the McDowell Sonoran Preserve. Off-trail travel in the Preserve and the removal or alteration of any material from the Preserve is strictly prohibited except with the express permission of the City of Scottsdale Preservation staff. The research project, all associated work, and all sample examination and removal described in this paper were done under a permit issued by the Preservation staff and with its approval and supervision. All geological project work was done by or under the scientific supervision of research geologist Brian F. Gootee of the Arizona Geological Survey.

Summary

The southwestern portion of the McDowell Mountains, located in the McDowell Sonoran Preserve in Scottsdale, Arizona, was last mapped geologically more than 30 years ago. The curiosity of volunteers with the McDowell Sonoran Conservancy—a non-profit organization created to advocate for, educate about, and provide stewardship to the Preserve—about rocks from a prehistoric tool quarry in that area led to a project to conduct a preliminary geologic survey of the vicinity near the quarry.

This project was conducted largely by volunteers who spent hundreds of hours working in the field with permission and managerial oversight from the City of Scottsdale Preservation staff and under the scientific supervision of Brian F. Gootee, research geologist with the Arizona Geological Survey. The volunteers did most of the field data collection, recording, and preliminary analysis, much of the mapping, and some initial geologic interpretation. Gootee did the thin-section analysis and photomicrographs, most of the geologic interpretation, and conducted numerous field visits and reviews of the volunteers' work.

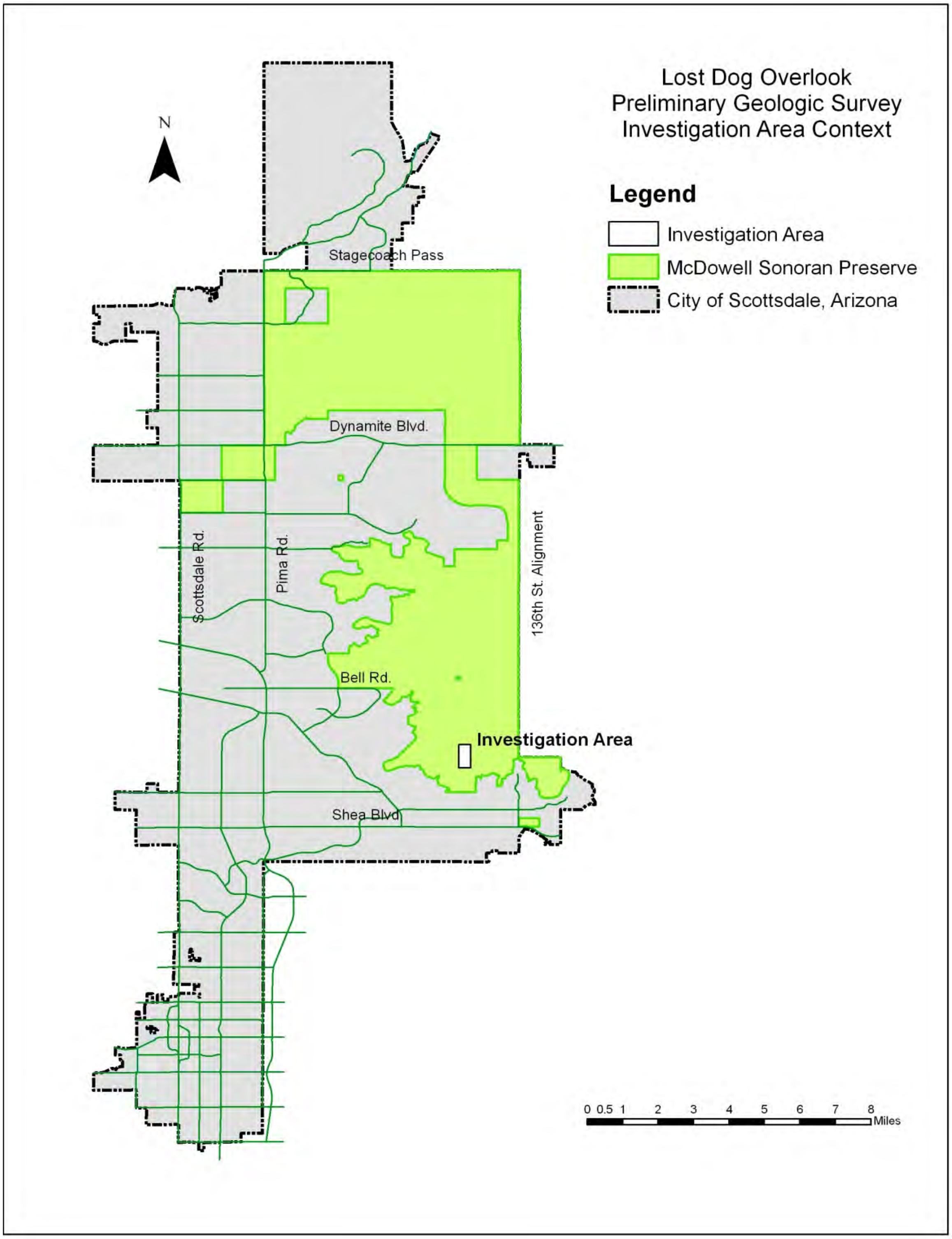
Because of the unusually extensive volunteer involvement in the project, this paper describes the project approach, process, and intermediate findings of the field work and analysis in addition to the final project results. Each phase of the project is described based on the then-available information, analysis, and interim hypotheses. As more information was collected and more analysis was performed, the conclusions and therefore the nomenclature changed. This narrative approach accurately reflects the nature of field work and the scientific process.

The investigation area was approximately rectangular around the tool quarry, located near a prominent ridge called Lost Dog Overlook in the southwestern foothills of the McDowell Mountains. The mountains and surrounding areas, including the investigation area, are part of the McDowell Sonoran Preserve. The investigation focused on the tool quarry area in order to determine why the rocks in that particular area were useful for tool-making.

The rocks in the vicinity of the tool quarry reflect an extensive series of geologic events in several major episodes over the last 1,700 million years. A series of eruptions approximately 1,700 million years ago produced rhyolite flows. Subsequent burial, deformation, metamorphism, mineralization, uplift, and exposure produced an array of mineralized colors, fractures, joints, shear zones, and erosional patterns now visible at the surface. In addition, the survey noted newly-discovered outcrops of granite and limestone within the investigation area.

Background

The McDowell Sonoran Preserve (the Preserve) is a natural open-space area currently encompassing approximately 16,000 acres including and surrounding the McDowell Mountains in north-central Scottsdale, Arizona. When completed within the next decade, the Preserve is planned to encompass 36,000 acres. Map 1 shows the general location and planned extent of the Preserve. Most of the southern area and portions of the northern area already are owned by Scottsdale and comprise the current Preserve.



Map 1. Planned extent of McDowell Sonoran Preserve in Scottsdale, Arizona.
(Note: All maps, photographs, charts and illustrations are by the authors except as otherwise noted. Maps were produced with the assistance of City of Scottsdale staff and utilize City of Scottsdale data layers with permission.)

The Preserve is owned by the City of Scottsdale and managed by the Scottsdale Preservation staff. The McDowell Sonoran Conservancy (MSC or the Conservancy) is a private, non-profit organization which has a formal agreement with the City of Scottsdale to provide a variety of services in and for the Preserve.

There are many known archeological sites within the Preserve. One is a prehistoric quarry site called the Taliesin Quartzite Quarry, designated AZ U:5:78 (ASM)[1], located in the vicinity of a ridge known today as Lost Dog Overlook (LDO).

"This outcrop *[i.e. Lost Dog Overlook]*, which was quarried by the aboriginal population, was identified as Taliesin Quartzite and micaceous *[containing mica, a group of sheet silicate minerals]* quartzite (Schroeder 1992a). This material type was originally described as follows:

> "'Light green to gray to black, very fine-grained to medium grained, platy to blocky, foliated metamorphosed rhyolite and dacite flows and tufts *[sic]* and argillaceous *[rich in clay-like components]* sandstone…. very locally hydrothermally altered to fissile *[platey fractured]* talc schist along fault zones.' (Welsch and Péwé 1979)

"Taliesin quartzite and micaceous quartzite, as described above, are present in the outcropping…." (Schroeder 1997)[2]

Quarries are interesting because they indicate ready availability of rock useful for some specific purpose, in this case tool-making. Rock samples from this quarry (see Figure 1) were displayed at a class taught by the McDowell Sonoran Conservancy. Those samples were described as quartzite as referenced in Schroeder 1997. However, casual observation by one of the authors indicated that the rocks didn't look like quartzite, which is a metamorphic rock derived from sandstone. The samples were photographed and the pictures sent to Brian F. Gootee, a research geologist with the Arizona Geological Survey. Gootee was a co-discoverer of a major landslide (Douglass, Dorn and Gootee 2004) in the northeastern McDowell Mountains and known within the Conservancy through a field trip he had conducted in that area.

Figure 1a and 1b. Rocks from archaic quarry site. Rocks are approximately 6 inches wide.

[1] Additional information about this archeological site can be obtained from the Arizona State Museum at the University of Arizona, Tucson, Arizona.
[2] Note that terms defined in the text (such as "micaceous", "argillaceous", and "fissile" above and others elsewhere in the text) also can be found in the Appendix: Glossary.

After viewing the rocks in person, he agreed that they probably weren't quartzite and suggested that they might be greenstone—metamorphic basalt, a form of lava chemically and physically changed by heat and pressure. This possibility indicated that the previous identifications might need updating. Furthermore, although an earlier geologic survey in the McDowell Mountains referred to occasional greenstone intrusions (Christenson, Welsch, and Péwé 1978), these intrusions weren't marked on the survey maps. This led to a desire to investigate the area further.

Overall Approach

After receiving permission for off-trail hiking from the City of Scottsdale Preservation staff, a site survey was performed in February, 2008. The central portion of what later was designated the investigation area is shown in Figure 2.

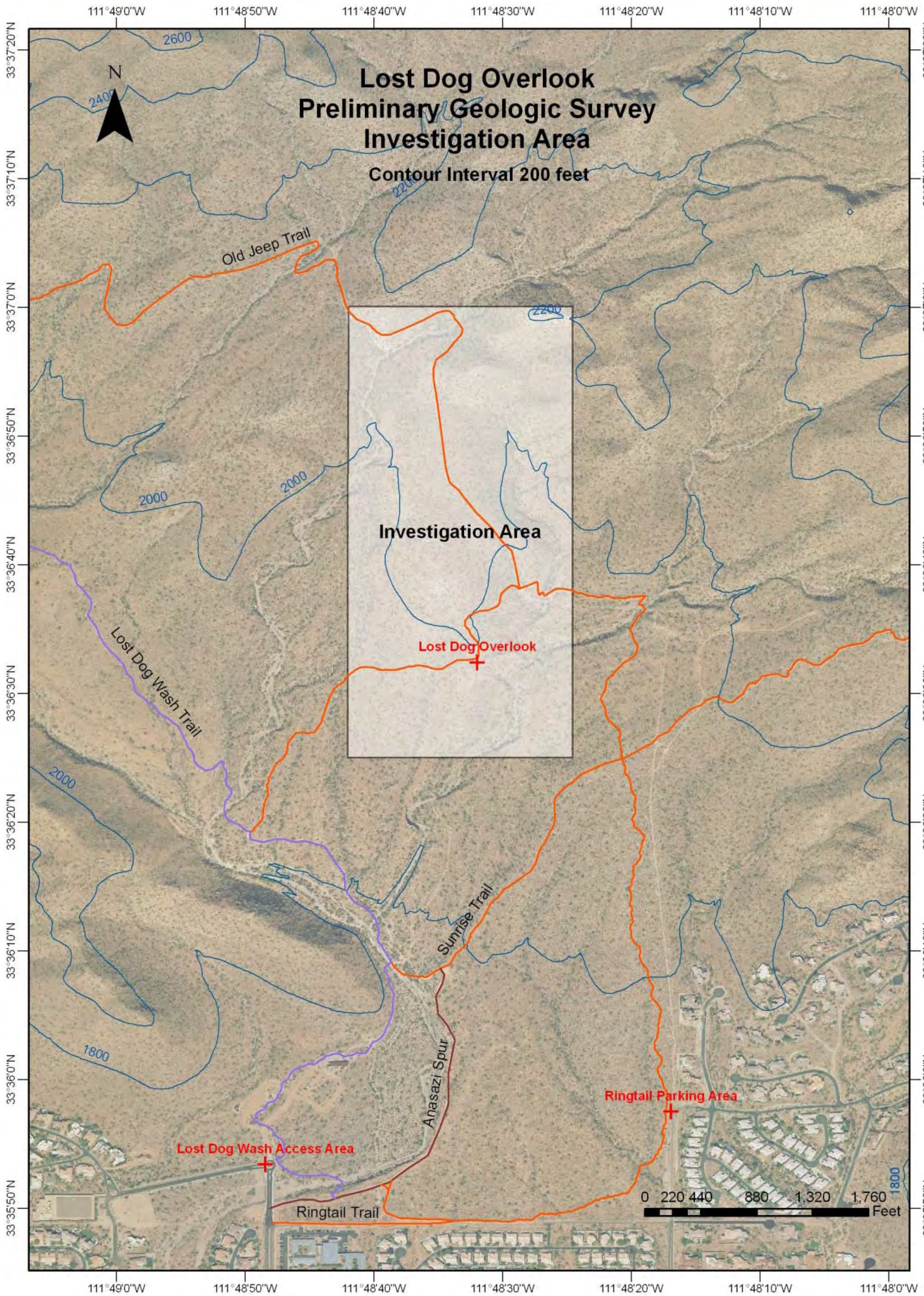
Figure 2. East side of Lost Dog Overlook looking southwest, showing the central portion of the investigation area.

The purpose of this initial site visit was to observe, enumerate, and describe the various rock types visible in the area near the archeological site. This initial work indicated that the area was quite complex, with multiple rock types in a variety of configurations. It appeared interesting and worthwhile to develop a preliminary geologic survey of an investigation area around the site, using professional methodology and techniques. Gootee offered to provide ongoing supervision, reviews, and occasional field participation if a volunteer project went forward.

Having seen the area, the volunteer project leaders were enthusiastic about doing such a survey. Because this would be an extended research project in the Preserve, it had to be done appropriately. A specific goal was established: developing and publishing a preliminary geologic survey map of a defined area around LDO. The field work would be done by volunteers under scientific supervision and with regular scientific reviews. Experienced MSC stewards would be the project leaders. The work would have an educational aspect for all participants. There would be a series of individual field projects to make observations, each approved and scheduled by Scottsdale Preserve Manager Claire Miller. Appropriate signs would be posted on nearby trails to alert Preserve users to the projects and to indicate that they were authorized. Finally, there would be periodic verbal and written briefings to City of Scottsdale Preservation staff about the work and progress. With these ground rules set, Scottsdale Preservation Director Robert Cafarella (since retired) issued a permit for the research project in March, 2008.

The primary effort was an extensive survey on the ground by volunteers. The investigation area was a rectangle as shown on Map 2. The area centered on the prehistoric tool site (not shown on the map) and was bounded by natural features and/or by surface deposits that covered up any bedrock (consolidated native rock). The majority of the investigation area proved to be covered with alluvial deposits (sediment transported and deposited by water) and/or colluvial deposits (sediment transported and deposited by gravity). The location of the south end of north-south trending LDO ridge is shown in the lower center of the investigation area.

The project was conducted in three stages—each involving field work, data entry and analysis, geologic literature research, a scientific review, and a summary for the Scottsdale Preservation staff and volunteer participants—followed by the process of interpreting and summarizing the results. There were a total of eight site visits by the supervising geologist plus numerous meetings and other consultations with him during the project.



Map 2. Investigation area.

Phase 1 – Initial Field Data Collection: March through May, 2008

Stewards (Conservancy volunteers) conducted the primary on-site field survey work by identifying and recording visually distinct rock types in bedrock exposures. Based on the earlier field work and first site visit, three different rock types (one of them with two variations) had been identified:

Rock type 1. This, the most widespread rock type, was called greenstone in gray/black and greenish varieties. These are the rocks in Figure 1a and 1b respectively. (Note that at this stage of the work all rock-type identifications and names were provisional and used strictly for convenience. As described in more detail below, the so-called greenstone later was identified as metarhyolite. The latter term will be used beginning with the description of Phase 2.)

Rock type 2. This rock is similar to greenstone but with distinctly pink or red crystalline regions intermixed in the matrix. This rock type is associated with vertically-oriented outcroppings having a distinctive, highly-foliated (layered along fractures) structure. (See Figures 3 and 4.)

Figure 3. Highly-foliated outcroppings of the second rock variety with pink or red crystalline regions, looking west-southwest from the east-central part of the investigation area. The tallest outcroppings are approximately 3 feet high.

Figure 4. Fracture surface of rock with reddish crystalline regions.

Rock type 3. This is light-colored on the surface and includes large dark areas distorted into oval or lozenge shapes called augens or blebs. (See Figure 5.)

Figure 5. Rock with augens. This rock is about 2.5 feet wide.

In the course of the field work during this phase, two additional types of rock were identified in the investigation area:

Rock type 4. This is consistently light-colored throughout and seems to be concentrated in a narrow but extended area generally trending northwest – southeast through the northern portion of the investigation area. (Not shown.)

Rock type 5. This resembles the highly foliated rock with reddish crystalline regions (type three), but without distinctive foliation. It is concentrated primarily in a relatively small area around the northwestern edge of the foliated outcroppings. (Not shown.)

Note that work in subsequent project phases indicated that what were called "rock types" early in the project often were different mineralization varieties of the same basic rock, metarhyolite.

At the beginning of each of the eight scheduled field surveys, samples of the rock types were shown to and discussed with the participants so that they would know what to look for and how to record each type. Rock not obviously identifiable as one of these types was labeled "ambiguous" or "unknown" and noted for subsequent review. The project leaders described how to identify bedrock outcrops, what information was needed, and how to record observations. Then the group divided into teams, each led by a project leader equipped with a 10X magnifying loupe, a GPS unit, a compass, and a geologist's pick.

The teams proceeded into the investigation area and travelled along parallel east-west tracks until encountering bedrock deposits. At each bedrock deposit, the team took an unobtrusive sample, broke it open to obtain a fresh surface, wet the surface, and observed it with the loupe. Once the rock was identified by type, this information plus its location and any other geologically significant features were recorded. The rock fragments then were replaced in the area. After each project, the observations were collected, compiled, and transcribed into Google™ Earth.

By the conclusion of the project, approximately 300 bedrock observations were recorded and reviewed. The field projects identified essentially all of the bedrock outcrops within the investigation area. Because of the extensive surface cover, bedrock exposures generally were limited to slopes and the banks of large washes. Otherwise, there were no bedrock exposures in large portions of the investigation area.

A portion of the observations recorded on Google™ Earth is shown in Figure 6. The color-coding on this image is as follows:

- Rock type 1, the so-called greenstone, is represented by either black pushpins (the gray/black variety) or green pushpins (the greenish variety).
- Rock type 2, highly foliated rock with pinkish or reddish crystalline regions, is shown with yellow pushpins.
- Rock type 3, rock with augens, is represented by downward-pointing white arrows.
- Rock type 4, consistently light-colored rock, is represented by white push-pin or balloon icons.
- Rock type 5, unfoliated rock with reddish crystalline regions, is represented by red pushpins.

Although Figure 6 shows only a portion of the raw data, it helps clarify the relative locations of the various rock types discussed above.

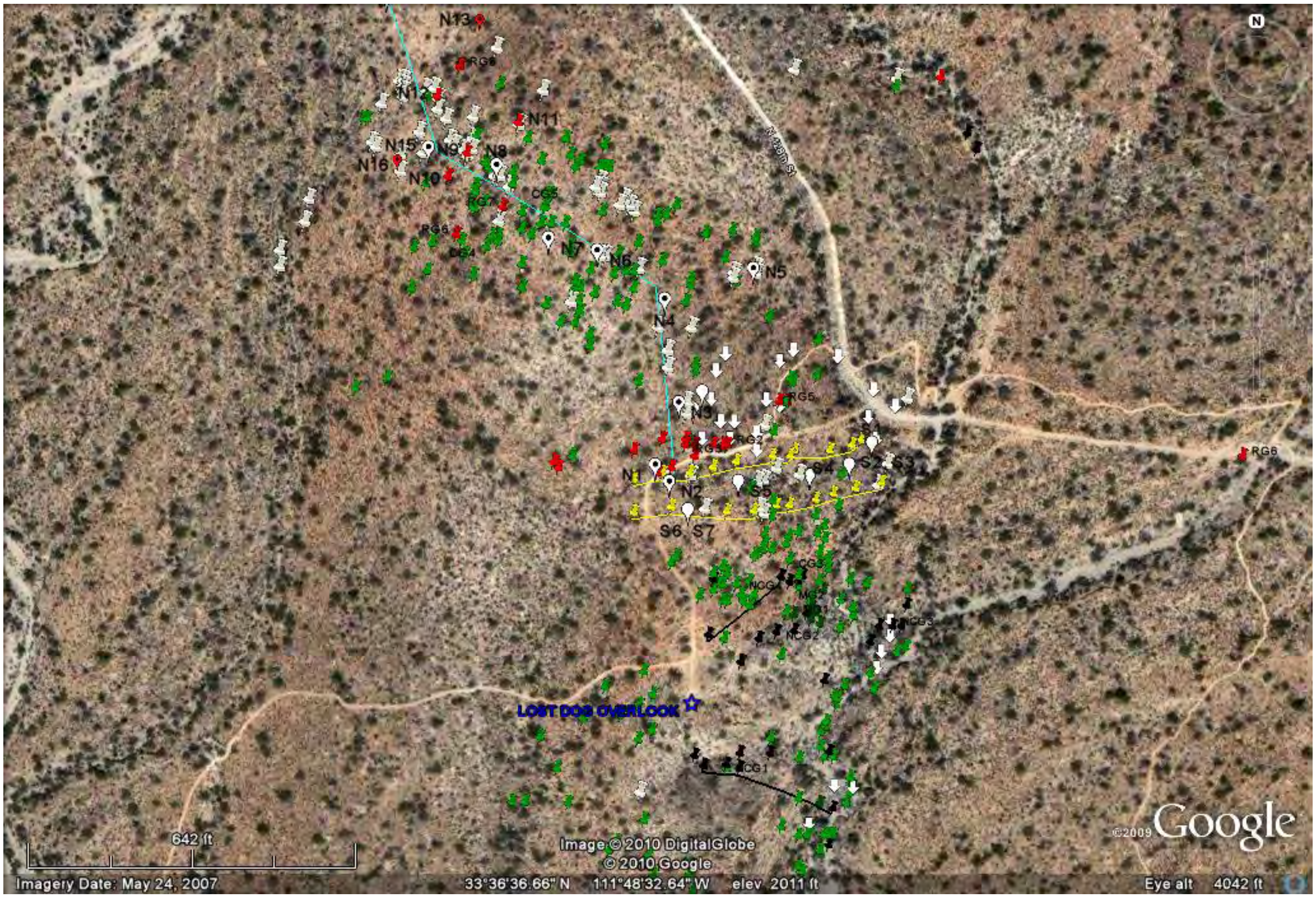


Figure 6. Sample of the observational results recorded during Phase 1 as displayed on Google™ Earth. See text for color-coding. Lines have been added to clarify selected rock-type locations. The south end of the Lost Dog Overlook ridge is at the lower center of the image. Note scale at lower left. North is toward the top of the figure.

Following the completion of this field work and subsequent data entry, the results underwent scientific review during a field visit in May, 2008. After every such field visit or other review, a written summary of the discussion, tentative conclusions and possible next steps was submitted to the Scottsdale Preservation staff and to the participating volunteers. There also were occasional meetings with City staff to discuss project status.

Phase 2—Recording Contacts and Lineaments, Preparing the Geologic Map: June through September, 2008

Phase 2, performed in eight additional field projects, focused on several categories of specific geologic lineaments. The first category included the boundaries between the various rock types. This was done by examining the collected data points, supplemented by additional field work to confirm the boundaries in areas where several rock types were in close proximity. The second category included the orientation (called "strike") of the foliated rock, the tilt angle (called "dip") of that rock, and the dip direction. This information had not been recorded initially.

The main emphasis in Phase 2 was on clarifying the boundaries between the rock types. The distinctive areas described below were identified, going generally south to north in the investigation area. Figure 6 may be helpful in visualizing the geographic relationships described. Note that the rock types listed above usually are localized or at least concentrated in a particular area. As a result, the distinctive areas identified generally correspond to a particular rock type. The primary exception to this was the greenish metarhyolite, which was widespread throughout the investigation area as seen in Figure 6.

Area 1. The gray/black variety of metarhyolite (black push-pins in Figure 6) is localized in the central portion of the eastern slope of the LDO ridge. To the south and north of this region is the greenish variety of metarhyolite (green pushpins in Figure 6), creating three regions within this area. These varieties of metarhyolite together constitute Rock type 1, above. Between these adjacent regions there is some bedrock with the two varieties intermixed, typically with one variety as veins or regions within a larger matrix of the other variety. (See Figure 7.)

Figure 7. Veins of greenish rock within a slab of gray/black material. The surface shown is about 6 inches across.

Generally, the northern and southern limits of the gray/black variety are associated with lines of large and distinctive standing slabs of this material. (Visible in Figure 2 and shown more closely in Figure 8.) These lines of slabs are represented by black lines in Figure 6.

Figure 8. Standing slabs up to 5 feet tall, looking downhill to the northeast from the top of Lost Dog Overlook

Area 2. The highly-foliated outcroppings consisting of rock with reddish crystalline regions (rock type 2, shown by yellow pushpins in Figure 6) are limited to a narrow band running east-west (represented by yellow lines in Figure 6). No other area resembling this was found within the investigation area. Immediately south of the foliated outcroppings is the greenish variety of metarhyolite in Area 1.

Area 3. The same rock with reddish regions but without fine layering (Rock type 5, shown by red pushpins in Figure 6) mostly borders the foliated outcroppings in a small area northwest of them, although additional occurrences of this rock were noted in the northern part of the investigation area.

Area 4. North and northeast of the foliated outcroppings in area 2 is an area of the rock with augens (Rock type 3, shown by white downward-pointing arrows in Figure 6). Isolated examples of this rock were noted elsewhere in the investigation area.

Area 5. There appears to be a line of different rock running generally northwest-southeast through the northern part of the investigation area (indicated by a pale blue line in Figure 6). This line of rock (Rock type 4, shown by white pushpins and balloons in Figure 6) generally is surrounded by the greenish variety of metarhyolite.

Most of the remaining area to the north is covered with alluvial or colluvial deposits and no bedrock is exposed for observation.

Along with the work to clarify boundaries, observations of strike, dip, and dip direction for a sample of bedrock locations also were recorded during this phase. A total of 42 bedrock outcroppings were selected, some along the various tentatively identified boundaries between rock types and the remainder within each of the five areas identified above. For each sample with observed foliation, the location, strike (the compass direction of the foliation or layering in the rock), dip (the angle below horizontal of any tilt in the rock), and the dip direction (the compass direction toward which the rock dipped) were recorded.

Accurately identifying foliation and measuring foliation characteristics in the field is not an easy or familiar process for volunteer investigators. Also, the relatively small number of observations did not provide much learning opportunity. These factors probably produced some erroneous data, so the observations should be considered preliminary and approximate.

Analyzing the collected data produced the following observations:

- Ten observations (nine with observed foliation) from the region of highly-foliated, vertical outcroppings described as Area 2 above and represented by yellow pushpins and lines in Figure 6 had consistent strike, dip, and dip direction. The average strike was approximately 081 degrees (N81E, standard deviation 5.6 degrees) with dip direction south-southeast and average dip angle of 70 degrees (standard deviation 7.7 degrees). Based on the data, this could be a single geologic unit.

- Ten observations (seven with observed foliation) from the line of rock running northwest-southeast through the northern portion of the investigation area, mentioned as Area 5 above and shown by white pushpins and balloons and a pale blue line in Figure 6, showed some general similarities in the recorded data but were not as consistent as those from Area 2. The average strike was about 090 degrees (E, standard deviation 21.3 degrees) with dip direction southerly and average dip angle of 56.5 degrees (standard deviation 21.7 degrees). The data indicate that this linear feature might be a distinct geologic entity.

- As noted above, the gray/black variety of metarhyolite in Area 1 is associated with two distinct lines of standing slabs, each with consistent orientation. The northern slab line has bearing 055 (N55E) and the southern slab line has bearing 115 (S65E). The slabs are two to four inches thick. The area of the east central hillside between the two slab lines is covered with mostly rectilinear fragments of this material several inches thick. No thinner foliation was observed (which could be the result of observer inexperience) and no dip or dip direction was recorded. Visually, each of the slab lines appears to have generally consistent dip and dip direction and each appears to be a single unit.

- In Area 3, there were only two observations with foliation and the data were quite different (possibly the result of observer inexperience).

- Observations made in Area 4 did not indicate any foliation (which again could be the result of observer inexperience) and therefore no strike or dip data were recorded.

While performing the field work in Phase 2, the various rock types were examined multiple times. It appeared possible that what previously had been considered different rock types actually might be different mineral alterations of the same basic rock type, metarhyolite.

It already had been suggested during the February, 2008, field visit that the greenish variety of metarhyolite might reflect chemical alteration of the original gray/black material. The possible mechanism for this alteration was exposure of the original material to a slightly hydrous environment underground. Water could have produced chlorite (aluminum, iron, and/or magnesium silicate), a mineral characterized by green color. The greenish rock was generally smoother and seemed to break more evenly than the gray/black rock. When chlorite mineral grains form they tend to align in a uniform direction, so the altered rock fractures along the alignment of the chlorite mineral grains at a microscopic level. This leads to a smoother fracture surface—and a better tool for prehistoric tool-makers. This variant was called chloritized greenstone (actually metarhyolite).

After examining the highly-foliated rock in Area 2, it was noted that the obvious reddish regions within a greenish matrix could reflect oxidation of iron minerals in chloritized rock. This conjecture meant that at least three types of apparently different rock might be progressive alterations of the same basic material.

Supporting this hypothesis is the existence of a consistent “marker”—small blue quartz crystals—in all three types of rock. Due to the stability of quartz crystals once formed, the assumption was made that this marker is associated with the original deposit and was maintained through subsequent chemical and physical alterations of the basic material. By the end of phase 2, this new hypothesis (one basic material undergoing a variety of alterations) was extended to include all of the observed rock types.

Recording and analysis of all this data was done during July, 2008. In late July there was another field review of the results to date and planning for subsequent work. In the field review, it was suggested that the boundary mapping performed at that point be expanded to include all of the five identified rock-types (and to separate the gray/black and green varieties of Rock type 1) to produce a geologic map showing contacts and relationships between all these regions.

During the July, 2008, field review, several other features also were noted. First, there were several additional areas of rock with augens. One such area included rock with “folded folds” (see Figure 9).

Figure 9. Rock with “folded folds”. The area shown is approximately 5 feet across.

Both the folds and the elongated augens are deformations resulting from shear (a combination of compressive and extensional stresses), similar to foliation. Shear zones are known to be quite narrow (less than 3 feet thick) and extend for miles in the northern part of the McDowell Mountains (Skotnicki 1996).

It also seemed possible that the east-west region of highly-foliated outcroppings showing consistent strike, dip, and dip direction (Area 2, shown in yellow on Figure 6) might be a fault (a fracture or break in originally continuous rock such that the rock on one side of the fracture has moved relative to the rock on the other side). Such features can extend over long distances.

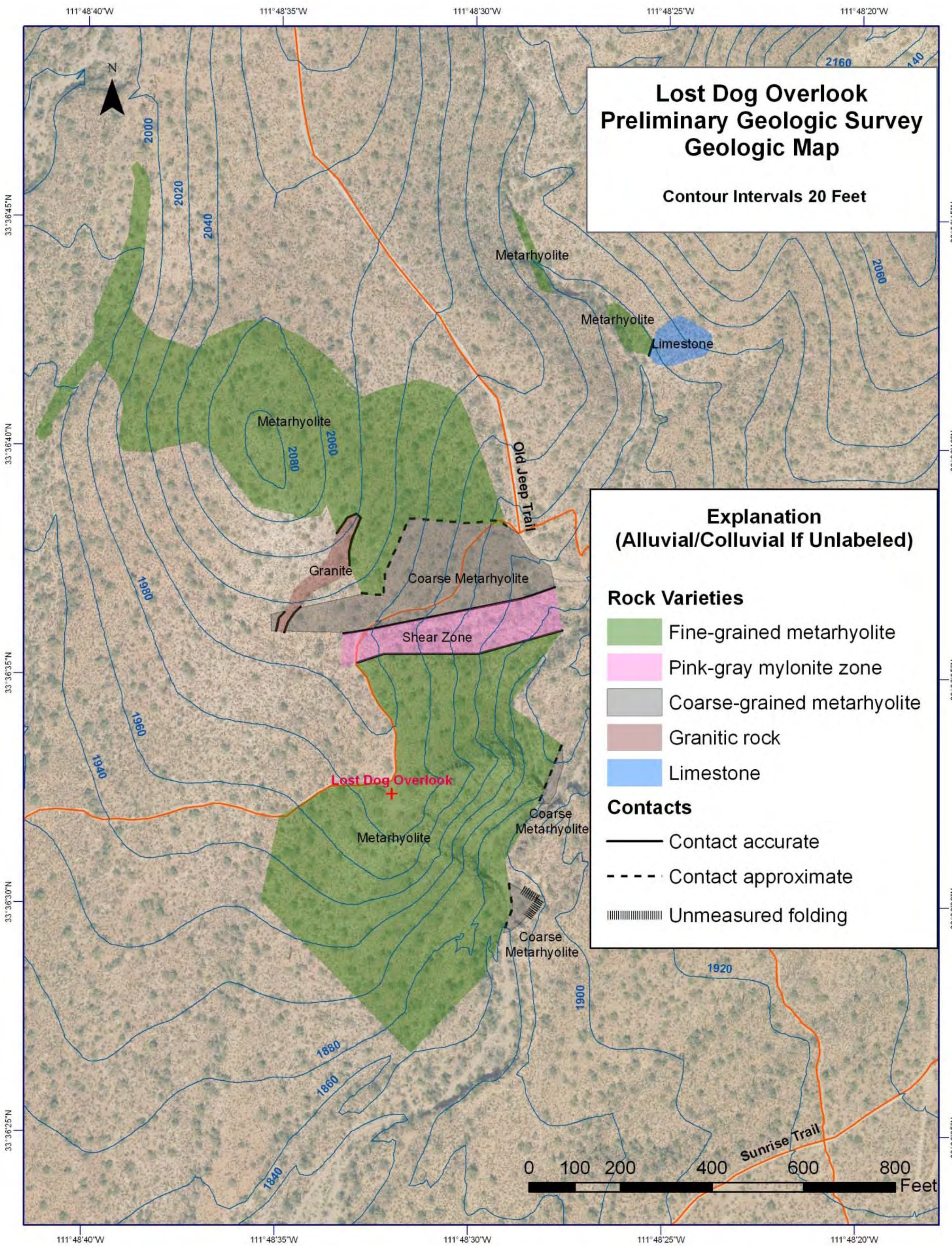
During this field review a small area of granitic (granite-like) bedrock was noticed lying north of LDO partway up a hill. This rock is unlike any other found in the investigation area and had been classified as "unknown" in the original field work. It was added to the mapping effort. (See Figure 10.)

Figure 10a and 10b. Portion of granitic outcrop (left). Area shown is approximately 2 feet across. Close-up of granitic rock surface (right).

With the inclusion of the granitic rock and the additional areas of rock with augens, it was believed that all the rock types in the investigation area had been located. The additional mapping work was performed in several field projects during August and September, 2008. Based on the field visits to the investigation area and a review of all the data recorded in the course of the volunteer field work, a geologic map was prepared showing the approximate locations and geographic relationships of the major rock varieties in the area, shown below as Map 3.

Often, a geologic map like Map 3 showing the distribution and nature of major rock units is the main result of a geologic survey, and the preparation of such a map was one of the original project objectives. However, it already had been conjectured that the observed rock types were related, possibly consisting of one basic material that had undergone a variety of alterations.

Although there were working hypotheses about the types of rock in the investigation area and their inter-relationships, the only way to accurately identify rock is to take a sample of each type, have a thin section (0.03 mm thick) made from each sample, examine the thin section slides under a microscope with and without polarized light, and perform a mineralogical analysis. The limited scale of this investigation was appropriate for exploring mineralogical variations and there was interest in understanding the localized conditions and pathways that existed in the area. As a result, the project team decided during Phase 2 to proceed with further analysis of the identified rock types while completing work on the geologic map.



Map 3. Geologic map of major rock varieties in investigation area, updated for limestone discovery made in January, 2009. Note scale at lower right; as shown on page, approximate map scale factor is 1:3,600.

Phase 3—Sample Collection and Analysis: July, 2008, through January, 2009

MSC agreed to fund the cost of preparing thin section slides and Gootee agreed to analyze them. During the July, 2008, field visit and shortly thereafter, samples of each of the seven rock types (separating the metarhyolite into distinct gray/black and greenish types and now including the granitic rock) were collected. Figure 11 shows the locations of the samples. Subsequent field work in January, 2009, resulted in the collection, thin-sectioning, and analysis of another sample labeled “Lime” in Figure 11.

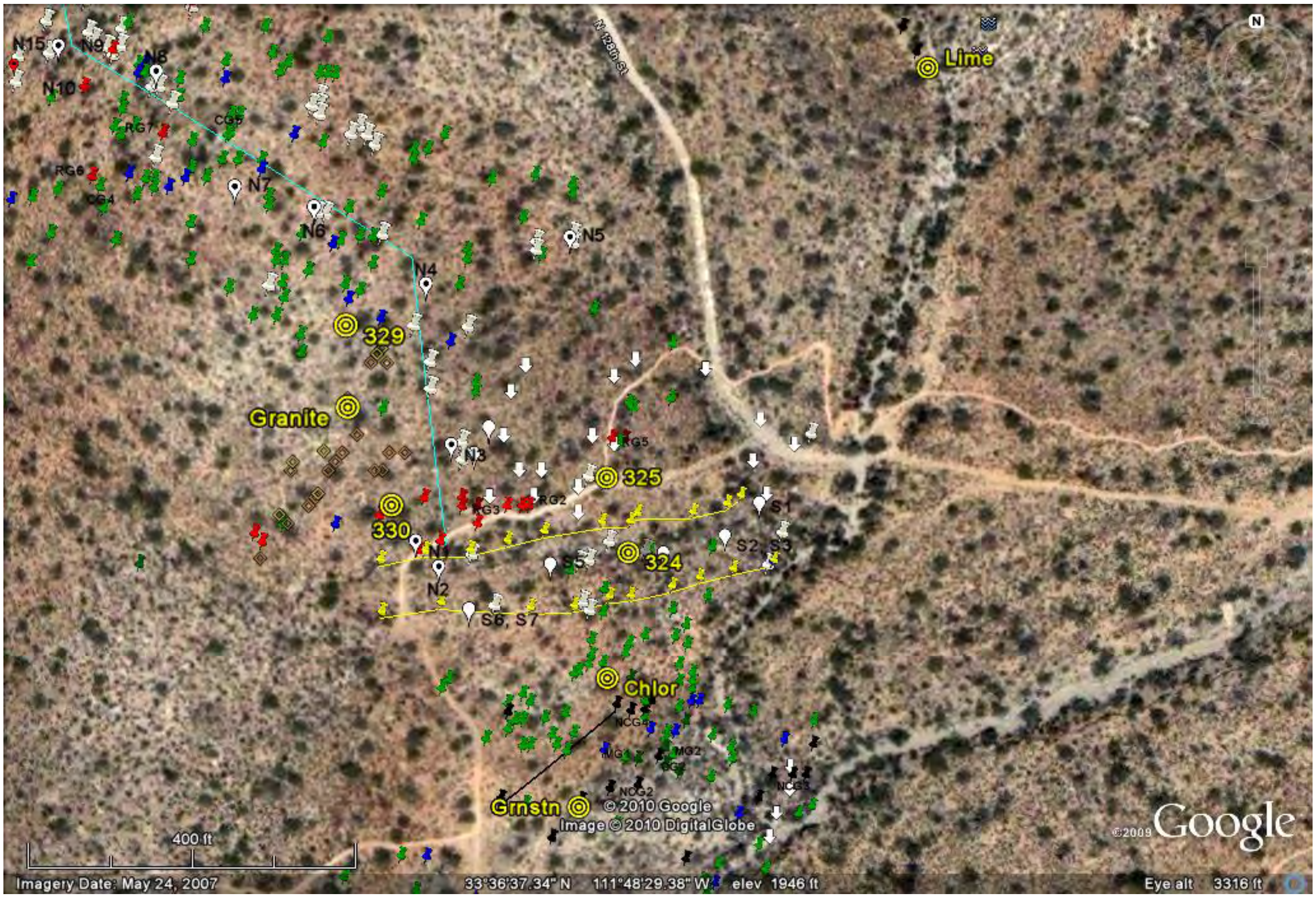


Figure 11. The central portion of Figure 6 with the granitic observations (brown diamonds) added and showing the sample locations (concentric yellow circles labeled with sample names) as displayed on Google™ Earth. Note scale at lower left. North is toward the top of the figure.

The raw samples and preliminary cuts are shown in Figure 12.

Figure 12. Samples and preliminary cuts prior to thin-sectioning

The thin-section slides were returned and analyzed in October, 2008. The thin sections were analyzed in a microscope with polarized and non-polarized light while taking photographs (called photomicrographs) at 10 to 100 times magnification.

The results of the analysis are presented below for each sample, generally progressing from south to north in the investigation area. Please refer to Figure 11 for the specific location of each sample relative to the other samples.

In thin section preparation, a thin piece of a sample is mounted onto a glass slide and then ground thinner and smoother until the section is only 0.03 mm thick. In thin section analysis, the resulting slide is examined in a polarizing (or polarized-light) microscope. Different minerals have different optical properties. By using polarizing filters, which produce light waves with uniform orientation, the different minerals in the thin-section sample can be distinguished from each other and identified by their characteristic appearance. These differences are invisible or harder to see using non-polarized light.

Sample "Grnstn": Non-chloritized metarhyolite

Sample "Grnstn" (seen in Figures 1, 7, and 8) looks gray/black to the eye and through a loupe. However, when cut to 0.03 mm thick the sample appears clear since it is abundant in silica (silicon dioxide) or "glass-rich". Figure 13 shows a photomicrograph of the gray/black variety of metarhyolite taken under polarized (Figure 13a, top) and non-polarized (Figure 13b, bottom) light to help see the rock's texture and composition of the grains. The composition of the gray (Figure 13a) or clear (Figure 13b) portions of the photomicrograph is primarily silica with 1 to 2% opaque minerals, likely iron-bearing.

The texture is a mixture of coarse- and fine-grained. The grain boundaries appear diffuse, a characteristic of fused grains during metamorphosis. The contrasting brown (Figure 13a) or gray (Figure 13b) feature is the remnant of a crystal, probably an original phenocryst (a large, conspicuous crystal) in the rhyolite. The "salt and pepper" texture is the glassy or silica-rich matrix.

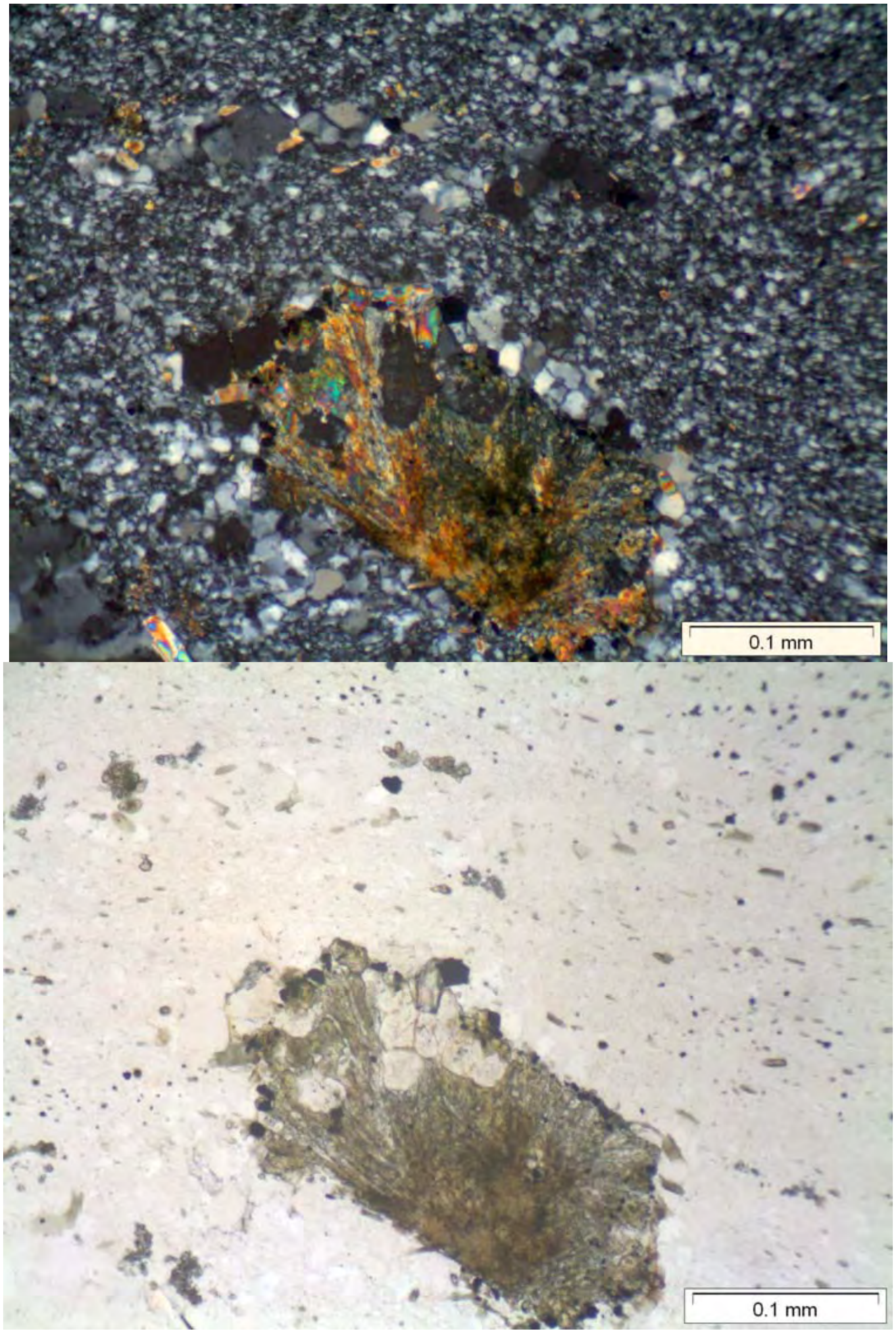
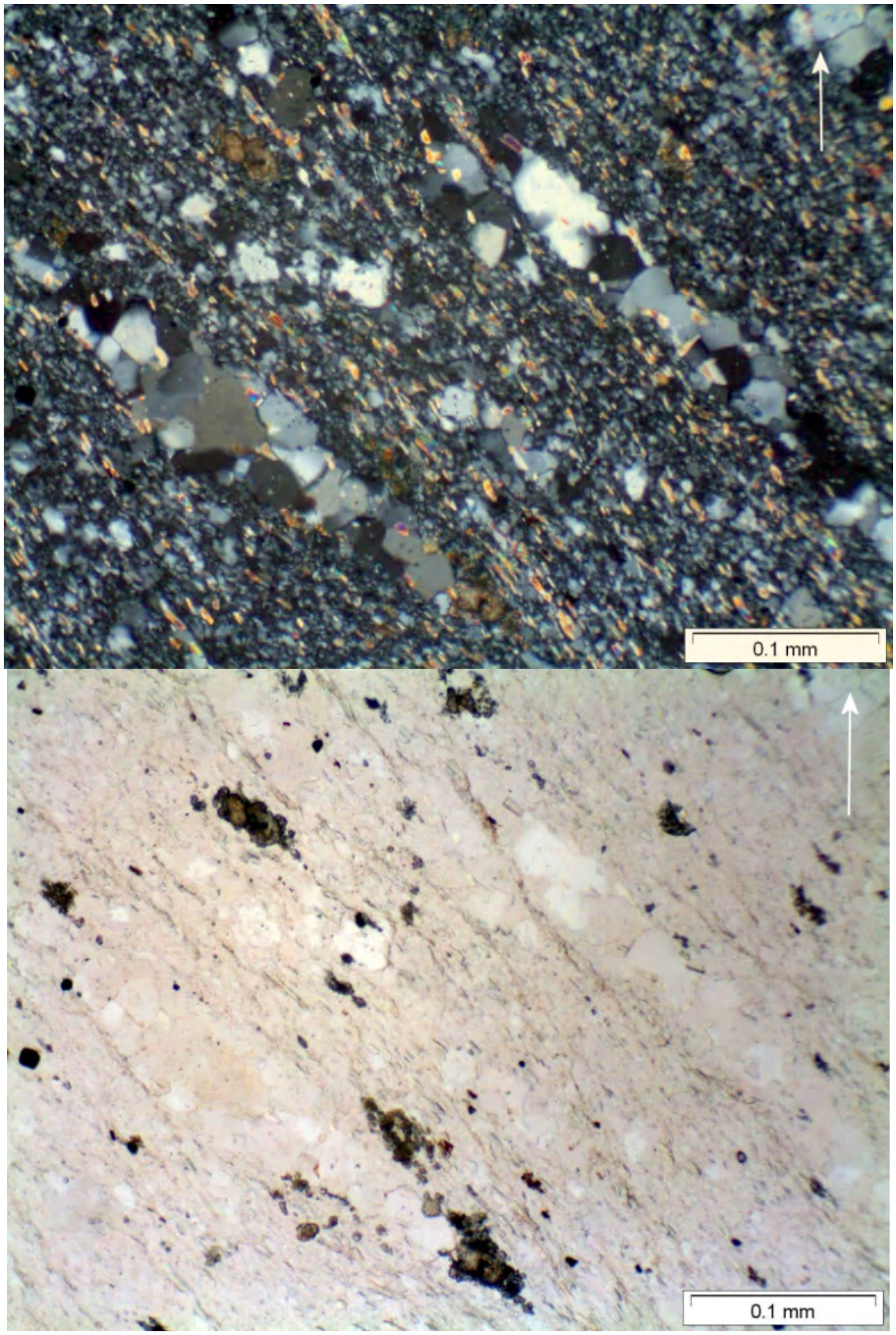


Figure 13a and 13b. Photomicrograph of a portion of sample "Grnstn" under polarized light (13a, top) and non-polarized light (13b, bottom). Scale at bottom right.

Based on the thin-section observations, sample "Grnstn" is interpreted to be metamorphosed rhyolite. Since the metarhyolite is volcanic in origin, by definition the original "parent" rhyolite cooled at or near the surface. This happened approximately 1,700 million years ago (Ma) by association with other rocks in the region. But the transformation from rhyolite to metarhyolite must have happened under conditions of moderate temperature and pressure, probably 10 – 20 kilometers (6 – 12.5 miles) below the surface. The burial and subsequent metamorphism of the rhyolite probably occurred around 1,650 Ma.

Sample "Chlor": Chloritized metarhyolite

The greenish variety of metarhyolite has more greenish chlorite crystals spread more uniformly through the material than the gray/black variety. (See Figure 14a.) Chlorite is a silicate of iron, magnesium, and/or aluminum. A similar-appearing silicate, epidote, is rich in calcium rather than iron. Visual examination of the thin-section photomicrographs shows that all the samples have a small amount of iron present, indicated by black dots. (See Figure 14b.)



Figures 14a and 14b. Photomicrographs of a portion of sample "Chlor" under polarized light (14a, top) and non-polarized light (14b, bottom). White arrow indicates vertically upright *in situ*. Note scale at lower right.

In the sample shown (see Figure 14a), the chlorite crystals appear sharper than the matrix crystals, implying that they formed later than the metarhyolite and probably under conditions of lower temperature and pressure than those which transformed the parent rhyolite into metarhyolite. The sharper crystals imply that the transition from metarhyolite to chloritized metarhyolite took place closer to the surface. The growth of the chlorite crystals might have been assisted by a slightly more hydrated environment.

Furthermore, increasing chlorite may be associated with increased shearing in the rock, visible in the thin section as linear features and alignment of the grains. The rock appears to have been subjected to ductile stress, that is, stress that occurred while the material still was plastic rather than fully solidified, sometime during or after the formation of chlorite underground. The ductile stress probably is associated with the metamorphic event approximately 1,650 Ma. The period of chloritization could have overlapped with the period of deformation of the rock. Note that several of the rock types and visible features in the investigation area were indicative of shear stresses (for example, the rock with augens and folded folds) and even faulting (the east-west region of highly foliated metarhyolite).

Sample "324": Shear zone

The next sample (seen in Figures 3 and 4) was taken from the highly-foliated region of rock that under visual examination had obvious reddish regions. This region had been characterized as a shear zone based on the extreme foliation, linearity of the feature, and consistency of the strike, dip direction, and dip angle characteristics. The thin section shows layers and zones of distinct foliated material. (See Figure 15.) The reddish color probably is iron oxide resulting from oxidation of the iron in chlorite. Oxidation may have occurred after the chloritization process because (a) the chlorite was a source of the iron, (b) the material had solidified, and (c) it was at or near the surface.

A foliation fabric also is visible across the thin section, seen in variegated colors against the gray silica matrix. The variegated colors likely are composed of mica and probably formed during foliation, similar to the formation of chlorite described above and interpreted also to have formed approximately 1,650 Ma.

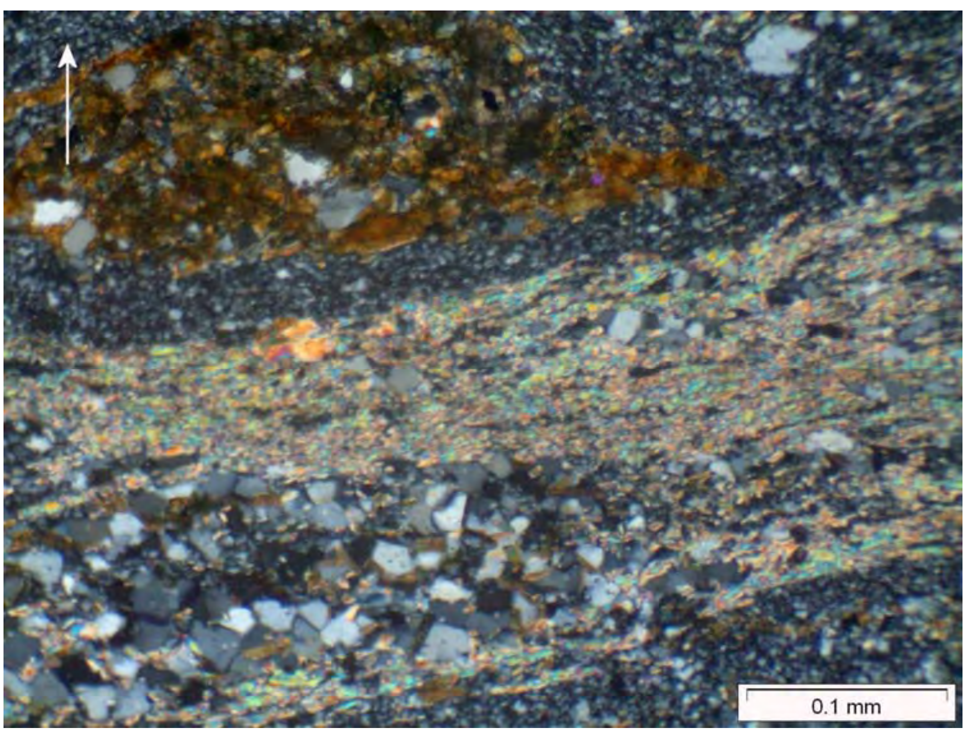


Figure 15. Photomicrograph of a portion of sample "324" under polarized light. White arrow indicates vertically upright *in situ*. Scale at lower right.

Sample “325”: Mylonite with augens

Sample “325” (seen in Figure 5) is the rock that had been identified as mylonite (a general term for rock showing structural evidence of strong ductile deformation during metamorphic processes) with augens, the distorted dark areas. The large rectangular feature seen in Figure 16 is plagioclase feldspar crystal. The obvious striations indicate that it is rich in sodium and calcium. Feldspar is a general name for a large group of very common silicate minerals.

This sample has undergone the same chloritization process as the others. Another interesting feature of this sample is the small light-colored shapes that can be seen within the feldspar crystal. This likely is a mineral called sericite, a form of mica that is a common alteration mineral of plagioclase feldspar in areas that have been subjected to hydrothermal (hot water) alteration. This is another feature of metamorphic conditions, often associated with decreasing pressures and temperatures.

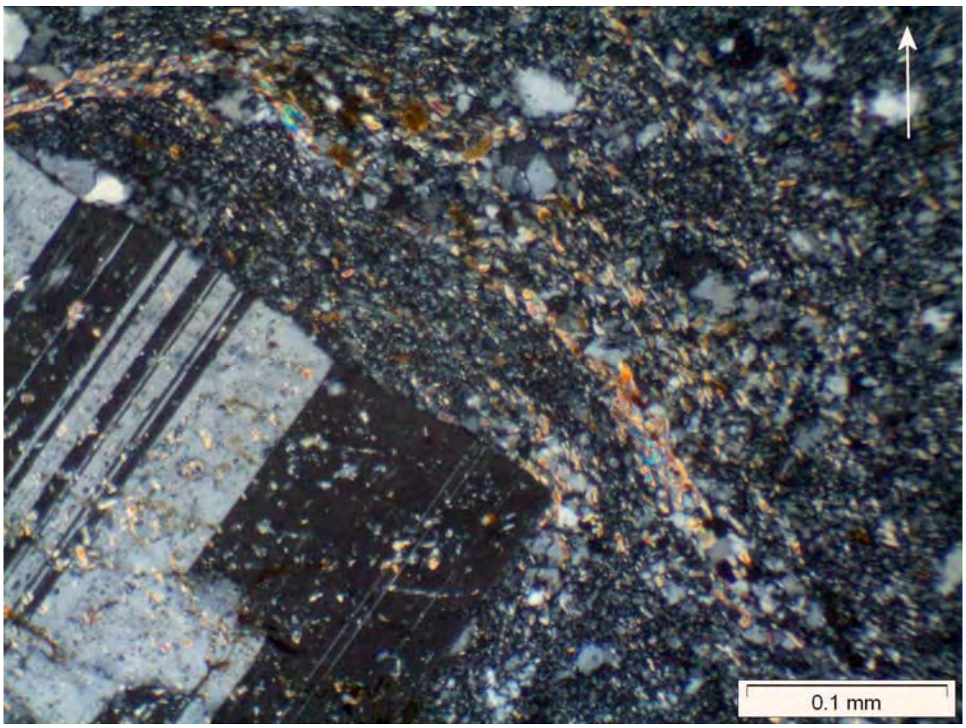


Figure 16. Photomicrograph of a portion of sample “325” under polarized light. White arrow indicates vertically upright *in situ*. Scale at lower right.

It previously had been noted that all the rock with augens (and/or with “folded folds” visible in the rock) were indicative of shear zones. Two general areas of such rock were observed in the LDO area. However, so much of the area is covered by alluvium and colluvium that no additional sheared rock is visible.

Sample “ 330”: Oxidized metarhyolite

Sample “330” (Figure 17) also had augens (although much less prominent than sample “325”) and was pinkish, probably due to iron oxide derived from chloritization and subsequent oxidation. Samples “325” and “330”, both lying not far north of the highly-foliated outcroppings, have the same basic minerals as the metarhyolite but a coarser structure. Examined visually, samples “325” and “330” both contained the small blue quartz crystals that previously had been identified as markers for the metarhyolite in this area. (See Figure 18.) This argues for these samples to be the same basic rock as the previous samples in spite of the difference in structure and texture. The coarser texture in sample “330” could be the result of proximity to a shear zone, indicated by the highly-foliated material to the south and the mylonite with augens to the east.

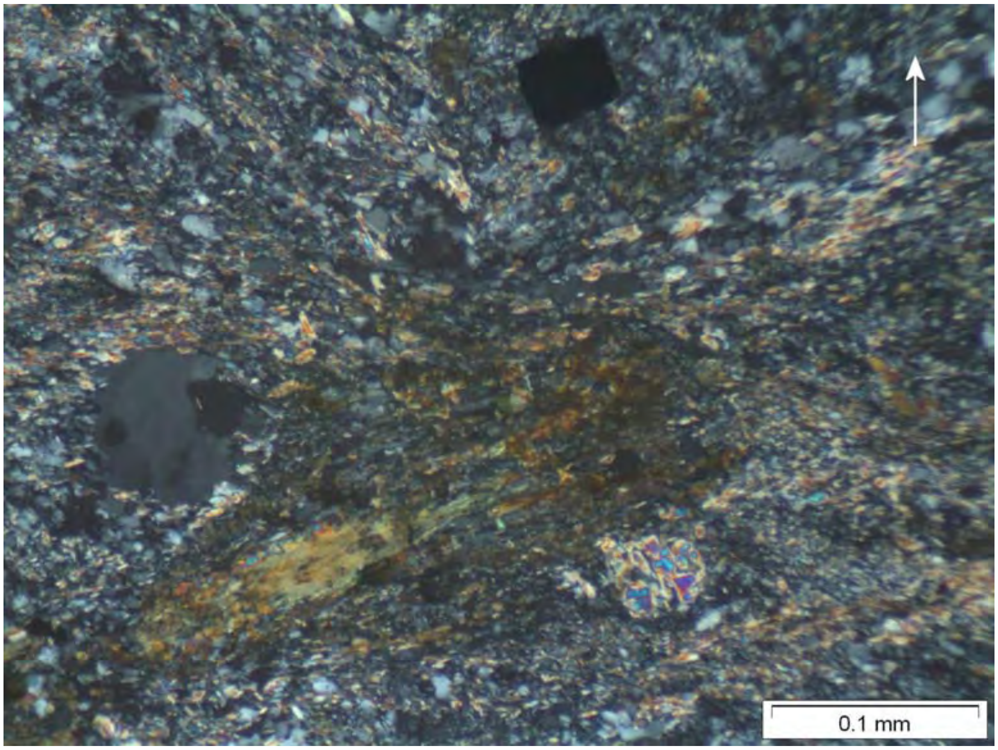


Figure 17. Photomicrograph of a portion of sample “330” under polarized light. A round marker crystal (appearing gray instead of blue) is at left. The bright round object at lower center is chlorite and an unknown opaque crystal is at top center. White arrow indicates vertically upright *in situ*. Scale at lower right.

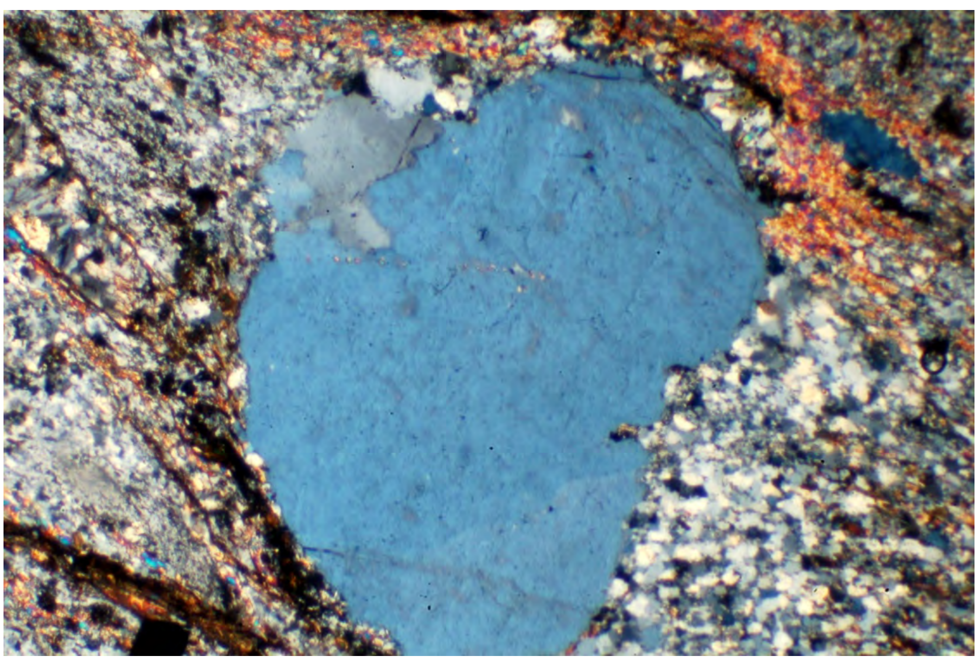


Figure 18. Photomicrograph of a large pale blue marker crystal in sample “330” under polarized light. Note that the blue quartz crystals are birefringent, that is, they take on slightly different colors depending on the angle at which they are viewed. Area shown is approximately 0.5 mm wide.

Sample “Granite”: Granite

The “granite” sample (Figure 19) is pinkish and coarse-grained, plus the bedrock outcrops of this material are spheroidally weathered (weathered by processes that produce rounded shapes) rather than foliated. Although not obvious in the small area shown in Figure 19, the thin section contains abundant feldspar crystals, which are the source of the pink coloration.

At the time this sample was collected, it was unclear whether it was granite or another possible alternative, a metamorphosed sandstone. More information was needed to support or refute this alternative. It seemed clear from both visual and microscopic analysis that this rock is not the same as the metarhyolite; for one thing, it has much more feldspar.

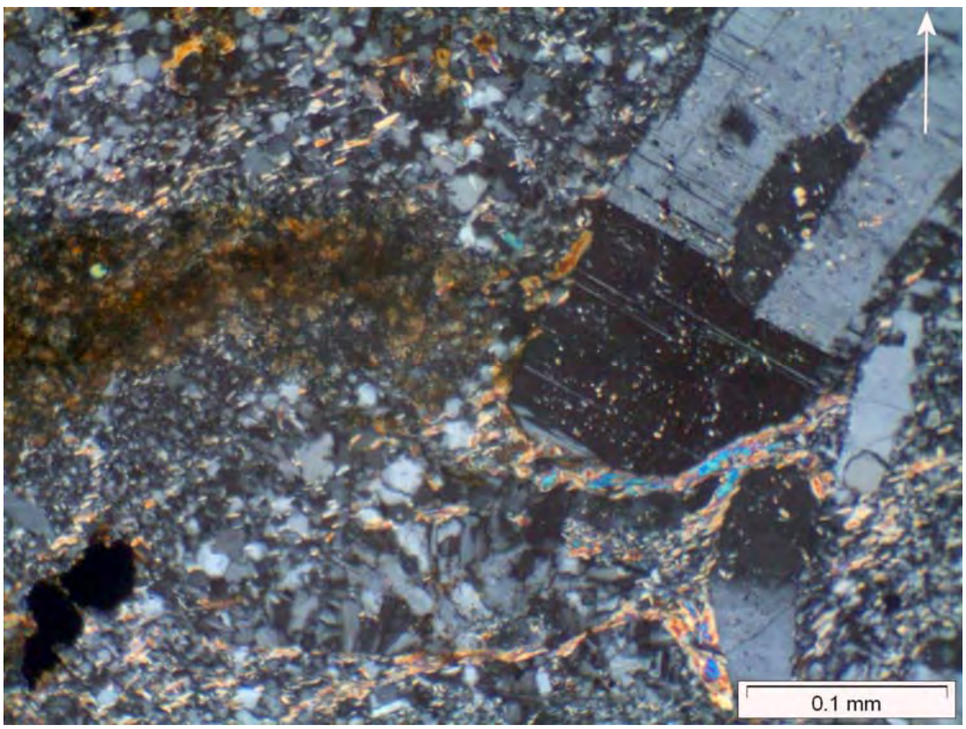


Figure 19. Photomicrograph of a portion of sample “Granite” under polarized light. The white arrow indicates vertically upright *in situ* and the scale is at lower right.

In late January, 2009, there was another field visit to the LDO investigation area. One of the focuses of this trip was a re-examination of the granitic rock. Although the thin-section photomicrograph was ambiguous, leaving open the possibility that this rock could be either granitic or some sort of metamorphic sandstone, after another detailed field examination it was concluded that it probably is granite based on the following observations:

- The rock consists of roughly equal proportions of quartz, potassium feldspar, and black biotite (a sheet silicate mineral in the mica group, often dark-colored), similar to the composition of granite elsewhere in the McDowell Mountains.
- The feldspar in the other rock samples was rich in sodium and calcium rather than potassium as seen here. These crystals are unsorted in the rock, supporting a plutonic rather than sedimentary origin.
- There is no layering in the rock.
- Foliation is absent.

- It has a coarse-grained crystalline texture which is indicative of a plutonic rock (igneous rock formed at depth).
- The outcrops of this rock show spheroidal weathering.

It now appears that this small area is a granitic intrusion that is younger than the metarhyolite. Since the granite is not foliated, it was created after the main deformation episode that affected the other area rocks. Therefore the granite intruded the metarhyolite.

Sample "329": Sericitized metarhyolite

Sample "329" (Figure 20) is microscopically similar to samples "324" and "325", and it is compositionally similar to the chloritized metarhyolite (sample "Chlor"). The large feldspar crystal in the photomicrograph shows extensive sericite like sample "325". Whitish sericite results when the underlying feldspar is high in sodium and calcium, as this material seems to be. This could explain the whitish appearance of this rock which was observed in several extended linear features running mainly northwest-southeast in the northern portion of the investigation area. Sample "325", the rock with distorted dark augens, also had a whitish matrix macroscopically and feldspar with sericite in the micrograph. (Refer to Figure 16.)

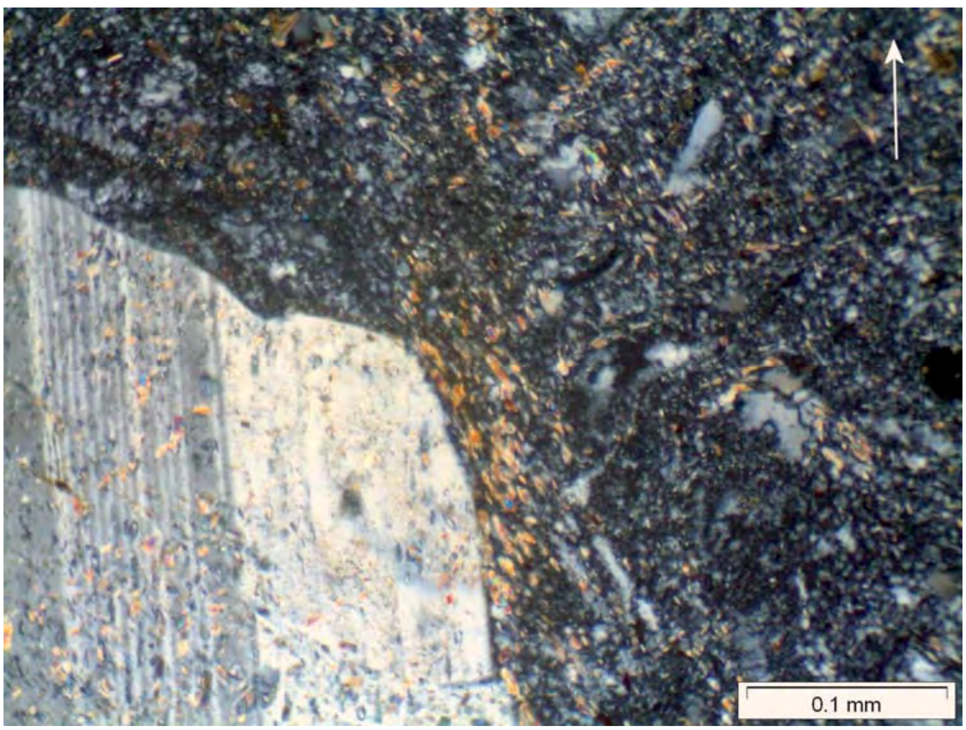


Figure 20. Photomicrograph of portion of sample "329" under polarized light. White arrow indicates vertically upright *in situ* and scale is at lower right.

Sample "Lime": Travertine Limestone

During the late January, 2009, field trip to observe the granitic area more closely and to review some isolated bedrock deposits elsewhere in the investigation area, rock was observed that had been seen previously but thought to be caliche—a geologically recent and very common calcium carbonate deposit typically formed by mineral precipitation from evaporating rainwater. Caliche deposits are common throughout the investigation area and were not recorded during the Phase 1 field survey work in March and April of 2008.

Based on further work and observations made following the January, 2009, trip, including analysis of an additional thin section, it was concluded that this outcropping was likely a travertine limestone deposit. (Travertine is a form of limestone—calcium carbonate and other calcium minerals—deposited by mineral springs.) Details about this discovery, including photomicrographs from the thin section, are described in Gootee et al 2009.

This outcrop is unique in that no limestone deposits are known to exist in the McDowell Mountains or other mountain ranges in the immediate area. In addition, this limestone outcrop contains unusual orange-weathered chert, a fine-grained, silica-rich sedimentary rock often associated with limestone. This outcrop rests directly on metarhyolite bedrock and pieces of metarhyolite are incorporated into the basal portion of the limestone—indicating that the limestone is younger. The limestone is tilted and fractured with thick rock varnish and dissolution pits on the surface, indicating that the deposit probably is more than a million years old based on regional age-relationships.

Interpretation and Discussion of Results—February, 2009, through January, 2010

Conclusions

Based on the thin section observations and analysis, the original parent rock appears to have been rhyolite rather than basalt as originally conjectured. Rhyolite and basalt are both extrusive (fast-cooled and fine-grained) igneous rocks of volcanic origin. But rhyolite has more quartz and much less iron-bearing minerals than basalt. Rhyolite "derives from the rapid cooling of a very viscous magma of granitic composition…" (Mottana et al 1978)

This conclusion was based on the observation that the thin sections from all of the samples are almost transparent due to abundant quartz, but basaltic thin sections would have been dark because of the greater iron content. Therefore the rocks whose confused identity started the project (Figure 1) probably are metamorphic rhyolite (metarhyolite) rather than metamorphic basalt (greenstone) as originally thought. Note that this is consistent with the 1979 identification by Welsch and Péwé, quoted in Schroeder 1997.

The eight so-called rock types observed through June, 2009, in the investigation area now have been given preliminary descriptions:

- The gray/black rock (a variety of Rock type 1) is metarhyolite and seems to be representative of the other rocks in the area.
- The fine-grained greenish rock (the other variety of Rock type 1) is chloritized metarhyolite.
- The material with both greenish and reddish crystalline regions is oxidized and chloritized metarhyolite. This material was observed in two variations, (a) the highly-foliated outcroppings identified as a possible fault and shear zone (Rock type 2) and (b) unfoliated rock (Rock type 5) lying just northwest of the foliated region.
- The light-colored mylonite with augens (Rock type 3) found in areas north, northeast, and southeast of the possible shear zone appears to be texturally-distinctive metarhyolite containing coarse blebs of metarhyolite within it.
- The whitish rock in several linear features (Rock type 4) running generally northwest from just north of the unfoliated oxidized metarhyolite appears to be metarhyolite that has predominantly sericite mineralization.

- The pinkish localized outcropping of rock appears to be granite, i.e. igneous rock different from all the metamorphic rock around it.

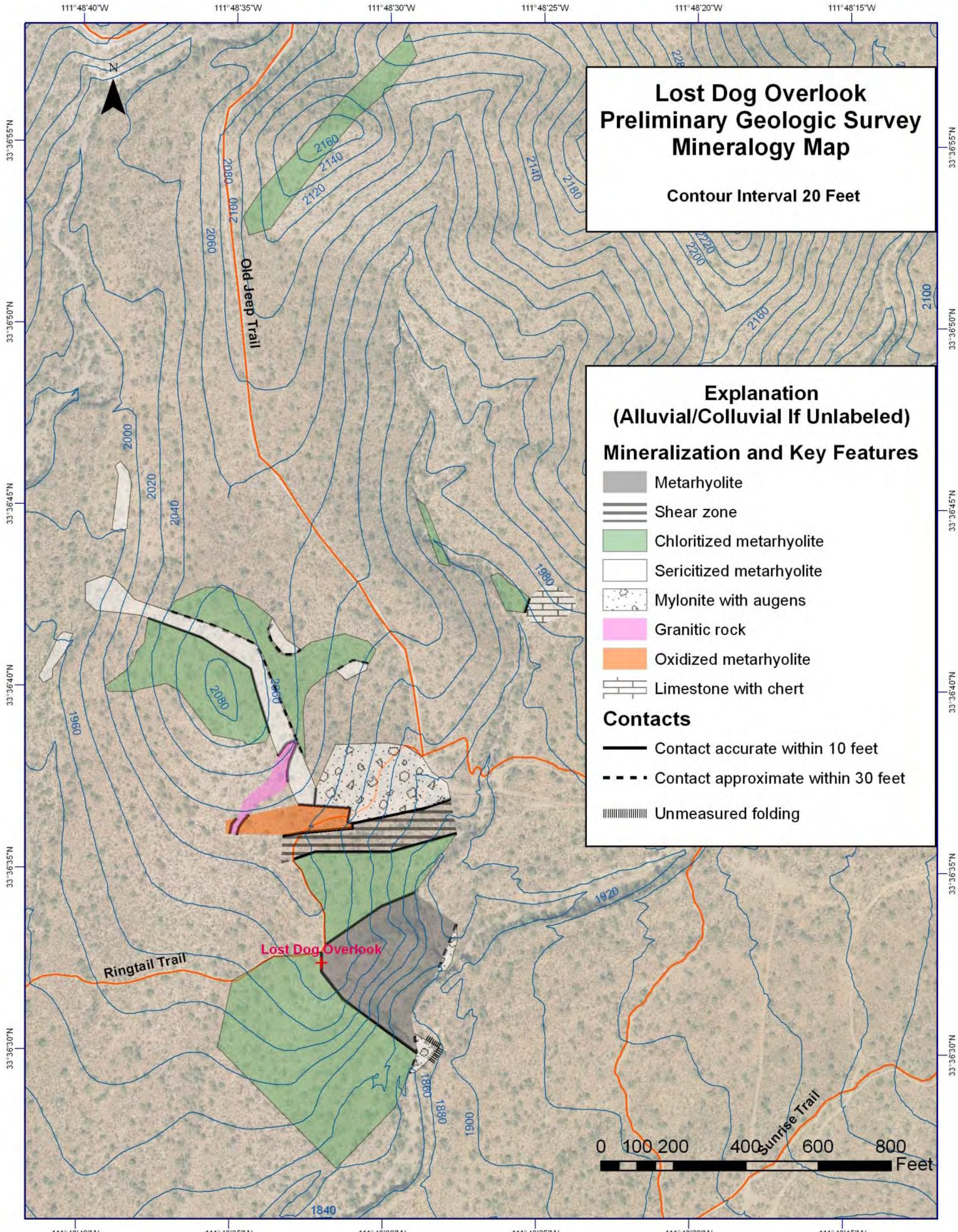
- The likely travertine limestone found in the investigation area is a sedimentary rock, unlike everything else observed.

As conjectured during Phase 2, many of the so-called rock types reflect mineralization alterations of metarhyolite. The mineralogy maps (Maps 4 and 5) provide this additional detail about the rocks in the investigation area to supplement the geologic map (Map 3) developed earlier.

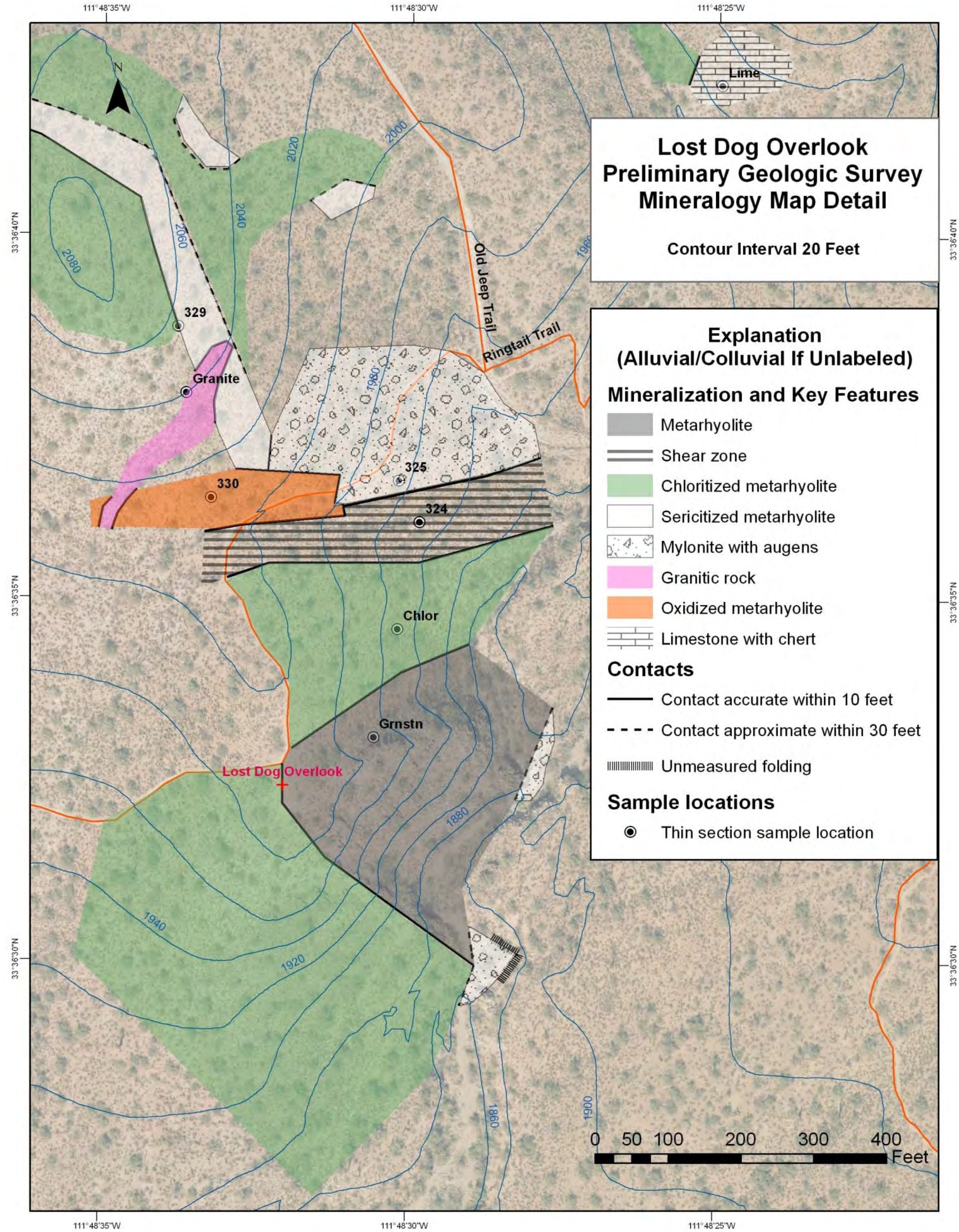
Note that much of the investigation area is unmapped because of extensive coverage by alluvial and colluvial overburden covering any bedrock. This overburden prevented determination of even approximate boundaries in numerous areas. Maps 3, 4, and 5 also show isolated areas with similar characteristics whose complete spatial relationships cannot be determined due to the overburden. For the same reason, it was not possible to establish the inter-relationship, if any, between the areas with rock showing evidence of shear.

Significant levels of ductile deformation are present in most of the samples examined, albeit more apparent in some samples than others. Thin section analysis confirmed the degree of deformation seen in the surface outcrops. Most samples showed some foliation fabric as a result of the ductile deformation. Foliation is most intensely associated with the shear zone (Maps 3, 4, and 5).

This likely explains why the rock at this particular location was used to make tools by archaic people. Proximity to the shear zone produced a strong foliation fabric in the rock, evident for example in Figures 14 and 15. This foliation fabric would have resulted in relatively straight and relatively sharp edges when the rocks were fractured in the tool-making process.



Map 4. Preliminary mineralogy map of Lost Dog Overlook vicinity. Note scale at lower right; as shown on page, approximate map scale factor is 1:4,500.



Map 5. Preliminary mineralogy map detail near Lost Dog Overlook. Note scale at bottom right; as shown on page, approximate map scale factor is 1:2,250.

Preliminary Geologic History of the Lost Dog Overlook Area

Based on all the recorded information, the thin-section analysis, and numerous field visits, the following preliminary summary of geologic events was developed that could explain the geology observed in the Lost Dog Overlook area. (See Chart 1, a graphical illustration of geologic events showing the inter-relationships between fundamental geologic processes over time.)

Approximately 1,700 million years ago (Ma), there was volcanism in the area. This produced thick flows of rhyolite, a silicon-rich extrusive (eruptive) material. Based on their composition, thickness, and relative proximity to other rocks mapped in central Arizona, these flows probably are associated with the voluminous, silicon-rich rocks belonging to the Red Rock Group (Anderson 1989; Johnson et al. 2003: Karlstrom and Bowring 1991; Karlstrom et al. 1990; Skotnicki 1996). Eruptions during this time are thought to have been the result of a continental volcanic arc along the edge of an ancient continent, a distant precursor to what is today North America (Murphy and Damian 2004; Blakey and Ranney 2008).

About 1,650 Ma, this region contracted during a mountain-building episode called the Mazatzal Orogeny (Anderson 1989; Karlstrom and Bowring 1991). The rhyolite flows were buried and subsequently folded, foliated, and subjected to low-grade metamorphic conditions about 10 – 20 kilometers (6 – 12.5 miles) below the surface (Couch 1981). These conditions produced metarhyolite, which is the main rock observed in the investigation area. Burial associated with the Mazatzal Orogeny could have introduced hot fluids into the bedrock. If the metarhyolite encountered a slightly hydrous environment (≥0.5% water), this could have chloritized some of the metarhyolite and created the greenish stone common in the investigation area. Sericite mineralization also may have occurred during this time, perhaps as pressures and temperatures were decreasing.

The granitic intrusion appears to be associated with other such intrusions found in the northwestern part of the McDowell Mountains and the Four Peaks area which are thought to have occurred approximately 1,450 Ma (Anderson 1989; Skotnicki 1996). The apparent lack of foliation and metamorphic minerals in the granite may indicate a shallow intrusion into the metarhyolite, probably less than 10 kilometers (6 miles) below the surface. Uplift and a period of erosion after this episode might have brought some local metarhyolite close enough to the surface for oxidation of the iron-bearing chlorite, creating the reddish regions of oxide mineralization observed in several area samples.

No Paleozoic or Mesozoic age sedimentary rocks were observed in the investigation area, although such rocks—similar to those found on the Colorado Plateau—probably were deposited across the McDowell Mountains region. (These two geologic eras span the period from 541 to 65 Ma. See Chart 2 in the Appendix: Glossary.) If such rocks were in fact deposited, they may have been removed by uplift, exposure, and erosion during the Laramide Orogeny (80 – 40 Ma), which is known to have affected rocks in this area. Some of the many fracture patterns visible in the rocks of the LDO area may be a signature of the Laramide event. The uplift, exposure, and erosion associated with this event provide another possible mechanism for the oxide mineralization observed in some LDO area samples.

The next major geologic episode in the region is the Basin and Range disturbance. This episode was accompanied by extensional (pulling) forces resulting from widespread tectonic activity throughout the Southwest. These forces thinned the crust and allowed alternating basins and ranges to form, separated by large faults. The McDowell Mountains are one of the blocks formed by this process within the Basin and Range Province. The nearby mountains to the northeast and southwest also formed during this period, and adjoining closed basins were formed and began to fill with sediment derived from the mountains.

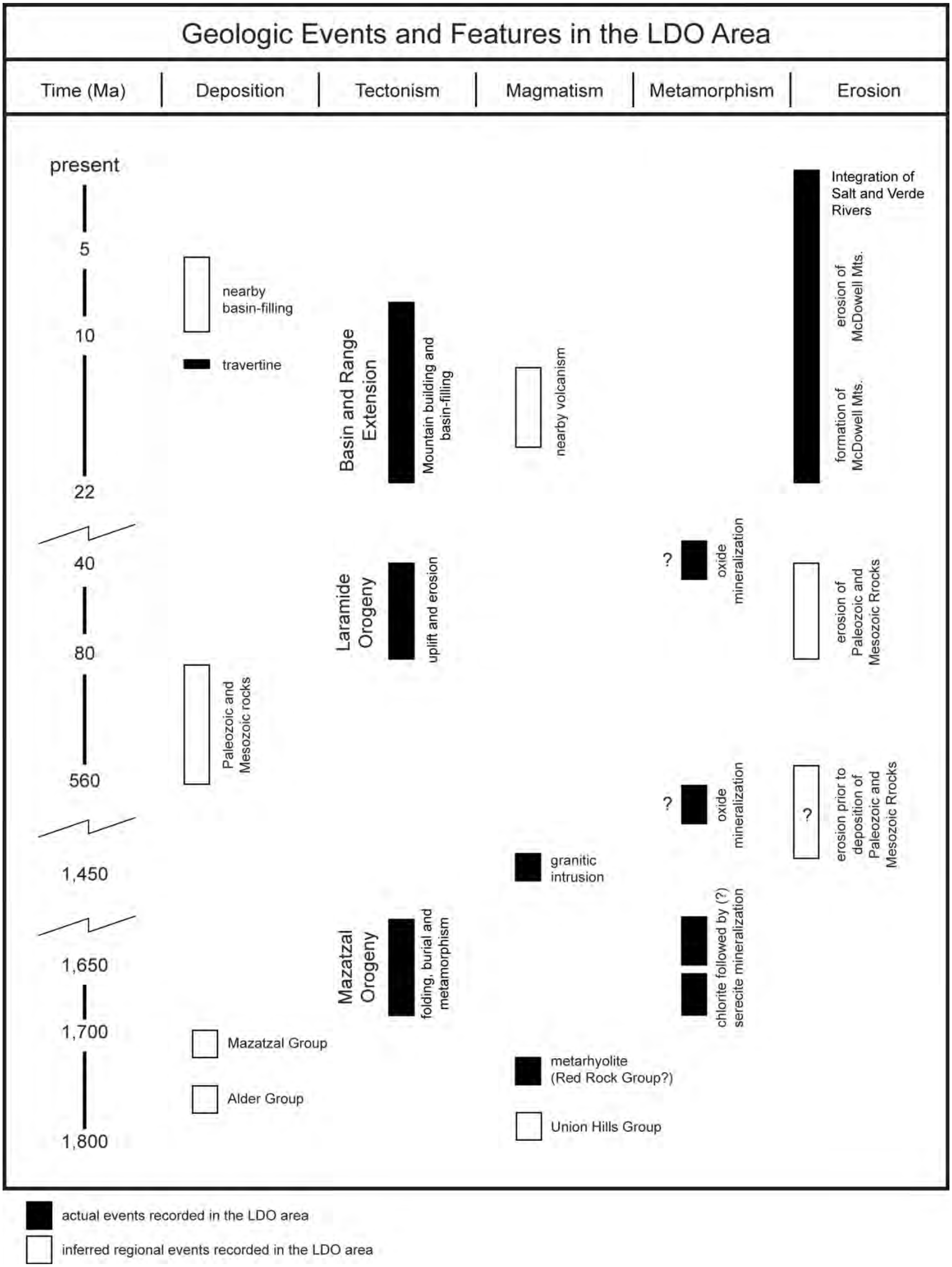


Chart 1. Geologic events and associated features in the investigation area.

It is not clear when the McDowell Mountains began to form or how long this process took, although the current estimate is 22 – 10 Ma. The crustal extension which created the Basin and Range topography of the Southwest pulled from the northeast and the southwest, causing fractures generally running northwest/southeast—which is the orientation of many of the basins and ranges. Uplift during this period and subsequent erosion also could have brought the chloritized metarhyolite close enough to the surface so that it was exposed to oxygen.

In an unusual event, bicarbonate-rich spring water apparently bubbled to the surface and crystallized into travertine directly onto the metarhyolite within the investigation area. This event likely occurred sometime after the McDowell Mountains formed, possibly during the waning stages of the mountain uplift. The specific formation, timing, and origin of the travertine remain uncertain, but the tilting fractures and erosional relationship of the deposit suggests that it may have formed during or after the formation of the McDowell Mountains.

Eventually the adjoining basins between the McDowell Mountains and nearby mountain ranges exceeded their capacity to hold sediment and they connected with one another to form an integrated network of drainages leading to major local tributaries such as the Verde, Salt, and Gila River systems. These networks probably integrated within the last 5 million years and are responsible for much of the erosional landscape visible today.

The following is a summary of the approximate history of the LDO area from the perspective of time and depth:

1. Deposition of the Red Rock Group (~1,700 Ma): Formation as extrusive volcanic rhyolite at the surface.

2. Mazatzal Orogeny (1,650 – ~1,600 Ma): Burial of the rhyolite to a depth of 10 – 20 km, where it was metamorphosed into metarhyolite and subjected to ductile deformation. Exposure to a hot fluid medium during this period produced chlorite and possibly sericite within the metarhyolite.

3. Magmatism (1,450 Ma): Widespread magmatism in the region and intrusion of the granite into the older metarhyolite. Possible oxide mineralization during subsequent erosional episodes.

4. Deposition (541 – 65 Ma): Deposition of Paleozoic and Mesozoic sedimentary strata over the region.

5. Laramide Orogeny (80 – 40 Ma): Uplift and erosion of Paleozoic and Mesozoic sedimentary strata and the older rocks of the Red Rock Group, including the LDO metarhyolite. Possible oxide mineralization.

6. Basin and Range extension (~22 – 10 Ma): Uplift during a more recent episode of mountain-building accompanied by volcanism, nearby basin formation, and possibly travertine deposition in the investigation area. Continued uplift and erosion might have led to oxidation of minerals at or near the surface.

7. Basin-filling (10 – 5 Ma): Erosion of the McDowell Mountains continues, adjoining basins fill with sediment, some volcanism continues nearby, and a local spring may have deposited travertine.

8. Integration of drainage systems and formation of the modern area landscape (5 Ma – present).

Commentary

This project was a process of discovery for all involved. As data were collected and analyses were performed, there were changes in the thinking of the project team about what was being observed, what processes might have created the observed features, and the timing and inter-relationships of those processes. Even the presumed identity of the representative rock in the area changed. In addition, the original project approach and objectives were expanded to study the mineralization of area rocks in more detail.

This is the scientific process at work: initial observations leading to the formation of preliminary hypotheses, which then are tested and refined in further cycles of data collection and analysis. Even now—after more than two years of field observation, data collection, analysis, and interpretation—significant questions remain. However, the basic nature and *raison d'être* of the prehistoric tool site near Lost Dog Overlook has been elucidated and far more now is known about the geology and mineralogy of the area. The visibly striking features of the LDO area have been described and given a preliminary explanation. Further work undoubtedly will deepen the understanding of the relationship between geologic processes and the observed features.

Additional Research Opportunities

Additional research and analysis will be required to confirm and possibly expand these tentative conclusions about the geologic history of the rocks in the Lost Dog Overlook area as well as to address other significant questions raised by this work:

- Can a complete geologic survey of the Sawik Mountain quadrangle be conducted by the Arizona Geological Survey in conjunction with other organizations? This quadrangle, which includes the LDO area, is the only one in the vicinity which has not been surveyed at 1:24,000 scale.

- Can the dates and inter-relationships of the sequence of geologic events described above be determined more precisely?

- Can the existence of the possible fault and/or shear zones identified in the investigation area be confirmed and their date(s) and extent(s) determined more precisely?

- What is the stratigraphic relationship(s) of the metarhyolite in the investigation area to neighboring rock groups in the region? (Stratigraphy is the inter-relationship and mapping of rock types vertically and horizontally within a region.)

- What model best explains the observed mineral diversity and relationships in the metarhyolite? This includes such questions as:

  - What is the origin of the extended linear feature of sericitized metarhyolite running northwest from the highly-foliated zone?
  - Can the timing and mechanism of the observed sericite and oxide mineralization be determined more precisely?
  - Why was only a single small zone of non-chloritized metarhyolite found and why is this zone uniquely demarcated by lines of large standing slabs of this material?

- What is the nature and origin of the travertine limestone discovered in the investigation area (and other questions related to this discovery as noted in Gootee et al 2009)?

Acknowledgements

The authors would like to thank the many people who made this project and paper possible. First, we appreciate the ongoing interest and involvement of the City of Scottsdale staff. Preservation Director Bob Cafarella (now retired) helped shape the project objectives and issued the permit for the work. Preserve Managers Claire Miller and Robbin Schweitzer managed our field work. Planner Scott Hamilton's and Geographer Rob Chasan's assistance in producing the maps in the paper was invaluable. We also appreciate being permitted to use City mapping software and basic data layers.

Many volunteer stewards of the McDowell Sonoran Conservancy participated in the field work. Our thanks to Brian Akmon, Chet Andrews, Alice Bauder, Beth Baumert, Ron Behm, Dick Benson, Denise Carpenter, Pat Catalano, Doug Ervin, Bernie Finkel, Sue Hamm, Lorraine Houle, Ray Houle, Wayne Johnson, Susan Jorgensen, Lynn Luger, Len Marcisz, Jerry Miller, Martha Miller, Barb Pringle, Jane Rau, Frank Romaglia, Gary Shapiro, Sherrill Sigmen, Mark Slicker, Jerry Thompson, Doug Watson, and Linda Watson. (We apologize for any omissions.) Jennifer Polakis, a volunteer with the Arizona Geological Survey, also participated. Without their help, it would have been impossible to complete the work. We hope they found it interesting and educational and that the results are worthy of their considerable efforts.

We are grateful to the board and staff of the McDowell Sonoran Conservancy for funding this project and for their ongoing support and encouragement.

Co-authors Gruber, Levy, Millavec and Ruppert would like to acknowledge and thank our supervising geologist and co-author, Brian Gootee of the Arizona Geological Survey. Brian's ongoing guidance and involvement were key to successfully completing the work. We are very grateful for his time and his patient teaching and mentorship. This project took us on a path of learning and discovery that we all will remember. It is an example of how a team of dedicated amateurs under the guidance of a scientist can do worthwhile research in the McDowell Sonoran Preserve.

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Appendix: Glossary

Alluvial deposit (alluvium)	Generally loose sediment transported and deposited downslope by running water
Argillaceous	Composed of or containing clay-like minerals
Augen	Large eye-shaped mineral grains or aggregates visible in some foliated metamorphic rocks
Basalt	Extrusive volcanic (igneous) rock relatively poor in silicon dioxide (silica), usually fine-grained due to rapid cooling at the surface
Bedrock	Consolidated native rock that may be exposed at the surface in outcrops or covered by loose material or water
Biotite	Sheet silicate mineral in the mica group; often dark-colored
Birefringence	Property of certain crystal types which refract incoming light into two different directions, making the crystals appear to have different colors when viewed from different angles
Chert	Fine-grained, silica-rich, microcrystalline sedimentary rock often associated with limestone
Chlorite	Chlorites are a large family of common metamorphic minerals, often green in color; chloritization is the process of forming chlorite mineralization
Colluvial deposit (Colluvium)	Generally loose sediment transported and deposited downslope by gravity
Ductile deformation	Deformation without breaking; plastic deformation without fracture
Extrusive (igneous rock)	Volcanic rock formed when magma reaches the surface and cools relatively quickly, resulting in limited (or no) crystal formation
Fault	Fracture or break in originally continuous rock with relative displacement or separation of one side from the other
Fissile	Easily split into thin sheets, a common property of foliated metamorphic rocks
Foliation	Planar texture or structure in rock, often associated with the flattening or alignment of mineral grains due to metamorphic conditions such as compressive stress; a feature related to shear
Granitic rock	Granite-like rock, i.e. generally light-colored, coarse-grained plutonic rock containing quartz and other minerals
Hydrothermal activity	Activity relating to hot water, often associated with volcanic or magmatic activity
Igneous rock	Rock produced by the cooling and solidification of molten rock (magma), either on the surface as extrusive volcanic rock or below the surface as intrusive plutonic rock
Ma	*Mega annum*, i.e. millions of years (ago)
Magmatism	Geologic activity involving molten rock (magma)
Mesozoic	Geologic era extending from 250 Ma to 65 Ma (see Chart 2, below)
Metamorphic or Metamorphosed Rock	Rock produced by metamorphic conditions, i.e. heat and pressure sufficient to cause physical and/or chemical changes in the original rock but not sufficient to melt the rock into magma
Metarhyolite	Rhyolite that has been subjected to metamorphic conditions underground
Mica or Micaceous	Consisting of or containing mica (a sheet-like mineral containing

	silicon and oxygen) or resembling mica, usually in being thinly foliated; mica is a common alteration mineral in plagioclase feldspar in areas that have been subjected to hydrothermal alteration
Minerals	Rocks usually are aggregates of different minerals, each of which has characteristic chemical composition and physical properties; the basic building blocks of rocks
Mylonite	Fine-grained rock that has been deformed plastically (ductilely) without fracturing; often indicating a ductile shear zone
Orogeny	Process of forming mountain ranges by deformation of the Earth's crust
Paleozoic	Geologic era extending from 542 Ma to 250 Ma (see Chart 2, below)
Phenocryst	Relatively large and conspicuous crystal larger than the grains within the groundmass of an igneous rock
Photomicrograph	Photograph taken through a microscope
Plagioclase feldspar	Feldspars are a large family of related minerals consisting of aluminum silicates combined with potassium, sodium, or calcium; plagioclase feldspar contains only sodium or calcium, not potassium
Plutonic (or intrusive) rock	Rock formed from magma cooling slowly beneath the surface, typically coarse-grained and/or crystalline
Polarized light	Light waves with a uniform orientation of their electric field; in non-polarized light, the electric field orientation is not uniform
Proterozoic	Geologic eon extending from 2,500 Ma to 542 Ma (see Chart 2, below)
Quartzite	Hard metamorphic rock, originally sandstone
Rhyolite	Extrusive volcanic (igneous) rock rich in silica (silicon dioxide)
Sericite	Whitish, fine-grained mica that is a common alteration mineral of feldspars, often due to hydrothermal activity; sericitization is the process of sericite mineralization
Shear zone	A planar or tabular and usually extended region of rock that has been deformed (sheared) by compressive stress
Silica	Silicon dioxide
Silicate	Rock consisting primarily of minerals composed of combinations of silicon and oxygen with other elements
Spheroidal weathering	Chemical weathering that creates rounded structures
Stratigraphy	The inter-relationship and mapping of rock types vertically and horizontally within a region
Travertine	Form of limestone—calcium carbonate and other calcium minerals—deposited by mineral springs

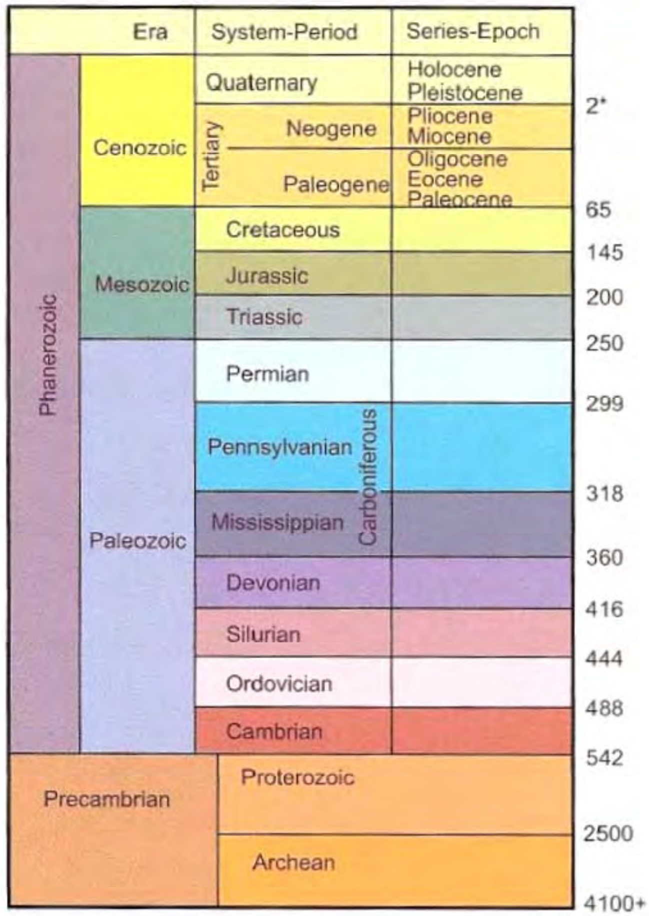

Chart 2. Geologic time scale. Dates in millions of years before present. (Source: Blakey and Ranney 2008, courtesy of R. Blakey.)