• Engineering Geology
• Hydrogeology
• GIS Services

NOLAN ASSOCIATES

January 29, 2016 Job No. 13021

Chris Berry
Watershed Compliance Manager
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SUBJECT: FINAL REPORT
Karst Protection Zone Investigation
City of Santa Cruz
Santa Cruz County, California

Dear Mr. Berry:

This report summarizes the findings and conclusions of our karst protection zone investigation. The purpose of the proposed study was to develop an inventory of karst related rock formations in western Santa Cruz County as part of an overall effort to protect and manage ground and surface water resources in Santa Cruz County. Figure 1, Topographic Index Map, shows the location and topography of the study area.

Our scope of services for this project included the following tasks:

a. Collection and Review of Existing Data, including:
   i. Comprehensive review of existing geologic and hydrologic mapping.
   ii Reconnaissance geologic mapping from stereographic aerial photos of the study area utilizing aerial photographs ranging in age from the 1930's to the present.
   iii. Review of Lidar imagery available for Santa Cruz County.
   iv. Public outreach to the caving community and other earth science professionals.
   v. Review of boring/water well data.

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b. Field Reconnaissance and detailed geologic mapping of select areas within the study area.
c. Production of a marble outcrop map.

PROJECT AREA GEOLOGIC SETTING

For the purposes of the present project, the study area is roughly defined as the Ben Lomond Mountain block, bounded to the north by the Zayante fault, to the west and south by the Pacific Ocean, and to the east by the Ben Lomond fault (Figure 2, Study Area Geologic Map). The Ben Lomond Mountain Block is a large mass of granitic rock that was uplifted and tilted to the southwest by the Ben Lomond fault, which parallels the San Lorenzo River Valley for much of its length. The granitic rock that forms the core of Ben Lomond Mountain is locally overlain by relatively thin deposits of metamorphic and sedimentary rocks, consisting primarily of schist and marble (Figure 2).

The metamorphic rocks of Ben Lomond Mountain are derived from very old sedimentary rocks that have been altered (metamorphosed) by high pressure and heat, owing to deep burial in the earth's crust. This process resulted in the production of marble, schist, and quartzite– metamorphic rock derived from the original sedimentary layers of limestone, shale, and sandstone, respectively.

The metamorphic rocks originally formed a cap over magma chambers located miles underground. The magma eventually cooled and crystallized into the granitic rock that makes up the core of Ben Lomond Mountain. The granitic rock has since been uplifted from depth and the metamorphic rock cap that covered the granitic rock was mostly eroded away, leaving only remnants of metamorphic rock that now form scattered outcrops of marble, schist, and quartzite over the crest of the granitic rock of the Ben Lomond block (Figure 2).

Because the metamorphic outcrops are small erosional remnants of an originally extensive rock formation, the outcrops tend to be irregular and randomly distributed. The metamorphic rocks have also been subjected to great tectonic forces and are deformed by folding and faulting, making it difficult to trace individual layers from place to place.

Our study has focused on the occurrence of marble bedrock. Marble is a metamorphic form of limestone. Both rocks are composed of the mineral calcite, but marble has been re-crystallized by high heat and pressure so that it is usually denser and more massive than the original limestone from which it formed. The terms marble and limestone are sometimes used interchangeably. There is a long history of the mining of marble in Santa Cruz County for the production of lime, which is used to make the cement used in concrete. Many of the historical accounts of the mining industry refer to the rock as limestone.

The marble bedrock is unique among the different rock types on Ben Lomond Mountain because marble (and limestone) will dissolve in water, forming open fissures and caverns underground. Where caves or fissures reach the ground surface, sinkholes form. Collectively, these features result in a unique appearing landscape known as karst terrain. Several areas of karst terrain are recognized on Ben Lomond Mountain.

Significance of Karst Terrain

The interest in karst terrain is occasioned by its unique effect on ground water flow. Normally, ground water flows through the small spaces between the grains that make up rock or through small cracks in the rock. Flow rates in these rocks are generally slow, from factions of an inch to not more than a few feet per day, and the water flowing through these small spaces is filtered to some extent. In karst terrain, the water flows through open fissures or caverns created by dissolution of the marble, and flow rates can be hundreds or thousands of feet per day, with little or no filtration. Where the system of open fissures and caverns contains water, the system is referred to collectively as a karst aquifer.

The karst aquifer system acts as a collector, accepting water from surrounding rocks and concentrating it into underground flow through the fissure system. A karst aquifer also commonly acquires water from surface streams where the streams cross sinkholes. The sinkholes in this case are known as swallow holes and they may capture part or all of the surface flow of the stream. This feature of karst terrain often prevents ordinary surface drainage systems from forming in areas underlain by marble or limestone. Where the flow through the underground karst channels reaches the ground surface, it forms karst springs.

Karst springs are often good water supply sources. Karst springs are important water supply sources for the City of Santa Cruz Water Department and the San Lorenzo Valley Water District. However, because of the lack of filtration and direct and rapid flow of surface water into the sinkhole or swallow holes and back out at karst springs, these water sources can also be easily contaminated by surface activities.

LITERATURE REVIEW

For this study we reviewed geologic literature and maps for the study area. Early descriptions of the geology of the Ben Lomond Mountain area included Branner, Newsom, and Arnold (1909) and Fitch (1931). Leo (1961, 1967) provided the first comprehensive look at the granitic and metamorphic rocks of Ben Lomond Mountain. Comprehensive mapping of the Central Santa Cruz Mountains, including Ben Lomond Mountain was provided by Brabb (1970). The geologic mapping and Tertiary stratigraphy of Ben Lomond Mountain was further refined by Clark (1981).

Detailed studies of portions of Ben Lomond Mountain relevant to the present study were conducted by Nolan Associates (1996), Nolan, Zinn, and Associates (2005) and Nolan Associates (2007), for Pogonip, the UCSC campus, and Bonny Doon quarry areas, respectively. The area of karst terrain surrounding the Bonny Doon marble quarry was also the site of dye tracer studies conducted by P.E. LaMoreaux and Associates (2005). The dye tracer studies involve introduction of dyes into entry points for the karst aquifer (sinkholes or swallow holes) and monitoring of karst springs downstream for the appearance of dye. The dye tracer studies can be used to determine flow patterns and connectivity between specific sinkholes and springs in karst aquifers. Dye tracer studies have also been performed for the karst system under the UCSC campus (Ayers, 1991).

REMOTE SENSING IMAGERY

Two types of remote sensing imagery were used for this study. Stereographic aerial photos ranging age from 1940 to 1973 were studied to identify areas of karst terrain within the Ben Lomond block. In addition to aerial photos, Santa Cruz County has lidar coverage that was analyzed to identify sinkholes.

Aerial Photos

The aerial photo flight lines and coverage consulted for this study area are listed in the references section, at the end of the text. Two of the flight lines received the closest scrutiny: 1943 and 1972-73. These flight lines were chosen for age, clarity, scale, and coverage. Air photo review for the southern portion of the study area was supplemented by 1940 aerial photos.

Much of Ben Lomond Mountain is heavily forested. The aerial photography is of limited use in forested areas. Because Santa Cruz County was heavily logged in the early and mid 20th century, the terrain in the older photos is more lightly forested. We therefore relied more heavily on the 1943 flight line. The photos were observed through a stereographic viewer and notes were taken on separate topographic sheets to identify areas of interest for later field inspection.

Lidar Coverage

Lidar data sets are collected using airborne ranging lasers combined with very tightly controlled geographic positioning. The resulting data sets consist of millions or billions of individual points for which a geographic location and an elevation are known. The data sets can be processed to produce topographic maps or shaded relief maps of the terrain. Figure 3 shows a shaded relief map of the study area based on the lidar coverage. The advantage of lidar imagery over conventional aerial photographs is that it can penetrate the forest canopy, so that it shows a truer picture of the ground surface.

The lidar coverages are in digital form and can therefore be processed digitally to identify or isolate key features. We processed the lidar coverage to identify closed topographic depressions. The principal surface characteristic of karst terrain are sinkholes, which form closed topographic depressions, that is, surface depressions that form basins. Closed topographic depressions do not form in the ordinary process of landscape evolution, which is driven principally by weathering of earth materials and erosion by flowing water. Therefore closed depressions indicate more specialized landscape processes, such as glacial erosion, active faulting, landsliding, or sinkhole formation in areas underlain by marble or limestone.

We used the hydrologic tools in ArcMap to identify all closed depressions recorded by the lidar data set within the study area. The resulting data set contained a good deal of false closed depressions, particularly along stream drainages, due to the random distribution of the lidar data points. In streams, the data points may not follow the thalweg (flowline) of the creek, and may represent the top of a boulder or the stream bank, rather than the bottom of the creek, making it appear that there is an increase in elevation moving downstream, rather than a decrease. To remove some of these false signals, we filtered the data by removing closed depressions below a certain size limit.

For the purposes of this study, we filtered out all closed depressions less than 100 square feet in area (roughly a 10-foot by 10-foot rectangle.) We chose this filter for two reasons: 1) while there may be closed depressions related to karst terrain in the study area smaller than 100 square feet, there is a low likelihood that they would be accurately recorded by the lidar data, and 2) the filter substantially reduced the amount of noise (false positives) in the data set.

We evaluated this methodology by comparing the ArcMap generated map of closed depressions with a map of actual sink holes located by field mapping. Nolan, Zinn, and Associates (2005) performed detailed mapping of the UCSC campus and their study provided a map layer showing all recognized sinkholes on the campus. Figure 4 includes the sinkhole map for the central portion of campus. Also shown on Figure 4 is the campus sinkhole map overlaid with the closed depression layer we generated.

The GIS analysis recognized about half the mapped sinkholes. False positives still appear, despite the filter, but the closed depression layer was effective in identifying sink holes in areas that are not heavily forested. Despite the ability for lidar data sets to "see through" the vegetation canopy, the data set's resolution in areas of heavy tree cover is lower than in more open areas. The map was less accurate in areas under forest canopy and in areas with a high concentration of large buildings, as might be expected. It should be noted, however, that a number of the sinkholes mapped, especially in the northern portion of the map, were identified based on drill hole data rather than surface expression, and would not show up as closed depressions in any case. Consequently, we consider the accuracy of the close depression layer to be better than is indicated by simple inspection of Figure 4.

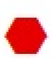
The closed depression layer also identifies ponds, reservoirs, and areas where fill embankments for roadways cross stream drainages. For example, an old City reservoir shows up as a closed depression on Figure 4, as does a stream drainage crossed by a large road fill (Figure 4). The closed depression layer for the study area is shown on Plate 1. The lidar data correctly identified closed depressions associated with wave troughs offshore (Plate 1). The closed depression layer was used in conjunction with the aerial photo review to select areas for field study.

WELL RECORD REVIEW

As part of this study, we reviewed 1,305 well records available from Santa Cruz County Environmental Health for the study area. These well records were classified based on whether they showed direct evidence for marble or evidence for large voids, which would be indirect evidence for the presence of marble.

The interpretation of well records is not always straight forward. Well drillers are not trained in rock identification and the purpose of well drilling is to find water, not to document rock types. Consequently, rock types may be mis-identified and changes in rock type may be missed or logged at the wrong depth. We therefore evaluated the well records both on the basis of whether or not marble was reported on the well log and also according to whether rock types indicated on the well log could be reasonably inferred to be marble. One of the principal indicators of marble or limestone are void spaces underground, which do not occur significantly in rocks that do not dissolve in water.

The well logs were classified as to whether marble was possibly or definitely observed and whether voids were possibly or definitely observed. The well locations with a probable or definite occurrence of marble or voids are plotted on Plate 1 according to the following classification scheme:

SYMBOL	MARBLE OBSERVED	VOID OBSERVED
	no	P
	P	no
	P	D
	D	no
	D	D

no = not observed
P = possible
D = definite

FIELD MAPPING PROGRAM

The field mapping program involved 133 hours of field time and was focused on areas of known marble outcrop and areas identified by the remote sensing and well record reviews as being areas of interest. Marble outcrops on the northeastern side of Ben Lomond Mountain and including the Fall Creek basin received particular scrutiny. There areas had not previously been mapped in detail, as had other areas of significant marble outcrop on and around the UCSC campus and the Bonny Doon marble quarry, including Laguna Creek. Field mapping was done on topographic base sheets at a scale of 1:4800. Significant features were located with gps- derived UTM coordinates. The results of the field mapping program are depicted on Plate 2, Marble Outcrop Map. Plate 3, Marble Structure, is a larger scale map of the marble outcrops showing structural information

We did not discover any large new outcrops of marble on Ben Lomond Mountain. We did, however, refine the mapping of marble, especially on the northeast side of Ben Lomond Mountain and near the Ice Cream Grade crossing of Laguna Creek, with modest increases in the areas mapped as marble . We also mapped a new, small marble body in the area of the Granite Construction Felton Quarry (Plate 2) that had not previously been documented. There may be some additional, though likely small, outcrops in the adjacent section of Gold Gulch Creek that we were not able to access.

Marble Outcrop Characteristics

The marble cropping out on Ben Lomond Mountain has been described in some detail by Leo (1967). In general, relict bedding is visible in the marble as foliations or expressed as thin layers of schist, a relict of thin sedimentary layers intercalated in the original limestone. Contacts with bounding bodies of schist or quartzite are generally parallel to the foliations in both bodies. The contacts and foliation in both the marble and schist are generally consistent over substantial areas. Veins or sills of granitic rock are common.

The structure of the metamorphic rocks is well documented on the UCSC campus because of the relatively large size of the mass, the exposure afforded by numerous marble quarries, and the boring logs from hundreds of geotechnical investigations that have been performed for campus development. The metamorphic rock is cut by a grid of east-west and north-south trending faults that is visible on topographic maps and aerial photos (Plate 3). The fault system is well expressed in surface topography due to solution of the marble by preferential ground water flow along the fault lines, which has etched them into the campus topography. Faulting is accompanied by some open folding.

The metamorphic body at UCSC appears as a mostly coherent, although faulted mass showing roughly east-west striking, moderately north or south dipping foliations and contacts between marble and schist layers (Plate 3). This pattern is repeated to a large extent in the marble bodies along the northeastern flank of Ben Lomond Mountain and in the marble sequence extending from the Bonny Doon marble quarry to the Ice Cream Grade crossing of Laguna Creek.

Marble outcrops on the northeast side of Ben Lomond Mountain and in the upper part of the Laguna Creek watershed show a consistent pattern of relatively small, lense shaped bodies elongate in and east-west direction, approximately parallel to strike of foliations (Plate 3). We also noted small lense shaped bodies of marble cropping out in Majors Creek (Plate 3). The larger marble bodies on the UCSC campus and at the Bonny Doon quarry are more tabular in form, but they maintain the mostly east-west to southeast-northwest strike of foliation.

In contrast, the marble in the San Vicente Creek marble body shows little in the way of coherently oriented foliations through much of the quarry. This marble body is partially enveloped in granitic rock, and it is possible that it suffered a higher degree of thermal alteration during intrusion of the granitic magma than in other areas.

We noted a modest cockpit karst type terrain forming over areas of marble at the Bonny Doon marble quarry (now mined out) and the marble mass along Ice Cream Grade. The terrain on the UCSC campus has a somewhat less well developed surface expression. Ben Lomond Mountain has been undergoing gradual uplift over the last 800,000 years or more and it is marked by a flight of marine terrace increasing in age with elevation. The geomorphic surface at UCSC is at a lower elevation than the Bonny Doon outcrops and it is therefore younger in age, which may explain its less mature karst related topographic expression. The San Vicente Creek quarry had already been substantially mined by the time of the early aerial photos (1940), so we could not tell whether it was associated with any particular surface expression prior to mining. The marble bodies on the northeast side of Ben Lomond Mountain have been extensively mined and are obscured by a dense forest canopy. It is difficult to drawn any conclusions regarding pre-mining surface expression.

All of the substantial marble bodies appear to be cut by faults and/or fractures (Figure 3). Contacts with surrounding igneous rocks usually cut across foliation and across contacts between the different metamorphic units. In some cases, the contacts between metamorphic rocks and granitic rocks appear faulted. In other cases, there is a noticeable thermal contact zone.

The marble body in the San Vicente Creek quarry is partially encapsulated by granitic rock (Plate 3). The contacts at the southwestern and northern ends of the lenticular mass dip back under the granitic rock. The eastern margin of the marble body is in fault contact with the granitic rock and it appears that the granitic rock was thrust over the marble. Vanishing River Cave extends back from the northeastern wall of the limestone quarry several hundreds of feet, indicating that the marble mass extends northeasterly from it surface exposure, at least partially under granitic rock thrust over the marble.

We also mapped a new marble body in a drainage that flows in a southerly direction from the middle of the Granite Construction's Felton Quarry property. Based on our field traverse, this marble body appears to be fully encapsulated in granite, but is bounded along it eastern margin by faulting. We also noted several boring logs that indicate marble bodies within the granite mass along a northwest- southeast axis passing through the quarry (Plate 2). One of the most southernly of these wells encountered "limestone" and a 50' high water filled void overlain (apparently) by granite. We did not note any evidence for a surface outcrop of limestone in this area.

Subsurface Occurrence of Marble

As can be seen on Plate 2, a number of wells encountered marble bodies at depth. In some cases, the marble bodies appear to be encapsulated in granite. We did not see evidence for surface outcrops of marble at these locations. However, the wells are typically approximately located, and in some cases mis-located, and not all well locations were readily accessible. We presume that, in most cases, the marble encountered in the wells comprise isolated masses that do not connect to form a karst aquifer, but we do not have adequate information in all cases to make that judgement.

We noted a feature of the sedimentary rocks overlying the marble body at San Vicente quarry that is of interest. The sedimentary unit directly overlying the marble is the Santa Margarita Sandstone. This unit typically consists of a weakly cemented friable sand. Where it overlies the marble, it is a hard, highly calcareous sandstone. The calcareous cementation at this site was also noted by Clark (1981). We also observed a similar calcareous cementation in the Lompico Sandstone in the lower portion of Laguna Creek.

We infer from the calcareous cementation in the Lompico Sandstone in Laguna creek below Smith Grade Road that the sandstone is locally underlain by marble. We made several other observations that support this inference. There are a number of wells in the vicinity that encountered marble (Plate 2). We also noted a tufa deposit on the bank of Laguna Creek about one-third of the way down Laguna Creek towards the ocean from Smith Grade Road. We infer this tufa deposit to be indicative of a former karst spring at this location.

We have noted a pattern of small lense-shaped marble bodies in the metamorphic complex (Plate 3). It is considered likely that additional marble bodies occur beneath the Tertiary sedimentary cover, including a sizeable marble mass underlying the Lompico Sandstone in lower Laguna Creek, as noted above.

Karst Springs

Plate 2 depicts karst springs derived from field observation and compilation of springs identified by other sources (Weber and Associates, 1989; Nolan Associates, 1996; Nolan, Zinn, and Associates, 2005; Nolan Associates, 2007). The karst springs are typically located on the down-gradient (downhill) side of marble outcrops where they abut non-soluble bedrock.

We have mapped a karst spring in San Vicente Creek under the existing quarry based on inference rather than direct observation. San Vicente Creek is carried through an at least partially artificial channel under the San Vicente Quarry. This channel intersects the cave system under the quarry and the cave system extending northeastward from the quarry face (Vanished River cave (Rogers, 1970)). These caves represent a small karst aquifer and we consider it likely that the karst aquifer drains into San Vicente Creek beneath the quarry.

Creegan and D'Angelo (1984) compiled stream flow data for flow gages on the upstream and downstream sides of the quarry. If there were a substantial spring under the quarry, we would expect to see significantly greater stream flow at the gage below the quarry during the dry season (corrected for the diversion for the Davenport water supply). The stream flow data is equivocal. We have included a spring at this location on our compilation map (Plate 2), but we consider the existence of a significant spring under the quarry to be an open question.

SUMMARY OF PRINCIPAL FINDINGS

1. We did not identify any large new outcrops of marble on Ben Lomond Mountain. Detailed mapping of previously recognized out crops in the Ice Cream Grade area of Laguna Creek and on the northeast flank of Ben Lomond Mountain did show that several of these out crops were somewhat larger than previously documented, but not substantially larger. We did identify a relatively small new outcrop of marble in the Felton Quarry.

2. There may be significant masses of marble buried by sedimentary rock in the lower Laguna Creek basin. There may also be some buried marble in the middle portion of the Majors Creek basin, although the evidence for this inference is not strong.

3. There appear to be masses of marble occurring as inclusions within the granite, based on review of the well data. These masses are very probably relatively small in size and not generally interconnected.

Please contact us if you have any questions regarding the marble mapping information or other aspects of this investigation.

Very truly yours,

NOLAN ASSOCIATES

Jeffrey M. Nolan, R.G., C.E.G.
Principal Geologist

Attachments: References
Figures 1-4
Plates 1-3

REFERENCES

Air Photos

1. UCSC Catalog Number: 1973-74
Flight Sponsor: Big Creek Lumber
Flown By: WAC Corporation
Scale: 1:15,840
Type: Black and White, 9"x9" prints
Frames: Flight Line 5, frames 5-1 to 5-10
Flight Line 6, frames 6-1 to 6-11
Flight Line 7, frames 7-1 to 7-13
Flight Line 8, frames 8-1 to 8-15
Flight Line 9, frames 1-1 to 1-15
Flight Line 10, frames 2-1 to 2-11
Flight Line 11, frames 3-1 to 3-8
Flight Line 12, frames 4-1 to 4-6

2. UCSC Catalog Number: 1943
Flight Sponsor: USDA
Flown By:
Flight Symbol: CJA
Scale: 1:10,000
Type: Black and White, 18"x18" prints
Frames: 2B-89 to -97
2B-75 to -85
2B-58 to -69
2B-38 to -50
2B-20 to -30
2B-3 to -10
1B-71 to -76

3. USCS Catalog Number: 1940
Flight Sponsor: USACOE
Flown By: Fairchild Aerial Surveys
Flight Symbol: C-6472
Scale: 1:18,000
Type: Black and White, 9"x9" prints
Frames: 47-57
61-70
80-98
103-111

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