Geologic, Hydrologic, and Hydrogeologic Technical Appendix for Bonny Doon Quarry Proposed Expansion EIR

1 Introduction

1.1 Purpose

CEMEX operates the Bonny Doon Limestone Quarry near Davenport in Santa Cruz County, California (Figure 1). In an application originally filed by RMC Pacific Materials (RMC), the previous quarry operator, CEMEX seeks to amend its use permit by expanding the working area of the quarry into an adjacent area of approximately 17.1 acres (Figure 2). The processing of this application by the Santa Cruz County Planning Department (SCCPD) requires preparation of an environmental impact report (EIR). In support of the EIR, this technical appendix provides an analysis of geologic, hydrologic, and hydrogeologic factors relevant to potentially significant impacts identified in the project's Initial Study (SCCPD, November 2001), and an assessment of potentially applicable mitigation measures.

A primary focus of this analysis has been to support an evaluation of the proposed CEMEX mining expansion in the context of protecting the City of Santa Cruz Liddell Spring water supply. This analysis has involved:

- Analyzing existing data on surface water and groundwater elevations, flow rates, and chemistry.
- Conducting any additional exploration, sampling, and analysis necessary to characterize the aquifer systems beneath the quarry.
- Developing a sound understanding of the hydrogeologic system underlying the quarry, the proposed expansion area, and the remaining recharge area of Liddell Spring.
- Identifying the dominant groundwater sources and flow pathways to Liddell Spring, particularly those pathways with the potential to be impacted by mining operations in the proposed expansion area.

1.2 Previous Work

Studies of the quarry-area hydrogeology were conducted prior to surface mining during the late 1950's through the 1960's (e.g., Wisser and Cox, April 1959; Todd, January 1963; Lindsey, July 1968). The conditions of Liddell Spring discharge were documented following site preparation and initial quarrying in the late 1960's and early 1970's (e.g., Wyckoff, February 1970; Nordquist, August 1970; Stewart, December 1971).

An EIR for the quarry operation in 1991 (Engineering-Science, April 1991) prompted two follow-up hydrogeologic assessments (Schipper and Reppert, February 1992; Watkins-Johnson Environmental, November 1992). A subsequent EIR (Thomas Reid Associates, October 1996) was followed by a series of hydrogeologic studies that included continuous springflow monitoring (e.g., SECOR, December 1998; EMKO Environmental, August 1999; Farallon Consulting, August 2001; Balance Hydrologics, December 2002). Concurrent studies addressed the landslide near Liddell Spring (Woodward-Clyde Consultants, 1997; Pacific Geotechnical Engineering and Balance Hydrologics, February 2002).

Most recently, the area hydrogeology has been investigated by P.E. LaMoreaux & Associates (PELA, May and October, 2005), for RMC, with ongoing monitoring of Liddell Spring and nearby springs by Balance Hydrologics (e.g., April 2005), for the City of Santa Cruz.

1.3 Available Data

The available database relevant to this hydrogeological analysis includes the following information:

- Lithologic logs for approximately 225 borings associated with the quarry.
- Water level and water quality data for approximately 40 quarry monitoring wells, 25 of which are still active.
- Information summarized from driller's reports of 43 water wells on surrounding and upgradient properties.
- The quantities and quality of water diverted by the City of Santa Cruz from Liddell Spring and Laguna and Majors Creeks.
- Monitoring of intermittently continuous discharge and water quality for Liddell Spring (since 1997), Plant Spring (since late 2002), the East Branch of Liddell Creek (since 2000), and Laguna and Majors creeks (most recently since 2003).
- Monitoring of quarry-pond water levels and x-ray diffraction analyses of suspended sediment samples, conducted by Nolan Associates.
- Various precipitation records.

Table 1 summarizes the periods of data record and data sources. Other recent data sets include those for tracer tests and an isotopic survey (PELA, May and October, 2005). Copies of some older studies with additional historic data were not available (e.g., Wisser and Cox, June 1960).

1.4 Study Objectives

The purpose of this study was to provide an evaluation of potential geologic, hydrologic, and hydrogeologic environmental impacts and constraints relevant to the proposed project. The proposed quarry expansion has the potential to cause several significant environmental impacts with respect to geologic and hydrogeologic conditions. The quarry is located in an isolated body of marble surrounded by granitic, metamorphic, and sedimentary rocks. Dissolution of the marble rocks along fractures by percolating groundwater has created a localized karst aquifer system of interconnected subterranean channels and caverns that are fed by groundwater inflow from adjacent rock bodies and by percolating surface water from above. Surface outflow from the karst aquifer system occurs at springs located in the Liddell Creek drainage on the southerly (downslope) side of the marble body. The principal spring in Liddell Creek is an important water supply for the City of Santa Cruz. Environmental concerns associated with the proposed quarry expansion include:

- Turbidity in Liddell Spring has the potential to impact the water supply for the City of Santa Cruz. Expansion of the quarry could cause additional turbidity in the spring water.
- The expanded quarry activity could potentially alter flow paths in the karst aquifer and reduce flows to Liddell Spring and Liddell Creek. Such an occurrence would impact the city water supply and the fisheries downstream of the spring.
- The renewed quarrying (including blasting), in conjunction with changes in surface or subsurface water flow, could affect the stability of a landslide adjacent to the spring facility, potentially impacting the spring diversion facilities and turbidity at the spring. These activities could also induce new landsliding within or adjacent to the quarry, potentially impacting the environment or persons working in the quarry.
- Extensive grading to remove overburden from the marble deposit in the expansion area and placement of the overburden soils as fill in the existing quarry will expose a considerable area to accelerated erosion, potentially leading to increased sedimentation downstream.

1.5 Scope of Services

Our study approach has been to organize and interpret the existing geologic, hydrologic, and hydrogeologic data for the quarry area and Liddell Spring, supplemented by specific, additional data collection. Because of the large volume of previous work that has been done in the Quarry area, we have been careful to acknowledge previous work and build on it, or refute it, as appropriate. Our scope of services for this project is summarized, below. The scope of our services included:

1) Review of relevant background geologic, hydrologic, geotechnical, and groundwater literature for the area.
2) Comprehensive review of existing reports regarding the project site and analysis of existing data to formulate a preliminary system model.
3) Peer review of existing geotechnical reports relevant to the proposed quarry expansion and potential quarry impacts on Liddell Spring
4) Inspection of stereographic aerial photos of the site and preliminary structural and geologic mapping from aerial photos.
5) Detailed, supplemental field mapping of the quarry site and surrounding area. This field mapping was intended to confirm and augment previous mapping. The field mapping included observations of high-flow conditions during, or shortly following, major storms, to document the flow paths, volumes, and fate of surficial waters.
6) Field observation and office review to assess the integrity and overall design of

the field studies by P.E. LaMoreaux & Associates. Included were observations of PELA tracer tests, field geophysical studies, and other field activities; inspection of field instrumentation sites; and review of raw data generated by PELA during these investigations.

7) Drilling and development of one additional groundwater monitoring well and observation of the drilling of three additional monitoring wells by P.E. LaMoreaux and Associates.

8) Monitoring of the new observation well for groundwater levels and monitoring of standing surface-water levels in the quarry during periods of heavy rainfall.

9) Collection and laboratory analysis of water samples as part of the dye tracer study performed by P. E. LaMoreaux and Associates (PELA, May 2005).

10) Collection of suspended sediment samples at Liddell Spring and other locations for mineralogical assay by x-ray diffraction.

11) Independent analysis of all available data and formulation of conclusions. Data analysis included development of a conceptual flow model for the local aquifer system (including the karst and surrounding rock bodies) to provide a framework for evaluating the potential impacts of quarry expansion. For this study, we relied on the following data, collected by other parties:

    i) groundwater level data from all monitoring wells.

    ii) flow, turbidity, and specific conductance measurements from Liddell Spring, the East Branch of Liddell Creek, and Plant Spring.

    iii) results of the dye tracer tests and geochemical or isotopic analyses of water samples.

    iv) results of the ground penetrating radar and other geophysical studies.

    v) results of ongoing monitoring of the landslide sites near Liddell Spring.

    vi) records showing the time and location of blasting at the quarry.

12) Preparation of this technical appendix, which summarizes our conclusions and recommendations. Our analysis and recommendations have addressed the following issues:

    i) description of the geologic, geotechnical, hydrologic, and hydrogeologic setting of the project.

    ii) assessment of the proposed mining plan with respect to the required separation from groundwater.

    iii) identification of potential geologic, geotechnical, hydrologic, and hydrogeologic impacts from the project, including:

        - increased turbidity at Liddell Spring due to the proposed quarry expansion and continuing quarry operation (including blasting);

- renewed movement of the landslides adjacent to Liddell Spring;
- slope instability, accelerated erosion, and sedimentation of downstream waters related to overburden removal and grading associated with quarry expansion;
- changes in recharge volumes, rates, water quality in the karst aquifer caused by overburden removal; and
- altered groundwater flow and quality caused by new quarry excavations intercepting voids or channels in the marble bedrock.

(iv) Mitigation recommendations for recognized, potentially significant or unavoidable impacts.

13) Attendance at project meetings.

14) Respond to comments on the Public Review Draft EIR

1.6 Bonny Doon Quarry

1.6.1 History

According to the Initial Study for the quarry expansion (SCCPD, November 2001), mining for marble at Bonny Doon began over 100 years ago, initially from a subsurface mine. The scope of this early mining, and whether or not it occurred at the same site as Bonny Doon Quarry, is unclear, however. Another marble quarry once operated to the northwest, along San Vicente Creek. Other nearby quarries yield mudstone (“shale”), which is also used in cement production.

Second-growth forest was logged from the Bonny Doon Quarry mining area in 1968 or 1969. The removal of overburden, consisting of soil and non-marble deposits, was completed by January 1970. Mining of the 80-acre marble quarry began in August 1970 (SECOR, November 1997). As anticipated by Todd (January 1963), quarry operations involved “blasting, vibrations by heavy equipment, and creation of fine rock particles and dust," while mining to within 20 to 100 ft of the water table.

Based on the estimated and actual rates of mining provided in the following table, roughly 37 million cubic yards of marble have been removed during the past 36 years. Averaged over the existing 80-acre quarry, this represents an average depth of mining of nearly 300 feet (excluding the depth of overburden).

1.6.2 Current Operation

The overall area of existing disturbance encompasses 240 acres, including the 80-acre marble quarry, shale quarry, disposal areas, sediment basins, and roads. On-site runoff is directed to the sediment basins. Silt is removed from the sediment basins each year, typically in August or September.

Period	yrs/ period	cum. yrs	yd^3/yr	yd^3/ period	cumulative yd^3	Source
1970 - 1985	15	15	1,000,000	15,000,000	15,000,000	estimate
1986 - 1997	12	27	1,236,000	14,834,000	29,834,000	actual (R. Walker/RMC, written communication, June 2006)
1998 - 2006	9	36	837,000	7,531,000	37,365,000	actual plus estimate for 2006 (D. Carlson/SCCPD, written communication, May 2006)
2007 - 2016	10	46	1,288,000	12,881,000	50,246,000	remainder of post-1998 modified mining plan, including 17.1 acre expansion area

The quarry operation diverts up to 21 gallons per minute (gpm) from Plant Spring southeast of the quarry (Figure 2), mostly for dust control. Reported water use from June through October 2005 averaged 19 gpm (D. Carlson/SCCPD, written communication, May 2006). Sewage is pumped weekly from a holding tank at the quarry office area.

The permits, regulations, and agreements under which the quarry operates include the following:

- Santa Cruz County Use Permit 3236-U.
- 1964 agreement with City of Santa Cruz, "Minimum Water Quality Requirements to be Maintained at Liddell Spring During Quarrying."
- Mining Certificate of Compliance (COC) 89-0492, July 1997, in accordance with County Mining Regulations (Chapter 16.54) and State regulations of the Surface Mining and Reclamation Act (SMARA); includes a Reclamation Plan for the Bonny Doon Limestone and Shale Quarries; the COC and Reclamation Plan are both addressed by the October 1996 Final EIR (Thomas Reid and Associates, October 1996).
- National Pollutant Discharge Elimination System (NPDES) Permit CA04775.
- Central Coast Regional Water Quality Control Board (RWQCB) Stormwater General Permit for Industrial Activities, regulated under Order 88-129.

- State Water Resources Control Board Water Quality Order 97-03-DWQ, General Permit CAS000001, Waste Discharge Requirements for Discharges of Storm Water Associated With Industrial Activities.
- 1600 Permit for sediment removal from the California Department of Fish and Game.
- 1600 Permit for waste disposal area C.
- HCP for the California red-legged frog.

County Ordinance Section 16.54.050 stipulates that the lowest elevation of any mining operation shall at all times be 20 ft above the peak groundwater elevation (unless the Planning Commission determines that a lower or higher elevation would ultimately benefit recharge of the aquifer). The ordinance defines an aquifer to be a saturated, permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients (Section 16.54.020).

1.6.3 **Proposed Expansion**

CEMEX proposes to amend Use Permit 3236-U, as modified under COC 89-0492, to expand the working area of the marble quarry into an adjacent area of approximately 17.1 acres. This area is outside the currently approved mining plan but within the maximum mining limit defined in the original use permit. Overburden material will be placed within approximately 17.1 acres of the existing quarry pit. The quarry's existing rate of water use will continue.

Mining will consist of working the benches outward toward the permit limits and dropping the pit floor from its current elevation of 763 feet above mean sea level (ft msl) to the permitted maximum depth of 750 ft msl. The working benches will maintain current dimensions—approximately 40 ft high by a minimum 16 ft wide.

As of 1998, RMC (the previous quarry operator) estimated a mining reserve of approximately 20.4 million cubic yards, including the 17.1-acre expansion area. Of this amount, an estimated 12.9 million cubic yards remain to be mined over an expected period of about 10 years (see the above in-text table). This additional mining would represent an increase of about 34 percent over the volume mined since 1970, and would result in an average mining depth of about 360 ft across the entire 87.5 acres (excluding the depth of overburden).

Because of the difficulty in pre-determining peak groundwater elevations due to the complex hydrogeology, CEMEX (following RMC's August 1999 application) proposes drilling shallow borings as the pit is lowered to test for groundwater. If groundwater is encountered in any borehole, CEMEX proposes to pump groundwater from the hole for 12 to 24 hrs. A sustained yield of 50 gpm or more would suggest that this zone is part of the "marble aquifer" (see RMC Lonestar, August 1999).

The County has concluded that the existing sediment control basins will adequately serve future quarry operations including the expansion area (SCCPD, November 2001). The quarry pit now acts as the terminus of a closed basin, allowing captured drainage to percolate to groundwater. The final quarry drainage plan will include grading an outlet from the quarry so that all runoff from the quarry is captured and directed to Sediment Basin 3 (Bowman and Williams, 2001). No increase in water use is expected.

2 Geology

2.1 Introduction

The Bonny Doon Limestone Quarry site is situated on the gently sloping southwestern flank of Ben Lomond Mountain, a large, eroded plutonic massif that has been up-faulted along its steep northeast-facing slope. The quarry presently occupies about 80 acres between native (pre-quarry) elevations of about 800 and 1100 feet above mean sea level (ft msl). Due to quarrying, the original topography has been modified into a large open pit with a floor between 750 and 760 ft msl. The proposed 17.1 acre amendment area will extend northeasterly from the present quarry into an area with native elevations between 1100 and 1235 ft msl.

The following discussion of the site geology is based on a review of published geologic maps and reports for the region, review of geologic and hydrogeologic reports prepared for the quarry by private consultants, a comprehensive review of the logs of exploratory borings and wells drilled on the quarry property, and limited field mapping by Nolan Associates on the quarry property and in surrounding areas. A catalog of borings reviewed for the project is appended as Appendix B.

The study area, as discussed below, includes the existing quarry and immediately adjacent terrain, as well as areas north and east of the quarry, extending eastward to Laguna Creek and northward to Ice Cream Grade. The study area is depicted on the Quarry Area Geologic Map (Plate 1). The study area was expanded east and north of the quarry because the dye tracer tests undertaken by P.E. LaMoreaux and Associates (PELA, May and October, 2005) indicated that these areas serve as source areas for groundwater exiting at Liddell Spring.

The existing geologic mapping for the quarry and surrounding area consists of a few regional-scale geologic maps (Leo, 1967; Clark, 1970; Clark, 1981; Brabb, 1997) and numerous larger scale geologic maps by various consultants who have worked on the quarry (e.g., Wisser and Cox, 1958; Watkins-Johnson, October and November, 1992; Jo Crosby and Associates, July, 1997; Farallon Consulting, March, 2000). Earth Sciences Associates (1971) also prepared a geologic study of the local area for Pacific Gas and Electric Company. The Earth Sciences Associates study included a portion of the present study area. The Wisser and Cox (1958) map was prepared primarily to help evaluate the occurrence of marble bedrock in the area before the local geologic setting was well understood. Many of the later maps were prepared for hydrogeologic investigations and were not based on detailed geologic mapping.

There is a wealth of boring data available for the current project. Exploratory drilling for the quarry began in 1958. In addition to the exploratory borings related to quarry development, several series of monitoring wells have been developed over time to help track groundwater conditions. We reviewed the logs of 309 borings (Appendix B); the locations of these borings are shown on Plate 2.

Our field mapping included four days of detailed mapping in the quarry, primarily to collect information regarding small-scale structures (faults, fractures, and bedrock layering), two days of reconnaissance mapping of terrain immediately around the quarry, and three days of field traverses in the area of Laguna Creek, Reggiardo Creek, and the Bonny Doon Ecological Preserve. The purpose of the mapping was to provide us with a better understanding of local bedrock structures that may influence groundwater flow.

Our field mapping served to refine previous geologic mapping, but we did not attempt to resolve every detail of the local geology. In preparing the geologic map, we made use of the exploratory boring data to the greatest extent possible. The boring data proved accurate in identifying igneous or metamorphic rock types but was unreliable for characterizing the nature and thickness of the overlying sedimentary rocks. In a substantial number of cases, the drilling data for the sedimentary rocks was contradicted by outcrop information.

The locations of borings shown on Plate 2 were based primarily on the locations given by SECOR (1997). We were also provided with a digital boring database by Mr. Robert Walker of CEMEX. We noted some differences in boring locations between the SECOR (1997) map and other sources, but have generally deferred to the SECOR locations. The locational accuracy of many of the borings, particularly the older ones, proved questionable. Monitoring wells M1A and M1B (and sinkhole SH-11), for example, were mislocated by 350 to 400 feet. Plate 2 shows the correct location of these features. As another example, boring 92D, located about 700 feet west-northwest of Liddell Spring, plots on top of a granitic rock outcrop, but the log of the boring shows about 30 feet of quarry spoils overlying 50 feet of shale on top of marble. We infer that this boring was actually located several hundred feet to the southwest, on the large mass of quarry spoils mapped there. Consequently, the boring data was used with care, and usually only to identify basement rock types. It was used only sparingly in defining the distribution and thickness of the sedimentary rocks and we deferred to outcrop data in all cases.

There are other potential sources for the disagreement between the boring logs and outcrop data other than locational inaccuracy. The marble surface underlying the sedimentary rocks is quite irregular and is marked by deep fissures and older (filled) dolines. We have not attempted to map the irregularities in the contact between the marble and the sedimentary rocks, and some of the variability in the boring data may reflect these irregularities. In some cases, the driller may also have mistaken doline fill for older sedimentary rocks.

2.2 Physiographic Setting

The study area is located in the central portion of the Coast Ranges physiographic province of California. The Coast Ranges include a series of mountain chains and intervening valleys paralleling the pronounced northwest-southeast structural grain of coastal California geology between Point Arguello, in Santa Barbara County, and the Oregon border. The study area is located on the southwestern flank of Ben Lomond Mountain, overlooking the Pacific Ocean (Figure 1). This side of Ben Lomond Mountain is a relatively broad, gently sloping surface displaying a series of ascending, stairstep-like topographic benches that are the remains of old marine terraces preserved by gradual uplift of the mountain. Visible marine terrace deposits are identified up to about 800 feet in elevation, and the effects of marine erosion probably extend farther up the mountain.

The broad surface forming the flank of Ben Lomond Mountain is cut by a series of southwest flowing streams occupying narrow, V-shaped stream valleys separated by wide, flat-topped ridges (Figure 3). This drainage pattern is locally interrupted where large bodies of marble bedrock crop out. In these areas, dissolution of the marble by percolating groundwater leads to the formation of sinkholes (or swallow holes) connecting to underground caverns. This type of topography is known as karst terrane and is typical in areas underlain by marble or limestone bedrock. Stream systems in karst areas tend to be discontinuous or absent entirely, since surface water flows into sinkholes rather than collecting into an integrated network of stream channels.

The topography of Ben Lomond Mountain in areas underlain by marble can be highly irregular, appearing as knobs or short ridges separated by short, intersecting valleys, with sinkholes often formed at the valley intersections. This topographic pattern is due to dissolution taking place preferentially along older fractures in the marble and is readily apparent in the study area on aerial photographs taken prior to development of the quarry. This pattern can also be seen in shaded relief on the Quarry Area Fracture Map (Figure 3). Figure 3 depicts the local fracture pattern based on inspection of pre-quarry aerial photographs. Similar patterns of fracture-controlled solution channels have been well documented in studies on the University of California campus in Santa Cruz (Nolan, Zinn, and Associates, 2005). The impact of the fractures on geology and groundwater flow will be discussed in more detail in a later section of this report.

2.3 **Regional Geologic Setting**

The quarry property is situated on the western slope of the central Santa Cruz Mountains, part of the Coast Ranges physiographic province. The northwest-southeast structural grain of the Coast Ranges is controlled by a complex of Pleistocene- and Holocene-active faults within the San Andreas fault system. Southwest of the San Andreas fault, the Coast Ranges, including the Santa Cruz Mountains, are underlain by a large, northwest-trending, fault-bounded, elongate prism of granitic and metamorphic basement rocks, collectively known as the Salinian Block. The Salinian Block is separated from contrasting basement rock of the Franciscan Complex to the northeast and the southwest by the San Andreas and the Sur-San Gregorio-Nacimiento fault systems, respectively (Figure 4, Regional Geologic Map). The granitic and metamorphic basement is overlain by a sequence of dominantly marine sedimentary rocks of Paleocene to Pliocene age and non-marine sediments of late Pliocene to Pleistocene age (Figure 4).

Throughout the latter part of the Cenozoic Era, this portion of California has been dominated by tectonic forces associated with lateral or "transform" motion between the North American and Pacific lithospheric plates, producing long, northwest-trending faults such as the San Andreas and San Gregorio, with horizontal displacements measured in tens to hundreds of miles. Accompanying the horizontal (strike-slip) movement of the plates have been episodes of compressive stress, reflected by repeated episodes of uplift, deformation, erosion and deposition of sedimentary rocks. In the Santa Cruz Mountains, this tectonic deformation is evidenced by folded bedding, faulting, jointing, and fracturing in the sedimentary rocks. Along the coast, the ongoing tectonic activity is most evident in the formation of the series of uplifted marine terraces that sculpt the southwest slope of Ben Lomond Mountain. The Loma Prieta earthquake of 1989 and its aftershocks are recent reminders of the geologic unrest in the region.

2.4 Regional Seismicity

California's broad system of strike-slip faulting has a long and complex history. Locally, the San Andreas, Zayante-Vergeles and San Gregorio faults and the Monterey Bay-Tularcitos fault zone present a seismic hazard to the subject project. These faults are associated with Holocene activity (movement in the last 11,000 years) and are therefore considered to be active (Cao, et al., 2003; Petersen et al, 1996; Hall et al., 1974). The properties of these faults are summarized below.

The region as a whole is subject to ongoing seismicity. The most severe historical earthquakes to affect the project site are the 1906 San Francisco earthquake and the 1989 Loma Prieta earthquake, with Richter magnitudes of about 8.3 and 7.1, respectively. Other historical earthquakes of note include two magnitude 6.1 earthquakes in Monterey Bay in 1926 and a host of smaller or more distant events. Refer to the Regional Seismicity Map (Figure 5) for the locations of faults and historical earthquake epicenters around the Monterey Bay area. The intensity of seismic shaking that could occur at the site from an earthquake generated by local active faults will be discussed in a later section.

2.4.1 Significant Faults

The principal active or potentially active faults in the study region are the San Andreas, San Gregorio, and Zayante-Vergeles faults and the Monterey Bay-Tularcitos fault zone (Figure 5). The San Andreas fault is the most active source for large earthquakes that may affect the study area. This major strike-slip fault (i.e., horizontal motion) is over 700 miles long and has been associated with several large, historical earthquakes, including the magnitude 8+ 1906 San Francisco earthquake and the magnitude 7.1 1989 Loma Prieta earthquake. The San Andreas is considered capable of producing a large (magnitude 7 or greater) earthquake every 100 to 200 years.

The San Gregorio is a moderately active strike-slip fault, although it has not been responsible for a large earthquake during historical time. The San Gregorio fault is generally considered capable of producing an earthquake of magnitude 7.0 to 7.6 (WGCEP, 1999), but the available data on its activity is poorly constrained. Such events are expected on the order of one every 400 years (Petersen et al., 1996).

The Zayante-Vergeles fault is a reverse or reverse/oblique fault (i.e., combined vertical and horizontal movement). It is considered to be active and has been associated with a recent magnitude 4.0 earthquake (Gallardo et al., 1999). However, the fault is thought to have a very long recurrence interval for large earthquakes, almost 9,000 years (Petersen et al., 1996). Consequently, the likelihood of a major earthquake on the Zayante-Vergeles fault during the next 50 years, and the corresponding risk posed to the project site, is probably small.

The Monterey Bay-Tularcitos fault zone is a postulated tectonic structure connecting a well-defined on-land fault, the Tularcitos, with one or more elements of the offshore Monterey Bay fault zone, which trends northwesterly from the Monterey-Seaside area across the Monterey Bay. This fault zone is considered to be Holocene active, with a recurrence interval for a magnitude 7.1 earthquake of about 2,800 years (Petersen et al., 1996)

The Ben Lomond fault is the fault closest to the study area (Figure 5). There is no evidence suggesting that the Ben Lomond fault is currently active, and we do not consider it to be a potential source of significant seismic shaking.

There are other active faults in the region that could impact the study area, such as the Hayward and Calaveras faults, in the eastern San Francisco Bay area, the Sargent fault, or the Monte Vista-Shannon fault. However, these other faults are more distant from the study area and are not expected to produce ground shaking at the project site as strong as that associated with seismic events on the San Andreas, San Gregorio, Zayante-Vergeles, or Monterey Bay-Tularcitos faults.

2.4.2 Historical Seismicity

The study area is located in a region that is characterized by moderate to high levels of seismic activity. The Regional Seismicity Map (Figure 5), depicts earthquakes of magnitude 4 or greater that have occurred in historical time within the region surrounding the study area. Table 2 lists the size and year of occurrence for earthquakes greater than magnitude 5 occurring in the proximity of the study area. It should be noted that earthquakes prior to about 1900 were not measured or recorded by modern seismographs. Consequently, the assigned magnitudes and locations of the pre-1900 earthquakes are approximate, at best. The older historical events were located principally by surveying published damage reports from local newspapers, entries in personal diaries, records of expenditures for repair of public buildings, reminiscences, and other historical sources.

A common measure of the severity of ground shaking accompanying an earthquake is the Modified Mercalli Intensity scale (MMI). The MMI scale is a subjective measure of ground shaking based on damage reports and eyewitness descriptions of shaking intensity. The MMI scale is given in Table 3. Modified Mercalli intensities that occurred near the study area during the 1906 and 1989 earthquakes on the San Andreas are summarized in Table 4. In each event, the higher intensities were reported for areas closest to the fault or areas underlain by young river deposits (alluvium), which tend to amplify shaking.

2.5 Local Geologic Setting

The geology of the study area is complex, a result of over 100 million years of geologic history, including collisions of crustal plates and multiple cycles of tectonic upheaval and erosion of the land surface. These episodes of tectonic deformation are recorded as metamorphism of older sedimentary rocks, intrusion of plutonic igneous rocks, folding and faulting of sedimentary layers, and by erosional remnants of once extensive geologic formations. The following sections summarize the types of geologic materials and geologic structure in the study area. The Local Geologic Map (Figure 6) and the geologic maps for the study area (Plates 1 and 2) show the distribution of these rock units.

2.5.1 Geologic Units

Rock units in the study area are separable into three major groups: granitic intrusive rocks, metasedimentary rocks, and sedimentary rocks of Tertiary and Quaternary age. These are described below:

2.5.1.1 Granitic Intrusive Rocks

The granitic intrusive rocks form the core of Ben Lomond Mountain and the pre-Tertiary basement for most of the Santa Cruz Mountains. Although primarily granitic, these rocks actually range in composition from gabbro to quartz monzonite and have been radiometrically dated as between 71 and 92 million years old, or Late Cretaceous (Leo, 1967). Field relationships and petrographic evidence indicate two or more distinct episodes of emplacement or intrusion (Leo, 1967). Generally, the granitic rocks are highly fractured and jointed and are now deeply weathered.

The largest body of granitic rock exposed in the study area is the Ben Lomond pluton, a medium-grained quartz diorite. The pluton is roughly elongate in shape, bounded to the east by the Ben Lomond fault, and is continuously exposed at the surface along the crest of Ben Lomond Mountain for a distance of about 12 miles. The quartz diorite is composed primarily of feldspar, quartz, hornblende, and biotite. It is light grey in color on fresh surfaces. Outcrops of the Ben Lomond pluton bound the quarry to the west and south (see Figure 6, unit qd).

The next largest plutonic rock unit is the medium- to coarse-grained granite of the Smith Grade pluton. The Smith Grade pluton extends eastward from Laguna Creek about 2-1/2 miles across the crest of Ben Lomond Mountain. This rock is described as adamellite (quartz monzonite) to granite in composition by Leo (1967) but is more properly called granite under the commonly accepted IUGS classification system. It is pinkish to grey in color where fresh. The major mafic constituents (dark minerals) are biotite and garnet. An oddly shaped finger of this pluton intrudes marble on the eastern side of the quarry property (see Figure 6, unit ga).

Numerous smaller bodies of intrusive igneous rocks outcrop on Ben Lomond Mountain, including gabbro, gneissic granodiorite, alaskite, and granite (Leo, 1967). In addition to these smaller bodies, dikes and sills of diorite, aplite, and pegmatite cut the both the plutonic igneous and metamorphic rocks of Ben Lomond Mountain. These thin, tabular or sheet-like bodies of rock are commonly injected along faults, joints or bedding and are generally not more than a few feet to a few tens of feet thick. The dikes and sills are not portrayed on the maps and cross sections that accompany this report, due to their small scale.

2.5.1.2 Metasedimentary Rocks

The granitic plutonic rocks intrude older (probably Paleozoic age) metasedimentary rocks consisting of schist, quartzite, and marble, with some hornfels and calc-silicate rocks. Schist is the most abundant of these rock types, followed by quartzite and marble. Leo (1967) estimated that marble makes up about 10% of the metamorphic assemblage. The metamorphic rock units form the majority of bedrock exposed in the quarry area. These rocks formed under regional metamorphic conditions and are thought to be correlative with the Sur Series metamorphic rocks of Trask (1926). Some local contact metamorphism is apparent near the igneous intrusive rocks (e.g., hornfels associated with diorite dikes and sills).

The schist, quartzite, and marble are exclusively metasedimentary. Foliation in the schist, and laminae of mafic minerals or thin schist layers in the marble, are parallel with each other and with non-faulted contacts between the two rock types, indicating that these metamorphic textures express relict sedimentary bedding. The age of the parent sedimentary rock is unknown and may be Paleozoic or Precambrian. Descriptions of the individual rock types follow.

- Schist

The schist is described as pelitic in origin (Leo, 1967) and is composed principally of quartz, biotite, and muscovite. Fresh unweathered exposures of the schist are metallic gray in color, but where deeply weathered and oxidized, the schist is a deep red-brown to reddish color. The schist displays excellent foliation, defined by the alignment of platy biotite and muscovite grains parallel to the original bedding planes. Numerous other minerals are present in the schist in minor amounts, including garnet, feldspar, cordierite, andalusite, sillimanite, and tourmaline. Quartzite is commonly interlayered with the schist (Leo, 1967; Stanley, 1984), reflecting the character of the original sedimentary rocks (shales and sandstones) prior to regional metamorphism, as well as the effects of contact metamorphism adjacent to the granitic intrusions.

- Quartzite

The quartzite is a dense, white to blue-gray metasedimentary rock composed primarily of quartz. The rock was formed by metamorphic recrystallization of relatively pure quartz-rich sandstones. The original sandy texture is visible in some hand specimens. Minor amounts of biotite (red-brown to black), and graphite (black) are present in the rock. Potassium feldspar-rich and calcite-rich quartzites are also present at some locations, reflecting the metamorphism of sandstones with mixed original mineralogy. The quartzite typically occurs as isolated blocks and as thin layers or lenses interbedded with marble and schist (Stanley, 1984).

- Marble

Marble is exposed throughout the quarry area. It is a finely to coarsely crystalline, calcite-rich marble, white where pure, and light green, blue, red, grey, or brown where colored by impurities. Outcrops are heavily fractured and jointed, and the marble is separated into large blocks by intersecting joint sets, as noted in local quarry wall exposures. The marble ranges from massive to having well expressed relict bedding, and it may contain thin interbeds of schist, quartzite or calc-silicates. Relict bedding may be expressed by thin laminae of mafic minerals, thin interbeds of other metamorphic rocks, or thin, alternating layers with variable resistance to chemical weathering (likely a result of compositional variations at the time of sedimentary deposition). Although there are moderate variations in relict bedding attitudes within any given marble body, the marble generally shows coherent structure.

The marble is dissolved by percolating ground water, with dissolution occurring preferentially along fracture surfaces. In the quarry walls, solution-widened fractures and cavities are identifiable by their distinctive solution-sculpted surfaces coated by “terra rosa,” a clayey residual soil composed of insoluble mineral constituents left behind after the calcite making up the bulk of the marble has dissolved.

2.5.1.3 Tertiary and Quaternary Sedimentary Rocks

Sedimentary rocks of Tertiary age and thin, surficial deposits of Quaternary age occur in isolated bodies on and around the quarry property. The Tertiary rock units include the Monterey Formation, Santa Margarita Sandstone, and Santa Cruz Mudstone, while Quaternary deposits include marine terrace deposits, doline fill, alluvium, colluvium, landslide deposits and soil (residuum).

- Tertiary Units

Monterey Formation

The Monterey Formation, of middle Miocene age, is described as an olive grey to light grey or light brown, thin- to medium-bedded shale and mudstone with some interbeds of silty sandstone. The unit is diatomaceous and often has a light, punky appearance (Earth Science Associates, 1971). Only a few scattered outcrops of Monterey Formation occur in the study area (Plates 1 and 2). The Monterey Formation is in conformable contact with the underlying Lompico Sandstone.

Santa Margarita Sandstone

The Santa Margarita Sandstone, of late Miocene age, is draped across a middle- to late-Miocene unconformity that cuts across all older rocks. The Santa Margarita is a medium- to coarse-grained, weakly cemented, poorly to moderately consolidated sandstone, composed primarily of rounded to sub-rounded, well-sorted grains of quartz and feldspar. Phillips (1981) describes the Santa Margarita Sandstone as "white, gray to yellow arkosic sandstone that locally contains abundant gravel, echinoid beds, extensively bioturbated sediment and abundant uni-directional crossbedded cosets."

The Santa Margarita Sandstone crops out at higher elevations throughout the quarry area (Plates 1 and 2). The Santa Margarita constitutes much of the "overburden" that must be removed before quarrying of the marble can begin in the quarry expansion area.

Santa Cruz Mudstone

The Santa Cruz Mudstone, of late Miocene age, consists of medium- to thick-bedded siliceous organic mudstone that is locally laminated. It is olive grey to dark yellowish brown where fresh, weathering to yellowish grey or off-white (Clark, 1981). It is moderately fissile, highly fractured, and tends to weather into small angular blocks. The Santa Cruz Mudstone conformably overlies the Santa Margarita Sandstone.

- Quaternary Units

Marine Terrace Deposits

Marine terrace deposits consist of well sorted, fine- to coarse-grained sand of marine provenance, overlain by fluvial and alluvial sediments deposited on a broad, coastal plain. The marine terrace deposits are mapped by Clark (1981) up to an elevation of about 800 feet. These deposits vary from about five to twenty-five feet in thickness. Only a few scattered terrace remnants are observed within the study area. Marine terrace deposits may exist at higher elevations, but they have not been distinguished from older, Tertiary sedimentary rocks.

The marine terrace deposits lie on relatively gently sloping topographic benches carved into the flank of Ben Lomond Mountain. This morphology reflects the origin of the terraces as wave-eroded platforms bounded on their landward edges by sea cliffs (comparable to modern sea cliffs). Each bench records one episode of marine erosion of the coastline, and the sequence of stairstep benches has been preserved due to gradual uplift of Ben Lomond Mountain. The lower terraces still form large, laterally continuous flat benches. The older terraces, occurring at higher elevations, have been subjected to erosion for a longer period of time and now appear mostly as flat spots or notches that can be traced from ridge crest to ridge crest.

Doline Fill

A doline, also called a sinkhole, is a closed depression resulting from collapse of the ground surface due to dissolution of the underlying rock. Doline fill consists of surficial materials that fill the depression, including alluvial or colluvial soils, residuum from weathering of the rocks in place, and rock that has collapsed or slid into the cavity. Doline fill has been mapped in areas where it was obvious at the surface, but it is likely that other areas of doline fill have not been identified.

We suspect that part of the problem with using the older boring data from the quarry to identify sedimentary rock formations is that doline fill often has been mistaken for sedimentary rock by the drillers.

Alluvium

Alluvium in the study area consists of thin, narrow bodies of unconsolidated stream gravel, sand, and silt deposited in the channels of creeks. These deposits are typically too small and thin to depict at the scale of our geologic maps and cross sections.

Colluvium

Colluvium consists of thin layers of unconsolidated rock fragments, gravel, sand, silt, and clay derived from the downhill creep (gravity transport) of soil and other surficial materials. The rock fragments in colluvium are usually angular, and the deposits are poorly sorted and massive (i.e., do not display bedding). The distribution of these deposits can be patchy, but most slopes are covered with at least a thin layer of colluvium. Colluvial deposits are generally are not more than a few feet thick, except at the base of steep hills, where they accumulate over time. Colluvium was not mapped for this study.

Residuum (soil)

All bedrock units are generally covered by a mantle of residuum produced by weathering of the rock in place. In the case of the granitic rocks and schist, the weathering mantle commonly retains relict rock structure (except within a few feet of the surface) and can generally be identified with its parent rock, even in a highly decomposed condition. In contrast, areas of the soluble marble bedrock are overlain by residuum that retains little character of the parent rock. In areas of marble bedrock, the residuum consists of insoluble clays and gravel- to cobble-sized fragments of marble (i.e., all that is left after dissolution of the bulk of the bedrock), sometimes admixed with colluvium or alluvium washed in from surrounding areas. Texturally, these materials range from clayey sand to silty clays and have a distinctive, deep reddish or reddish brown color. Residuum is not depicted on the geologic maps (Plates 1 and 2) because (a) it would obscure the more important, underlying bedrock geology, or (b) it occurs in deposits too small or discontinuous to be depicted at the scale of these maps.

Landslide Deposits

Landslide deposits consist of earth materials that have been transported downhill by sliding or earthflow. These deposits are unconsolidated, irregularly shaped and consist of mixed masses of soil, broken and decomposed rock, and/or recent sediment. We noted two landslide deposits in the quarry area (Plates 1 and 2). A landslide mapped adjacent to Liddell Spring has been extensively studied (Pacific Geotechnical Engineering, 2001). A second landslide occurred in the southeast slope of the quarry in 2006.

2.6 Geologic Structure

The study area is situated within the Salinian Block, defined by basement rock of metamorphic and igneous origin. The metamorphic and granitic rocks of the Salinian basement are sandwiched between basement rocks of the Franciscan Complex, a subduction zone mélange, with which they are in fault contact. The Salinian basement is akin to batholithic rocks and metasediments of the southern Sierra Nevada and the Southern California Batholith, but the mode of transport for this piece of crust from its point of origin to its present location is not well understood. Explanations include large scale strike-slip displacement of both right-lateral and left-lateral variety (Dickinson, 1976) or crustal scale overthrusting combined with right lateral displacement on the San Andreas fault system (Hall, 1990). Other models, based on paleomagnetic data, favor accretion of far-traveled blocks onto the California continental margin by plate movements (e.g. Howell et al., 1987). Geologic structure in the Salinian Block is a result of the intrusion of granitic plutonic rocks at depth into the metasedimentary “country” rock, in Cretaceous time, followed by uplift and erosional unroofing of the plutons and repeated cycles of sedimentary deposition and tectonic deformation throughout the Tertiary Period -- all of which reflects the Salinian Block’s location along an active continental margin for at least the last 100 million years. Deformation of the metasedimentary rocks during regional metamorphism and intrusion by granitic rocks, and also during later tectonic cycles, has been substantial. Nevertheless, the structure of metamorphic rocks in the study area appears to mimic the regularly bedded sequence of the parents sedimentary rocks (Plate 1 and 2). Our field reconnaissance included traverses down Laguna Creek and Reggiardo Creek, as well as across the Bonny Doon Ecological Preserve north of the quarry. Relict bedding expressed in both the schist and marble is consistent in and between Reggiardo and Laguna creeks and the Ecological Preserve (Plate 1). These rocks show regular, approximately east-west strikes with moderate northerly dips. Leo (1967) had previously mapped a pair of approximately east-west oriented fold axes crossing Laguna Creek within the mapped area. We did not see evidence for folding in our field traverses.

The elucidation of geologic structure in the metamorphic terrane was dependent on available exposures and the intensity of the mapping effort. In the few areas where exposures allowed access to detailed structural information, such as in the walls of the existing quarry, some degree of certainty was possible regarding the geologic structure. More commonly, the available exposures were insufficient, and any interpretation of geologic structure was necessarily based on a number of assumptions. We noted isolated schist layers within the marble, and also discrete marble layers within the dominantly schistose exposures. Consequently, it was not always clear whether isolated outcrops were expressive of the dominant rock type in the immediate area, or were merely prominent, less weathered interbeds within a contrasting rock section. Similarly, faulting appeared to be nearly ubiquitous in the metamorphic section, but determining the displacement on these faults was very difficult. Topographic lineaments, readily visible on aerial photographs, were common in areas underlain by the metamorphic complex. Experience has shown that such lineaments are often associated with faults or fractures. Nevertheless, the strikingly linear, north-south section of Reggiardo Creek east of the quarry lies hundreds of feet west of a well-defined, north-south fault in the marble, rather than following the trace of the fault as might be expected (Plate 1).

Because of these factors, the structural detail shown on the geologic maps of the study area (Plate 1) and quarry (Plate 2) reflects the availability of exposures rather than the actual structural complexity across the study area. In Laguna Creek, many isolated outcrops of marble are depicted simply as outcrops. In a few areas, outcrops were numerous enough that we inferred a thicker, more coherent section of marble, and these areas are depicted as such on Plate 1.

In our description of geologic structure, we have identified some features as fractures and others as faults. We define a fracture as a roughly planar break in the continuity of the bedrock. A fault is defined as a fracture that has experienced differential movement: rock on one side of the fracture has been displaced relative to rock on the other side, in a direction parallel to the fracture surface. (This basic definition of a fault does not address the question of its activity, however.) Accordingly, we have identified structural discontinuities as fractures if there was no indication of displacement and as faults if we observed concrete geologic evidence for differential movement. It should be noted, however, that some features interpreted as fractures -- based on the lack of evidence for substantial displacement -- may in fact be faults.

2.6.1 **Structure within Metamorphic and Granitic Terrane**

In areas with considerable marble, the metamorphic rocks are cut by orthogonal or near-orthogonal fractures, which are visible in the landscape as aligned valleys, swales, or notches in ridges. The fracture lineaments are often short and intersecting. In areas of karst, the fracture intersections are frequently marked by sinkholes. In some cases, these fractures are clearly faults with substantial displacement. In other cases, the fractures appear to have little displacement but have been etched into the landscape by preferential dissolution of the marble bedrock.

This type of structural pattern has been well documented in the nearby University of California campus, in Santa Cruz, where bedrock structure is revealed in multiple quarry exposures, road cuts, and over 1,000 exploratory borings associated with campus development. The strong topographic lineaments associated with these faults and fractures are generally not visible in adjacent areas of schist or granitic bedrock, however. Since it seems likely that any faults or fractures that cut the marble also cut the surrounding bedrock, it is our opinion that the clear geomorphic expression of these structures is dependent on dissolution of the marble. It is not clear whether these structures also extend into the younger plutonic rocks.

In the study area, there are two areas where the fracture patterns are clearly visible on aerial photographs. The principal area where these lineaments are visible is in the quarry area. Fault and fracture patterns taken from pre-quarry aerial photographs are depicted in Figure 3. A second area where this distinctive topography is visible lies near the crossing of Ice Cream Grade over Laguna Creek. Several sizeable marble bodies are found in this area (Plate 1). A lime kiln was constructed below Ice Cream Grade to process marble from nearby quarries on the east side of Laguna Creek 1.

In addition to the strongly expressed, semi-orthogonal lineaments noted in areas of marble outcrop, there are a number of weakly to moderately expressed lineaments trending east-northeast and north-northeast across the terrain between the marble quarry and the Ice Cream Grade marble outcrops (Plate 1). Some of these lineaments traverse areas dominated by schist outcrops, and some are even visible through the Santa Margarita Sandstone that blankets the metamorphic rocks north of the quarry.

Leo (1967) mapped a long fault trending northeast to southwest across the crest of Ben Lomond Mountain, which he named the Bald Mountain fault. This fault forms the contact between the Ben Lomond pluton and the Smith Grade pluton. Clark (1981) does not show the Bald Mountain fault on his geologic map of the Felton and Davenport 7.5-minute quadrangles. However, Clark does show several short, sub-parallel faults near the head of Gold Gulch, which follow the trace of Leo's postulated Bald Mountain fault. The faults on Clark's map displace pre-Miocene sedimentary rocks, as well as the plutonic rocks, but do not extend eastward or westward. Clark shows the contact between the Ben Lomond and Smith Grade plutons as being unfaulted.

We have mapped a portion of the contact between schist and the Ben Lomond pluton as a fault on the southwest side of the quarry (Plates 1 and 2). This fault was inferred on the basis of an apparent vertical offset in the contact between the Santa Cruz Mudstone and Santa Margarita Sandstone, which cap the basement rocks in this area. We did not see any additional evidence for faulting along this contact.

In the quarry exposure, we mapped a major structural discontinuity trending west-southwest. The layering of the marble within the quarry dips south to south-southwest on the southeast side of the discontinuity and west to northwest on the northwest side (Plate 2). This zone of discontinuity is coincident with several parallel or sub-parallel, curvilinear faults mapped in the quarry (Plate 2) and may represent a faulted antiform. The schist-marble contacts on either side of the zone are consistent with the relict bedding attitudes. The curvilinear faults follow a well-expressed topographic lineament that includes the narrow valley containing sinkhole SH-11 (PELA, May 2005), monitoring wells M1A and M1B, and a large, former sinkhole that has been mined out. This zone forms a major structural boundary in the quarry.

The Bald Mountain fault, as mapped by Leo (1967), would pass through the quarry roughly along the trend of this zone of discontinuity. However, it seems unlikely that a fault with the major offset postulated for the Bald Mountain would coincidentally juxtapose two large bodies of marble, with matching marble-schist contacts, as we observed in the quarry. Therefore, if the Bald Mountain fault does exist, it must pass south of the quarry. Although we did not observe any field evidence for this fault, our brief reconnaissance in the area east of Liddell Spring and south of the quarry did not rule out the possibility of the Bald Mountain fault passing south of Liddell Spring.

We mapped two faults trending northwest through the north west portion of the quarry (Plate 2). The eastern of these two faults truncates small igneous dikes visible in the quarry walls on the northeast side of the fault. It consists of a series of closely spaced surfaces, some of which are solution widened. The western fault is not well displayed, but appears to mark a change in relict bedding attitudes. The relict bedding in the marble on the northeast side of these faults dips northwesterly to north-northwesterly, consistent with relict bedding and the orientation of the schist-marble contact in the Reggiardo Creek area, to the east of the quarry. These faults therefore also appear to represent a structural boundary within the quarry, although not as pronounced as the discontinuity described earlier.

We noted many lesser faults throughout the quarry, but these features were not associated with distinct changes in the orientation of relict bedding. These faults included both low-angle thrusts and high-angle faults, with the amount of total offset usually indeterminate. In some cases, the faults seemed to form local structural boundaries, often marked by a difference in the spacing or orientation of joints across the fault. In other cases, offsets appeared to be minor. These lesser faults (or fractures) were numerous and have not been included on Plate 2.

The rocks exposed in the quarry are universally jointed. Although there is a fair amount of scatter in the data, two joint orientations predominate north of the axis of the postulated antiform within the quarry, one striking northwest and dipping nearly vertically, and the second striking northeast and dipping moderately to steeply northwest (Figure 7a). We did not collect enough joint attitudes from the south limb of the antiform to clearly define joint sets, but the available data show a rotation relative to the joints on the north limb (Figure 7b). Many of the joints in the quarry show evidence of solution, including raspy “meringue” weathering patterns and thick linings of terra rosa sediment. In visual inspection, concentrations of solution fractures in the walls of the quarry stand out as dark, steeply dipping zones separated by relatively lighter colored marble. The darker color of these zones derives from the concentration of terra rosa on the fracture surfaces.

2.6.2 **Structure within the Tertiary Sedimentary Section**

Geologic structure within the Tertiary sedimentary section is relatively simple. Formations below the mid-Miocene unconformity, the Monterey Formation and Lompico Sandstone, show local folding and faulting; these units crop out east of the quarry. The younger formations in the quarry area, the Santa Margarita Sandstone and Santa Cruz Mudstone, unconformably overlie the Monterey Formation and are relatively undeformed, with shallow dips to the southwest (Figure 6).

We have mapped a queried fault offsetting the Santa Cruz Mudstone and Santa Margarita Sandstone on the southwest side of the quarry (Plate 2). This fault was mapped to explain an abrupt change in elevation at the top of the Santa Margarita Sandstone between two adjacent but discontinuous exposures. Although the elevation mismatch could conceivably be explained by a buttress (cut and fill) unconformity between the Santa Margarita Sandstone and the overlying Santa Cruz Mudstone, this alternate interpretation seems unlikely given the deep-water depositional setting of the mudstone.

2.7 Surface Processes

Surficial geologic processes in the study area include weathering, erosion, and mass wasting (landsliding). Weathering of surficial materials and erosion by wind and water are the principal processes active in developing natural landscapes. When erosion leads to the development of steep slopes, landsliding may occur. In turn, landsliding breaks up the rock formations on the slope, leading to additional weathering and erosion. Weathering, erosion, and landsliding in the study area are discussed below.

2.7.1 Weathering and Soil Formation

Temperature changes near the ground surface, percolation of rainwater, and biological activity all contribute to weathering, which reduces solid rock to loose soil through a combination of chemical and physical processes. The thickness of the soil layer varies with slope gradient and direction, rainfall, temperature, biological activity, and rock type. Soils tend to be thinnest on ridge crests and steep slopes, where they are continually stripped by erosion and downhill creep. Thick soils develop on gently sloping surfaces, where the rate of weathering and soil formation greatly exceeds the rate at which the soil is removed by erosion.

For most rock types, the upward transition from unweathered, intact rock to soil takes place gradually, with the zone of weathered rock extending many feet, or even tens of feet, below the ground surface. In areas underlain by marble or limestone, however, the contact between rock and soil may be very abrupt. Weathering effects can be particularly deep in landslides, where pervasive mechanical fracturing of the landslide mass allows deep and rapid percolation of groundwater. The boundary between weathered rock and soil is generally fixed where the original mineralogy and "fabric" of the bedrock (e.g., the layering of sedimentary rocks, or the interlocking crystalline texture of granitic rocks) are replaced by the altered mineralogy and chemical by-products of weathering and the loose, open fabric of the soil. By this criterion, the soil thicknesses observed in natural exposures and road cuts in the study area varied from about one foot on the steeper slopes to about five feet on more gentle slopes.

2.7.2 Erosion

During our site investigation, we observed turbid runoff from the quarry area, some of which is captured by the quarry drainage system and carried to the sediment basins. However, most of the runoff from the quarry is retained within the topographic sink of the quarry floor, where it percolates into the marble bedrock. A small percentage of this ponded runoff evaporates.

The sediment carried by the runoff is derived from erosion of exposed slopes cut in the sedimentary units overlying the marble (the "overburden"); from weathered schist or diabase and hornfels exposed in and around the quarry; from residuum left behind after dissolution of the marble (terra rosa); from doline fill; and from spoils deposited following removal of overburden from the marble. This type of erosion is limited by the resistance of the rock materials, the relatively limited amount of erodible material actually exposed in the quarry, and by the lack of significant stream flow entering the quarry from surrounding areas (which would provide more erosive potential). The most erodible areas are the exposed surfaces of Santa Margarita Sandstone, covering a relatively limited area of the quarry.

The most erosion associated with proposed quarry expansion will likely to occur during stripping of vegetation and overburden removal, when large amounts of loose sediment will be generated by excavating and transporting the Santa Margarita Sandstone and Santa Cruz Mudstone. The excavation should be carefully staged to prevent erosion and sedimentation of downstream areas. The spoils piles generated by stripping the overburden will present the greatest danger of accelerated erosion. However, under the present mining plan, the spoils are to be placed and compacted within the quarry, where the hazard from erosion will be minimal.

2.7.3 **Landsliding**

Landsliding is a natural process that accompanies erosional downcutting and oversteepening of slopes. Like erosion, it can also be exacerbated by cultural activities. Road building or earth moving results in steep cut slopes and loose fill soils, both of which can be prone to landsliding. Roads can also collect naturally dispersed runoff and concentrate it into a rapidly flowing stream that can trigger erosion or landsliding.

We observed two landslides of significance in the area of the quarry (Plates 1 and 2). One of the landslides has been studied extensively by Pacific Geotechnical Engineering (PGE, 2001), because of its potential impact on Liddell Spring. The second one occurred in the winter of 2006 in the southeastern quadrant of the quarry. These landslides are discussed in greater detail, below.

2.7.3.1 Liddell Spring Landslide

The Liddell Spring landslide, as documented by PGE (2001), consists of two separate landslides that coalesce near the spring (Plates 1 and 2). Both landslides occupy swales in a topographic bowl east of the spring. They are relatively thin, surficial landslides developed in residual soils and colluvium overlying bedrock. The easterly of the two landslides was characterized by PGE (2001) as an earth flow developed in native soils. The western landslide is considered to be a series of debris flows that involve both native soils and spoils deposited on the slope by the quarry operation. The deposits from both landslide sources coalesce near the spring, resulting in a maximum combined thickness of about 29 feet. Landslide movement appears to have displaced the centerline of Liddell Creek about 30 feet westward, and it appears that Liddell Spring is exiting through landslide debris.

The landslide complex appears to have been stable since monitoring began in 2000 (Reid Fisher, personal communication, 2006). PGE (2001) concluded that the likelihood of renewed landslide movement was high in the eastern branch of the landslide and in the thick deposits near the toe of the landslide complex, but that this renewed movement would have a relatively low impact on the City of Santa Cruz's spring facilities. PGE (2001) considered the likelihood of renewed movement in the western branch of the landslide to be low. They also concluded that the future impact of quarry operations on landsliding would be low, assuming the quarry operator continues to maintain drainage control in the area. PGE's (2001) recommendations for mitigating landslide hazards included the following:

* continued monitoring to detect renewed slope movement within the landslide complex;

* continued measurement of groundwater levels and precipitation within the landslide area;

* dewatering of the landslide mass;

* maintenance of surface drainage controls, with improvements as necessary;

* hardening of spring facilities to reduce the potential for damage should landsliding recur; and

* development of a flexible emergency catchment/conveyance system.

To our knowledge, continued monitoring has been pursued, but dewatering of the landslide mass or other site improvements have not been implemented.

The hydrologic studies at the site indicate that the landslide mass is trapping water above relatively impermeable bedrock, and that seepage of this water from the landslide mass has the potential to impact turbidity in Liddell Spring. This conclusion implies that renewed movement of the landslide mass would likely increase turbidity of the spring (more so if the springbox were damaged by landslide movement).

2.7.3.2 Landslide in the Quarry

We mapped a recent landslide in the southeast quadrant of the quarry during our field reconnaissance in April 2006. We located the landslide using GPS-derived coordinates and examined materials exposed in its headscarp and lateral margins, but we did not conduct a detailed investigation. The landslide, about 150 feet wide and 320 feet long, moved as a rock and debris slide in weathered marble, along with a substantial soil component. The southern lateral margin of the landslide exposed up to 20 feet of soil, which we interpreted as quarry spoils; it is possible that the spoil-pile surcharge was a contributing factor in the formation of the landslide. We also examined the area on older aerial photographs and concluded that prior to quarrying there may have been a landslide on this slope adjacent to and south of the present landslide location.

The detachment surface exposed in the headscarp was an older shear zone of undetermined thickness, striking about N55°W and dipping steeply to the southwest (roughly parallel to prominent joints in this wall of the quarry). The older shear plane thus appears to have contributed to landslide movement. In our opinion, this landslide probably resulted from surcharge by quarry spoils and removal of subjacent support by quarrying, facilitated by a pre-existing plane of weakness. Monitoring wells M3A and M3B were destroyed by the landslide movement.

2.8 **Karst Processes: Geologic Influence on Groundwater Flow**

The study area has experienced episodes of subaerial erosion and submarine deposition throughout its geologic history, as indicated by the middle to upper Tertiary sedimentary sequence overlying the granitic and metamorphic basement. In the early to mid Pleistocene, the study area was subject to sea level fluctuations of 300 to 400 feet every 100,000 years on average, caused by worldwide climatic variations and episodic glaciation in the higher latitudes. More recently, it has been elevated hundreds of feet above sea level and exposed to subaerial erosion for at least the last 500,000 years (mid Pleistocene to Holocene), based on estimated uplift rates for this section of the coastline (Bradley and Griggs, 1976). In other words, over the last 25 million years, the marble body in the study area has had an extraordinarily complex hydrogeologic history, characterized by dramatic fluctuations in climate and base level.

Groundwater flow in areas underlain by soluble rock, such as marble or limestone, is substantially different than groundwater flow in most other types of rock. In most sedimentary rocks, water flows through the pore spaces between individual mineral grains. Sand and gravel, which have large, interconnected pore spaces, can have quite high hydraulic conductivities. Granitic rocks, composed of interlocking crystals formed in place, may have quite low hydraulic conductivities. The permeability of a rock unit can be enhanced by fracturing, which forms an intersecting network of cracks. Conversely, permeability can be greatly reduced by secondary cementation.

In marble or limestone, the initial permeability may be quite low, but even slight downward flow over time will gradually dissolve the rock, forming solution channels through which water can flow more readily. In some cases, the solution channels enlarge to form caverns with underground ponds and streams. These solution cavities usually begin forming along bedding planes, fractures, or faults. In the quarry area, solution of the marble is strongly controlled by the fracture patterns. The influence of the fracture system on dissolution of marble bedrock and groundwater circulation is well documented by the alignment of sinkholes along major fractures (or faults) -- and particularly by the preferential location of prominent sinkholes (open or buried) at the intersection of two fractures. This pattern of control is well expressed in the analogous but larger marble body underlying the University of California campus in Santa Cruz, located at the southern end of Ben Lomond Mountain (Nolan, Zinn, and Associates, 2005)

The exposure afforded by the quarry walls provides a remarkable view of the hydrogeologic character of the marble over a vertical distance of 350 feet. Solution-widened fractures in the quarry walls are steeply dipping to vertical and commonly form continuous zones of solution channeling from the original ground surface through the quarry floor.

For example, the mining operation has bisected a large, soil-filled sinkhole in the northeast corner of the quarry (identified as a large area of doline fill on Plate 2). This sinkhole was identified by PELA (May 2005) in their pre-Miocene bedrock contour map but had not been mapped as a sinkhole by prior researchers (probably because it was not visible at the original ground surface). The sinkhole is situated in a topographic low at the intersection of two prominent fracture trends. As exposed in the quarry wall, the sinkhole is filled at the surface with a reddish-brown sandy soil. The filled solution fractures are very wide near the surface (from several feet to a few tens of feet in width) and gradually narrow downward. We noted open and filled solution fractures at the level of the quarry floor that were on trend with the topographic lineament passing through the sinkhole. These open fractures were nearly vertical and several inches wide, displaying the irregularities characteristic of solution-sculpted surfaces.

PELA (May 2005) described the local karst system as including two semi-distinct aquifers, one serving the saturated zone (reflecting the “permanent” water table) and one serving the unsaturated zone (i.e., perched groundwater reservoirs), with poor hydraulic connectivity between the two. This characterization is not consistent with our geologic observations. Even a partial disconnect between the shallow (unsaturated) karst channels observed in the quarry walls and a deeper system of conduits would imply a pronounced change in the geologic structure that controlled the formation of these solution channels. Specifically, the vertical fractures observed in the quarry walls would have to be truncated at a depth just below the quarry floor, over an area at least as large as the existing quarry and the proposed amendment area. In our opinion, however, the observed steeply dipping to vertical bedrock fractures -- with solution channeling developed over repeated cycles of emersion and submersion -- favor the existence of a steeply dipping, through-going, system of groundwater conduits.

Our analysis does not preclude the existence of shallow, localized "sinks" that detain groundwater above the permanent water table. We observed sediment filled fractures as well as open fractures in the quarry walls and it is clearly possible for flow through specific fractures to be blocked. Although there is interbedded schist throughout the marble section (as well as igneous sills and dikes), SECOR (1997) concluded that these interbeds do not have a major impact on flow paths through the marble. We concur with this conclusion, because the formation of solution channels has been guided by fractures and faults that cut across the rock layering. However, it is possible for schist layers or igneous rocks to form local perched zones.

2.8.1 Groundwater Flow in the Karst Terrane North of the Quarry

The results of the dye tracer tests conducted by PELA (May 2005) indicate a groundwater connection between the streambed sinks in Laguna Creek, near Ice Cream Grade, and Liddell Spring, a distance of about 2.7 miles (Plate 1). Our reconnaissance of Laguna Creek, Reggiardo Creek, and the Bonny Doon Ecological Preserve provided additional geologic information for understanding the nature of this connection. We observed numerous, previously unmapped marble outcrops in Laguna Creek but were unable to define the lateral extents of the underlying marble bodies. We therefore mapped many of these exposures simply as "marble outcrop" (Plate 1). We did note sufficient field evidence to infer the existence a larger marble body near the contact with the Smith Grade pluton (Plate 1). It should be emphasized, however, that the marble contacts in this area are inferred. We did not observe any marble outcrops in our traverses across the Bonny Doon Ecological Preserve.

Prominent topographic lineaments in the Bonny Doon Ecological Preserve, an area largely underlain by the Santa Margarita Sandstone, are consistent with the pattern of fractures mapped in the marble terrane (Plate 1). These lineaments strike northeast to east-northeast from the quarry area across the Ecological Preserve, with the two southernmost lineaments trending toward marble outcrops mapped in Laguna Creek. These lineaments imply the presence of solution-widened fractures in marble underlying the Santa Margarita Sandstone in the Ecological Preserve. Mapping in Laguna Creek indicates that marble layers within the schist are relatively common throughout this area. These observations, in conjunction with the dye tracer test results (PELA, May 2005), indicate the existence of karst solution channels beneath Laguna Creek and the Ecological Preserve.