Appendix A: Suspended Sediment Mineralogical Study

We performed two series of x-ray studies on both water and sediment samples. The first series included x-ray diffraction (XRD) analyses on samples collected in February, March, and June 2004. The initial series was intended as an index study to evaluate the finest fraction of suspended sediment from different sources, to look at key mineral constituents that might permit us to identify specific sources for Liddell Spring. The second series consisted of XRD studies of sediment from the quarry, intended principally to evaluate the amount of calcite in fine sediments in the quarry. These samples were collected in March 2006. For the loose material samples, only the finest fraction of sediment was analyzed by mixing the material in distilled water and selecting only the particles that remained in suspension after set periods of time. These two series will be discussed separately, below.

2004 Series

In February and March 2004, we collected 1-gal water samples containing suspended sediment from Reggiardo, Whitesell, and West Branch of Liddell creeks; Liddell and Plant springs; and quarry monitoring wells PELA-3 and NZA-1. The samples from West Branch of Liddell Creek were collected above the confluence with the East Branch of Liddell Creek. The stream and spring samples were collected on February 24, 2004, during a period of significant rain (Figure A-1). The samples from the two wells, PELA-3 and NZA were collected on March 16, 2004, about two weeks following significant rain. The time lag between collection of the two sample groups was based on logistical concerns, and was not part of the sampling strategy.

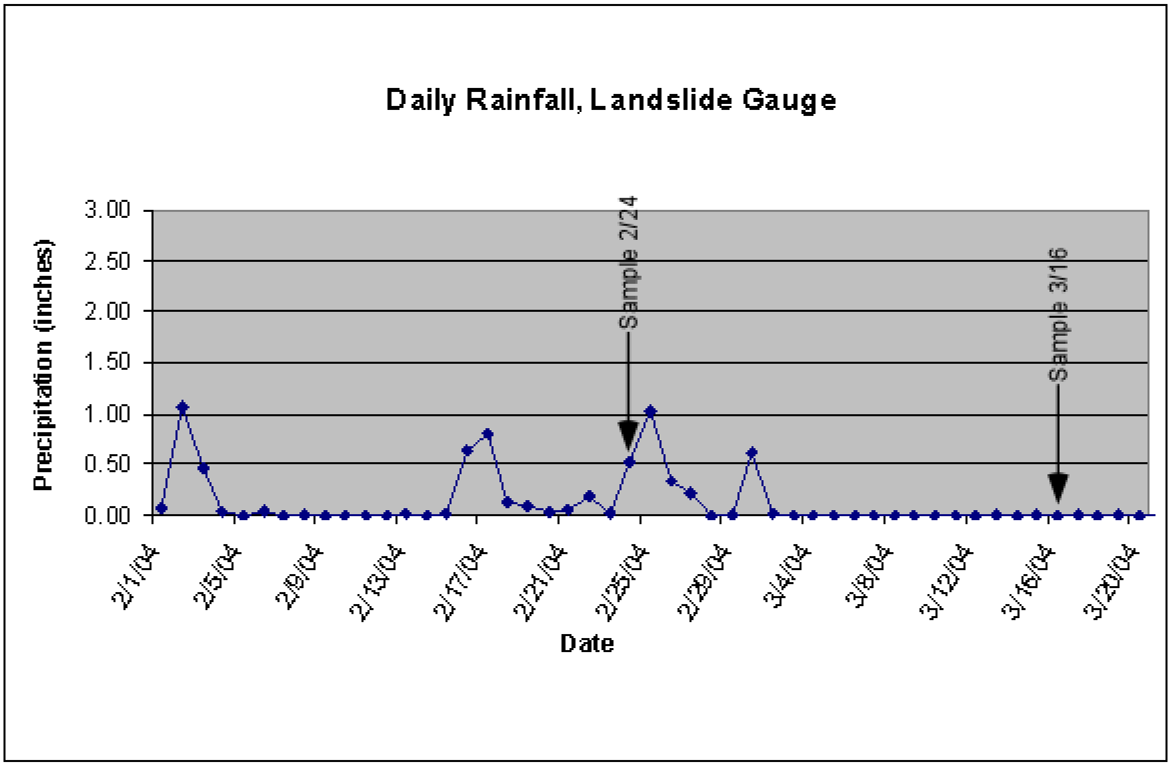
In June 2004, we collected the following two bulk samples of doline fill from Bonny Doon Quarry:

- Sample GS-1 was from a 20-ft wide doline formed in marble on the first bench off quarry floor on the north side of the quarry. It consisted of a mix of moist to wet gray, clayey, silty, fine-grained sand and dry to moist, red to reddish brown, sandy, angular gravel with abundant marble fragments.
- Sample GS-2 was from a thin (<1 ft) crack fill in the marble on the third bench (counting upward from the floor of the quarry) on the northeast side of quarry. It consisted of dry red silt with fine-grained sand that was weakly cemented into friable rounded fragments.

Samples GS-1 and GS-2 were prepared for analysis by placing them in buckets with approximately 2 gal distilled water. After sitting for one week, the water and suspended sediment were decanted into 1-gal containers.

All suspended samples were run through a filtration device using glass fiber filters. The sediment adhered to the filters, which were then placed wet onto standard glass slides and dried at approximately 60ºC. The slides were loaded into the diffractometer and scanned from 4 to 45 degrees two-theta. The resulting XRD plots are shown on Figures A-2 to A-4. The analytical results of the XRD analysis are summarized below in Table A-1. This testing did not attempt to determine relative proportions of the various constituents. The water sample from Plant Spring was essentially sediment free and therefore no results are reported for the spring.

Figure A-1



The results show a predominance of quartz and clays, as would be expected. Both of the well samples showed a significant calcite component. Well NZA is situated within the quarry and might be expected to show significant calcite if there is seepage from the quarry floor. However, PELA3, located upgradient from the quarry, also showed a significant calcite content. The West Branch of Liddell Creek showed a calcite component, although the stream is not shown as draining any marble on the regional geologic map (Brabb, 1997). This result could indicate previously unrecognized flow into the creek from the karst aquifer.

These results do not provide an obvious means of identifying a specific source or sources for Liddell Spring. Goethite was identified in the sediment samples taken from the quarry. Goethite is an iron oxide mineral derived from weathering. It is reddish brown in color and probably accounts for some of the color in the *terra rosa* sediment that lines many solution widened fractures in the marble. The results do suggest that goethite could be used as an indicator of turbidity that is due to mobilization of the *terra rosa* sediment.

2006 Series

We collected a second set of samples in April 2006. Samples were collected from near the NZA well site at the south end of the quarry. There were two types of samples

Table A-1

	STREAMS			WELLS		SEDIMENT SAMPLES		SPRINGS
	Reggiardo	West Branch Liddell	Whitesell	PELA3	NZA	GS-1	GS-2	Liddell
Prevalent Mineral Species	*Quartz* *Kaolinite* *Illite*	*Quartz* *Calcite* *Albite* *Illite* *Mont.**	*Quartz*	*Quartz* *Calcite* *Kaolinite* *Mont.**	*Calcite* *Mont.**	*Quartz* *Albite* *Goethite* *Mont.**	*Goethite* *Kaolinite* *Illite* *Mont.**	*Quartz* *Kaolinite* *Illite* *Mont.**

**Montmorillonite*

collected: a) sediment lining the surfaces of marble fractures and b) sediment that had washed off the sides of the quarry and settled in the pond at the bottom of the quarry. After mixing each sediment sample into a volume of water, we poured off 1-gal samples of water at different time intervals, creating the following suspended sediment samples:

- BDQ NZA-C1: fracture lining sediment that remained suspended after 1 minute.
- BDQ NZA-C10: fracture lining sediment that remained suspended after 10 minutes.
- BDQ NZA-P10: pond sediment that remained suspended after 10 minutes.

The 10-minute samples were intended to represent sediment more likely to be transported in suspension to Liddell Spring. The purpose of the 1-minute sample was to evaluate changes in suspended sediment composition relative to average grain size, which is inversely proportional to settling time.

All of the samples were analyzed by UCSC staff. At the time of analysis, the samples were shaken to re-suspend the sediment. A split sample was then passed through a glass-fiber filter. Sediment that adhered to the filters was placed wet onto standard glass slides and dried at approximately 60°C. The slides were then loaded into the diffractometer and scanned from 4 to 45 degrees two-theta (corresponding to 22 to 2.01 angstroms d-spacing). The resulting XRD patterns were plotted and analyzed using an Omni Instruments TXRD v. 4.10. Estimates of relative mineral proportions were performed by measuring the principal peaks (minus background) and comparing their relative heights to one another. This process provided approximate estimates of the relative proportion of minerals.

The XRD results are presented in Table A-2, along with XRD data collected previously by Balance Hydrologics (2005). Five mineral species were found in all three samples: quartz, smectite clay, illite clay, calcite, and hydrous chlorite. All samples were dominated by quartz and clay, and only one sample had a third mineral above 10 percent (calcite in NZA-C1).

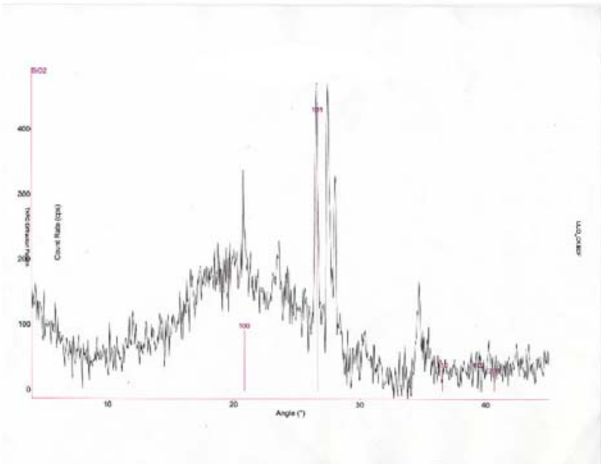
Table A-2

	BALANCE HYDROLOGICS						**NOLAN ASSOCIATES**		
Source	Liddell Spring					Liddell Creek	Fracture Coating in Quarry		Pond Sediment from Quarry Floor
Sample Date	12/7/04	12/8/04	12/8/04	12/28/04	1/3/05	12/27/04	3/15/06	3/15/06	3/15/06
Sample No.							bdq-nza-c10	bdq-nza-c1	bdq-nza-p10
Quartz%	10	16	7	10	10	12	38	35	43
Feldspar%	14	15	15	19	27	19	--	--	--
Amorphous%	--	--	--	--	--	10	--	--	--
Calcite%	5	14	19	5	12	10	10	21	10
Total Sheet Silicates*%	72	54	59	66	50	48	47	37	46
Unaccounted%	<5	<5	<5	<5	<5	<5	5	17	2
Totals	101	99	100	100	99	99	100	100	101

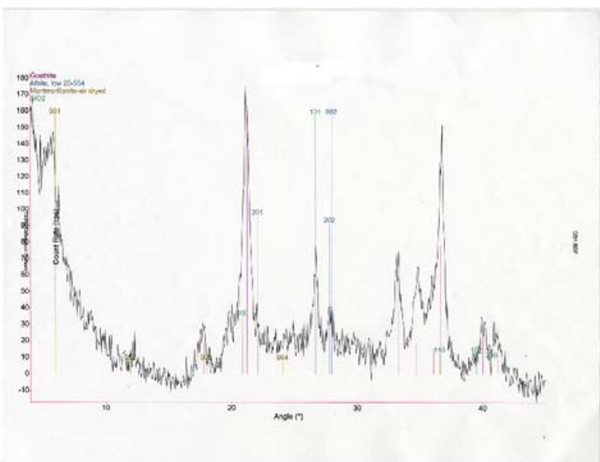
*Clays, micas, chlorite

About twice as much calcite was in the 1-minute settling sample compared to the 10-minute settling sample. Much of the macroscopic sized sediment observed on the quarry floor appears to be fresh, angular grains of calcite. Based on its visual appearance, we are of the opinion that this material is derived from mechanical reduction of marble as part of the quarrying process. It was our hypothesis that the percentage of calcite in the samples would decrease with decreasing particle size due to two factors: a) the mechanically derived calcite grains found in the quarry are likely to be relatively course in comparison to natural weathering products (such as clays), and b) the smaller calcite particles tend to dissolve more readily, due to the increase in surface area relative to volume with decreasing particle size. The results of the analysis suggest that one or both of these factors are in effect.

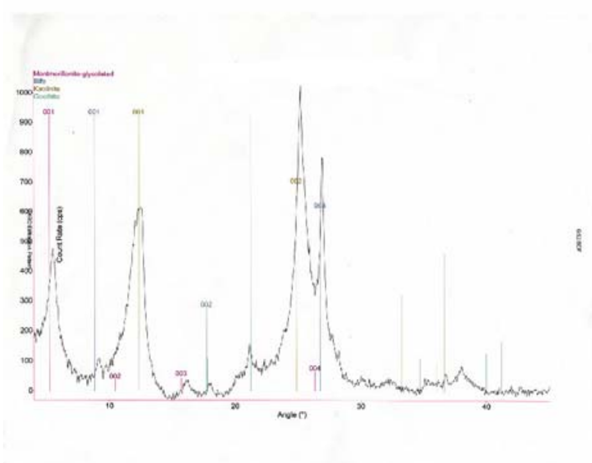
PELA (May 2005) asserted that the suspended sediment observed in Liddell Spring could not originate from quarry operations because only a relatively small portion consisted of calcite. However, we found that our prepared samples of loose material from the quarry had similar percentages of calcite as suspended sediment samples from Liddell Spring (e.g., samples BDQ NZA-C10 & -P10, Table B-2). The quarry sediment samples differed from the Liddell Springs samples most conspicuously by the occurrence of feldspar in the Liddell Spring samples that is entirely missing from the 2006 quarry sediment samples. These results suggest that there is a significant allogenic source for turbidity at Liddell Spring. However, we note that one of the grab samples from the quarry in 2004 contained albite, and the Reggiardo Creek sample did not. Additional sampling and x-ray diffraction studies would likely refine our understanding of turbidity sources. In particular, x-ray analyses of specific particle size ranges responsible for turbidity at Liddell Spring may provide a better understanding of the analytical results.



Whitesell Creek



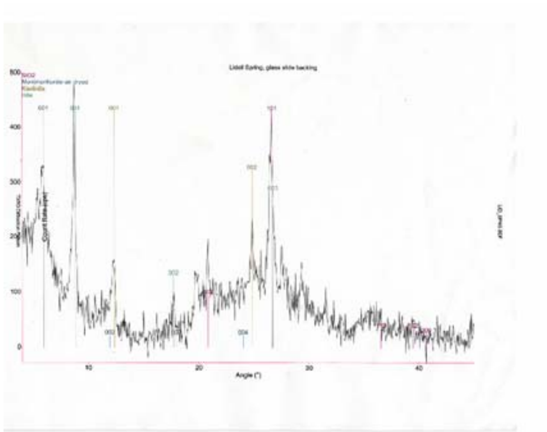
Grab Sample-1



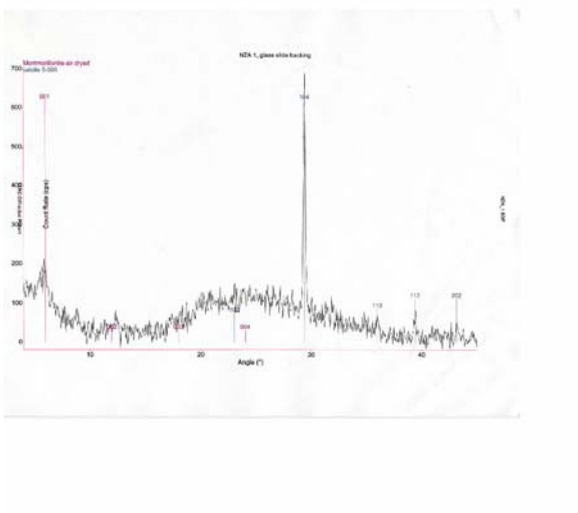
Grab Sample-2

Figure A-2

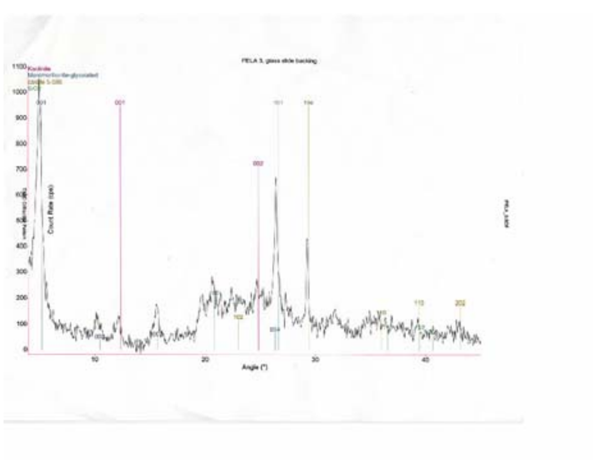
Nolan Associates



Liddell Spring



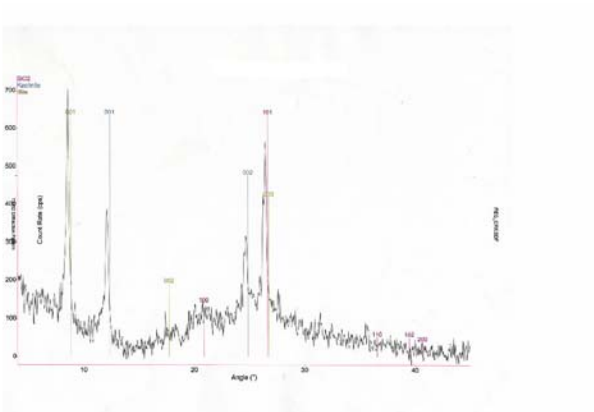
NZA



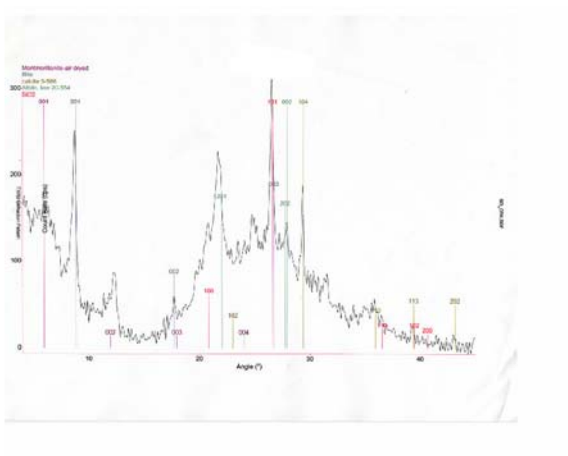
PELA-3

Figure A-3

Nolan Associates



Reggiardo Creek



West Branch Liddell Creek

Figure A-4

Nolan Associates