APPENDIX G

FINAL DUST STUDY

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DEVELOPMENT, DUST AND ROCK ART IN NINE MILE CANYON, UTAH

A REPORT ON THE IMPACT OF DUST GENERATED BY INDUSTRIAL TRAFFIC ON DIRT ROADS IN NINE MILE CANYON

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BACKGROUND AND SUMMARY INTRODUCTION TO THE REPORT

1.1 INTRODUCTION

Nine Mile Canyon is located within the rugged heartland of central Utah. It offers many outstanding scenic, recreational, historic and prehistoric resources. Among all of these resources, the prehistoric and early-historic rock art of Nine Mile Canyon arguably takes pride of place. The rock art primarily is petroglyphs (with some pictographs) carved and etched into the sandstone shelters, cliff faces and boulders of Nine Mile Canyon and adjacent canyons.

The West Tavaputs Plateau is rich in energy resources, specifically large fields of natural gas. Nine Mile Canyon provides the primary access road to the West Tavaputs Plateau. The need for energy has increased exponentially in the United States. The technologies employed to extract and transport gas from any site, including the West Tavaputs Plateau, have improved greatly. A need for energy, in tandem with advanced technology, now make exploitation of the gas fields economically feasible.

The West Tavaputs Plateau does not have a single "owner." There are privately held lands (6 percent) and State of Utah lands (8 percent), but much of the West Tavaputs Plateau is in the public domain as federal lands (86 percent), under the jurisdiction of the Bureau of Land Management (BLM). The BLM has existing leases with the Bill Barrett Corporation (BBC) and other oil and gas operators. These leases allow BBC and other operators to exercise valid lease rights. Utilization and upgrades of existing infrastructure are permitted, including installation of gas well pads, pipes, roads, and other support systems for the purpose of extracting and transporting natural gas.

Although utilization of Nine Mile Canyon remains subject to strict federal regulations, environmental organizations, Native Americans, and other citizen groups have raised many concerns. The outstanding rock art has become a major issue and source of contention. Specifically, there is fear that the drilling of gas wells, road construction, road traffic, and installation of other infrastructure, will create extraordinary amounts of dust that will settle on, permanently disfigure, and otherwise damage the many important rock-art panels. Secondarily, there is concern that hydrocarbon pollutants from industrial traffic and other sources also may impact the rock art.

There has been alarm about the use of the salt, magnesium chloride, employed for dust abatement on the roads in some areas of the canyon. Magnesium chloride can be an effective control for dust. However, it is also a documented agent of deterioration of concrete and some works of art, as will be explained in this report. While there is no evidence that magnesium chloride has---or can---damage the sandstone substrate of the rock art, its use in the canyon has become a major concern.

Several types of salts are a natural component of the dust that in Nine Mile Canyon. Hence, additional concerns have been raised about the potential to contaminate the rock art with salts found *in situ* in the canyon. Internal pressure from salts is but one natural agent that can cause the weathering of stone.

The BLM is the principal steward of the resources of Nine Mile Canyon, the rock art, natural environment and natural gas. The BLM anticipated that dust could pose a threat to the rock art of Nine Mile Canyon and thus took action in 2005 to initiate a scientific study of potential dust problems, including possible mitigation measures. Under the supervision of Julie Howard, BLM archaeologist (Salt Lake City), a grant application was written to the Department of Energy requesting funds for a study of impacts from dust. Unfortunately, the grant application was declined.

Subsequently in 2006, at the request of the BLM, BBC agreed to fund a study of dust in Nine Mile Canyon. Preservar, Inc. (principal and author of this report, Constance S. Silver) initiated this study in 2006. The first phase of the project was completed in December, 2006. The primary objectives were to research precedents, if any, for scientific studies of the effects of dust on rock art, and to establish a research design that would conform to prevailing scientific standards for the study of particulates, especially the impacts of particulates on cultural property

A significant finding is that this study of the effects of dust on rock art in Nine Mile Canyon is pioneering research. One earlier study of dust and auto emissions near rock art was undertaken in Australia at the Split Rock Site (Watchman 1998). Currently, only one study relevant to Nine Mile Canyon was located and is now underway at the highly important petroglyph site in Burrup, Australia. As will be discussed in this report, the differences between the two projects---Burrup and Nine Mile Canyon---are substantial, and the Burrup project cannot serve as a model for the current research in Nine Mile Canyon.

The second phase was initiated in July, 2007. It entailed field work in Nine Mile Canyon to record scientifically the genesis and impacts of dust on five selected rock art-sites, and to collect samples for laboratory analysis. A first draft of the report was submitted to the BLM in August, 2007. A preliminary report followed in October, 2007.

The third and final phase of this research is the final report, which was written following peer review and additional research. The final report includes all data and provides recommendations for a course of action to protect the rock art of Nine Mile Canyon from impacts from dust.

1.2
THE WEATHERING OF STONE AND THE SCOPE OF THE RESEARCH

All stone that is exposed to the environment will weather and deteriorate: the rolling Appalachian mountains once were as high as the Himalaya peaks. The weathering of stone can be defined as the physical and/or chemical breakdown of geologic materials. However, the actual processes of weathering can be quite complex, as well as being stone-specific and environment-specific. Arid and semi-arid environments can be especially destructive to stone through the actions of several agents of deterioration: insolation; freeze-thaw cycles; condensation; rain-washing; aeolian abrasion; and salt burst and efflorescence are possible agents of deterioration.

Biodeterioration has been recognized as a major agent of the weathering of stone, resulting primarily from the metabolic reactions of a myriad of highly specialized bacteria. Some bacteria metabolize calcium carbonates, others silica stones. Yet other bacteria are specific to iron and manganese. Man-made agents of deterioration can be added to the long-list of natural ones. These include the very destructive acidic by-products of industrial life, generally referred to as acid rain, and various caustic and abrasive particulates.

Thus, very complex processes of deterioration are at work on stone everywhere on the planet. Identification of the agent, or multiple agents, of deterioration that are responsible for the weathering of a particular stone in a specific place, such as Nine Mile Canyon, presents many challenges. For this reason, the scope of the research by necessity had to remain focused specifically on dust deposition and the special issues inherent in the use of magnesium chloride in the canyon. Secondarily, possible exacerbation of weathering as a result of deposition of naturally occurring salts also was considered.

This study of dust on rock art in Nine Mile Canyon encompasses many disciplines; the fields of geology, stone conservation, particulates, pollution, and rock art are all superimposed in this research. Each of these fields now has a vast body of literature and attendant pages of bibliographic references. However, some of this literature is out of date, has been proved inaccurate by subsequent studies, is simply not germane to Nine Mile Canyon and, in the case of many "rock art studies" does not withstand normal scientific peer review. For these reasons, the bibliographic references have remained highly focused and selective.

1.3
RESEARCH DESIGN: WHAT IS DAMAGE FROM DUST AND IS THERE A REMEDY?

This study of the effects of dust on rock art of Nine Mile Canyon is predicated on an assumption that required scientific investigation: that excessive amounts of dust generated by industrial traffic can---and have---settled on and damaged the canyon's rock art. Is this assumption correct? To answer this question it is imperative to articulate how dust could damage rock art. It is also essential to clarify an inherent handicap that effects this study.

One type of damage is disfigurement of a rock-art panel by heavy deposition of dust so that the panel is visually marred and obfuscated. Because the rock art of Nine Mile Canyon is eligible for listing on the National Register of Historic Places, visual disfigurement is a prohibited negative impact. Some rock-art panels in Nine Mile Canyon do manifest buildups of dust. Hence, it is all but certain that proscribed visual disfigurement has resulted from the dust generated by industrial traffic.

But does the deposition of dust truly cause physical harm to the rock art? How can physical harm be defined? Isn't dust always present in arid and semi-arid environments and, therefore, always settling on the rock art? More specifically, hasn't the road been in place for more than 70 years and hasn't traffic always generated dust that was deposited on the rock art?

For the purposes of this study, physical harm is defined as the irreversible entrapment of road-generated dust into the surface of the sandstone, permanently changing its original appearance and physical properties. What are the mechanisms that cause this type of harm? It is likely that this harm can only occur when the pores of the stone surface of any panel are larger than the particle size of the depositional dust. As a result, the fine particulates become permanently entrapped in the pores. This process can be visualized by imagining a room in a house. The window is left open and a storm carries dust into the room. The dust that settles on the glass window is easily removed because the glass is a slick, non-porous surface that the dust cannot enter. However, a white silk scarf left near the window might be permanently altered because the fine particulates are blown into the interstices of the silk fibers, become fixed in place, and create a spotty beige appearance rather than the original pristine white.

Other negative impacts also are possible, but not immediately able to be confirmed. Dust could damage the sandstone substrate of the rock art by facilitating deposition of airborne salts, introduced magnesium chloride and the naturally occurring salts that were scientifically identified in the dust in the course of this study. All of these salts are hygroscopic to varying degrees and could, therefore, provoke expansive pressures in the pores and interstices of the sandstone, leading to fractures and flaking. Salt-related weathering of stone is well known, but freeze-thaw cycles resulting from water entrapped in rock also can provoke mechanical damage and flaking.

Excessive amounts of dust in the air could exacerbate aeolian abrasion of the rock art by repeated abrasive scouring. Aeolian abrasion of temples did occur at the sandstone site of Petra, Jordan. However, the vector was removal of protective vegetation, which permitted local sandstorms to reach the surface of the temples.

These types of damage remain hypotheses because there are many mitigating factors. Magnesium chloride becomes destructive only when in contact with specific materials, such as concrete, and with adequate ambient water present to facilitate the corrosive chemical reactions. The cementious minerals of the sandstone of Nine Mile Canyon may be impervious to the effects of magnesium chloride. The sandstone surfaces of Nine Mile Canyon may be so dense and compact that they are largely impervious to infiltration by airborne salts. For dust to become abrasive, its particulates must be considerably harder than the sandstone itself.

All of these potential conservation problems are further complicated and obfuscated by the absence of baseline data on the rock art, such as archival-quality photographs. There are site forms for many rock-art sites in Nine Mile Canyon. However, there is almost no photographic documentation of the rock art. Consequently, there is no way to compare the condition of sites before and after the current industrial traffic commenced in the canyon. In the absence of baseline data there is no way to objectively measure changes in condition that could be the result of deposition of dust. Such changes could be sudden growth of microflora, obfuscation of the surfaces, and new weathering patterns.

The research design for the study of dust in Nine Mile Canyon was developed to address several questions within a delineated scope of investigation. The first objective is to determine whether dust released into the air, primarily by industrial traffic in Nine Mile Canyon, can settle on and alter adjacent rock art. The second objective is to determine if magnesium chloride can be identified on dust at rock art sites and to review the advisability of this salt as a dust-abatement system. The third objective is analysis of naturally occurring salts in the dust and their deposition on rock-art sites. The fourth and final objective is to develop a second-phase program whose goals will be development of remedies.

1.4
LITERATURE REVIEW

A general review of literature was undertaken on the scientific analysis of dust and particulates. A more focused literature review was carried out on the effects of dust on cultural property, specifically rock art. There were secondary reviews of the effects of salts on cultural property.

This research confirmed that the overall scientific literature on dust is remarkably vast because dust is a powerful vector that affects the entire planet, from climate change to human health. However, scientific literature on the impacts of dust on cultural property outside of museums is quite sparse, although there is a large body of literature on the effects of combustion-derived particulates. Indeed, there is almost no scientific literature on the effects of dust on rock art specifically.

The literature on salt-related damage to cultural property created from stone is quite extensive. However, much of it is not germane to Nine Mile Canyon, for many reasons. Some of the literature addresses materials other than sandstone. Some sites are in steaming tropical jungles or polluted and snowbound cities rather than arid steppe climates. Other sites are complex buildings rather than sandstone massifs and boulders.

1.5
DEVELOPMENT OF THE RESEARCH DESIGN: THE SCIENTIFIC STUDY OF DUST IN NINE MILE CANYON

Theoretical and instrumental methodologies appropriate for analysis of dust on rock art in Nine Mile Canyon were developed following literature searches. As described, there is a vast amount of scientific literature on dust and other particulates, and on many possible research methodologies. Consequently, the major challenge for this study was to cull information in order to develop highly practical and cost-effective systems for the scientific study of dust specifically in Nine Mile Canyon.

The selected analytical methods eventually were adapted from industrial hygiene models. A major analytical laboratory in the United States, EMSL (New Jersey), was selected to provide analytical services, for several reasons. EMSL has a dedicated department for the study of particulates and has had extensive experience in this area of analysis and research. EMSL also can offer unified services: assist in development of field collection systems; provide the required instrumentation; undertake laboratory analysis of samples collected in the field; produce scientific reports on the findings; and assist in the interpretation of data. EMSL also has a geologist on staff.

Two field collection systems were devised in collaboration with EMSL. One system utilizes a particle counter (the Lighthouse 3016/5016). This instrument records the size and concentration of particulates by size in the air in real time. By using the particle counter, it is thus possible to record the relative concentrations of particulates in the air, by particle size, at any site before, during and after the approach of a vehicle.

Five quite different rock-art sites in Nine Mile Canyon were selected for study. In addition to on-site analysis with the particle counter, samples were collected in the field. Bulk samples were taken from roads adjacent to the five rock-art sites, to determine the size and mineralogical profile of particulates subject to disturbance by vehicles. Petri dishes were also left at the selected rock-art sites for a period of 24 hours. The purpose was to determine deposition of dust that settles from the air and to analyze the settled dust to ascertain the composition and likely source of the particulates.

Additionally, at some sites small samples of rock were removed from the extremities of panels, in order to determine if they have become contaminated overtly with dust and with magnesium chloride.

1.6
FIELD WORK

In July, 2007, the author and Julie Howard, Archaeologist, BLM, spent four days in Nine Mile Canyon, to observe traffic and dust at five selected rock-art sites. On-site observation of the roads and rock-art sites was a highly important component of the research. It was possible to study the industrial traffic, its effects on the road, the generation, height and duration of clouds of dust, and the deposition of the dust on rock-art sites.

Particulates in the air were studied with the particle counter before and after the passage of traffic on the road at the five selected rock-art sites. As described in 1.4, depositional particulates were collected in petri dishes exposed at sites for a period of 24 hours. Comparative samples were collected from adjacent sections of the road(s). Samples of some rock also were collected at sites, to determine if magnesium chloride is a component of the dust.

1.7
LABORATORY ANALYSES

Sixteen samples were collected during the field work in July, 2007. They were sent to EMLS for analysis. The results will be discussed in a following section of this report.

1.8
SUMMARY CONCLUSIONS AND RECOMMENDATIONS

Data collected during the field work in July, 2007, confirmed that heavy vehicular traffic has pulverized the dirt roads of Nine Mile Canyon and releases clouds of fine particulates into the air. If a rock art panel is nearby---as is the case with site 42Cb239, the Hunt Scene---dust will settle on the panel and does create a serious conservation problem because the panel is visually marred. Because Nine Mile Canyon is eligible for the National Register of Historic Places, this obfuscation by dust constitutes a proscribed condition that must be remedied.

At this stage of the study, other research questions about possible negative impacts have not yielded such clear answers. The final section of this report will review other dust-related problems that may impact the rock art of Nine Mile Canyon.

1.9
RECOMMENDATIONS

In order to develop remedies, additional research will be required. The final section of this report will outline a recommended program for conservation research and dust abatement.

2
UNDERSTANDING PARTICULATES AND SANDSTONE

The rock art of Nine Mile Canyon occurs on sandstone. Thus, the research is really an investigation of the ability of dust to provoke the weathering of, or other damage to, sandstone. Therefore, preparatory to discussing the research undertaken in the course of this study, it is useful to review dust and sandstone.

2.1
SUMMARY OF THE LITERATURE REVIEW: FOCUS AND CAVEATS

In its many forms, dust has become a critical subject of research in all scientific disciplines. The result is scientific literature on dust that is truly vast. A major challenge for this study, therefore, was to narrow the focus to areas of research that are specifically germane to the understanding of dust deposition on rock art.

Consequently, the literature review focused on the following areas:

- The scientific definition of dust.
- Scientific standards for the measurement and analysis of dust.
- The general effects of dust, in general, on cultural property.
- Analysis of dust specifically on rock art.

A general summary of the scientific definition of dust is provided as an essential preface to the study.

2.2
THE SCIENTIFIC DEFINITION OF DUST AND THE EFFECTS OF DUST GENERALLY ON CULTURAL PROPERTY

There is no doubt that deposition of dust on cultural property is a major concern in conservation. At the very least, dust soils a surface, and the soiling can become a permanent aesthetic flaw if the particulate is so fine that it becomes entrapped within the surface or fabric of an object.

However, dust also can be chemically active and even corrosive. Some dusts are hygroscopic and will attract and hold water. That liquid water, in turn, can become acidic and act as a corrosive or, conversely, create a welcoming microclimate for microbes. In this regard, it should be noted that micro-organisms can act as a significant vector for the deterioration of stone. If freezing occurs, very damaging mechanical stress could take place through freeze-thaw cycles.

It is illuminating to examine dust that is generated by modern building construction. Harmful dust can come from many sources, including new concrete and cement buildings. These buildings give off a dust of ultra-fine particulates at the low end of the range (0.01 microns) which can easily pass through most normal air filtering systems. The alkalinity of these particulates is strong enough to damage hardened oil paint, silk, and various dyes and pigments (Toishi 1965). This single example provides some idea of the complexity of air-borne particulates and their potential to harm cultural property.

A standard publication on conservation *The Museum Environment* (Thomson 1994), helps to answer questions essential to this study: how is dust defined scientifically and why is it a source of real concern for the conservation of all types of cultural property? Relevant passages from *The Museum Environment* (1994: 131-135 and 244-253) are provided:

> THE PROBLEM
>
> . . .The problem of solid dirt in the air of cities is not new, and complaints date back much further than Faraday and Eastlake's investigation of air pollution in the National Gallery, London.[1] The acid vaopours which belched out of furnaces with the smoke were also known to Faraday. However, the automobile has produced a distinctly modern form of pollution known as the oxidant type.
>
> Air pollution is associated with towns and industry and is almost entirely caused by the burning of fuels.
>
> To deal with air pollution we must be able to measure it, and it is simplest to adopt a universal system applicable to both solids and gases, for gasses can be weighed just like solids. We therefore measure the concentration of a pollutant by finding the weight of it in a given volume of air. The unit commonly used is *micrograms* of pollutant per cubic metre of air, abbreviated $\mu g/m^3$ or μgm^{-3}. A microgram is a millionth of a gram. If we write the word 'Air Pollution' firmly with a soft pencil on a piece of paper we might add about 100 µg to its weight.
>
> Concentrations of gases are often quoted in parts per million (ppm) or parts per billion (ppb). Note one billion equals one thousand million. One part per million of sulphur dioxide in air simply means that if we could separate the sulphur dioxide from the air its volume would be one millionth of the volume of the air it came from. . .
>
> . . . In town museums the suspended dirt in the air gives rise to an obvious problem. Some of the particulates are heavy enough to settle in still air, but our major concern is

[1] Thompson refers to a report of 24 May, 1850, written by the interdisciplinary team of scientist Michael Faraday, designer Charles Eastlake, and art historian William Russell, to the House of Commons regarding the effects of air pollution on works of art in the National Gallery, London.

> with those that are too small ever to settle under their own weight, and therefore to enter into the furthest corners of buildings. Dirt on museum objects, especially textiles, not only becomes unsightly as it accumulates, but sooner or later necessitates the risky operation of cleaning.
>
> Within the last half-century various gaseous pollutants have become a world-wide hazard to the health of both people and antiquities.

Thompson then provides a concise explanation of the nature and behavior of particulates:

> PARTICULATES
>
> Two terms are currently in common use for the solid particles suspended in the air: particulates and aerosol. The former will be used here. Other terms, particularly 'smoke' which is sometimes limited to the products of incomplete combustion, are too imprecise. Particles that settle in still air can be referred to as dust, or sometimes grit, which seems most appropriate.
>
> The sizes of particulates are conveniently scaled by quoting diameters in microns (1 micron ((abbreviated as μm) = 1 thousandth of a millimetre). In what follows, a size of one micron means a diameter (not radius) of one micron.
>
> The particulates, though they might all seem too small to measure, vary hugely in size. Particles larger than 15 or 20 microns settle near their source of origin or at worst on window sills. Particles smaller than this remain suspended until trapped on some surface. The bottom end of the scale can be taken as 0.01 micron, a hundredth of a micron. . . and a good deal smaller than the wavelength of visible light (1/2 micron). This gives us a range of three orders of magnitude in diameter, or 1000 to 1. . .
>
> Since the particulates produced outside the building arise largely from the burning of fuels in power stations, and from vehicles and heaters there is a lot of sooty and tarry material in them. They are also usually acidic from adsorbed sulphur dioxide and often contain traces of metals such as iron which can catalyse deterioration.
>
> Particulate distributions are today most commonly represented in this fashion, following the work of Junge. The only differences are that we usually divide particulates into groups by diameter rather than area, and it is more useful to consider the mass of particulates in a given size range rather than their number. . .

Thompson's discussion of particulates in the air is especially useful for the dust study in Nine Mile Canyon. It also provides some idea of the complexity of the study of particulates, which also has a forensic component:

> . . . The particulates in the air – the actual suspended dirt particles – fall into three distinct size ranges. Starting at the large end, the upper size limit is governed by the maximum size of a particle still in the air at some distance from its source. This is obviously a variable quantity: in a sandstorm grains well over 1mm (1000 microns) in diameter can be carried large distances. In still air everything over about 15 microns settles, but smaller particles remain indefinitely suspended until they hit and stick to something. . .
>
> The size range of the largest particulates, from above 1 to 20+ microns, is called the Coarse Particulate range, because it has been formed either by direct mechanical action (e.g dust formation, grinding processes, fine sand) or shot directly into the air as particles (e.g. ash, pollen, sodium chloride from the sea). Rain rapidly scavenges coarse particulates but has little effect on particulates below 2 microns.

> But not all particulates are thrown into the air directly. Some are formed in the air itself. So we now turn our attention to the smallest particulates, in the Nuclei range, comprising all particles below 0.1 microns diameter. A more or less complete coverage is obtained with a scale that begins at 0.01 microns. One typical man-made source of these ultra-fine particles is the automobile (there is a wider range from the combustion of coal), but nature produces them too from aromatic plant evaporates which polymerise in the air on dry sunny days to form a haze of Nuclei.
>
> Whatever the source, the Nuclei are unstable and therefore transient, with a half-life of no more than 12 hours. Indeed to bag a fair sample of man-made transient Nuclei from a heavy traffic route the sampler should be less than a couple of kilometers away.
>
> By coagulation the Nuclei transfer themselves to the Accumulation range. This, our third and middle range, comprises diameters roughly between 0.1 and 2 microns. We shall now be able to see that this Accumulation range is the most important for museums to deal with and therefore dictates the type of air filter to use.
>
> First, the black tarry matter in smog started life as gases formed in the higher-temperature combustion processes (cars and oil-fired power plants). Photochemical reactions yielded particulates in the Nuclei range, which presently coagulated into the Accumulation range.
>
> Secondly, this range includes sulphates and nitrates, the end oxidation products of SO_2 and NO_2, together with ammonia.
>
> Thirdly, it can be calculated that most of the surface in an average collection of particulates is on those in the Accumulation range. All particles adsorb gases and vapours. Therefore, most of the adsorbed pollutant gases will be on particles in the Accumulation range. . .
>
> . . .To make sure of a sample where the distribution of particles had aged, falling into the Accumulation range of about 0.1 to 2 microns, the sampler was taken out to the desert 200 km NE of Los Angeles where local emission of large particles was very low and cars were not present. Nevertheless, when the wind was in the right direction a fairly large sample of aged Fine particulates carried from Los Angeles was collected. The small hump between 1 and 10 microns shows that some Coarse particulates were also present.
>
> In general particulate counts have this bi-modal distribution, meaning that there are two peaks. The peak with mass maximum around 10 microns shows the Coarse particulates. The second peak, near 0.1 microns represents the Nuclei and accumulation particulates. . .

It is useful to conclude with a final passage from Thompson. Thompson points out that no area of Europe of North America is free from industrial pollutants, and that particulates are produced naturally by forests and plants.[2] As will be discussed further in this report, Thompson's observations about the constant "background noise" of natural and man-made particulate pollution motivated some caveats for interpretation of data from the field work in Nine Mile Canyon:

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[2] Very detailed scientific discussions of the nature of particulates and their impacts on cultural property also can be found in the 2002 publication *Pollutants in the Museum Environment: Practical Strategies for Problem Solving in Design, Exhibition and Storage*. However, this publication addresses these issues as they relate to objects in museums.

PARTICULATE CONCENTRATIONS TODAY

In the U.K. and probably in most of Western Europe the situation was - literally – at its blackest before the passing of the Clean Air Act in 1956. Smoke levels at Kew, a suburb of London, were falling when records were started in 1922. Average winter levels were near 1000 $\mu g/m^3$ in London in the early 1950s, whereas the average winter level near the National Gallery (one of the smokiest areas of London) had fallen to 160$\mu g/m^3$ by 1967. The yearly average level for London now is only 40$\mu g/m^3$. This can be taken as an average sort of figure for towns in Western Europe. . .

There are not now any pockets of pure country air left in Europe and North America, industrial pollution having spread over the whole area to give background levels of around 20 $\mu g/m^3$.

Apart from urban pollution, natural particulates produced by forest and plant cover, including volatile material given off by them and polymerisd by sunlight, may contribute up to 15 $\mu g/m^3$, but usually much less. . .

2.3
UNDERSTANDING SANDSTONE

Sandstone is widely found throughout the American Southwest. The magnificent scenery of Nine Mile Canyon owes its dramatic beauty to the local sandstone geology. But what is sandstone and how do its properties potentially interact with deposition of dust on rock art in Nine Mile Canyon?

Sandstone is a sedimentary rock composed for the most part of sand-size mineral grains and a cementing mineral that binds the grains. Most sandstone is composed of quartz and/or feldspar grains, which are the most common minerals in the earth's crust. Sandstones are *clastic* in origin. By contrast, chalk and coal have organic origins and gypsum and jasper develop chemically.

The grains of sandstone are cemented together typically by calcites, clays or silica. The grain sizes are in the range of 0.1mm to 2mm. Formation of sandstone from these components requires two principal phases. First, layers of sand must develop. The sand is deposited either by water, such as ancient oceans, or by wind as is typical in deserts. The sand is turned to sandstone from compaction from pressure exerted by overlying deposits and cementation of the grains. Cementation is effected by precipitation of minerals within the pore spaces between the grains. The most common cementing materials are silica and calcium carbonate, but some sandstones have a clay component.

Sandstones fall within three broad groups:

- *Arkose* sandstones have a high feldspar content (more than 25 percent) and a composition similar to granite.
- *Quartzose* sandstones (sometimes termed orthoquartzites) are composed mostly of quartz (more than 90 percent).
- *Argillaceous* sandstones have a high silt and clay content

Because of these and many other factors, there are several different types of sandstones that manifest very different qualities that can affect their weathering over time. For example, a sandstone that has a calcium carbonate "cement" will be far more sensitive to acidic agents than will sandstone bound with silica. The recent publication by Turkington and Paradise in 2004, *Sandstone Weathering: A Century of Research and Innovation*, is the most up-to-date study of the broad issue of the deterioration of sandstone. The authors point out that determination of weathering rates often is very difficult. They also posit that biodeterioration and chemical processes are as significant as physical causes of weathering. Paradise is a professor in the Department of Geosciences, University of Arkansas, and has supervised the study of the sandstone of Petra (Jordan) for many years. Data from the Petra project, and its relevance to Nine Mile Canyon, will be examined further in this report.

3.
DUST ON ROCK ART

3.1
BACKGROUND

A literature search was undertaken utilizing the key words "rock art" and "dust." Not surprisingly, several titles were located that incorporate these key words. However, the articles are general and predictable in their concerns and advice, for example, urging care not to stir up dust that could settle on rock art when visiting sites.

Over the last 40 years, undoubtedly the best scientific studies of rock art environments and conservation have taken place in the great Paleolithic caves of France and Spain. However, the caves differ so greatly from the canyons and cliff faces of Nine Mile Canyon that they do not present useful analogs for this study.

Consequently, when the articles on the Paleolithic caves and the generalized literature on rock-art preservation are filtered out, there is scant scientific literature that examines dust on rock art.

However, before examining the few relevant studies on dust and rock art, it is useful to review environmental studies undertaken in Venice, Italy, almost 40 years ago because in many ways they set the foundation for subsequent studies of particulates and air pollution on cultural property made from stone. This pioneering research was on the origin and effects of air pollution on monuments and exterior sculpture in Venice. Operating out of Palazzo Papadopouli, monitoring stations were set up all over the ancient city of Venice, recording the types and rates of air pollution, particulates and other meteorological data. The resulting data were impressive and ultimately quite critical for the preservation of the city.

Briefly summarized, it had been assumed that most of the harmful pollution came from two nearby industrial centers on the mainland, Mestre-Marghera. However, the long-term monitoring proved that much of the harmful pollution, in reality, was being generated in Venice itself. This research led to the development of a phased program to control air pollution in Venice. This pioneering research demonstrated that pollution and particulates can be monitored and quantified, and the remedial interventions can be effective. In Venice, many assumptions about the origins of the pollution and particulates were proved wrong. Venice remains a cautionary tale for Nine Mile Canyon about the potential pitfalls when assumptions pre-empt verifiable data.

3.2
RELEVANT LITERATURE ON DUST IMPACTS ON ROCK ART

The few relevant studies of the impacts of dust on rock art come from past and on-going research in Australia.

The role played by dust in the deterioration of rock art located on panels and in shelters probably first was articulated by Moorwood in 1994 (Moorwood 1994). However, the first true scientific study of this problem appears only recently, in 1999 (Watchman (1999). Watchman's research confirmed that dust kicked up from vehicular traffic on nearby unpaved roads can settle on and perhaps impact rock art. His research took place at the Split Rock site in North Queensland. Analyses indicated that dust particles can include carbon-rich compounds that probably are created in diesel exhausts which become attached to the dust while still hot. Transported as aerosols[3] in the wind, this material settles on rock art and can significantly distort the carbon system of the surface deposits

In 1998, Kakadu National Park in Australia became a focus of concern due to the ascertained and potential dangers posed to this World Heritage Site by proposed uranium mining at the Jabiluka mining and milling centers. Prof. F. Francioni was sent on a mission to Kakadu by ICOMOS, and he produced a report *ICOMOS World Heritage Committee Mission to Kakadu 1998.* Unfortunately, it would appear that few of the report's sixteen recommendations were enacted. Mining has gone ahead, including several lawsuits over safety lapses, as reported by BBC news in February, 2006. Unfortunately, there seem to be no follow-up studies in Kakadu that would confirm or refute the assumption that particulates from mining and milling have affected the rock art.

However, a line literally has been drawn in the sand at the spectacular rock art site at Dampier, in northwest Australia. This site and the current and on-going studies for its conservation undoubtedly provide the most relevant analog for Nine Mile Canyon, although with important caveats. Specifically, the environments of Nine Mile Canyon and Dampier are almost diametric opposites. Nine Mile Canyon is located at a relatively high altitude in the semi-arid Southwest, while Dampier is a humid marine environment. In Nine Mile Canyon, the rock art is both pictographs and petroglyphs in shelters and on rock faces. At Dampier the rock art is petroglyphs primarily on boulders.

The primary threats are from industrial development at Dampier, so air pollution is the focus of the research. In Nine Mile Canyon dust is the principal threat, although possible contamination of sites by magnesium chloride and naturally occurring salts is a concern, as is possible deposition of hydrocarbon particulates from industrial traffic.

There is an excellent summary of the Burrup Peninsula/Dampier Island site, controversy and scientific research, in *GeoNews* (Nov 2004). When completed, it is assumed that

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[3] There is some question as to whether the transport occurs as aerosols. More recent and sensitive systems of instrumental analysis may be better able to clarify this phenomenon.

results of the Burrup Peninsula research will have relevance for continuing studies in Nine Mile Canyon, especially regarding analysis of air-borne hydrocarbons and their effects on rock art.

The research organization referred to as CSIRO is a scientific research arm of the Australian government. Information on the Burrup/Damper Island project follows:

> The Burrup Peninsula formerly Dampier Island is one of the 47 islands that make up the Dampier Archipelago. The Burrup (Peninsula) and the islands house what is considered to be the largest and possibly the oldest gallery of petroglyphs anywhere in the world. The Dampier Archipelago is located off the northwest coast of Western Australia in the Pilbara.
>
> The Burrup, an artificial peninsula, previously called Dampier Island, is the largest of the islands. It was connected to the mainland in the mid-1960s and is a 117 sq km assemblage of huge granophyre (granite) rock boulder hills interspaced with meandering valleys. The petroglyphs date back from 6000 – 40,000 years. There may be as many 500,000 and the mix of styles and engravings in one location makes this site globally unique.
>
> In northwestern Australia, more than one million aboriginal petroglyphs are concentrated in the landscape. On a scattering of remote islands called the Dampier Archipelago, located off the northwest coast of Australia, people have been carving images on rocks for thousands of years. In some areas the rock carvings are so dense that they cover every available surface of the deep red weathered rocks. Over the past 30 years, this remote region, once home only to Aboriginal tribes, has become increasingly industrialized. With further development planned, the government of Western Australia has commissioned a study of this rock art to determine what role industry might play in the deterioration
>
> This is the largest and most important petroglyph series in the world, but no one knows for sure how many petroglyphs there are in the 2.7-billion year old plutonic stones in Dampier, but almost certainly there are more than one million.
>
> Currently the 22 kilometer long Burrup Peninsula, which is located in the middle of the Dampier region, is one of Australia busiest ports and hosts three large industrial facilities, a salt processing plant, a liquid natural gas processing plant and an iron processing plant. The government of Western Australia had proposed adding six new industries to Burrup, thus bringing the debate over development versus cultural heritage preservation to a head
>
> The government appreciates the cultural and heritage value of the rock art while recognizing (that) the Burrup industrial precinct is of vital economic importance to the local state and national economies. So before deciding on a location, the government commissioned researchers from CSIRO (Australia's national scientific research organization) and Murdoch University to monitor sites both near the industrial building and far across the Burrup Peninsula.
>
> Work began in the summer of 2004 and will continue for 4 years. Scientists will monitor atmospheric emissions and their effects on the rocks. At the end of the study

> period, they will report their findings to the government and recommend any future actions, says Murray who is chair of the Burrup Rock Art Monitoring Management Committee, which oversees the studies. "These studies are to be the most thorough scientific research of impacts on rock art ever undertaken in Australia." Murray says.
>
> The CSIRO project is interdisciplinary and large in scope. Atmospheric scientists will measure ambient concentrations and deposition of pollutants from seven different sites. Microbiologist will examine the role of microbes in deteriorating the rock, and test whether increased level of nitrogen or sulfur from emissions promote further microbial activity. And geochemists and archaeologists will assess the amount of weathering on the rock by analyzing physical, mineralogical and chemical changes of the rocks using optical and scanning electron microscopes. They will also use a mineral mapping tool to record subtle color and mineral spectral changes in the surface minerals over time between the engravings and the adjacent undisturbed rock surfaces.

The *GeoNews* article was in response to the CSIRO Newsletter of September, 2004, and to a large body of adverse publicity brought against the government of Australia by many rock-art organizations and the World Monuments Fund. A delegation from the World Monuments Fund was sent to the Burrup and the entire site was put on its "Most Threatened List," to the consternation of the government of Western Australia.

The CSIRO Newsletter, of CSIRO Atmospheric Research, Issue 14, September 2004, summarizes the research project:

> CSIRO has been commissioned by the Western Australian Government to complete the first ever study into possible effects of industrial emission on Aboriginal rock art on the Burrup Peninsula, in the Pilbara region of Australia's remote northwest.
>
> In addition to housing internationally significant collections of rock art, the area is home to a busy port and industries, including natural gas exploration and iron ore loading, which employ tens of thousands of people. Allegations have been made that increased rainwater acidity, dust deposition and enhanced gas concentrations have deteriorated the art over several decades, but no systematic study of the problem has been completed.
>
> The four-year monitoring program supported by the local Aboriginal communities, involves monitoring air pollutants by CSIRO Atmospheric Research, studies of colour changes by CSIRO Manufacturing and Infrastructure Technology, and investigation of the mineral composition of the rock surfaces by CSIRO Exploration and Mining. The project is in collaboration with Murdoch University, who are carrying out microbiological studies of the rock art.
>
> The CSIRO Atmospheric Research component of the project, led by Mr. Rob Gillett and involving Dr. Greg Ayers, has established sampling systems in consultation with the local Aboriginal community at seven sites, from north Burrup, Gidley Island and Dolphin Island to close to the industrial areas. Ambient concentrations of a range of pollutants and dust in the air and on the rock surfaces are being measured along with the microclimate.

"At each site we will measure nitrogen dioxide, sulfur dioxide, ammonia, BTEX gases (benzene, toluene, ethylbenzene and xylenes), aerosols such as air pollutant particles and dust, as well as rain, temperature, humidity, wind speed and wind direction," says Mr. Gillett.

The collected gas, particle and weather data will be used to establish the origin of air pollutants and dust, to address concerns about possible effects of current and future industry emissions on the rock art of the Burrup Peninsula.

The study aims to investigate natural processes and emissions that might degrade the rock art, to monitor changes over time and propose management measures if required for on-going preservation and conservation.

This research project has now reached its mid-point. Apparently, no provisional reports on the results have been published to date.

3.3
CONCLUSIONS

The literature search confirmed that there is no project that sets a precedent or provides an exact model for a study of deposition of dust on rock art in Nine Mile Canyon. However, research that took place almost 40 years ago in Venice confirms that atmospheric monitoring over a wide area can provide critical information about pollution and its effects on cultural property. Currently only one project, at Burrup, Australia, appears to have research goals similar to those outlined for Nine Mile Canyon. However, Burrup and Nine Mile Canyon are also dissimilar in many ways. Nevertheless, it is possible that Burrup can provide useful analogs for Nine Mile Canyon once the Burrup research concludes in about a year.

However, the problem of dust in Nine Mile Canyon is current and active and must be addressed immediately. Consequently, it was concluded that site-specific avenues of research would have to be developed and implemented in Nine Mile Canyon.

4.
NINE MILE CANYON AND DRY CANYON: FIELD SAMPLING AND LABORATORY ANALYSES

4.1
SUMMARY BACKGROUND ON NINE MILE CANYON

Nine Mile Canyon is about 70 miles long (figures 1). It was formed around 55 million years ago from lake sediments. As the land was up-lifted, Nine Mile Creek began cutting the canyon. The sediments of the lake formed the massive sandstone and shale formations visible today.

Native Americans utilized the area for at least 8,000 years, leaving behind the outstanding rock art that is the focus of this study. Nine Mile Canyon was first mapped around 1869 by John Wesley Powell. In 1886, a trail in the canyon became a Federal Highway. The US 9th Cavalry built the road in the canyon and a telegraph line to service the military post at Fort Duchesne, soon after. Homesteading in the canyon began in earnest around 1905, with the introduction of cattle throughout the network of primary and secondary canyons. By the 1950s, networks of roads were installed to facilitate mining and energy-related extractive work. This industrial activity has continued on and off since the 1950s, but resumed on a major scale beginning around 2000. Not surprisingly, industrial traffic on the canyon's dirt road creates dust.

4.2
SUMMARY OF SAMPLING METHODOLOGY

4.2.1
RESEARCH QUESTIONS AND SITE SELECTION

From July 9-12, 2007, the author and Julie Howard, Archaeologist, BLM, undertook sample collection in Nine Mile Canyon. Five sites were utilized. There were five research questions:

1. Is dust generated by vehicular traffic and, if so, to what extent can the impacts on the rock-art sites be documented, identified and quantified?

2. Can magnesium chloride be identified in the dust collected at rock art sites?

3. Has aeolian abrasion been exacerbated?

4. Can other potentially damaging agents, such as hygroscopic salts, be identified in deposited dust?

5. Is there entrapment of dust into the surface of the sandstone panels? Has it altered the appearance and composition of the sandstone, and is that alteration permanent?

The five sites were selected based on their locations and configurations, allowing the development of a simple hypothesis for sampling. It was hypothesized that a rock-art site located close to an untreated area of road would be subjected to the heaviest contamination by dust generated by vehicles. Contamination by dust should be markedly minimized if a site is located on a section of road that was treated with magnesium chloride for dust abatement or is located in some sort of protected environment, such as a shelter, like Rasmussen Cave.

A site in Dry Canyon was selected as the control for the research because Dry Canyon is not subject to daily development and the concomitant industrial traffic on its road, which remains relatively undisturbed and hard-packed. It was hypothesized that a site located away from industrial activity, on a road that has no heavy vehicles, should show the least amount of dust contamination.

4.2.2
METHODOLOGIES FOR SAMPLING AND SELECTION OF ANALYTICAL SYSTEMS

As discussed earlier in this report, there is a vast body of scientific literature on the study of particulates, which includes an extensive discussion of possible analytical systems, from the simple to the highly complex in specialized laboratories. Indeed, the complexity and refinement of these analytical techniques are reflected in the journal, *Environmental Forensics,* which focuses on analysis of minute traces of any material, including their presence as very small particulates. In a word, currently an almost unlimited number of analytical services are available, given the availability of time and funding for research. Thus, a primary challenge for this study was to select analytical methodologies that would be accurate and within established due diligence, but also highly practical, time-effective and cost-effective.

In the United States, due diligence begins with the methods, systems and criteria developed and established by the American Society for Testing Materials, or ASTM. Under ASTM, there is now a large corpus of protocols for the testing and analysis of virtually all materials. For example, there is the ASTM Standard Practice D6602 *Sampling and Testing of Possible Carbon Black Fugitive Emissions or Other Environmental Particulate, or Both* (ASTM, 2003). This protocol addresses the differentiation of carbon-black particulates from combustibles derived from other agents, such as mildew and rubber dust.

For the objectives of the dust study in Nine Mile Canyon, it was determined that analyses must conform, at a minimum, to ASTM D 6913 *Standard Test Methods for Particle Size Distribution (Gradation) of Soils Using Sieve Analysis* (2004) and ASTM D422-63 *Standard Method for Particle Size Analysis of Soils* (ASTM 2002). Complimentary laboratory analyses also would be employed

Two field-collection systems were devised in consultation with scientists from the analytical laboratory, EMSL.[4] One collection system utilizes the Lighthouse Airborne Particle Counter 3016/5016. This instrument employs a laser-diode light source and collection optics for particle detection. Particles scatter light from the laser diode. The collection optics "gather" and focus the light onto a photo diode that converts the bursts of light into electrical pulses. The pulse height is a measure of the particle size. Pulses are counted and their amplitude is measured for particle sizing. Results are displayed as particle counts in the specified channel.

The data format is either Raw or Normalized. Raw data displays the actual number of particles counted. The format from the Differential, rather than the Cumulative count, was selected for the field work because the measurements were being taken in the open air, rather than in a discrete volume of air, such as would be found in a room.

During the field work in Nine Mile Canyon, readings of one minute were taken at the five sites. A count was taken when no traffic was on the road. A second count was taken just after the transit of vehicular traffic. The two counts were then compared to develop a general understanding for the extent to which industrial traffic generates particulates into the air.

Physical samples also were taken from each of the five sites, for analysis by EMSL. Bulk samples of adjacent road material were collected. Petri dishes were left at all the sites for a period of 24 hours. The purpose was to collect the particulates that settle from the air and to analyze their elemental composition, with the objective of determining their loci of origin. Additionally, particle size distribution analysis was undertaken.

At some sites, small samples of rock were removed from the extremities of panels, in order to determine if they have become contaminated with dust and magnesium chloride.

Secondarily, a study will be made of the porosity of the rock samples, to determine the extent to which particulates can become entrapped on and in the surface of a rock-art panel. Such irreversible entrapment would be considered permanent damage.

Fifteen samples were sent to EMLS for analysis. The following methods and equipment were used: stereo microscopy; scanning electron microscopy (EDX); energy dispersive

[4] EMSL is located in Westmont, New Jersey.

X-ray spectrometry (EDX); X-ray diffraction (XRD); sieves; and scale (0.01 g sensitivity).

Sieving for particle size analysis entails the use of a set of "coarse" sieves and "sonic sieving" for the very fine particulates. Sonic sieving is similar to coarse sieving, but the sieves are much finer and ultra-sonic vibration is used. Typically the smallest sieve used is about 10μm size. Particles smaller than 10μm are sized by scanning electron microscope (SEM). With this high-powered microscope, images of individual particles are taken and the size distribution is measured by the diameter of each observed particle. Typically, this technique is used for particles between 10μm to 0.1μm.

The results of the analyses are included as Appendix 1 of this report.[5] The particle size distributions and elemental spectra created by scanning electron microscopy/EDX are provided. These spectra are like *de facto* signatures that identify each sample. Very similar spectra almost certainly indicate that dust samples have the same point of origin. Conversely, different spectra almost certainly indicate different points of origin. Consequently, identical or nearly identical spectra from a road sample and from depositional dust on an adjacent rock art panel would signal that the panel is being contaminated from the road.

EMSL was requested to investigate the possible presence of magnesium chloride in each sample. It is known that some sections of the road have been treated with a dust suppressant, assumed to be magnesium chloride or perhaps another suppressant that contains magnesium chloride with other constituents. Identification of magnesium chloride in bulk samples from the road and in particulates deposited at sites almost certainly would confirm contamination from the road. Such contamination would be a cause for concern because increasingly magnesium chloride is being condemned as a highly reactive and corrosive agent that can damage concrete structures, vehicles and vegetation. However, at present there is no hard evidence that direct harm to the rock- art panels has occurred, or will be inevitable if contamination has taken place.

Magnesium chloride is the name for the chemical compounds that are salts having the formulas $MgCl_2$ and its various hydrates, $MgCl_2{\cdot}nH_2O$. They are highly soluble in water because they are typical ionic halides. Liquid magnesium chloride, or in powder form, is applied to control dust and erosion on unimproved dirt and gravel roads and at dusty job sites. Because it is so hygroscopic, it will absorb moisture from the air even at very low relative humidity. It is the constant damp state that acts to restrain small particulates from getting into the air.

Magnesium chloride also can be mixed with hydrated magnesium oxide to form a hard material called Sorel cement that is used as a sort of paving material on dirt roads. In the case of Sorel cement, the magnesium chloride component becomes fixed. When the samples were first analyzed by EMSL in August, 2007, all the samples tested positively for magnesium and/or chlorine; however, no magnesium chloride *per se* was identified.

[5] Note that the positive detection for gold in the laboratory analyses indicates gold scatter used as part of the analytical process, not the actual presence of gold in the sample.

EMSL technicians assumed that the magnesium and chloride were naturally occurring components of the sediments that would be expected in the roadbed in Nine Mile Canyon.

At that time, the author hypothesized that Sorel cement, rather than magnesium chloride *per se*, had been use on the road. The magnesium chloride component does not escape from the Sorel cement, thus explaining its absence from the samples. Thus, initially there was support for the hypothesis that magnesium chloride was not being generated into the air and then deposited on the rock-art sites.

However, it was also possible that naturally occurring magnesium and chlorine in the samples created so much similar "background noise" that it was impossible to factor out the magnesium chloride, if indeed, it had escaped from the road. Thus, at the insistence of the author, supported by the BLM and BBC, additional analysis for magnesium chloride was carried out.

For the second round of testing, an aqueous extraction method was used. This technique is employed to concentrate the magnesium chloride, if it is present. The samples were immersed in water to dissolve the magnesium chloride. The water was filtered off and evaporated. If present, the magnesium chloride would be left in the dried residue. With use of this technique, magnesium chloride was positively identified in samples 1.1, 2.1, 2.2, 3.3 and 5.3.

Lastly, simple visual examination of the sites in Nine Mile Canyon proved invaluable. As the photographs included with this report show, it is possible to identify road areas that produce exceptional amounts of dust as a result of vehicular traffic and road degradation, and to observe dust deposition on rock-art panels.

4.3
THE FIVE TEST SITES:
RESULTS OF FIELD SAMPLING
AND LABORATORY ANALYSES

Each test site is described. The descriptions of the five sites are derived from site forms provided by the BLM. Data from readings with the particle counter are provided. The results of the laboratory analyses are explained.

4.3.1
SITE 1
HARMON CANYON SITE
42Dc162

Site Description:
The site is located along a low cliff face, about 46 feet from the road. The site consists of groups of petroglyphs located on the second tier of cliffs above the road, facing southeast. The panels include: an interesting sheep-hunting scene with two hunters with bows and

arrows; two sheep tracks; two fields of dots; two crude anthropomorphic figures; and a complex abstract, web-like configuration.

The road has been heavily treated for dust abatement with (assumed) magnesium chloride, and it is watered constantly. Dust is visibly abated by this road treatment. Nevertheless, substantial dust is present on areas of the panel, but it is not clear when this dust was deposited.

Date of Examination: July 10, 2007

Photographs:

1.1
1.2
1.3

Samples/Request for Laboratory Analysis:

Sample 1.1. Road, bulk sample: particle size analysis; mineral identification; and presence of magnesium chloride.

Sample 1.2. Stone taken from the base of the panel: porosity study; nature of particulates on the surface; presence of magnesium chloride.

Sample 1.3. Stone from the base of the panel: porosity study; particle size analysis; identification particulates; possible presence of magnesium chloride.

Particle Counts:

Particle Count taken at 10:20 AM, with no road traffic:

μ	Δ
0.3	10,658.4
0.5	611.8
1.0	146.8
2.5	189.9
5.0	41.7
10.0	10.7

Particle count taken at 10:30AM, during moderate road traffic:

μ	Δ
0.3	11,600.7
0.5	643.6
1.0	189.3
2.5	222.5
5.0	32.7
10.0	5.9

SITE 1
HARMON CANYON SITE
INTERPRETATION OF DATA

Particulates in the air were only slightly increased during the passing of vehicular traffic. This section of the road is outside the purview of the BLM. It is subject to maintenance by the county. The exact system of road maintenance is not known, but it has been heavily treated with a dust suppressant and is constantly watered from a truck.

The results of the laboratory analyses are quite interesting. During the first analyses undertaken in July, 2007, EMSL failed to identify magnesium chloride in sample 1.1, a bulk sample from the road. During the second round of analyses in October, 2008, magnesium chloride was identified. Thus, it seems all but conclusive that the road has been treated with magnesium chloride.

The two samples of depositional dust were collected from rocks and not from petri dishes left at the site for 24 hours. Magnesium chloride was not identified in samples 1.2 and 1.3 removed from the site. The SEM/EDX for the road sample (1.1.1) and the site samples, 1.2.1 and 1.3.1 are quite different. Samples 1.2.1 and 1.3.1 do not contain chlorine, and thus cannot contain magnesium chloride. The depositional material more closely resembles samples from untreated sections of the road. A likely conclusion is that the dust was deposited prior to dust-abatement treatment of the road, and that the magnesium-chloride has not escaped from the treated road.

4.3.2
SITE 2
COTTONWOOD CANYON SITE,
THE PANEL ABOVE THE "HUNTING SCENE"
42Cb238

Site Description:
This is an outstanding petroglyph panel that is closely associated with the "Hunting Scene" panel, recognized as a major example of prehistoric rock art in the area.

This site was originally recorded in 1976 by Lindsay and Sargent and revisited in 1993 by USAS. It consists of four rock-art panels on a large rock face above a 4-meter high ledge. Panel 1 consists of a possible shield motif, a zoomorph, historic initials (TJ) and a zoomorph and a deep groove. Panel 2 is a wide panel located to the left (south) of panel 1. It exhibits: five zoomorphs; three snakes; a nine-dot group; one coiled circle; two bullseye designs; and one anthropomorph balanced atop a half-pie design. Panel 3 is an isolated square-like element above and to the left of Panel 2. Panel 4 displays historic letters, numbers, and some very faint anthropomorphs.

Both panels have been visibly affected by deposition of dust. The road near the panels has been worn down to a powdery consistency. When any vehicle passes, clouds of fine dust are generated. This dust from the road has settled on the rock-art panel.

Date of Examination: July 10, 2007

Photographs:

2.1
2.2
2.3
2.4

Samples/Request for Laboratory Analysis:

2.1 Road, bulk sample: particle size analysis; mineral identification; presence of magnesium chloride.

2.2 Petri dish collection, after 24 hours, taken from below the large panel: particulate settling; particle size analysis; mineral identification; presence of magnesium chloride.

2.3 Rock sample taken from panel (below and to left of large panel): porosity study; particle size analysis; mineral identification; presence of magnesium chloride.

Particle Counts:

Particle count taken July 10, 2007, 11:30AM, with no traffic on the road:

μ	Δ
0.3	9235.8
0.5	3307.4
1.0	2752.8
2.5	4802.1
5.0	1105.3
10.0	682.2

Particle count taken July 10, 2007, 11:40AM, during the passing of a wide-load truck and a large dumpster coming in opposite directions:

μ	Δ
0.3	13,093.6
0.5	14,391.3
1.0	13,059.5
2.5	25,622.8
5.0	5,750.8
10.0	11,009.0

SITE 2
COTTONWOOD CANYON SITE,
THE PANEL ABOVE THE "HUNTING SCENE"
INTERPRETATION

The road adjacent to the site has been reduced to fine powder. As the included photographs show, the powdery particulates are thrown into the air by traffic; the finest particles remain suspended until they settle on a surface. There is obvious heavy deposition of dust and fine particulates on the panel. The particle counts confirm these visual observations.

The elemental analysis of the sample from the road adjacent to site *42Cb238* raises several questions. It is assumed that this section of the road has never been treated with magnesium chloride. However, magnesium chloride was identified in sample 2.1, a bulk sample from the road; indeed, the SEM/EDX spectra are quite distinctive for this sample.

Magnesium chloride also was identified in sample 2.2, depositional particulates collected from a petri dish left for 24 hours at the site. The inevitable conclusion is that the road was treated with magnesium chloride at some time in the past, and that the magnesium chloride now is made air-borne by heavy traffic on the road.

4.3.3
SITE 3
THE HUNT SCENE
42Cb239

Site Description:
This site was originally recorded in 1976 by Lindsay and Sargent and re-visited in 1993 by USAS. This is the famous rock-art site in Nine Mile Canyon known as "The Great Hunt." The site is described as two types of rock art, petroglyphs and pictographs. Panel 1 consists of seven white-daub pictographs. The southernmost appears to be an outline of a shield containing four short lines hanging from the bottom and three vertical lines. There are several indiscernible white marks and a circle with three vertical lines inside.

Panel 2 exhibits: three large red and chalked-circle pictographs with underlying petroglyphs; zig-zag lines; oval shaped pictograph of grayish-white pigment; a yellowish-gold pictograph; and a small circle of gray pigment. Below and above the pictographs are petroglyphs, including numerous sheep, deer, zoomorphs, and a buffalo. There are modern historic inscriptions present on the panel as well.

The panel is along the back wall of a shallow overhang with an oxidized ceiling from campfires which were probably ancient and modern. Component B consists of six petroglyph panels including the "Great Hunt" (Comp B, Panel 1) which contains a total of 43 figures. The panels consist of anthropomorphs, bow and arrow hunters, numerous zoomorphs, sheep, and abstract designs.

Date of Examination: July 10, 2007

The rock-art panel is located 125 feet from the road. The road has been reduced to a powdery surface. When large industrial vehicles passed, large clouds and plumes of fine particulates were thrown at least 150 feet in the air and remained suspended until settling on nearby surfaces. There is obvious deposition of fine particulates on the panel, as shown in the included photographs.

Photographs:

3.1
3.2
3.3
3.4

Samples/Request for Laboratory Analysis:

3.1 Rock sample taken from panel below "T" of vandalism: porosity study; particle size analysis on surface; mineral identification; presence of magnesium chloride.

3.2 Petri dish, particulate settling after 24 hours: particle size distribution; mineral identification; presence of magnesium chloride.

3.3 Road, bulk sample: particle size analysis; mineral identification; presence of magnesium chloride.

Particle Counts:

A particle count was taken with no traffic on the road, on July 10, 1007, at 1:25PM.

μ	Δ
0.3	10,475.9
0.5	480.6
1.0	52.7
2.5	51.7
5.0	7.4
10.0	16.4

A particle count taken at 1:45 PM, with one pickup truck and three heavy industrial trucks converging on the site:

μ	Δ
0.3	40,100.00
0.5	10,108.00
1.0	7,275.20
2.5	14,334.60
5.0	3,560.90
10.0	2,028.60

SITE 3
THE HUNT SCENE
INTERPRETATION

The road adjacent to site 3 has been reduced to a powdery consistency. As the photographs show, when any vehicles pass large clouds and a plume of fine dust are thrown at least 150 feet into the air and linger for at least 10 minutes. When the vehicular traffic is especially heavy, the plume of dust visibly increases in size and density. This fine dust is blown against the nearest rock face and settles on it.

The initial interpretation of the laboratory analyses has been up-dated. There is no record that the section of road near the site had been treated with magnesium chloride. However, magnesium chloride has been identified in the bulk sample removed from the road (3.3). The spectra of this sample are quite distinctive and closely match sample 2.1, a bulk road sample that also contained magnesium chloride.

Sample 3.3 is quite different from the spectra derived from analysis of depositional samples, taken from a petri dish left for 24 hours and from dust samples from a rock removed from the base of the panel. Magnesium chloride was not identified in these samples, but it could be present. The anomalies associated with these samples cannot be explained currently.

4.3.4
SITE 4.
DRY CANYON PETROGLYPHS
43Cb31

Description:
This is a Fremont rock-art site located north of the Dry Canyon road and designated on the topographic map as "petroglyphs." The site was originally documented by the BLM over 30 years ago (Fike 1972) and re-recorded by MOAC in 2002 (Raney and Montgomery 2002), and again by the BLM in the same year (Maloney 2002). The site contains five petroglyph panels executed on the cliff face, attributed to the Fremont Culture. Panel 1 (12 ft ags) has a central spiral/serpent element surrounded by about 24 smaller anthropomorphs (including a figure with a bow and arrow), zoomorphs, serpents, dot grids, and other abstract elements. Panel 2 (3 ft ags) displays a solid pecked 'horned' anthropomorph and two serpents. Panel 3 (9 ft ags) shows two spiral serpents and two dot grids. Panel 4 (6 ft ags) has three elements, two quadrupeds, and an abstract element. Panel 5 (6 ft ags) exhibits a series of dots.

Maloney (2002) trowel-tested two possible circular structural features to a depth of 20cm below ground surface that failed to reveal cultural deposits. No artifacts were found at the site.

Dry Canyon served as a control because there is no development activity on the old access road that runs through the canyon. Unlike the main road of Nine Mile Canyon, the access road into Dry Canyon receives almost no traffic at all. For this reason, the road has retained its hard-pack gravel surface. The adjacent rock art has no visible deposition of dust.

Date of Examination: July 11, 2007

Photographs:

4.1
4.2
4.3

Samples/Request for Laboratory Analysis:

4.1 Petri dish left at panel for particulate settling after 24 hours: particle size distribution; mineral identification; presence of magnesium chloride.
4.2 Rock sample removed from panel below snake image: porosity study; particle size analysis; mineral identification; presence of magnesium chloride.
4.3 Road, bulk sample: particle size analysis; mineral identification; presence of magnesium chloride.

Particle Counts:

Particle count taken at 2:50PM:

µ	Δ
0.3	12,069.7
0.5	517.1
1.0	30.7
2.5	26.4
5.0	2.3
10.0	0.6

SITE 4
DRY CANYON PETROGLYPHS
INTREPRETATION

As the included photographs show, the lightly used road adjacent to the panel has retained a natural hard-packed surface. In this regard, it is interesting to note that the particle count quite closely resembles those taken at sites where the main road in Nine Mile Canyon has been treated with magnesium chloride and constant watering; that is, in both instances a hard-packed surface demonstrably lowers the creation of dust. However, the slightly elevated particulate count in the 0.3µ range could be due to other factors, such as naturally occurring particulates resulting from pollen or smoke from the huge forest fires that burned nearby while the count was being taken.

Data generated from the laboratory analyses of the collected samples from Dry Canyon are quite interesting. The compositional "signature" of the dust samples taken from the road (4.3) and from a rock removed from the base of the panel (4.2) are quite distinctive when compared to almost all the other samples taken in Nine Mile Canyon, but closely resemble each other: they are unusual for the presence of potassium (P). Potassium is found in only one sample from Nine Mile Canyon, sample 3.1, and only in a very small amount in that sample.

These data indicate that the elemental signatures of the particulates throughout the area will be different depending on their geological loci of origin and will be "legible" through laboratory analysis. However, the third sample from Dry Canyon is especially interesting, 4.1, depositional material taken from a petri dish left at the site for 24 hours. The elemental "signature" differs from the signatures of samples 4.2 and 4.3 in several ways, but specifically in the absence of potassium and the presence of titanium.

A probable explanation is that there have been many depositional events throughout the canyons of this area, and sample 4.1 is simply the latest. If this is indeed the case, it could complicate determination of when critical contamination of rock art occurred in Nine Mile Canyon.

4.3.5
SITE 5
RASMUSSEN CAVE
42Cb16

Description:
The site is located in an overhang of a cliff face approximately 30 meters north of the Nine Mile Canyon road, due north across the canyon from the entrance to Dry Canyon. This site is commonly known as Rasmussen Cave. It was originally recorded as part of the Claflin-Emerson expeditions in the 1930s. Details about the artifacts recovered and the excavation are provided in *The Fremont Culture* authored by James Gunnerson in 1969.

In 1991, the site was revisited as part of the Nine Mile Canyon Survey (Report No U-91BL661). At that time, the site was reported as an overhang measuring 28 meters wide and 7.5 meters deep at its deepest point. The eastern half of the cave floor was littered with large boulders that fell from the ceiling in pre-occupation times. The western portion of the cave contained a flat area that may have served as the main activity area. Almost all surface boulders within the overhang contain petroglyphs and/or pictographs.

The site has been vandalized extensively. The entire floor of the cave has been dug, and historic names, dates, and other writings are superimposed over much of the rock art. Portions of panels 15 and 18 have been chiseled off. A total of 30 rock panels were described at the site. Three clefts (Clefts A, B, and C) were originally excavated within the cave. Some of the artifacts recovered include: Emery Grayware sherds; ceramic figurines; clay blobs; a scraper; a mano; hide pieces; bone fragments; cord fragments; a reed tube; reed mat fragments; basket fragments; corn; a digging stick; stone points; a stone drill; one serrated bone tool; a spear foreshaft; and an atlatl.

A Basketmaker-type burial was excavated in Cleft A. During the last inventory, a datum stamped with the permanent site number was placed at the site and an updated topographic map was prepared. No further documentation has been undertaken.

The road in front of the cave has been treated with magnesium chloride and is often watered. Nevertheless, there is a substantial layer of fine dust on the rock fall in front of the panel.

Date of Examination: July 11, 2007

Photographs:
5.1
5.2
5.3

Samples/ Request for Laboratory Analysis:
5.1 Petri dish left at the panel, particulate settling after 24 hours: particle size analysis; mineral identification; presence of magnesium chloride.
5.2 Dust samples removed from rocks in front of the panel: particle size analysis; mineral identification; presence of magnesium chloride.
5.3 Road, bulk sample: particle size analysis; mineral identification, presence of magnesium chloride.

Particle Counts:
The particle count was taken at 12:05PM on July 11, 2007, with no traffic on the road:

μ	Δ
0.3	10,176.5
0.5	448.0
1.0	79.2
2.5	1,51.3
5.0	40.0
10.0	9.8

The particle count was taken at 12:30PM with two vehicles passing in opposite directions:

μ	Δ
0.3	10,437.5
0.5	693.0
1.0	288.8
2.5	723.2
5.0	180.0
10.0	58.0

SITE 5
RASMUSSEN CAVE
INTERPRETATION

The particle counter readings were quite similar because the road in front of the site has been treated with magnesium chloride, is often watered, and thus releases little dust.

The elemental analyses are particularly interesting and useful because all three samples proved to have very different elemental signatures. Sample 5.3 was removed from the road, which has been treated with magnesium chloride. The elemental signature is quite distinctive and closely resembles other bulk samples from road sections treated with magnesium chloride.

However, the depositional samples are quite different. Sample 5.2 was collected from the dust on the rocks at the front of shelter. Sample 5.1. is depositional dust sampled from a petri dish left at the front of the site for 24 hours. The two dust samples differ. Sample 5.1 contains aluminum and silica. Its elemental "signature" more closely resembles sample 3.2, a depositional sample from site 3. Silica and aluminum are absent from sample 5.2, which contains sulfur.

The interior of the cave is heavily covered in dust, but it is not clear when and how this dust accumulated. The origin of this dust remains an interesting question. It may have been generated within the cave by the activity of unauthorized hikers, campers and illegal excavators; indeed, during the course of this study prehistoric corn cobs were observed on the floor of the shelter, suggesting "pot-hunting." However, another possibility is that the dust from samples 5.1 and 5.2 was deposited from the road and/or from a wind-related event prior to the road's treatment with magnesium chloride. If this is the case, it may be difficult to determine when critical contamination of the rock art occurred.

4.4
FIELD SAMPLING AND ANALYSIS: CONCLUSIONS

The field sampling methods and laboratory analyses utilized for the study of particulates at rock-art sites in Nine Mile Canyon provided significant data. They resulted in positive identification of magnesium chloride in some areas of the road and on some depositional samples from sites. The analyses also confirmed that particulates from different canyons and roads can have unique elemental signatures. The analyses were able to identify different depositional histories within a site and grade particle size distribution.

The SEM/EDX analyses also confirm that the dust contains components that are consistent with the constituents of various naturally occurring salts, including chlorine, sulfur, sodium, potassium, magnesium, and calcium.[6] These data strongly suggest that

---

[6] Review of naturally occurring salts in samples from Nine Mile Canyon was provided by Kirk Anderson, Ph.D (personal communication, 2008).

halite, calcium carbonate, potassium chloride, magnesium chloride, gypsum and perhaps other salts are thus present in the dust.

The SEM/EDX analyses also confirm that the constituents of salts were identified in bulk samples taken from the road (samples 1.1, 2.1, 3.3, 4.3, and 5.3) and from depositional dust at the rock art sites (samples 2.3, 3.1, 4.2, and 5.2) and from depositional dust collected in petri dishes. Identified salts include chloride and sulfate salts, sodium bicarbonate, sodium chloride (halite), gypsum, and calcite. More generally, all the samples were positive for major constituents of salts: Na, Mg, K, Ca, S, C,O, and Cl

The laboratory analysis also identified several naturally occurring salts in the depositional dust. Salts are minerals composed of cations (Mg, K, Na, and Ca), combined with anions (sulfate, nitrate, carbonate, and chloride). Halite and gypsum are common salts. Magnesium chloride also is a salt, but one that has been introduced into the canyon

The presence of these salts in the dust was expected because salts occur naturally, especially in arid and semi-arid environments, and because they become easily airborne. Some researchers have raised concerns about contamination of the rock-art panels by these naturally occurring salts. The possible impacts on the weathering of the panels by salts will be discussed in the following section of this report.

5
CONCLUSIONS AND RECOMMENDATIONS

5.1
SUMMARY CONCLUSIONS

It is possible to conclude that the degraded sections of road in Nine Mile Canyon are generating large amounts of particulates as industrial traffic passes. These particulates are very fine and their behavior appears to conform to the descriptions by Thomson: that the finest particles are the most dangerous for cultural property because they travel and remain suspended in air until they find a surface upon which to settle. In the case of Nine Mile Canyon, that surface can be a rock-art panel.

Observations of the road in Nine Mile Canyon strongly suggest that heavy industrial traffic has increased substantially. This traffic quickly cuts through any hardpack on the road and reaches and liberates the powdery substrate. It should be recalled that the base of the canyon was created by water-borne depositions which included silts. The heavy traffic further pulverizes these very fine particulates.

It is also clear that road treatments that stop the generation of dust have been effective, although not perfect. In this regard, particle counts taken in Dry Canyon, where the road remains naturally hard-packed and receives little traffic, are very close to the particle counts taken at sites where the adjacent road sections have been treated with magnesium chloride and are watered.

Magnesium chloride raises many red flags. Magnesium chloride is a salt that will deliquesce at a very low relative humidity; that is, it will pull ambient water out of the air and remain wet. Its ease of deliquescence is the property that makes it work as a dust suppressant. The possible impacts of magnesium chloride on stone were made evident at the Metropolitan Museum. The Abbydos Frieze is an important work of art from dynastic Egypt, on display in the museum. It is made from carved limestone, which was constantly deteriorating. Eventually, it was determined that naturally occurring magnesium chloride in the stone was heavily deliquescing in the humid climate of New York City. The magnesium chloride could not be removed from the fabric of the stone. Therefore, the frieze had to be placed in a climate-controlled case to ensure its stability.

During the period of public comment about the uses of magnesium chloride in Nine Mile Canyon some years ago, several conservation scientists and conservators raised objections to its use for dust abatement. A major concern was the possibility that some magnesium chloride could escape from the road and be deposited in the rock art panels. Studies undertaken during this research have shown that some magnesium chloride has escaped from treated areas of the road. However, for damage to occur at the very least the magnesium chloride would have to be able to react with specific components of the sandstone or be able to penetrate into the porosity of the stone's fabric and mobilize salts. There is no proof thus far that magnesium chloride has, or can, damage the sandstone of Nine Mile Canyon in this manner.

It is also possible that magnesium chloride could be damaging in a more subtle way. Because magnesium chloride remains wet even in low relative humidity, it could perhaps provide a micro-climate for micro-organisms capable of damaging the sandstone; increasingly, biodeterioration of stone is viewed as a major cause of damage (Turkington 2004). However, there is no indication that this pathology has occurred, and indeed, it would be difficult to differentiate naturally occurring biodeterioration from artificially induced biodeterioration.

A recent article by Snow (Snow 2002), explains how magnesium chloride can damage concrete. This article is graphic and alarming, but it must be remembered that the destructive processes that are described occur because of the unique synergy between magnesium chloride and the constituents of concrete in the presence of substantial amounts of ambient water. There is no evidence that the constituents of the sandstone of Nine Mile Canyon will react like man-made concrete.

As discussed, magnesium chloride is a salt that occurs in nature and may perhaps be endemic to Nine Mile Canyon, in addition to being introduced for dust abatement. However, the analyses carried out in this study also confirmed the presence of naturally occurring salts and constituents that indicate salts. Salts are minerals with two components, cations (Mg, K, Na, and Ca) and anions (sulfate, nitrate, carbonate, chloride). Salts are highly soluble. In their dissolved form they can seep into the pores and crevices of stone. After the water evaporates, the salts remain in place. When they come into contact with water, for example from rain, they crystallize and increase in volume. This expansion exerts mechanical stresses that can damage the rock. Ambient water can also damage rock in this way if it freezes in the stone and expands in its solid form. Such water-induced damage is commonly known as the *freeze-thaw cycle*.

The weathering of stone from salt damage has been well known for many years, and well explained (Winkler 1975). It has also been recognized that stone in deserts and semi-arid regions are particularly susceptible to salt-related weathering because of the frequency of extreme wetting and drying cycles and from the cycles of extreme heat and extreme cold. Thus, concern has been raised regarding contamination of the sandstone panels from airborne salts in the dust created by industrial traffic in Nine Mile Canyon.

However, many conditions must be in place for this type of damage to occur. First, the stone must have certain characteristics. Returning again to the example of Venice---the wettest and most salt-infused environment for stone---stone buildings have survived for almost 1,000 years. One explanation is the use of *pietra d'Istria,* stone from Istria (on the

Dalmatian coast) which is magnesium carbonate. It is very dense and lacks a true pore structure and thus blocks the infusion of dissolved salts into the fabric of the stone. Venetian masons recognized this property and thus imported it for centuries for use in the foundations of Venetian buildings, to prevent salt and freeze-thaw weathering.

The salt-induced weathering of stone in deserts was described as early as 1968 (Cooke 1968). It was observed that for rocks of equal mechanical strength those with large pores separated from each other by microporous regions are most susceptible to salt weathering. These processes can be exacerbated by the heat-related expansion of salts in the confined spaces of the pores and by additional stresses induced by hydration of specific salts in the confined spaces. It is not known if all or some of the sandstone of Nine Mile Canyon meets these criteria.

It has been proposed that there will be an increase in abrasive damage of sandstone panels because of increased volumes of wind-borne particulates generated by the industrial traffic. For this damage to occur, certain conditions must be in place. Specifically, the dust must have a grit component that is harder than the sandstone itself. At present, the relative hardness of all the sandstone panels and all the dust is not known. Further, it is not known if weather patterns in the canyon are conducive to scouring actions.

It is theoretically possible that salt contamination from dust, with its concomitant damage, could occur in Nine Mile Canyon. However, *The Petra Project* of the University of Arkansas provides firm scientific data that indicates that some sandstones in deserts remain highly resistant to any type of weathering. Petra is one of the world's greatest archaeological sites, a glorious Roman-era city carved from the sandstone cliffs of the desert of Jordan. Since 1990, the University of Arkansas has undertaken very comprehensive studies of Petra. The objectives are to document the causes and rates of weathering of the sandstone escarps and cut stone from which the various buildings were constructed.

This research is the best database on the weathering of sandstone in a desert environment. Researchers found that some buildings suffered almost no weathering in 2,000 years and that many factors will affect the rate of weathering. That is, the Petra research indicates that the weathering of sandstone in arid regions is a complex process and blanket explanations are not possible:

> . . .Sandstone matrix constituents of iron and silica were found to decrease overall sandstone weatherability, while calcium matrix components were found to increase deterioration in areas that receive more than 5500 megajoules/square meter/year of solar radiation – a typical; southern aspect in mid-laltitude, arid regions. Moreover, when iron matrix concentrations exceed 4-5% (by weight), original stonemason's dressing marks are still clearly evident, indicating a nearly unweathered state in 2,000 years. Surface recession rates for sandstone in the Roman

> Theatre were determined to range from 15 – 70mm per millennium on horizontal surfaces to 10 – 20mm per millennium on vertical surfaces. . .
>
> . . .Insolation was found to have the greatest effect on weathering on southwestern and southeastern aspects (and not southern aspects as is often discussed) indicating that insolation may be most influential in sandstone weathering when in tandem with increased wetting-drying and/or heating-cooling cycles (Paradise 2008:4).

What, then, can be concluded about the effects of dust on rock art in Nine Mile Canyon? To summarize, the research undertaken has confirmed that industrial traffic does pulverize the road in Nine Mile Canyon, generating dust that is able to settle on and visually mar the appearance of rock art panels. Under the National Historic Preservation Act, this deposition does constitute an adverse effect. Adverse effects include introduction of visual, atmospheric or audible elements that diminish the integrity of a property's significant historic features.

Other possible adverse effects cannot be so easily confirmed. At present it is not clear if the dust has become physically incorporated into the surface of the rock-art panels, causing irreversible physical and visual alterations. Further, if permanently entrapped dust were to be identified it may prove difficult to determine its provenance. For example, was the dust deposited recently or during previous commercial and recreational uses of the seventy-year-old road? Contamination may have been a *fait accompli* prior to the current industrial use of the road.

The extent to which dust produced by vehicular traffic is able to migrate throughout Nine Mile Canyon and settle in a deleterious manner on all rock-art panels remains unclear. It is also important to factor in the now-constant "background noise" of industrial and particulate pollution everywhere in North America and Europe. There is always particulate "background noise" produced naturally, by normal soil erosion conditions, wind, and vegetation in the form of pollen and resinous exudates.

Perhaps most importantly, human activity in Nine Mile Canyon had altered the natural environment at least 80 years before the current energy-related work began. To this constellation of issues must be added the extraordinary drought conditions and massive fires near Nine Mile Canyon in July, 2007. These conditions certainly added to the "background noise" of fine particulates, in the form of smoke and extensive fine dust produced by the desiccation of the natural and altered landscapes of the area. Consequently, there is no way to determine what a normal particulate "baseline" would have been for Nine Mile Canyon.

Nevertheless, even when these caveats are factored into the overall analysis, the collected data do support the visual observation that heavy vehicular traffic on untreated roads will produce fine particulates that settle on, and may have the capacity to damage, nearby rock art. The outstanding rock art of Dry Canyon proved to be a highly instructive study site.

The Dry Canyon site was used as a control because it is not subject to daily development activities. There is almost no vehicular traffic in Dry Canyon, and its road has remained hard-packed and in good condition. In Dry Canyon, the particle counter's readings of air-borne particulates were relatively low and were very similar to readings taken at sites that are adjacent to roads in Nine Mile Canyon that have been treated with magnesium chloride, a dust abatement chemical.

These readings contrasted greatly with the very elevated particulate readings taken at the Hunt Scene, located on a pulverized area of the Nine Mile Canyon road, after the passage of heavy traffic. Hence, it can be concluded that where the roads remain compacted, blocking the genesis of dust, clouds of particulates are not created.

The possibility of salt contamination and resulting salt-related weathering of the sandstone has been raised. Some areas of the road in Nine Mile Canyon have been treated with a hardening substance generically referred to as "magnesium chloride." Magnesium chloride was documented on some of the rock-art sites. Magnesium chloride has the capacity to damage concrete buildings and works of art. For this reason, its use in proximity to the rock-art sites of Nine Mile Canyon has elicited general negative feedback. However, the damaging effects have been observed when magnesium chloride occurs naturally in limestone or as a component of a de-icing compound that comes into contact with concrete. There is no proof to date that magnesium chloride has damaged, or has the capacity to damage, the sandstone of Nine Mile Canyon.

The identification of magnesium chloride at some rock-art panels in Nine Mile Canyon raises questions about its provenance. Magnesium chloride can be used alone to suppress dust, but generally it is mixed with hydrated magnesium oxide and water to produce the hardening agent known as Sorel cement. Research undertaken in the course of this study suggests that the magnesium chloride is chemically transformed during the creation of Sorel cement and would not escape into the air. If this is the case, the true origin of the magnesium chloride identified in samples needs to be determined by further research. However, at this stage of the research it is assumed that the magnesium chloride identified at rock art sites does originate on treated areas of the road.

Naturally occurring salts were identified in dust samples collected at rock-art sites in Nine Mile Canyon. These data are not surprising because salts are common in desert and semi-arid regions and in ancient river and lakebeds. Mechanical pressures exerted by some salts can cause damage to sandstone if they have penetrated the pores and interstices. However, at present it cannot be confirmed if the salts are able to penetrate the sandstone to the extent that they can provoke damage over time. Nor is it known if all, or any, of the sandstone in Nine Mile Canyon is susceptible to salt weathering.

A related conservation problem could be aeolian abrasion from wind-borne grit in the dust. However, investigations of the relative hardness of the sandstone and of the grit have not been undertaken. Further, it is not known if weather patterns in the canyon favor generation of winds that can support abrasive action.

To conclude, therefore, this study has confirmed that the rock art is visually marred by dust generated by industrial traffic. It has also identified several other possible adverse effects from dust. When weighed together, they do tip the scale toward the need for an abatement and conservation program for the rock art of Nine Mile Canyon. The final section of this report outlines a program for remediation.

5.2
RECOMMENDATIONS

A program is outlined for continuing research on dust and its effects on rock art in Nine Mile Canyon and for remedial conservation treatments:

1. **Dust Abatement.** Research is needed to develop safe dust abatement treatments for the road in Nine Mile Canyon. This research has begun under the direction of BBC and the BLM.

2. **Baseline Documentation.** Baseline photographic and descriptive documentation of rock-art sites is very important. At present, it is almost impossible to judge if dust has altered the condition of the rock art because there are no detailed baseline studies of the sites to use to document change over time.

3. **Development of Analytical Methods for Determination of Damage.** This report has stressed that, thus far, it is not possible to confirm whether all or any of the rock-art sites have been permanently damaged by deposition of dust, which can include various types of salts. This avenue of research needs to be continued and developed, in order to answer the key question of this research: how has the rock art been damaged permanently by deposition of dust?

4. **Investigation of Possible Deposition of Hydrocarbon Emissions.** The study of industrial pollutants at Burrup, Australia, remains in progress. The resulting data will be extremely useful for developing methods to determine if industrial traffic and development in Nine Mile Canyon causes deposition of industrial pollutants.

5. **Development of Conservation Treatments.** Systems for removing dust from the affected panels will be developed in the laboratory and eventually tested on site. It is important that any dust removal system avoid contamination of the stone with chemicals that could alter analytical systems used now, or in the future, for the dating or rock art.

6. **Continuing Research on Magnesium Chloride.** Use of magnesium chloride in Nine Mile Canyon has provoked a high level of concern, but is this anxiety really justified? Additional research needs to be undertaken to understand better the origins, migration, deposition, and potential to cause harm posed by magnesium chloride in Nine Mile Canyon.

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APPENDIX 1:
LABORATORY ANALYSES

EMSL Analytical, Inc.

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Materials Science Division

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EMSL Case No.:	360700946
Sample(s) Received:	08/13/2007
Date of Analysis:	10/22/2007
Date Printed:	10/22/2007
Reported By:	D. D'Ulisse

- Laboratory Report -

Material Analysis

For

Project: Nine-Mile Canyon, Utah

Analyzed by: [signature] October 22, 2007

Dana D'Ulisse
Materials Scientist

Date

QA/QC : [signature] October 22, 2007

John Newton
Laboratory Manager

Date

EMSL Analytical, Inc.

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Conclusions:

- Magnesium Chloride with identified in samples 1.1, 2.1, 2.2, 3.3, and 5.3.
- Magnesium and/or chloride were identified in all of the remaining samples; however, they could not be isolated to show magnesium chloride.

Procurement of Samples and Analytical Overview:

The samples for analysis (15 bulk) arrived at EMSL Analytical's corporate laboratory in Westmont, NJ on August 13, 2007. The package arrived in satisfactory condition with no evidence of damage to the contents. The samples were submitted for the purpose of determining the particle sizes/distribution, porosity, mineral identification and presence of magnesium chloride. The samples reported herein have been analyzed using the following equipment and methodologies.

Methods & Equipment:
Stereo Microscopy
Scanning Electron Microscopy (SEM)
Energy Dispersive X-Ray Spectrometry (EDX)
X-Ray Diffraction (XRD)
Set of Sieves
Scale (0.01 g Sensitivity)

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Results and Discussion:

Table 1.1. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 1. Harmon Canyon**
Location	**1.1 Road. Bulk Sample**
Particle size range	
d > 20μm	100.00
10 μm< d ≤ 20 μm	0.00
d ≤ 10 μm	0.00

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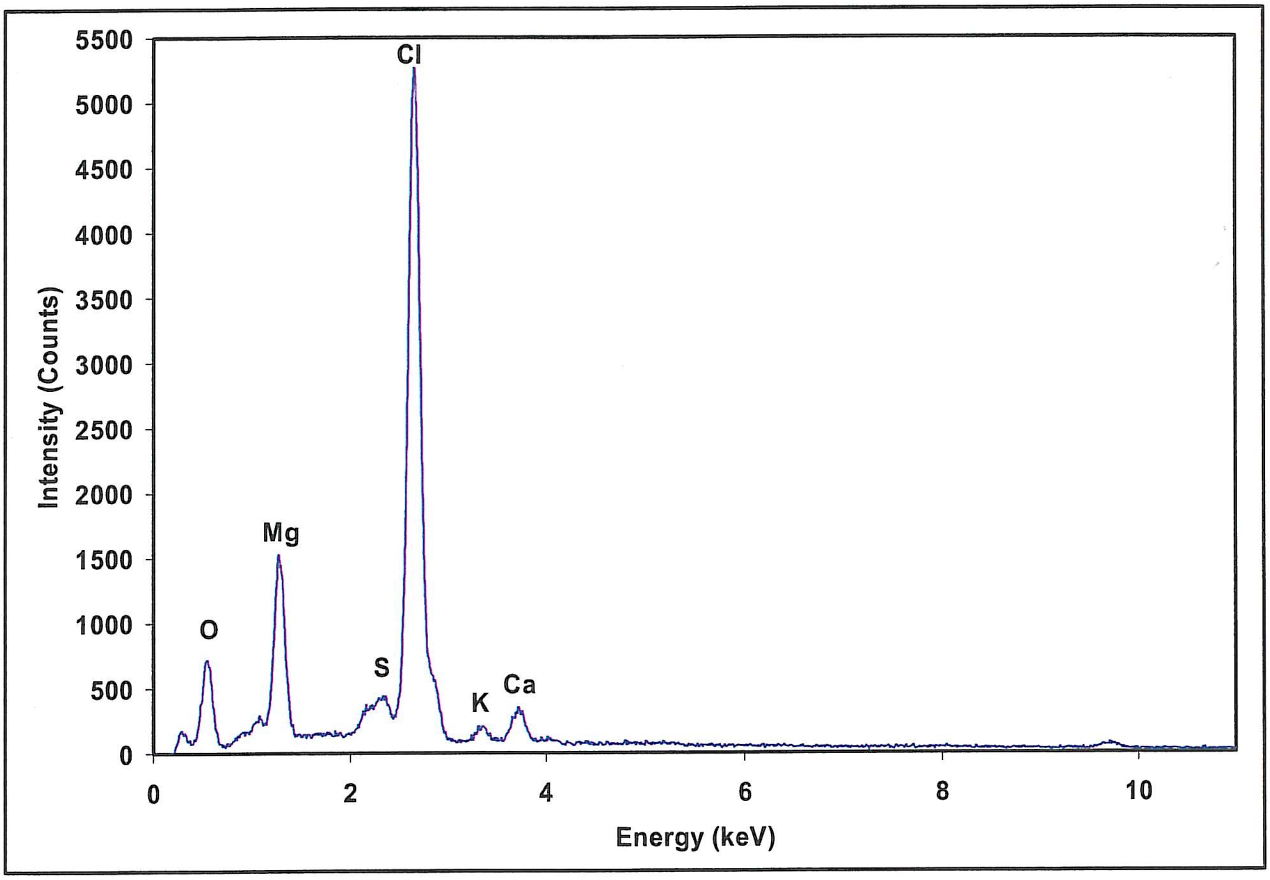

Figure 1.1.1: SEM/EDX elemental spectra of the materials extracted from sample 1.1 indicating the presence of magnesium + chlorine.

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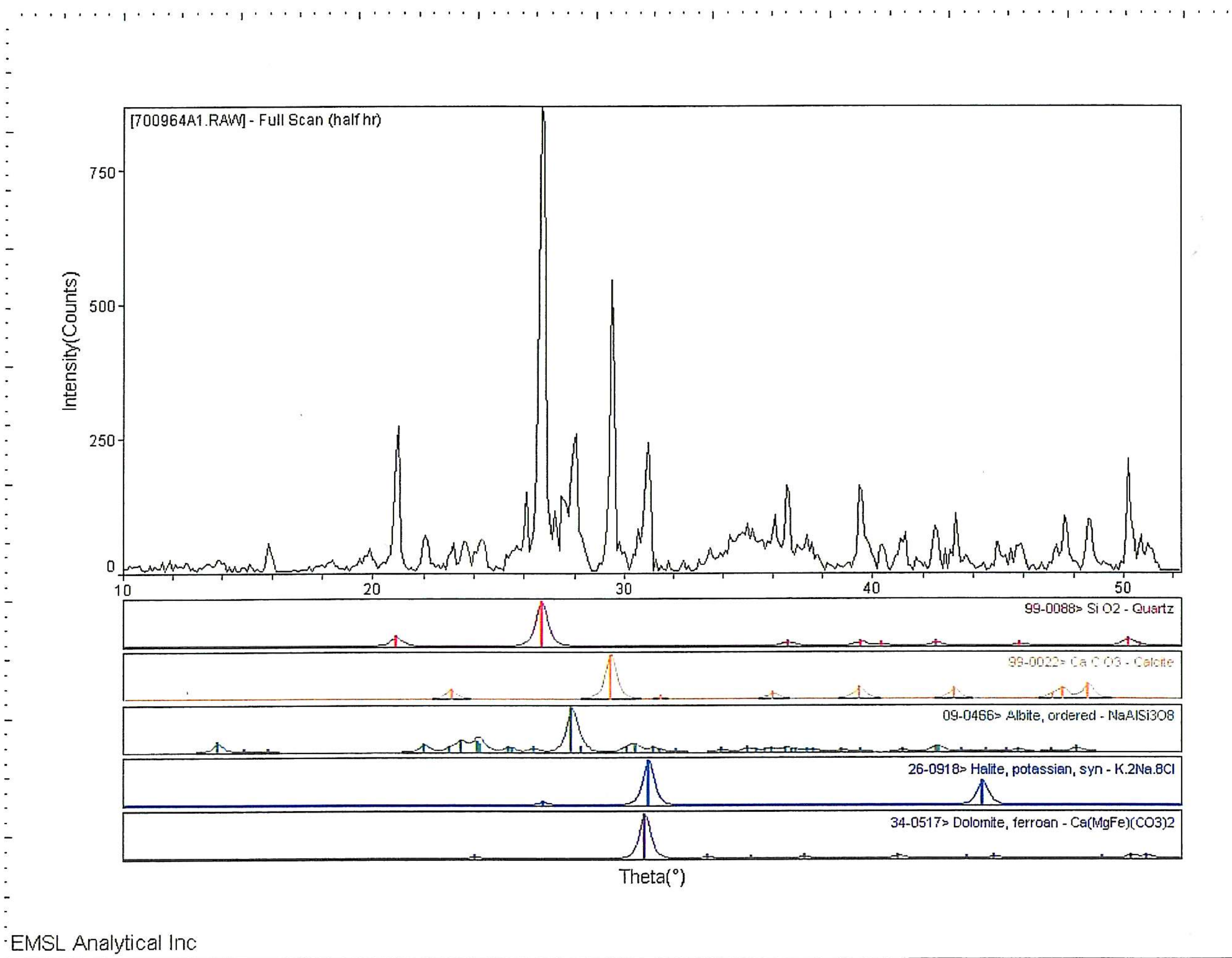

Figure 1.1.2: XRD spectra of sample 1.1 showing matches with the standard spectra for quartz (SiO_2), calcite ($CaCO_3$), albite ($NaAlSi_3O_8$), halite ($K.2Na_8Cl$) and dolomite ($Ca(MgFe)(CO_3)_2$).

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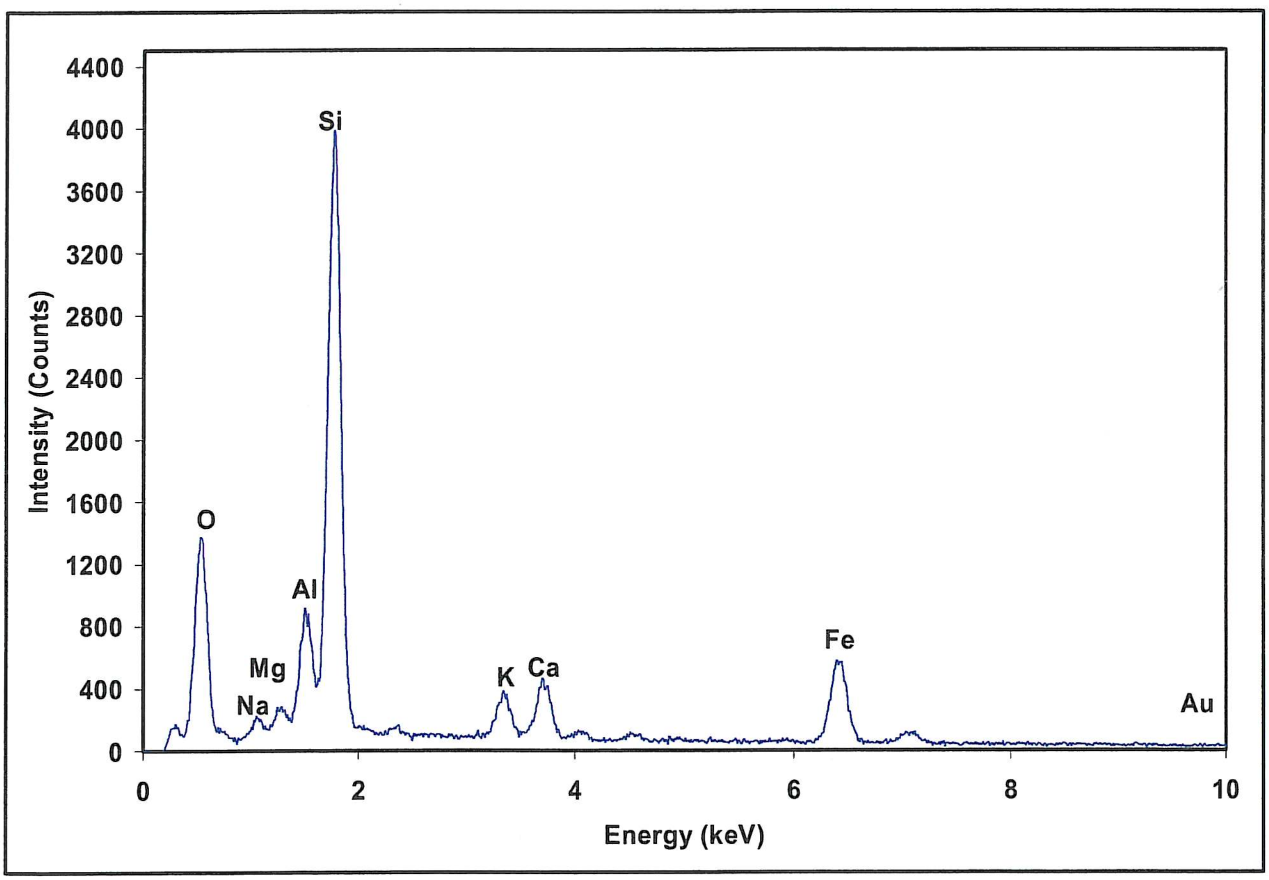

Figure 1.2.1: SEM/EDX elemental spectra of the particles on the surface of sample1.2 indicating the presence of quartz (SiO_2) and clays and feldspars (aluminum silicates). Magnesium chloride was not identified within the limit of detection.

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Table 1.3. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 1. Harmon Canyon**
Location	**1.3 Stone From Base of Panel**
Particle size range	
d > 20µm	99.03
10 µm< d ≤ 20 µm	0.54
d ≤ 10 µm	0.43

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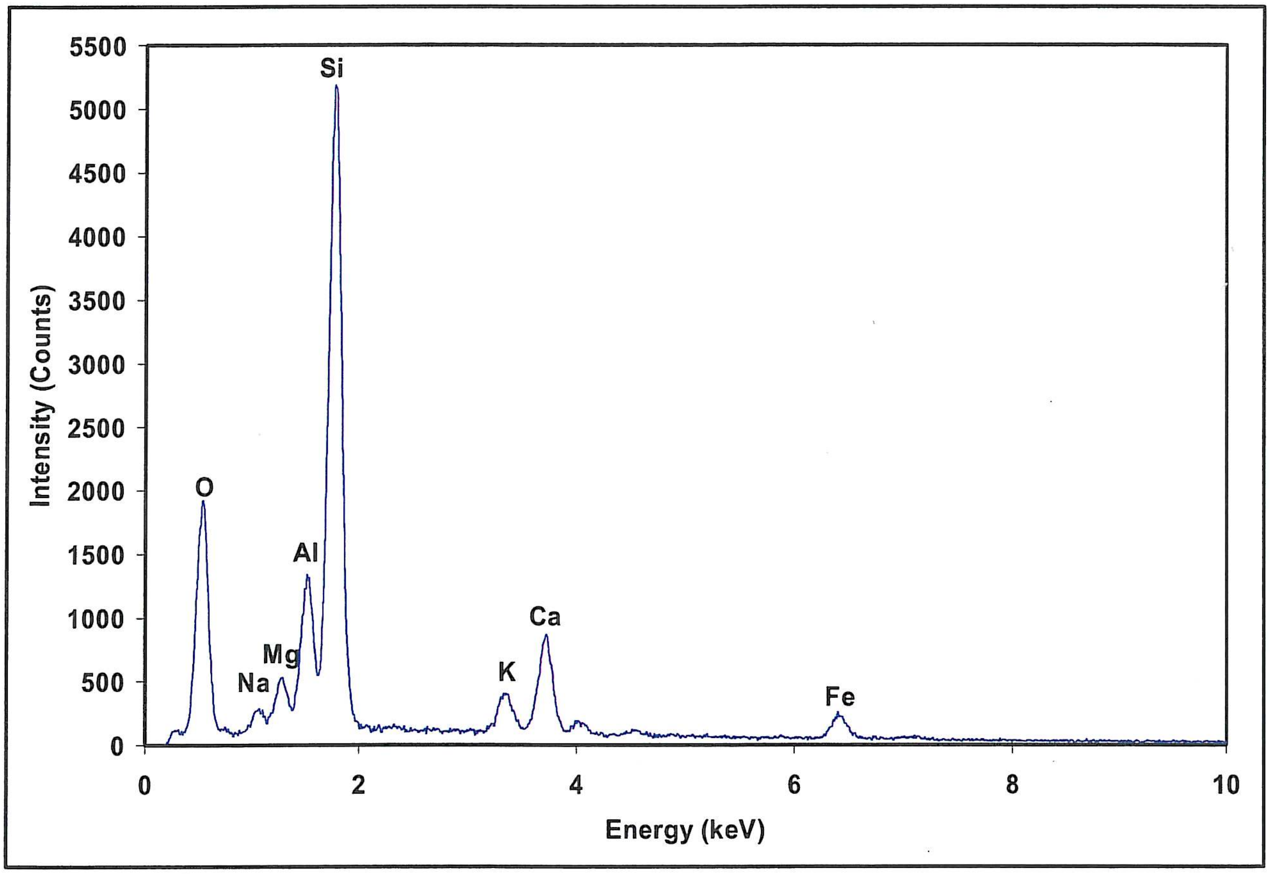

Figure 1.3.1: SEM/EDX elemental spectra of the particles on the surface of sample1.3 indicating the presence of quartz (SiO2) and clays and feldspars (aluminum silicates). Magnesium chloride was not identified within the limit of detection.

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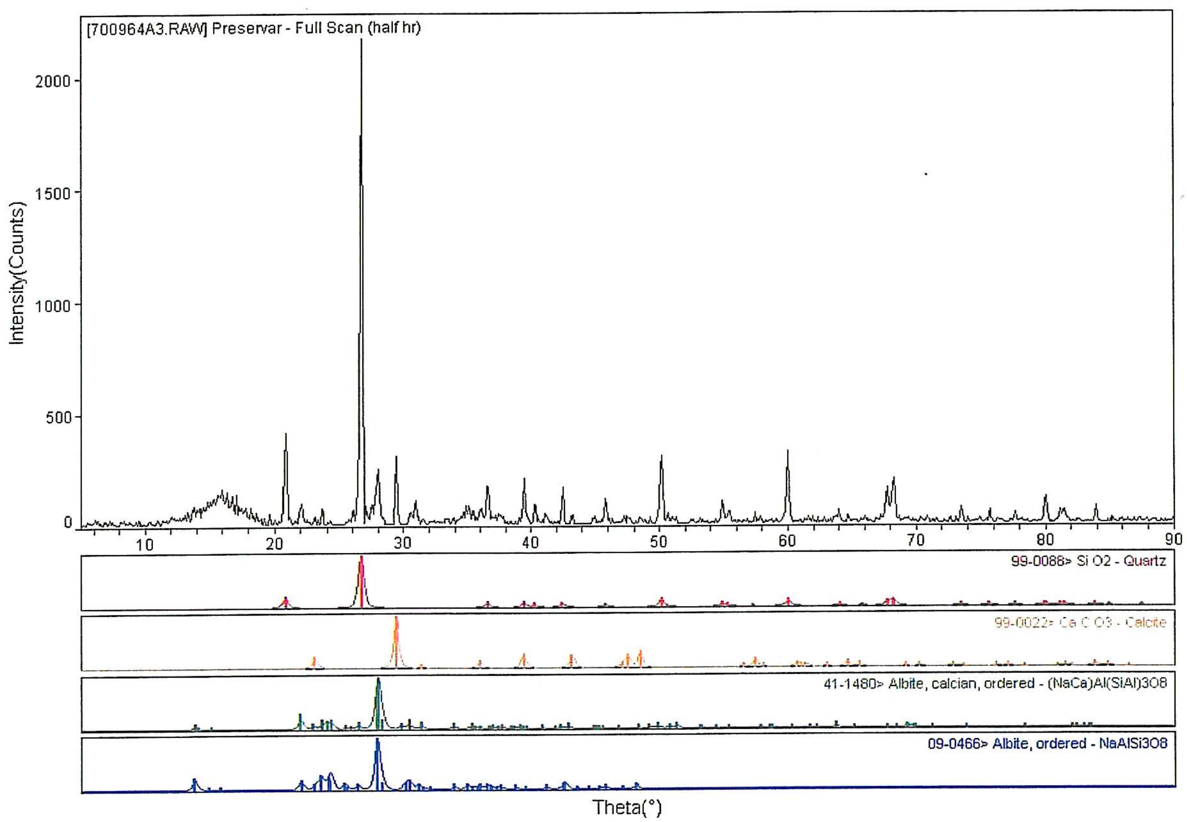

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Figure 1.3.2: XRD spectra of sample 1.3 showing matches with the standard spectra for quartz (SiO_2), calcite ($CaCO_3$), albite, calcian, ordered $(NaCa)Al(SiAl)_3O_8$ and albite, ordered ($NaAlSi_3O_8$).

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Table 2.1. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 2. Cottonwood Canyon, Hunt Scene**
Location	**2.1 Road. Bulk Sample**
Particle size range	
d > 20μm	95.75
10 μm< d ≤ 20 μm	1.50
1 μm< d ≤ 10 μm	2.75
0.1 μm< d ≤ 1 μm	0.00

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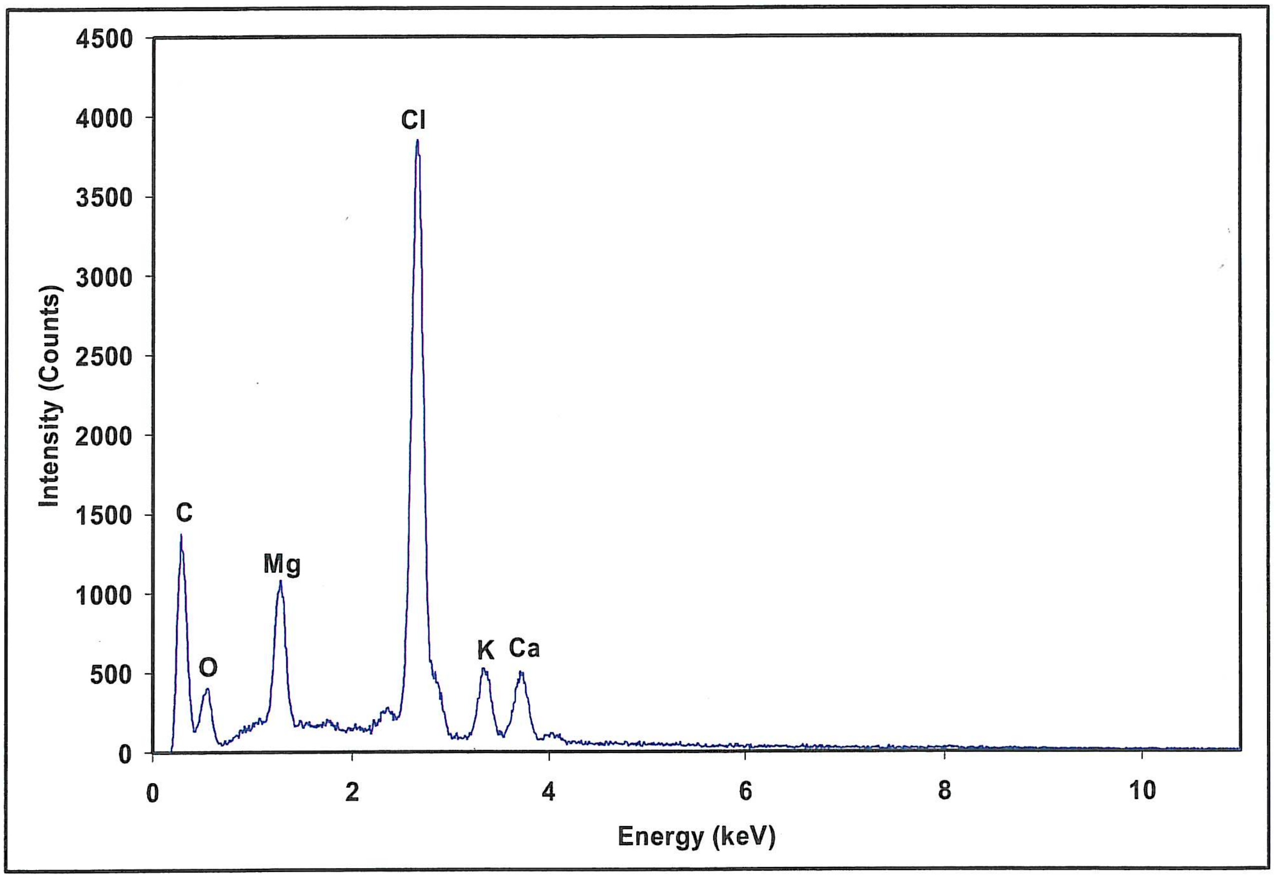

Figure 2.1.1: SEM/EDX elemental spectra of the material extracted from sample 2.1 indicating the presence of magnesium + chlorine.

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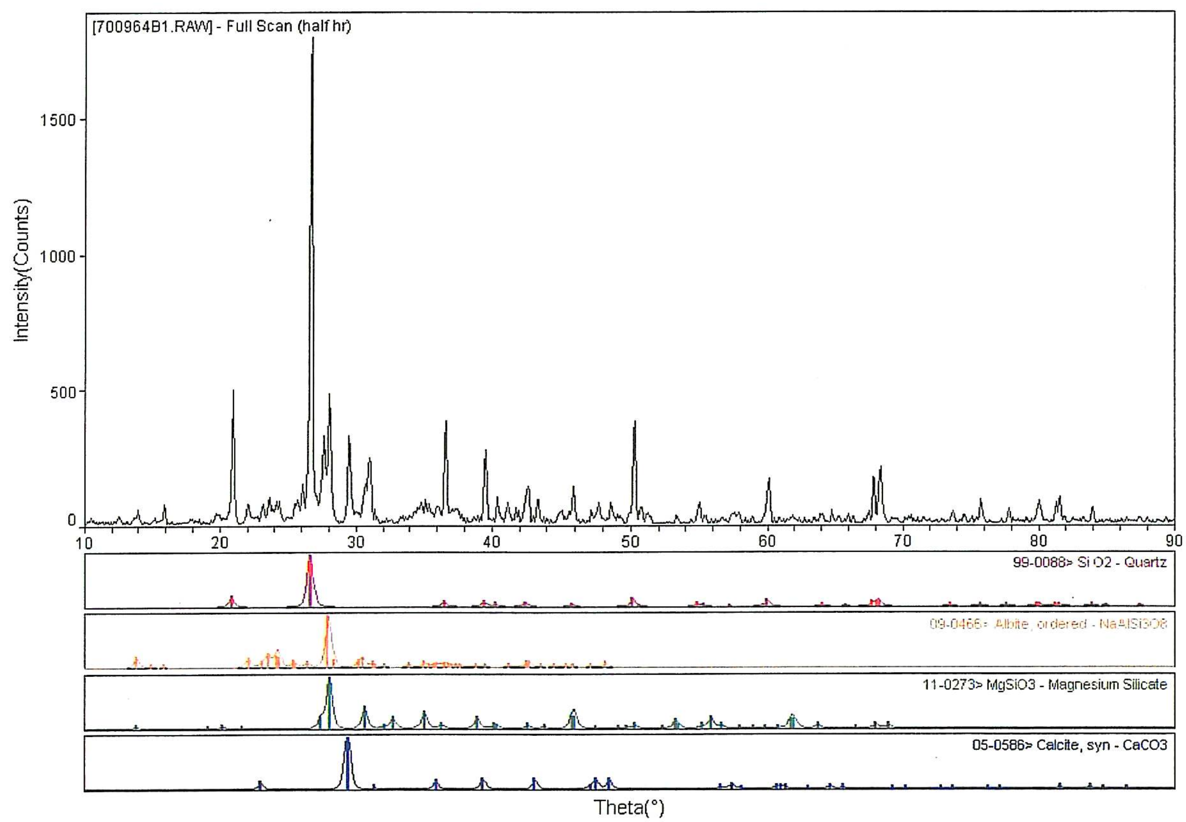

Figure 2.1.2: XRD spectra of sample 2.1 showing matches with the standard spectra for quartz (SiO_2), albite ($NaAlSi_3O_8$), magnesium silicate ($MgSiO_3$) and calcite ($CaCO_3$).

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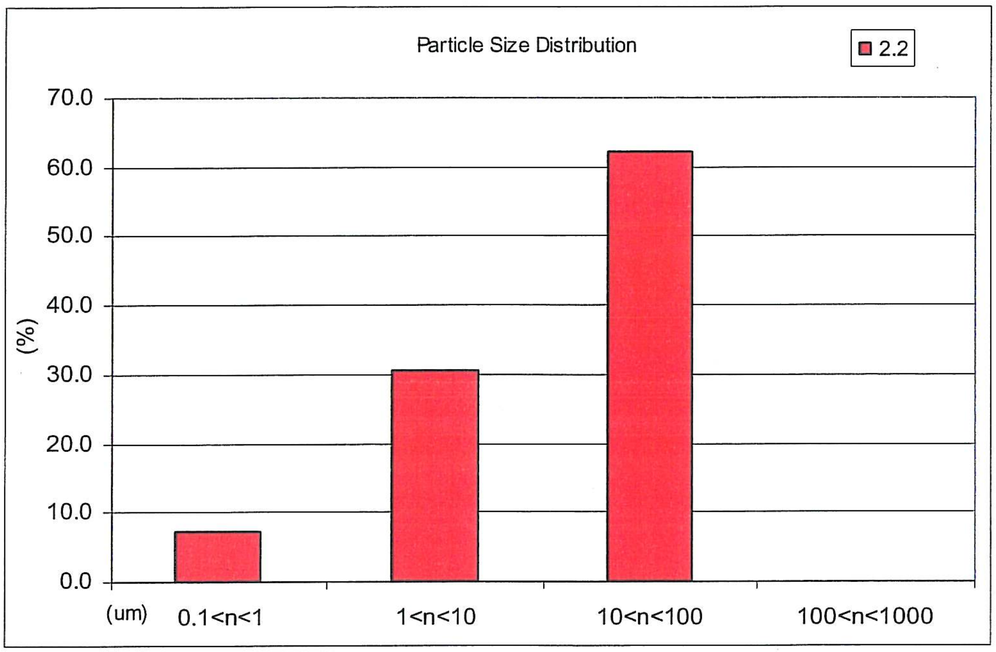

Table 2.2. Histogram of particle size and distribution for sample 2.2

		Range (um)	Count	(%)
Sample:	2.2			
Description:	From Under Large Panel	0.1<n<1	16	7.4
		1<n<10	66	30.6
		10<n<100	134	62.0
		100<n<1000	0	0.0

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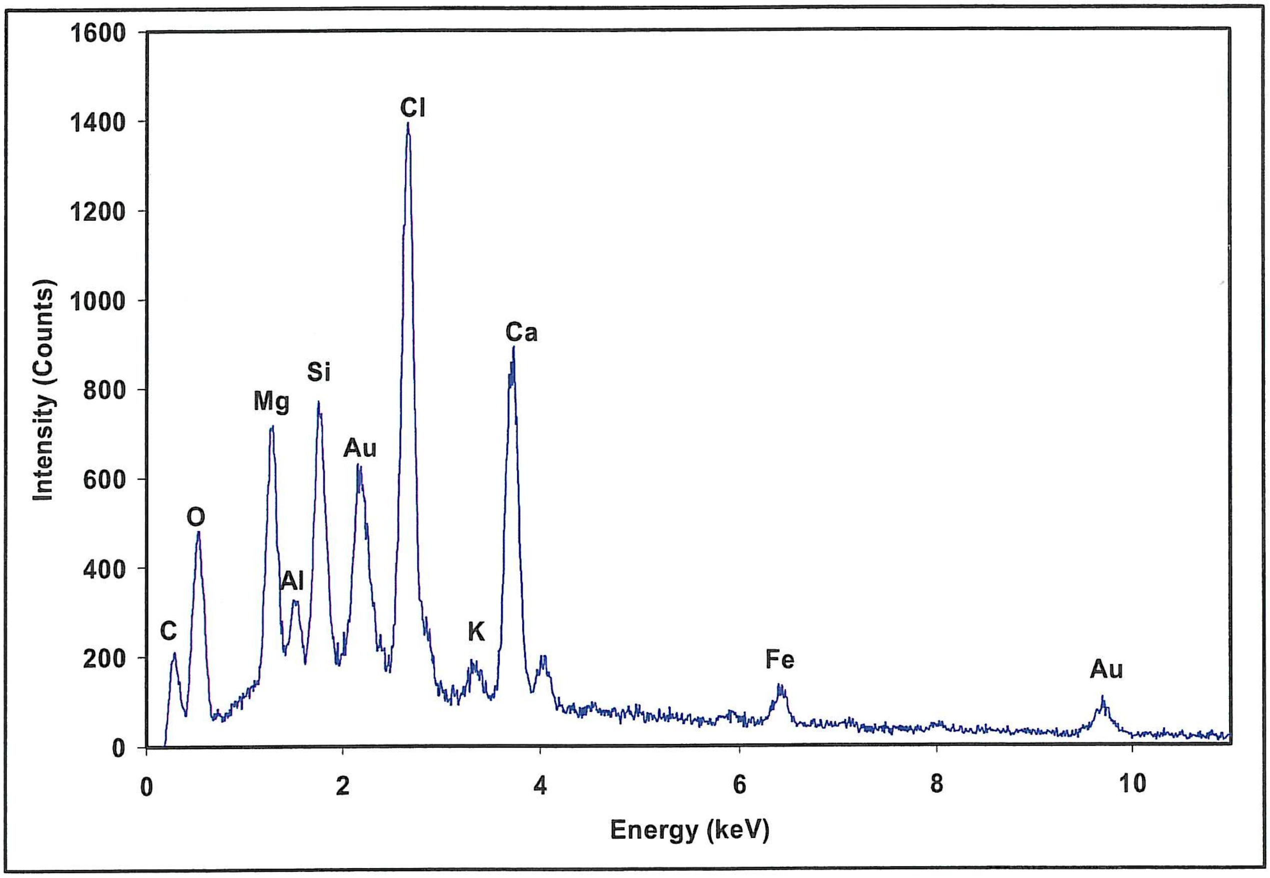

Figure 2.2.1: SEM/EDX elemental spectra of a single particle in sample 2.2 showing the possible presence of magnesium chloride.

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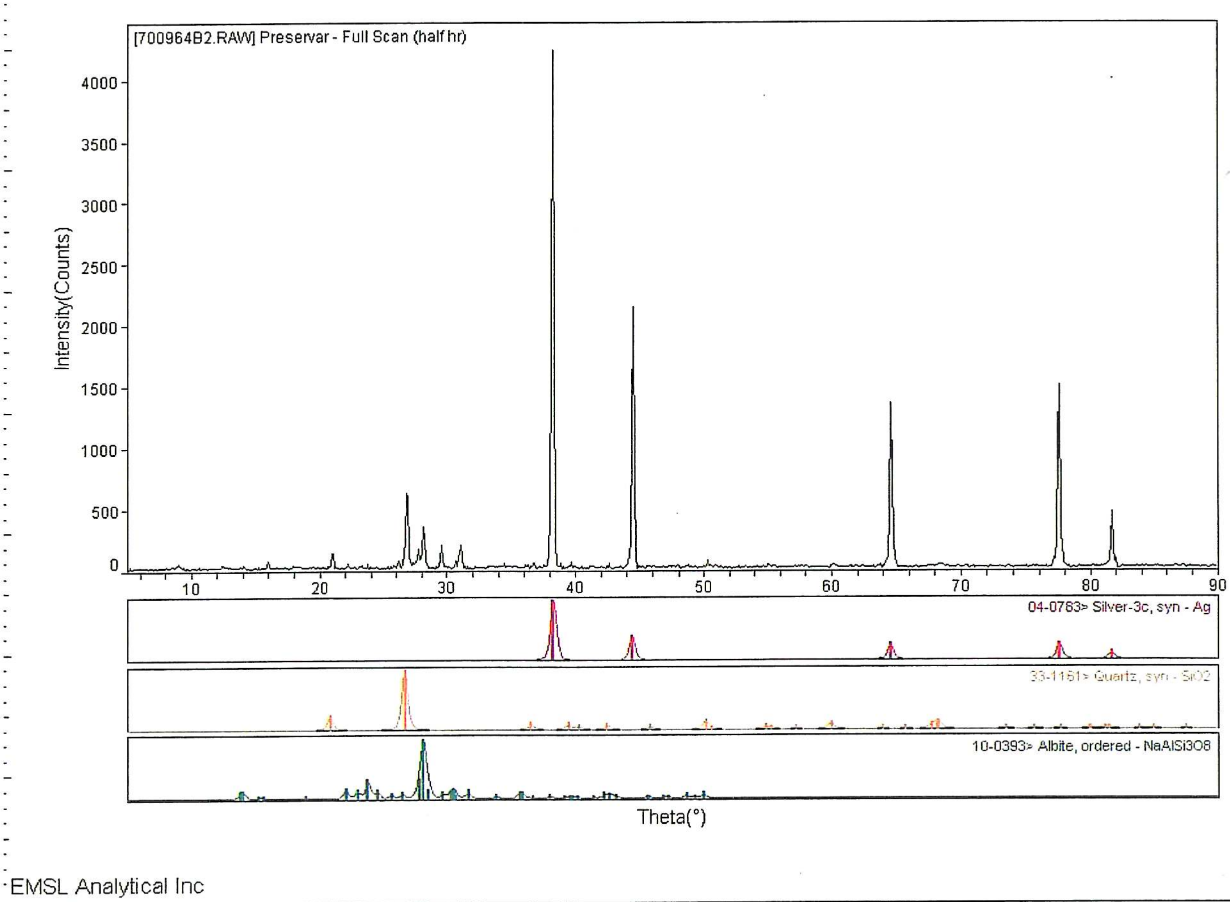

Figure 2.2.2: XRD spectra of sample 2.2 showing matches with the spectra for quartz (SiO_2) and albite ($NaAlSi_3O_8$). The sample was prepared on a silver [Ag] filter.

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Table 2.3. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 2. Cottonwood Canyon, Hunt Scene**
Location	**2.3 Taken From Panel (Below and to Left of Large Panel)**
Particle size range	
d > 20μm	100.00
10 μm< d ≤ 20 μm	0.00
d ≤ 10 μm	0.00

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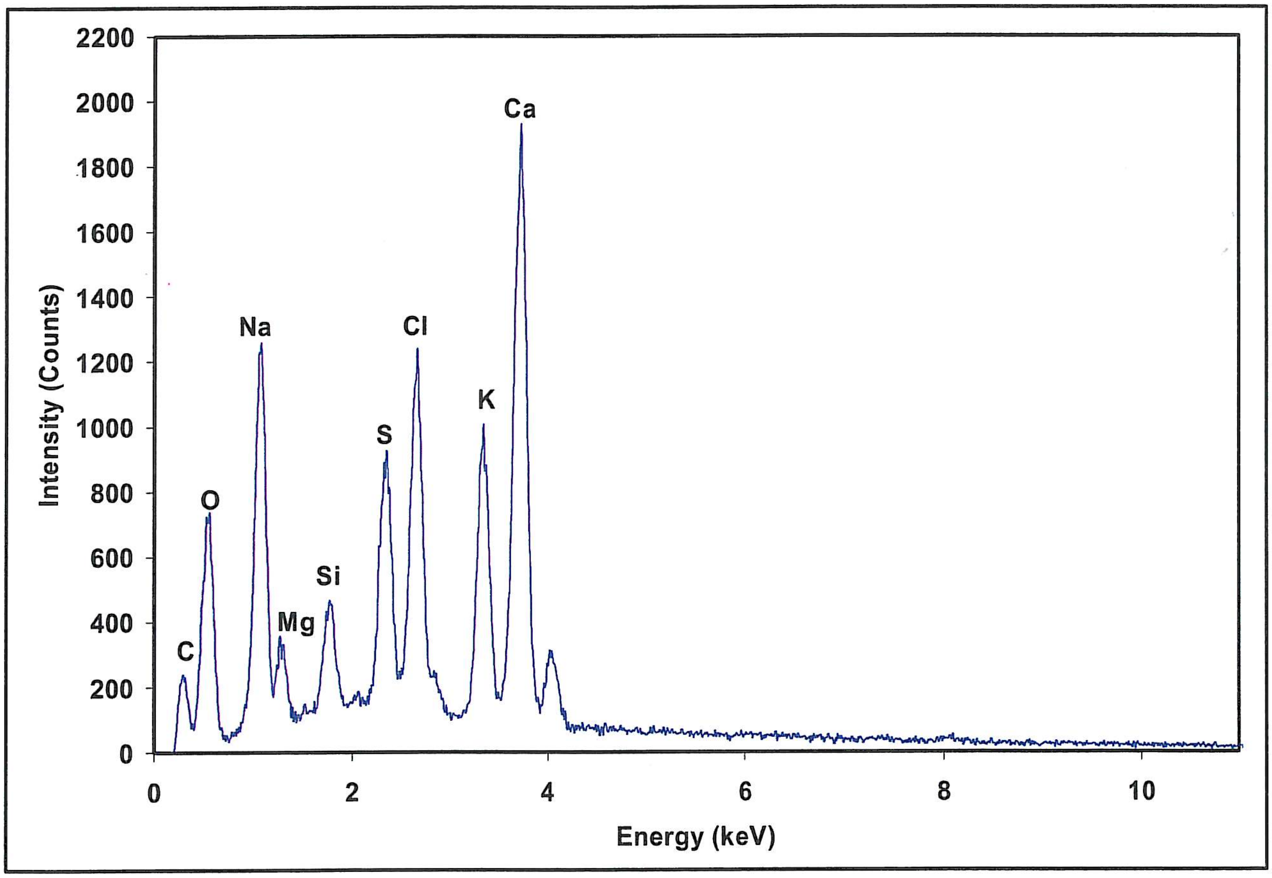

Figure 2.3.1: SEM/EDX elemental spectra of the material extracted from sample 2.3 indicating the presence of chlorides and sulfate salts. Magnesium and chlorine are present but could not be isolated to show magnesium chloride.

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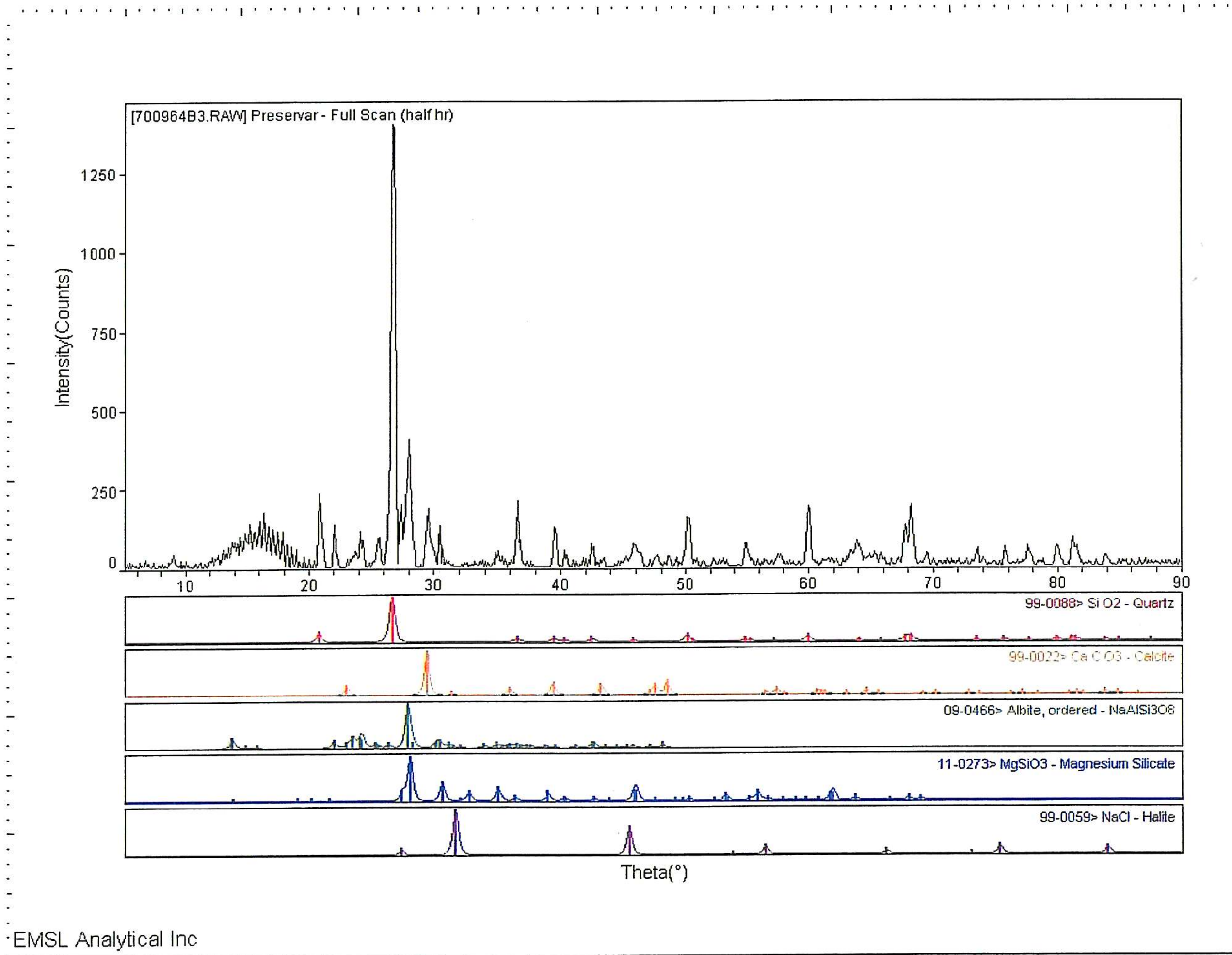

Figure 2.3.2: XRD spectra of sample 2.3 showing matches with the standard spectra for quartz (SiO_2), calcite ($CaCO_3$), albite, ordered ($NaAlSi_3O_8$), magnesium silicate ($MgSiO_3$) and halite (NaCl).

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Table 3.1. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 3. Hunt Scene**
Location	**3.1 Taken From Below "T" Vandalism**
Particle size range	
d > 20μm	100.00
10 μm< d ≤ 20 μm	0.00
d ≤ 10 μm	0.00

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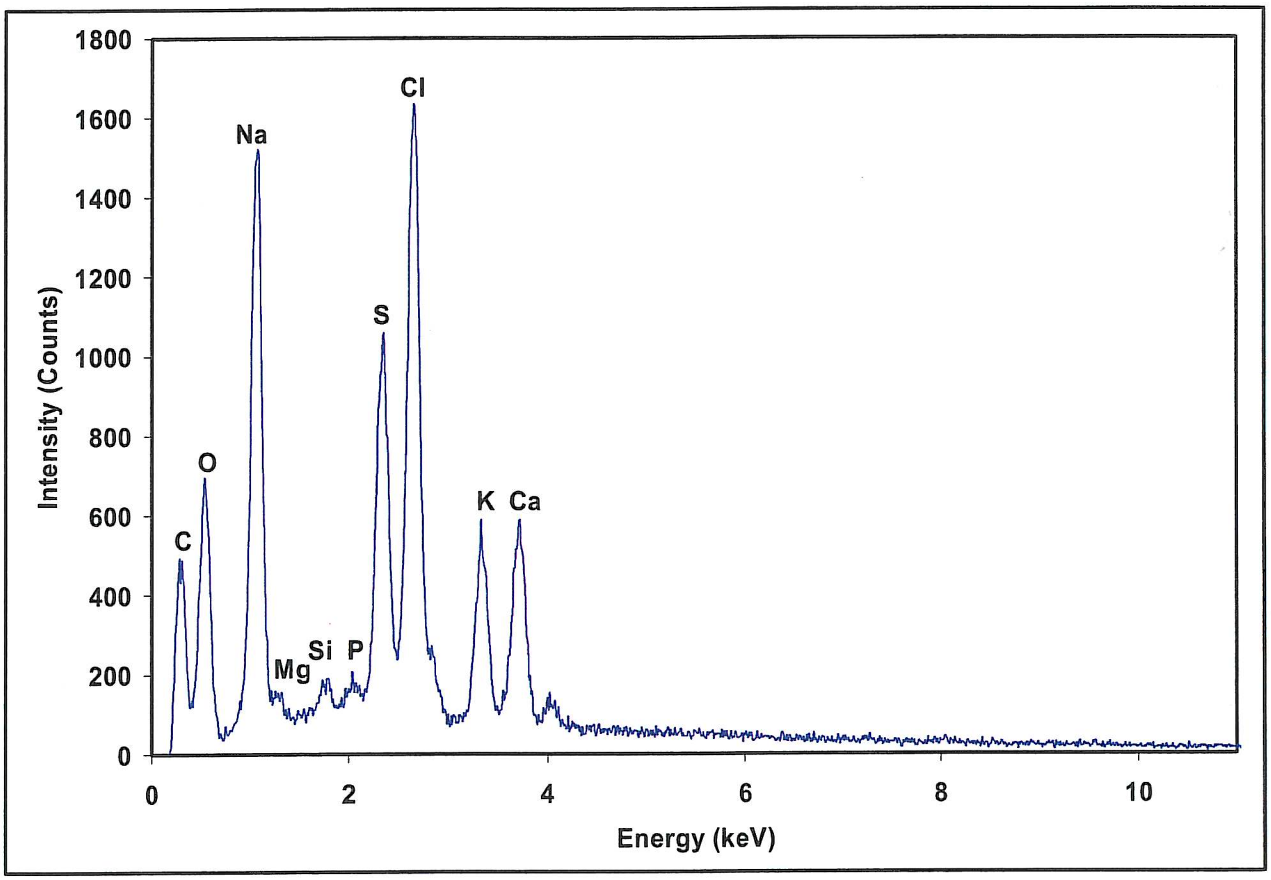

Figure 3.1.1: SEM/EDX elemental spectra of the material extracted from sample 3.1 indicating the presence of chloride and sulfate salts. Magnesium and chlorine are present but could not be isolated to show magnesium chloride.

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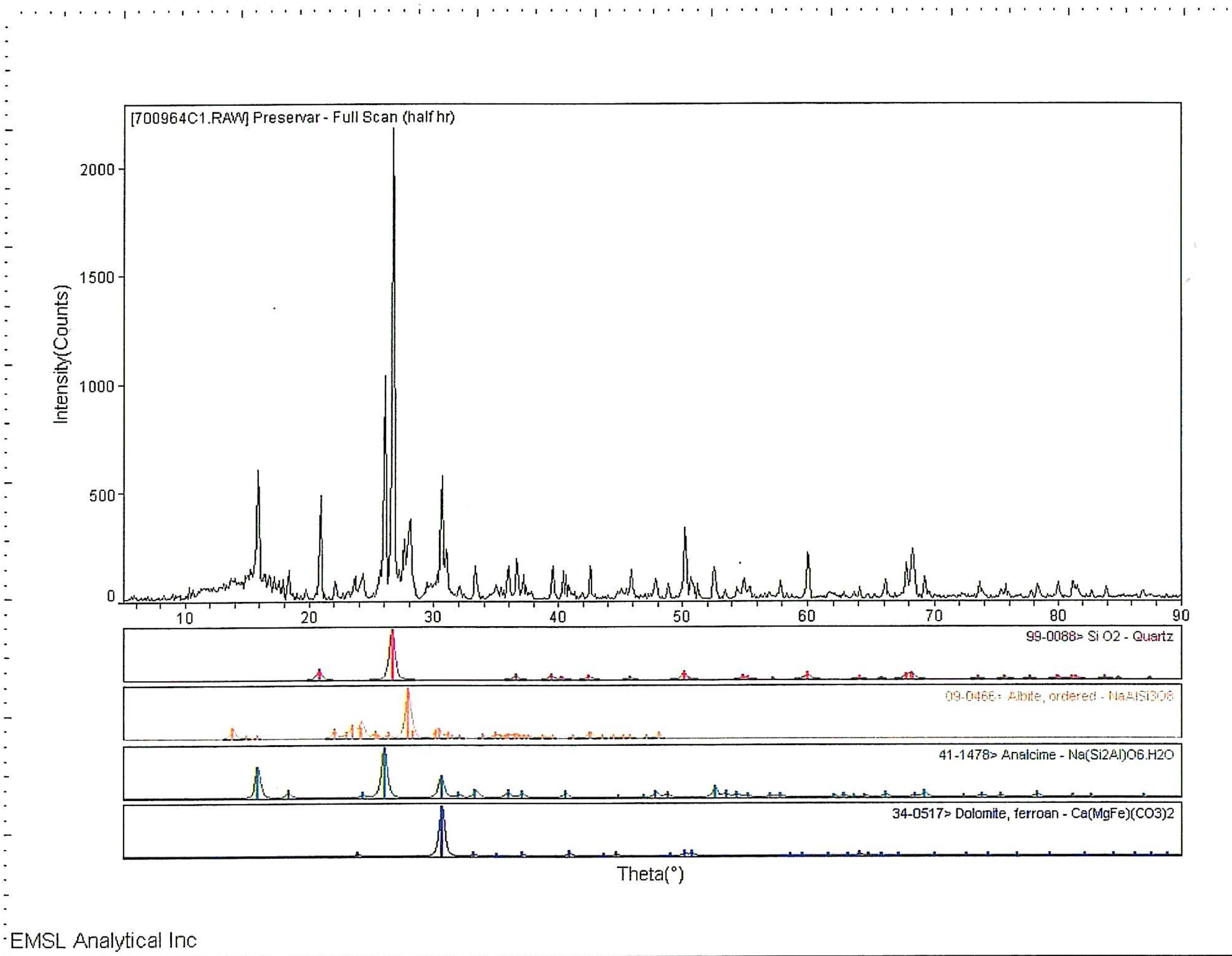

Figure 3.1.2: XRD spectra of sample 3.1 showing matches with the standard spectra for quartz (SiO_2), albite, ordered ($NaAlSi_3O_8$), analcime ($Na(Si_2Al)O_6.H_2O$) and dolomite, ferroan ($Ca(MgFe)(CO_3)_2$).

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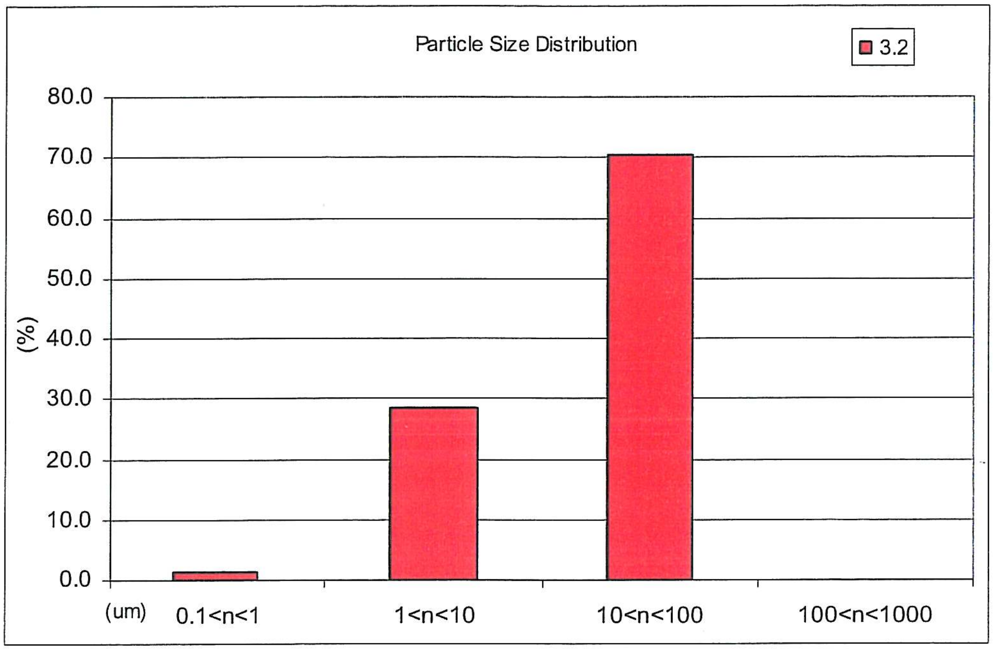

Table 3.2. Histogram of particle size and distribution for sample 3.2

		Range (um)	Count	(%)
Sample:	3.2			
Description:	Petri Dish Left at Panel	0.1<n<1	3	1.3
		1<n<10	68	28.3
		10<n<100	169	70.4
		100<n<1000	0	0.0

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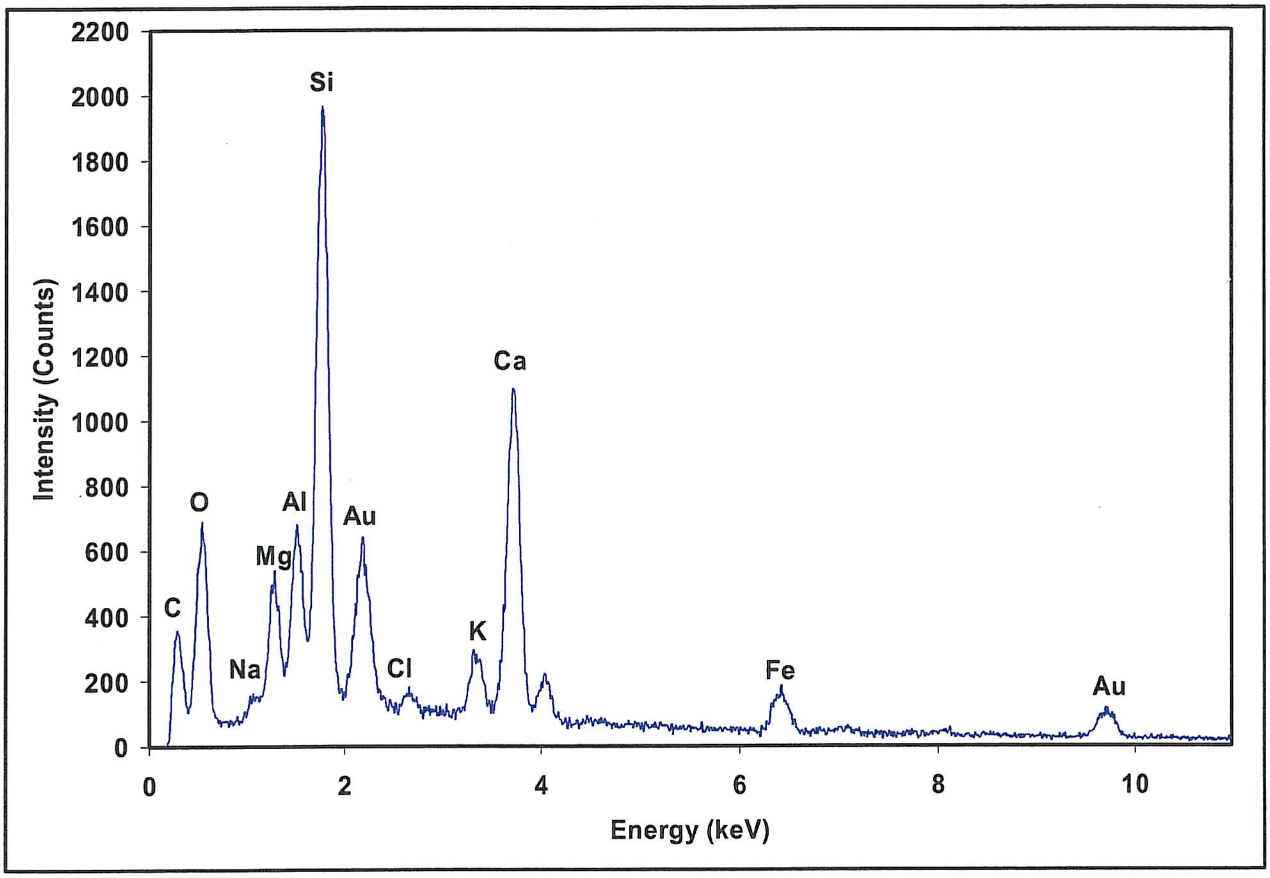

Figure 3.2.1: SEM/EDX elemental spectra of a cluster of particles in sample 3.2. Magnesium and chlorine are present but could not be isolated to show magnesium chloride.

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Table 3.3. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 3. Hunt Scene**
Location	**3.3 Road. Bulk Sample**
Particle size range	
d > 20μm	98.18
10 μm< d ≤ 20 μm	1.57
1 μm< d ≤ 10 μm	0.24
0.1 μm< d ≤ 1 μm	0.01

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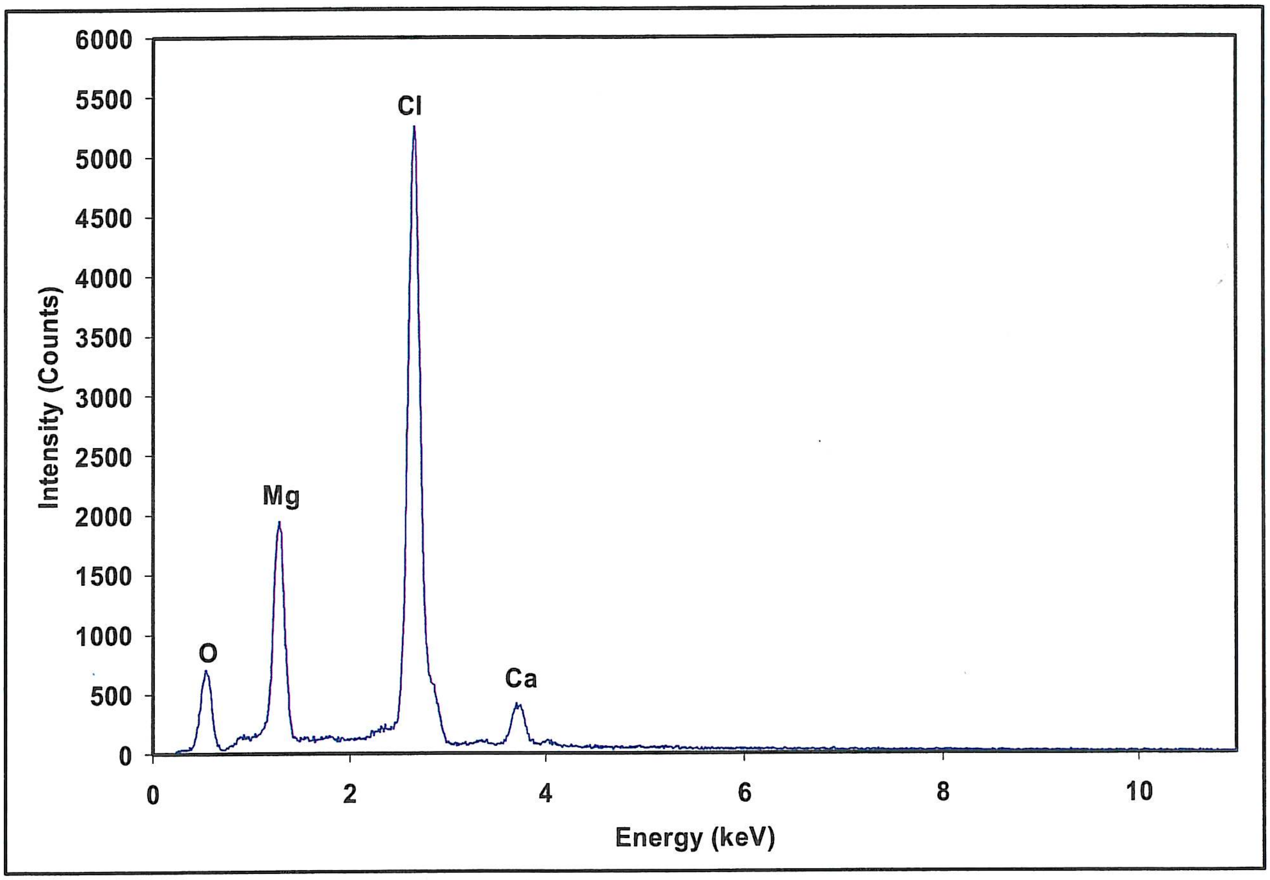

Figure 3.3.1: SEM/EDX elemental spectra of the material extracted from sample 3.3 indicating the presence of magnesium + chlorine.

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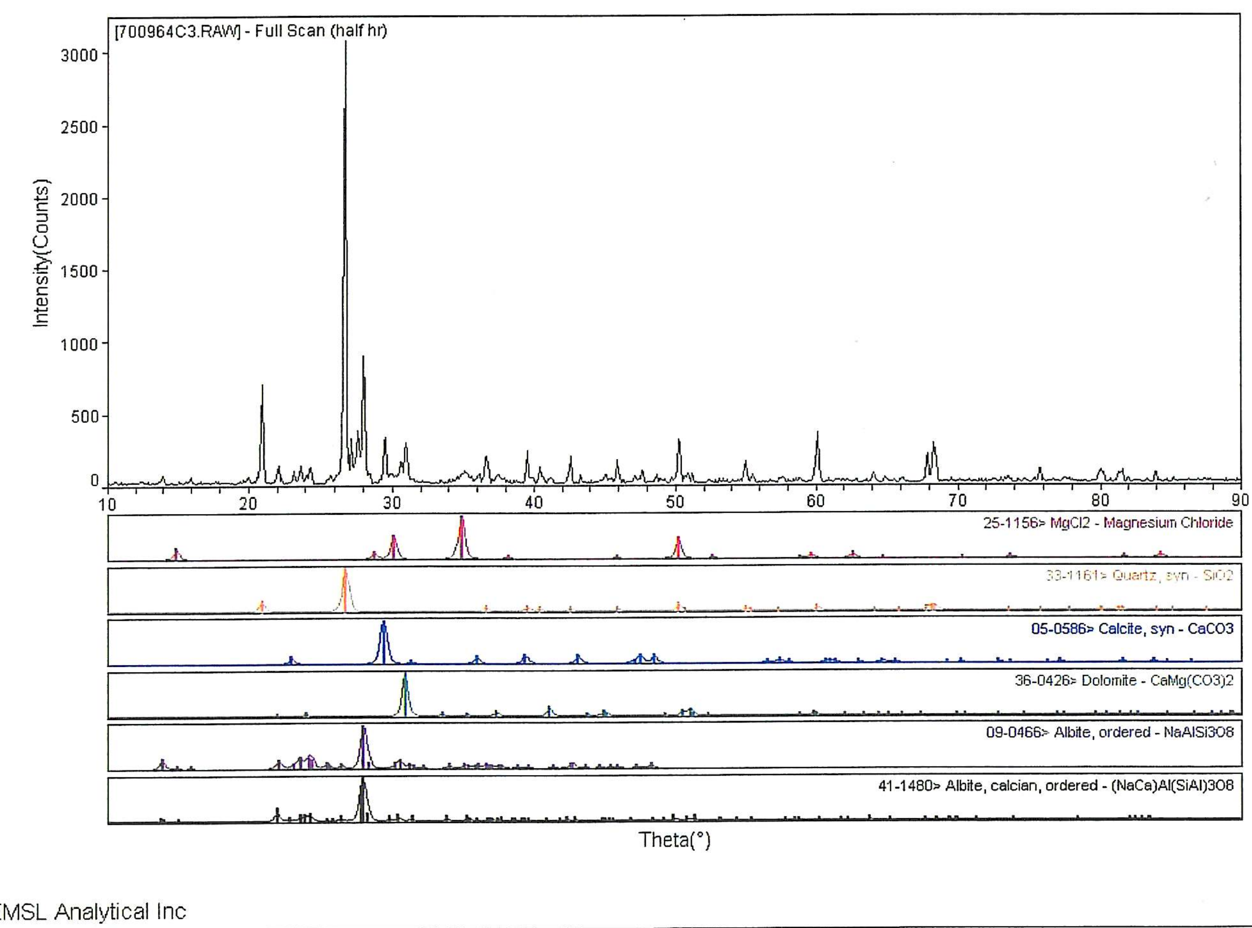

Figure 3.3.2: XRD spectra of sample 3.3 showing a match with the standard spectra for magnesium chloride ($MgCl_2$), quartz (SiO_2), calcite ($CaCO_3$), dolomite ($CaMg\ CO_3$), and albite ($NaAlSi_3O_8$).

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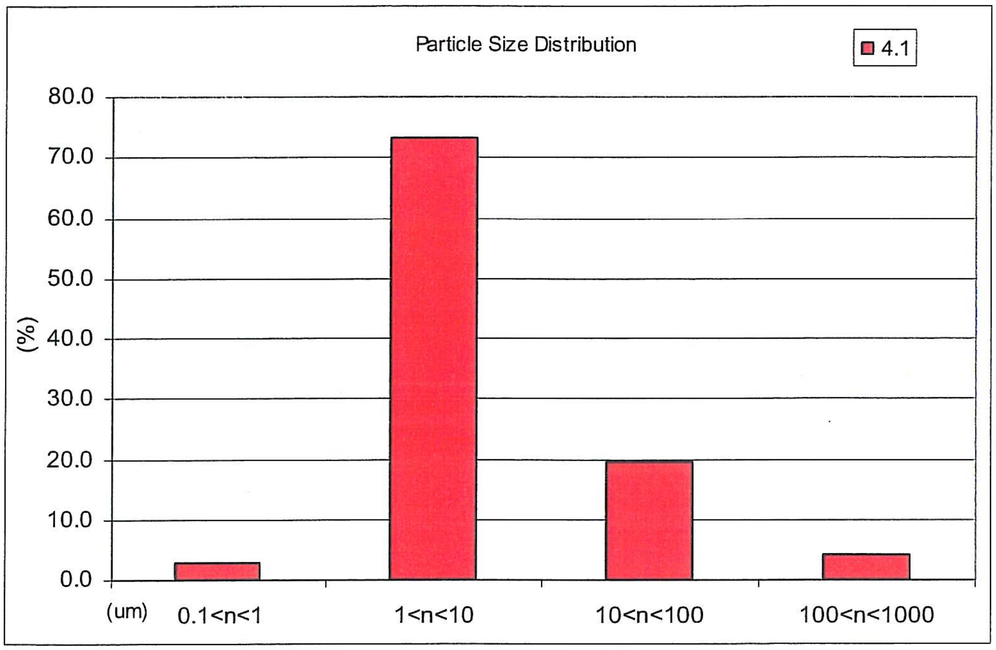

Table 4.1. Histogram of particle size and distribution for sample 4.1

		Range (um)	Count	(%)
Sample:	4.1			
Description:	Petri Dish Left at Panel	0.1<n<1	5	3.0
		1<n<10	121	73.3
		10<n<100	32	19.4
		100<n<1000	7	4.2

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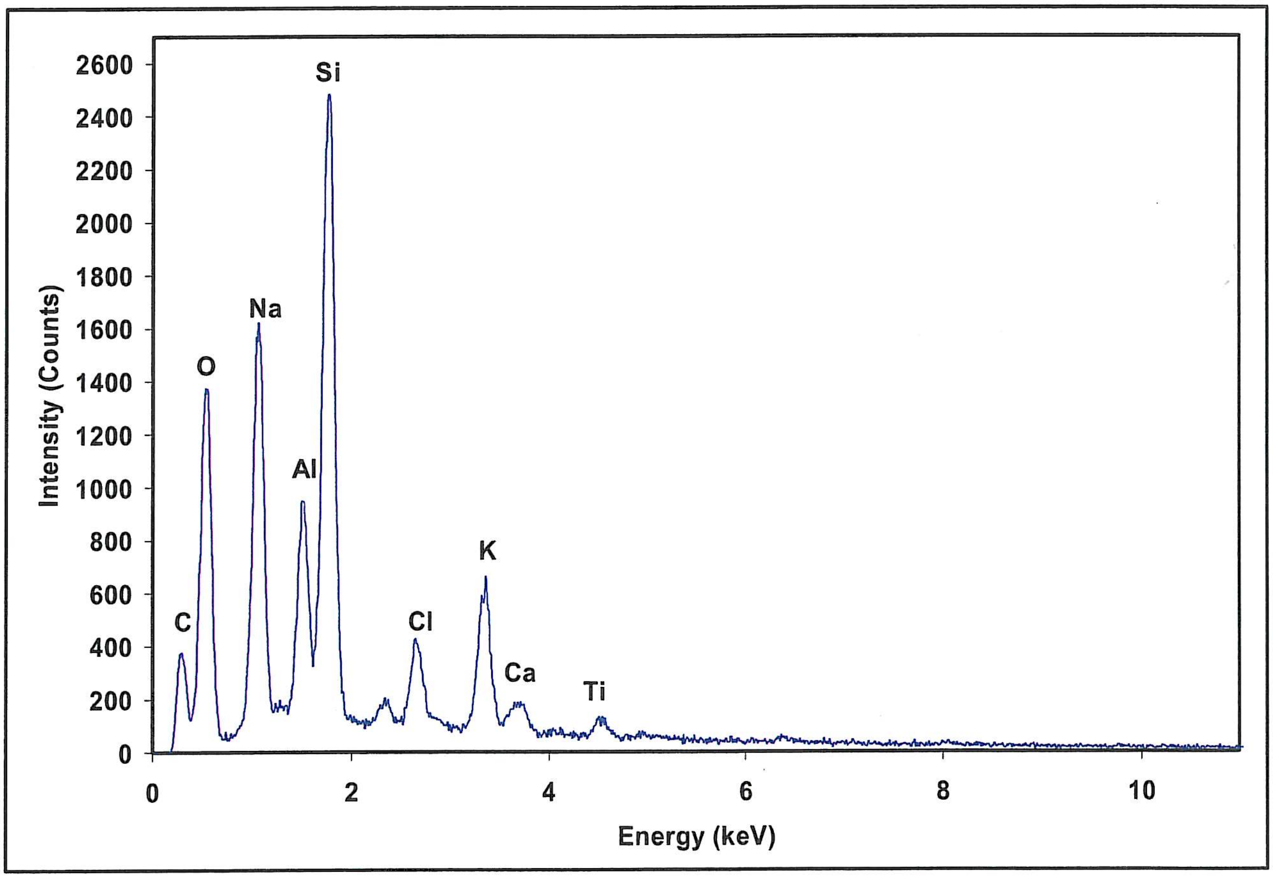

Figure 4.1.1: SEM/EDX elemental spectra of the particles in sample 4.1 indicating the possible presence of sodium bicarbonate, sodium chloride, quartz (SiO_2), feldspars (aluminum silicates), gypsum ($CaSO_4$), and calcite ($CaCO_3$).

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Table 4.2. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 4. Dry Canyon**
Location	**4.2 Sample Removed From Panel Below Snake Image**
Particle size range	
d > 20μm	100.00
10 μm< d ≤ 20 μm	0.00
1 μm< d ≤ 10 μm	0.00

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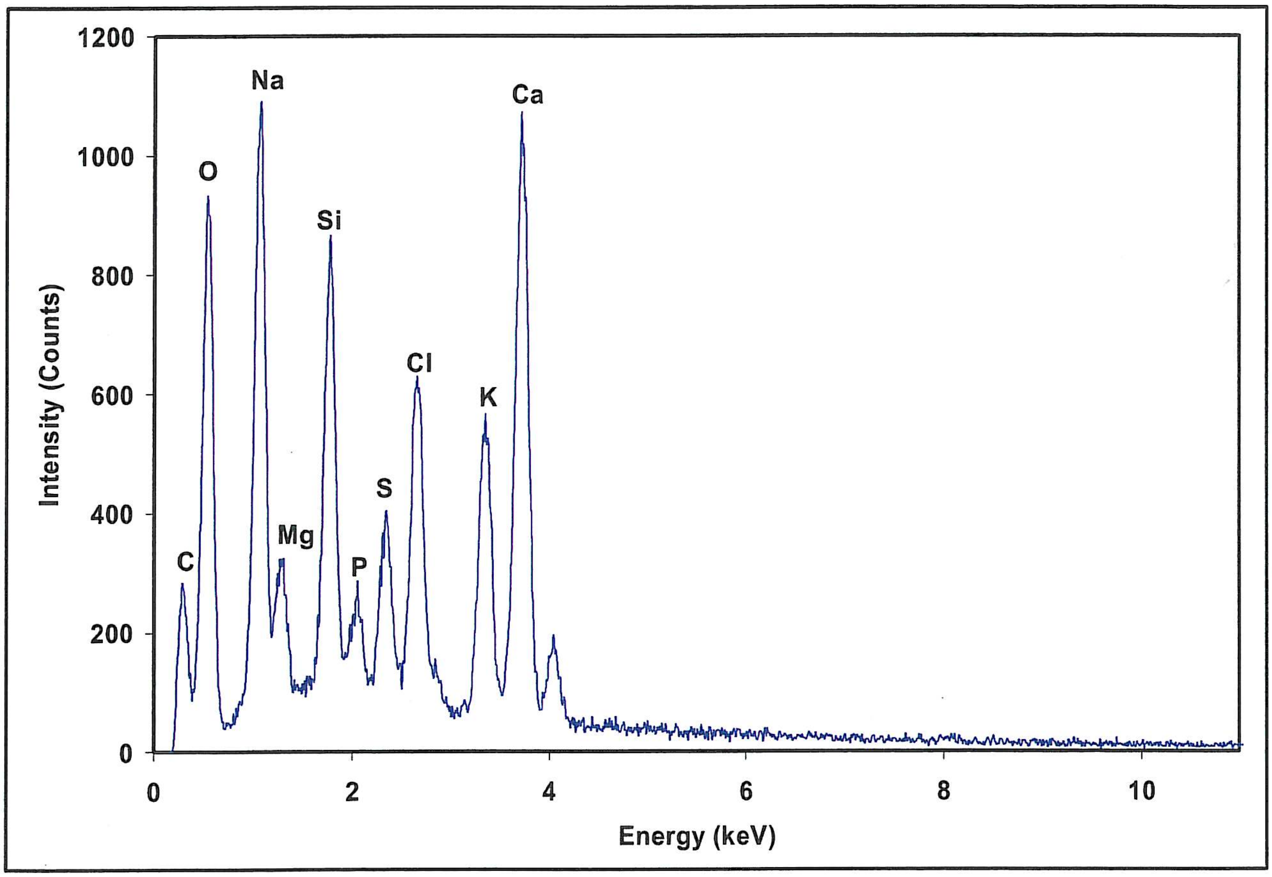

Figure 4.2.1: SEM/EDX elemental spectra of the material extracted from sample 4.2 indicating the presence of chloride and sulfate salts. Magnesium and chloride are present but could not be isolated to show magnesium chloride.

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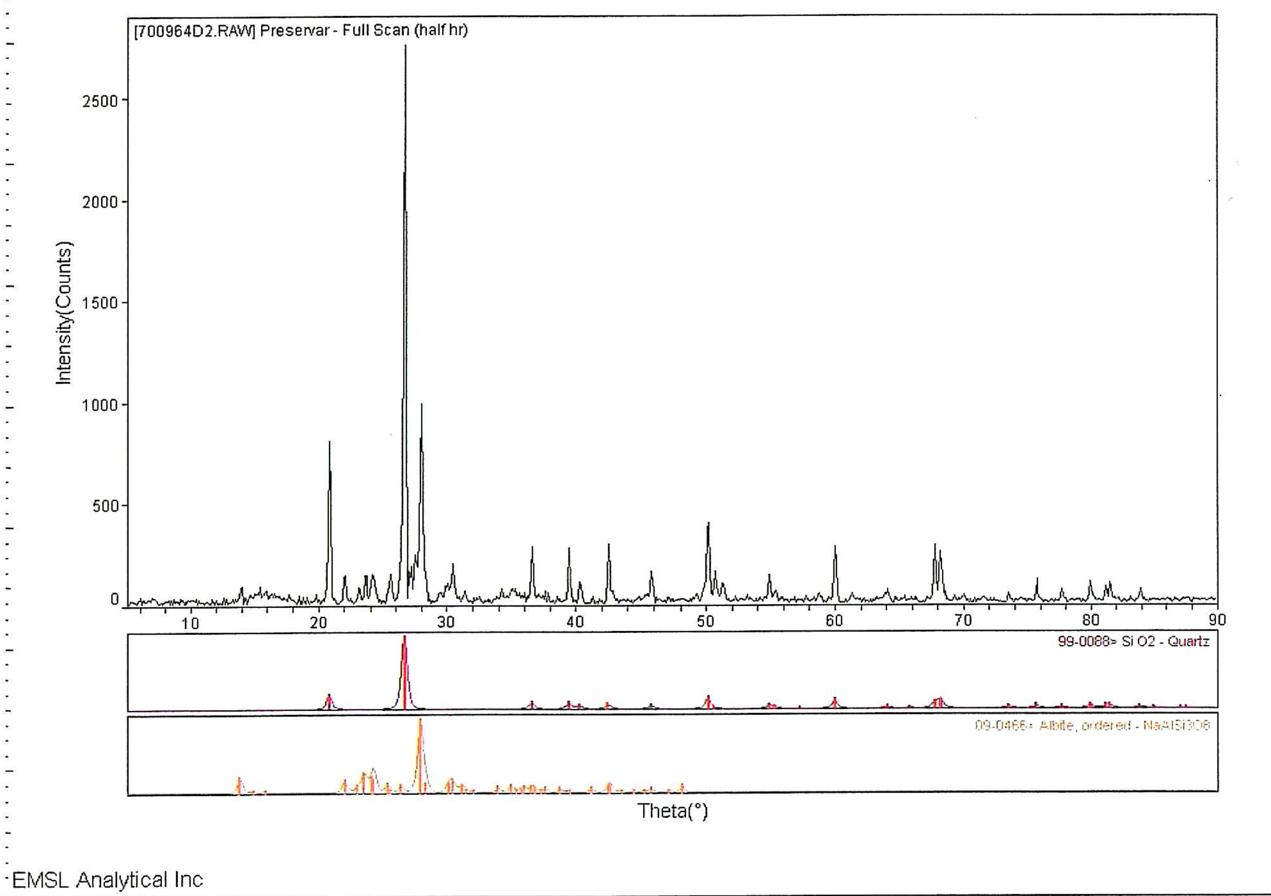

Figure 4.2.2: XRD spectra of sample 4.2 showing matches with the standard spectra for quartz (SiO_2) and albite, ordered ($NaAlSi_3O_8$).

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Table 4.3. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 4. Dry Canyon**
Location	**4.3 Road. Bulk Sample**
Particle size range	
d > 20μm	97.90
10 μm< d ≤ 20 μm	1.40
d ≤ 10 μm	0.70

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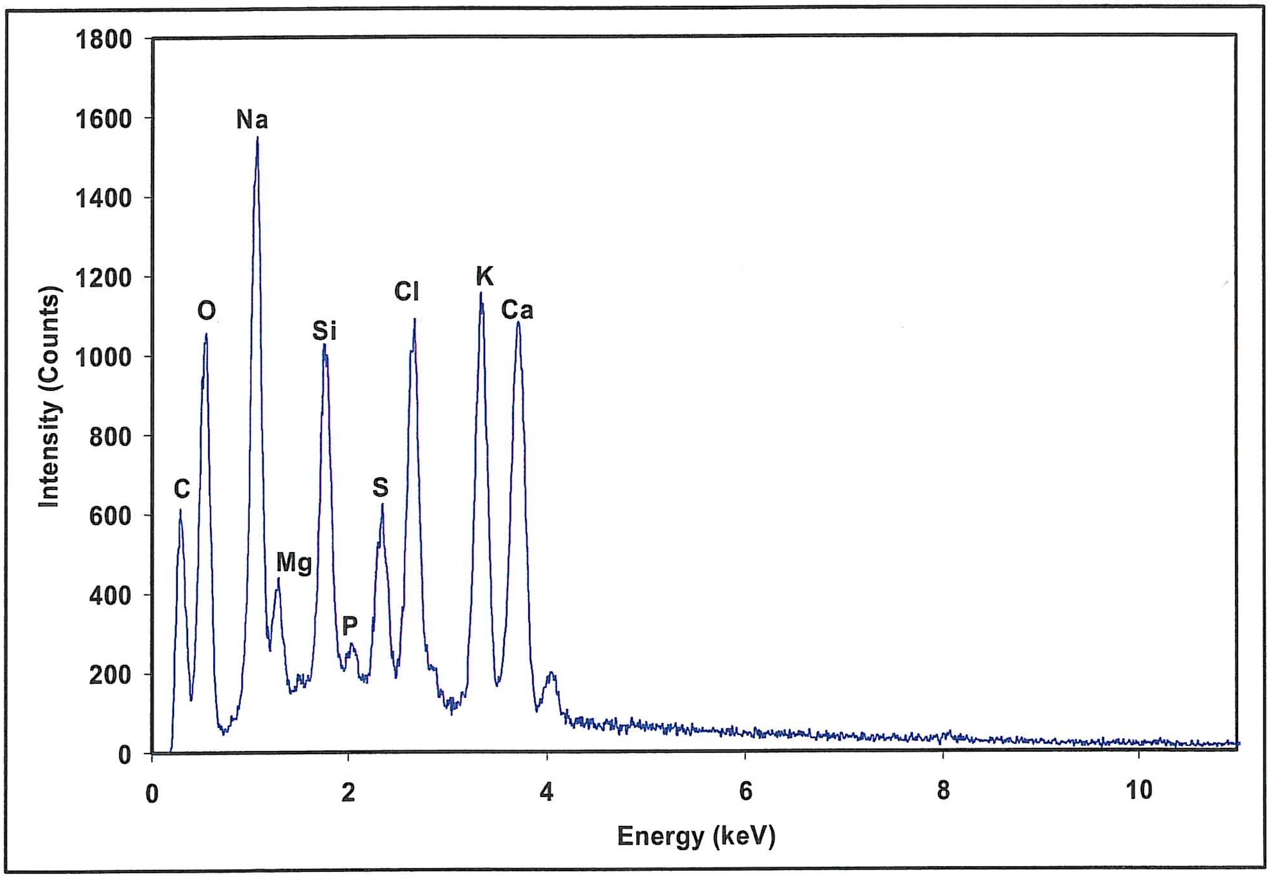

Figure 4.3.1: SEM/EDX elemental spectra of the material extracted from sample 4.3 indicating the presence of chloride and sulfate salts. Magnesium and chlorine are present but could not be isolated to show magnesium chloride.

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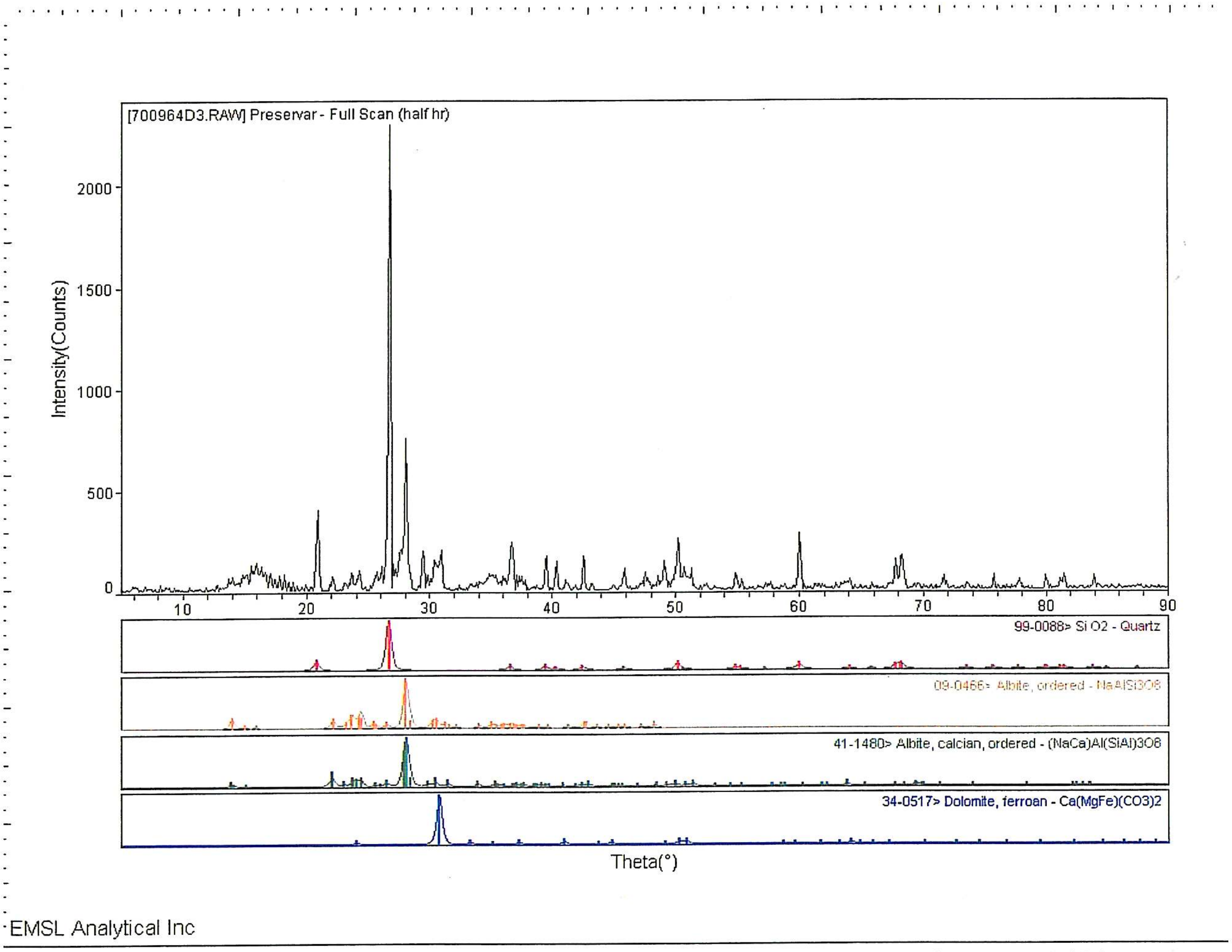

Figure 4.3.2. XRD spectra of sample 4.3 showing matches with the standard spectra for quartz (SiO_2), albite ($NaAlSi_3O_8$), albite, calcian $(NaCa)Al(SiAl)_3O_8$, dolomite, ferroan $Ca(MgFe)(CO_3)_2$.

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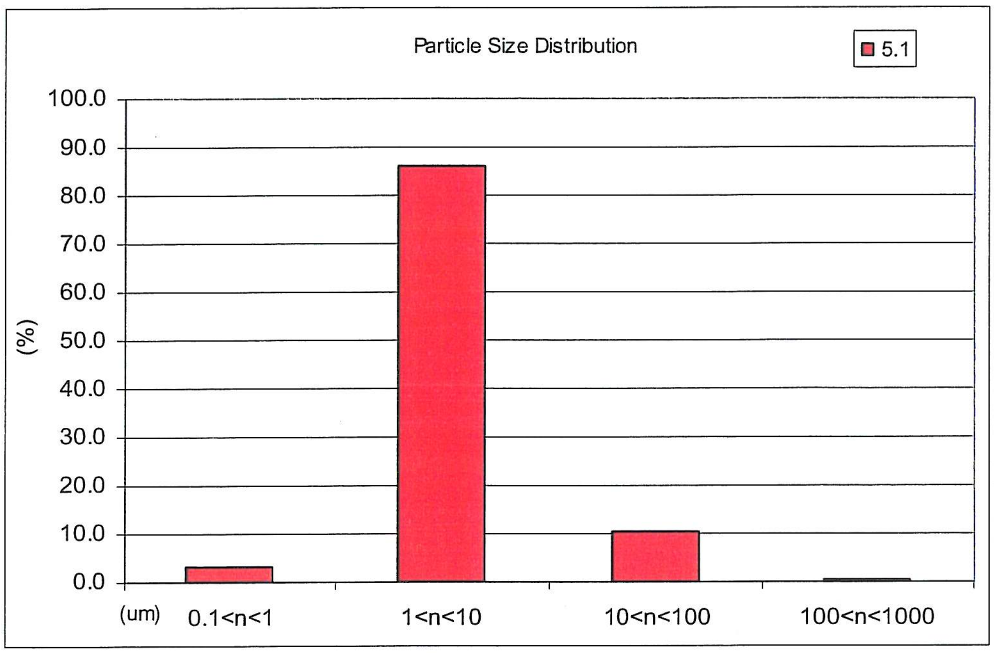

Table 5.1. Histogram of particle size and distribution for sample 5.1

		Range (um)	Count	(%)
Sample:	5.1			
Description:	Petri Dish Left at Panel	0.1<n<1	7	3.1
		1<n<10	193	86.2
		10<n<100	23	10.3
		100<n<1000	1	0.4

EMSL Analytical, Inc.

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Phone: (856) 858-4800

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Preservar, Inc.
15 Forest Street
Brattleboro, Vermont 05301

Phone: 802-246-1103

EMSL Case No.: 360700946
Sample(s) Received: 08/13/2007
Date of Analysis: 10/22/2007
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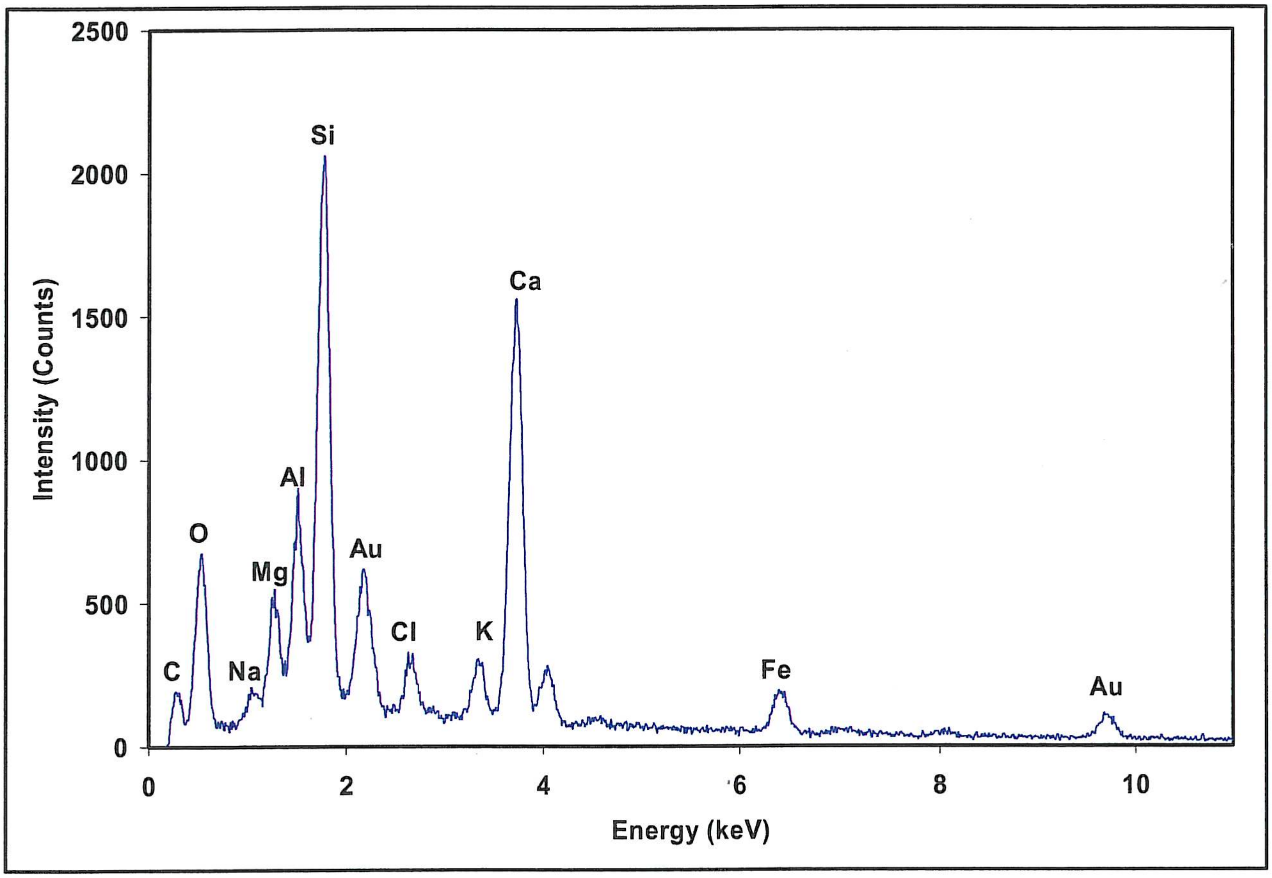

Figure 5.1.1: SEM/EDX elemental spectra of a cluster of particles in sample 5.1 indicating the presence of quartz (SiO_2), feldspars (aluminum silicates) and calcite/dolomite ($CaCO_3$/CaMg CO_3). Magnesium and chlorine are present but could not be isolated to show magnesium chloride.

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Table 5.2. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 5. Rasmussen Cave**
Location	**5.2 Sample Rocks in Front of Panel**
Particle size range	
d > 20µm	99.78
10 µm< d ≤ 20 µm	0.20
d ≤ 10 µm	0.00

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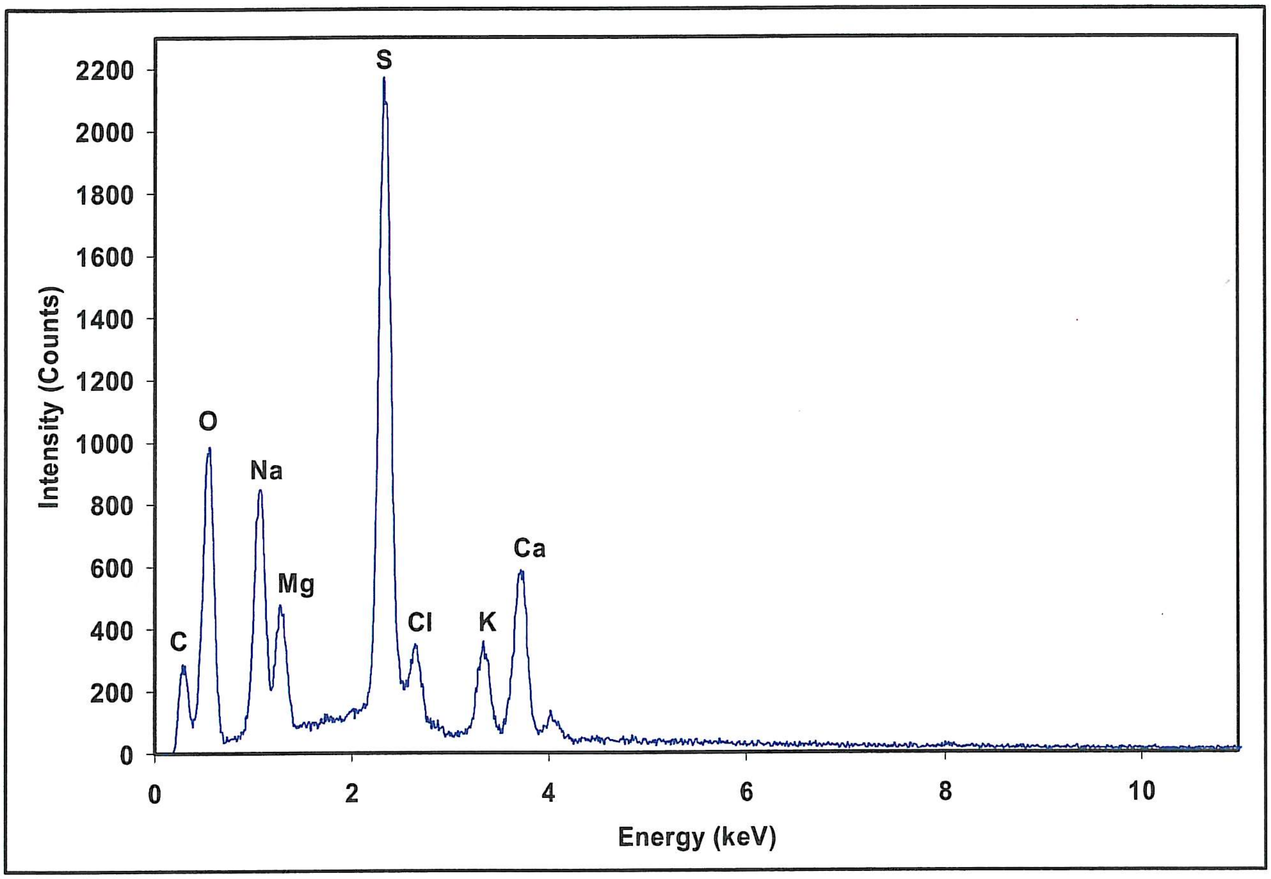

Figure 5.2.1: SEM/EDX elemental spectra of the material extracted from sample 5.2 indicating the presence of chloride and sulfate salts. Magnesium and chlorine are present but could not be isolated to show magnesium chloride.

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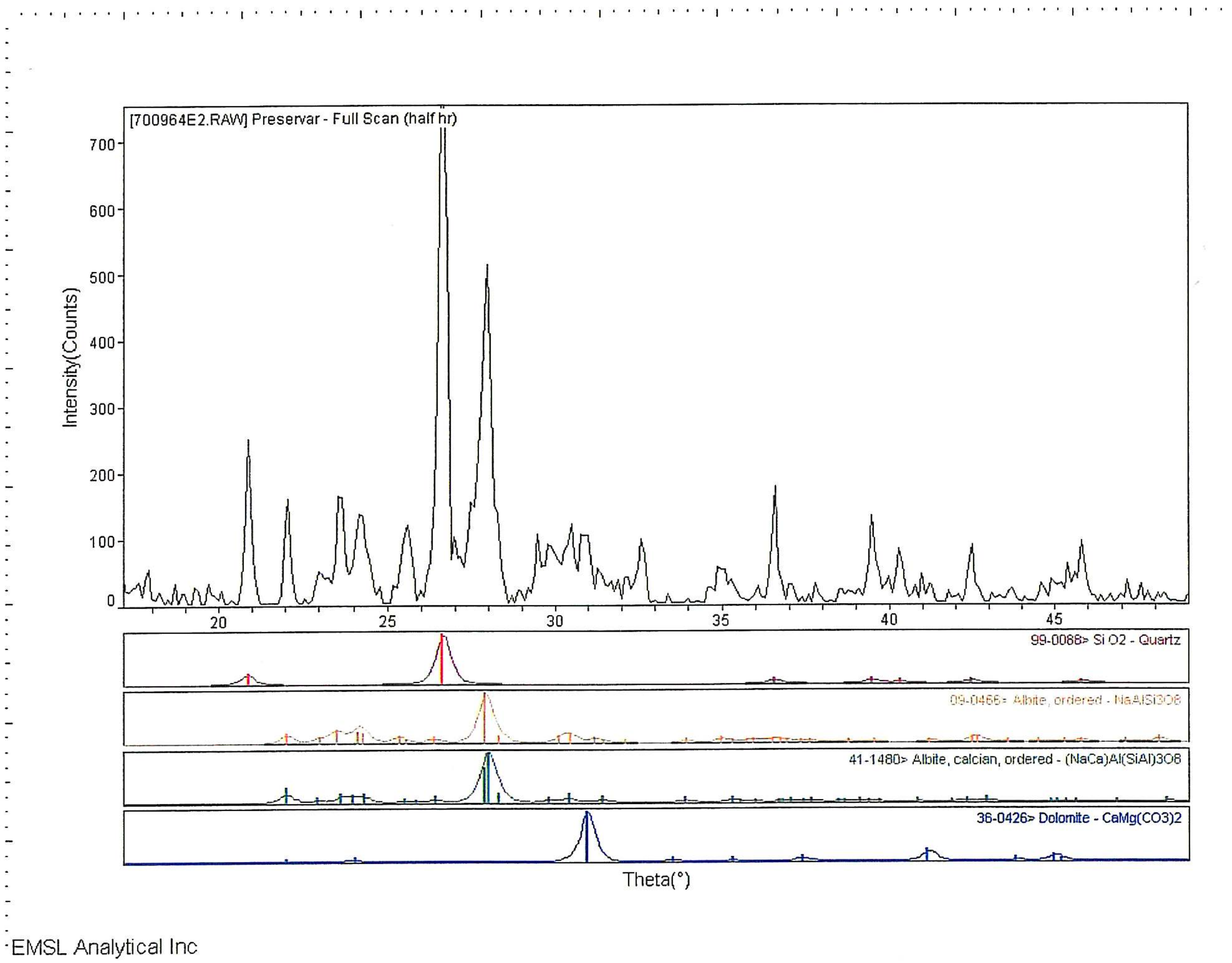

Figure 5.2.2: XRD spectra of sample 5.2 showing matches with the standard spectra for quartz (SiO_2), albite ($NaAlSi_3O_8$), albite, calcian $(NaCa)Al(SiAl)_3O_8$, and dolomite ($CaMg(CO_3)_2$).

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Table 5.3. Presents the percentage (by weight) of the particles obtained by sieving

Sample ID	**Site 5. Rasmussen Cave**
Location	**5.3 Road. Bulk Sample**
Particle size range	
d > 20μm	99.78
10 μm< d ≤ 20 μm	0.20
d ≤ 10 μm	0.00

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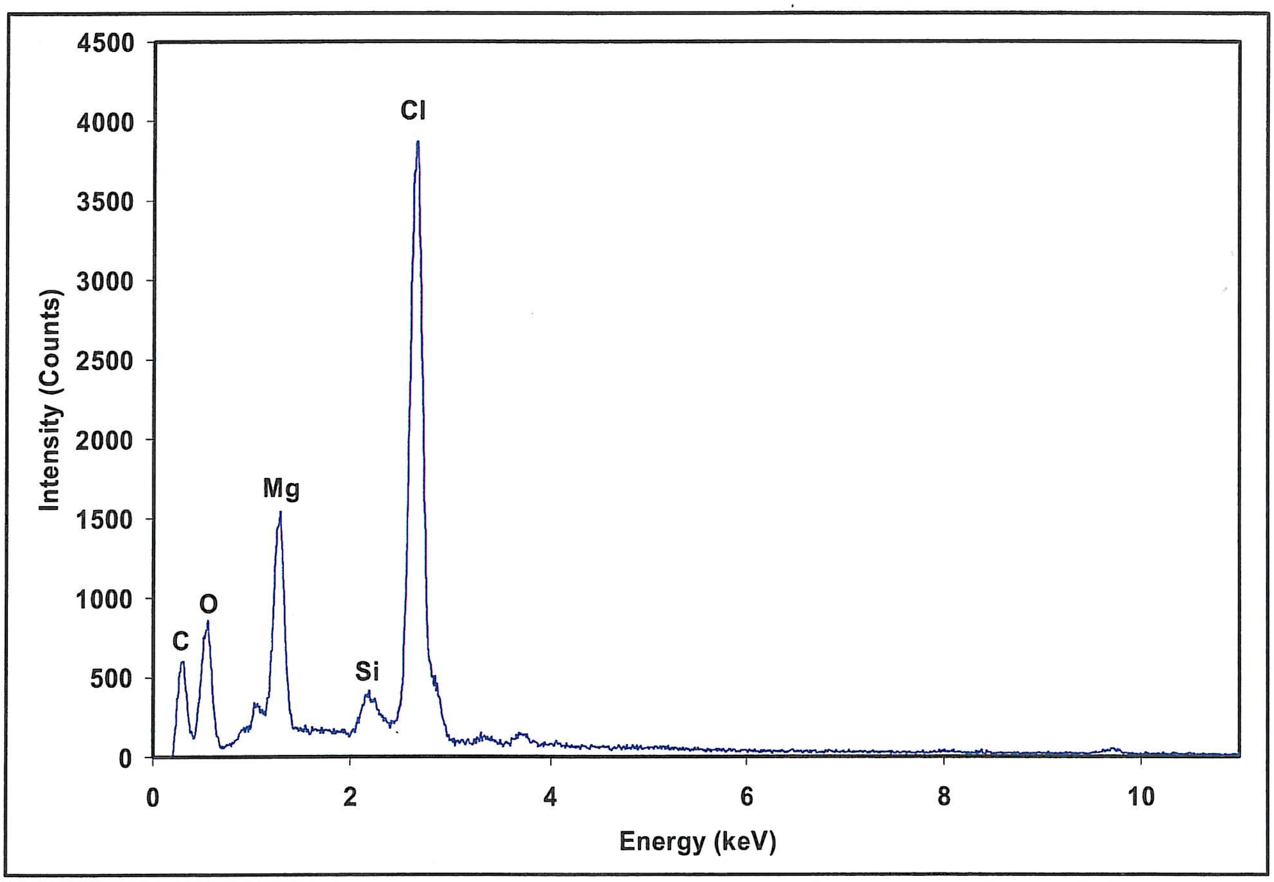

Figure 5.3.1: SEM/EDX elemental spectra of the materials extracted from sample 5.3 showing the presence of magnesium + chlorine.

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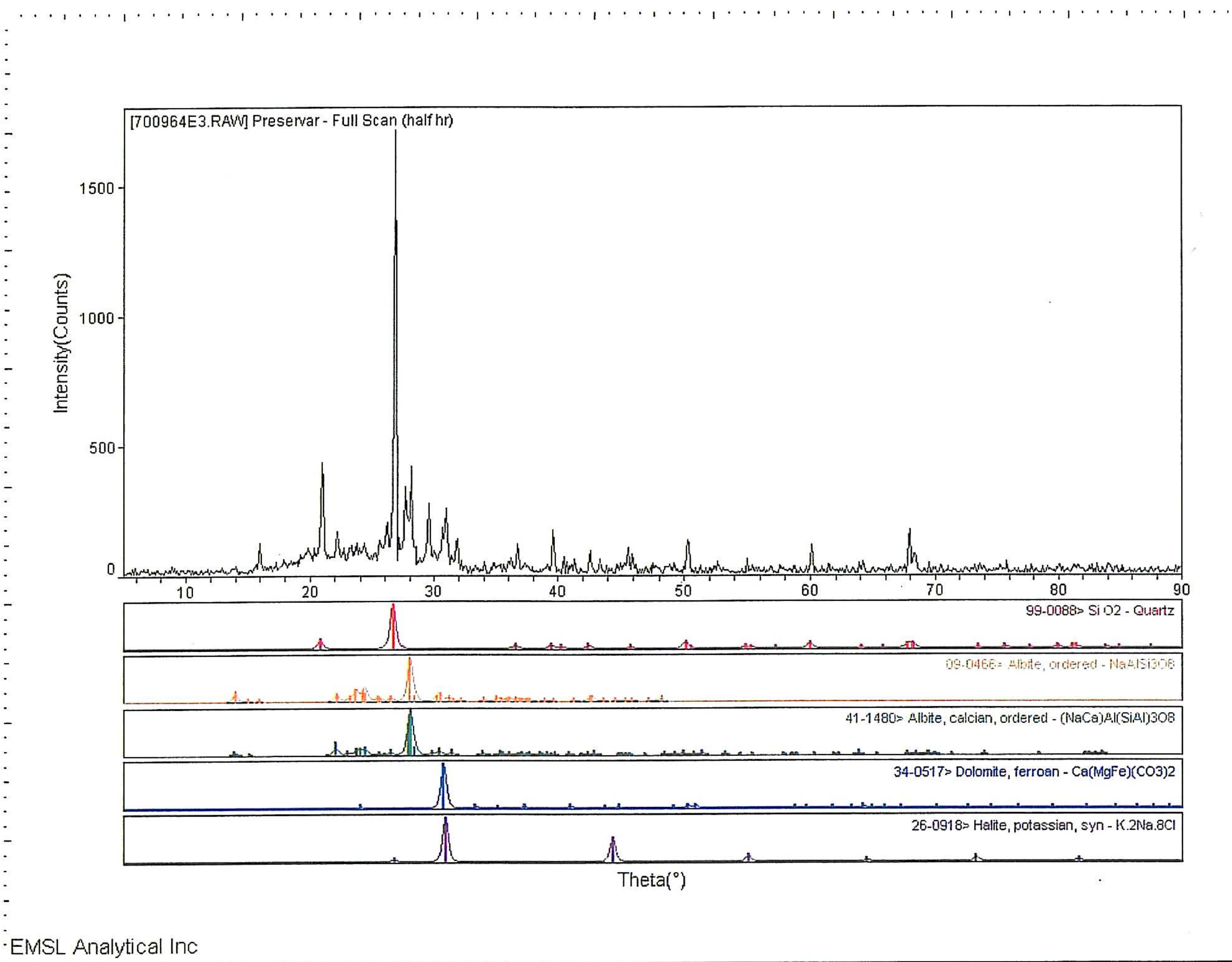

Figure 5.3.2. XRD spectra of sample 5.3 showing matches with the standard spectra for quartz (SiO_2), albite ($NaAlSi_3O_8$), albite, calcian $(NaCa)Al(SiAl)_3O_8$, dolomite, ferroan $Ca(MgFe)(CO_3)_2$, and halite, potassiun (K.2Na.8Cl).

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Sample ID	(T) Area (mm^2)	Void Area (mm^2)	Porosity
1.2	1.18	0.086	7.3
1.3	1.18	0.095	8.1
2.3	1.18	0.076	6.4
3.1	1.18	0.088	7.5
4.2	1.18	0.091	7.7

Table 6: Porosity data for the samples.

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Descriptions & Definitions:

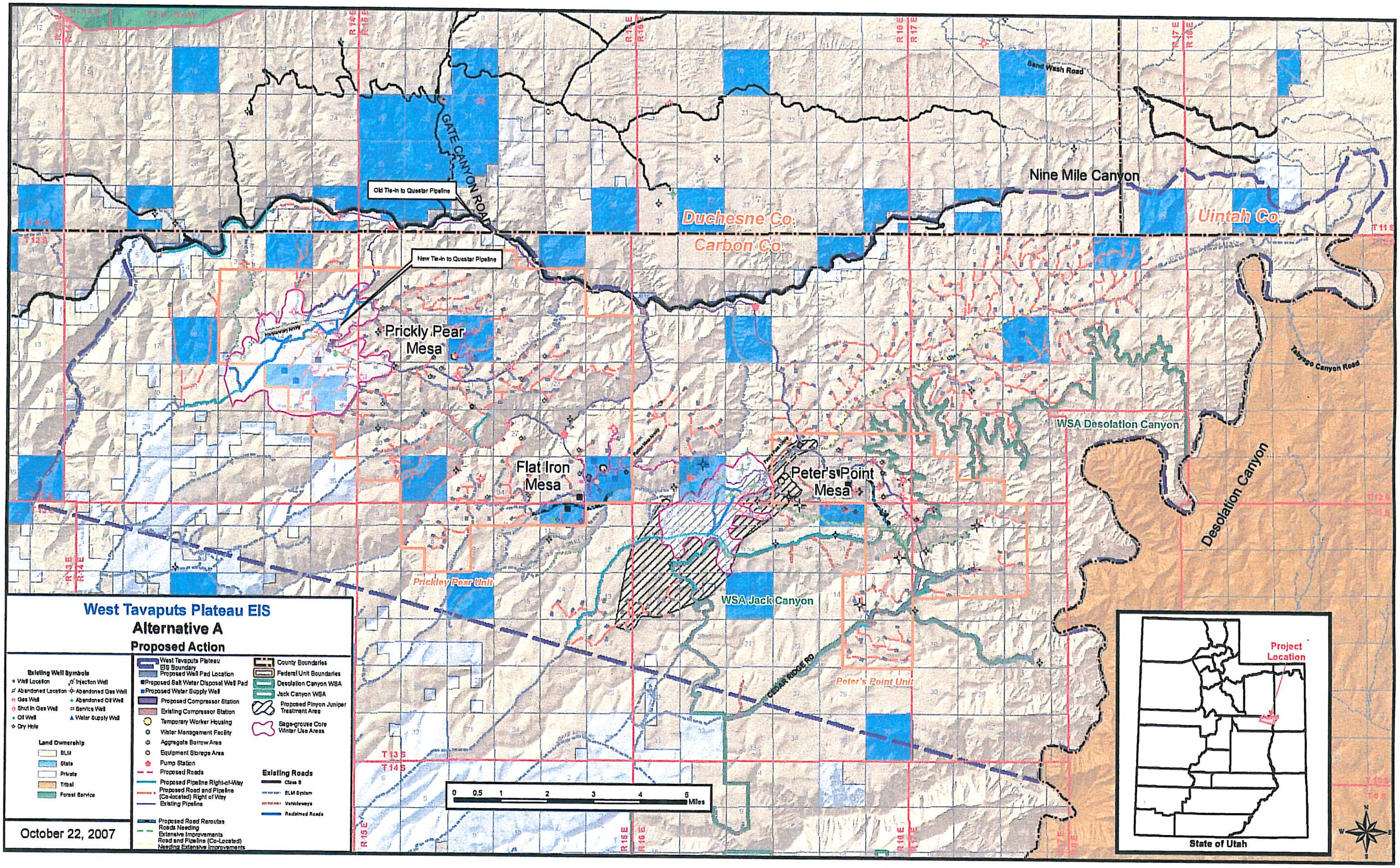
None Detected (ND) denotes the absence of an analyte in the subsample analyzed. Trace levels of the analyte may be present in the sample below the limit of detection (LOD).

Limit of Detection (LOD): The minimum concentration that can be theoretically achieved for a given analytical procedure in the absence of matrix or sample processing effects. Particle analysis is limited to a single occurrence of an analyte particle in the sub-sample analyzed.

Concentrations for bulk samples are derived from Visual Area Estimation (VAE) unless otherwise noted. Air sample concentrations are calculated to particles per unit volume.

VAE technique estimates the relative projected area of a certain type of particulate from a mixture of particulate by comparison to data derived from analysis of calibration materials having similar texture and particulate content. Due to bi-dimensional nature of the measurements, in some cases the particle thickness could affect the results.

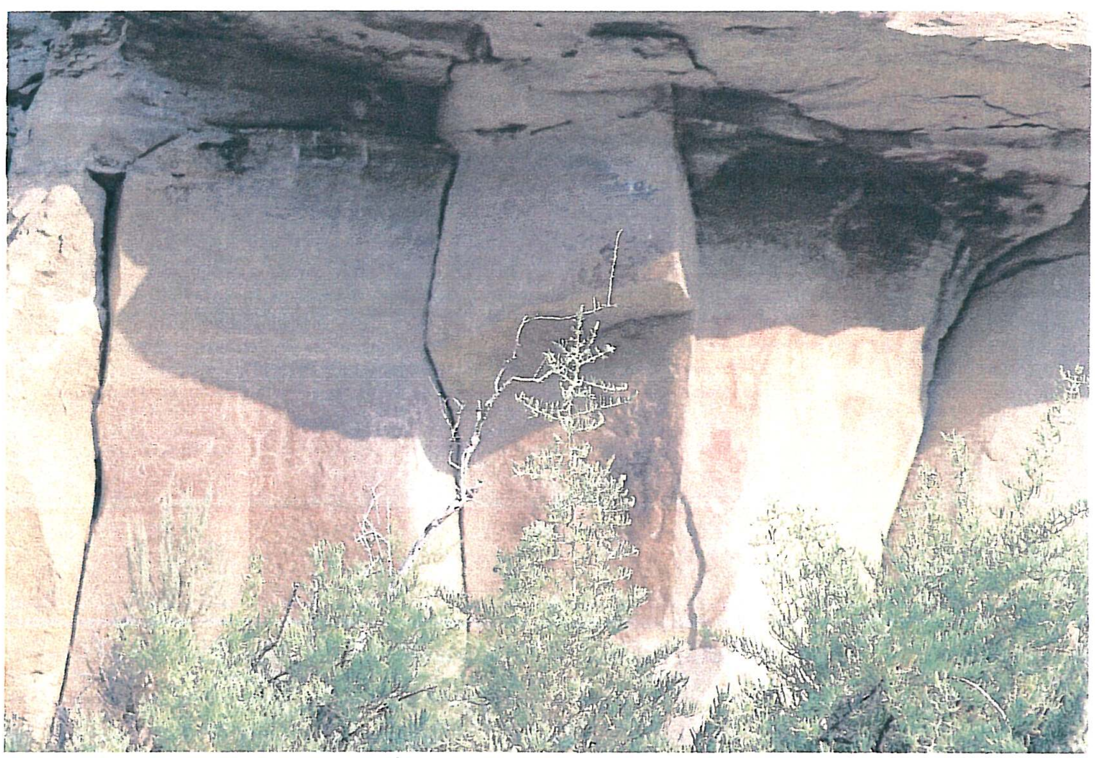
FIGURES



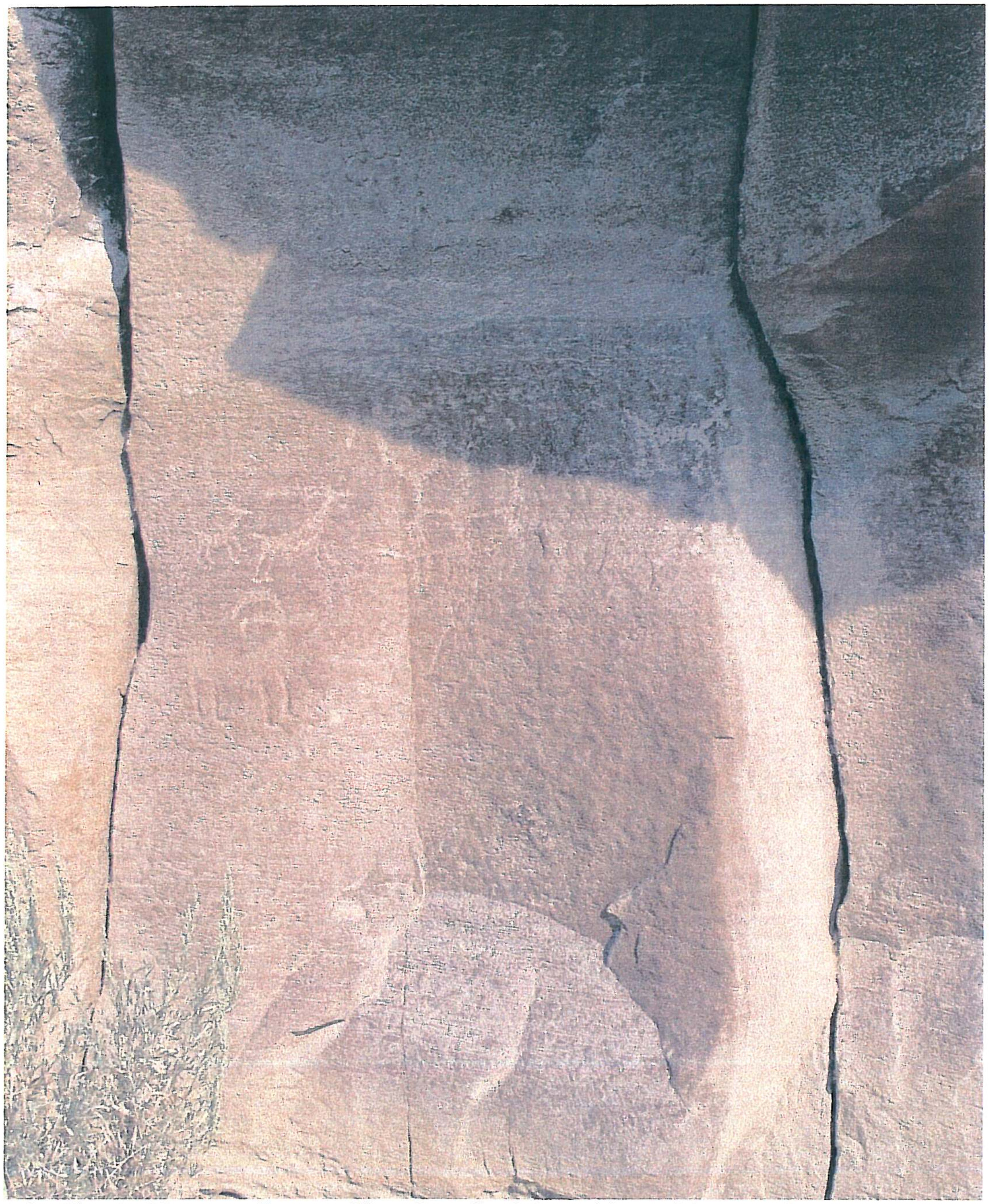
West Tavaputs Plateau EIS
Alternative A
Proposed Action
Existing Well Symbols
Land Ownership
BLM
State
Private
Tribal
Forest Service
West Tavaputs Plateau EIS Boundary
Proposed Well Pad Location
Proposed Salt Water Disposal Well Pad
Proposed Water Supply Well
Proposed Compressor Station
Existing Compressor Station
Temporary Worker Housing
Water Management Facility
Aggregate Borrow Area
Equipment Storage Area
Pump Station
Proposed Roads
Proposed Pipeline Right-of-Way
Proposed Road and Pipeline (Co-located) Right of Way
Existing Pipeline
Proposed Road Reroutes
County Boundaries
Federal Unit Boundaries
Desolation Canyon WSA
Jack Canyon WSA
Proposed Pinyon Juniper Treatment Area
Sage-grouse Core Winter Use Areas
Existing Roads
October 22, 2007
Nine Mile Canyon
Duchesne Co.
Carbon Co.
Uintah Co.
GATE CANYON ROAD
Old Tie-in to Questar Pipeline
New Tie-in to Questar Pipeline
Sand Wash Road
Prickly Pear Mesa
Flat Iron Mesa
Peter's Point Mesa
WSA Desolation Canyon
Desolation Canyon
Tabyago Canyon Road
WSA Jack Canyon
Prickley Pear Unit
Peter's Point Unit
CEDAR RIDGE RD
Miles
Project Location
State of Utah

PHOTOGRAPHS

1.1. Site 1, Harmon Canyon Site. Overview from the road.

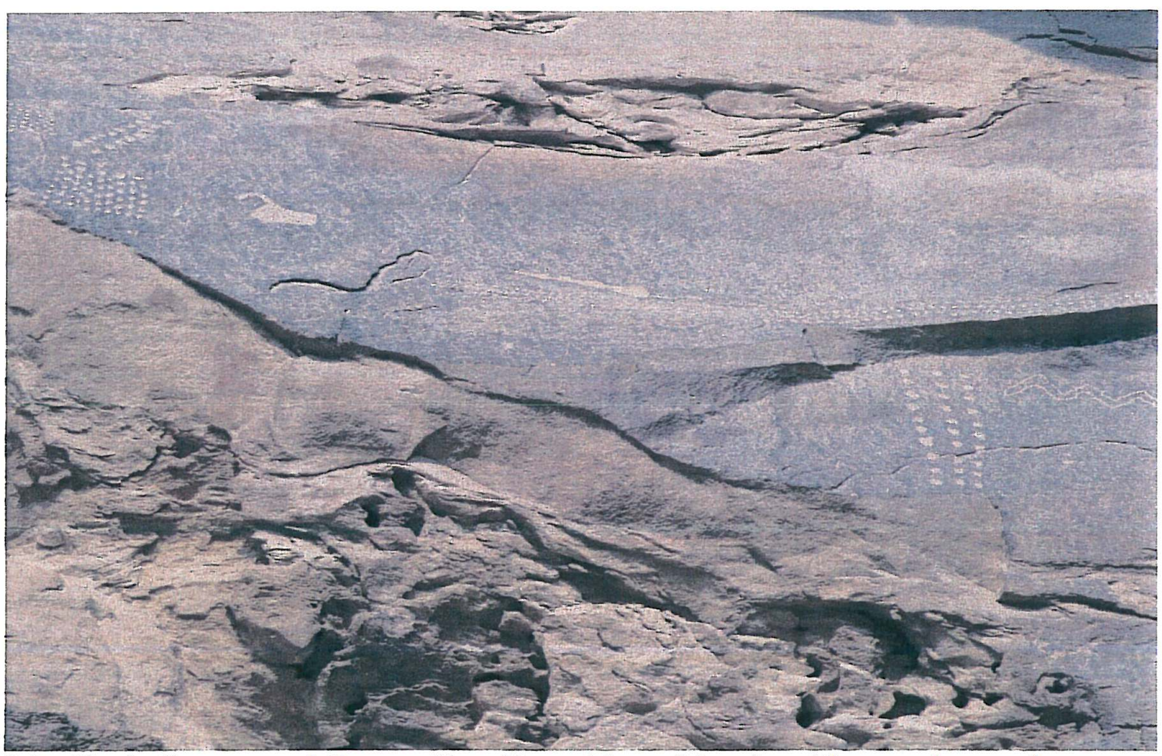


1.2. Site 1, Harmon Canyon Site. Detail of the rock art.



1.3. Site 1, Harmon Canyon Site. Detail of deposition of dust on the rock art.

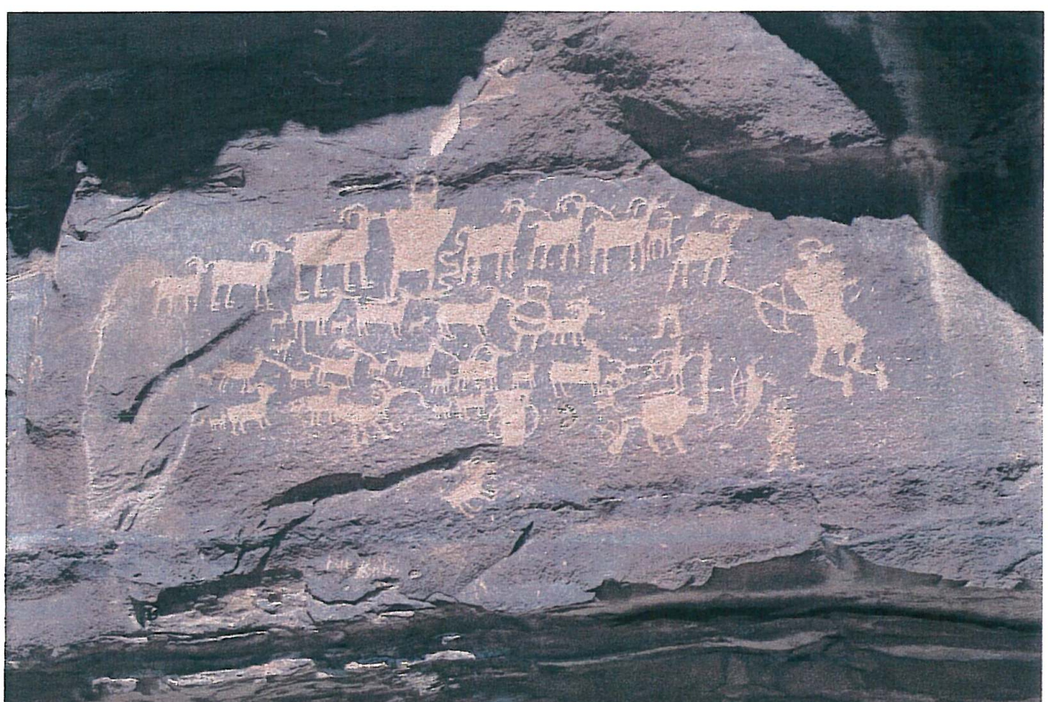

2.1. Site 2, Cottonwood Canyon Site. Detail of the panel. Deposition of dust is evident.


2.2. Site 2, Cottonwood Canyon Site. Deposition of dust is evident on the panel.

2.3. Site 2, Cottonwood Canyon Site. The road near the site and a plume of dust from passing traffic.

2.4. Site 2, Cottonwood Canyon Site. The plume of dust reaching a height of at least 150 feet and lingering for many minutes.

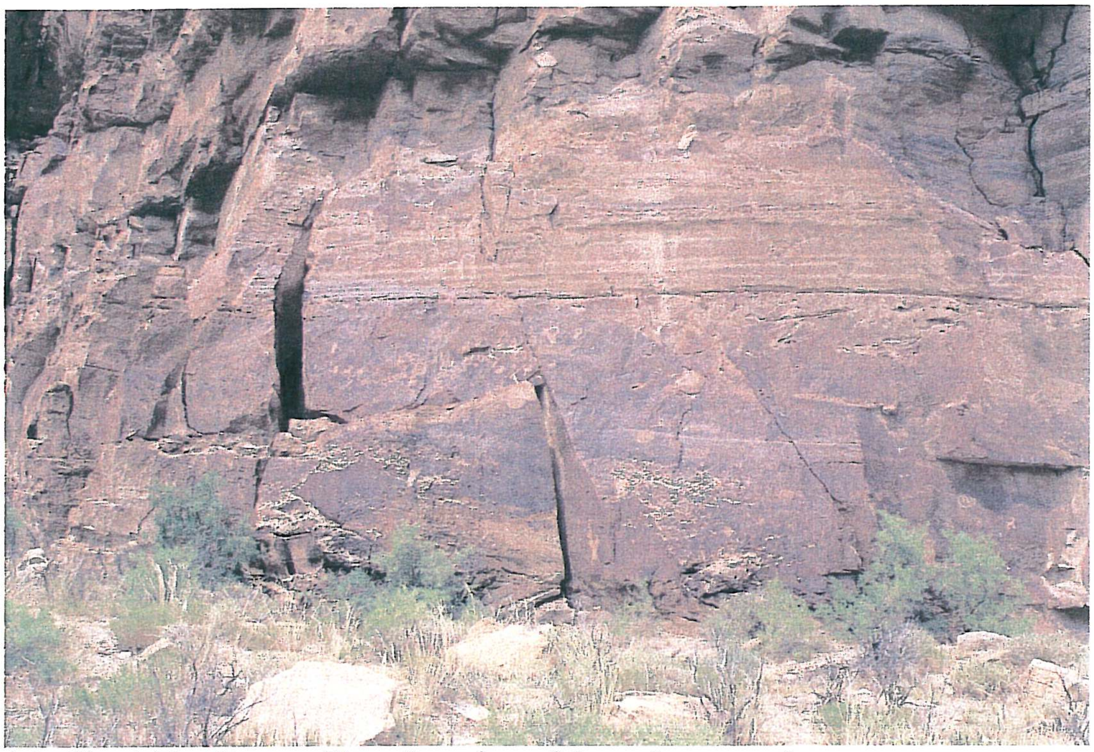
3.1. Site 3, Hunt Scene. The rock-art panel.



3.2. Site 3, Hunt Scene. Detail of the panel, showing deposition of dust.

3.3. Site 3, Hunt Scene. View of the road, with the development of dust from traffic.

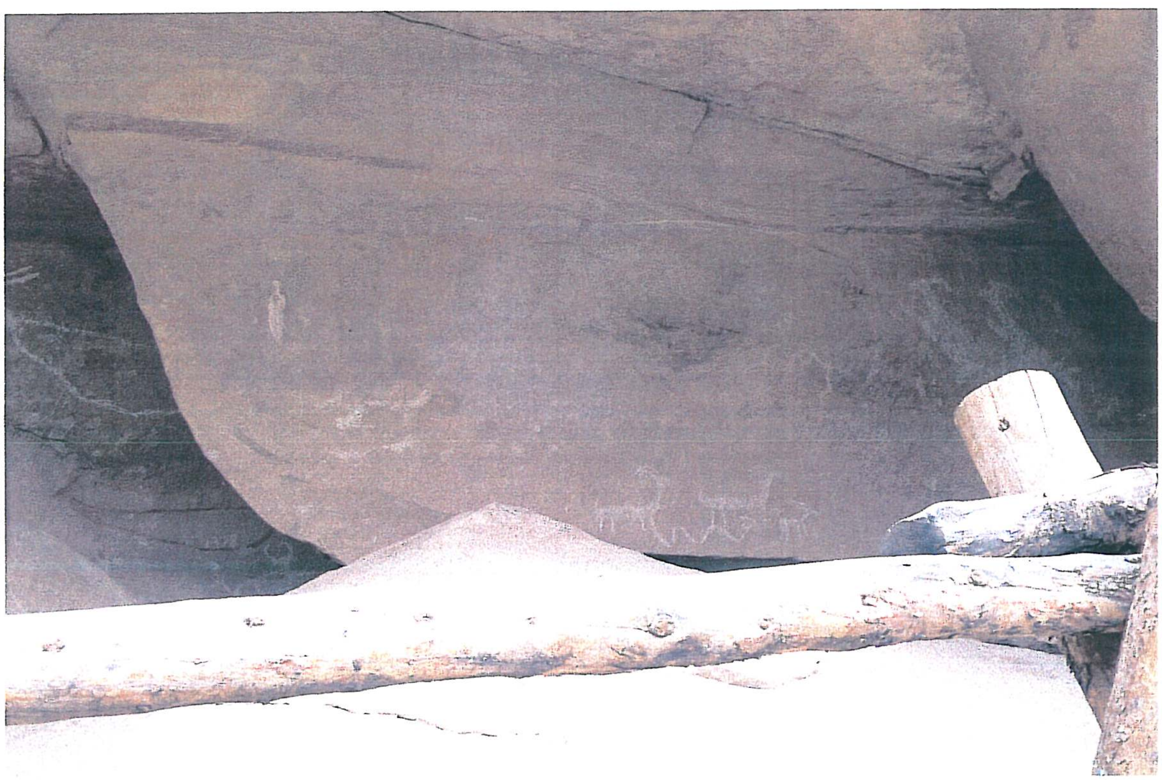
3.4. Site 3, Hunt Scene. The road near the site following heavy industrial traffic. The heavy plume of dust rose to a height of at least 150 feet and lingered for many minutes.



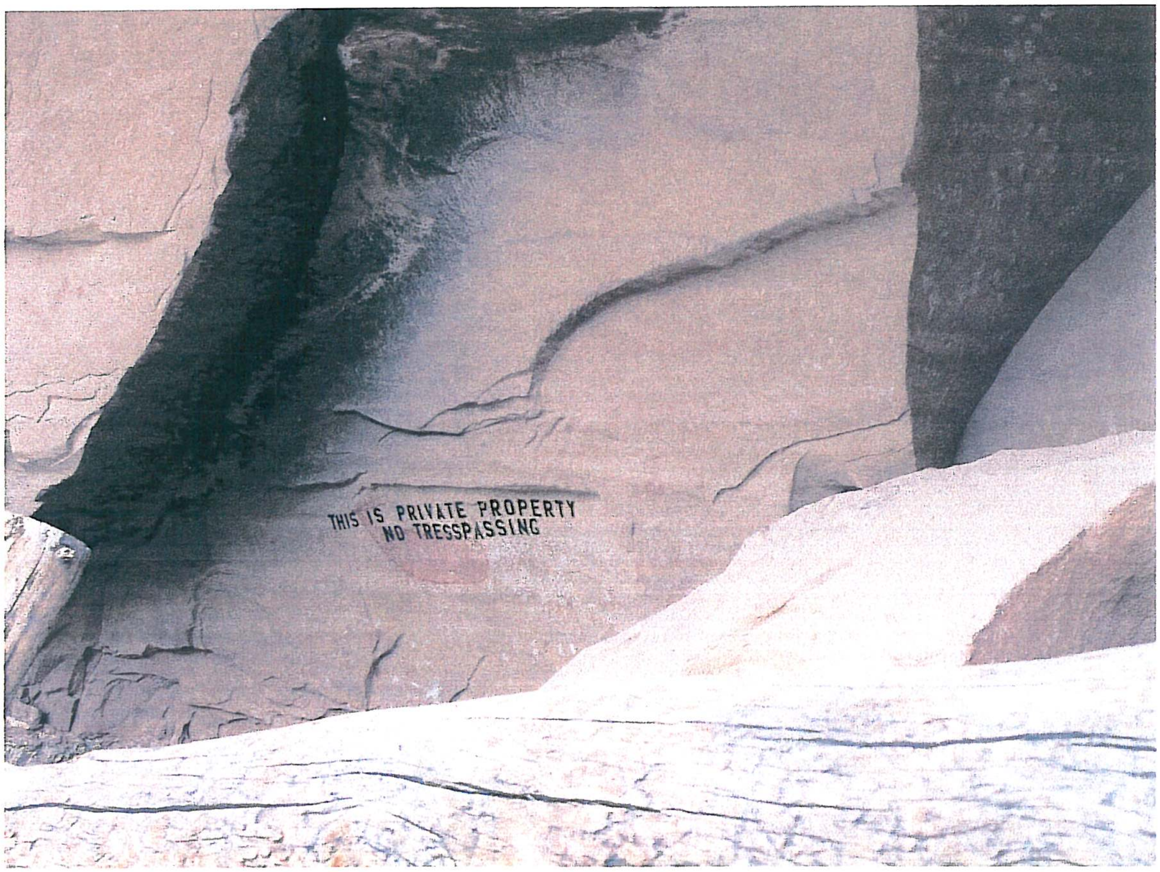
4.1. Site 4, Dry Canyon Site. Overview of the rock-art panel.

4.2. Site 4, Dry Canyon Site. Detail of the rock art panel, which remains in quite pristine condition and free from surface depositions like dust.

5.1. Site 5, Rasmussen Cave. Overview of the shelter, seen from the road.



5.2. Site 5, Rasmussen Cave. Detail of the rock-art panel.



5.3. Site 5, Rasmussen Cave. Detail of the rock-art panel on the cave wall and heavy dust on rock fall in front of the panel.