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RESEARCH ARTICLE

GEOCHEMISTRY AND MINERAL CONTENT OF ASH FLOW FROM THE MONTSERRAT SOUFRIERE HILLS VOLCANO

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Abstract

The Soufriere Hills Volcano of Montserrat has ancient origins and roared back to life in 1995 wreaking severe havoc and damage to the inhabitants, geography, and ecosystems of the Island. The pyroclastic ash flow reached temperatures of 1500 °F and progressed down the hillsides at speeds of 80 mph, causing incineration and virtual destruction of everything in its path, while the gaseous and particulate laden plume reached altitudes of 35,000 feet, impacting air quality and aircraft navigation. The local health authorities recommended masking and physical protection from any potentially harmful effects from the ash to all residents who remained on Island following the 1995 eruption. Volcanic ash can be an irritant to exposed skin and respiratory surfaces upon contact due in part to the sharp and jagged nature of the microcrystalline particulate matter. In addition, the minute size of the smallest particulate matter can impact deep into the unprotected respiratory tree in humans and animals, potentially causing severe respiratory injury. The composition and physicochemical nature of the ash was largely unknown in 1995 and subsequent years. The current study was designed to determine the geochemical composition of the ash. Samples of ash were collected from 7 locations and water samples from three free flowing creeks in Montserrat and indicated that the creek water was acidic in nature. The mean pH of water was 5.2, while the ash showed abundant levels of Iron, Phosphorus, Calcium, Magnesium, Sodium, Aluminum, and sulfur, in addition to lower concentrations of potassium, boron, copper and zinc and intermediate concentrations of Manganese and was devoid of toxic minerals including lead and mercury. The emergence of acute respiratory issues was not found to exceed similar events in other healthy populations including individuals relocated to the UK. In conclusion, direct human and animal exposure to Montserrat volcanic ash was deemed non-harmful to humans when adequate protective measures including masking and exposure precautions were undertaken, while the rich mineral content of the ash can provide a rich source of micronutrient mineralization to soils and surrounding seawaters and support vigorous revegetation and recovery of affected land and sea zones throughout the island community.

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Introduction:-

Volcanic soils have a well-earned reputation as potentially valuable sources of minerals and essential micronutrients that over time may contribute to the development of nutrient rich soils known as andisols that are capable of supporting abundant new plant and aquatic growth for decades during periods of volcanic recovery.[1-3] Most Volcanic ash is made of tiny jagged low density rock fragments of varying diameter, most less than 0.2 mm in diameter, plus finer dust particles as small as 0.2 µm in diameter which like the larger particles are virtually insoluble in water.[4,5]The larger, more coarse particles of volcanic ash have the consistency and feel like grains of sand, while very fine particles blended into the mixture have a have a smooth and powdery consistency. The smallest particulates have the capability of penetrating the most innermost parts of computers, electronics, aircraft engines, machinery and other finely manufactured surfaces where then can form an impermeable surface covering often contributing to instrument or mechanical failure.[6,7]Volcanic eruptions also result in the release of numerous potentially hazardous gasses into the atmosphere, including water, carbon dioxide, hydrogen, sulfur dioxide, hydrogen sulfide, carbon monoxide and hydrogen chloride.[4] The sulfur and halogen gases and associated metals are removed from the atmosphere by processes of chemical reactions, including dry and wet deposition on convenient surfaces and materials, and by adsorption onto the surface of the volcanic ash and granular particles. The crystalline-solid structures of the salts that may be formed from these chemical reactions may act more as an insulator than a conductor when in contact with electronic surfaces, in contrast to the liquid forms which may act as corrosive ionic conductors. In addition, the released gasses and particulates of the plume cloud block the sun's rays, temporarily disrupting ultraviolet radiation, and impart a transient environmental cooling effect.

During an active eruption, the volcanic materials are forced into the atmosphere by the rapidly expanding magma under great pressure and may form a tephra plume several miles high and which may be carried by prevailing air currents many miles from their origin.[6] The force of the eruption is such that large boulders 1-2 meters or more in diameter may be forced upwards and out of the volcano, and are then carried by the resulting ash flow and hurling down and away from the volcano.[7-9] The volcanic particles of the tephra typically consist of jagged pieces of rock, minerals, and silicates, sometimes referred to as volcanic glass.[4] The ash has an abrasive nature and may cause topical skin irritation upon physical contact. If the volcanic dusts are inhaled the fine lightweight particles, some of which are only the size and diameter of cigarette smoke, can become impacted deep within the lungs and cause severe and sometimes chronic breathing problems.[8],[11-13]If left untreated the damage to the lungs may lead to chronic respiratory illness or even more dire, acute exposure may result in suffocation, the most common cause of early death following volcanic eruptions.[8] Thus, the need for individual preventive measures including masking and covering of exposed all skin surfaces in addition to relocation to a safe area is imperative. The types of minerals usually present in volcanic ash are dependent on the chemistry of the magma from which it erupted. Considering that the most abundant elements typically found in the silicate-rich magma of volcanos like the one in Montserrat are silicone and oxygen, the various types of magma (and therefore ash) produced during volcanic eruptions are often commonly explained in terms of their silica content, which can range from approximately 45 to 70 percent by weight in any given volcano.[4,5]

The Montserrat Soufriere Hills volcano once believed virtually extinct roared back to life after a long dormancy in July 1995 and began a long series of violent eruptions which persisted for over a decade.[9] The volcanic eruptions resulted in virtually total destruction of much of the Southern half of the lush island Nation including the capital city of Plymouth and surrounding towns which were covered with hundreds of tons of volcanic ash, sand, and volcanic boulders which often reached depths of 1 meter or more in areas in closest proximity to the volcano. Several (19) lives of Montserratians were lost after having been trapped by the rapidly moving ash and sand flows, which encircled, incinerated, and buried scores of trees and vegetation, dozens of vehicles, homes, and other buildings located in harm's way with great and unrelenting force. The composition of the ash and sand flow was largely unknown, and the temperature of the rapidly moving ash flows were recorded as exceeded 1500 °C and traveling at rates up to 80 miles per hour in areas closest to the volcano, thereby capable of rapidly incinerating much in its direct path. The land area of the Island reportedly increased from 39.5 to 40 square miles due the voluminous quantities of ash released into the coastal areas located downstream from the volcano during the repeated eruptions. Montserrat is a mountainous island, thereby enabling the ash to flow an easy downhill slope until it reached the sea on both the Easterly and Westerly sides of the Island, leaving only the northern half of the island protected from direct ash flow and the most severe exposures to the expanding tephra. The ash fall covered much of the island and reached other islands and surrounding sea surfaces and seabed over 50 miles distant and disrupted air traffic throughout the region.[9]

The chemical content of the minerals and particulate matter present in volcanic ash are heavily dependent on the chemistry of the magma from which the volcano erupted. Silicone and Oxygen are the most abundant elements found in most magma, and the various types of magma (and therefore ash) produced during volcanic eruptions are most commonly explained in terms of their percent of silica content. Low energy eruptions containing basalt generally produce a characteristically dark colored ash containing only ~45–55% silica, in association with iron and magnesium which contribute to the darker coloration. The most explosive eruptions are termed rhyolite eruptions and produce an ash with a silica content that approaches 70% while other types of ash including andesite and dacite have an intermediate content of silica that ranges between 55–69% by weight.[4] The particles in ash tend to be porous and lighter in weight than most stones due to the high gaseous pressures exerted on them during their formation.

The current trends in expansions in global population has caused the progressive encroachment of urban development into higher risk areas, often in closer proximity to volcanic centers. In so doing, this population growth has increased the potential for human exposure to volcanic ash fall events. The direct health effects of volcanic ash on humans residing in close proximity to such danger zones are usually short-term and mild for persons in normal health as given adequate forewarning such areas tend to be evacuated to safer areas in advance of the eruptions. However, chronic prolonged exposure should it occur potentially poses an increased risk of silicosis among unprotected workers and local inhabitants who may choose to delay relocation. Ash particles of less than 10 µm diameter become suspended in the air and are known to be inhalable, and people exposed to ash falls have often experienced immediate respiratory discomfort, difficulty in breathing, eye and skin irritation, and nose and throat symptoms. Most of these early symptoms tend to be of short duration and are not considered to pose a significant health risk to those without pre-existing respiratory conditions. The more long-term adverse health effects of volcanic ash depend largely on the particle size of the exposure, the mineralogical composition of the ash and the chemical coatings adherent to the surface of the ash particles inadvertently inhaled or in contact with exposed surfaces. Additional factors related to potential respiratory symptoms are the frequency and duration of exposure, the concentration of ash particles and residues in the air and the respirable ash fraction; the proportion of ash with less than 10 µm diameter, commonly known as the $PM_{10.}$ The most minute particlescan impact deep in the respiratory tree and alveolar tissues and pre-existing comorbid conditions including COPD and others can further compromise patient outcomes. Chronic health effects from volcanic ash fall are possible, as exposure to free crystalline silica from any source and in any amount is known to be a primary contributory cause of silicosis, where the amount inhaled correlates with the severity of respiratory illness produced. The social context may also be important, as rescue workers and others involved in recovery efforts may be inadvertently over exposed during recovery efforts.

While much of the recent ash flow from the Soufriere Hills took the form of a fine powders and granular sand, the mineralogic composition of the ash which fell over Montserrat and nearby islands and the gaseous exposures at the time were largely unknown, causing much alarm and apprehension among residents, but which has now subsided and considered little more than an environmental nuisance. Montserrat now has several black sand volcanic beaches which have now been well washed via local weather and tidal flow during the years following the volcanic eruptions and are somewhat unique for beaches among Caribbean Islands. To this end, mixed ash and sand samples were collected from 7 locations on the Island from close in and several miles distant from the volcano and assayed for mineral content via mass spectrometry to determine not only the mineral composition but to also determine the safety of the once volcanic environment should any noxious or otherwise toxic minerals be present. In addition, water samples were collected from 3 distinct sites in a similar fashion for chemical analysis.

Methods:-

Approximately 100 g samples of ash+sand mixture were aseptically collected in sterile vials from 7 randomly selected sites labelled A thru G that were accessible to the investigators via well-established protocols.[10] In addition, water samples of approximately 100 ml each were collected in a similar fashion and labeled Plymouth, Olveston and Egret House corresponding to their area of collection. Care was taken to not permit the solid or liquid samples contact with the skin of the collection personnel so as to avoid possible contamination. Mineral analyses were determined via atomic absorption mass spectrometry at the University of Vermont Agricultural Analytic Laboratory, Burlington Vermont and are expressed as parts per million of the individual minerals, as a percent for Carbon and

Nitrogen, and a pH pm a 0-14 scale for H+ concentration. Microbial content was not determined but all samples were clear and colorless, and visually clear of obvious gross microbial contamination. The water samples are derived from aquafer runoff from three of the thirteen known aquafers surrounding the volcano.

Results:-

The results of the organic residue and mineral analysis are shown in Tables 1 and 2 below. Table 1 shows the Carbon and Nitrogen content of the volcanic efflux, expressed as a percentage of the composite efflux. While the origins of the carbon and nitrogen matter are unclear, they may represent at least in part incinerated organic materials consumed by the volcano during its downward egress from the volcanic eruption. In table 2, the mineral content of the sandy efflux is shown, and show higher concentrations of Iron, Phosphorus, Calcium, Magnesium, Sodium, Aluminum, and sulfur, in addition to lower concentrations of potassium, boron, copper and zinc and intermediate concentrations of Manganese. Importantly, no minerals known to be toxic to humans or animal wildlife were identified in any of the samples studied. The concentrations covered a broad range of values for most samples, indicative of variations in the mineral content in different collection sites, some distant from their volcanic origin and the possibility of some mineral loss due to mineral leaching, weather, and other environmental factors in the more distant collection sites.

Water quality and quantity throughout Montserrat is considered remarkably high and in considerable abundance compared to other neighboring islands, in that Montserrat is blessed with more than a dozen natural aquifers, only a few of which at the higher elevations have been tapped to date. The various creeks represent overflow from the natural aquifers, some of which have been reported to have been present from the earliest recorded history of Montserrat and giving rise to support the lush vegetation covering much of the island. The water samples were collected during a quiescent period between eruptions from the three accessible creeks reflect at least in part the acidic nature of the volcanic efflux, in addition to the acidic nature of the surrounding soils During periods of active eruptions, the air often contains the fragrance of the sulfur content, and the acidic nature has been sufficient corrode unprotected metallic and other surfaces over time. Thus, the quality of the water sampled may not fully reflect the most extreme conditions that may occur during period of volcanic activity. None the less, the water is consistently sufficiently acidic in nature, which likely contributes to the minimal if any microbial presence in the samples as many microbial organisms tend to prefer less acidic environments for optimal growth. The water samples are presumed to also contain residual amounts of the various minerals detected in the solid efflux samples in the leachates as well but were not tested for all minerals that may have been present.

Table 1:- Carbon and Nitrogen content of Volcanic ash+sand efflux.

Constituent	A	B	C	D	E	F	G	Mean %
Carbon, %	0.03	<0.01	0.08	0.16	<0.01	<0.01	<0.01	0.070
Nitrogen, %	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Data are individual samples collected from seven random sites labeled A thru G from approximately ¼ mile to five miles distant from the volcano.

Table 2:- Mineral Content of Volcanic Ash and Sand efflux in ppm .

Mineral	A	B	C	D	E	F	G	Mean ppm
Phosphorous	563.76	254.88	294.68	298.78	413.71	449.83	676.74	421.77
Potassium	241.40	490.57	577.08	498.05	209.70	663.39	54.15	390.62
Calcium	7755.0	8832.7	9413.0	8736.8	7001.0	8960.3	6821.6	8217.3
Magnesium	492.23	582.15	733.89	763.54	411.04	731.86	1298.67	716.20
Sodium	1418.9	2493.6	2789.4	2495.3	1262.9	2690.2	1080.6	2024.1
Aluminum	12759.4	17616.2	15621.3	16373.4	11277.1	5057.6	2766.8	13067.5
Boron	30.08	13.47	10.63	<0.01	<0.01	8.81	2.99	9.43
Iron	35318.1	20336.7	17541.5	18489.8	24882.9	19084.8	26810.6	23209.2
Manganese	209.72	134.68	172.09	205.45	152.17	157.63	177.41	172.74
Sulphur	833.49	664.65	981.40	699.73	1061.54	875.93	239.53	765.18
Copper	9.18	13.57	11.96	13.90	11.04	17.97	2.99	11.50
Zinc	43.68	26.26	27.57	29.00	23.75	28.81	29.57	24.81

Data are individual samples collected from seven random sites labeled A thru G from approximately ¼ mile to seven miles distant from the volcano.

Table 3:- Water analysis from volcanic drainage.

Constituent	Plymouth creek	Olveston creek	Egret House creek	Mean
pH	5.2	5.3	4.7	5.1
Salt	4.6	4.7	4.1	4.47
Available Phosphorous, ppm	4.6	4.9	3.0	4.17
Potassium, ppm	26	80	41	49.0
Magnesium, ppm	18	86	17	40.33
Reserve Phosphorous, ppm	26	33	26	28.33
Aluminum, ppm	28	26	53	35.67
Calcium, ppm	1021	686	94	600.3
Zinc, ppm	0.3	1.3	2.7	2.87

Data are individual samples collected from random creek sites labeled as above from approximately three miles to seven miles distant from the volcano, the Egret House being the most distant and Plymouth Creek the closest.

Results and Discussion:-

Volcanic soils have a well-earned and longstanding reputation as being nutritionally beneficial for a wide variety of plant growths, including the propagation of many tropical fruits and other tropical vegetations. The compositional analysis of the Montserrat ash and sand mixture is fully consistent with this earned reputation. The mineral content of the sand includes the nutritionally essential nutrients Magnesium, Potassium, Manganese, Phosphorous, Calcium and Zinc are important on both plant and animal life and are especially impressive in their relative abundance. The acidic pH of the ash flow, as indicated by the pH of the water obtained from various free-flowing creeks draining the volcanic areas supports such an observation, enabling the ash to compliment fertilizers when needed, although for most agricultural uses, on island experience has shown that additional fertilizer or lime treatment is seldom needed to restore adequate growth potential to the formerly volcanic-enriched soils.

While the ash is generally limited in organic matter, the rich mineral content is unique, not only adding much nutritional benefit to the soil on the island but also contributing to an abundant supply of construction grade sand. Availability of construction quality sand is often a scarce commodity among Caribbean Islands, where their only other source of sand for construction would be their common sandy beaches that contribute to recreational tourism and to the vibrant tourist economies of the islands. Thus, the abundant availability of the Montserrat volcanic sand residuals has become a daily export and enable Montserrat and other Island jurisdictions to preserve their otherwise pristine sandy beaches for other commercial, recreational, and environmental endeavors and help to sustain their economic viability. Many of the Caribbean Islands were formed by volcanic eruptions throughout the region, as evidenced by the geographic features which typically include mountainous central areas dotted with extinct volcanoes. The Montserrat volcano vents frequently releasing steam clouds which may linger over the higher elevations, and thus is still considered active volcano.

Wildlife soon re-established residence in the volcanic impacted areas, including wild chickens, birds, goats, wild boars, ground lizards and other animal species endemic to the area. In addition, local streams that survived the volcanic eruptions were also observed to have established aquatic life, thereby affirming the absence of substances which may have been toxic to mammalian, reptilian or freshwater aquatic life and enabling those species of animal life to flourish in the affected areas once again. The entry into volcanic areas has been restricted to only those individuals with a need to enter. Individual masking was required throughout the island during the active eruptions and among those construction workers during the sand excavation and rock crushing activities, where strict safety precautions were implemented. The health of the residents who remained on Island during and after the volcanic eruptions has been closely monitored in the local health facilities including the Glendon Hospital and thankfully to date, no acute or chronic respiratory or other health hazards from the volcano have been reported in the two plus decades since the peak of the volcanic activity occurred.

Volcanic activity is common in many regions of the planet, and while initially immensely destructive to nearby environments, in the longer term they may contribute to the regeneration of the environments continuing for decades after the eruptions have occurred. It is unfortunate that in the past communities have all too often been established in areas in close proximity to earlier volcanic eruptions and proven to be in harm's way should an active volcano spontaneously re-emerge and come back to life as occurred in Montserrat, where it obliterated numerous towns including the capitol of Plymouth, and which communities have not been reestablished as the memories of 1995 and subsequent years are still fresh in the history and memory of Montserratians. The Island of Montserrat rests on two tectonic plates, the more Southern of which supported the volcanic activity, while the more Northern plate remains stable and largely unaffected by the direct effects of the ash flow activity. Thus, the geography of the Northern half of the island provided an area of safe refuge for those who remained on Island during the acute phase of the volcanic eruptions and provided safe land mass for the redevelopment of Montserrat, in addition to providing ample high quality construction grade sand to support the redevelopment activities. The mineral content of the volcanic sand from Montserrat includes naturally occurring cement hardening agents and is highly valued in the construction industry throughout the Caribbean. Thus, the Montserrat Soufriere Hills volcano has played an important role in the establishment and development of Montserrat over the recent centuries and is likely to continue making its beneficial contributions to the economy and well-being of Montserrat and its residents well into the future, whether it be in the valued construction, agriculture, or tourism industries. The sand is safe, the skies are clear and unpolluted, the beaches and waters clean and warm, and the environment highly inviting. At least for now, the Soufriere Hills volcano has had it day in the sun for all to see and enjoy.

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