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A geomorphological analysis of the Piparo and Digity mud volcanoes in south Trinidad

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ABSTRACT. Mud volcanoes are conduits in the ground that discharge mud, gases and sometimes hydrocarbons. They are surface expressions of fluidised muds and silts forced to the surface along zones of crustal weaknesses, and are associated with thick, over-pressured, regressive clay sequences. In Trinidad, these occurrences are more noticeable in the southern parts of the island because of its geological inheritance. The Piparo and Digity mud volcanoes located south of the Central Range's southern flank in Trinidad were selected for investigation because of their local prominence and eruption histories. A geomorphological approach was used to analyze cone morphology and a sedimentological analysis to compare both cones and ejecta. Results indicated that the morphology and crater size varied substantially more at Piparo than at the Digity's volcano. Both mud volcanoes compositions were clay dominant, followed by silt and then sand concentrations. The Piparo cone was found to have a higher alkalinity than Digity's, and the mud released at both sites were non-saline. The mud in the Digity cone contained overall higher moisture content than the mud at Piparo's. Both mud volcanoes had significant but weak relationships between clay content and pH, and slope angle and pH. Even though a significant relationship existed between clay and moisture content for both mud volcanoes, a stronger relationship was observed at the Digity site. These studies may prove helpful in monitoring geomorphological and sedimentological changes that occur pre and post eruption events.

Keywords: Sedimentology, geomorphology, alkalinity, moisture content, electrical conductivity, pH.

1. INTRODUCTION

Mud volcanoes are surface expressions of fluidised muds and silts forced to the surface along zones of crustal weaknesses as faults or deformed anticlinal crests. These muds are associated with thick, over-pressured, regressive clay sequences. In contrast to magmatic volcanoes, they have much smaller shapes, sizes, mud flows (1.7g/cm³ density at cones 1.2g/cm³ at pools) and occur along fault lines or the crests of anticlines both onshore and offshore. Mud volcanoes are fascinating geological structures which have recently been receiving greater attention among scientists (**Deville et al., 2003a; Deville and Guerlais, 2009; Mazzini, 2009; Tinivella and Giustiniani, 2012; Ranjbaran and Sotohian, 2015**).

Mud volcanoes tend to have similarities in terms of their formation. They occur where rocks are folded, imbricated or quickly buried leading to highly over-pressured shale being compressed. Compressional areas include thrust belts, overthrust belts and accretionary prisms (**Dimitrov, 2002**; **Tinivella and Giustiniani, 2013**). They commonly erupt at strike-slip fault lines, along or close to anticlines and are capable of raising rocks and fluids from down to a depth of 5000 m (**Castrec - Rouelle et al., 2002; Deville et al., 2003a; Skinner and Mazzini, 2009**). The main engine behind eruptions is gas rising up from petroleum producing rock or reservoir rock at considerable depths (Cretaceous Cuche, Gautier and Naparima Hill Formations, Southern Basin Trinidad). Gas and oil are lighter than water and as such, they frequently try to migrate upward a sedimentary pile in order to maintain a stable center of gravity.

Likewise, they occur in areas where sedimentation patterns are significantly higher due to the influence of rivers which dump tonnes of sediments thereby compressing or quickly burying fluid shales as in the Orinoco Delta and the southeastern Caribbean (**Yassir, 1989**; **Kopf and Deyhle, 2002**; **Kopf, 2002**; **Planke et al., 2003**; **Alain et al., 2006**; **Vignesh et al., 2013**). The release of gas from richly buried organic matter, and in areas of high temperatures and compact clay layers also build up pressure in overlying shales eventually causing traps to become breached (**Yassir, 1989**; **Kopf and Deyhle, 2002**; **Kopf, 2002**; **Planke et al., 2003**; **Alain et al., 2006**; **Vignesh et al., 2013**). The surface temperatures of the mud ejected ranges between 25 - 33˚C (**Deville et al., 2003a**). The main gas emitted by these mud volcanoes is methane (**Castrec-Rouelle, 2002; Dimitrov, 2002; Kopf, 2002; Deville, 2003b; Kopf et al., 2003; Roy et al., 2004**) but carbon dioxide, ethane, propane, butane, pentane, nitrogen, hydrogen sulphide, argon and helium can also be present (**Deville, 2003b; Ranjbaran and Sotohian, 2015**).

Mud volcanoes experience both eruptive and dormancy stages. During the dormant period, no mud, fluids or sediment are discharged by the mud volcanoes (**Mazzini, 2009**). Dormant activity of mud volcanoes, however, is said to be varied in that most of the volcanoes show no activity, but some may seep mud and fluids (**Planke et al., 2003**). **Deville and Guerlais** (**2009**) studied the cyclic activities of mud volcanoes during their dormant phases by using temperature measurements. They stated that during two eruptions, the mud flows became lessened or ceased. These observations are similar to that of the Piparo mud volcano where prior to the explosive eruption in 1997, mud flow activity was greatly reduced.

2. STUDY AREA

According to **Deville and Guerlais** (**2009**), mud volcanism is responsible for extensive amounts of subsurface clay-rich sediment mobilization, and in Trinidad this phenomenon developed in the convergent orogen between the Caribbean and South American plate that lies amid the accretionary prism of Barbados and the transform system of northern Venezuela (**Deville et al., 2003a, b**). A considerable volume of methane build-up and release may have assisted in the formation of mud volcanoes along the Barbados accretionary prism as it can contribute to over-pressured conditions (**Reed et al., 1990**; **Aslan et al., 2001**).

Trinidad's stratigraphy is divided into five different morphological sections: the Northern Range, the Caroni plains, the Central Range, the Naparima and southern lowlands/ Southern Basin and the Southern Range (**Woodside, 1981**; **Yassir, 1989**). The different sections comprised of a range of geological formations dating back to the upper Jurassic and Cretaceous periods into the Cenozoic. Trinidad and Tobago being an oil and gas producing country, has many petroleum pockets (that originated during the Cretaceous period) that are drilled into for both hydrocarbons and core rock samples (**Deville et al., 2003a**). The hydrocarbon onshore fields and mud volcanoes of Trinidad occur in the Southern Basin in the Southern Range where the Miocene Formations are dominant. These hydrocarbons can become separated and along with mineral water are also discharged by these volcanoes (**Yassir, 1989**).

Piparo's mud volcano is located in the region Couva-Tabaquite-Talparo (**Figure 1a**). **Yassir** (**1989**) reported that the main vent of this volcano was a circular muddy pool 50 cm in diameter and 1 m in depth that bubbled gas continuously and was filled with mineral water. However, this volcano had undergone changes over the years due to its active and occasionally violent nature. From recent measurements, the volcano field extended over an area of 172 hectares (**Outdoors Trinidad, 2007**) and the main vent had developed into a conical shape of approximately 1 m in height (**Figure 2a**). The Digity mud volcano is located in Debe, south Trinidad (**Figure 1a**). **Hosein et al.** (**2014**) described it as having a classical conical shape (**Figure 2b**). It's cone was once 12 feet (4 m) high with a crater diameter of 40 cm (**Yassir, 1989**), however more recent measurements heighted the volcano at approximately 20 feet (6 m) (**Outdoors Trinidad, 2007**). Numerous mud and gas eruptions had been detected in the past few years indicating that the volcano was active. A second mud volcano characterized by a cone-less structure was situated a short distance away from the main cone (**Castrec-Rouelle et al., 2002**).

The Piparo mud volcano resided in the Naparima fold and thrust belt (**Figure 1b, 1c**) in the southern section of Trinidad. The Naparima thrusts and folds trend in a WSW – ENE direction. The core of the anticline comprised the Late Oligocene to Miocene Nariva and Lower Cipero Formations and plunges in a SW direction. This is an asymmetrical anticline, with a moderately dipping north flank (45 degrees) and a steeply dipping (80-90 degrees) south flank. At the core of the anticline is a zone of highly disturbed rock marked by a line of oil and gas seeps and occasional mudflow. There is also a number of NW-SE trending tensional normal faults with dips to the E-NE associated with transtensional tectonics from the Mid Miocene onwards. The last major eruption of this mud volcano occurred on February 22nd, 1997 damaging a part of the town itself. 25,000 m^3 of mud was ejected from several open ground vents which depicted ENE-WSW dextral strike slip movements (**Deville et al., 2003a**) that advanced into the surrounding village, displacing over 100 people (**Patrick et al., 2004**). Digity's mud volcano is located in Trinidad's Southern Basin (**Figure 1b, 1c**) where younger Neogene sedimentary rock units as the Lengua, Cruse and Forest Formations which were folded and imbricated to form the Penal-Barrackpore anticline (**Woodside, 1981**). This area also forms part of the Naparima fold and thrust belt, lying further south of the Central Range. The Digity mud volcano is located precisely on the crest position, of the Penal and Barrackpore anticline.

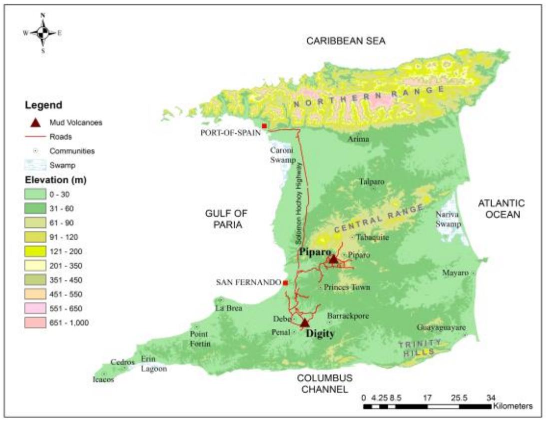

Figure 1a: Map of Trinidad showing the location of the study sites.

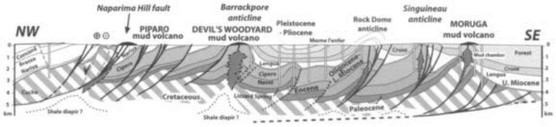

Figure 1b: Geological cross section of south Trinidad (Deville et al., 2016).

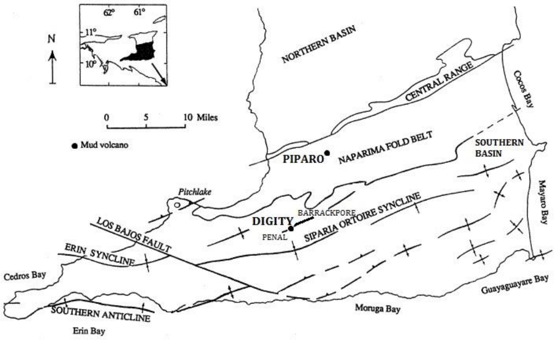

Figure 1c: Map of southern section of Trinidad (after Castrec-Rouelle et al., 2002)

The source of the Piparo mud was thought to be from a deposit of swelling clays (such as smectite) located over 2000 m underground (**Yassir, 1989**) as ascertained by an oil well which penetrated this horizon. An onshore well was constructed before 1986 adjacent to the Digity volcano that collided with the source bed of the volcano causing the well to disappear overnight (**Yassir, 1991**). A mud volcano named Lusi in East Java was formed in a similar way to the mud volcanoes studied in this paper, by the drilling of an exploration well into over-pressured muds resulting in hydraulic fracturing (**Davies et al., 2007**). Lusi's birth provided an opportunity to learn more about the creation of mud volcanoes. In the creation of Lusi, the water from its eruption came from a deeper source than the erupted mud, allowing the mud to become entrained. The processes of hydraulic fracturing and entrainment were also responsible for the creation of mud volcanoes in Trinidad (**Davies et al., 2007**).

Figure 2: a (upper) Piparo mud volcano; and, b (lower) Digity mud volcano in September 2016

The Piparo mud volcano released clasts of Cretaceous to late Miocene age (**Deville et al., 2003a**) and the source of the mud volcano was said to be the Late Oligocene- Nariva Formation (**Pindell and Kennan, 2001**). The Nariva Formation consists of interbedded mudstones and sandstones units deposited (**Pindell and Kennan, 2001**). The Nariva underlies the Late Oligocene to Middle Miocene calcareous claystones, marlstones, sandstones and siltstones of the Cipero Formation with both formations interdigitating on many intervals due to the equivalent ages of the two formations (**Woodside, 1981**; **Yassir, 1989**). The Nariva was deposited in an open marine, shelfal to upper bathyal setting dominated by aranaceous siltstone and mudstones, whereas the Cipero was deposited in a clear, deep marine (>1,500 m water depth) with the majority of the formation constituting the skeletal remains of calcareous foraminifera with irregular sandstone turbidite units. The Penal-Barrackpore anticline comprised of the Lower Cipero Formation and its constituent, Herrera, and Retrench sandstone members as well as the calcareous shales of the Late Miocene Lengua Formation and the Late Miocene to Early Pliocene aranaceous Cruse and Forest Formations which are both thick sequences of interbedded deltaic sandstones, siltstones and claystones. The mudflow covered an area of 2 hectares and was dominated by the Lengua shales. Middle Miocene faunas were also found with occasional pieces of Herrera sandstone fragments.

There had been no observed relationship between the eruptions of the mud volcanoes in Trinidad to seismic activity. The eruptions were mainly due to the build-up of pressure from the sediments within and below the mud volcanoes (**Deville et al., 2003a**). However, earthquakes can trigger mud volcanic eruptions by increasing fluid pressure (**Manga et al., 2009**; **Vona et al., 2015**) but it is difficult to differentiate between an actual trigger and a coincidental eruption. There had been records of mud volcanoes around the world erupting due to earthquakes for example in Niikappu, Japan with magnitudes of the earthquakes ranging from 4.6 – 9.1 (**Manga et al., 2009**).

3. Ejecta characteristics

The ejecta from mud volcanoes can contain different lithologies including liquefied clay and sands that are derived from deeper horizons. The clay mineralogy of the mud volcanoes in Trinidad were composed of kaolinite, montmorillonite, vermiculite (**Hosein et al., 2014**), smectite and illite (**Yassir, 1989**). Several sand minerals were also present such as quartz, feldspar and carbonates (**Deville et al., 2003a**). **Yassir** (**1989**) compared some of these mud volcanoes in Trinidad, in terms of stratigraphy, structure, field description and particle size distribution. In his particle size distribution test, he noted that a greater clay percentage was found at Piparo than at Digity using the hydrometer test. His mud samples weighed 75 g and were treated with 20% solution of hydrogen peroxide to remove oil contamination. In this study, standard hydrometer test guidelines will be followed using 50 g mud samples with no oil contamination to determine if the same result would occur.

Deville and Guerlais (**2009**) reported that the pH of the mud in Trinidad's onshore mud volcanoes ranged from 7 – 8.2, implying that the mud was neutral to slightly basic in nature. This was similar to the pHs of two of Taiwan's mud volcanoes (7.5-8.1) and a mud volcano studied in Romania (7.8) connoting that mud volcanoes even though geographically distributed, have a neutral to slightly alkaline nature (**Alain et al., 2006**; **Liu et al., 2009**). When the pH of both mud volcanoes was compared in a recent study by **Hosein et al.** (**2014**), Piparo had the higher pH (8.5-9.0) than that of Digity (8.0-8.5). This suggests that their pH values corresponded to the alkalinity reported by **Deville and Guerlais** (**2009**), although their alkalinities were slightly higher. Noting the pH obtained by **Hosein et al.** (**2014**), pH tests will be conducted along the flanks of both mud volcanoes for comparison and to observe how the pH changes along the length of each mud volcano.

Soil electrical conductivity is a measurement that correlates with specific soil properties (pH, soil texture, salinity) to determine the effects on crop production (**Grisso et al., 2009**). Electrical conductivity of soils varies with soil texture, particle size and the ability of the soil to retain water; whereby clay has a higher soil electrical conductivity than sand (**Grisso et al., 2009**). The relationship between clay content and electrical conductivity will be tested at both sites, since high clay contents are expected in mud volcanoes.

According to **Deville et al.** (**2003b**) the water ejected from the mud volcanoes of Trinidad had a deep origin (at least 2 km deep) associated to the loss of water by over-pressured claystone intervals. **Hosein et al.** (**2014**) compared the water content between the Piparo and Digity mud volcanoes and found the latter to have the higher water content. However, the location/s on the volcanoes where these tests were conducted was not stated. The water content of the crater mud in both mud volcanoes would be compared in this study. Clay particles have low bulk densities that result in high water holding capacities, and this relationship between water content and clay concentration will be examined for both sites.

In this study, morphological and sedimentological data was analyzed and compared against existing reports on the characteristics of these mud volcanoes and their ejecta. This study aimed specifically to analyze the morphology of the cones, and the sedimentology of the ejecta released from the Piparo and Digity mud volcanoes by (1) assessing the structure and crater size, 2) determining particle size distribution, pH and electrical conductivity (EC) of the sediment present, and 3) determining the moisture content of the mud in the cones. Recent studies can be invaluable in providing up to date information on this geological phenomenon and how they have evolved over time.

2. METHODOLOGY

The methodology adopted in this paper sought to determine the sedimentological characteristics of both Piparo and Digity mud volcanoes by an examination of particle size distribution, pH, electrical conductivity and gravimetric moisture content. Statistical analyses were computed based on the sedimentological results. Slope profiling at both sites were conducted during field surveys which occurred once monthly over a six-month period from September 2016 to February 2017.

2.1. Morphological Surveys

Slope transects were conducted across both mud volcanoes in an east-west direction to determine any changes to their structure and size over the study period. The survey rods were placed starting at the base of the cone (A) and then at appropriate breaks in the slope (B) (**Figure 3a**) where the clinometer was then used to measure the angle of the slope. This was then repeated for points B – F (**Figure 3a**). The horizontal distances and elevations were calculated using the slope angles and distances (**Goudie, 1990**; **Darsan, 2013**) to produce the slope profiles for each cone respectively. The elevations were determined considering the base of the cones as zero (i.e., elevations were not tied to the national datum).

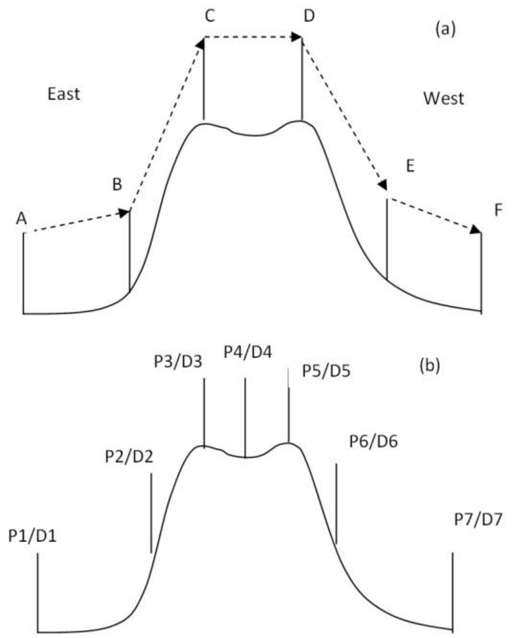

Figure 3: a) Slope survey method, b) Sediment sampling points

2.2. Sediment Analysis

Seven mud samples of approximately 300 g were collected from both mud volcanoes at the same positions every month (**Figure 3b**). The sample bags were labeled (P1 - P7) for the samples collected at Piparo and (D1 - D7) for those collected at Digity. The samples were collected in an east – west direction at both sites. An 8th control mud sample was also taken on the outskirts of each cone (P8/D8) where no recent mud flows occurred and where vegetation was present. The 16 mud samples were taken to the soils laboratory at the University of the West Indies, St. Augustine where particle size distribution, pH, electrical conductivity (EC) and gravimetric moisture content tests were conducted.

2.3. Gravimetric Moisture Content

Gravimetric moisture content was calculated using the samples collected inside the conduits of both volcanoes (i.e. samples P4 and D4) following the standard gravimetric moisture content procedure by Topp and Ferré (2002). All the samples were then air dried for seven (7) days, grinded and sieved.

2.4. Particle Size Distribution

Standard hydrometer method instructions (Gee and Or, 2002) were used to divide the sediment into their respective sand, silt and clay fractions. The respective readings at 30 seconds, 1 minute, 90 minutes and 24 hours were taken and used to calculate the amount of sand, silt and clay that were present in each sample. 50 ml of calgon was poured into a measuring cylinder, where a ‘blank reading ⟦(R⟧_L)’ was taken using the hydrometer and the relative temperature ⟦(R⟧_T) was calculated using the formula: [(T – 19.5) × 0.3]. The corrective hydrometer readings were calculated using the formula: [(R +R_T) -R_L], where R is the respective hydrometer readings.

2.5. pH

pH was measured using a calibrated pH meter following standard laboratory procedure to determine the acidity or alkalinity of the muds ejected (**Thomas, 1996**).

2.6. Electrical Conductivity

Rhoades (**1996**) saturated soil paste process was used to determine electrical conductivity. A desktop EC meter was used to test the excess water drained from the saturated paste.

2.7. Statistical Analysis

Linear regression tests were performed on different variables to determine if a straight-line relationship existed between them and whether one variable was dependent on the other. The coefficient of determination (R^2) was also used to measure the variability of the data, the proximity of the data points to the line of best fit and the strength of the relationship. A two tailed t-test with a statistical significance of 0.05 was applied in calculating the p-values to determine the significance of the relationship between the variables.

3. RESULTS

3.1. Morphological Surveys

The Piparo cone was significantly smaller than that of Digity both in height and width. However, greater morphological variations were observed at the Piparo site over the study period. Shifting of the crater opening and subsequent eruptions assisted in re-shaping the morphology of the cone as evident from December 2016 to January 2017. The Piparo mud volcano underwent changes in its structure and crater sizes over the six-month period (**Figure 4**) due to its active nature. The crater size ranged from 0.127 m to 0.991 m over the study period. In the first four months of the study, the sides of this cone were generally steep especially on the eastern flank and symmetrical. This was due to the mud being more actively ejected into the air from gas build up, following a rumble from the ground. The eruption at this volcanic cone differed from the surrounding smaller cones where eruptions were continuous, fluid and flowing. However, in January 2017, the mud volcano had grown considerably with gently sloping sides compared to the previous four months. The sides of the mud volcano also became slightly steeper in February.

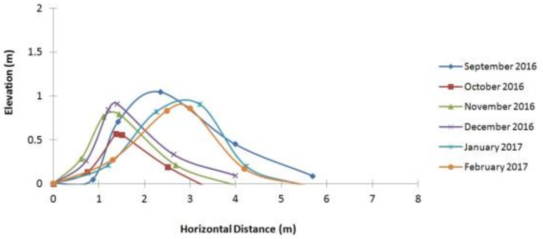

Figure 4: Morphological changes of the Piparo mud volcano over the 6-month period.

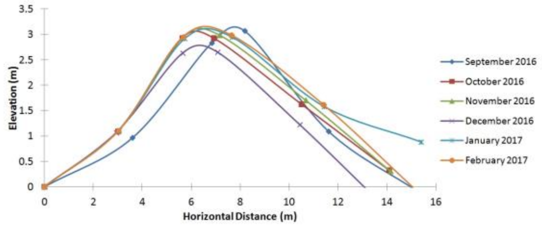

Figure 5: Morphological changes of the Digity mud volcano over the 6-month period.

Figure 5 showed little changes in the structure and crater size of the Digity mud volcano. This volcano had a conical shape that was slightly steeper on the western flank with a small dome at the top. The crater size ranged from 1.296 m to 1.524 m in the first four months of study. This mud volcano was undergoing a period of dormancy when study at this site began. However, in January there were signs of activity at this mud volcano (dried mud flows on the northern flank and an increase in crater size to 1.93 m). In February, the mud in the crater appeared dry and no new signs of activity were observed.

3.2. Piparo and Digity particle size distribution

Figures 6-8 display the sand, silt and clay percentages of each sample over the six-month period for both Piparo and Digity respectively. Digity contained a greater percentage of clay compared to Piparo. At both sites, there were slight fluctuations in the sand concentrations over the study period with little variation in the silt and clay compositions (**Figures 6-8**). At the Piparo site, there were more mudflows occurring on the eastern side of this cone compared to the western side. The old ejecta at the western base of the volcano was subjected to natural weathering and slope-wash processes that removed the finer clay particles, leaving behind more sand and silt-sized particles. This was evident in sample 7 (**Figure 8a**) where low clay concentrations were found. Mud sample (8) from the outer edges of the cone consisted of low sand but high silt and clay concentrations, similar to the samples taken along the volcanic cone. At the Digity site, mud sample (8) from the outer edges of the Digity cone where vegetation was present contained high amounts of sand and silt but low clay content.

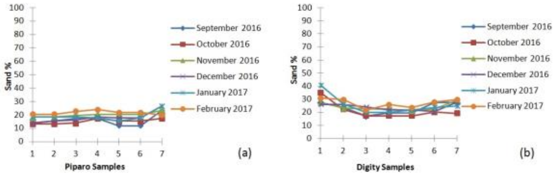

Figure 6 (a): Piparo sand concentration; (b): Digity sand concentration.

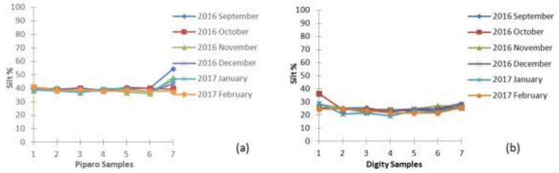

Figure 7 (a): Piparo silt concentration; (b): Digity silt concentration.

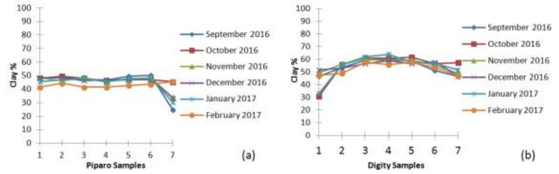

Figure 8 (a): Piparo clay concentration; (b) Digity clay concentration.

Table 1: pH values for Piparo and Digity volcanoes

	September 2016		October 2016		November 2016		December 2016		January 2017		February 2017	
Samples	P	D	P	D	P	D	P	D	P	D	P	D
1	9.43	9.05	8.94	8.99	8.84	9.02	8.85	8.64	8.88	8.89	8.44	8.54
2	9.79	9.16	9.32	9.11	9.51	9.04	9.00	8.83	9.39	9.19	9.12	8.62
3	10.01	9.50	9.85	9.25	9.82	9.16	9.20	9.00	9.78	9.24	9.33	8.73
4	10.01	9.39	9.93	9.20	9.96	9.07	9.48	8.84	9.85	9.04	9.54	8.77
5	9.99	9.30	9.97	9.28	9.93	9.25	9.32	8.97	9.81	9.28	9.24	8.87
6	9.51	9.20	9.36	9.28	9.37	9.19	8.93	8.85	9.33	9.11	8.89	8.56
7	8.90	9.06	9.26	9.11	8.98	9.05	8.48	8.66	9.02	8.87	8.90	8.43

Note: P = Piparo; D = Digity

Table 2: Electrical conductivity values for Piparo and Digity volcanoes

	September 2016		October 2016		November 2016		December 2016		January 2017		February 2017	
Samples	P	D	P	D	P	D	P	D	P	D	P	D
1	0.1460	0.1118	0.1603	0.1173	0.1110	0.0917	0.1167	0.0666	0.0506	0.0512	0.1331	0.0682
2	0.0792	0.0505	0.1048	0.0978	0.0700	0.0886	0.0790	0.0480	0.0722	0.0451	0.1034	0.0526
3	0.0871	0.0779	0.0781	0.0762	0.0672	0.0660	0.0606	0.0368	0.0575	0.0354	0.0430	0.0458
4	0.0748	0.0420	0.0736	0.0862	0.0620	0.1439	0.0514	0.0516	0.0495	0.1036	0.0463	0.0685
5	0.0704	0.1312	0.0706	0.1103	0.0660	0.1013	0.0554	0.1282	0.0541	0.0633	0.0565	0.0320
6	0.0703	0.0893	0.1270	0.0919	0.0973	0.0755	0.0537	0.0438	0.0471	0.0660	0.0862	0.0863
7	0.1176	0.1517	0.1128	0.0745	0.1412	0.0655	0.0755	0.0534	0.0413	0.0637	0.0189	0.0770

Note: P = Piparo; D = Digity

3.3. pH

Table 1 above compared the pH of both mud volcanoes on a month to month basis. Figures 9a-b depicted an alkaline pH each month over the study period for both the Piparo and Digity mud volcanoes.

A higher pH was observed for most of the samples at the Piparo cone compared to Digity each month (**Figures 9a-b**). The pH in December 2016 and February 2017 were considerably lower than the other months at the Piparo and Digity sites (**Figure 9a-b**). At both sites, there was a general trend of decreasing pH values from September to December 2016, with a general increase in pH in January 2017 which decreased again in February 2017 (**Figures 9a-b**). The mud in the Piparo crater had a high pH value which decreased in alkalinity as the cone was descended. At the Digity site, the pH of the mud at sample points 3 and 5 was higher in alkalinity than the mud in the crater. The pH values on the outskirts at both volcanoes (sample 8) were slightly alkaline in nature but relatively lower than the pH values obtained along the cones.

3.4. Electrical Conductivity

Table 2 compared the electrical conductivity of both mud volcanoes on a month to month basis. A more noticeable trend in electrical conductivity was seen at the Piparo site when compared to the Digity site. The electrical conductivity measured each month was less than 1dS/m for both mud volcanoes.

Slight variations in electrical conductivity were observed at the Piparo site over the six months (**Figure 10a**). However, no apparent trends in electrical conductivity were seen at the Digity mud volcano (**Figure 10b**).

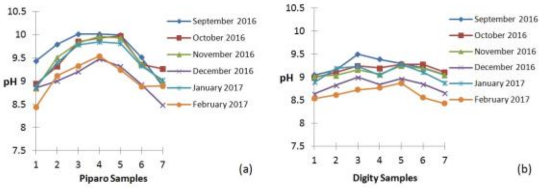

Figure 9 (a): pH values at Piparo volcano; (b) pH values at Digity volcano.

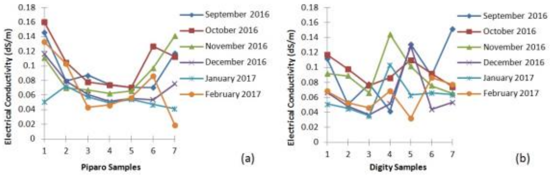

Figure 10 (a): Electrical conductivity at Piparo volcano (b) Electrical conductivity at Digity volcano.

3.5. Gravimetric moisture content

The gravimetric moisture content of the sample taken inside both the Piparo and Digity mud volcanic cones were calculated and displayed in **Figure 11**. Digity had slightly higher gravimetric moisture content than that at Piparo.

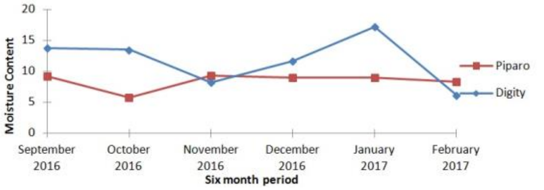

Figure 11: Gravimetric moisture content at Piparo and Digity volcanoes.

4. DISCUSSION

4.1. Morphological Survey Analysis

According to **Deville et al.** (**2003b**), no relationship between mud volcanic eruptions and earthquake activity has been found in Trinidad although it had been observed in different parts of the world (**Manga et al., 2009**). Both the Piparo and Digity mud volcanoes had an unusual increase in activity in the month of January 2017. There was a slight possibility that the increase in activity was a result of an earthquake that struck off the SSE coast of Scarborough, Tobago measuring a 6.2 magnitude on December 6th, 2016 (**Boodram, 2016**). Trinidad is located on a tectonically active margin with minor movements being observed on most faults which also could cause pressure build up and release. Migrating fluids and gases from deeper reservoir rocks could also contribute to increases in activity, in addition to recharging of shallow aquifers.

The overall shape of both cones remained conical over the six months, however, Piparo's crater size varied monthly with only slight changes to its structure. The only substantial change observed at the Digity mud volcano was the increase in crater size following the mud flow that occurred (December 2016-January 2017).

4.2. Particle Size Distribution

Both mud volcanoes were found to be clay dominant and showed similar particle size distributions; that is, high amounts of clay followed by silt and then sand. The Digity mud volcano was formed over deep water calcareous claystones and marlstones of the Cipero and Lengua Formations whereas the Piparo mud volcano was formed over calcareous claystones of the Lower Cipero and aranaceous mudstones of the Nariva Formations accounting for their high clay content. **Yassir** (**1989**) and **Hosein et al.** (**2014**) found that mud volcanoes in Trinidad were made up of various silicate minerals such as kaolinite, montmorillonite, smectite and illite which accounted for the high clay content. The Digity cone generally had a greater sand and clay content but lower silt concentration when compared to the Piparo cone.

This paper contrasted with the study done by **Yassir** (**1989**) where he found that Piparo had higher clay content. The hydrometer method was used in both studies; however, there were differences in the methodology followed to obtain the particle size distribution. The mud samples obtained in this study did not contain any oil contamination and hence, hydrogen peroxide was not used. This variation in laboratory methods, as well as the different sampling locations and weight of samples may be responsible for the contrasting results.

4.3. pH

The pH of the mud at both sites was alkaline in nature but there was a slightly higher alkalinity of the mud at the Piparo site than at Digity. The Piparo mud volcano was formed over deep water calcareous marls (calcium carbonate rich clays and silts) of the Early to Middle Miocene Lower Cipero Formation which may be responsible for its higher pH. The, Digity mud volcano however was formed over the Lengua Formation with overlying aranaceous Lower Cruse claystones and sandstones. The Lengua clays are calcareous in nature and may be responsible for its pH.

Hosein at al. (**2014**) also found the pH of the mud at Piparo volcano to be higher compared to that of Digity volcano. However, the pH range (8.44 - 10.01) at the Piparo site and (8.43 - 9.5) at the Digity site from this study, varied greater than the range (8.5-9.0) and (8.0 – 8.5) respectively found by **Hosein et al.** (**2014**). The reason for this increased range in pH may be due to differences in sample collection or the season in which the samples were collected. Variation in rainfall can affect mud's pH. Unpolluted rain is slightly acidic in nature averaging a pH of 5.6 (**Casiday and Frey, 1998**) and can affect sandy soils more than silt and clay by lowering their alkalinity. The samples were collected towards the end of the rainy season in September 2016 to the dry season in February 2017, where rainfall may not have been very extensive to lower the mud pH levels. However, the alkalinity of the mud in the Piparo crater also varied much higher than the mud in the Digity crater. This was probably due to the standing water observed in the Digity crater during the study period where rainwater was slower to filter through and hence, may be responsible for lowering the crater's mud pH over time.

4.4. Electrical Conductivity

The electrical conductivity of the mud in the Piparo crater was relatively low but increased towards the base of the cone and was observed to be decreasing in value from September 2016 to February 2017 (**Figure 10a**). Fluctuations in the electrical conductivity of the Digity mud volcano were observed every month (**Figure 10b**) with no apparent trends. The mud in the Digity cone contained a higher electrical conductivity value compared to Piparo from October 2016 to February

2017. Soil electrical conductivity indicates how saline the soil is. Electrical conductivity readings less than 1dS/m were obtained at both volcanoes which indicated that the muds were non-saline in nature (**Arnold et al., 2005**). According to **Grisso et al.** (**2009**) clay soils have a high conductivity and the higher electrical conductivity in the Digity crater may be due to the higher clay content found at this site. Even though these mud volcanoes are clay dominant, their electrical conductivities were relatively low.

4.5. Gravimetric Moisture Content:

The moisture content in the mud of the Digity vent was higher for a greater part of the study period when compared to Piparo (**Figure 11**). This may be due to higher clay content at the Digity site which could be responsible for a higher water holding capacity. The seasonal timing of this study may also be responsible for the fluctuations observed in moisture content. The water in mud volcanoes were generated from both deep and shallow sources and normally interact with the mud (clay clasts) to create different viscosity flows (**Tinivella and Giustiniani, 2012**). The mud at the Piparo site had a higher viscosity than that of the Digity site in tandem with its lower moisture content for most of the months.

4.6. Relationship between grain-size and cone morphology

Figure 12a-b display the relationship between sand, silt and clay percentages with slope angle respectively for both Piparo and Digity. The coefficient of determination (R^2) was depicted to represent the strength of the relationship.

Piparo (**Figure 12a**) depicted very weak relationships between sand, silt and clay composition versus slope angle respectively, whereas, moderately significant relationships existed between the particle size distribution (sand, silt and clay) and the slope for the Digity site (**Figures 12b**). A better relationship was found between clay and slope angle ($R^2 = 0.60$) at Digity (**Figure 12b**).

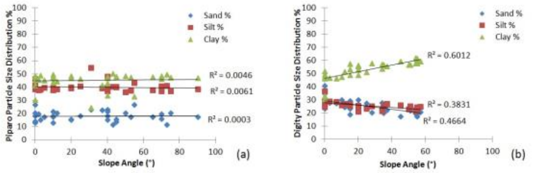

Figure 12: Relationship between sand, silt and clay % and slope angle at (a) Piparo and (b) Digity

4.7. Relationship among variables

Linear regression graphs representing the coefficient of determination (R^2) were created to determine whether any relationships existed between various variables for both Piparo and Digity (**Figure 13**). Different variables were compared but were found to have significant but very weak relationships. The clay % and moisture content (**Figure 13a (i)**) in the Piparo crater had a weak and insignificant relationship which contrasted with the significantly strong relationship found in the Digity crater (**Figure 13a (ii)**). A relationship between clay and moisture content was expected at both sites because of the high-water retention capacity of clay, with a stronger relationship being observed at Digity. Significant but weak relationships between clay % and pH (**Figure 13b**), and slope and pH (**Figure 13c**) were observed for both Piparo and Digity. Unlike most of the other mud volcanoes in Trinidad, the Piparo mud volcano had extruded a large number of rock clasts in the mud, which covered the tassik of the cone. These clasts were made up of a number of formations which the fluidized mud had passed through on its way to the surface. Fragments of mica rich Nariva sandstones, both oil impregnated and water wet were common, as well as lignite and parallel laminated shales being observed. Likewise, coarse-grained Eocene-Oligocene Point-a-Pierre Formation sandstones, marls similar to the Paleocene to Eocene Lizard Springs Formation, Early Cretaceous Cuche shales, chert rich material similar to the Late Cretaceous Naparima Hill argilline, with occasional greenish sandstone, red mudstones and abundant fibrous calcite were seen.

Deville et al. (**2003b**) analysed (XRD & MEB) various clasts and the mud matrix. The mud included several types of clays (kaolinite, illite, smectite and vermiculite) and other grains consisted of quartz, feldspar, siderite, rutile, anatase, chlorite and muscovite. The mud was very thin (less than 3 mm) and rich in angular fractured quartz grains. This and the presence of calcite suggested that they were affected by hydro-fracturing. This may be responsible for the relationship between clay and pH (**Figure 13b**) whereas, the relationship between slope and pH can be observed in **Figure 13c**, where the pH decreased from the crater to the base of the cone. The calcareous clayey soils from deep water marls which were dominant in the Cipero Formation accounted for the high alkalinity at the Digity site and similar to Piparo, the pH also decreased from the crater to the base of the cone.

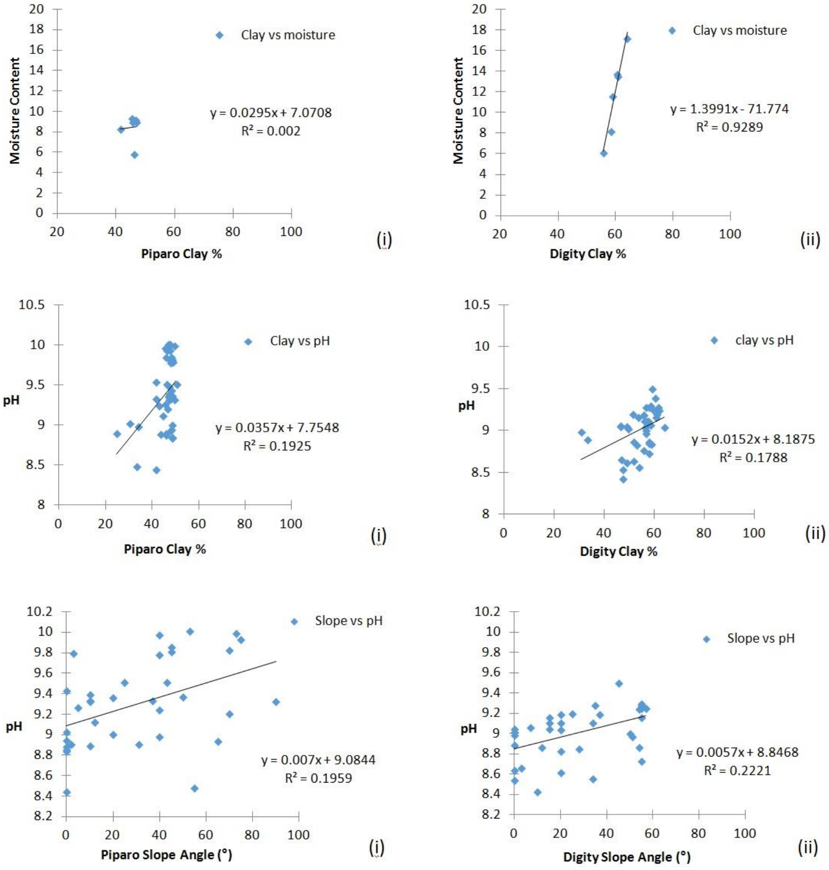

Figure 13a (upper): Relationship between clay % and moisture content at (i) Piparo and (ii) Digity. Figure 13b (middle): Relationship between clay % and pH at (i) Piparo and (ii) Digity. Figure 13c (lower): Relationship between slope angle and pH at (i) Piparo and (ii) Digity.

Table 3: Calculated p-values for the relationship between different variables at the Piparo mud volcano

Piparo	pH	EC	Clay	Moisture Content	Slope
pH		$p<0.05$	$p<0.05$	$p>0.05$	$p<0.05$
EC	$p<0.05$		$p<0.05$	$p<0.05$	$p<0.05$
Clay	$p<0.05$	$p<0.05$		$p<0.05$	
Moisture Content	$p>0.05$	$p<0.05$	$p<0.05$		
Slope	$p<0.05$	$p<0.05$			

Table 4: Calculated p-values for the relationship between different variables at the Digity mud volcano

Digity	pH	EC	Clay	Moisture Content	Slope
pH		$p<0.05$	$p<0.05$	$p>0.05$	$p<0.05$
EC	$p<0.05$		$p<0.05$	$p<0.05$	$p<0.05$
Clay	$p<0.05$	$p<0.05$		$p<0.05$	$p<0.05$
Moisture Content	$p>0.05$	$p<0.05$	$p<0.05$		
Slope	$p<0.05$	$p<0.05$	$p<0.05$		

4.7. T-test: Two samples assuming unequal variances

The t-test was used to determine whether a relationship existed between the different variables at both volcanoes. A statistical significance of 0.05 was used to determine whether the samples had an influence on each other or a relationship existed by chance. **Tables 3-4** in conjunction with the linear regressions, permitted further analysis of the relationships between the different variables.

Tables 3-4 indicated that significant relationships existed between electrical conductivity and pH, slope and pH and slope and electrical conductivity, however the relationships were very weak in nature. While Piparo showed no relationship between slope and clay %, (**Table 3**) there was a significant relationship for Digity at a 0.05 confidence level (**Table 4**). The strength of this relationship can be observed in **Figure 12a-b**.

5. CONCLUSION

Piparo and Digity mud volcanoes occurred above varying stratigraphic rock intervals. The Piparo mud volcano was dominated by the underlying Nariva Formation but was also influenced by the Lower Cipero Formation and reworked Paleogene and Cretaceous lithologies. The Digity mud volcano however was dominated by the Upper-Lower Cruse Formation as well as the Lengua and Middle to Upper Cipero Formations. However, based on this research and previous studies, they exhibited many similarities. This study was compared to previous research to also investigate whether these mud volcanoes displayed any changes from the past to present and whether any geomorphological signs are displayed by these mud volcanoes before erupting. It was observed that both volcanoes' ejecta muds were clay dominant and alkaline in nature. This may be due to the calcareous clays and marls found in their geology. The Digity site was found to have higher clay and sand concentrations compared to the Piparo site which had greater silt concentrations. This contrasted with a previous study done by **Yassir** (**1989**) who found Piparo to have a higher clay content. However, the alkalinities at both volcanoes were found to be slightly higher than those found in previous studies, with Piparo having the higher pH compared to Digity. Both sites comprised of non-saline muds (< 1 dS/m) and a significant relationship was found between clay % and moisture content for both mud volcanoes, although a stronger relationship was observed at the Digity site, probably due to the higher clay content.

The data presented in this study formed the most recent scientific inquiry into these mud volcanoes. As these geological landforms evolve with time, it becomes increasingly important to monitor and analyze its geomorphology and sedimentology for (1) changes in the shape and size of the cones, (2) changes in the sand, silt and clay content, pH, electrical conductivity and moisture content of the ejected mud, and (3) relationships between any mud characteristics and slope form. This is important as any significant changes to these volcanic characteristics may be indicative of a potential large eruption. If these studies were implemented pre-1997, emergency evacuation policies could have been implemented to the surrounding communities to minimize the damages that occurred in 1997 by the Piparo mud volcano. All mud volcanoes in Trinidad should continue to be the focus of scientific research, and their processes recorded and compared to each other. This can help determine whether they are related and how their eruptions can impact surrounding environments.

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