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Mapping of depth to bedrock in the Middle Lower Benue Trough Nigeria, using Seismic Refraction Method

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Abstract: *Seismic characteristics in the Middle Benue Trough were investigated at 39 acquisition stations Seismic refraction method. Two overlapping reversed profiles were shot into 12 stations of geophones at each station. Each shot hole was 1.5m deep primed with 0.20kg dynamite as source. The acquisition equipment was McSeis-160MX^{TM}. Analysis of the results revealed 2-layers cases. The velocity of the Low-Velocity Layer, V_o, varies between 399 and 944ms^{-1} with average of 659.13 ms^{-1}. The underlying Consolidated Layer has velocity, V_1, which varies between 1210 and 4240ms^{-1} with an average of 2214.00ms^{-1}. Velocity appears greater when shooting up-dip, while velocity is reduced when shooting down-dip which could be attributed to either dipping layers or/and subsurface sediment heterogeneity. Depth of refractor, Z, varies between 2.80 and 6.5m with average of 4.38m. Elevation varies between 63 and 228m with average of 148.51m. Weathered thickness and elevation were highly variable resulting from both surface- and surface-topographic undulations. The results of this work can be used for estimating rippability prior to excavation, mapping depth to bedrock/bedrock topography, mapping depth to groundwater, corrections of lateral, near-surface, variations in seismic reflection surveys and crustal structure and tectonics.*

Key Words: *- Seismic refraction, velocity, weathered and consolidated layers, bedrock, Middle Benue Trough, Nigeria.*

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I. Introduction

The near-surface layer of the earth usually differs markedly from the underlying part of the earth in velocity and in some other properties. This makes the low-velocity layer (LVL) or weathered layer especially important. The determination of depths, attitudes, and continuity of deeper events are affected as reflections pass through this layer. The term "weathered" as used by geophysicists is different from the geologist's "weathered," which denotes rocks disintegration under the influence of the elements. Seismic velocities are low in weathered layer or the low-velocity-layer (LVL). The weathered layer of bedrock is described as the shallow surface layer composed of unconsolidated materials such as soil, sand and gravel. It is heterogeneous in composition and it's characterized by low seismic velocity which account for the delay experienced in travel time of the seismic wave. Geophysicist uses the weather layer parameters in the design of receiver source array for field filtering purpose [1, 2]. This implies that gas (air or methane resulting from the decomposition of vegetation) fills at least some of the pore space [3]. This layer which is usually 4 to 50 m thick, is characterized by seismic velocities that are not only low (usually between 250 and 1000 m/s), but at times highly variable [4, 1, 5, 6].

The marked velocity contrast at the base of the LVL sharply bends seismic rays so that their travel through the LVL is nearly vertical regardless of their direction of travel beneath the LVL. Owing to the very high-impedance contrast at the base of the LVL, the base of the layer is an excellent reflector, making it a strong producer of multiples. This layer is also important in mode conversion and in the propagation of Rayleigh and Love ground roll waves. Since both thickness and velocity vary in this layer, travel times of seismic wave through the layer also vary. Moreover, reflection arrivals may vary, because of the near-surface variations. Unless correction is made for the variation in the LVL as well as for the changes in elevation, a spurious structure can be introduced at depth.

The absorption of seismic energy is high the LVL [7]. It acts as a variable low-pass filter and therefore changes the shapes of waves passing through it making record quality poor. Shot effectiveness lies in locating shots below the base of the LVL. Prior to reflection survey targeted at deep subsurface mapping, the variation of the thickness of the weathered layer of a prospect area has to be studied. With the LVL information, drilling and shooting can be planned effectively. Because of the low velocity, wavelengths are short and hence much smaller features produce significant scattering and other noise. Frozen near-surface (permafrost) where velocity is appreciably larger than (3600 – 4200ms^{-1}) within the layer than the velocity beneath the permafrost (2100 – 2700ms^{-1}), and energy travels at a greater angle in the upper layer, producing distortions in travel paths.

The velocity-depth information is used for static corrections and drilling programmes in any reflection work because this layer slows down and absorbs seismic energy, and therefore increases travel times. Since the base of the

LVL is often coincides with water table, the information resulting from the work can be used for groundwater exploration. Moreover, the base of the LVL is the bedrock due to the large velocity-contrast; therefore foundations could be located there for bridges, dams, high-rise buildings. It can be used to delineate waste landfill (depth of fill). Seismic characteristics in LVL also provide information about rock quality or other geotechnical parameters for geotechnical investigations [8]. The LVL parameters are used to design receiver-source array for reflection work. The weathered layer parameters are also used in the analysis of soil behaviour under static and dynamic loads. The elastic constants obtained are input variables into the models defining the different states of deformations such as elastic, elasto-plastic and failure [9, 10]. The main purpose of this work is therefore to estimate the weathered layer seismic characteristics of velocities, depths and dips in the study area using seismic refraction technique.

II. Geology of Study Area

The study area is located in the Middle Benue Trough, North Central Nigeria and it lies within Latitude 07.50° - 08.50°N and Longitudes 08.00° and 09.30°E (Figure 1).

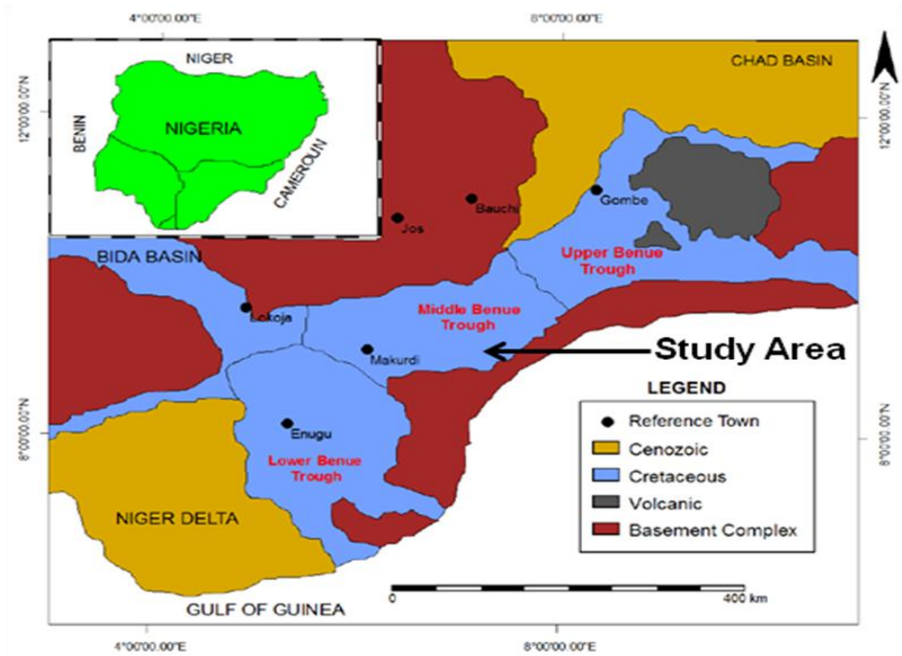


Figure 1: Map of the Benue Trough showing the Study Area. Source: [11]

The Benue Trough is an intra-cratonic rift structure, which extends from the Northern limit of the Niger Delta to the Southern margins of Chad Basin. The valley which is occupied by up to 600m of marine and fluviodeltaic sediments, that have been compressionally folded in non-orogenic shield environment has been subdivided geographically into the Lower, Middle and Upper Benue Trough for the ease of mapping. The Middle Benue Trough which is of particular interest in this project work encompasses the study area located in the central part of Nasarawa State.

The geology of Nigeria is made up of three major litho-petrological components, namely, the Basement Complex, Younger Granites, and Sedimentary Basins [12, 13, 14, 15, 16]. The Basement Complex, which is Precambrian in age, is made up of the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites. The Younger Granites comprise several Jurassic magmatic ring complexes located in Jos and other parts of north-central Nigeria. They are structurally and petrologically distinct from the Older Granites. The Sedimentary Basins comprise the Niger Delta Basin, the Benue Trough, and the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida/Nupe) Basin and the Dahomey Basin.

The linear NE-SW trending Benue Trough (Figure 1) has a length of approximately 800km and open into the Gulf of Guinea where the Cenozoic Niger Delta has built out upon oceanic crust [17]. Proximately it bifurcates into an E-W trending Yola arm and a N-S trending Gongola Basin. The Benue Trough is conventionally subdivided into a “Lower Benue Trough”, “Abakaliki Trough” [18], a “Middle Benue Trough” and an “Upper Benue Trough” (“Benue valley” [18]. The Benue Trough was terminated by a Late Santonian episode of compressional folding.

Subsequent sedimentation was centred on basins developed on the North-Western flank of the resultant deformed sediments.

The stratigraphic succession of the Benue Trough is shown below (Figure 2). The six formations include the Asu River Group, Awe Formation, Keana Formation, Ezeaku Formation, Awgu Formation and finally the youngest which is the Lafia Formation, while the two formations exposed in the studied area are the Awe Formation and Keana Formation which are essentially sandstones with intercalations of calcareous shale and claystone which are covered by laterite resulting from the weathering of volcanic rocks which were emplaced during the widespread volcanic activities that took over in the Tertiary Period [17, 18]. The Benue Trough is arbitrarily sub-divided into three portions; Lower, Middle and Upper portion (Fig. 1). No concrete line of subdivision can be drawn to demarcate the individual portions, but major localities (towns/settlements) that constitute the depocentres of the different portions have been well documented [12, 13, 14, 15, 16].

The Middle Benue Trough extends Northeast ward approximately as far as line joining Bashar and Mutum Biyu. This boundary marks the Southern limit of the Gombe and Keri-Keri Formation while the older sediments of the Upper Benue Trough undergo lateral facies change in this area. The Middle Benue Trough is relatively poorly known, especially in its North-eastern part; no detailed geological maps of this portion are available but the area immediately south of Bashar was included in a photogeological map. Maps of the Lafia-Keana-Awe region were presented by Offodile [19], Offodile and Reyment [20] and Ofoegbu and Onuoha [21] and of the area around Makurdi by Kogbe *et al.* [22] and Nwajide [23].

III. Theoretical Background of Seismic Refraction Method

Considering a hypothetical two-layer medium, the upper separated from the lower by a horizontal interface at depth D_w (Figure 3). The velocity of seismic wave in the upper layer is V_o and the lower V_1, with $V_1 > V_o$. A seismic wave created at a depth, D_s, in the weathered layer is detected at E (Figure 3).

The total travel time, T, is given by:

$$T = T_{BC} + T_{CD} + T_{DE}$$

$$= \frac{BC}{V_o} + \frac{CD}{V_1} + \frac{DE}{V_o} \quad (1)$$

From Figure 2.2,

$$BC = \frac{D_W - D_S}{\cos i};\ DE = \frac{D_W}{\cos i}\ CD = x - (2D_W - D_S)\tan i \quad (2)$$

$$\sin i = \frac{V_o}{V_1};\ \cos i = \sqrt{\frac{V_1^2 - V_o^2}{V_1^2}};\ \tan i = \sqrt{V_1^2 - V_o^2}; \quad (3)$$

Hence substituting into Equations 1, 2 and 3 and simplifying, we have:

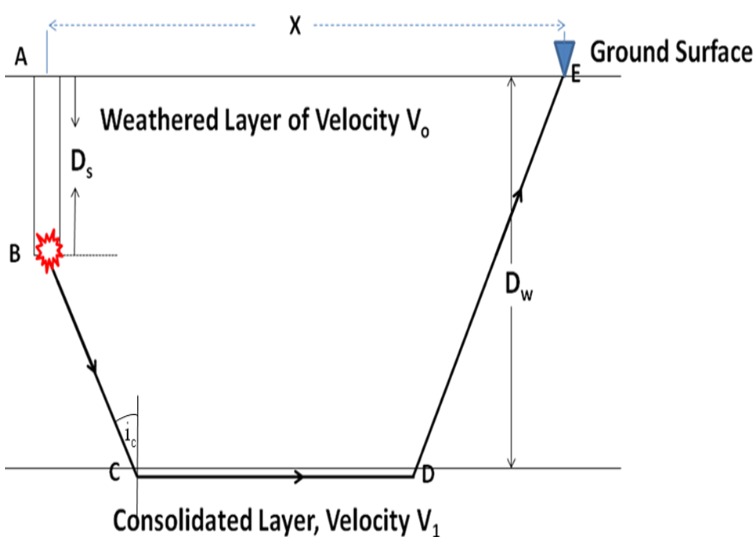
$$T = \frac{X}{V_o} + (2D_W - D_S)\frac{\sqrt{(V_1^2 - V_o^2)}}{V_o V_1} \quad (4)$$

Equation 2.14 gives an intercept time T_i expressed as:

Hence, weathered thickness:

$$D_W = \frac{T_i}{2} \bullet \frac{V_o V_1}{\sqrt{V_1^2 - V_o^2}} \bullet \frac{D_S}{2} \quad (5)$$

For a given shot, a plot of arrival times (T) versus offset distances (x) gives a straight line graph of gradient $1/V_1$. The direct wave travels from the shot to detector near the earth surface at a speed of V_o, so $T = x/V_o$. This is represented on the T-X graph as a straight line which passes through the origin and has a gradient of $1/V_o$.



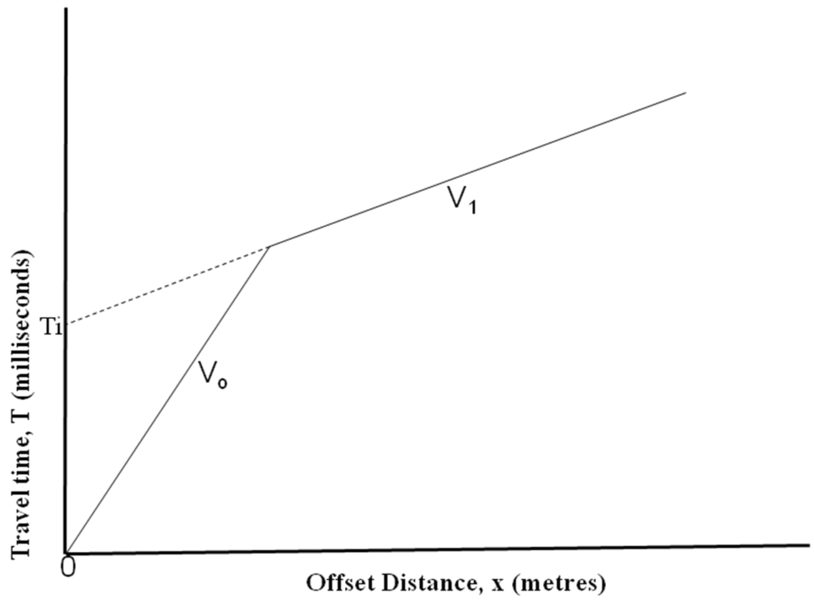


Figure 3: Travel-time versus distance curves of the direct and refracted rays when the refracting boundary is horizontal.

IV. Material and Methods

Using benchmarks as controls, the surveyors used GPS, matches, staff and poles and cut open the seismic traverse lines (Figure 4). The Equations 4 and 5 represent the mathematical models used in the velocity, depth, and angle determinations. In using these equations, we assume that the interfaces are horizontal and therefore each layer of the rock has a uniform thickness. We also assume that a straight ray path for the waves. This means that there were no faults, no unconformities, no facies changes, and no weathering changes. We never find this situation in nature. However, we often deal with situations that approximate the ideal model. During the survey, the terrain in the vicinity of data acquisition station was sufficiently flat. This level ground approximated the horizontal bedding assumption model and it also eliminated the need for elevation.

For a selected data acquisition location, two reversed profiles were taken. This condition provided a valuable check for the comparative interpretation of the travel-time data. The importance of the reverse shooting as a means of cross-checking the results is obvious when we bear in mind that we are working with complex geological layering and not with models.

The field set-up is shown in Figure 5. Here a shot was located at each end of the spread of 12 geophones which were planted on the earth surface as shown in the intervals. Since we are interested in the layering in the immediate vicinity of the shot point, the source-detector offset was 5 metre minimum and 75 metres maximum. The first 5 geophones were spaced 5 metres apart near the source; the others were spaced 10 metres towards the centre and 5 metres towards the end of the spread for adequate sampling of shallow depths from the surface down to the depth of interest, and to obtain a good resolution.

At each data recording set-up, 2 overlapping reversed profiles were shot into 12 stations of geophones. Each shot hole was 1.5 metres deep primed with 0.20kg of dynamite. The reversibility criteria **[24]** for reciprocal and intercept times were not satisfied by our data. We attributed this condition to either inhomogeneity along the lines or to velocity anomalies [25] or dips. We therefore assumed a laterally-homogeneous horizontal layer models, and computed the layer thickness and velocities separately for LVL_1 and LVL_2, and then found the average.

Figure 6 shows a typical refraction monitor record from the survey. The first arrivals gave us the basic travel times with which to compute the velocity and depth structure of the near-surface of the earth in the study area. The ground electronics consist of geophone array connected to take-outs wired into pairs within the cable. The cable was connected to the McSeis-160MX Instrument. All data flows through McSeis-160MX for processing, formatting, recording and playback functions. Real time geophone monitoring was accomplished with visual display on the McSeis oscilloscope.

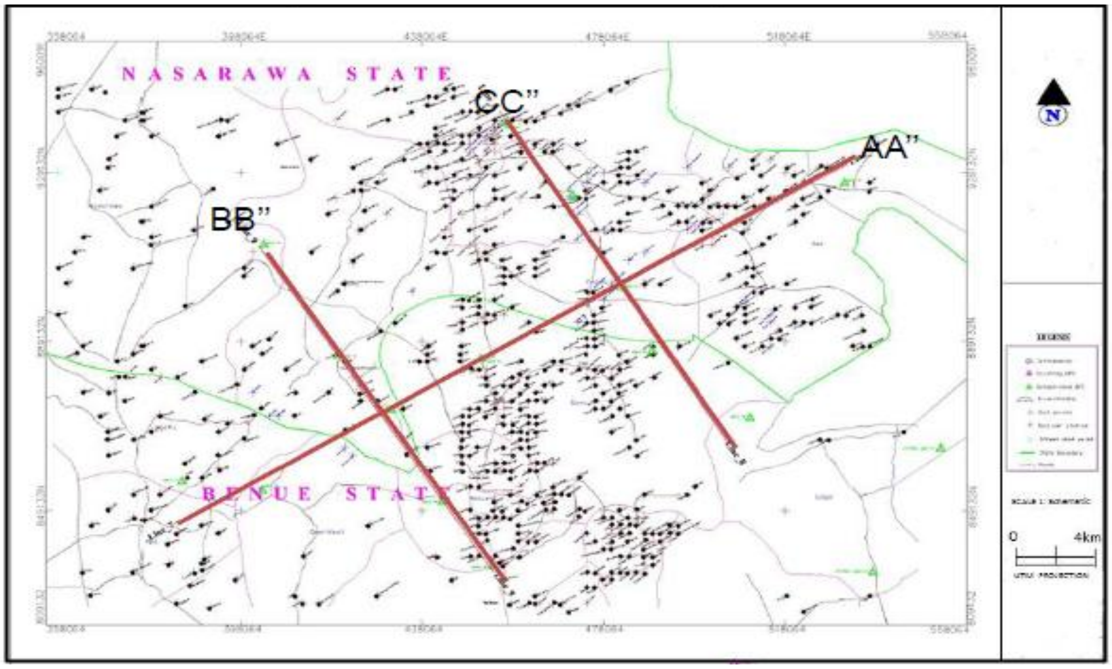


Figure 4: Location Map showing the Survey Lines

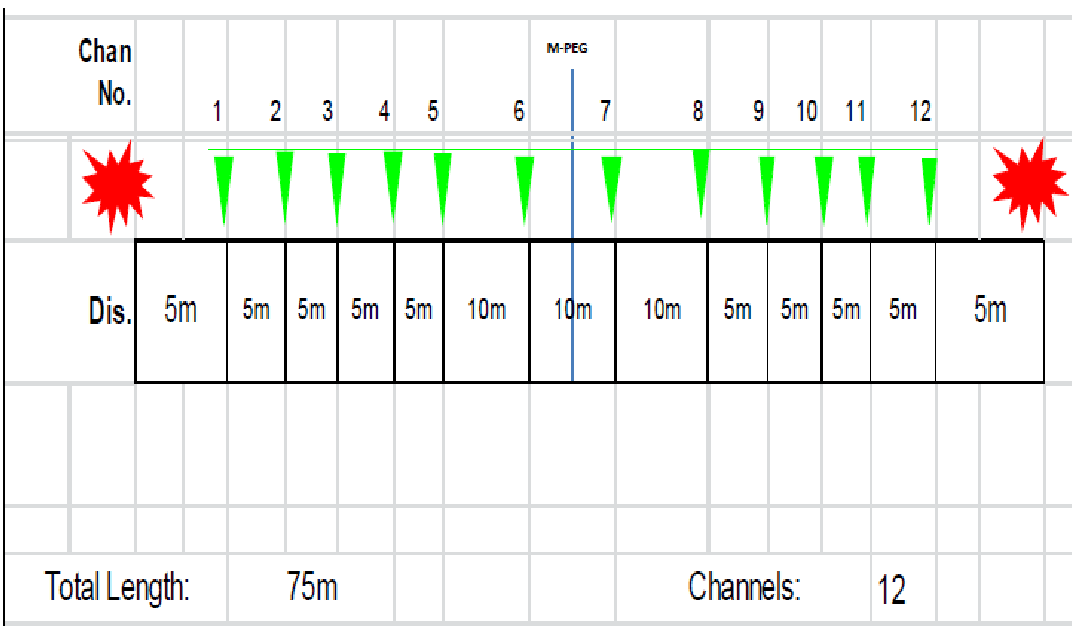


Figure 5: Source-Detector Array Spread

A radio-controlled firing device was used. At the McSeis recorder, the "fire" control consisted of a fire command encoder and a time-break modulator which was used to detect the exact moment of energy release. At the shot point, the Shooting Unit consisted of fire command decoder, a time-break modulator and a Blaster. The later was used to detonate the dynamite and through transformer coupling, generated an electrical impulse at the exact moment of detonation enabling modulation of the radio carrier by a "time zero". The start of the time zero, signal was detected by the McSeis Recorder.

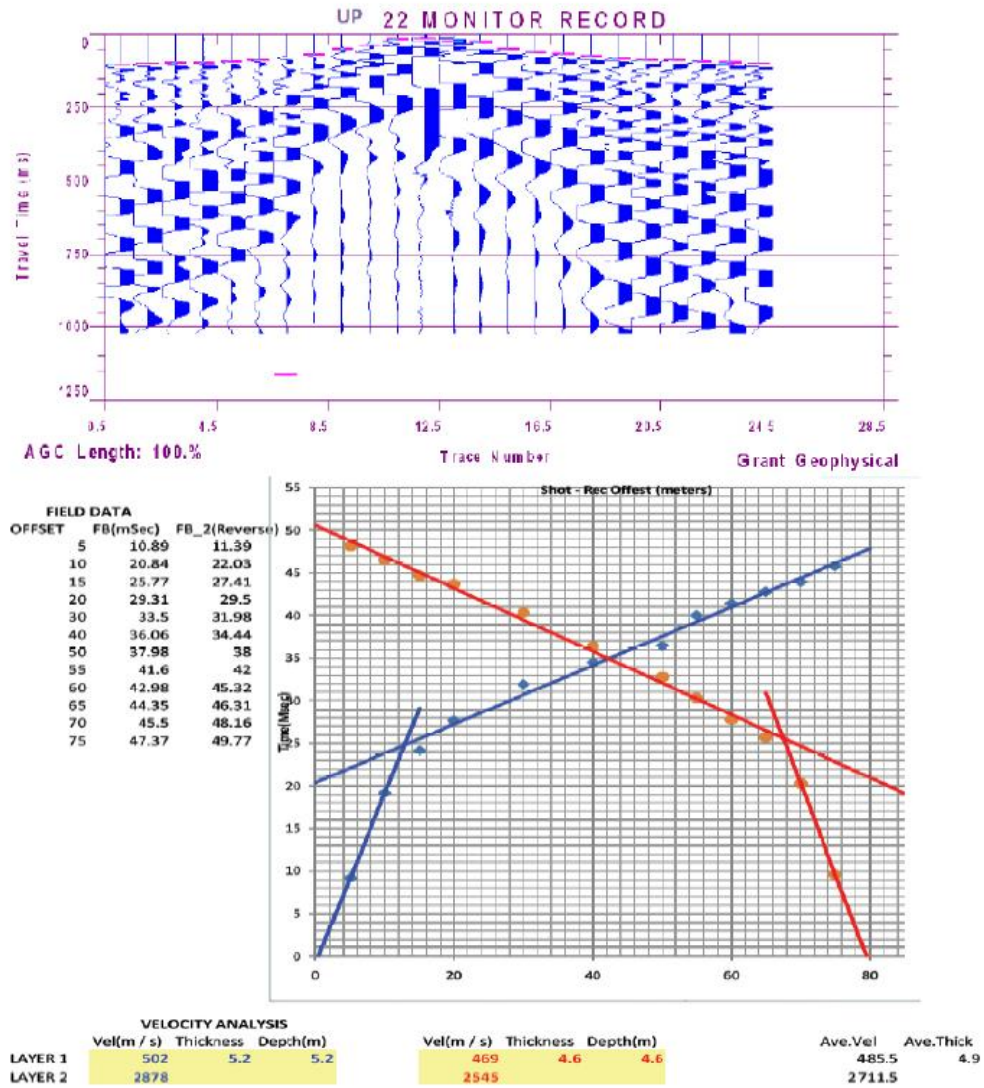


Figure 6: Seismic Monitor Record and T-X Crossplot for Station UP22 example

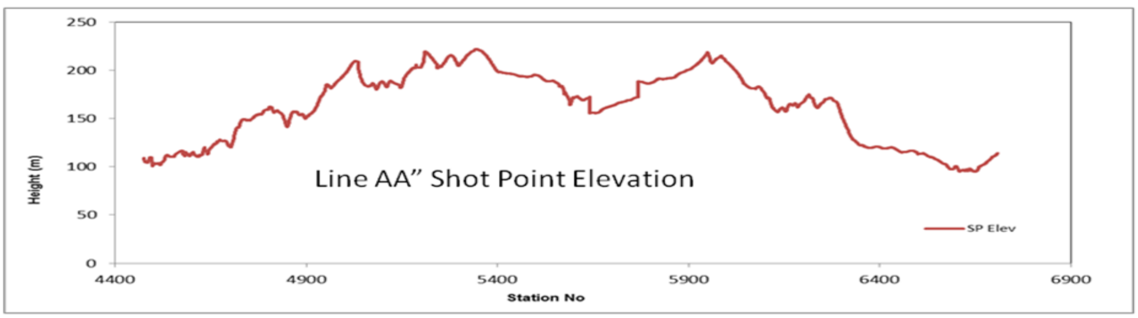
V. Results

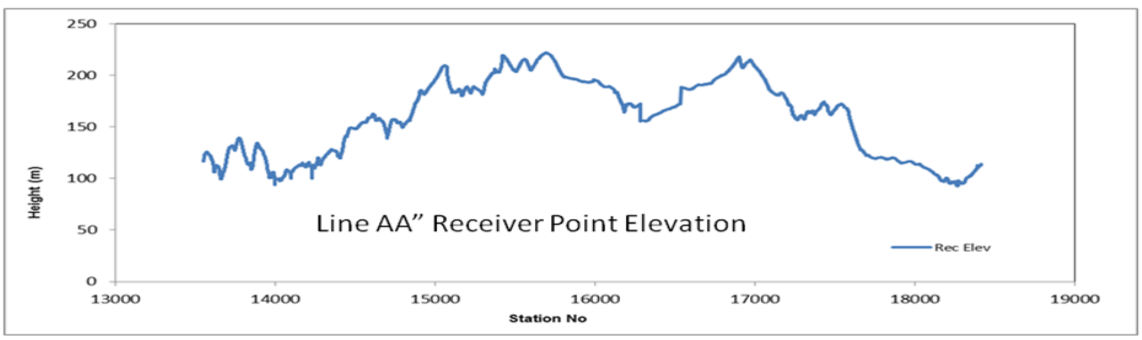
The results of the work are presented in Table 1 and Figures 7 and 8.

Table 1: Results of LVL parameters of the Study Area

SN	Line No.	LVL No.	Station No.	Weathered Layer Velocity, V_o (m/s)	Consolidated Layer Velocity, V_1 (m/s)	Weathered Thickness, D_w (m)	Easting	Northing	Elevation (m)
1	AA"	22	4552	485	2711	4.9	475708.0	898956.0	110.0
2	"	23	4719	901	3069	3.2	475230.0	899100.0	147.0
3	"	24	4901	871	3172	3.8	484789.0	904169.0	152.0
4	"	25	5053	892	2550	4.5	488789.0	906534.0	184.0
5	"	26	5220	843	2386	4.6	493089.0	908931.0	218.0
6	"	27	5387	815	2571	6.1	497434.0	911426.0	205.0
7	"	28	5554	548	4240	4.6	501820.0	913986.0	180.0
8	"	29	5721	717	2354	4.9	506123.0	916416.0	184.0
9	"	30	5888	861	1851	3.1	510469.0	918911.0	198.0
10	"	31	6055	753	2471	3.8	514814.0	921814.0	183.0
11	"	32	6222	501	3183	4.6	519028.0	923825.0	172.0
12	"	33	6389	944	3223	3.3	523503.0	926393.0	120.0

13	BB"	34	6556	399	3257	5.4	527847.0	928888.0	105.0
14	"	35	1045	756	1406	2.8	402958.0	910372.0	115.0
15	"	36	1211	494	1212	4.6	406753.0	906214.0	106.0
16	"	37	1379	520	1211	4.9	408547.0	902056.0	114.0
17	"	38	1546	592	1601	4.9	411342.0	897898.0	169.0
18	"	39	1713	686	1744	4.2	414137.0	893740.0	124.0
19	"	40	1880	519	1955	5.0	416932.0	889582.0	129.0
20	"	41	2041	700	2182	3.4	419625.0	885573.0	110.0
21	"	42	2214	642	1381	3.4	422520.0	881266.0	133.0
22	"	43	2318	767	1754	3.1	425316.0	877107.0	78.0
23	"	44	2539	721	1621	2.9	427960.0	873173.0	64.0
24	"	45	2715	595	1626	4.4	430905.0	878791.0	63.0
25	"	46	2882	573	1650	4.4	433700.0	864633.0	74.0
26	"	47	3049	500	2007	3.9	436495.0	860475.0	63.0
27	CC"	53	1042	538	1367	3.2	455440.0	942502.0	228.0
28	"	54	1212	473	1210	3.0	458594.0	938210.0	199.0
29	"	55	1379	899	1880	2.9	461518.0	934140.0	210.0
30	"	56	1546	566	2622	6.5	464005.0	929777.0	200.0
31	"	57	1713	408	1808	4.9	466711.0	925560.0	194.0
32	"	58	1880	475	2029	5.5	468650.0	922537.0	168.0
33	"	59	2040	797	1655	6.4	422006.0	917304.0	135.0
34	"	60	2114	530	1753	4.7	473207.0	915435.0	195.0
35	"	61	2381	711	2150	5.7	477402.0	908895.0	176.0
36	"	62	2548	483	2791	5.9	480237.0	904476.0	113.0
37	"	63	2615	660	2670	4.7	481323.0	902785.0	146.0
38	"	64	2782	867	2994	3.8	48835.0	897312.0	198.0
39	"	65	2955	704	3029	4.9	486831.0	894199.0	130.0
Average				**659.13**	**2214.00**	**4.38**			**148.51**





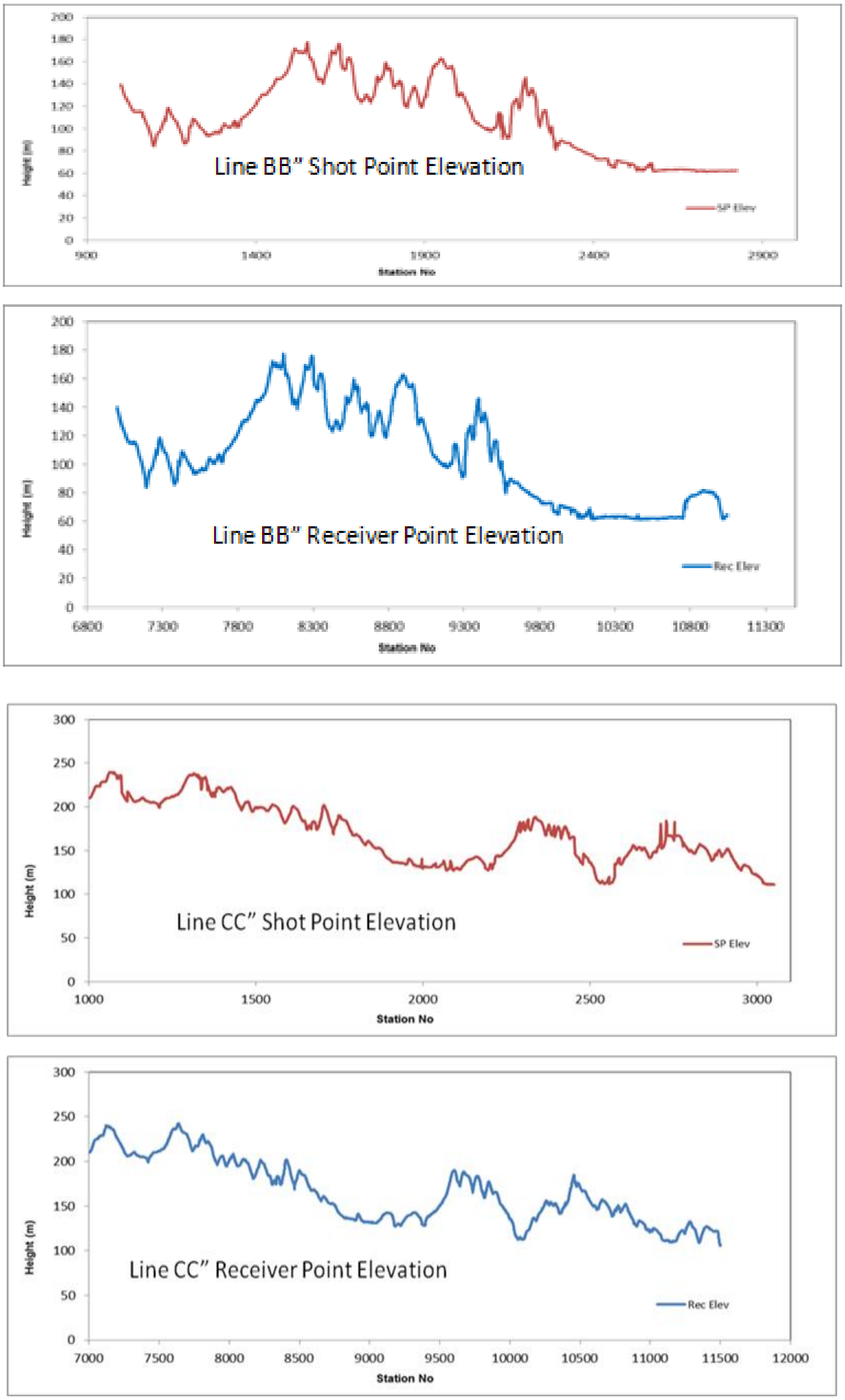
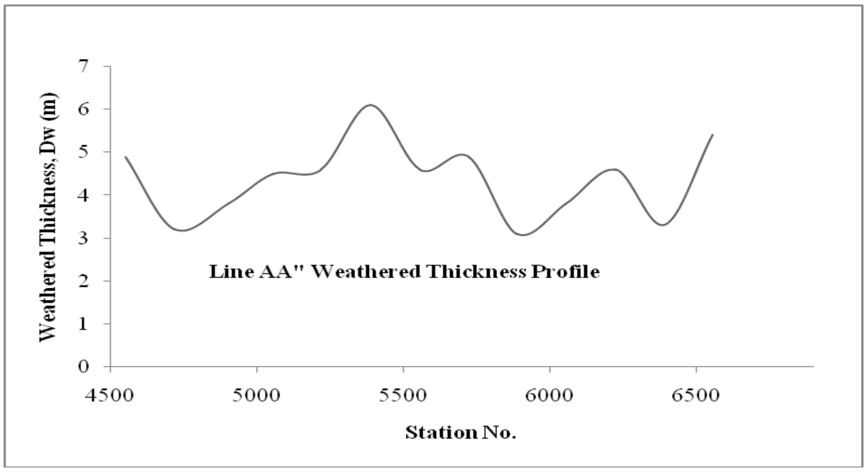
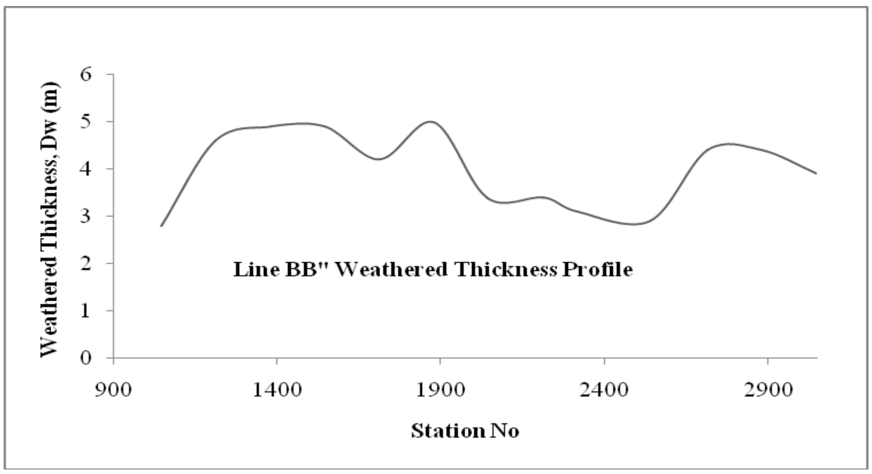


Figure 7: Topographic (Elevation) Profile along Survey Lines





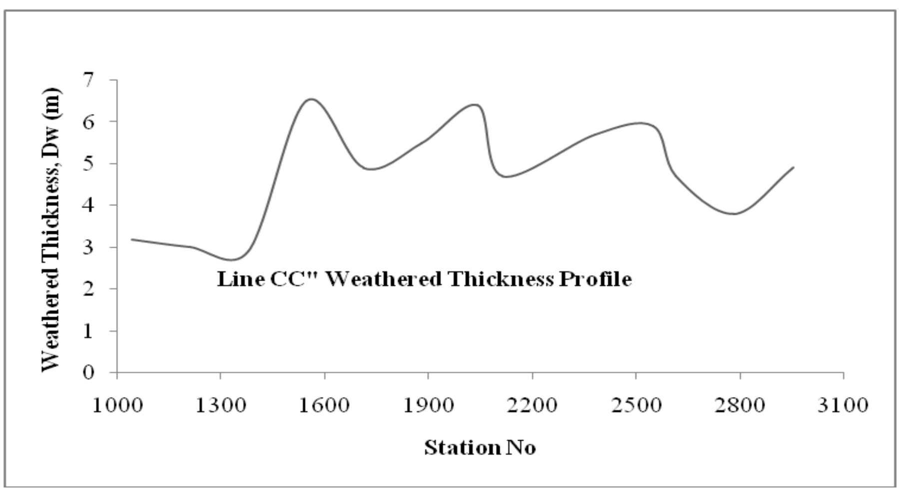


Figure 8: Weathered Thickness Profile along Survey Lines

VI. Discussion

Depth of refractor is observed to be highly variable with no trend. This indicates the necessity to correct for this layer when conducting reflection seismic survey in the area. The weathered thickness varies between 2.80 and 6.5m with average of 4.38m.

In estimating this thickness, we assumed that seismic velocity is uniform in each layer, layer velocities increase in depth, and that the layers are horizontal. The principle of reciprocity criteria [24] that states that the time required for seismic energy to travel between two points, that it will require the same time T if the source and detector are interchanged. These requirements were not satisfied by our data (See Figure 6). Travel times were not equal in forward and reverse directions for source/receiver positions.

From our computation of the thicknesses, and velocities forward and reverse directions, the differences were not much, we find that these assumptions were not badly violated. Velocity was observed to generally increase with depth, from surface to the refractor and into the consolidated layer continuum, at each location.

Weathered thickness and elevation were highly variable resulting from both surface- and surface-topographic undulations as seen in Figures 7 and 8. Weathered thickness does not show any trending with elevation for the same reason of undulations of the study area. The spatially-averaged velocities and depths estimated by this surface-detector method are very reliable for the site-specific characterization.

VII.Conclusion

Based on the results gotten, the following conclusions are reached:

(i) The velocity of the Low-Velocity Layer, V_o, varies between 399 and 944ms^{-1} with average of 659.13 ms^{-1}.
(ii) The velocity of the underlying Consolidated Layer, V_1, varies between 1210 and 4240ms^{-1} with average of 2214.00 ms^{-1}.
(iii) Velocity appears greater when shooting up-dip, while velocity is reduced when shooting down-dip.
(iv) The boundary between the subsurface layers was not parallel but highly undulating as depicted from the highly variable thickness of the refractor, Z, which varies between 2.80 and 6.5m with average of 4.38m.
(v) Elevation is highly variable. Weathered thickness does not show any trending with elevation for the same reason of undulations of the study area. Elevation varies between 63 and 228m with average of 148.51m.

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