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Seismic Imaging for Geothermal Exploration: A Case Study from Dholera, India

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Abstract: An important contribution of geosciences to the renewable energy production portfolio is the exploration and utilization of geothermal resources. Geological and geophysical methods are the two most important branches in geothermal exploration. All geophysical activities are very much contributing to identify geothermal prospect. The geophysical activities like Magnetotelluric, Gravity, Magnetic and Seismic methods are used to delineate geothermal prospect in this paper a case study from Dholera, Gujarat has been taken to find out the prospect of geothermal reservoir in application with the refraction seismic survey. A finite study modelling of seismic wave propagation was conducted to determine the layers of the earth which are consisting zones of geothermal energy. This case study is basically dependent on seismic API survey i.e. Seismic Acquisition, Processing and Interpretation has been conducted here. This seismic survey has been deployed along four profiles in the area identified by previous studies conducted in the area including MT survey. Seismic data are processed to find the shallow subsurface features and tomograms. The tomograms obtained from the seismic survey are integrated with SP and Resistivity well log data, which were carried out in a nearby location offset to the seismic profiles. The integration helped to get a clearer picture of the subsurface.

Keywords: Geological, geophysical, Dholera, Gujarat, Magnetotelluric, Gravity, Magnetic and Seismic imaging.

INTRODUCTION

The major objective of any scientific investigation for a geothermal resource is to locate a potentially mature reservoir which can be economically exploited for power generation and other utilization. The parameters like flow channels, heat sources, reservoir temperature, reservoir pressure and characteristics of fluids are investigated **(Georgsson, 2009)**. To investigate these parameters and identify the geothermal prospect, different geological, geochemical and geophysical techniques have been applied in the geothermal fields. In oil industry where there is enormous financial support, the geothermal industry has lack of capacity to set up large seismic networks and developed techniques for resource evaluation in geothermal areas **(Simiyu, 2009).**The major objective of this paper is to identify shallow as well as deep geothermal prospect in Dholera field using refraction and reflection seismic methods.

The reason for the widespread application of seismic methods in many exploration tasks is that they provide the most detailed structural information at depth. They are standard exploration methods in HC exploration and therefore highly developed in every aspect: data acquisition, logistics, and interpretation **(Liberty, 1998)**. In geothermal exploration, the focus are fluid-filled rock volumes that are not necessarily linked to specific structures but the structural setting itself (e.g., faults, dykes, and graben) and the parameters of possible resource regions as well as underground conditions (e.g., stress, strain, and pore pressures) are also in focus of the investigations **(Lane et al., 2012)**.

Dholera is an ancient port city which is located 30 km from Dhandhuka village of Ahmadabad district and 60 km far from the Bhavnagar main city. It covers an area of about 920 sq. Km. The hot springs of Dholera area are basically located along Saurashtra peninsula margin falls in the region of the west coast lineament and along the west marginal fault of the Cambay Basin **(Sharma, 2013)**. The alluvium and mud flats have covered the terrain in Dholera. At 500- 600m depth Deccan Traps are overlapped by the tertiary sediments of about 100m in thickness and also by the quaternary soils deposited at subsiding side of Cambay basin. Sediments like old mud, flats, flood plains, mud flats and salt flats are also present in this area. The formation of Dholera region mainly consist alternating layers of gravels which are further followed by the fine to coarse grained sand and clay. Hot springs in Dholera are located along the high gravity region which basically indicates the granitic basement and presence of shallow mantle **(Sharma, 2013)**. Amongst all the four hot springs found in the radius of 4km around the Dholera namely, Dholera, Utahan, Swaminarayan temple and Bhadiyad, the Dholera hot spring has the highest flow rate in Gujarat **(Dwijen et al., 2015)**.

Geology-

Geomorphologic ally, the Gujarat state has been divided into three distinct divisions which are as follows:-

(1) Gujarat Mainland
(2) Saurashtra Peninsula
(3) Kutch Peninsula

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The Dholera area basically falls under the Saurashtra Peninsula. The Saurashtra peninsula is one of the three conspicuous physiographic divisions of the Gujarat state and lies between 20° 30′ N to 22° 30′ N. latitude and 69° 00′ E to 72° 30′ E. longitude. The Saurashtra Peninsula is located along the North Western margin of the Indian Shield, occurs as a horst block between the three intersecting rift namely Kutch, Cambay and Narmada **(Biswas, 1987)**.

Geologically, the Saurashtra region contains rocks belonging to the Mesozoic and Cenozoic Era. Stratigraphically the sequence begins with the Juro-Cretaceous sedimentary rocks which are non-conformably overlain by the Upper Cretaceous volcanic igneous rocks followed by the Mio-Pliocene and Quaternary sedimentary sequences. Approximately 5000 sq. km area in the NE of the Saurashtra peninsula is occupied by Upper Jurassic to Middle Cretaceous sedimentary rocks which are divisible into two Formations i.e. Dhrangadhra Formation and Wadhwan Formation.

Dhrangadhra Formation

The rocks constituting the Dhrangadhra Formation are arkosic sandstone, argillaceous sandstone, sandy shale, and clay with occasional coal bands. Sandstone is the dominant rock type of this Formation. The thickness of the Formation has been estimated up to 550m near Dhandhuka where it lies over granite basement. Physical continuity of Wagad and Bhuj sandstone with this Formation has been envisaged by Biswas (1987).

Wadhwan Formation

This Formation can be divided into three members i.e. Surendranagar Limestone Member, Navania Limestone Member and Badhuka Limestone Member in ascending order. They correlated these with Nimar Sandstone, Nodular limestone and Coralline limestone respectively of Bagh beds of lower Narmada valley. However, Biswas (1987) has explained them by correlating them with Bhuj sandstone based on his study.

Deccan Trap Formation

Most of the Saurashtra peninsula is covered with rocks of the Deccan Trap Formation. These rocks constitute elevated tableland with an uneven topography forming flat topped hills with black cotton soil cover. The bulk of the Formation is made up of succession of lava flows dominantly tholeiitic basalt. Common rock type encountered is fine to medium grained grayish black basalt with its variations **(Merh, 1995)**.

Saurashtra Peninsula	
Rock/Sediment Type	**Age**
Coastal sediments, Alluvium, Marine to Fluvio- marine and Aeolian rocks, Miliolite Marine and Fluvio- marine rocks	Quaternary Upper Tertiary (Neogene)
--------------------Unconformity-------------	
Laterites Deccan flow basalts (associated differentiates Including alkaline intrusive rocks Laterite)	Palaeocene Upper Cretaceous to Lower Eocene
--------------------Unconformity------------	
Marine and Fluvio-marine sediments (Surendranagar and Wadhwan Formations)	Upper Jurassic to Lower Cretaceous
--------------------Unconformity------------	
Subsurface Crystalline basement of Granites	Precambrian (Proterozoic)

Table 1: Generalized stratigraphy of Saurashtra peninsula exhibiting the chrono- stratigraphic markers (**Modified after Sircaret. al., 2015**)

Seismic Survey-

To understand the subsurface formation seismic survey is basically done in the field of mining, hydrocarbon exploration, ground water exploration etc. **(Ocheing, 2013)**. In this survey acoustic echoes are recorded from the sedimentary layers beneath the earth surface. This survey is basically done to know the thickness of the beds, various layers of the beds and to understand the geology of the subsurface. The seismic survey is done along several gridlines of sensitive receivers which are known as "Geophones". Source for this survey here is developed by the explosion or vibration created by dynamite explosion, hammering on steel plate or by vibrosis at the "shot points" on the surface. The dynamite explosion and

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mechanical vibrosis process are traditional methods which are used for source generation.

Seismic methods are widely applied to exploration problems involving the detection and mapping of subsurface boundaries of, normally, simple geometry. They also identify significant physical properties of each subsurface unit. The methods are particularly well suited to the mapping of layered sedimentary sequences and are therefore widely used in the search for oil and gas. The methods are also used, on a smaller scale, for the mapping of near-surface sediment layers, the location of the water table and, in an engineering context, site investigation of foundation conditions including the determination of depth of bedrock.

Geomaterial	**V_p (km/s)**
Soils	
Sand and fine grained top soil	0.2 – 1.0
Alluvium	0.5 – 2.0
Compacted clays	1.0 – 2.5
Rocks	
Sandstone	1.5 – 5.0
Slate and Shale	2.5 – 5.5
Granite	4.0 – 6.0

Table 2- The p-wave velocity for different types of formation.
(https://pangea.stanford.edu/courses/gp262/notes/8.seismicvelocity.pdf.)

The predominance of seismic method over other methods is due to various factors, important to note are high accuracy, high resolution, great penetration of which the method is capable. After the source is generated basically three types of phenomenon takes place beneath the subsurface which are Reflection, Refraction and Deflection. In seismic survey only the Reflection and Refraction phenomenon are considered **(Shah et al., 2015)**.

Seismic Refraction	Seismic Reflection
Fewer source and receiver locations and are thus relatively cheap to acquire.	Many sources and receiver locations and can be expensive to acquire.
Because such a small portion of the recorded ground motion is used, developing models and interpretations is not much difficult.	Because of the overwhelming amount of data collected, interpretations of the reflection seismic observations require more sophistication and knowledge of the process.
Refraction seismic observations require relatively large source receiver offsets.	Reflection seismic observations are collected at small source- receiver offsets.
Refraction seismic observations are generally interpreted in terms of layers. These layers can have dip and topography.	Reflection Seismic observations can be more readily interpreted in terms of complex geology.
Refraction seismic observations only use the arrival time of the initial ground motion at different distances from the source.	Reflection seismic observations use the entire reflected wave field (i.e. the time- history at different distances between the source and the receiver)
Refraction seismic only works if the speed at which motions propagate through the earth increases with depth.	Reflection seismic method can work no matter how the speed at which motions propagate through the earth varies with depth.

Table 3: Comparison between Seismic refraction and reflection method (**Chaubey, 2010**)

Seismic method can be dealt in three different phases, and it is also known as API survey:
1. Acquisition
2. Processing
3. Interpretation

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Data Acquisition

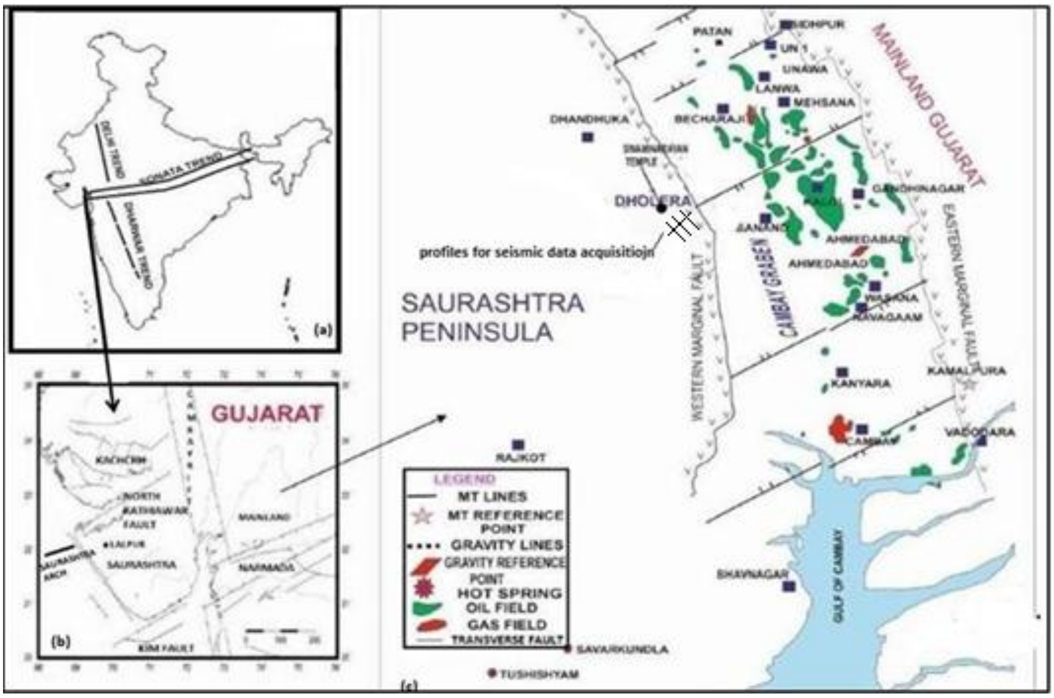

Fig1. Geological Map of Study Area (Dholera) indicating the seismic profiles along which the data has been acquired (Modified after Sircar et al., 2015)

The seismic refraction survey was carried out at Dholera for understanding the subsurface topography. The refraction survey was conducted along four profile lines, three profiles parallel to each other and the fourth one perpendicular to the other three. Inline shooting is carried out at all four profiles. The receivers used for the seismic survey are 28Hz Geophones. 24 Geophones are used for survey along profile – 1, 2 and 3, twelve on both sides of the seismograph. For survey along profile- 4, 12 Geophones are used, six on both sides of seismograph. 2 m interval is taken between geophones in all the four profiles. Seismic waves are produced by striking a 12kg hammer on a metal plate, thus serving as the source of seismic energy. The geophone array arrangement for each profile is shown below.

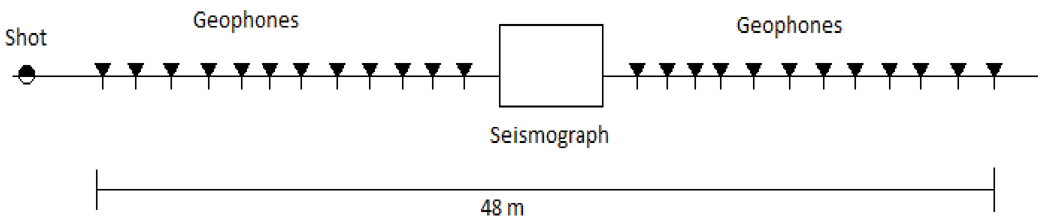

Figure 2: Geophone array arrangement for Profile – 1, 2 and 3

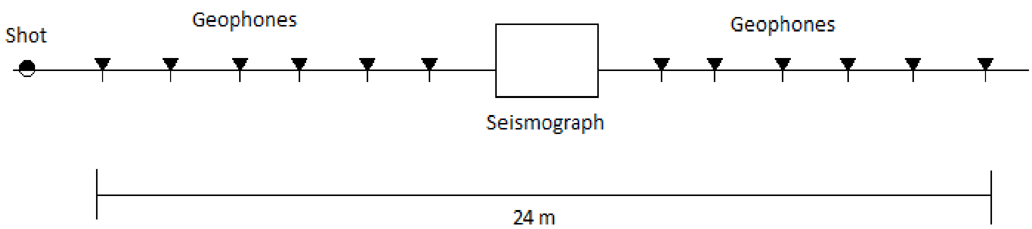

Figure 3: Geophone array arrangement for Profile – 4

Along each profile length 14 shots were taken, seven in forward direction and seven in reverse direction. Different shooting methods used are far offset shooting, end on shooting, symmetric split shooting and asymmetric split shooting. Stacking of data is applied for better results. The seven shots taken in the forward direction of Profile 1, 2 and 3 are shown below. On the reverse direction the same shot pattern will be repeated in the reverse direction.

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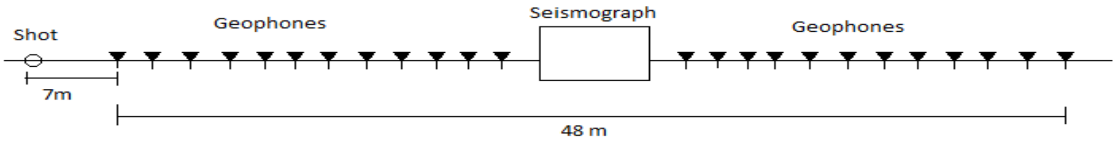

Figure 4: Shot 1

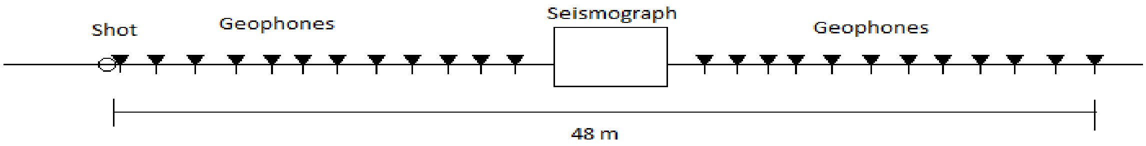

Figure 5: Shot 2

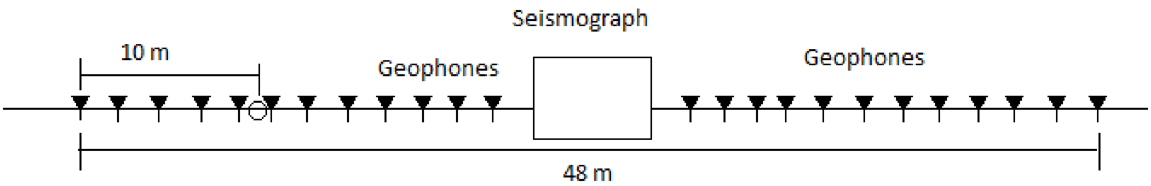

Figure 6: Shot 3

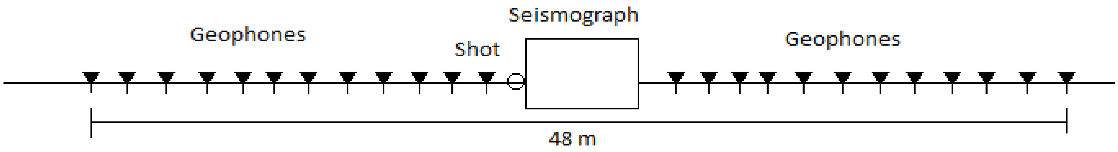

Figure 7: Shot 4

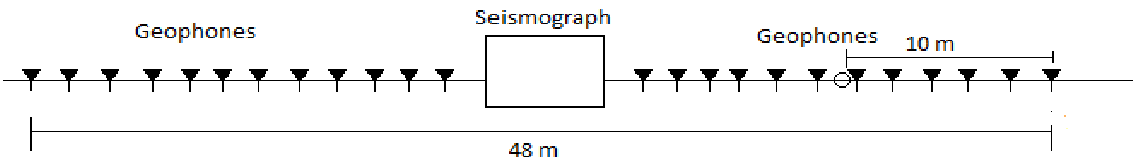

Figure 8: Shot 5

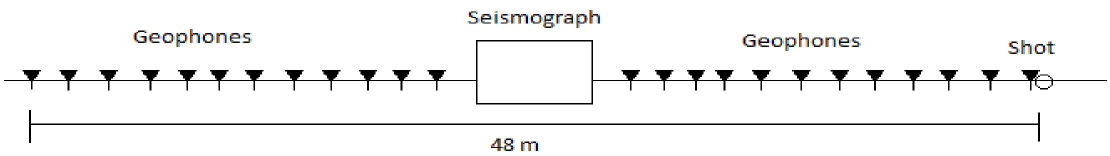

Figure 9: Shot 6

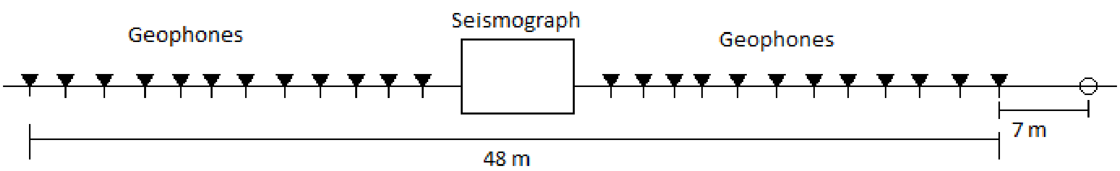

Figure 10: Shot 7

The recording instrument, seismograph is connected to the geophones through channels. The seismograph records the arrival time of the seismic waves at geophones and produces seismogram, which is used to produce travel time graph.

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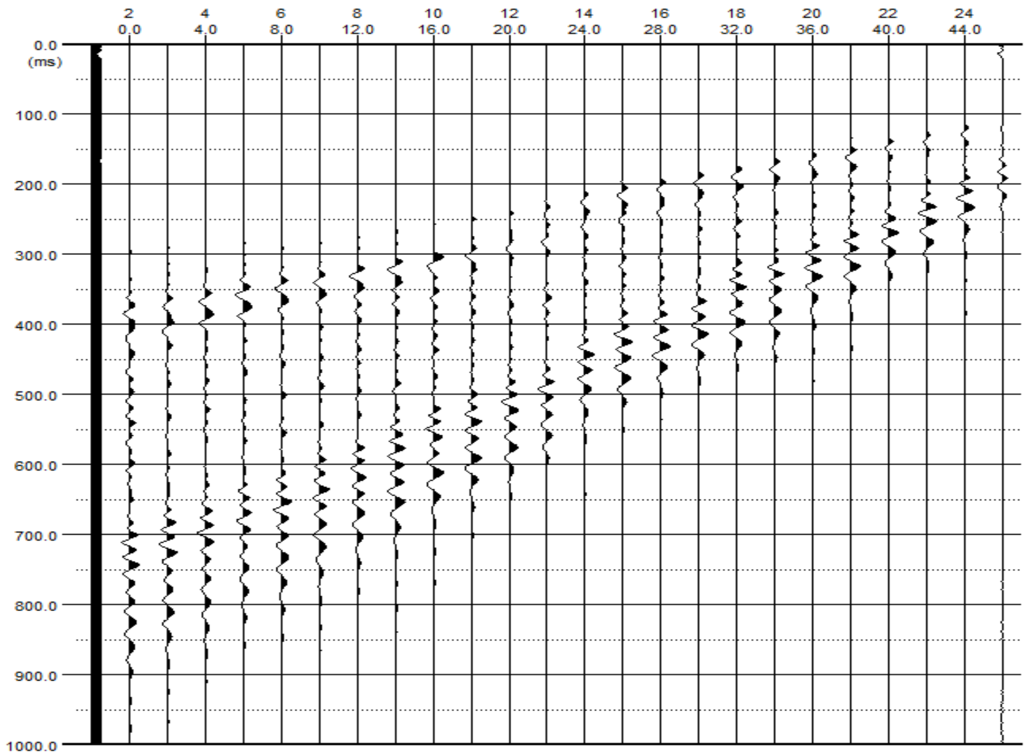

Figure 11: Example of seismogram

Data Processing

The refraction method consists of measuring travel time of compressional waves generated by an impulsive energy source (**Redpath. 1973**). The Snell's Law and the phenomenon of critical incidence is the fundamental physics behind the seismic refraction method. The seismic waves or pulses propagate through the subsurface in a similar way as the light waves propagate through transparent medium. When seismic waves travel from one medium to another they get refracted or reflected back based on the ratio of velocity of transmission between the two mediums. During the seismic refraction survey in addition to the refracted waves there will be also surface waves generated. This wave that travels directly from source to a receiver is called direct wave. (**A. A. Bery., 2013**). Direct wave reaches faster than the refracted waves. The Figure: 2 show the travel path of refracted and direct waves along with the travel time graph. Travel time graph depicts the first arrival time of the seismic waves at each geophones along with distance.

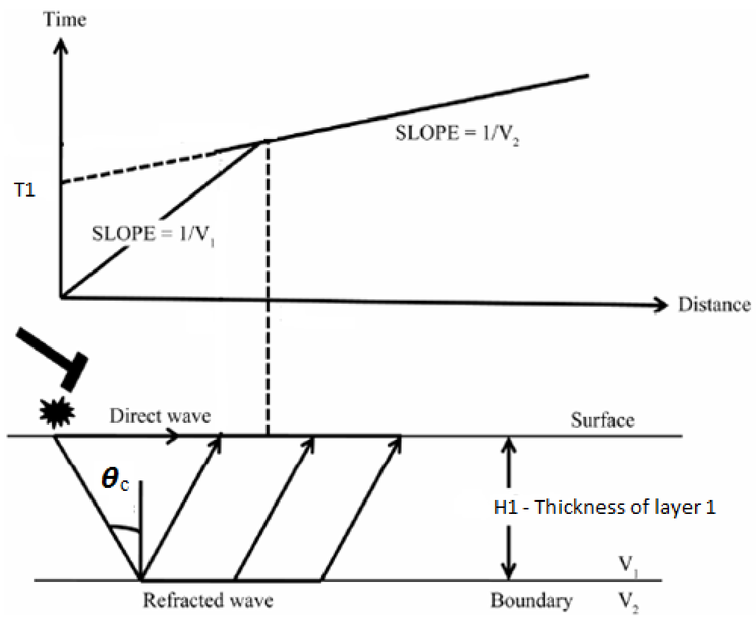

Figure 12: A schematic diagram of seismic waves generated during refraction survey and travel time curve. (**A. A. Bery., 2013**)

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The following steps have been followed during the field operation and interpretation:

1. Seismograph records are obtained in .dat format, with records of the time the sound source is initiated and the time of the ground movement as the waves arrive at each geophone. In seismic refraction work, only the first arrival of energy at the geophone (the compressional sound wave) is utilized. Upon completion of data acquisition in the field, the interpretation phase is begun.

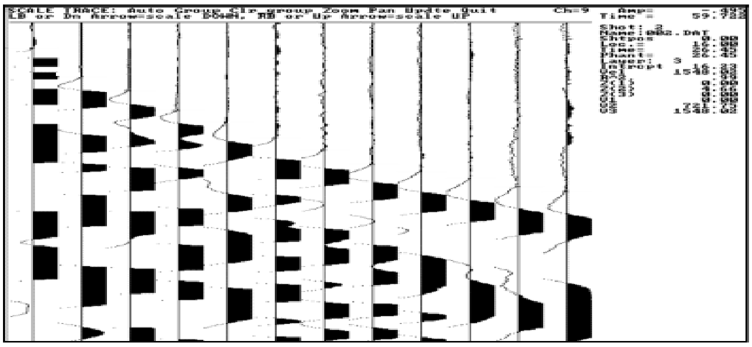

Figure 13: Shorter Segments from 12 Geophone

2. The first step in interpretation is to stack all the receiver data for a particular shot point. The resulting data so obtained is then used for picking first arrival times.

3. Then, the time from initiation of the sound source to the first arrival of energy is determined, for each geophone. When there is sufficient energy in the sound source, and ambient noise is minimal, the first breaks are sharp and this procedure is straightforward. When ambient noise exists (such as operation of heavy equipment or highway traffic) and/or mechanical sound sources are used, picking first-arrival times can become difficult.

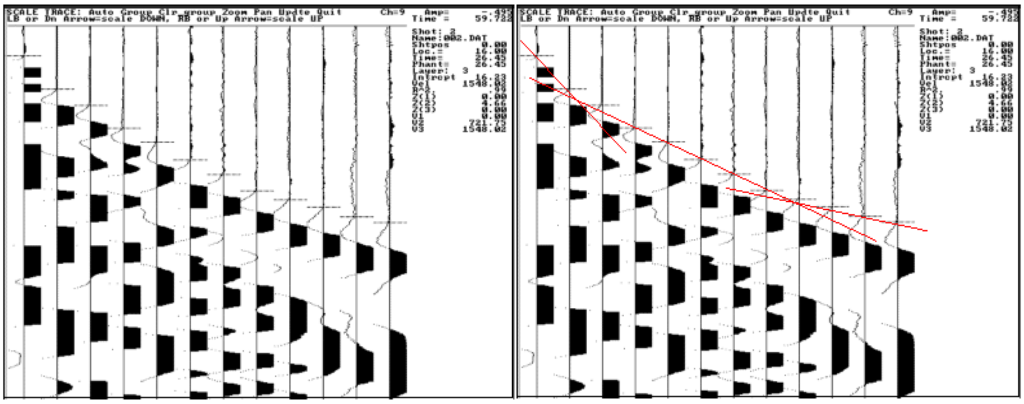

Figure 14- Shows first arrival time picking for different traces. (b) Showing straight line segment formed by joining and interpolating first arrival time for different traces.

4. The signal amplitudes were amplified, so all ground motions were visible. There are clear beginnings of ground motion for each trace, which appear later in time for traces farther from the source. As expected, ground motion occurs earlier at geophones closest to the source. For geophones it seems as if there was no ground motion at later times, however this is an artifact of the "gain" (amplification) applied to these traces. Gain is lower for geophone signals near the source because signal amplitudes are larger.

Calculation of Velocity and thickness of the layers

The velocity and thickness of the layers are calculated from the travel time graph. The number of layers resolved will be equal to the number of trends in the graph. If the graph has only a single trend then there will only a single layer. Velocity of propagation of seismic wave through the layer is calculated by taking the reciprocal of the slope of travel time distance curve. Thickness of the layer cannot be calculated as the boundary of the layer lies beyond our depth of investigation. If the travel time curve shows two trends then there will be two layers. The thickness of the first layer is calculated from the y intercept T_1. T_1 corresponds to the time taken by the direct wave to reach the first geophone. T_1 can be calculated using simple trigonometric relations and Snell's Law.

$T_1 = \frac{2h \times \cos\theta c}{v1}$, where 'h' is the thickness of Layer 1 --------------------- Equation (1)

The thickness of layer 2 in a 2 layered structure cannot be calculated, since the boundary between the second layer and next consecutive layer is beyond our depth of investigation. Similarly in a three layered structure we cannot find the thickness of 3^{rd} layer.

Thickness of Layer 1 is calculated from the equation;

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$$h_1 = \frac{T_1 V_1}{2\cos(\sin^{-1}\frac{V_1}{V_2})}$$ ------------ Equation (2)

In case of three layer structure the Travel time – distance graph will show three trends of separate slopes. The velocity of the layers will be found by taking the reciprocal of slope of distance travel time curve. The thickness of the first Layer, h_1 will be found by the same equation used for two layer structure.

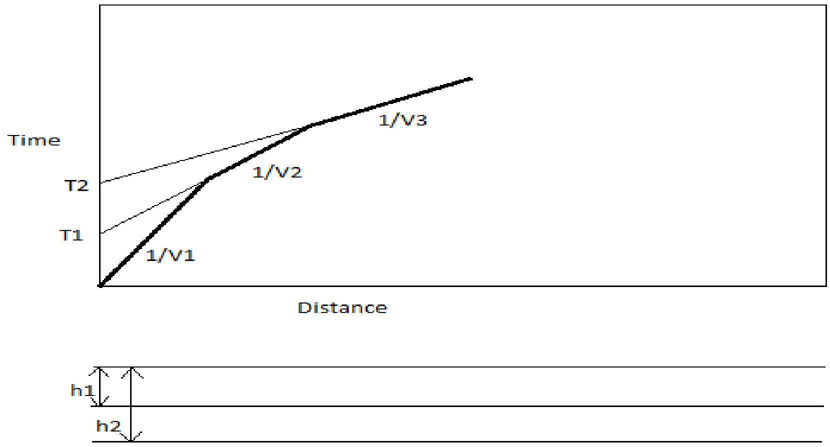

Figure 15: Travel time graph for a three layer structure

The depth of layer 2 is calculated by the following equation.

$$h_2 = \frac{\left[T_{i3} - T_{i2}\frac{\cos(\sin^{-1}V_1/V_3)}{\cos(\sin^{-1}V_1/V_2)}\right]V_2}{2\cos(\sin^{-1}V_2/V_3)} + h_1$$ ------------------------ Equation (3)

Refraction Seismic survey at Dholera

The seismic refraction survey is carried out at Dholera to identify the subsurface characteristics and topography. Four profiles are taken, three profiles parallel and one profile perpendicular to the others. The travel time graphs of the four profiles are given below. From the Distance travel time plot a three layer structure subsurface is identified in the first three profiles. In the fourth profile only two layers are identified since the depth of investigation was less compared to the other three profiles. The velocity and the thickness of the layers are tabulated below.

Profiles	Velocity of Seismic waves			Thickness of Layers		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
Profile 1	75.69 m/s	107.15 m/s	129.97 m/s	4.182 m	6.617 m	Infinity
Profile 2	82.85 m/s	116 m/s	138.18 m/s	4. 156 m	5.694 m	Infinity
Profile 3	83.85 m/s	116.83 m/s	139.75 m/s	4.04 m	7.29 m	Infinity
Profile 4	77.69 m/s	106.04 m/s	-	3.558 m	Infinity	-

Table 4: Velocity and thickness of different layers

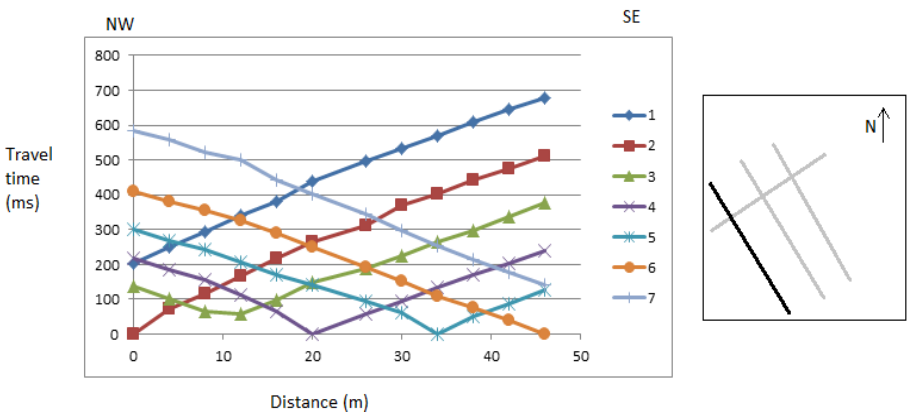

Figure 16: Travel time curve – Profile 1

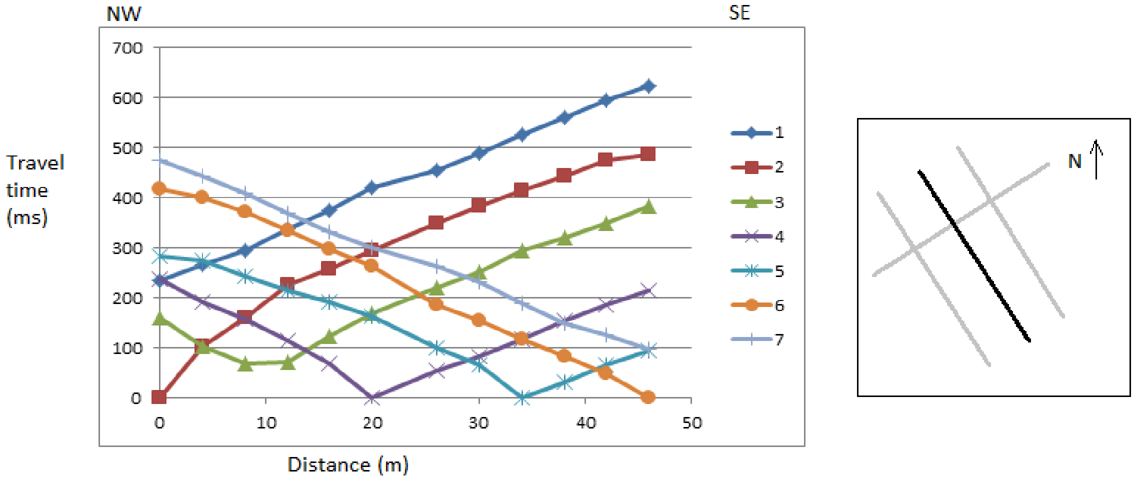

Figure 17: Travel time graph –Profile 2

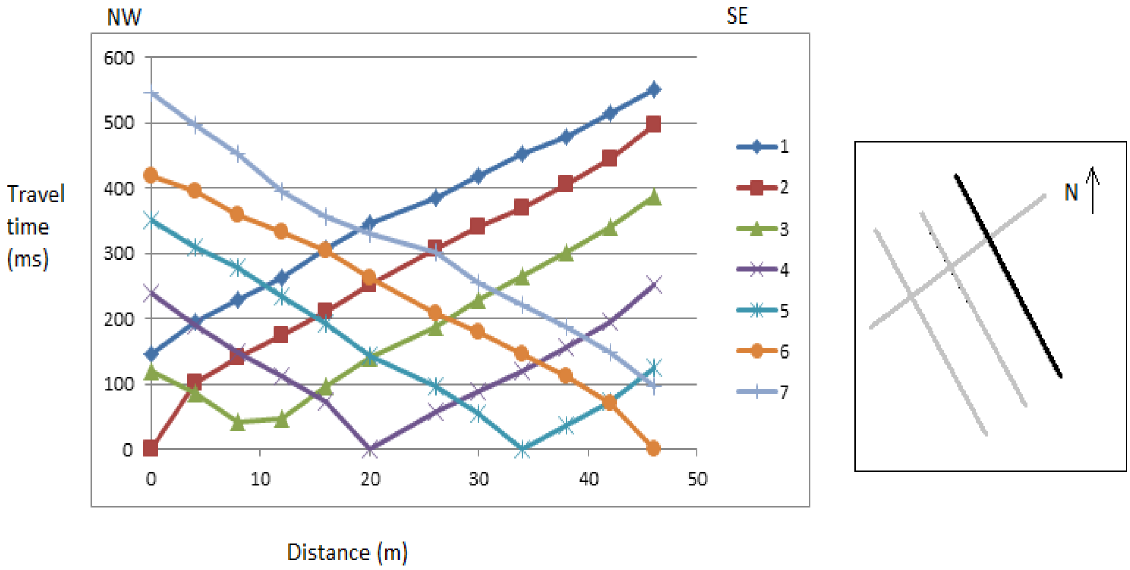

Figure 18: Travel time graph – Profile 3

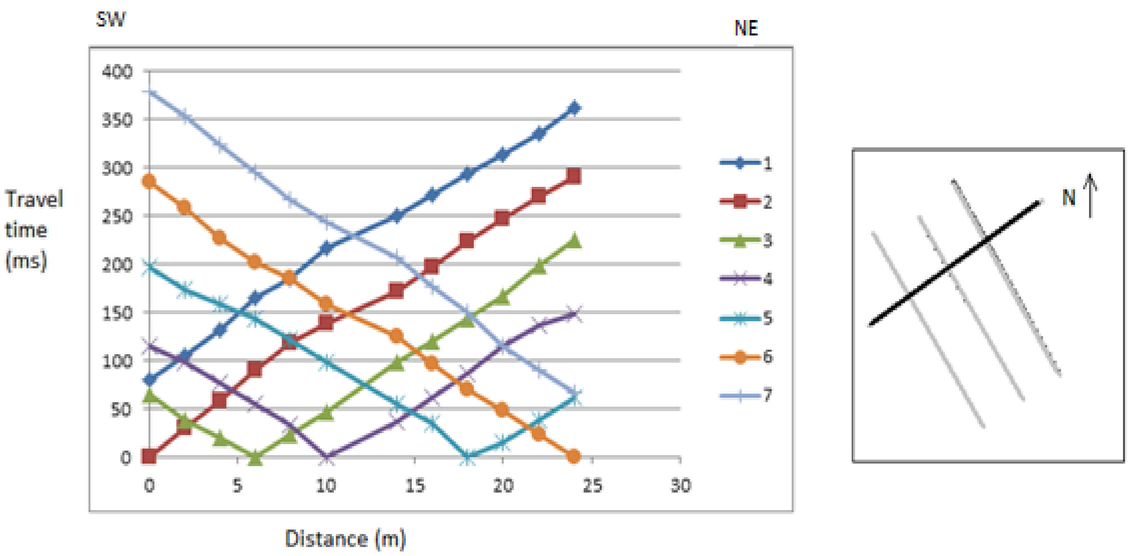

Figure 19: Travel time graph – Profile 4

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The depth of investigation is proportional to the spread of geophone. As of now, the seismic data acquired results into a three layered system. It should be noted that the third layer could extend till infinity. Now, the densities of these layers were found using the Gardner's equation. The average densities of each layer can be tabulated as below.

PROFILES	AVERAGE DENSITY g/cc		
	Zone 1	Zone 2	Zone 3
Profile 1	0.678403	0.73999	0.776584
Profile 2	0.693907	0.754818	0.788568
Profile 3	0.695991	0.756165	0.790798
Profile 4	0.68284	0.738066	-

Table 5: Average Density of Layers Interpreted by Seismic.

These densities are then used while integrating the subsurface model and also to understand the lithology present at different depth.

Tomography Results

Tomography of the subsurface is found out by calculating the velocity and thickness at each shot points. Seven shots are carried out at each profile. The tomography maps produced for each profile are shown below.

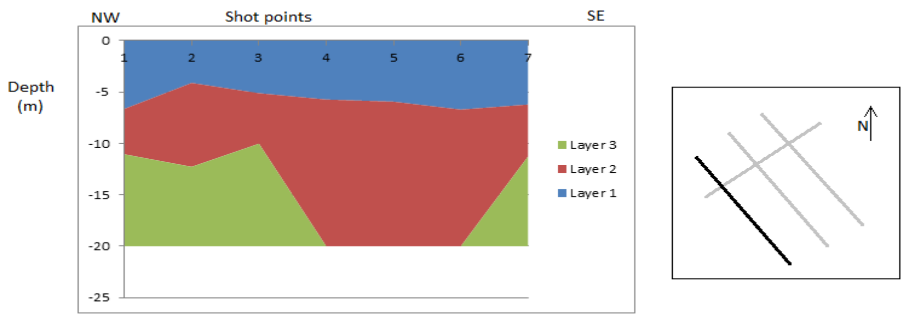

Figure 20: Topography map – Profile 1

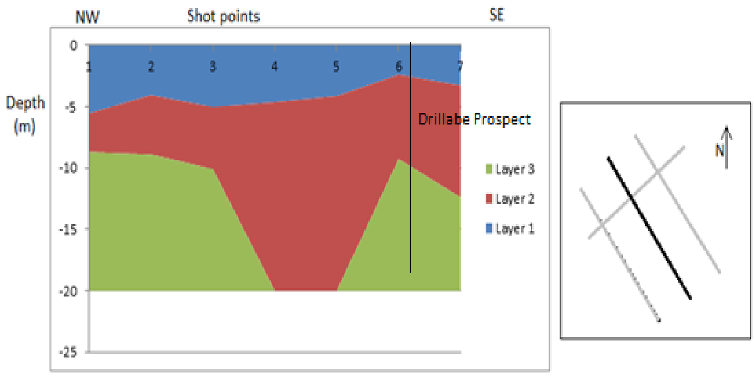

Figure 21: Topography map – Profile 2

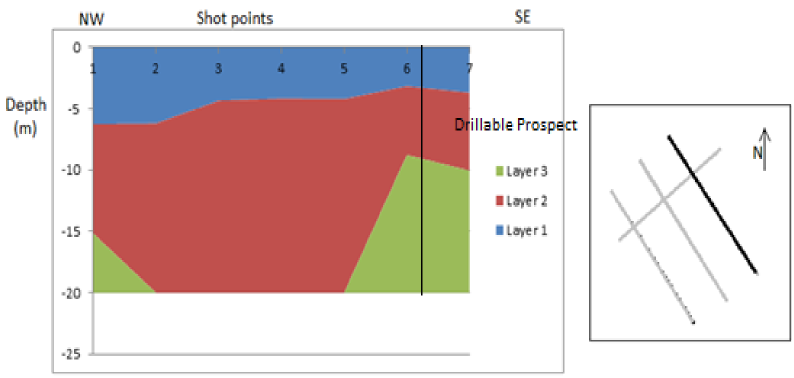

Figure 22: Topography map – Profile 3

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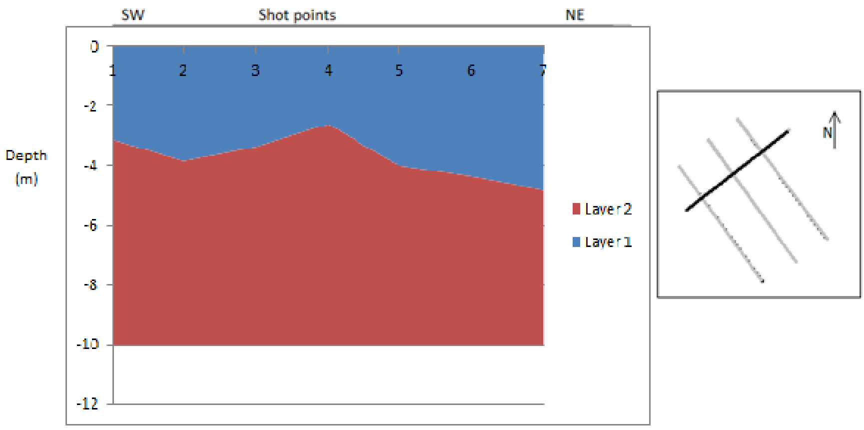

Figure 23: Topography map – Profile 4

Interpretation

A three layer structure subsurface is identified under the area covered by the seismic survey. Profile – 1, 2 and 3 shows a three layer structure, while only two layers are identified in profile – 4. One reason for this is the length of geophone array taken for profile – 4 is only half of the other profiles, making its depth of investigation almost half compared to others. This can be a reason why profile – 4 couldn’t detect the boundary between layer two and three.

From the seismic refraction survey the average thickness of layer one and two is identified to be 3.984 meters and 6.533 meters respectively. In a three layer structure the thickness of third layer cannot be identified.

The average velocities of layer one, two and three are 80.02m/sec, 111.505m/sec and 135.97m/sec respectively. The velocity range shows that the underlined subsurface is unsaturated sand. All the three layers are identified as unsaturated sand. The densities of the three layers are in the increasing order with respect to depth. This can be due to compaction. Till 20 meters no layer of clay is identified by the seismic refraction survey. Antiform structure is identified in SE direction of both second and third profile. The structure has SW- NE orientation in the subsurface. The seismic data will also be integrated with other exploration methods for better understanding and confidence.

Integration of log data with seismic data

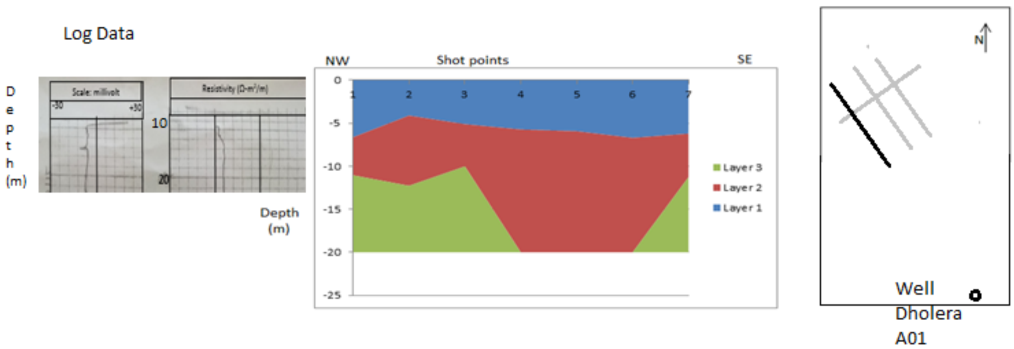

Figure 24: Comparison of Log data with seismic data

The tomography obtained from the seismic data is matched with the Log data of well Dholera A01. The log data shows the reading from 8m to 22m. Even though seismic survey is carried out at off -set of the well, layer boundary at 9m depth is identified at both data. The third layer identified by the seismic is extended till the well. The log data at the zone from 9m to 22m shows a deflection to the left, showing the presence of sand. From the density and velocity of this layer determined from seismic data also shows this layer as loose sand or alluvial deposit. The log data identifies a clay layer from 22m to 25m, shows that the depth of the third layer is 22m. Log data and seismic data prove each other.

CONCLUSION

From the seismic refraction survey a three layer structure subsurface is identified in the shallow region under the seismic survey. All the three zones are identified to be unsaturated sand zones, considering the velocity of propagation of seismic waves. Velocity of propagation increases with consecutive layers with respect to depth, but the difference in velocities between consecutive layers in not much. One reason for this is, there is no significant change in geology between the layers and the velocity increase is due to the increase in density of the consecutive layers. These results are also verified by comparing with

SP and resistivity log data from parametric well Dholera A01. From the well log data it not possible to identify deferent layers in the shallow zone, from 0m to 20m. SP log shows little deflection to left in the region from 0m to 22m. This region is most likely unsaturated sand. So the shallow seismic refraction survey doesn't contradicts the well log data, it also resolves the layered structure of the shallow region which could not be resolved using the well log data.

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