

**INVESTIGATION OF TTI ANISOTROPY OF P-WAVE
VELOCITIES IN SAND DUNES IN EASTERN SAUDI
ARABIA**

BY

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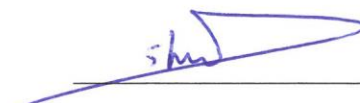
DEANSHIP OF GRADUATE STUDIES

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I dedicate this work to my mother, father, siblings, mentors, and to all who have assisted me in my pursuit for knowledge. |

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First and foremost, all praise be to Allah almighty for blessing me and bestowing upon me the knowledge, drive, and perseverance on my academic journey.

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LIST OF ABBREVIATIONS

P-wave	:	Primary/compressional wave
S-wave	:	Secondary/shear wave
SV, SH wave	:	Vertical and horizontal components of a shear wave
TTI	:	Tilted transverse isotropy
HTI	:	Horizontal transverse isotropy
VTI	:	Vertical transverse isotropy
EM	:	Electromagnetic
DGPS	:	Differential Global Positioning System
GPR	:	Ground Penetrating Radar

|

ABSTRACT

Full Name : Khalid Yassin Makki
Thesis Title : Investigation of TTI Anisotropy of P-Wave Velocities in Sand Dunes in Eastern Saudi Arabia
Major Field : Geophysics
Date of Degree : 11/23

Unconsolidated dune sands pose unique challenges to geoscientists and seismic data, many of which lead to poor seismic images. This can be attributed to their complex topography, internal structure, and high attenuation effects, which are commonly overlooked during data processing. This study aims to investigate the azimuthal anisotropy of P-wave velocity in sand dunes through the design and deployment of a circular seismic array on a barchan sand dune in Eastern Saudi Arabia. The studied sand dune exhibits dipping cross-strata and thus was viewed as a tilted transversely isotropic (TTI) medium.

The acquisition geometry consists of 24 receivers placed on the circumference of a circle spaced at a polar (azimuthal) angle of 15° with a constant offset of 9 m from a source that is placed at the circle's center. The measured velocity data show a sinusoidal behavior with a maximum velocity along an azimuth that is parallel to the slip face (cross-strata) of the dune. The measured velocity-azimuth data is fitted to a TTI model with four known parameters: azimuth ($\varphi = 0^\circ, 15^\circ, \dots, 330^\circ, 345^\circ$), incidence angle ($\theta = 71.33^\circ$), tilt of symmetry axis ($\theta_0 = 30^\circ$), and velocity along symmetry axis ($V_{P0} = 274 \text{ m/s}$), and two unknown Thomsen parameters (ε, δ). The best-fit values for ε and δ are 0.035 and 0.005, respectively, which proves that the studied sand dune has the characteristic of a weakly anisotropic TTI medium.

ملخص الرسالة

الاسم الكامل: خالد يسن مكي

عنوان الرسالة: دراسة تباين TTI لسرعات الموجة P في الكثبان الرملية في شرق المملكة العربية السعودية

التخصص: جيوفيزياء

تاريخ الدرجة العلمية: 11/23

تشكل رمال الكثبان الرملية غير المجمعة تحديات فريدة لعلماء الجيولوجيا والبيانات السيزمية، وكثير منها يؤدي إلى صور زلزالية سيئة. ويمكن أن يعزى ذلك إلى تضاريسها المعقدة، وبنيتها الداخلية، وتأثيرات التوهين العالية، والتي يتم التغاضي عنها عادة أثناء معالجة البيانات. تهدف هذه الدراسة إلى دراسة التباين السمتي لسرعة الموجة P في الكثبان الرملية من خلال تصميم ونشر مصفوفة زلزالية دائرية على الكثبان الرملية في شرق المملكة العربية السعودية. تُظهر الكثبان الرملية المدروسة انحدارًا عبر الطبقات، وبالتالي كان يُنظر إليها على أنها وسط مائل متناحي الخواص (TTI). تتكون هندسة الاستحواذ من 24 جهاز استقبال موضوعة على محيط دائرة متباعدة بزاوية قطبية (سمتية) قدرها 15 درجة مع إزاحة ثابتة قدرها 9 أمتار من مصدر موضوع في مركز الدائرة. وتتكون هندسة الاستحواذ من 24 جهاز استقبال موضوعة على محيط دائرة متباعدة بزاوية قطبية (سمتية) قدرها 15° درجة مع إزاحة ثابتة قدرها 9 أمتار من مصدر موضوع في مركز الدائرة. تُظهر بيانات السرعة المقاسة سلوكًا جيبياً مع أقصى سرعة على طول السمات الموازي لوجه الانزلاق (الطبقات المتقاطعة) للكثبان الرملية. تم تجهيز بيانات السرعة والسمات المقاسة بنموذج TTI بأربعة معلمات معروفة: السمات $(\varphi = 0^\circ, 15^\circ, \dots, 330^\circ, 345^\circ)$ ، زاوية السقوط $(\theta = 71.33^\circ)$ ، ميل محور التماثل $(\theta_0 = 30^\circ)$ ، والسرعة على طول محور التناظر $(V_{p0} = 274 \text{ m/s})$ ، ومعلمتين من معلمات Thomsen غير المعروفة (ε, δ) . أفضل القيم الملائمة لـ ε و δ هي 0.035 و 0.005، على التوالي، مما يثبت أن الكثبان الرملية المدروسة لها خاصية وسط TTI متباين الخواص.

CHAPTER 1

INTRODUCTION

Sand dunes are a globally occurring phenomenon, most common but not limited to desert environments, with a large portion of the world's natural resources, from hydrocarbons to water, buried under them. Therefore, understanding the acoustic and elastic properties of these sand dunes and the challenges they impose on seismic data acquisition and processing is essential to accurately study these areas of interest.

Seismic-driven subsurface characterization in desert environments overlain with mountainous sand dunes, such as those in areas of the middle east and north Africa, is confronted by a multitude of technical and operational challenges. In Rub' Al-Khali of Saudi Arabia, the dunes are 90 m high on average, with some dunes boasting heights of more than 250 m, as well as covering over a kilometer laterally (Al-Marzooq et al. 2019).

In regard to seismic data acquisition, the large size, extensive reach, and steep repose angle of the dunes present logistical obstacles. These factors hinder the efficiency of shooting techniques and, in numerous regions, cannot be circumvented by altering the seismic traverse without compromising the density of the seismic grid. As a result, it becomes imperative for the seismic profile to directly traverse the dune (Robinson and Al-Husseini 1982).

The imaging of geological structures overlain by near-surface geophysical anomalies such as sand dunes and irregular topography introduces noise and unpredictable irregularities to the seismic data (Figure 1). These irregularities can affect the velocity and amplitude contents through many forms of incoherent seismic disturbances, such as reverberations, diffractions, refractions, scattering and energy absorption (Evans and Greaves 2009).

In addition, sand dunes exhibit vertical velocity profiles within their structures as the overburden stress of the weight of the sand of layers above increases their velocity (Al-Shuhail 2002; 2004; Bachrach, Dvorkin, and Nur 2000). All of these factors introduce additional challenges to geophysicists that rely on the quality of the near-surface velocity profile in static corrections, time-to-depth conversion and near-surface engineering applications (Hanafy et al. 2020).

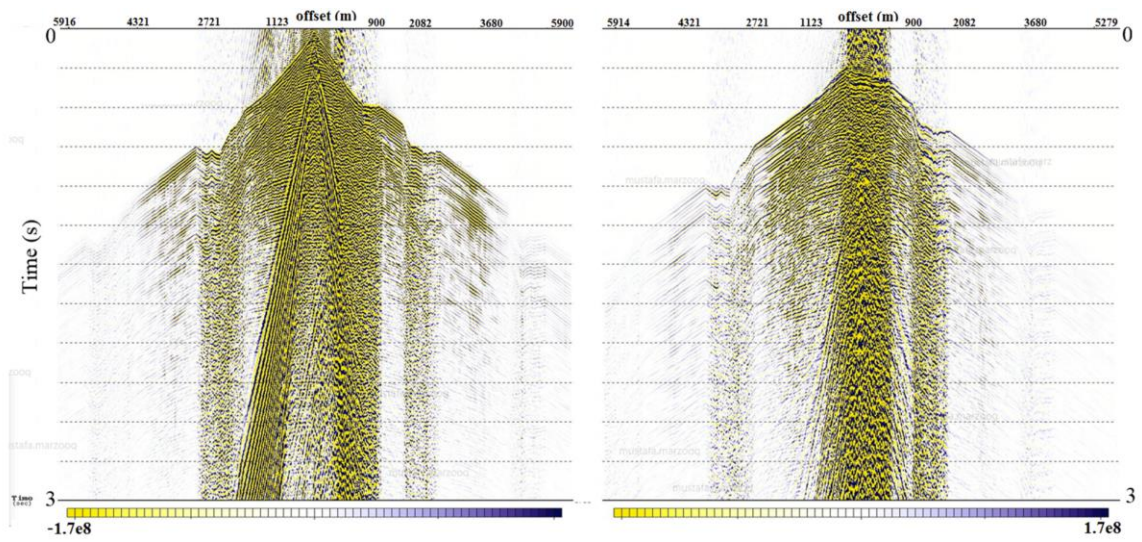


Figure 1: Recorded signal confirming the effects of the two distinct conditions on image quality. When shooting at the salt flats (sabkha) (a), there is a high signal-to-noise ratio (SNR). Conversely, shooting at the top of the dune (b) leads to a low SNR. (Al-Marzooq et al. 2019).

Extensive research has been conducted to address the challenges posed by sand dunes in seismic data acquisition and processing. Robinson and Al-Husseini (1982) introduced a methodology referred to as the "sand curve" for reflection prospecting. Their approach aimed to mitigate the impact of sand dunes on seismic data collected from the Rub' Al-Khali region in Saudi Arabia. By establishing a correlation between the transmit time of P-waves in the sand and the elevation of the dune, they successfully derived sand dune statics. The application of this technique resulted in the production of high-quality broadband reflection profiles characterized by enhanced continuity beneath the dunes.

The sand curve was revisited 25 years later by Liner (2008), who proposed the calculation of a new sand curve from laboratory data reported by Zimmer et al. (2007) that resembled those of dune sands in Saudi Arabia to compare the two sand curves. The report exhibits a level of agreement between the sand curves increasing confidence and refinement to the existing sand curve.

(Al-Shuhail 2004) details a study to estimate sand dune thickness by assuming a vertical velocity profile in sand dunes and quantifying its effects using seismic refraction data of sand dunes with porosities greater than 0.2 and thicknesses less than 200 m. The study concluded that the assumption of constant velocity in the sand dune causes the error in the thickness estimation to increase with increasing thickness and decreasing porosity which could reach up to 15%.

In a more recent study, (Hanafy et al. 2020) proposed a slightly different method of estimating the thickness of the dune by designing a seismic array that would allow for the measurement of a P-wave vertical velocity profile in the upper 1 m, combined with another

that gives the vertical velocity profile from 1 m to 7 m (Figure 2). This allowed them to study the sharp increase in velocity in the first few centimeters of the dune due to overburden stress. They concluded that the use of more classical approaches such as tomogram velocities would result in an increase which could reach up to 44% error in static correction under the constant velocity assumption.

This work explores the effects induced on P-wave velocities by sand dunes, azimuthally, using a TTI anisotropy model. The results of Hanafy et al. (2020) are proof that the omittance of accurately measuring the P-wave velocity changes in the weathering layer leads to large errors in the static corrections and can be extended to this work.

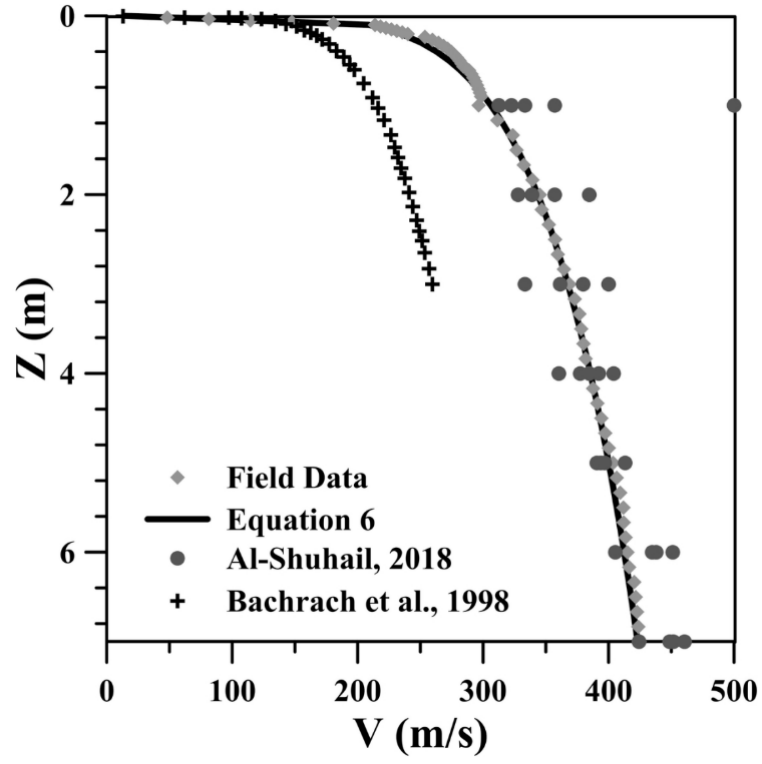


Figure 2: A compilation of velocity versus depth profiles compiled from various data sources. The black-cross symbols are from Bachrach et al. (1998), the gray-circle symbols are from Al-Shuhail et al. (2018), and both the diamond symbols and the solid line are from Hanafy et al. (2020).

1.1 Problem Statement

Accurate seismic imaging of natural resources in areas with sand dunes presents unique challenges for geophysicists, mainly due to the unique properties of the unconsolidated sands and their adverse effects on the seismic data. These effects include amplification of amplitudes, introduction of incoherent noise, and varying velocities with depth and saturation. While extensive research has been conducted to understand and mitigate the aforementioned phenomena, most seismic studies assume that the sand dunes behave in an isotropic manner. However, the literature remains sparse on the characteristics of seismic velocity at varying offsets and azimuths sand dunes. Furthermore, the absence of full azimuthal information in traditional seismic data has imposed constraints on the examination of the various anisotropic effects (HTI and TTI) of sand dunes in seismic studies.

1.2 Research Objective

The objective of this research is to investigate and test for the presence of TTI (tilted transverse isotropy) with azimuthal variation in sand dunes. This is achieved by designing a circular seismic survey geometry over the sand dune that will facilitate the collection of seismic data at 15° increments of azimuth while maintaining the thickness of the sand dune, as illustrated in Figure 3. In addition, the seismic data will be processed using a workflow that preserves the azimuthal effects. Furthermore, I calculate the velocities, explain any velocity trends with azimuth using a TTI model, and estimate Thomsen's parameters in the dune.

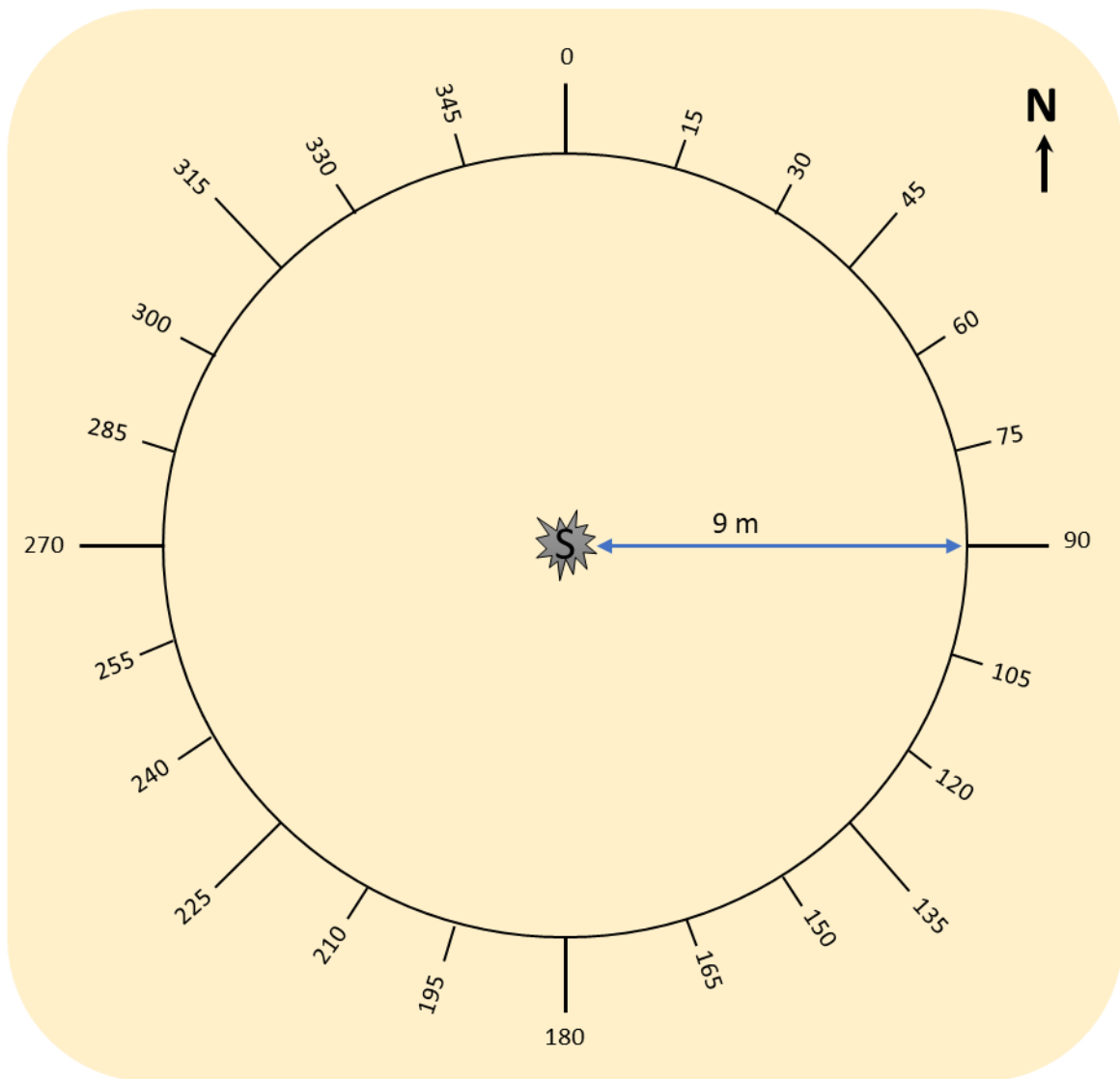


Figure 3: Schematic of concentric survey geometry centered in an unconsolidated sand sheet/dune environment (demarcated by the beige background), with azimuthal increment of 15° (clockwise from north).

CHAPTER 2

LITERATURE REVIEW

In contrast to isotropy, anisotropy is the variation of a property with the direction in which it is measured (Anderson et al. 1994). Many properties display anisotropic behavior in sand dunes due to their unconsolidated nature, such as seismic wave speed velocity (Al-Shuhail 2002; 2004; Zimmer et al. 2007; Hanafy et al. 2020; Vega et al. 2006), hydraulic conductivity (Stephens and Heermann 1988) and specific discharge (McCord and Stephens 1987; McCord et al. 1991; Berndtsson et al. 1996). Yilmaz (2001) reviews two cases of seismic anisotropy, which are both special forms of transverse isotropy (Figure 4). The first is vertical transverse isotropy (VTI), in which velocities vary on a vertical plane that is perpendicular to a given lateral direction but do not vary laterally in direction. The second is horizontal transverse isotropy (HTI), which is a special case of azimuthal anisotropy, for which the velocities do not vary vertically but only laterally about a given horizontal symmetry axis (Winterstein 1990). A third case of seismic anisotropy is a mixture of VTI and HTI, namely, tilted transverse isotropy (TTI), in which the transverse isotropy exhibits an inclined axis of symmetry.

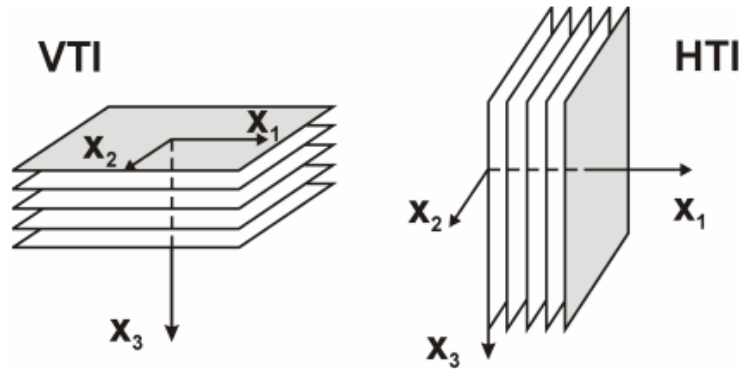


Figure 4: Models of VTI and HTI finely layered media with symmetry axes shown (Danek et al. 2010).

It has been proven that velocity increases with depth in sand dunes in many studies (Al-Shuhail 2002; Bridle, Ley, and Al-Mustafa 2007; Hanafy et al. 2020; Liner 2008; Zimmer et al. 2007). This phenomenon is primarily attributed to the vertical stress resulting from the overburden weight of the overlying sand, which significantly surpasses the horizontal stresses. Consequently, this leads to the development of greater elastic moduli in the direction of the applied stress compared to the moduli in the perpendicular direction (Gofer, Bachrach, and Marco 2017). On the other hand, literature is sparse on the topics of HTI and TTI in sand dunes in the field, although it exists on seismic wave velocities in transversely isotropic unconsolidated media, mostly in laboratory settings.

Levin (1979) computed the velocities of P-waves, SV-waves, and SH-waves traveling in a transversely isotropic two-component solid made up of equal parts of gypsum and unconsolidated material by equations given in White (2000), for a reflector at 5,000 ft and a 0-10,000 ft spread. This resulted in a nonelliptical P-wave surface with three SV-waves exhibiting three different velocities in the $t^2 - x^2$ graph and an SH-wave that is still an ellipsoid but with a horizontal axis twice as large as its vertical axis, as shown in Figure 5. This indicates HTI and shear wave splitting in the medium.

Coincidentally, the sands of the eastern region of Saudi Arabia (the proposed study area) are coarse in texture with high salt, gypsum, and carbonate contents (Shadfan et al. 1984). However, realistically, it would be highly unlikely to find a sand dune of equal thicknesses of gypsum and unconsolidated sand. Thus, a more likely observation would be similar to that of Levin (1979) on equal parts of gas sand and wet sand, Figure 5.

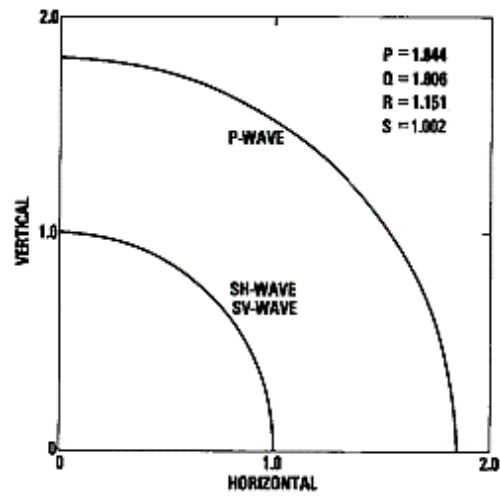
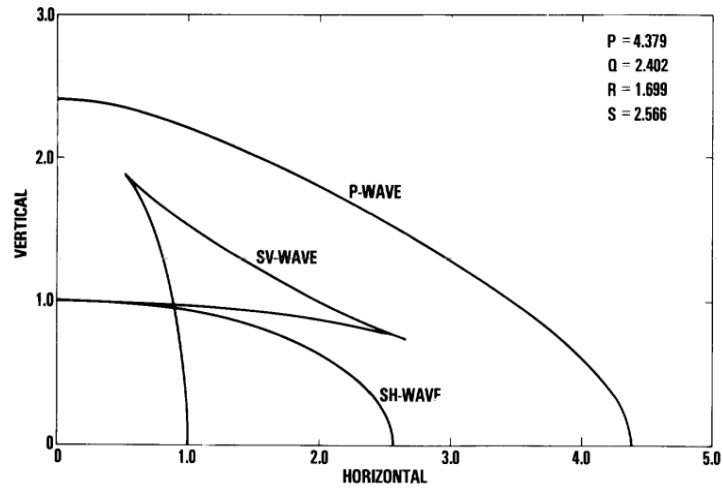


Figure 5: P-wave, SV-wave, and SH-wave velocity surfaces for an earth section consisting of equal thicknesses of gypsum and nonconsolidated material (left) and for an earth section consisting of equal thicknesses of gas sand and water sand (right) (Levin 1979).

Vega et al. (2006) detected stress-induced velocity anisotropy in unconsolidated sands using P-waves but not S-waves, as they are highly attenuated in unconsolidated soft sediments in field settings. The experiment was carried out under laboratory conditions on three sands of different grain sizes, the finest (0.25 mm) exhibiting natural stratification, the fine (0.39 mm) exhibiting slight stratification and the coarse (0.91) exhibiting no stratification. The findings indicate that when stress is applied in the z-direction, there is a concurrent generation of compressive stresses in the orthogonal (x-y) directions, which are comparable but not equal in x and y, with observed nonelastic behavior after unloading, as shown in Figure 6.

Furthermore, Figure 7 shows that the P-wave velocities in the orthogonal directions are fairly similar but not equal during both loading and unloading events. In addition, the study's conclusion highlights that stress anisotropy exerts a more substantial influence on the anisotropy of P-wave velocity in unconsolidated sands compared to textural anisotropy. This hints at the possibility of azimuthal velocity anisotropy in sand dunes in field settings due to the unequal stresses and hence elastic constants in orthogonal directions.

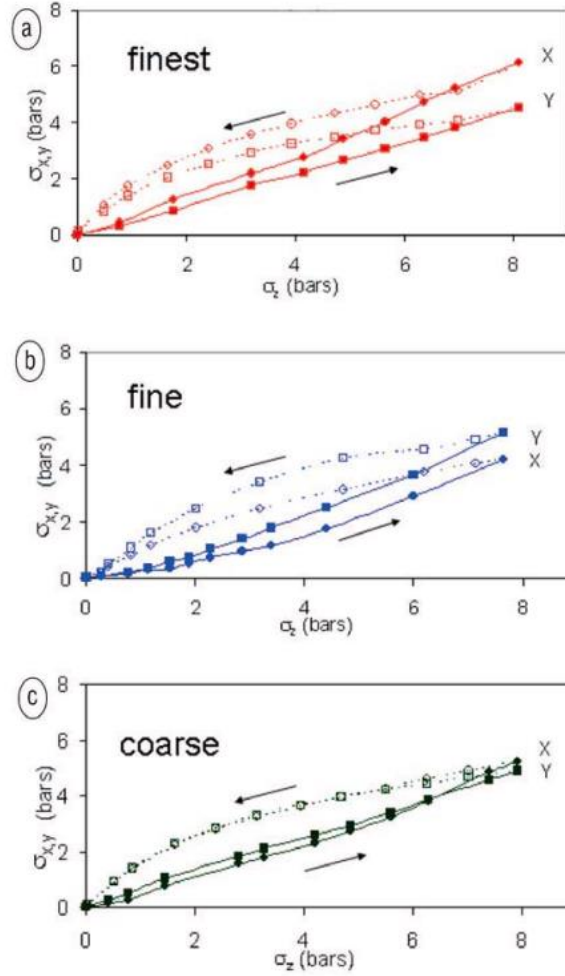


Figure 6: The applied stress (σ_z) and the resulting stress response (σ_x and σ_y) for three samples of finest, fine, and coarse-grain sands with porosities of $\phi = 0.45, 0.42, 0.41$, respectively. The x and y directions are represented by circles and squares, respectively. Filled symbols indicate the loading path, while open symbols represent the unloading path (Vega et al. 2006).

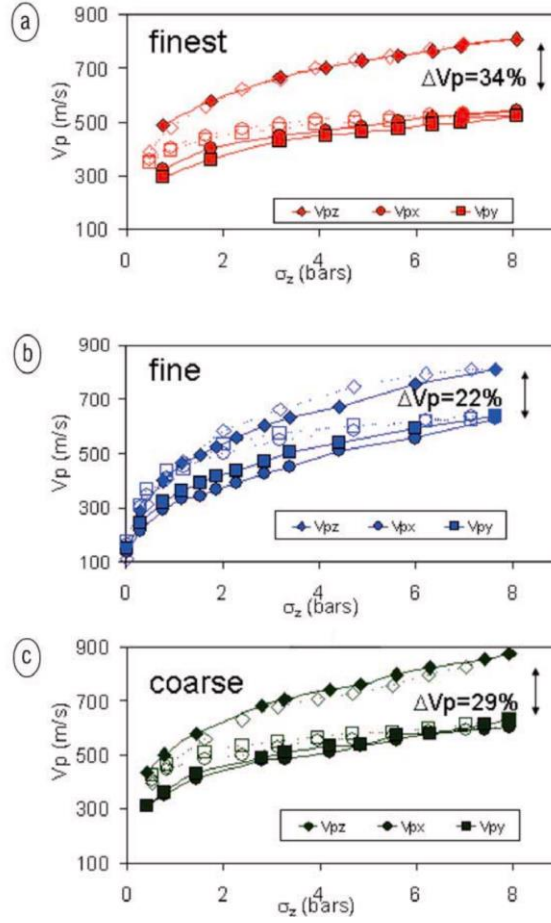


Figure 7: Relationship between V_p and the applied stress (σ_z) for three samples of finest, fine, and coarse grain sizes with porosities of $\phi = 0.45, 0.42, 0.41$, respectively. The x, y, and z directions are represented by circles, squares, and diamonds, respectively. Filled symbols represent the loading path, while open symbols indicate the unloading path (Vega et al. 2006).

Textural anisotropy and the effect of sand dune laminations (stratification) on the isotropy/anisotropy of the velocities in sand dunes cannot be fully appreciated in seismic data. Typical seismic wavelengths range from 40 to 250 m, meaning that these thin laminations are not resolvable. Lower wavelength alternatives, such as electromagnetic waves used in ground penetrating radar (GPR), can resolve these laminations, and are affected by their orientation.

This is made evident in a study by Lu et al. (2018) of anisotropy in GPR data collected on sand dunes in the Badain Jaran Desert, China. There was a noticeable delay in the arrival time of the EM waves propagating parallel (A to C) to the calcareous laminations of the sand dune and those propagating normal (B to C) to the laminations, as shown in Figure 8.

The effect of sand dune stratification and textural anisotropy can also be noted in their hydrological processes. The presence of these laminations and grain size differences introduces anisotropy as a noncollinearity of the specific discharge and hydraulic gradient (Stephens and Heermann 1988). In addition, the soil water content patterns in arid desert sand dunes have been observed using soil water tracer experiments. The results indicate nonhomogeneous transport of soil water after rainfall and a large spatial variability in soil water content.

Numerous studies provide substantial support for the hypothesis that dune sand exhibits pronounced anisotropic behavior under unsaturated conditions. This can primarily be attributed to the presence of millimeter-scale laminations, which tend to conform to the dune's topography and often contain regions of elevated water content (Berndtsson et al. 1996; McCord and Stephens 1987; McCord, Stephens, and Wilson 1991).

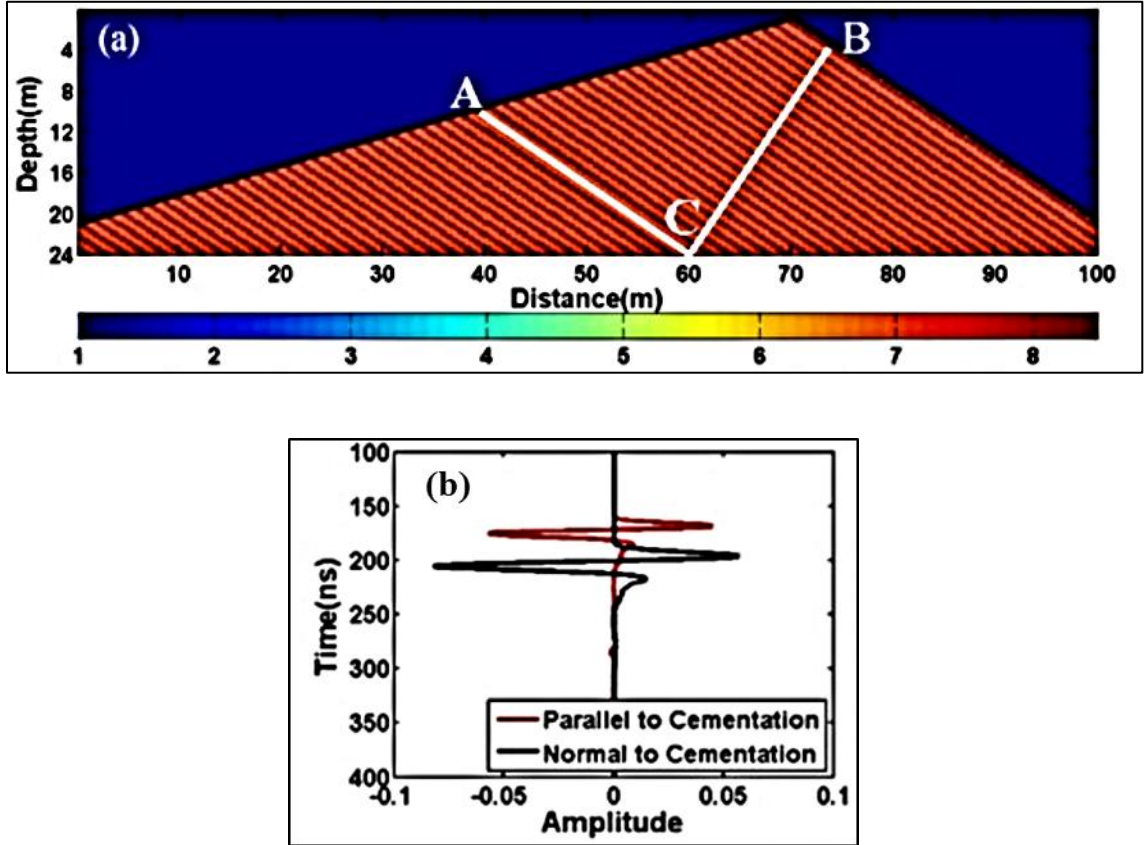


Figure 8: (a) Geometry of a sand dune with calcareous laminations. (b) EM travel times in from parallel (A to C) and normal (B to C) to the lamination surfaces (Lu et al. 2018).

CHAPTER 3

METHODOLOGY

3.1 Sand Dunes

3.1.1 Introduction to Sand Dunes

Sand dunes are accumulations of unconsolidated sand deposited as mounds or ridges by a number of driving factors, mainly wind or water under the influence of gravity. They occur globally, from the Arctic to the equator, in both arid and semiarid environments and mainly in the following landscapes: arid regions, river valleys, seacoasts and lakeshores (Maun 2009).

Sand dunes manifest in arid regions as a result of sand being exposed to a medium that induces the entrainment of particles into surface flow (Parteli et al. 2014). The predominant mode of surface transport within dune systems is saltation (illustrated in Figure 9), whereby sand particles travel in close proximity to the surface, following nearly ballistic trajectories. Subsequently, upon collision, these particles dislodge and eject new particles into the surrounding environment (Bagnold 2012).

Sand dunes are typically composed of fine particles with diameters ranging from 0.125 mm to 0.250 mm. This is mainly due to the intrinsic property of sand, in which sand grains with a diameter between 0.062 mm and 2.0 mm exhibit no cohesion and are therefore easily combusted by wind. In contrast, finer grains with a diameter of less than 0.050 mm (such

as silt and clay) exhibit cohesive characteristics that enable them to effectively withstand wind erosion (Tsoar 2001).

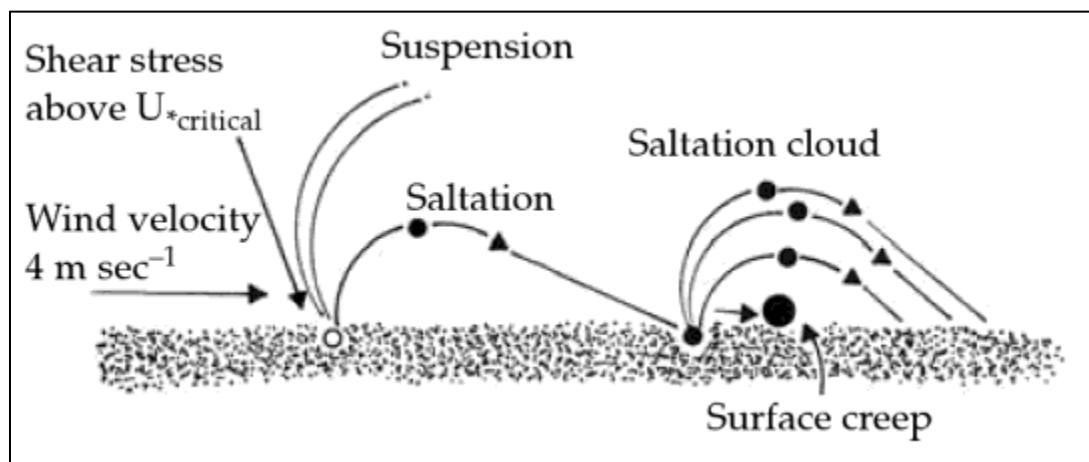


Figure 9: Illustration of the different mechanisms of surface transport (saltation and suspension) of sediments initiated by a wind velocity of 4 m/s (Maun 2009).

3.1.2 Geomorphology of aeolian sand dunes and internal structure

Sand dunes may take one of a plethora of forms and structures, owing to the many different combinations of wind velocity, direction, sediment supply and many other factors. Every dune has a stoss slope (upstream/upward direction) and a leeward slope (downstream/downwind direction), also known as a slip face.

A) Main types of sand dunes

Barchan (Crescentic)

Barchans are isolated dunes formed in areas with a limited sediment supply overlying coarse sand or non-sandy surfaces (Pye and Tsoar 2008). These represent the predominant category of sand dunes and are recognized for their mobility, Figure 10.

Transverse

Transverse dunes (otherwise known as zibar dunes) are the same as barchan dunes in that they are formed under a unidirectional wind regime, but they are not isolated. They form parallel lines of dunes with a unidirectional slip face (McKee 1979), Figure 11.



Figure 10: Aerial view of the barchan dune from Mesquite Sand Dunes, where the left side of the dune is the stoss side and the right side of the dune is the steep slip face (Mayer, Mesquite Sand Dunes, 2003, [https://commons.wikimedia.org/wiki/File:Mesquite Sand Dunes.JPG](https://commons.wikimedia.org/wiki/File:Mesquite_Sand_Dunes.JPG)).



Figure 11: Astronaut photograph of transverse dunes in the central-eastern part of the Tenéré Desert, Niger (NASA, ISS022-E-5258, 2009, https://eoimages.gsfc.nasa.gov/images/imagerecords/42000/42070/iss022-e-5258_lrg.jpg).

Linear

Linear (otherwise known as seif) dunes are straight or relatively straight elongated dunes that form under opposite facing bidirectional wind regimes. These dunes are also characterized by their triangular profile and sharp crests (Pye and Tsoar 2008), Figure 12.

Star Dunes

These dunes are distinguished by their sinuous arms extending from a central peak in the shape of a pyramid. They originate within regions subject to a wind regime marked by substantial directional fluctuations, typically observed in high-latitude deserts where seasonal variations significantly impact the prevailing wind direction (Pye and Tsoar 2008), Figure 13.



Figure 12: Astronaut photograph of linear/seif dunes in the Namib Sand Sea (NASA, ISS047-E-23405, 2016, <https://www.nasa.gov/image-article/linear-dunes-namib-sand-sea/>).



Figure 13: Satellite image showing star dunes in the Sahara Desert. Note the long sinuous arms emanating from the center of the dune (NASA, ISS013-E-75141, 2006, <https://earthobservatory.nasa.gov/images/7401/erg-oriental-algeria>).

B) Internal structure of sand dunes

The depositional environmental and wind regime variations dictate the type of dune and its internal structure. Using conventional seismic methods, dune structures and laminations cannot be fully appreciated given the long wavelength of seismic waves.

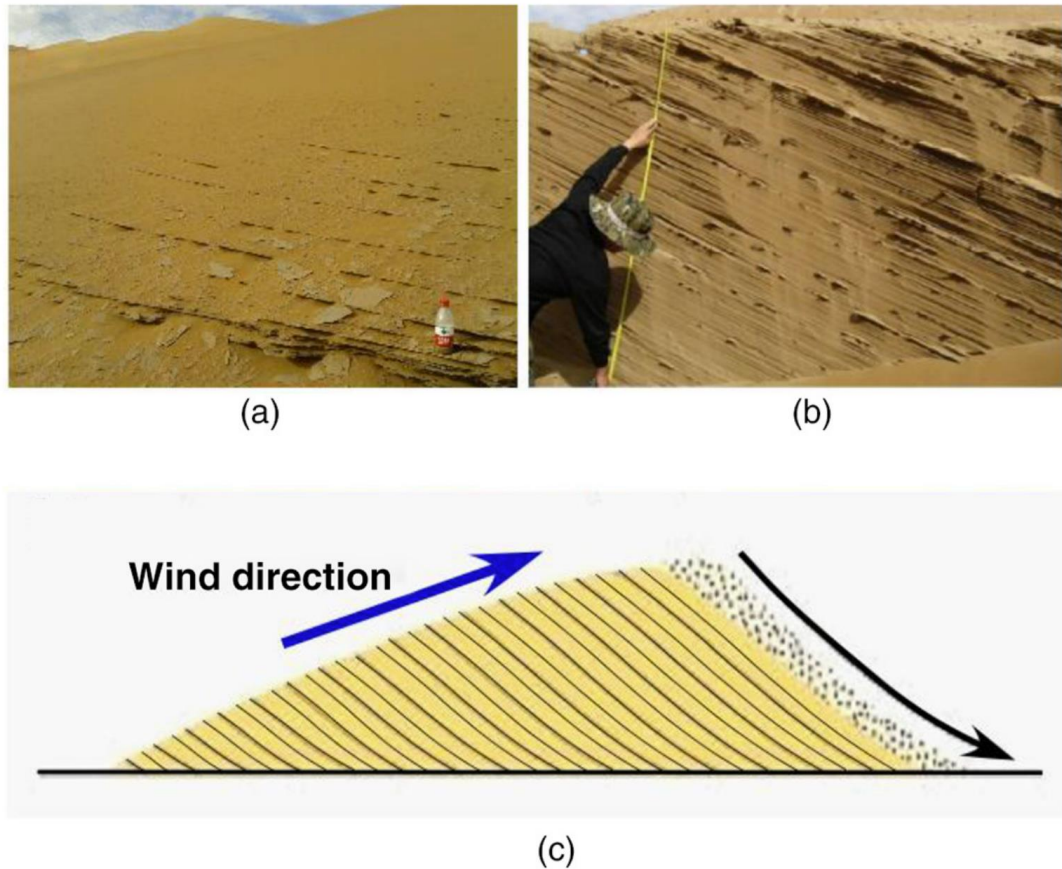


Figure 14: (a) The exposed calcareous internal layering structure exposed on the surface of a sand dune in the Badain Jaran Desert, China. (b) Cross section of a trench excavated in the sand dune showing its internal structure, offering a better view of the calcareous layering. The dip angle of the laminations closely matches the repose angle of the slip face of the sand. (c) Illustration of the motion and formation of a sand dune under a unidirectional wind regime (Qian & Liu, 2015).

On the other hand, the use of low wavelength methods of imaging such as GPR produces highly detailed images of the internal architecture of the dune, Figure 14. A study taken in proximity to the study area better illustrates the sand dunes of the area and their internal structure using detailed photography of trenches and GPR data. The cross strata and laminations caused by the changing wind regime in the area can be observed in trenches shown in Figure 15.

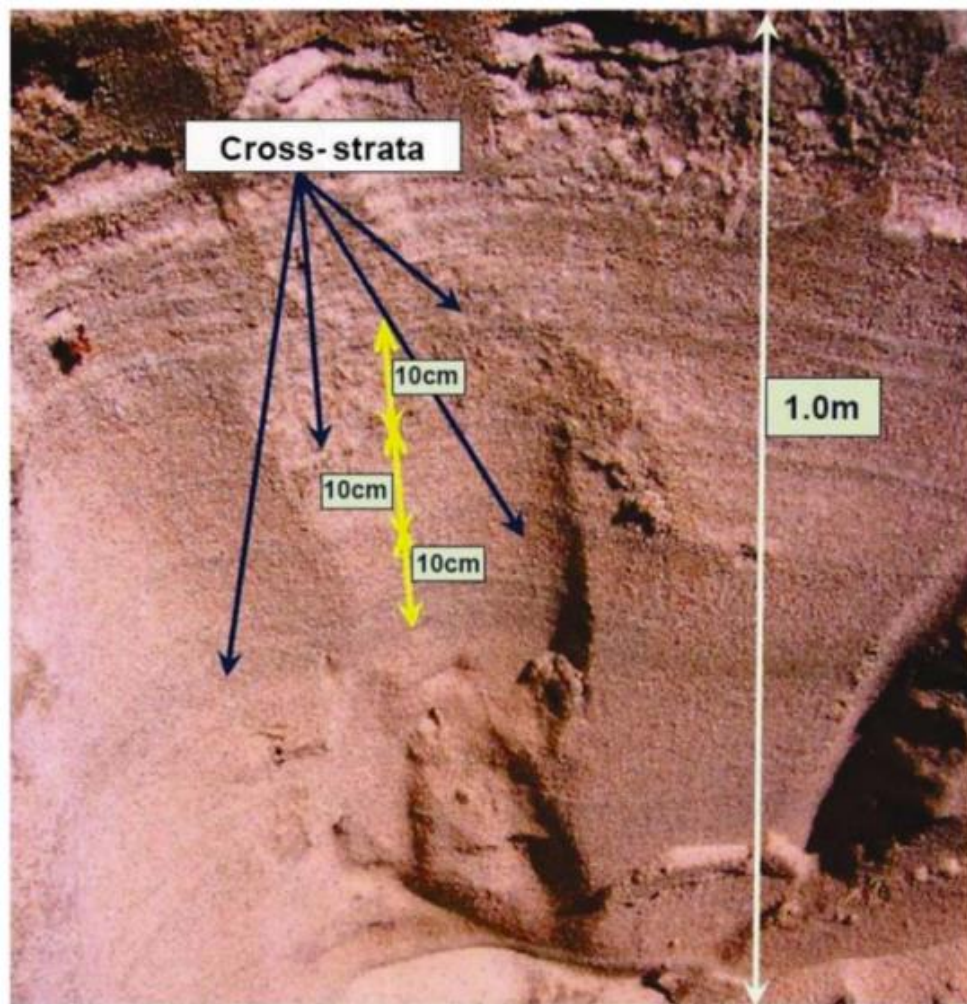


Figure 15: Picture of a trench of 1 m depth near the study area in the Dhahran region, Eastern Saudi Arabia, showing cross-strata with a thickness of 10 cm (Adetunji et al. 2008).

The radar profile shown in Figure 16 was conducted in the location of the sand dune portrayed in Figure 15. The profile shows resolved sand beds with a thickness of 10 cm. The characteristics of the profile in conjunction with measurements taken from the trenches have allowed for the computation of the dipping angles of the cross-strata which were 30-32° (Adetunji, Al-Shuhail, and Korvin 2008).

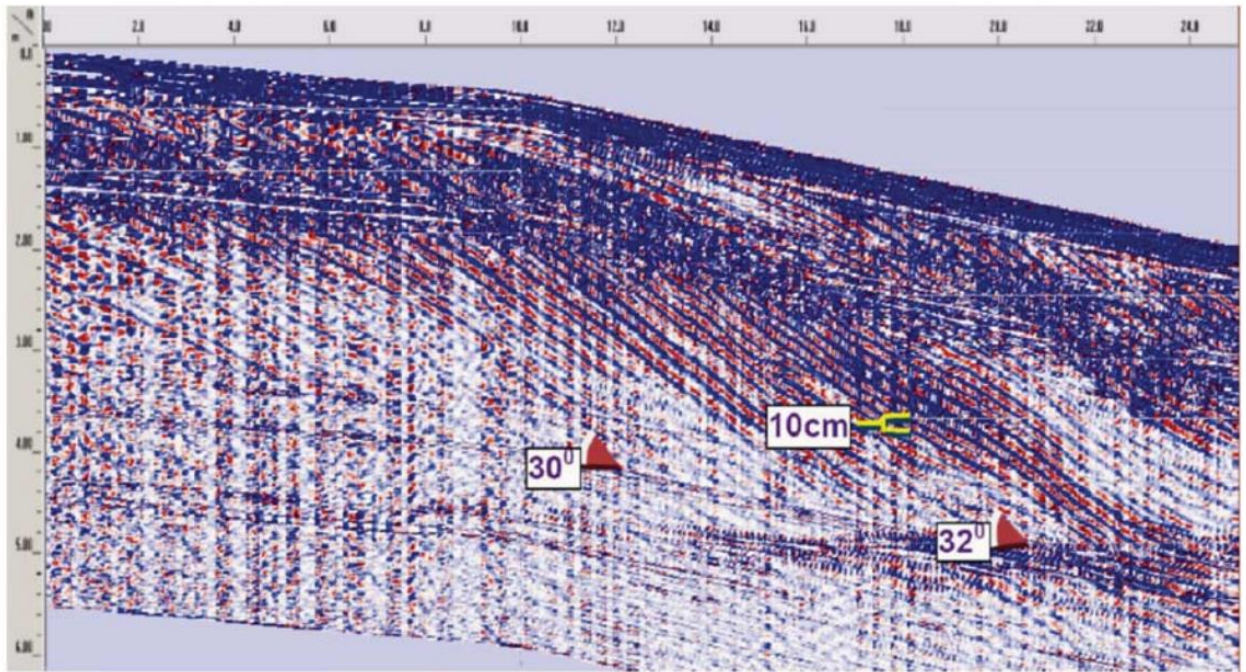


Figure 16: Radar profile taken in the location of the trench in Figure 15, showing the cross-strata and sand beds resolved to a thickness of 10 cm (Adetunji et al. 2008).

3.2 Anisotropy

The presence of even minor anisotropy in the medium can have an impact on the sensitivity of P-wave amplitudes (Rüger 1998). To investigate the impact of anisotropy and the orientation of the symmetry axis on P-wave velocities, it is imperative to establish a suitable model for analysis (Ivanov and Stovas 2017). Given that sand dunes in the study area exhibit dipping cross-strata or laminations (Adetunji, Al-Shuhail, and Korvin 2008), the use of a tilted transversely isotropic (TTI) medium model would prove appropriate to quantify their effect on the velocity of P-waves traveling through the dune.

Thomsen (1986) defines a linear elastic material as that in which the stress σ_{ij} in each component is directly related to every component of strain ε_{kl} (Nye, 1957). As there are three directional indices, denoted as 1, 2, and 3 (representing x, y, z), there are a total of nine relationships. Each relationship involves one stress component and nine strain components. These nine equations can be expressed concisely as follows:

$$\sigma_{ij} = \sum_{k=1}^3 \sum_{l=1}^3 C_{ijkl} \varepsilon_{kl}, i, j = 1, 2, 3 \quad (1)$$

where C_{ijkl} is the elastic modulus tensor (describing the elasticity of the medium), σ_{ij} is the stress, and ε_{kl} is the strain. Furthermore, Thomsen (1986) states that due to the symmetry of stress and strain, out of the set of equations (1), only six equations are independent, and only six terms on the right side of each equation set are independent. Thus, in accordance with the Voigt notation, the elastic coefficient matrix of the VTI medium can be represented as a 6 x 6 matrix, as in Wang et al. (2017).

$$C^{VTI} = \begin{pmatrix} C_{11}^{VTI} & C_{11}^{VTI} - 2C_{66}^{VTI} & C_{13}^{VTI} & 0 & 0 & 0 \\ C_{11}^{VTI} - 2C_{66}^{VTI} & C_{11}^{VTI} & C_{13}^{VTI} & 0 & 0 & 0 \\ C_{13}^{VTI} & C_{13}^{VTI} & C_{33}^{VTI} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^{VTI} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44}^{VTI} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^{VTI} \end{pmatrix} \quad (2)$$

Following the assumption that the medium exhibits a weak anisotropy, Wang et al. (2017)

use the following Thomsen (1986) parameter definitions and an approximation for C_{13}^{VTI} in equation (3) to linearize equation (2):

$$\gamma = \frac{C_{66}^{VTI} - C_{55}^{VTI}}{2C_{55}^{VTI}}, \quad \varepsilon = \frac{C_{11}^{VTI} - C_{33}^{VTI}}{2C_{33}^{VTI}}, \quad \delta = \frac{(C_{13}^{VTI} + C_{55}^{VTI})^2 - (C_{33}^{VTI} - C_{55}^{VTI})^2}{2C_{33}^{VTI}(C_{33}^{VTI} - C_{55}^{VTI})} \quad (3)$$

$$C_{33}^{VTI} = \rho V_{P0}^2, \quad C_{55}^{VTI} = \rho V_{S0}^2 \quad (4)$$

$$C_{13}^{VTI} \approx (1 + \delta)C_{33}^{VTI} - 2C_{55}^{VTI} \quad (5)$$

$$C^{VTI} = \begin{pmatrix} (1 + 2\varepsilon)C_{33}^{VTI} & (1 + 2\varepsilon)C_{33}^{VTI} - 2(1 + 2\gamma)C_{55}^{VTI} & C_{33}^{VTI}(1 + \delta) - 2C_{55}^{VTI} & 0 & 0 & 0 \\ (1 + 2\varepsilon)C_{33}^{VTI} - 2(1 + 2\gamma)C_{55}^{VTI} & (1 + 2\varepsilon)C_{33}^{VTI} & C_{33}^{VTI}(1 + \delta) - 2C_{55}^{VTI} & 0 & 0 & 0 \\ C_{33}^{VTI}(1 + \delta) - 2C_{55}^{VTI} & C_{33}^{VTI}(1 + \delta) - 2C_{55}^{VTI} & C_{33}^{VTI} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{55}^{VTI} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^{VTI} & 0 \\ 0 & 0 & 0 & 0 & 0 & (1 + 2\gamma)C_{55}^{VTI} \end{pmatrix} \quad (6)$$

where γ , ε and δ are Thomsen parameters, ρ is the density of the medium, and V_{P0} and V_{S0} are the P-wave and S-wave velocities along the axis of symmetry of the anisotropic medium.

To obtain an elastic coefficient matrix for the TTI medium model (illustrated in Figure 17) from the VTI medium model (equation (6)), Wang et al. (2017) state that a rotation of the

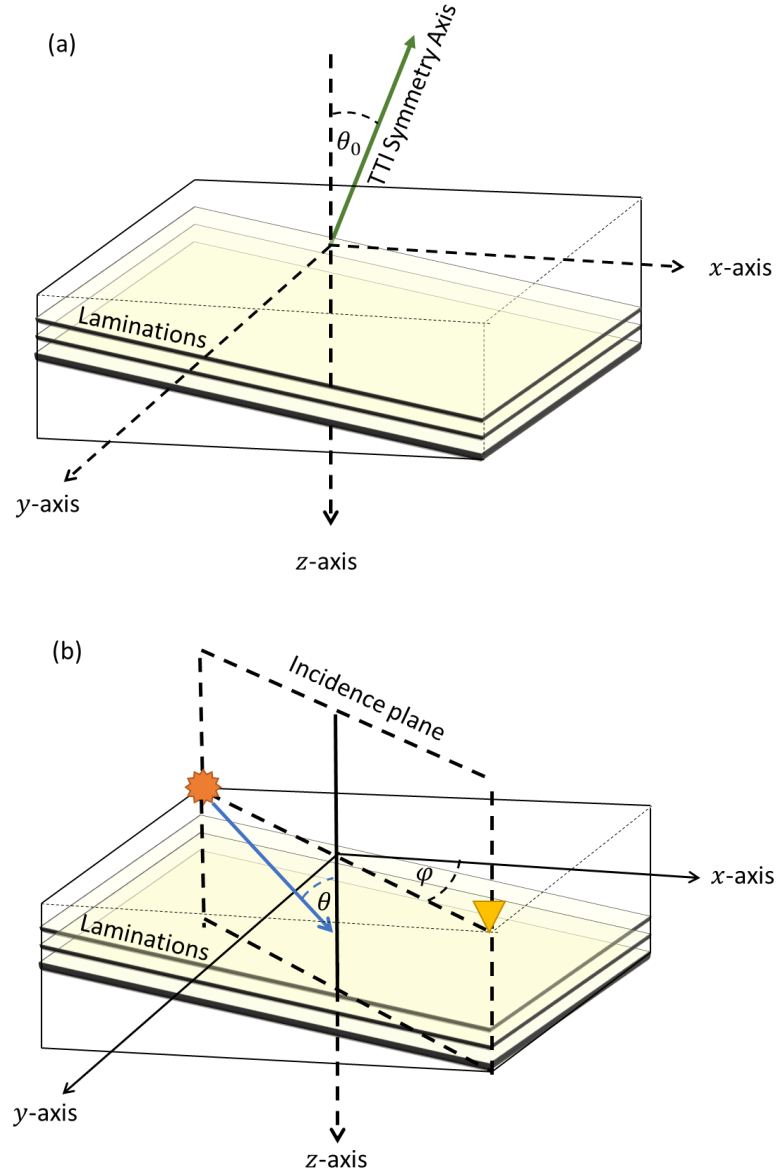


Figure 17: Illustration of the TTI medium model showing the tilt of the symmetry axis θ_0 (a), in addition to the azimuth angle ϕ and the incident angle θ (b).

symmetry axis is required. The VTI medium's symmetry axis, located in the xz -plane, undergoes a rotation represented by θ_0 . Figure 17a illustrates the specific mode of rotation for the symmetry axis, where θ_0 is considered positive for clockwise rotation and negative for counterclockwise rotation. After the completion of the rotation (Bond 1943), the elastic coefficient matrix for the TTI medium is derived, as demonstrated in equation (7). The elements in equation (7) are further described in Wang et al.'s (2017) equation (6).

$$C = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & C_{15} & 0 \\ C_{12} & C_{22} & C_{23} & 0 & C_{25} & 0 \\ C_{13} & C_{23} & C_{33} & 0 & C_{35} & 0 \\ 0 & 0 & 0 & C_{44} & 0 & C_{46} \\ C_{15} & C_{25} & C_{35} & 0 & C_{55} & 0 \\ 0 & 0 & 0 & C_{46} & 0 & C_{66} \end{pmatrix} \quad (7)$$

Under the assumption that the direction of propagation for the phase velocity aligns with that of the group velocity within the weakly anisotropic medium, Wang et al. (2017) presents the solution to the Christoffel equation, offering the following formulation for the P-wave phase velocity within the TTI medium:

$$V_{qP} = \sqrt{\frac{1}{2\rho} (C_{55}^{VTI} + C_{11}^{VTI}F + C_{33}^{VTI}E^2 + \sqrt{D})} \quad (8)$$

The expressions from equation (8) are expanded in Wang et al. (2017) as:

$$D = [(C_{33}^{VTI} + 2\epsilon C_{33}^{VTI} - C_{55}^{VTI})F - (C_{33}^{VTI} - C_{55}^{VTI})E^2]^2 + 4(C_{33}^{VTI} + \delta C_{33}^{VTI} - C_{55}^{VTI})^2 F E^2 \quad (9a)$$

$$E = -\sin \theta \cos \varphi \cos \theta_0 + \cos \theta_0 \cos \theta \quad (9b)$$

$$F = (\sin \theta \cos \varphi \cos \theta_0 + \cos \theta \sin \theta_0)^2 + \sin^2 \theta \sin^2 \varphi \quad (9c)$$

Moreover, under the prior assumption of weak anisotropic approximation, equation (8) is further simplified in Wang et al. (2017), thus providing an expression for the P-wave velocity within the TTI medium in terms of the angles θ , θ_0 and φ , as well as the Thomsen parameters ε and δ as follows:

$$V_{qP}(\theta, \varphi) = (1 + \varepsilon F^2 + \delta F E^2) V_{P0} \quad (10)$$

3.3 Hertz-Mindlin Theory

To calculate Thomsen parameters from equation (10), the P-wave velocity along the TTI medium's symmetry axis (V_{P0}) is required. The lack of borehole data in the study area leads me to resort to a theoretical method for calculating V_{P0} . Al-Shuhail (2002) describes the behavior of the direct wave in a layer of sand as a diving wave. This allows me to infer that the propagation velocity of the wave is calculated at its maximum depth of penetration in the sand dune.

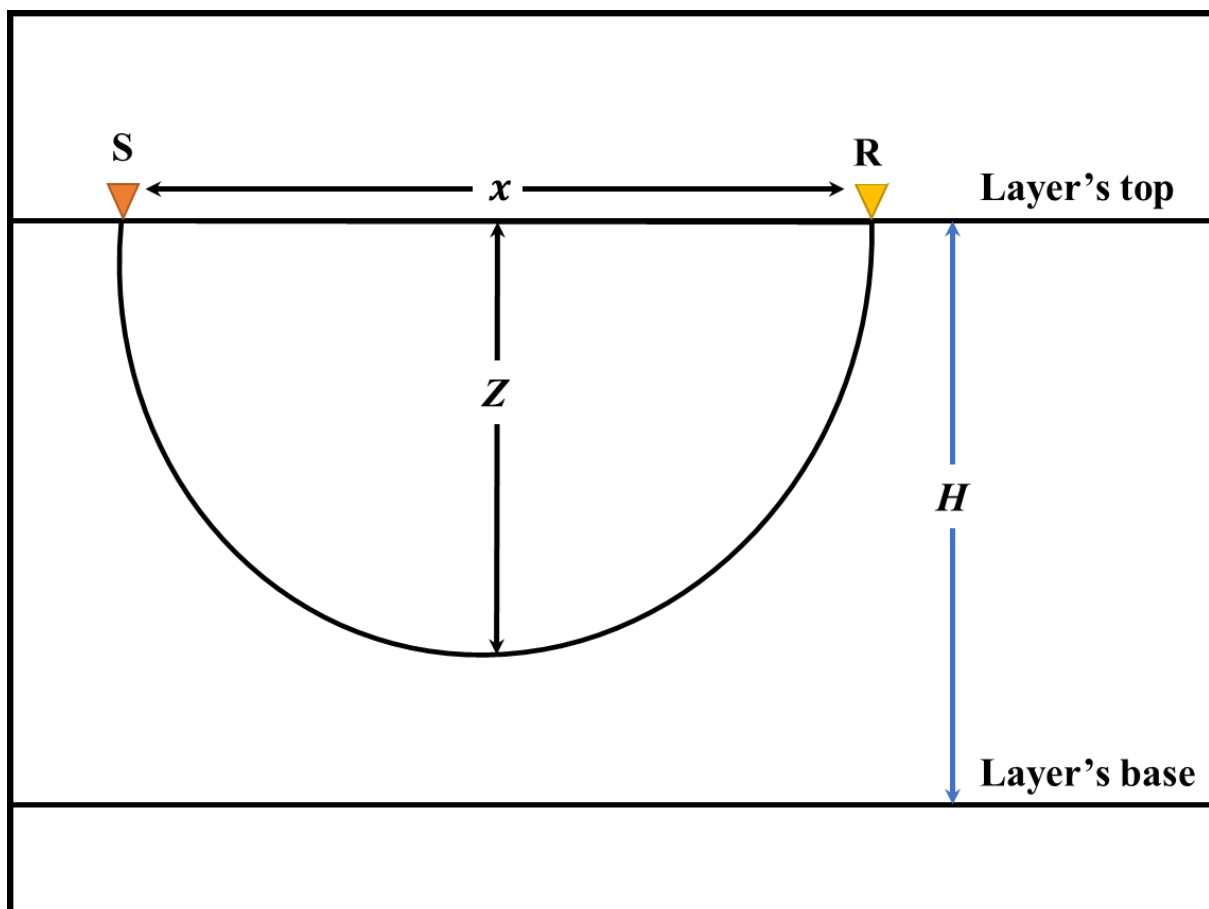


Figure 18: Diagram showing the behavior of the direct wave acting as a diving wave in a sand layer due to the vertical velocity profile of the sand layer, where z , H and x represent the depth of penetration, layer thickness and the source-receiver offset respectively. Adapted from Al-Shuhail (2002).

Al-Shuhail's (2002) theory leverages a combination of the Hertz-Mindlin model (Mindlin 1949) and an approximation of Gassmann's equation (Mavko 1998) to derive a relationship by means of best fit, simplified for a single sand layer in Hanafy et al. (2020):

$$V(z) = V_0 \sqrt{1 + kz^{\left(\frac{1}{3}\right)}} \quad (11)$$

where $V(z)$ denotes the P-wave velocity as a function of the depth of penetration, V_0 represents the velocity at the surface, and z is the depth of penetration. k is an adjustable coefficient that is a function of the porosity, pore-fluid properties, stress-depth relation, mineralogy, and coordination number (Hanafy et al. 2020).

The computation of the surface velocity V_0 involves utilizing the Reuss (1929) average, which considers the bulk moduli of the sand grains K_g and air K_a in a suspended state, along with the arithmetic average of their respective densities (ρ_g and ρ_a).

$$V_0 = \sqrt{\frac{K}{\rho}} \quad (12a)$$

$$K = \left(\frac{1-\phi}{K_g} + \frac{\phi}{K_a} \right)^{-1} \quad (12b)$$

$$\rho = (1 - \phi)\rho_g + \phi\rho_a \quad (12c)$$

The work of Hanafy et al. (2020) was undertaken on a sand dune in a locality neighboring that of my study area, thus allowing for the use of their field experiments and assumptions. The following values are examples: $\phi = 40\%$ of the dune, $K_g = 36.6$ GPa, $K_a = 0.00014$ GPa, $\rho_g = 2650$ kg/m³ and $\rho_a = 1.2$ kg/m³, $V_0 = 15.1$ m/s and $k = 410$. A relationship between the offset (x) and the depth of penetration (z) is described in Duska (1963) as:

$$z = \frac{8x}{15\pi} = \frac{x}{5.89} \quad (13)$$

The information above gives rise to the equation used in Hanafy et al. (2020) to calculate $V(z)$. Al-Shuhail's (2002) velocity function is subsequently evaluated analytically in Al-Shuhail et al. (2018), as shown in equation (14), to calculate the one-way vertical traveltimes T_v that corresponds to $V(z)$ in equation (11) across a thickness of dune (H), respectively, where " H " is equivalent to " z ":

$$T_v(H) = \frac{2[-8 + \sqrt{1 + H^{\frac{1}{3}}k} (8 - 4H^{\frac{1}{3}}k + 3H^{\frac{2}{3}}k^2)]}{5k^3V_0} \quad (14)$$

Hanafy et al. (2020) of picking the first arrival travel times t of the recorded traces from the field experiment and using them in conjunction with their respective source-receiver offsets to compute the P-wave propagation velocities as:

$$V_P = \frac{x}{t} \quad (15)$$

CHAPTER 4

DATA ACQUISITION AND PROCESSING

4.1 Geology of Study Area

The study area is a barchan sand dune located approximately 30 km east of Dhahran city in the Eastern Province Saudi Arabia, at UTM coordinates: 383107.214E and 2915235.18N (Figure 19). The area of investigation belongs to the Al-Jafurah sand sea, an aeolian landscape stretching approximately 800 km along the Arabian Gulf coast, spanning from Kuwait in the north to the Rub Al Khali in the south. Within this area, sand is carried by the prevailing winds from regions of intense wind energy in the north toward areas of lower wind energy in the south, predominantly drifting in a southward to southeastward direction (Fryberger et al. 1984).

The sand properties within the studied barchan sand dune are reported by Benaafi et al. (2020) as having a mineral composition of mainly quartz, feldspars and calcite with minor amounts of gypsum and heavy minerals, with values of 86.8%, 9.4%, 2.9% and 0.9%, respectively. The grain size in the bulk of the sand dune ranges from fine (0.22 mm) to medium (0.40 mm) with no variation laterally from dune crest to limb, except for the upper 0.5 m where the sand grains at the dune limb were observed to be relatively coarser in comparison. In addition, Benaafi et al. (2020) reported that the sorting of dune sand ranges from poorly sorted to moderately well sorted with no noticeable variation vertically within the dune crest, while the sand at the dune limb shows alternating sorting in the lower parts between poorly sorted and better sorted sand.



Figure 19: Satellite map showing the location of the study area in Eastern Province, Saudi Arabia.



Figure 20: Satellite image of the studied barchan sand dune. The red circle represents the seismic data acquisition geometry and location on the dune limb. The red line represents the strike of the slip face dip at the dune limb.

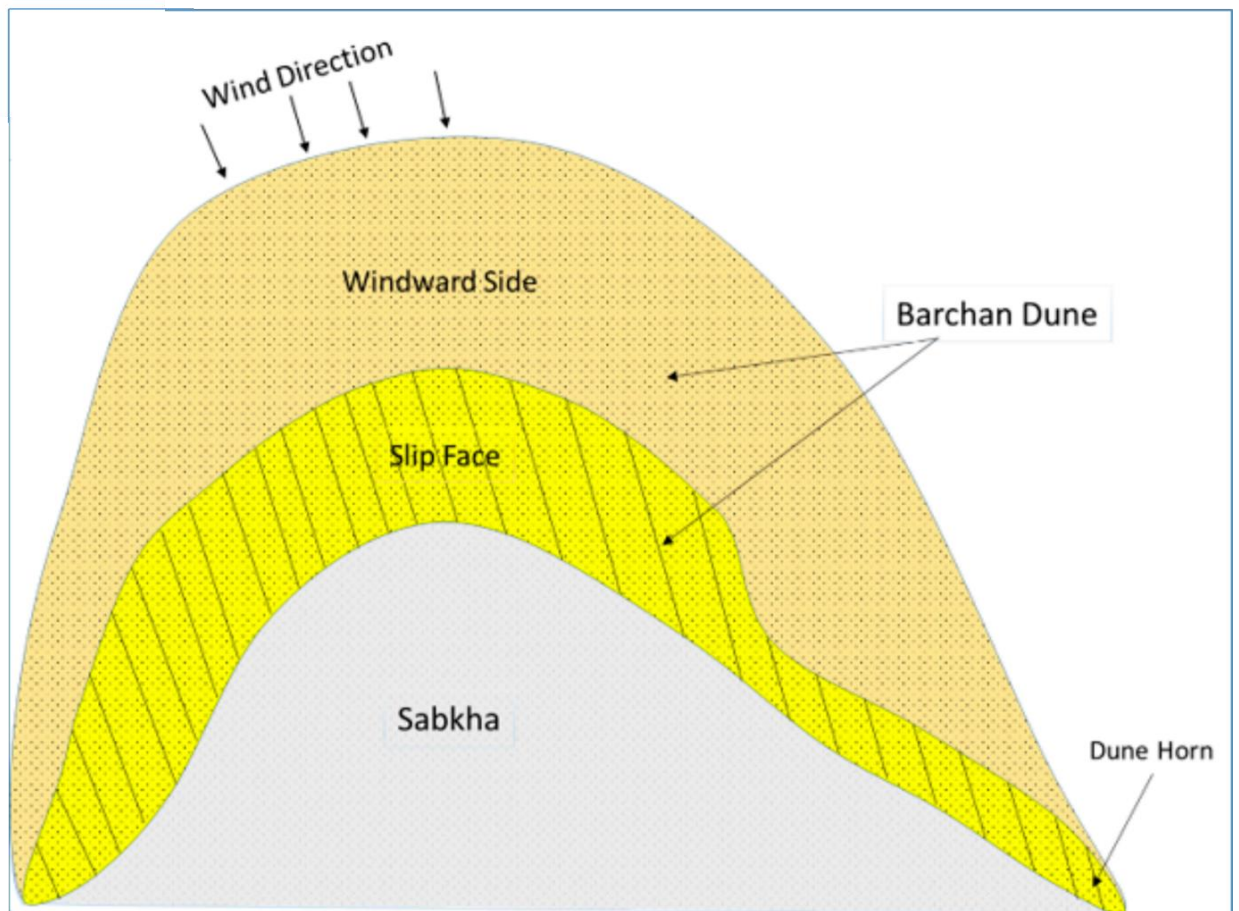


Figure 21: Schematic of the studied barchan sand dune, illustrating the wind direction, windward side, slip face and dune horn overlaying the sabkha (Benaafi et al. 2020).

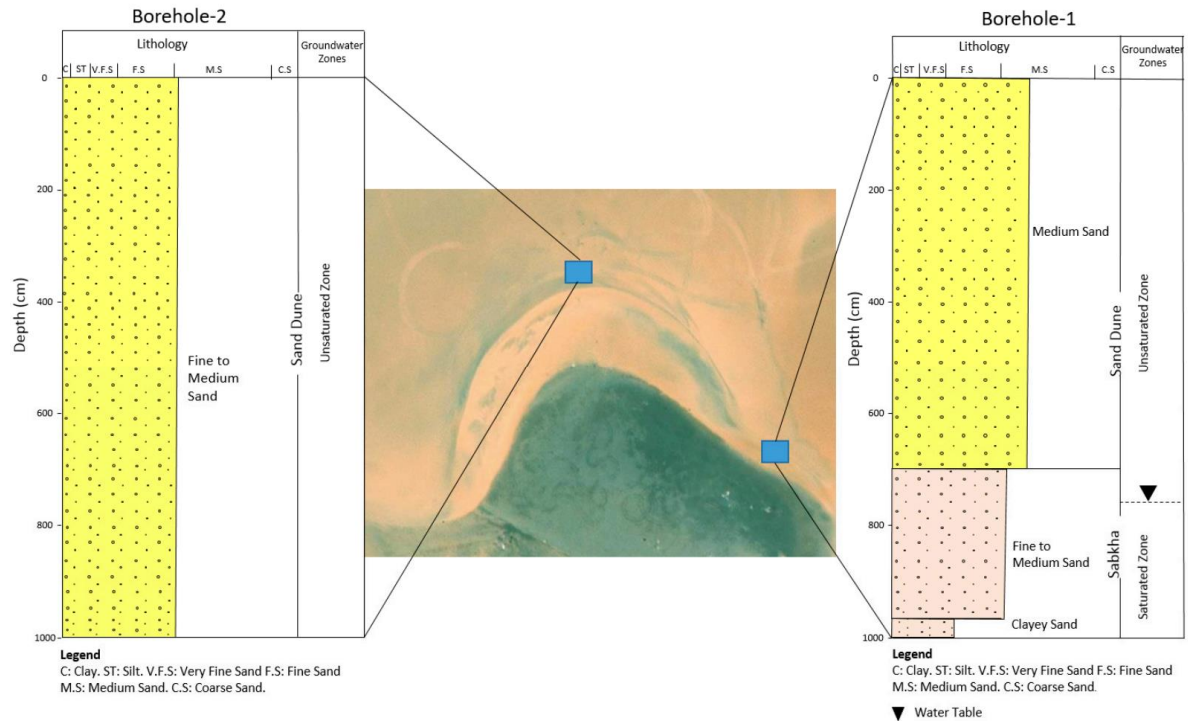


Figure 22: Lithology logs of two 10 m boreholes drilled onto the dune crest and limb detailing the sand types observed along with identification of the groundwater zone at approximately 750 cm depth on the dune limb (Benaafi et al. 2020).

This suggests that the process of sand deposition and accumulation remains consistent across all sections of the examined barchan sand dune. Most importantly, the sand properties remain consistent laterally at the dune limb and can be treated as a laterally homogenous medium. This leads to the expectation that any anisotropic effects observed from the sand dune would be due to the dipping sand layers shown in Figure 23.

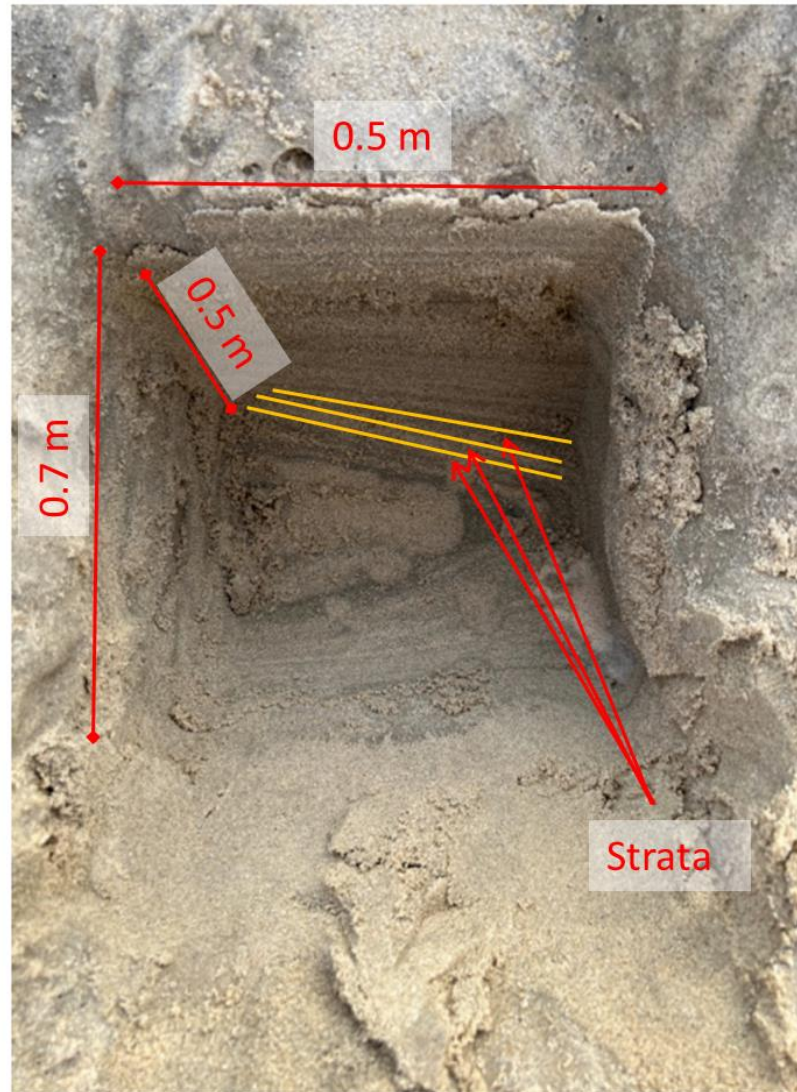


Figure 23: An approximately 50 cm trench excavated at the dune limb exposing the stratification pattern of the sand dune. The laminations or dark sand strata are shown to be slightly dipping as described in the work of Adetunji et al. (2008) at a nearby locality. The lighter colored sand is coarser sand, while the darker colored sand has a finer grain size.

The bedding of a sand dune is commonly parallel to its slip face due to the mechanics of the sand during deposition. Since the strike of the slip face at the dune limb (Figures 20 and 21) is oriented approximately NW-SE from north, this would suggest that the bedding of the sand dune is oriented in the same direction as the strike of the slip face.

4.2 Data acquisition

To test for the TTI effects of sand dunes on P-wave velocity, a circular seismic array geometry with a source in the center has been utilized to capture the data with respect to azimuth. The array has 24 vertical-component geophones with a natural frequency of 15 Hz all at an offset of 9 m from the point source and placed at an interval of 15° clockwise, with the first geophone (0° azimuth) along the north direction. A 2 kg small hammer and a metal plate of size 20 x 20 x 4 cm³ placed in the center of the seismic array were utilized as the source in this experiment. The metal plate was tightly pressed against the surface of the sand to secure contact between it and the dune. The data were recorded on a 24-channel Geode seismograph.

The seismic array was set up on the dune limb at an elevation of approximately 12 m, as it was relatively flat, with the target of maintaining the elevation of the geophones to not introduce further complications and errors that might mask the weak anisotropic effect. Finally, the positions of the geophones and the metal plate were recorded using a Trimble R10+ Differential GPS (DGPS) to obtain the most accurate reading for the positions of the equipment, which will be used later to retrieve the actual offset of each geophone.

The seismic experiment resulted in the collection of 20 shot gathers with 24 traces per shot gather, amounting to a total of 480 traces. Each of those traces has 501 samples at a sampling interval of 1.25 msec and a total recording time of 0.0625 seconds. An example of a common shot gather recorded at the site is shown in Figure 26.



Figure 24: Photograph capturing a lateral view of the studied dune limb and slip face. The red circle represents the survey geometry and location on the dune limb. The red line represents the strike of the slip face, which is usually parallel to the bedding of the dune.



Figure 25: Areal view of the study area with an illustration of the seismic array geometry, with a point source (demarcated by orange star) in the center of the 9-m radius circle and the 24 geophones (demarcated by green triangles) and their azimuth relative from north.

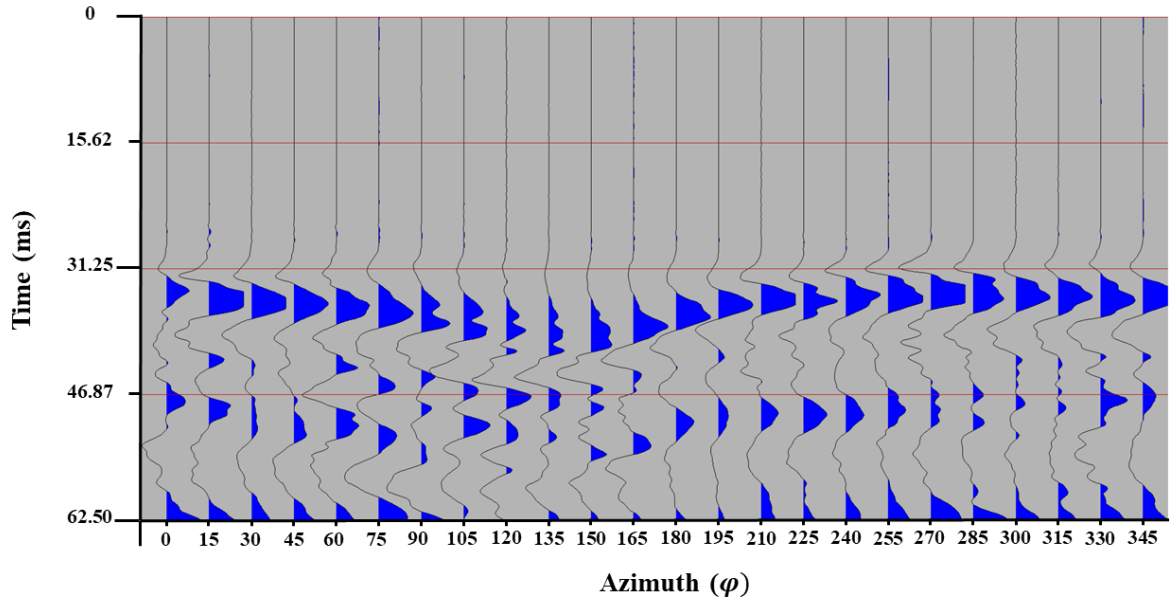


Figure 26: Sample shot gather. Data are clean with a high signal-to-noise ratio (SNR) and show 24 traces representing the traces recorded at each geophone and thus the azimuth of that geophone. A gain has been applied to the traces for visual purposes.

4.3 Data Processing

This section highlights the processes and procedures used to transform the raw seismic data recorded during the acquisition step to meaningful values of P-wave velocity with respect to both the incidence angle (θ) and azimuth (φ).

After collecting the recorded field data, gain was applied, and the first arrivals were picked for each of the 20 shot gathers (Figure 27). The first arrival picking step was performed on in-house software using an automated picking option and further revised manually to ensure coherency and consistency in the automated picks. The first arrival picking step results in a dataset of 480 arrival times, 20 for each of the 24 geophones used in the seismic experiment. The 20 time values corresponding to each geophone are then averaged to obtain one representative arrival time for that geophone and hence a representative arrival time for that azimuth.

Furthermore, the next step is to calculate the accurate distances of each geophone from the source using the DGPS coordinates. This is done on the UTM data with the easting, northing and elevation represented as x, y and z , respectively. Given this information, a Pythagorean relationship is presented in equation (18). This process is then repeated for the UTM data for each geophone (gp) against that of the source location to obtain the resulting distance (offset).

$$\text{Offset } (x) = \sqrt{(x_{gp} - x_{source})^2 + (y_{gp} - y_{source})^2 + (z_{gp} - z_{source})^2} \quad (16)$$

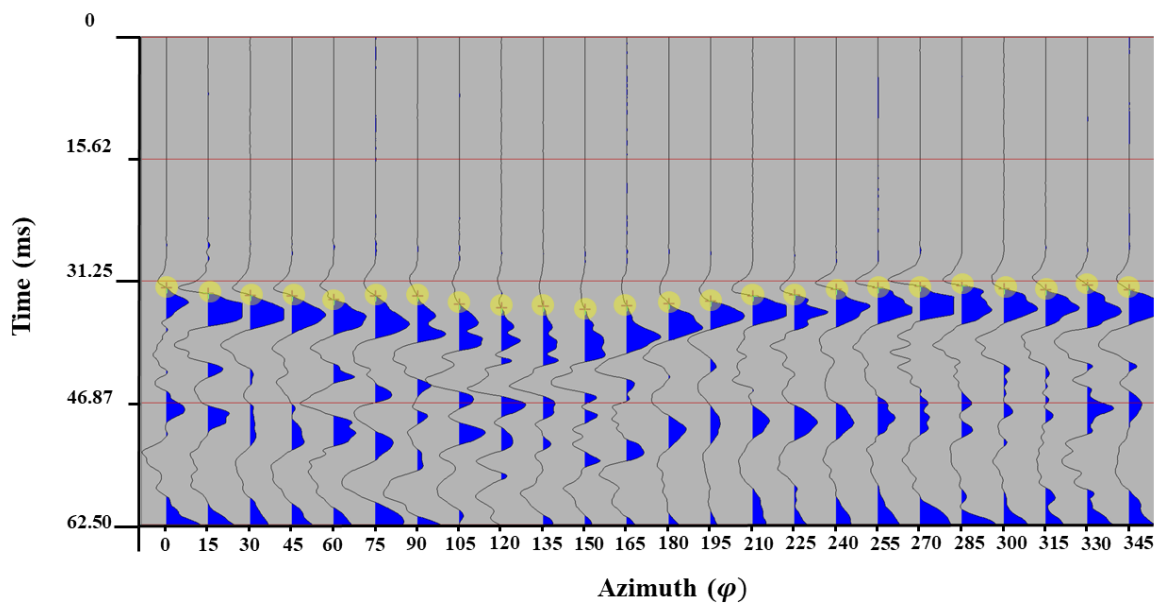


Figure 27: Shot gather 1 with the first arrival picks highlighted.

The averaged picked first-arrival traveltimes t can now be used in conjunction with their source-receiver offset (x) to calculate the P-wave propagation velocities in the sand dune. The source-receiver offset, respective average picked first arrival traveltime and P-wave velocity data are compiled for each geophone and displayed in Table (1). The 1st receiver is oriented north of the survey geometry, indicated as azimuth 0° in the table below. Given the circular nature of the geometry of the seismic array, every receiver has another receiver occupying the same line at 180° clockwise rotation, thus allowing us to view these receiver pairs as lines crossing the center of the seismic array.

Theory shows that the fastest wave path in a TTI medium is along the bedding, which can be quantified through a larger velocity of propagation. The opposite holds true for waves propagating against the dune bedding, which have relatively slower velocities of propagation. The data in Table 1 show that the fastest velocities occur in the lines occupied by receiver pairs 8-20, 9-21, and 10-22. These receiver pairs are oriented in an approximately NW-SE direction, which evidently matches the strike of the slip face and hence the bedding of the sand dune.

On the other hand, the slowest velocities, given by the data in Table 1, are those of receiver pairs 2-14, 3-15 and 4-16. These receiver pairs generate lines that are oriented in the NE-SW direction, which suggests that they are perpendicular to the dune bedding. This finding confirms the geological field observations of the orientation of the dune bedding and ties them with the geophysical results of seismic experiments.

Geophone number	Azimuth(φ)	Offset(m)	Averaged time(s)	Calculated Velocity(V_{qP})
1	0	8.8591960	0.0317188595	279.3037372608
2	15	8.8983176	0.0325358555	273.4926579693
3	30	8.9025215	0.0325420680	273.5696299326
4	45	8.8895013	0.0325556370	273.0556708198
5	60	8.8713596	0.0321282600	276.1232509946
6	75	8.8337687	0.0318179025	277.6351678116
7	90	8.8301777	0.0314397500	280.8603026424
8	105	8.8171720	0.0318244905	277.0561872782
9	120	8.9047602	0.0314246400	283.3687259424
10	135	8.8826840	0.0322910565	275.0818636114
11	150	8.8667440	0.0329267215	269.2871806262
12	165	8.9012117	0.0325144750	273.7615077592
13	180	8.9846605	0.0327837285	274.0585318110
14	195	8.9964292	0.0327281310	274.8836833976
15	210	8.9472061	0.0327076200	273.5511205034
16	225	8.9931657	0.0326618940	275.3412187303
17	240	8.9808985	0.0319311770	281.2579849468
18	255	8.9477574	0.0318180825	281.2161103674
19	270	8.9245093	0.0316095945	282.3354567234
20	285	8.9975486	0.0316637515	284.1592727886
21	300	8.9661163	0.0318465565	281.5411550068
22	315	8.9431966	0.0315728280	283.2561150366
23	330	8.9704119	0.0314051445	285.6351098783
24	345	8.8807667	0.0316626960	280.4804335045

Table 1: Azimuth, offset, averaged picked first arrival travelttime, and P-wave propagation velocity for each geophone in the seismic experiment.

4.4 Exploratory Data Analysis

In this section, the dataset is statistically explored and graphically summarized. The dataset is split into its two constituents, offset data and traveltime pick data, allowing for a more reliable analysis.

The offset dataset consists of data on the geophone number (also indicating the azimuth), source-receiver offset in meters, the difference between the offset and the nominal mean of 9m represented by Δx and lastly, the percentage residual against the nominal mean (Table 2 and Figure 28).

On the other hand, the traveltime pick dataset is extensive with 20 time values at each geophone number, thus only the mean, median, minimum, and maximum of the time picks at each receiver as shown in Table 3. The mean value of the mean traveltime pick values at each receiver is taken as the nominal mean and subsequently subtracted from the mean traveltime picks to compute Δt and the percentage of the residual against the nominal mean (Figure 29).

GP Number	Offset	$ \Delta x $	$ \Delta x /9\%$
1	8.86	0.140804	1.564488889
2	8.90	0.1016824	1.129804444
3	8.90	0.0974785	1.083094444
4	8.89	0.1104987	1.227763333
5	8.87	0.1286404	1.429337778
6	8.83	0.1662313	1.847014444
7	8.83	0.1698223	1.886914444
8	8.82	0.182828	2.031422222
9	8.90	0.0952398	1.05822
10	8.88	0.117316	1.303511111
11	8.87	0.133256	1.480622222
12	8.90	0.0987883	1.097647778
13	8.98	0.0153395	0.170438889
14	9.00	0.0035708	0.039675556
15	8.95	0.0527939	0.586598889
16	8.99	0.0068343	0.075936667
17	8.98	0.0191015	0.212238889
18	8.95	0.0522426	0.580473333
19	8.92	0.0754907	0.838785556
20	9.00	0.0024514	0.027237778
21	8.97	0.0338837	0.376485556
22	8.94	0.0568034	0.631148889
23	8.97	0.0295881	0.328756667
24	8.88	0.1192333	1.324814444

Min	8.8171720000
Max	8.9975486000
Mean	8.9162533792
Median	8.9036408500
Standard Deviation	0.05583273

Table 2: Exploratory data analysis of Offset dataset

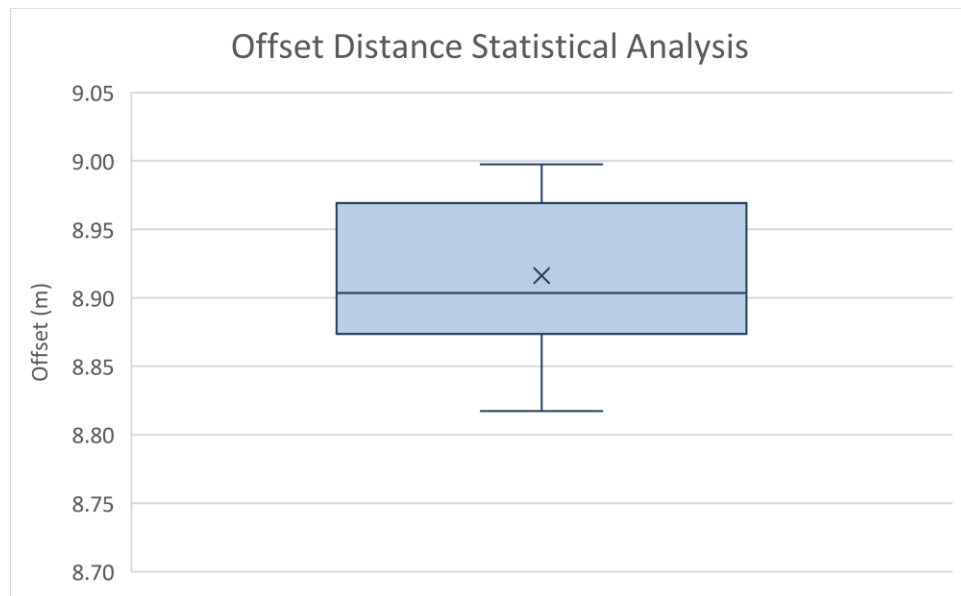


Figure 28: Statistical summary of the offset dataset, where the whiskers represent the maximum and minimum values, the x marks the mean and the line going across denotes the median.

GP Number	Mean of Traveltime Picks	Min of Picks	Max of Picks	Median of Picks	Standard Deviation of Picks	Δt	$\Delta t / \text{Nominal Mean } \%$
1	0.0317	0.0315420100	0.0320331100	0.0317194000	0.000131006	0.000369096	1.150261835
2	0.0325	0.0323464400	0.0328847400	0.0325315300	0.0001501221	0.0004479	1.395852431
3	0.0325	0.0323575000	0.0328917000	0.0325260950	0.0001497834	0.000454113	1.415213279
4	0.0326	0.0323743200	0.0328971400	0.0325346950	0.0001503892	0.000467682	1.457500174
5	0.0321	0.0319501500	0.0324048900	0.0320926500	0.0001311444	4.0305E-05	0.12560788
6	0.0318	0.0315310600	0.0320486300	0.0318200900	0.0001543169	0.000270053	0.841600844
7	0.0314	0.0312424200	0.0315999600	0.0314096700	0.0001155945	0.000648205	2.020088223
8	0.0318	0.0315196700	0.0320311800	0.0318443500	0.0001254862	0.000263465	0.821069775
9	0.0314	0.0312452000	0.0315896600	0.0313988650	0.0001013407	0.000663315	2.067177544
10	0.0323	0.0320209300	0.0325570800	0.0322920450	0.000145882	0.000203101	0.632952458
11	0.0329	0.0323234500	0.0335472300	0.0329794400	0.0003744893	0.000838766	2.613960597
12	0.0325	0.0319237300	0.0330142800	0.0325522750	0.0003174434	0.00042652	1.32922151
13	0.0328	0.0326204400	0.0329099500	0.0328131700	0.0000932229	0.000695773	2.168332323
14	0.0327	0.0325599500	0.0328919200	0.0327501400	0.0001036282	0.000640176	1.995066373
15	0.0327	0.0325457000	0.0329781400	0.0326803600	0.0001264519	0.000619665	1.931145191
16	0.0327	0.0324832300	0.0329890700	0.0326209100	0.0001398541	0.000573939	1.788643122
17	0.0319	0.0317718500	0.0322664600	0.0318892650	0.0001364004	0.000156778	0.488588319
18	0.0318	0.0316772900	0.0320843500	0.0317857000	0.0001132994	0.000269873	0.841039886
19	0.0316	0.0314721000	0.0319878000	0.0315645550	0.0001346858	0.000478361	1.490779017
20	0.0317	0.0315409000	0.0320526100	0.0316083150	0.0001358241	0.000424204	1.32200229
21	0.0318	0.0317323600	0.0321938500	0.0318120150	0.0001167949	0.000241399	0.752302538
22	0.0316	0.0314228600	0.0319310200	0.0315514700	0.0001182063	0.000515127	1.605359394
23	0.0314	0.0312383900	0.0317773200	0.0313818900	0.0001220146	0.000682811	2.127933986
24	0.0317	0.0315039200	0.0319245500	0.0316698950	0.0001181109	0.000425259	1.325291687
Mean	0.0320879550						
Min	0.0314051445						
Max	0.0329267215						
Median	0.0318888668						
Standard Deviation	0.000501165						

Table 3: Exploratory data analysis of traveltime picks dataset.

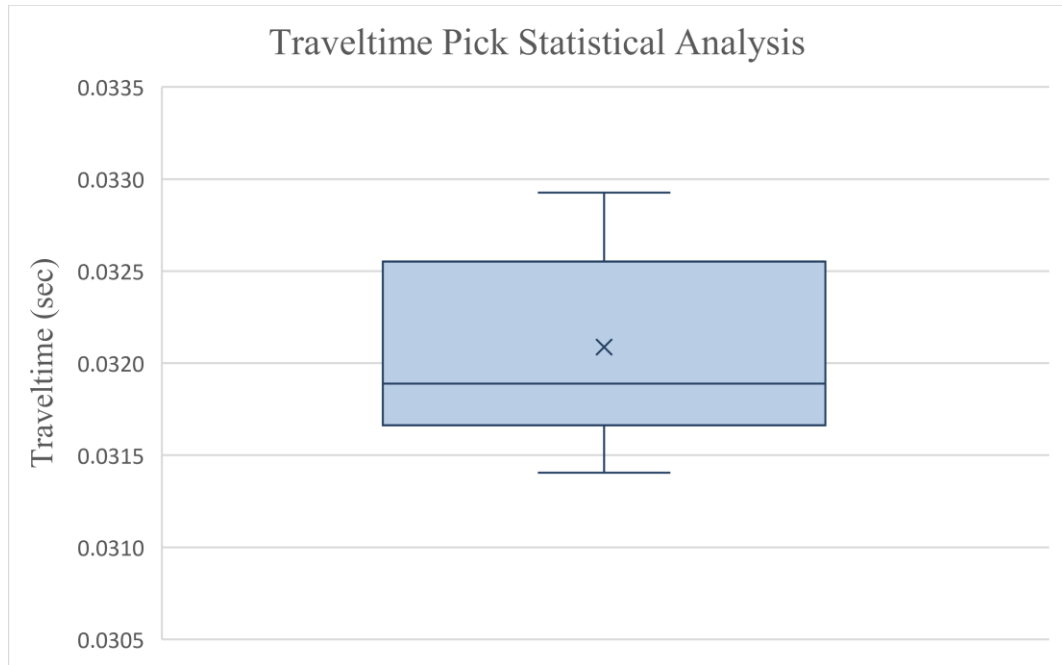


Figure 29: Statistical summary of the picked traveltime means dataset, where the whiskers represent the maximum and minimum values, the x marks the mean and the line going across denotes the median.

CHAPTER 5

RESULTS AND DISCUSSION

V_{qP} represents the measured P-wave propagation velocity while the rest of the expressions in equation (10) are the relevant angles φ , θ , and θ_0 calculated as illustrated in Figure 17. The values for φ are given by the seismic array geometry ranging from 0° - 345° corresponding to the position of the receiver. In addition, the value of θ_0 is dictated by the dip of the dune bedding, which is appropriated as the dip of the TTI symmetry axis. The work of Adetunji et al. (2008) describes field measurements of the dipping angle of the strata equal to about 30° in a barchan sand dune near the study area (Figure 16). Moreover, the value of θ is calculated using a simple trigonometric relation that transpires when viewing the propagation of the P-wave along the strike direction (Figure 28). The depth of penetration “z” is 1.52 m calculated using equation (13). The result is then utilized in conjunction with the information in Figure 28 to obtain θ by the following simple trigonometric relationship:

$$\theta = \arctan\left(\frac{4.5}{1.52}\right) = 71.33^\circ \quad (17)$$

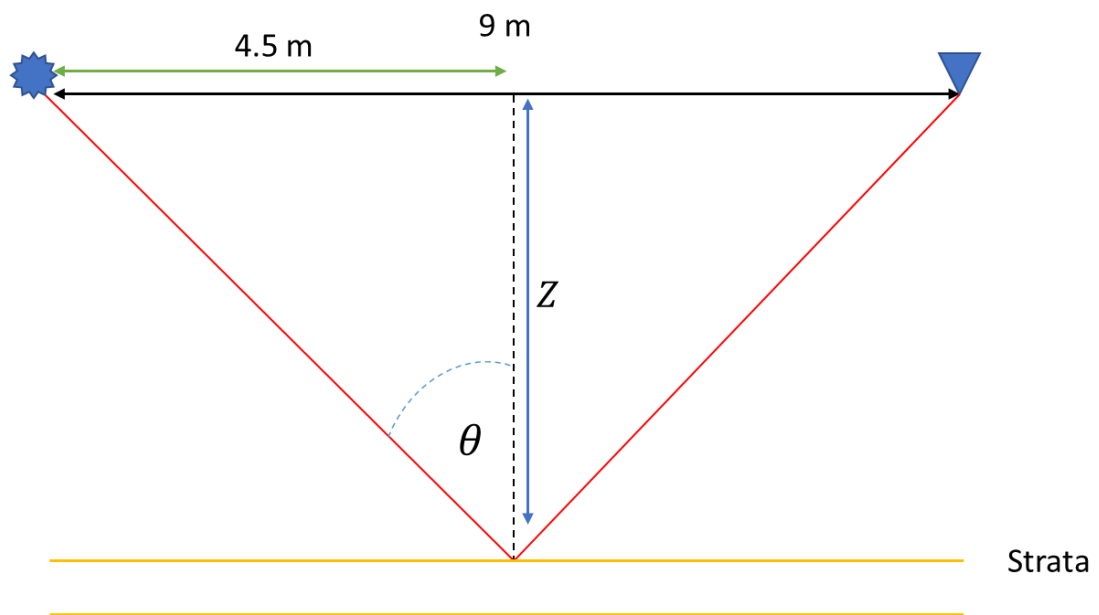


Figure 30: Illustration of simplified P-wave propagation along the strike, where the 9 m line represents the source-receiver offset, z is the depth of penetration and θ is the incidence angle. The star represents the source, while the triangle signifies the receiver location.

Following the computation of “ z ”, equation (14) was used to calculate the velocity as $V_z = 328.198$ m/s. V_0 and k were measured at the locality of the study area by Hanafy et al. (2020) with values of 15.1 m/s and $410 \text{ m}^{(-1/3)}$, respectively. Utilizing these values, the vertical one-way travel $T_2 = 0.0055537$ s is computed using equation (16) and later substituted in equation (17) as “ t ”. “ z ” is used as “ d ” to obtain the average one-way P-wave velocity along the symmetry axis $V_{p0} = 273.691$ m/s.

The values of E and F are computed using equation (9) at each receiver given the relevant corresponding angles (shown in Table 2). Note that angles θ and θ_0 are constant for all receiver locations at 71.33° and 30° , respectively, while φ is variable.

φ	E	F
0	-0.196565153	0.401593088
15	-0.180424004	0.441523046
30	-0.13310055	0.549581669
45	-0.057819807	0.693788908
60	0.040287969	0.830691156
75	0.154536893	0.917332626
90	0.277141091	0.923192816
105	0.399745288	0.83886227
120	0.513994212	0.679098068
135	0.612101988	0.479403908
150	0.687382732	0.287014739
165	0.734706185	0.148667689
180	0.750847334	0.098406912
195	0.734706185	0.148667689
210	0.687382732	0.287014739
225	0.612101988	0.479403908
240	0.513994212	0.679098068
255	0.399745288	0.83886227
270	0.277141091	0.923192816
285	0.154536893	0.917332626
300	0.040287969	0.830691156
315	-0.057819807	0.693788908
330	-0.13310055	0.549581669
345	-0.180424004	0.441523046

Table 4: Results of computation of E and F using equation (9) at each corresponding azimuth, where $\theta = 71.33^\circ$ and $\theta_0 = 30^\circ$.

Finally, the Thomsen parameters (ε and δ) are determined through the use of an algorithm that uses nonlinear least squares to fit the two parameters under a function, given by equation (10), to the measured velocity data $V_{qP}(\theta, \varphi)$ (Figure 29). $V_{p0} = 273.691$ m/s represents the P-wave propagation velocity along the TTI symmetry axis, and E and F are based on the three angles φ, θ and θ_0 (Table 2). Subsequently, the values of ε and δ are evaluated to be:

$$\varepsilon = 0.03461668$$

and

$$\delta = 0.00511634.$$

These small values prove that the studied sand dune was an anisotropic medium exhibiting weak TTI anisotropy ($\varepsilon < 0.1$, $\delta < 0.1$).

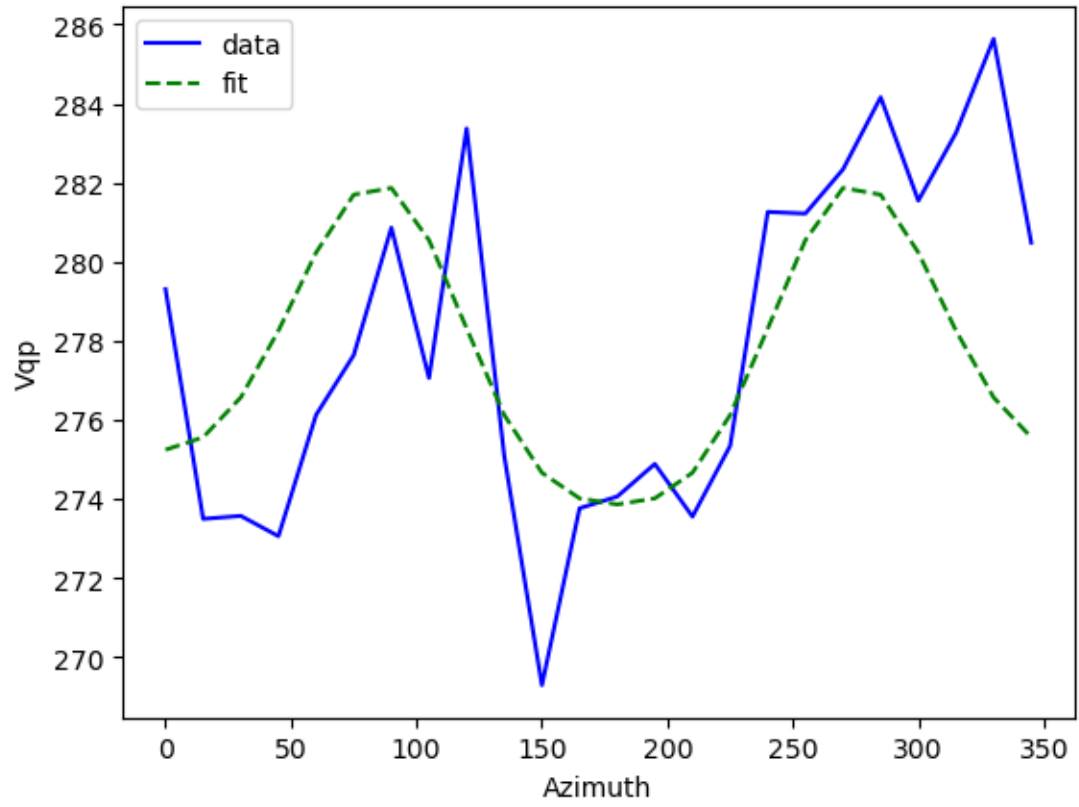


Figure 31: Visual representation of the fitted function (green color) overlaying the measured $V_{qp}(\theta, \varphi)$ data (blue color)

5.1 Error Analysis

In this section, the accuracy of the results is inspected through the computation of a predicted dataset using the determined Thomsen parameter (ε and δ) values. This is followed by a comparison between both the measured and predicted datasets. This process allows for the evaluation of the quality of fit and quantification of the error incurred during the experiment. I start by defining the sum of squared errors (SSE) and root mean square error (RMSE) as:

$$SSE = \sum (y_i - \hat{y}_i)^2, \quad RMSE = \frac{\sum (y_i - \hat{y}_i)^2}{n} \quad (18)$$

where y_i is the actual measured value for $V_{qp}(\theta, \varphi)$, while $\hat{y}_i$ represents the predicted value of $V_{qp}(\theta, \varphi)$ using the fitting algorithm. The SSE and RMSE are computed as 310.087 and 3.594, respectively. The SSE is then be divided by the sum of squares of the measured $V_{qp}(\theta, \varphi)$ dataset to obtain a percentage error relative to the measured data:

$$\frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i)^2} \quad (19)$$

resulting in a value of 0.0167 (or) 1.67%. This value constitutes the residual sum of squared errors between the measured and predicted datasets as a percentage of the sum of squares of the measured dataset, further exemplifying the quality of the fit.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Unconsolidated dune sands cover the surface of many of the world's largest natural resource reservoirs and pose unique challenges for geoscientists and seismic data, many of which lead to poor seismic images with low signal-to-noise ratios. This can be attributed to their complex topography and the loosely compacted nature of the sediments. Given that sand dunes in the study area exhibit dipping cross-strata, this study suggests modeling the dune as a homogenous tilted transversely isotropic (TTI) medium and investigating the effect on compressional wave velocities.

The seismic data are collected through the design and deployment of a circular seismic array geometry on a barchan dune's limb, with a total of 24 receivers all equally spaced at 15° apart azimuthally, with a nominal source-receiver offset of 9 m. A total of 20 common shot gathers were recorded, each consisting of 24 traces. Each trace houses 501 samples with a sampling interval of approximately 1.25 ms and a total recording time of 0.0625 seconds.

The P-wave propagation first arrival traveltimes of the recorded data are picked, while the accurate source-receiver offsets are obtained from the DGPS data on their exact locations, allowing for the calculation of the P-wave propagation velocity $V_{qP}(\theta, \varphi)$. The characteristics of the TTI model are dependent on three angles, namely, the azimuth $\varphi = 0^\circ - 345^\circ$ corresponding to the geophone placement on the seismic array about north at

0° , the tilt of the symmetry axis $\theta_0 = 30^\circ$, which follows the dip of the strata, and finally $\theta = 71.33^\circ$ representing the incidence angle of the P-wave.

Under the assumption that the medium exhibits a weak anisotropy, the direction of propagation of the phase and group velocity are aligned within it. The values of E and F are then calculated at their corresponding azimuths, as well as $V_{p0} = 273.961$ m/s. Finally, the Thomsen parameters ε and δ are calculated through an algorithm that utilizes nonlinear least squares to fit a TTI function against the measured velocity data $V_{qp}(\theta, \varphi)$. The resulting Thomsen parameter values were evaluated to be $\varepsilon = 0.03461668$ and $\delta = 0.00511634$. The subsequent use of the Thomsen parameters for the prediction of P-wave velocity produces results with a 1.67% error and an RMSE of 3.594.

The results of this study proves that the sand dune can be viewed as a weak anisotropic medium which affects the P-wave velocities. Along a 2D section this would corroborate the work of Hanafy et al. (2020) which proves that accurately measuring and accounting for the velocity changes within the weathering layer during static correction leads to a large reduction in error as opposed to using a constant replacement velocity. Ultimately leading to less shifts in the positions of deeper reflectors and a seismic image more representative of the subsurface.

On the other hand, in the case of 3D data with P-waves arriving at different times from different azimuths. If the arrival times are gone unaligned or uncorrected for these azimuthal effects, stacking the data can prove detrimental to the quality of the stacked image. As the unaligned arrivals will tend to cancel each other out, which will inversely reduce the signal to noise ratio rather than increase it.

I believe that this study provides many avenues to be expanded upon in the realm of the anisotropic behavior of unconsolidated sand. I would recommend future works to do the following:

1. Explore different seismic acquisition geometries that would allow for the capturing of the effects not only with azimuth but with offset as well. Some extensions to this work would be to study the effects of anisotropy along each line of receivers at the same intervals to gain insight into the effect on P-wave velocities relative to different offsets.
2. Repeating the experiment in different localities would prove invaluable in examining whether the observed weak anisotropic behavior of sand dunes is a global phenomenon.
3. Simulation of the results on a synthetic dataset would allow control of such variables as the tilt of the symmetry axis, allowing for the investigation of the magnitude of the role each variable contributing to the overall result.

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