Why accelerating the rush towards seismic for prospecting?

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SUMMARY

We have used seismic data from a sedimentary basin and taken examples from hard rock provinces to present an overview of seismic potential in delineating faults and fracture zones. Faults can act as fluid migration pathways, one of the most important components of petroleum and mineral system concepts. Migration pathway along with source, entrapment, and preservation form the critical geological elements required for the existence of resources. Our focus in this paper is on the utility of seismic for fault characterisation, however additional applications of seismic have been implemented by many workers for prospecting in petroleum and mineral systems which is not covered in our review.

Features consistent with fault zones can be revealed in seismic volumes through the creation of specific attributes. Coherence, local structural dip, spectral decomposition, are some attributes that have been used to discriminate discontinuities and trends within seismic data. We interpreted several features related to structural and stratigraphic patterns, for example damage zones indicating NW-SE striking faults in onshore Taranaki Basin. Fault interpretations which are performed based on a range of seismic attributes, are a more realistic approach to narrow down the search space in prospecting phase.

Key words: seismic attributes, fault, petroleum system, mineral system, mineral exploration

INTRODUCTION

Reflection seismic data is one of the critical elements of successful petroleum exploration campaigns. Two factors that contribute to the utility of seismic for exploration are its role to the creation of subsurface models and reliability for geological mapping and prospecting. Seismic, like many geophysical techniques, does not directly measure the target rock geological properties. Rather, it measures the transmission times of seismic waves between source and receiver and the two main physical properties of rocks that control the transmission time are velocity and density. The elements of geology and their delineation, either in two-dimensional or three-dimensional space, can be recognised if their properties can be expressed in acoustic impedance (product of velocity and density) variations. Faults and damage zones cause lateral and vertical changes in acoustic impedance as there has been displacement of rocks along a surface (Sheriff, 2002). Faults can be tracked as discontinues patterns on seismic data, however, the magnitude of their imprint depends on the impedance contrast of the two sides of faults relative to one another, structural setting and the characteristics of seismic data itself – vertical resolution, noise content and reliability of imaging for example (Herron, 2011).

There are two common methods to recognise fault patterns on seismic data, one is based on visual observations of discontinuities, displacements (offsets) and terminations of the reflectors. The most used technique in fault interpretation is correlation of geometries along the fault plane as they mark boundaries of packages of reflectors with consistent character (continuity, amplitude, and frequency). The main limitation of this method is that discontinuity patterns and offsets are not always obvious and clearly defined. For example, the accuracy of tracking faults on two-dimensional seismic data depends on the strike of faults and orientation of the seismic lines – most often observed in the displacement of reflectors– does not represent the true dip of the fault. This is especially true in greenfield exploration regions where there is minimum information available about the structural styles and hence reflection patterns have multiple potential causes that may or may not be related to fault processes.

Another technique for detecting faults is through seismic attributes (mathematical measurements obtained from seismic data (Sheriff, 2002)). An attribute or combination of attributes can provide further insights into geological context that was previously impossible or difficult to interpret visually on reflection data, with the caveat that generated features may not always be geologically meaningful. Structural attributes have enormous role to assist in interpreting structures at all scales from regional scale (1000’s of km) to deposit scale (100’s of m) (Alistair, 2011; Brown, 2011; Chopra & Marfurt, 2007).
In this article, we discuss few structural attributes including coherence, local structural dip and spectral decomposition that we used for a three-dimensional seismic volume from onshore Taranaki Basin in New Zealand. Additionally, some examples from literature are narrated to add insight into the application of seismic for mineral prospecting.

FAULTS IN PETROLEUM AND MINERAL SYSTEM CONCEPTS

The petroleum and mineral system concepts are models that address prospectivity of a region based on the critical elements required for the formation and preservation of the resources of interest. The petroleum system has been practised as the prominent approach in targeting for hydrocarbon accumulations for many decades (Magoon & Dow, 1991) while mineral system concept has been championed by mining industry in the last 25 years (Hronsky & Groves, 2008; Wyborn et al., 1994). McCuaig et al. (2010) argue that the mineral systems approach mimicked the conceptual targeting stablished in the petroleum industry in its early days.

The common ground of both concepts for prospectivity are the critical elements required for the existence of the resource in question, in adequate size and economic value. These elements are source (hydrocarbon generating rocks or fertile ore-component fluids) in a suitable geological setting for migration (from source to trap), trap and finally suitable processes to preserve the entrapped resources (Magoon & Dow, 1994; McCuaig et al., 2010; McCuaig & Hronsky, 2014).

The important geological element required for migration pathway in both petroleum and mineral system are faults, which act as a conduit for petroleum, hydrothermal, and/or magmatic fluids. Permeability is another important parameter of the rocks that form pathways for fluid migration. A fault can lead to the development of migration pathway due to increased permeability along its surface; a more in-depth discussion is presented in Moretti (1998).

In petroleum, the role of faults for hydrocarbon migration and charge is well documented in literature (Allan, 1989; Aydin, 2000; Eng & Tsuji, 2019; Hooper, 1991; Jin et al., 2008; Lampe et al., 2012; Ligtenberg, 2005; Magoon & Dow, 1994; Moretti, 1998; Weber et al., 1978). The relationship between petroleum discoveries and major structures in onshore Taranaki Basin, New Zealand (where the three-dimensional seismic data used for this paper has been acquired (Figure 1)) is well considered by many researchers and companies conducting exploration in the area. For example, Sykes (2012) claims the vital role of fault mechanisms in the process for hydrocarbon migration in Kupe Area, South Taranaki Basin.

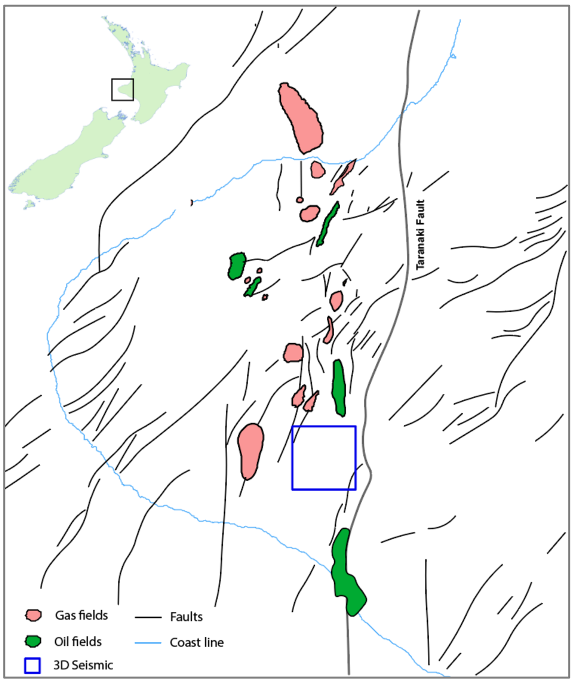

Figure 1. Location of three-dimensional seismic data, oil and gas fields and the regional faults in onshore Taranaki, New Zealand. Modified from NZ Petroleum & Minerals, 2013.

In mineral geology, like petroleum, faults are crucial in facilitating fluid flow through rocks by developing permeability. This is evidenced in numerous mineral systems as alteration zones (resulted from hydrothermal activities) and deposits have been encountered near fault intersections (Chauvet, 2019). Examples are orogenic gold and porphyry copper (formed by hydrothermal fluids migrating through deep crustal faults extended to the near surface environment) as two commodities controlled by structures. Figure 2 illustrates the mineralisation sites and major bedrock structures of the Yilgarn Craton in Western Australia, indicating a close relationship between the occurrence of gold and tectonic evolution of the craton (Groves, 1993).

Although not all faults have the required characteristics for migration pathways, many works have confirmed the relationship between networks of faults and shear-zones with regional-scale source volumes and prospect-scale trap sites leading to accumulation/deposition of economic resources (Bierlein et al., 2006; Blewett, 2010; Carranza & Hale, 2002; Groves et al., 1998; Groves et al., 2020; Mirzaie et al., 2015; Sibson et al., 1988; Witt, 1993; Yang et al., 2020; Yang & Cooke, 2019). Therefore, we claim that mapping faults and understanding their geometries has crucial importance to narrow down the search space in both petroleum and mineral systems.

SEISMIC REFLECTION FOR FAULT INTERPRETATION

With the current decrease in surface evidence for economic resources and increase in deep targeting, geophysics is an important exploration tool to understand faults and damaged zones leading to finding buried resources. Seismic is the main geophysical method used in petroleum exploration (Alsadi, 2017; Ashcroft, 2011; Ikelle & Amundsen, 2018), but for minerals is relatively new compared to potential fields and other methods. However, seismic has gained increasing acceptance and is being widely applied over the last two decades for mineral exploration as the method has potential to produce high resolution images at greater depths where other geophysical methods have significant limitations (Dentith & Mudge, 2014).

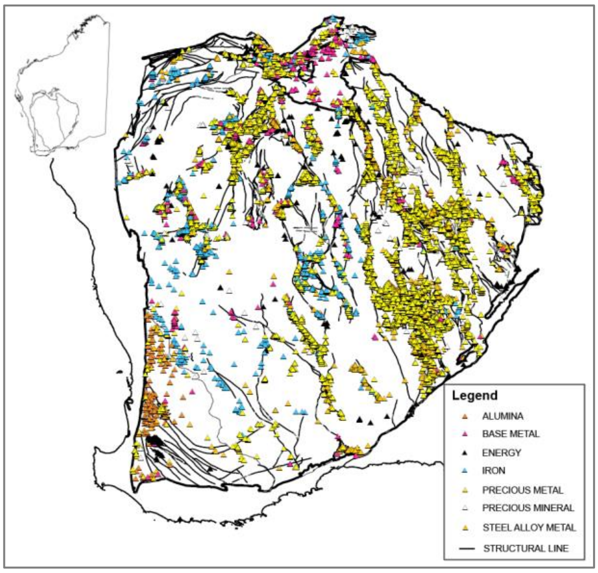

Figure 2. Mineralisation sites and major structures in Yilgarn Craton of Western Australia. Modified from GSWA's Mines and mineral deposits, 2021 and 1:2.5M State interpreted bedrock geology structural lines, 2021 GIS layers

Seismic reflections can be acquired as two- or three-dimensional data. The method is based on recording reflection arrivals from subsurface interfaces where there are changes in acoustic impedance. Examples are lithology boundaries with varying density and velocity of underlying and overlaying units or fault surfaces where a part of the transmitted energy is reflected back to the surface. Because of the physics of seismic method involves wave propagation in three-dimensions significant noise is recorded while acquiring seismic reflections. Therefore, data requires complex processing (Yilmaz, 2001). We are not discussing processing as it is out of scope for this paper but instead focus on reliability of seismic reflection for fault delineation once data is processed, reviewed and quality controlled.

Seismic reflections are commonly used to portray the extent of faults spatially and vertically (in depth) in different geological settings. Because the cornerstone of seismic is the changes in acoustic impedance of subsurface units, faults creating acoustic impedance contrasts could be imaged as far as the vertical resolution (which is a function of wavelength determined by direct relationship with velocity and reverse with frequency) is considered, regardless of fault type and depth. Velocity typically increases with increasing depth while frequency decreases. The higher the velocity and/or the lower the frequency, the bigger the wavelength and hence the lower the vertical resolution. When working with good quality data to interpret faults, amplitude sections can be used to observe discontinuities (separation between the packages of reflectors). Figure 3a illustrate features representing faults in different shapes and sizes, meaning the seismic data set has such a resolving power in terms of temporal and spatial resolution limits to portray faults. Interpreted extensional faults marked in dashed red lines (Figure 3b) offset the dashed green horizon with blocks downthrown to the right of the image. Other high amplitude reflectors on the section also provide clear-cut evidence for faulting.

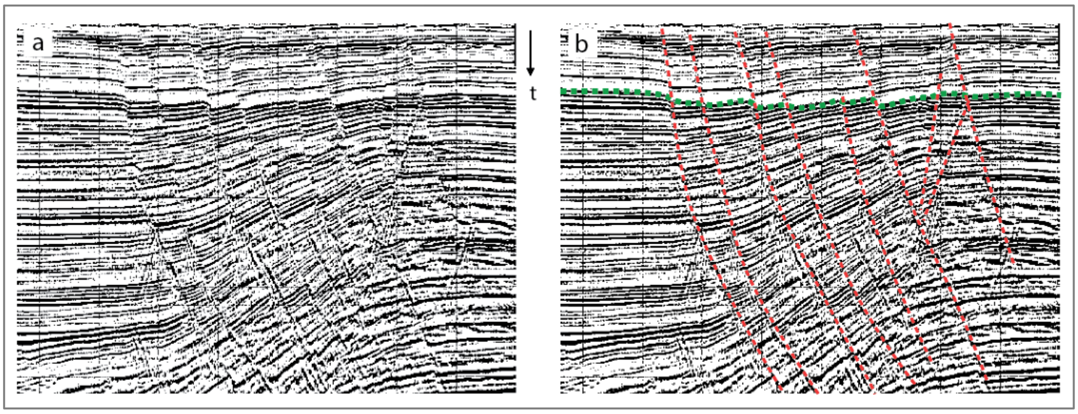

Figure 3. a) Seismic line with 'linear' features showing displacement of the two blocks relative to one another, b) Extensional faults marked in dashed red lines which offset the dashed green horizon and other high amplitude reflections downthrown to the right. Modified after (Herron, 2011)

Given varying quality of seismic and complex characteristics of faults, qualitative observation of data will not always assist with the interpretation of individual faults. Another way of detecting faults on seismic is using attributes which are derivatives of geophysical measurements (Brown, 1996). Many workers have classified attributes based on time, amplitude, frequency, and attenuation of seismic waves recorded in the dataset (Barnes, 1999; Chopra & Marfurt, 2007; Taner et al., 1994). Tens of measurements (attributes) can be driven from seismic data or from another seismic attribute to highlight geometry or other properties of geological features. The choice of an attribute depends on the type (two- or three-dimensional) and quality of available seismic data (e.g., signal to noise ratio), and the objective of the interpretation (stratigraphic or structural).

Table 1 summarises some attributes grouped by their application in seismic exploration and interpretation. These are the common attributes that is also used in Geology Designer - tNavigator® (Rock Flow Dynamics' geological modelling and seismic interpretation software). Additionally, spectral decomposition and Machine Learning Based Seismic Faults Detection are two other algorithms that are available in the software for either structural or stratigraphic interpretation purposes. The attributes mentioned here are by no means an exhaustive list of available attributes for seismic data analysis but are intended to exhibit their applicability if resolving geological features.

Structural Attributes	**Stratigraphic Attributes**
Coherence	Apparent polarity
Gradient magnitude	Chaos
Local structural azimuth	Local Flatness
Local structural dip	Relative acoustic impedance
Structural smoothing	Sweetness
Variance	

Table 1: Common seismic attributes grouped by category available in tNavigator®

We applied some of the attributes on an open-source three-dimensional seismic dataset from onshore Taranaki Basin to demonstrate the potential of seismic reflection data in imaging structures and damaged zone features. The examples discussed below are coherence, local structural dip, and spectral decomposition generated from reflector measurements.

Coherence calculates the degree of similarity between traces withing a specified 3D window. This trace similarity is represented by values ranging from 0-1 and is primarily used to highlight any discontinuities in the trace response which can arise from structural features such as faults.

Local structural dip is used to calculate extract specific properties from the seismic volume, such as estimating the degree of permanent depression within sediments, by computing the local dip of the reflectors. This dip can be calculated by three primary methods: 1) Gradient: Computing the dip (ranging from -90 to 90) of the instantaneous gradient of a sample neighbourhood; 2) Event: Computing the downslope dip (ranging from 0 to 90) of the estimated event; 3) Principal Component: local dip estimation from principal component analysis using a gradient covariance matrix.

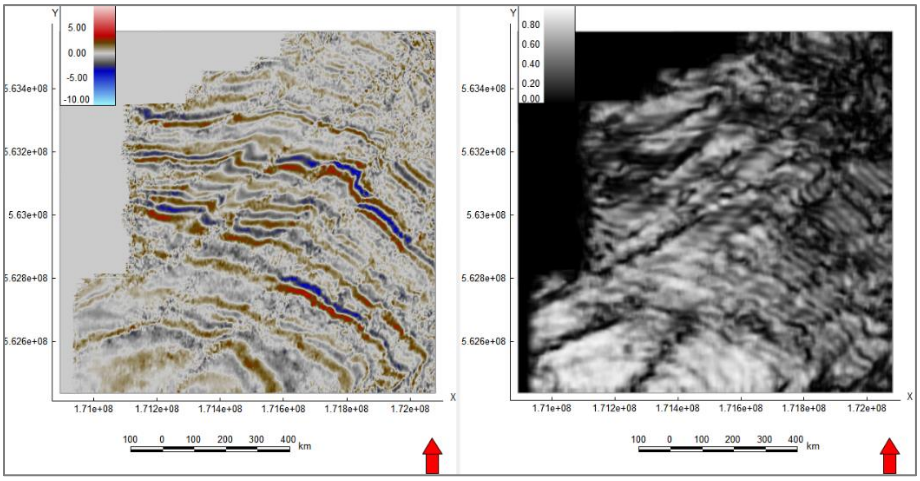

Figure 4. Time slice from a) amplitude cube b) coherence at 1000 milliseconds generated from three-dimensional seismic data from onshore Taranaki Basin in New Zealand. Faults are easier to portray accurately on coherence as they appear as dark north-north-east trending lineations.

Spectral decomposition can aid stratigraphic interpretation to reveal geological features not visible on the original seismic data by improving thin bed resolution and showing temporal bed thickness variability. The essence of the algorithm is to decompose the original seismic cube into frequency components, each of which is assigned its own colour channel (red, green, or blue) Usually, the red channel is assigned to the lowest frequency and the blue channel is assigned to the highest frequency due to the arrangement of these colours on the optical spectrum. Spectral decomposition removes the wavelet overprint from seismic data. Then using RGB blending of the three specified frequency components the user obtains the final attribute.

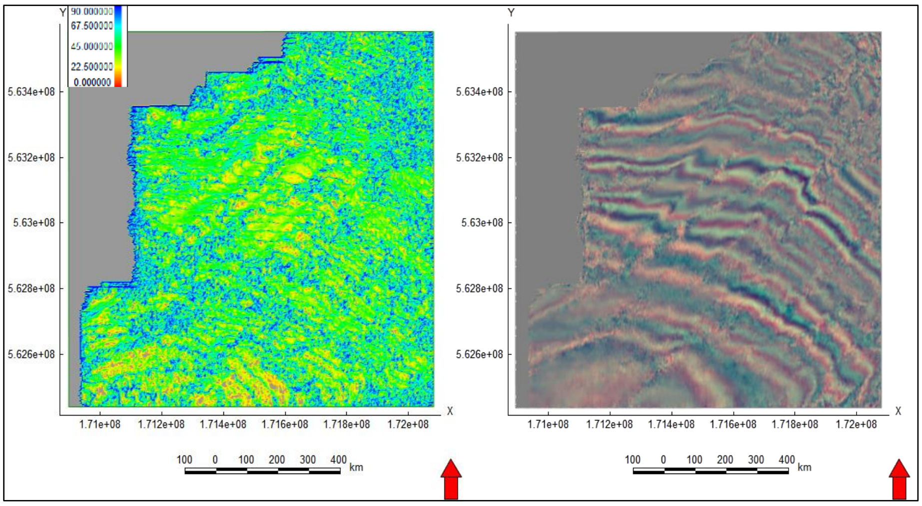

Figure 5. a) local structural dip, b) spectral decomposition. Detection time slices at 1000 milliseconds generated from three-dimensional seismic data from onshore Taranaki Basin in New Zealand.

The use of seismic attributes for faults detection is not limited to sedimentary basins and can be broadly applied to any seismic reflection data used at small scale in engineering and environmental to large scale datasets for coal and mineral exploration. The examples below are taken from hard-rock environments to gain additional insight into the potential of seismic data for prospecting.

Nkosi et al. (2018) used a three-dimensional seismic data acquired in Witwatersrand Basin (South Africa) to apply volumetric and horizon-based seismic attributes to improve stratigraphic and structural imaging in complex faulted areas. Their work is not specifically concerned with migration pathway, instead improving the delineation of minor faults cross-cutting the gold-bearing horizons, leading to improve the chance of exploration success of ore resources. Specifically, they used dip, dip-azimuth, edge detection and ant-tracking attributes to obtain a better insight into faults and their relationships. The observations and conclusions of their work indicate that the applied seismic attributes enhanced the detection of complex structures that fall below the vertical seismic resolution. Their approach generates a structural framework of the mining area that can play a key role in exploration for further resources. Figure 6 illustrates azimuth and edge detection attributes computed for Roodepoort shale Block B, modified after (Nkosi et al., 2018). The discontinuous reflections with north–east and north–north-east trending are integrated with borehole logs and interpreted to be faults. The resolved structural complexity using seismic attributes minimise biased visual interpretation and possible inaccurate mapping of faults.

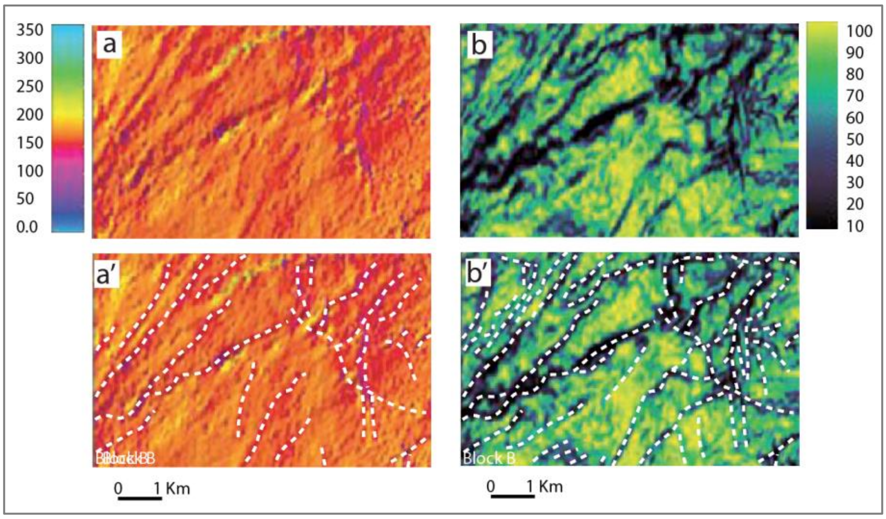

Figure 6. Azimuth (a) and edge detection (b) attributes, and discontinuities marked in dashed white lines at a´ and b´ (colour bar given in degrees and percentages respectively), adapted from Nkosi et al. (2018). For more detail discussion of geological settings and seismic attributes, we refer the reader to original citation.

Other examples are some seismic attributes different from conventional measurements introduced by Manzi et al. (2020) that attempt to sharpen reflections with the aim of extracting additional structural information. They developed a symmetry attribute (which is independent of amplitude) and a reflection-continuity detector attribute to enhance the visibility of the peaks and troughs of seismic traces which further assist delineation of the lateral continuity of reflections and hence better detection of weaker seismic feature associated with faults (see the original publication for details of calculated attributes and application on seismic data).

DISCUSSION

Over decades, petroleum industry has championed the use of seismic reflection data for prospecting. The potential of seismic reflection data in providing evidence to interpret structures in greater depths (especially faults and shear zones), is considered one of the key characteristics of the technique contributing to its success in exploration.

According to petroleum system concept, migration pathway is one the main critical components for the accumulation of hydrocarbon in economic capacities. Deep faults and fracture networks are the parameters that are most critical for fluid migration from source to reservoir rock. In the view of authors, for structurally controlled minerals exploration, as in analogous petroleum industry, faults and fractures are most likely to have the most significant importance on the migration of fertile fluids leading to mineralisation. Thus, mapping faults and shear zones can translate into reducing search space for prospecting, which may not be feasible without remote sensing techniques such as seismic for a variety of reasons (examples are exploration for deposits in terranes covered with tens of meters of regolith).

Understanding the limitations of seismic reflection data (in terms of acquisition parameters and processing workflows), and the complexity of faults and geological settings is important as well. For example, the imaging quality on a two-dimensional seismic line can be drastically poor in comparison to a three-dimensional seismic cube acquired over the same area. Depth is another critical factor in the utility of seismic reflection data for exploration. Although, seismic resolves deep structures (arguably better than other geophysical techniques) but still the quality of the image and true spatial position of seismic events is very much dependent on acquisition parameters, source and amount of energy and finally processing.

Because of all these complexities and uncertainties, qualitative interpretation of faults based on visual judgment of reflector discontinuities is not accurate most of the times. As described in this paper, seismic attributes can provide further insights into mapping fault spatially and vertically at greater depths. Not all the attributes are appropriate for fault interpretation but some of them (structural attributes) could be of great value to delineate faults and fracture networks (especially those that fall below vertical seismic resolution).

The authors claim that seismic reflection datasets provide a tool to explorers to focus and narrow down the search space (from regional to prospect scale) leading to identification and chose of prospective areas for further investigation and finally improving the chances of mineral discovery.

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