

LITHIUM EXPLORATION TODAY

High Resolution Refraction Seismic Tomography

State of the Art Geophysical Techniques applied in Lithium Exploration

Gravity Surveys: Mainly applied for basin / basement reconnaissance and geothermal reservoir localization.

EM / MT Surveys: Mainly applied for basin reconnaissance, geological contact definition as well as discontinuity / fracturation mapping.

Geoelectric Surveys: Mainly applied for localization of alluvial aquifers, overburden definition and saltwater intrusion / saltwater wedge mapping.

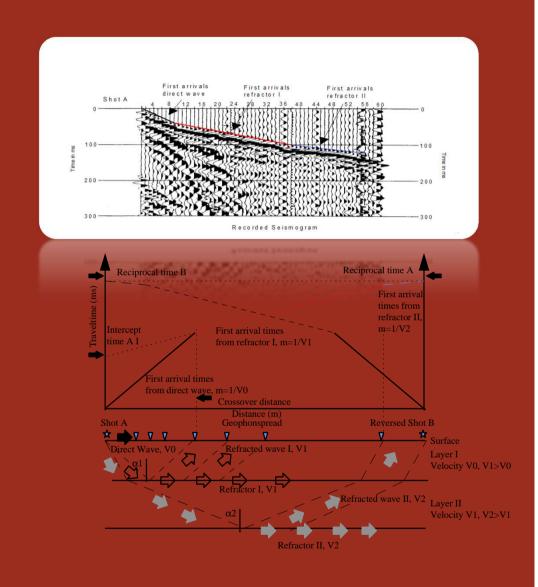
Seismic Surveys: Mainly applied for basin reconnaissance, detailed lithology and stratigraphy definition, structure, fault and discontinuity detection as well as overburden and aquifer mapping.

Gravity Surveys

EM / MT Surveys

Geoelectric Surveys

Seismic Surveys



SEISMIC TECHNIQUES FOR LITHIUM EXPLORATION

Seismic Techniques applied in Lithium Exploration

1. Reflection Seismic

2. Refraction Seismic

3. Refraction
Seismic
Tomography



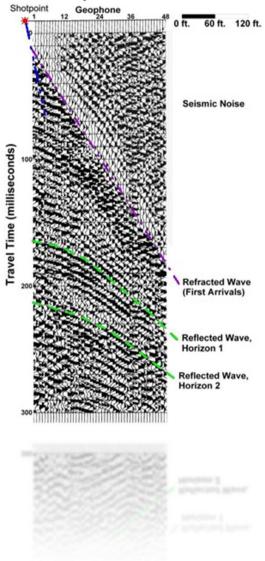
Introduction

The difference between seismic refraction and seismic reflection is never obvious to the non geophysicist, and rarely explained in simple terms by geophysicists. Due to the similarity of the names, many non geophysicists assume that the terms are interchangeable, or are unaware that there are critical differences between the two techniques that may make one vastly preferred or the other completely unusable given site specific conditions or project goals.

General Seismic Principles

Seismic techniques generally involve measuring the travel time of certain types of seismic energy from surficial **shots** (i.e. an explosion or weight drop) through the subsurface to arrays of ground motion sensors or **geophones**. In the subsurface, seismic energy travels in waves that spread out as hemispherical wavefronts (i.e. the three dimensional version of the ring of ripples from a pebble dropped into a pond). The energy arriving at a geophone is described as having traveled a ray path perpendicular to the wavefront (i.e. a line drawn from the spot where the pebble was dropped to a point on the ripple). In the subsurface, seismic energy is **refracted** (i.e. bent) and/or **reflected** at interfaces between materials with different seismic velocities (i.e. different densities). The refraction and reflection of seismic energy at density contrasts follows exactly the same laws that govern the refraction and reflection of light through prisms. Note that for each seismic ray that strikes a density contrast a portion of the energy is refracted into the underlying layer, and the remainder is reflected at the angle of incidence. The reflection and refraction of seismic energy at each subsurface density contrast, and the generation of *surface waves* (or ground roll), and the sound (i.e. the air coupled wave or air blast) at the ground surface all combine to produce a long and complicated sequence of ground motion at geophones near a shot point. The ground motion produced by a shot is typically recorded as a wiggle trace for each geophone (see **Example Seismic Record** at right).

Example Seismic Record



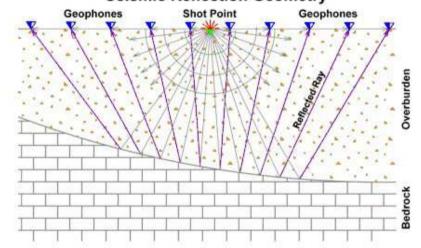
1. Reflection Seismic Method

Seismic reflection uses field equipment similar to seismic refraction, but field and data processing procedures are employed to maximize the energy reflected along near vertical ray paths by subsurface density contrasts (see Seismic Refraction Geometry on the net slide). Reflected seismic energy is never a first arrival, and therefore must be identified in a generally complex set of overlapping seismic arrivals - generally by collecting and filtering multi-fold or highly redundant data from numerous shot points per geophone placement. Therefore, the field and processing time for a given lineal footage of seismic reflection survey are much greater than for seismic refraction. However, seismic reflection can be performed in the presence of low velocity zones or velocity inversions, generally has lateral resolution vastly superior to seismic refraction, and can delineate very deep density contrasts with much less shot energy and shorter line lengths than would be required for a comparable refraction survey depth.

The main limitations to seismic reflection are its higher cost than refraction (for sites where either technique could be applied), and its practical limitation to depths generally greater than approximately 15 m. At depths less than approximately 15 m, reflections from subsurface density contrasts arrive at geophones at nearly the same time as the much higher amplitude ground roll (surface waves) and air blast (i.e. the sound of the shot). Reflections from greater depths arrive at geophones after the ground roll and air blast have passed, making these deeper targets easier to detect and delineate.

Seismic reflection is particularly suited to marine applications (e.g. lakes, rivers, oceans, etc.) where the inability of water to transmit shear waves makes collection of high quality reflection data possible even at very shallow depths that would be impractical to impossible on land.

Seismic Reflection Geometry



2. Refraction Seismic Method

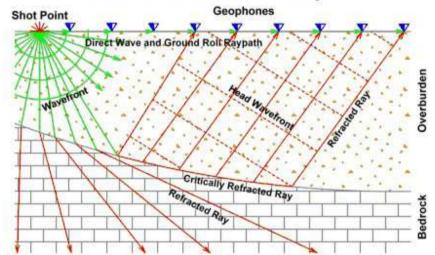
Seismic Refraction

Seismic refraction involves measuring the travel time of the component of seismic energy which travels down to the top of rock (or other distinct density contrast), is refracted along the top of rock, and returns to the surface as a head wave along a wave front similar to the bow wake of a ship (see **Seismic Refraction Geometry**). The shock waves which return from the top of rock are refracted waves, and for geophones at a distance from the shot point, always represent the first arrival of seismic energy.

Seismic refraction is generally applicable only where the seismic velocities of layers increase with depth. Therefore, where higher velocity (e.g. clay) layers may overlie lower velocity (e.g. sand or gravel) layers, seismic refraction may yield incorrect results. In addition, since seismic refraction requires geophone arrays with lengths of approximately 4 to 5 times the depth to the density contrast of interest (e.g. the top of bedrock), seismic refraction is commonly limited (as a matter of practicality) to mapping layers only where they occur at depths less than 100 feet. Greater depths are possible, but the required array lengths may exceed site dimensions, and the shot energy required to transmit seismic arrivals for the required distances may necessitate the use of very large explosive charges. In addition, the lateral resolution of seismic refraction data degrades with increasing array length since the path that a seismic first arrival travels may migrate laterally (i.e. in three dimensions) off of the trace of the desired (two dimensional) seismic profile.

Recent advances in inversion of seismic refraction data have made it possible to image relatively small, non-stratigraphic targets such as foundation elements, and to perform refraction profiling in the presence of localized low velocity zones such as incipient sinkholes.

Seismic Refraction Geometry



3. Seismic Refraction Tomography

The traditional technique for processing and interpretation of refraction seismic data (see 2. Refraction Seismics,) often results in geological models which show disturbed subsoil areas (deformations, weak zones, discontinuities, faults, etc.) as a thin sharp low velocity zone surrounded by fresh rock. The real case is most likely much more complex. Deformation zones may have a narrow core of heavily crushed rocks, but they are often surrounded by a wider zone (influence area) constituting altered, fractured rocks with deteriorated mechanical properties as compared to the fresh rock.

In order to extract more information from the seismic data as compared to the traditional processing technique, to overcome the limitations of the standard refraction seismic technique and to be able to create more advanced geological models (more diverse bedrock velocity models) that come closer to the complex reality, the data are processed by use of modern computerized tools for analyzing refraction seismic data with tomography inversion techniques.

The tomography inversion is performed with the software RAYFRACTTM. The program uses so called WET or *Wave Eikonal Traveltime* tomography processing. The software RAYFRACT is a windows based 32-bits software package for processing of refraction seismic data. The program basically offers two different ways of processing the data:

1.Delta T-V method, **Gebrande and Miller** (1985). The Delta TV method is a pseudo 2D Inversion method that delivers a continuous 1D velocity versus depth model for all geophone stations. The method handles real life geological situations such as velocity gradients / linear increasing of velocity with depth / velocity inversions / pinching out layers and outcrops / faults and local velocity anomalies gracefully. It is especially a very strong tool for structural interpretation of the geologic situation.



Refraction Seismic Tomography

2. WET or **W**ave **E**ikonal **T**raveltime Tomography processing. Wave propagation is modeled in a physically meaningful way with ray paths, using the output from the Delta-TV inversion as starting model. It handles several real life geological situations, such as discontinuities velocity distributions and sharp vertical or horizontal velocity gradients caused by e.g. deformation zones. Quality control of geological models is performed by direct graphical comparison of the measured travel time data to those calculated from the model solution.

The tomography inversion is performed with the software RAYFRACT TM . The program uses so called WET or **Wave Eikonal Traveltime** tomography processing (formula for the back projection of traveltime residuals in traveltime tomography). The special case of the WET formula leads to a computationally efficient inversion scheme in the space-time domain that is, in principle, almost as effective as WT inversion yet is an order of magnitude faster. It also leads to an analytic formula for the fast computation of wavepaths. Wave Eikonal Tomography models multiple signal propagation paths contributing to one first break. Conventional ray tracing tomography is limited to the modeling of just one ray per first break. The Eikonal solver (Lecomte, Gjoystdal et al. Geophysical Prospecting May 2000) used for traveltime field computation explicitly models diffraction besides refraction and transmission of acoustic waves. As a consequence the velocity anomaly imaging capability is enhanced with the WET tomographic inversion compared to conventional ray tomography and or standard refraction techniques. WET Tomography is a non-intrusive method that is performed on the ground surface with a conventional refraction seismic geophone spread and seismic source (e.g. sledgehammer, dropweight, etc.). WET Tomography supports any surface based 2D recording geometry, including roll-along seismic reflection lines. Up to 500 shots may be imported into the same 2D profile database. These shots may be recorded with just one or with multiple overlapping receiver spreads. 10 or more shots per receiver spread are recommended. The spacing of adjacent receivers may vary along the same user-defined receiver spread type. 12 or more active channels are recommended.

For further information on the WET-Inversion the specific references are attached on the next page:

References

- J. B. Diebold and P. L. Stoffa 1981. The traveltime equation, tau-p mapping, and inversion of common midpoint data. SEG Geophysics, volume 46, pp. 238-254.
- **Roland A. Winkelmann 1998** Ph. D. Thesis. Entwicklung und Anwendung eines Wellenfeldverfahrens zur Auswertung von CMP-sortierten Refraktionseinsaetzen. Akademischer Verlag Muenchen, Munich, ISBN 3-932965-04-3.
- Gawlas, Peter Florian 2001 Ph. D. Thesis. Möglichkeiten eines DMO-Prozesses in der CMP-Refraktionsseismik. LMU Munich: Faculty of Geosciences. See http://edoc.ub.uni-muenchen.de/archive/00000222/01/Gawlas Peter.pdf.
- **H. Gebrande 1986**. CMP-Refraktionsseismik. Paper presented (in German) at Mintrop Seminar / Uni-Kontakt Ruhr-Universitaet Bochum, Expanded abstract "Seismik auf neuen Wegen", pp. 191-205.
- H. Gebrande and H. Miller 1985. Refraktionsseismik (in German). In: F. Bender (Editor), Angewandte Geowissenschaften II. Ferdinand Enke, Stuttgart; pp. 226-260. ISBN 3-432-91021-5.
- **Bruce S. Gibson, Mark E. Odegard and George H. Sutton 1979.** Nonlinear least-squares inversion of traveltime data for a linear velocity-depth relationship. Geophysics, volume 44, pp. 185-194.
- **Barton P. and Barker N. 2003**. Velocity imaging by tau-*p* transformation of refracted seismic traveltimes. Geophysical Prospecting, volume 51, pp. 195-203.

	Seismic Method Comparison		
	Reflection	Refraction	Refraction Tomography
Typical Targets	Horizontal to dipping density contrasts, and laterally restricted targets such as cavities or tunnels at depths greater than ~15 m	Near-horizontal density contrasts at depths less than ~30 m	Near-horizontal density contrasts at depths less than ~2 m to depth down to 400 m
Required Site Conditions	None	Accessible dimensions greater than ~5x the depth of interest; unpaved greatly preferred	Accessible dimensions greater than ~5x the depth of interest; unpaved greatly preferred
Vertical Resolution	5 to 10 percent of depth	10 to 20 percent of depth	5 to 10 percent of depth
Lateral Resolution	~1/2 the geophone spacing	~1 the geophone spacing	~1/2 the geophone spacing
Effective Practical Survey Depth	>15 m	1/5 to 1/4 the maximum shot-geophone separation	1/5 to 1/4 the maximum shot-geophone separation
Relative Cost	\$3xN to \$5xN	\$N	\$2N

COMPARISON OF THE SEISMIC TECHNIQUES

Note that in situations where both could be applied, seismic reflection generally has better resolution, but is considerably more expensive. In those situations, the choice between seismic reflection and refraction becomes an economic decision. In other cases (e.g. very deep/small targets) only reflection can be expected to work. In still other cases, where boreholes or wells are accessible, neither refraction, nor reflection may be recommended in favor of seismic tomography.

CASE STUDY: CAUCHARI-OLAROZ SALAR SEISMIC REFRACTION TO MOGRAPHY SURVEY 2009 / 2010

CLIENT: LITHIUM AMERICAS CORP.

DeltaTV Results (Initial Seismic Model)

Field Recording Parameters:

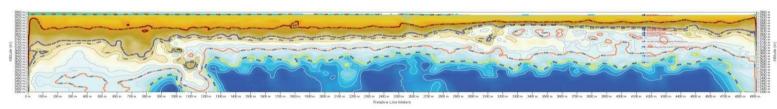
Instrument:

Geode Geometrics Inc. (48 -72 active Channels)

Source Type P-Wave: Accelerated Dropweight 150 Kg (buggy mounted)

Source Spacing P-Wave: 15 m Inline

Shot offsets outline: 30 / 60 / 90 / 150 / 250 / 500 / 750 / 900 m both sites



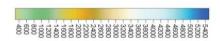
Receiver Type: 14 Hz single Geophone (Geospace)

Receiver Spacing P-Wave: 5 m

Average Investigation Depths: 500 m

Lateral Resolution: 2.5 m

Daily average Production: 600 Line Meter



Processing Sequence

P-Wave Seismic Refraction Tomography Processing Sequence

(Processing Software RAYFRACT 3.16)

- 1. Loading Seismic Raw Data groupped in Spreads (SEG-2 Format)
- 2. Applying Shot & Receiver Geometry based on Field Recording Sheets
- 3. Applying Coordinates to the Geometry Final Geometry Control
- 4. Shot & Trace Edit Interactive
- 5. Trace Signal Smoothing with running average Filter Filter width 5 ms / Central Filter Weight 5
- 6. Removing systematic DC offset from Traces
- 7. Correct Trigger Delays interactive
- 8. First Break Picking 1. Pass Automatic Picking : Search window width 10 ms / minimum propagation Velocity 400 m/s / maximum propagation Velocity 6.000 m/s
- 9. First Break Picking 2. Pass Interactive Correction of 1. Breack Picks
- 10. Interactive Delta TV Inversion (CMP Velocity vs. Depth) Delta TV Settings; CMP is Zero Time trace / Suppress Velocity Artefacts / Weight Picks in CMP-Curves
- 11. Delta TV Inversion: CMP curce stack width 15 / Regression over offset stations 5 / Linear regression method: least squares Weathering sub-layer count: 3 / Process all CMP / Maximum valid velocity 6,000 m/s / Surface consistent static corrections Weathering Crossover: 10 Stations / Topography Filter: 100 Stations / Inverse CMP offset power 0.5 1/Stations / Gridding method: Kriging
- 12. Refine Delta TV-output / Low Pass Filtering
- 13. Drawing Delta TV Results (Initial Input model for further WET-Tomography Processing)
- 14. Interactive WET-Tomography (Initial velocity model DELTA TV) correcting all velocities for Delta TV systematic error / correcting basement velocities for Delta TV systematic error
- 15. WET- Tomography parameters: Number of Iterations 5-50 / Central Ricker wavelet frequency 50 Hz / Wave path width 15.5 % Maximum valid velocity 6.000 m/s / Minimal velocity smoothing after each tomography iteration / Applying rectangular filter matrix to filter shallow dipping wavepath artefacts from model / Maximum relative velocity update after each iteration: 15%
- 16. Drawing WET-Tomography results

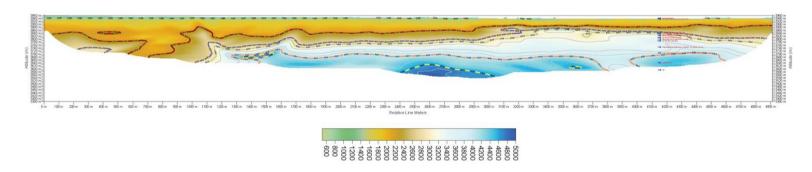
Calibration & Interpretation Process

- 1. Process Drillhole Information (Geologic Model)
- 2. Transform Geologic Model in 1D Gradient Seismic Velocity Model
- 3. Repeat Steps 9-13 to optimize Delta TV Model including geologic information
- 4. Repeat Steps 14-16 to refine Final Wet Inversion Model

Final WET Tomography Model

Receiver Configuration: Single Geophone

Spread Layout: Refraction P-wave Tomography 48 Channels

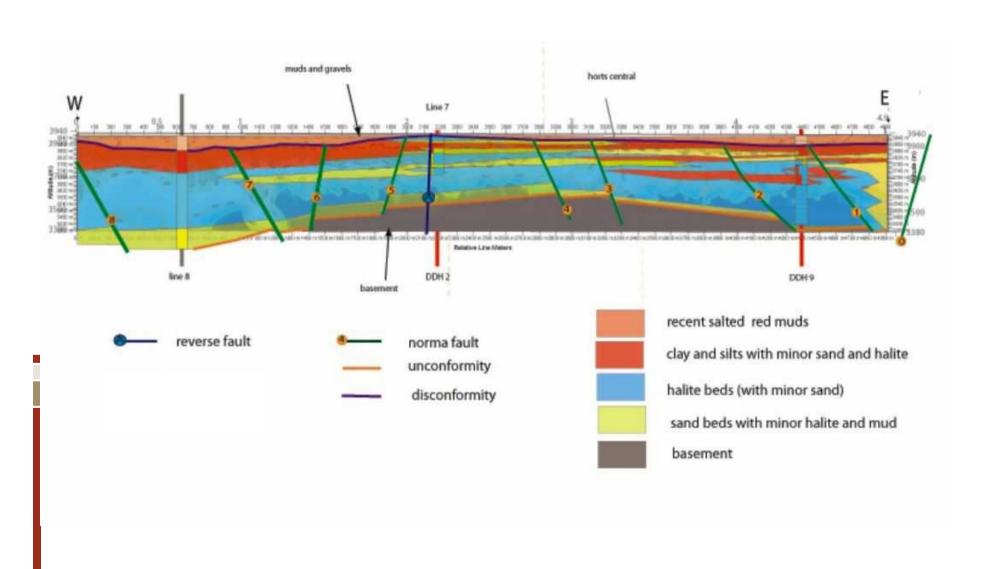


Fixed Spreads - overlap 12 Geophones

Trace Length P-Wave: 0.5 - 0.75 s

Sample Rate P-Wave: 1 ms

Final Product: Calibrated & Interpreted Seismic Section



Detailed 2D geologic Sections

3D Model Approach

Benefit of the Seismic Survey

Calibration of Gravity Model

Refinement of VES Results

References

Seismic Tomography

- 2010 50.000 m Salar de Cauchari / Olaroz / Pocitos for Lithium Americas
- 2011 52.000 m Salar de Diablillos for Rodinia
- 2011 20.000 m Salar de Maricunga for Lithium 3 Energy
- 2012 6.500 m Pastos Grandes Salar for Eramine South America
- 2012 33.000 m Salar de Centenario / Ratones for Eramine
 South America
- 2012 15.000 m Salar de Carachi Pampa for Eramine South America
- 2013 29.000 m Salar de Centenario / Ratones for Eramine South America
- 2014 8.000 m Salar de Centenario Norte for Eramine South America
- 2016 25.000 m Salar de Llullaillaco for International Lithium Corporation

CSAMT

- 2007 205 VES Soundings Salar de Arizaro, Vega Arizaro, Socompa, Llullaillaco, Ricon for Minas Argentinas
- 2010 110 VES Soundings Salar Cauchari / Olaroz for Lithium Americas
- 2011 50 VES Soundings Salar del Hombre Muerto / Sal de Vida for Lithium One / Galaxy
- 2011 134 CSAMT Soundings Laguna Verde, Pastos Grandes y Salar de Rincon for Eramine South America
- 2012 202 CSAMT Soundings Salar de Centenario / Ratones for Eramine South America
- 2012 19 CSAMT Soundings Salar de Carachi Pampa for Eramine South America
- 2013 44 CSAMT Soundings Salar de Centenario / Ratones for Framine South America
- 2013 46 CSAMT Soundings Salar del Hombre Muerto / Olaroz for Minera Santa Rita
- 2014 127 CSAMT Soundings Salar de Centenario / Ratones for Eramine South America
- 2015 68 CSAMT Soundings Salar de Arizaro for Eramine South America

SHOULD YOU REQUIRE FURTHER DISCUSSION, INFORMATION OR CLARIFICATION OF THIS PRESENTATION, OR SHOULD THE TECHNICAL REQUIREMENTS CHANGE, PLEASE CONTACT US ANYTIME. THIS PRESENTATION WAS PREPARED BY: SENIOR GEOPHYSICIST S. BOLLING -GEOPHYSICAL EXPLORATION & CONSULTING S.A. MAIL: SBOLLING5@GMAIL.COM