Effective Mineral Exploration Under Cover: Addressing the Challenge Using Passive Seismic Methodology

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SUMMARY

Passive seismic methodology is becoming a popular tool for estimation of cover depth, cover velocity structure and basement topography for mineral exploration applications. Analysis of passive seismic array data gives information on wavefield characteristics and constrains shear-wave velocity structure. Single station techniques are useful as a tool to rapidly estimate cover thickness but require further information from drill holes or array techniques for robust interpretation. The combined use of array and single station techniques provides an effective cover depth mapping methodology and allows for highly flexible survey design, adaptable for a range of applications. This paper provides a summary of relevant passive seismic techniques and overview of their effective use with several example mineral exploration scenarios.

Key words: passive seismic, mineral exploration, FK, SPAC, HVSR.

INTRODUCTION

Seismic methods which use the ambient seismic wavefield (also referred to as ambient vibrations, seismic noise or microtremor) as a source signal and a single or small portable array of three-component seismometers for data acquisition are beginning to gain popularity within the mineral exploration community. These methods are well suited to characterisation of sedimentary 'cover' overlying prospective crystalline basement, and for mapping the basement topography within a demonstrated depth range of 10's to 100's of metres. Data acquisition is cheap due to the minimal time and field logistical effort required, and the processed data outputs provide the explorer with indicators of basement prospectivity as well as a means to de-risk further project expenditure.

Passive seismic methodology encompasses a suite of techniques, and of these the Horizontal to Vertical Spectral Ratio (HVSR), Spatially Averaged Coherency (SPAC) and Frequency-Wavenumber (FK) techniques have proven relevant for mineral exploration application. Different combination of these techniques allow for varied levels of survey complexity and data constraint, and are highly flexible and scalable to the survey objectives. Importantly, these techniques provide an independent view of the earth's physical properties which can be well integrated together with other more-common geophysical datasets for improved overall interpretation.

This paper provides a brief review of this passive seismic methodology together with several example scenarios for their effective use in mineral exploration under cover.

PASSIVE SEISMIC METHODOLOGY

The basis for seismic surveying using ambient vibrations is that *a)* surface waves dominate the ambient wavefield, *b)* seismic sources are sufficiently distance from the receiver array that wave propagation is planar (far-field sources), and *c)* there is sufficient coherent signal in the frequency band of interest (generally from 0.1 – 30 Hz; *microtremor* band). When this is the case, characteristics of surface waves propagating across the array, such as phase velocity dispersion and particle motion ellipticity can be determined and used to constrain the shear-wave velocity structure of the earth beneath the sensor or sensor array.

Included under the banner of *passive seismic methodology* are several techniques relevant to mineral exploration which can be used either standalone for simple and rapid reconnaissance surveying, or in combination to produce a thorough, well-constrained and adaptable survey deliverable. The sections below provide a brief review of these techniques and examples of likely scenarios for their use.

Single-station technique

The simplest passive seismic technique is the Horizontal to Vertical Spectral Ratio technique (HVSR or H/V). This technique requires ambient vibration recordings from a single three-component broadband seismometer (ideally, a flat response from 0.1 – 50 Hz) and can be used to indicate the presence of major shear-wave impedance contrasts in the earth, which are generally interpreted to represent the cover-basement interface. As the name suggests, the ratio of amplitude spectra for horizontal and vertical components is calculated to produce the HVSR spectrum. With the assumption that fundamental mode Rayleigh waves dominate the recorded ambient vibrations, the HVSR method exploits the fact that the recorded motion for Rayleigh waves is elliptical and this ellipticity changes as a function of frequency when there exists a sufficiently large shear-wave impedance contrast in the earth beneath the sensor. For intermediate to high shear-wave impedance contrasts (values of about 3 to >5), Rayleigh wave motion degenerates to the horizontal plane producing a characteristic peak in the HVSR spectrum. The frequency at which the HVSR peak occurs is also very close to the resonance frequency for shear-waves.

Three approaches for interpretation of HVSR data are currently routinely used. The first approach directly matches Rayleigh wave ellipticity curves, calculated from a shear-wave velocity model of the earth, with the observed HVSR. This method is generally used when ambient vibrations data from an array of sensors is available to constrain the shear-wave velocity structure of the earth, and can be considered as a joint inversion procedure (e.g. Smith et al., 2013)□. The second approach related the HVSR peak with cover thickness using the resonance relationship (also known as the transfer function) for a simple 2-layer model, $f = Vs / 4z$ (e.g. Scheib, 2014). For this approach it is also necessary to estimate the average shear-wave velocity of the cover (from lab analysis of seismic velocities, or from the available literature)□. The third approach relies on a non-linear regression analysis of the form $z = af^{\,b}$, solving for parameters a and b, using data on known cover depths and corresponding HVSR peak frequencies. For a given cover velocity structure and sufficient data quantity this approach can directly relate the HVSR peak frequency to cover thickness (e.g. Ibs-von Seht & Wohlenberg, 1999).□

Array techniques

The main analysis techniques for the small portable sensor arrays relevant for mineral exploration are the Frequency-Wavenumber (FK; Capon, 1969; Gal et al., 2014□) and Spatially Averaged Coherency (SPAC; Aki, 1957; Asten, 2006) techniques. These techniques require more time and logistical effort than the single station method described in the previous section, but are useful for characterising the ambient wavefield and constraining the shear-wave velocity structure of cover in addition to cover thickness.

The FK technique estimates the *slowness vector* of seismic energy propagating across a sensor array using a time-lag semblance analysis (array beamforming) over a sliding narrow-band frequency window, and gives best results when vibration sources are directional. A spiral arm array configuration using a relatively large number of sensors (e.g. >10) gives good resolution to energy back-azimuth and suppresses side-lobes in the array response function (e.g. Kennett et al., 2015)□. Outputs from FK analysis include an estimate of azimuthal source distribution, relative power and propagation velocity for various wave phases (surface waves and their higher modes, body waves, etc.) and dispersion curves for surface waves.

The SPAC technique is used to extract the *scalar phase velocity* of surface waves propagating across the sensor array, using (in general) a simple circular or triangular array configuration with a relatively small number of sensors (e.g.<10). Best results are achieved with the valid assumptions that fundamental mode surface waves dominate the ambient vibrations and sources are distributed through a large azimuthal range. SPAC processing involves calculating the coherency between sensor pairs and then averaging the coherency for pairs with the same separation but different azimuth. Optimising array design is a trade-off between the number of unique sensor separations, degree of azimuthal sampling and deployment duration. For relatively long deployments the requirement for good azimuthal sampling is diminished because a time average can be used in its place (where wavefield source characteristics are sufficiently variable) and it is therefore more useful to use an array with a large amount of unique sensor separations so as to adequately sample a wide range of wavelengths. For shorter deployment durations it is better to increase the azimuthal sampling and / or try to artificially boost the wavefield energy (e.g. by using the field vehicle; Smith et al., 2013)□.

Scenarios for mineral exploration use

Information on depth of cover is most effective when it is acquired early in the exploration program. An understanding of cover depth variability allows de-risking of further exploration expenditure by removing the otherwise unknown variable of cover depth which is important for prioritising drill holes, planning subsequent geophysical and geochemical surveys and constraining the interpretation of their datasets. Basement topography and cover geometry information is also useful as a direct prospecting tool for diagnostic geometries within the cover (e.g. palaeochannels) or at the basement palaeo-surface (e.g. local basement highs/lows). For likely 'mineral exploration' cover depths (10s to 100s of metres) analysis of relatively *high-frequency* ambient vibrations (>1Hz; also termed 'microtremor' band) is relevant. Compared to *low-frequency* ambient vibrations (<1Hz, also termed 'microseism' band) microtremor energy characteristics show seasonal and daily variations, and average energy and wavefield composition is highly dependant on locality and local geology. It is thus important to gain a reasonable understanding on wavefield composition and characteristics to ensure robust data modelling and interpretation.

Several example scenarios for the use of passive seismic methodology at different stages in an exploration program are outlined below. But please note that, given the flexibility of these techniques, surveys can be adapted for a range of other applications not mentioned here:

Scenario A – Early stage cover depth reconnaissance

The exploration company wants to get an idea of cover depth variations over a broad area and assess the feasibility of passive seismic methodology on their project. In this case, reconnaissance surveying should be planned to minimise survey costs and logistical effort, to estimate wavefield characteristics and to deliver a cover depth dataset for a broad area with relatively low spatial resolution. This can be achieved with an initial spiral arm array deployment for at least 24 hours, with subsequent FK analysis, followed by redeployment of the single sensors at various locations in the project area for HVSR analysis. The array deployment gives an opportunity to assess wavefield characteristics and feasibility of passive seismic methodology as well as information on the shear-wave velocity structure of the cover. The average shear-wave velocity can then be used for robust HVSR analysis and cover depth estimation.

Scenario B – Follow-up greenfields exploration:

The exploration company wants comprehensive depth of cover (or depth of weathering) information for selected areas or throughout their project. In this case, survey speed is important in order to maximise time-efficiency and data density. Single-station HVSR surveying with sensors laid out in a grid pattern is well suited to this task, and for robust interpretation several short-duration array deployments with SPAC processing should be incorporated. 10-20 HVSR deployments for every 1 SPAC deployment is a reasonable amount, but this is highly dependant on the estimated cover stratigraphy variability (thus variability of average shear-wave velocity structure) and the specific survey deliverables.

Scenario C – Prospect scale or brownfields exploration:

The exploration company wants highly detailed information on cover stratigraphy, cover depth or basement topography for the constrained modelling of other exploration datasets or as an indication of prospective areas within the cover (e.g. palaeochannels). Different approaches to this task include Euler deconvolution or forward modelling of magnetic data, filtering and modelling of gravity data, acquisition and interpretation of electro-magnetic data, or constrained 3D geophysical inversion using drill hole data. Passive seismic methodology presents another approach to this task, with the benefit that the constraining information is *a)* independent from the data being constrained, and *b)* is cheap and rapid to collect. In this case, SPAC surveying on a dense grid or along a profile is well suited. Survey deliverables in this case could include a 2D and/or 3D cover velocity model, and tightly constrained basement topography surface.

CONCLUSIONS

Passive seismic methodology is useful for mineral exploration purposes because of the information on the velocity structure and thickness variations of cover that it offers, and the low cost and logistical effort required. The use of array techniques (FK and SPAC) as well as the single station HVSR technique for mineral exploration application has been demonstrated several times now in the literature, and is summarised in this paper. The general depth range of interest in this case extends from 10s to 100s of metres and therefore the microtremor frequency band (1 – 30 Hz) for surface waves is of interest. Given the highly variable nature of microtremor it is prudent to determine wavefield characteristics along with in-situ cover velocity structure, using array techniques, for the robust analysis and interpretation single-station ambient vibration data.

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