Development of a Low Cost Method to Estimate the Seismic Signature of a Geothermal Field From Ambient Seismic Noise Analysis

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ABSTRACT

To date, no cost effective method had been developed to estimate compressional (*P)*, shear (*S*) seismic velocity models and buried fault location, which provide essential information in geothermal exploration. Although active source reflection seismic experiments provide high resolution *P*-velocity models and direct information on the resource availability, widespread use is cost-prohibitive and must be used selectively, which is difficult when no seismic information is available in the area. Thus, developing an inexpensive seismic exploration methodology and identifying new seismic parameters (attenuation, spectral and stochastic properties) to be used for geothermal reservoir characterization is essential for reducing geothermal exploration technology costs.

Introduction

Because hydrothermal production relies on open fracture networks, highly localized geophysical information is critical for well location as well as for identification of the fracture network. Addition of *S*-velocity models to the *P*-velocity models is important, because studies of the *P*-phase velocity (V_p) relative to the *S*-phase velocity (V_s) at the same location have the potential to provide supplementary information necessary to locate and drill productive wells. To date, no widely accepted, technically feasible and cost-effective method for high-resolution *S*-velocity model estimation has been developed.

The University of Nevada, Reno (UNR) and Optim Inc. team are in the first phase of developing a new, non-invasive and cost-effective seismic velocity model estimation method, based on ambient noise analysis, which we expect will provide *P* and *S* seismic velocity models with a resolution of tens to hundreds of m^2, to a depth of at least 1 km. This method is also expected to be effective for fault identification and geothermal reservoir characterization using seismic indicators based on attenuation, waveform spectral content and media stochastic properties. We have chosen a study area where extensive geological studies have been performed to characterize potential and existing hydrothermal resources, however, these studies did not provide an *S*-velocity model at a useful resolution.

The primary objective of our research is cost-effective characterization of geothermal reservoir properties from which drilling targets will be identified. To accomplish this objective, we (1) Develop, test and calibrate a non-invasive and cost-effective seismic exploration method based on ambient-seismic noise analysis; (2) Investigate new, additional seismic parameters characteristic to geothermal reservoirs; (3) Use statistical methods to integrate new seismic information with other geophysical data in order to minimize the uncertainty and non-uniqueness associated with the drilling; (4) Evaluate the effectiveness of the new method when applied to a new area of interest.

This project seeks to answer the following questions: How effective is the newly developed ambient-noise seismic exploration method for fault identification and for *P*- and *S*- velocity estimation when compared to active seismic surveys and other seismic methods? What is the optimal design of the method? Would this method demonstrate the potential to replace costly active surveys? How does integrating data from two or more independent geophysical sources reduce the non-uniqueness and uncertainty inherent in seismic data? How effective are the seismic attenuation, spectral and stochastic analysis in estimation of new geothermal reservoir characteristics? Can geothermal reservoir parameters be more reliably inferred from the new seismic data when it is used in conjunction with other *geological* data? Can exploration costs be reduced by eliminating survey methods that do not appreciably reduce exploration uncertainty? Does the drilling favorability map produced for Soda Lake have sufficient accuracy to identify favorable drilling sites?

We are currently in the first phase of this project, working on the first task. The expected project outcomes/deliverables are: (1) Testing and evaluation of a novel seismic exploration method based on analysis of body-waves and surface-waves extracted from ambient seismic noise; (2) Development of a cost-effective technique, consisting of statistical integration of inexpensive seismic analysis techniques with other geological and geophysical data. (3) An assessment of whether or not this new technique allows reliable geothermal reservoir characterization; (4) Estimation of a drilling favorability map at Soda Lake, Nevada.

Study Area

The study area (Figure 1) is a well-characterized geothermal resource in Fallon, Nevada, where evaluation and calibration of the new exploration method is possible (Tibuleac and Eneva, 2011). Studies of the geothermal field operated at Soda Lake by Magma Energy Corporation, near Fallon, Nevada include drilling of temperature-gradient holes by the U.S. Geological Survey and the U.S. Bureau of Reclamation, as well as drilling of production, injection and monitoring wells. The hottest parts of the Soda Lake thermal anomaly coincide with intersection of faults trending north-northeast and west-northwest. Faults exposed on the surface are inferred from silicified sediments and some faults at depth were suggested, possibly along a rupture zone in the Tertiary or pre-Tertiary consolidated rocks (Olmsted *et al*., 1975). A comprehensive 3D geophysical model of the geothermal field was recently estimated using various data that were analyzed together for the first time, such as geological maps, locations and depths of wells, mud-logging and drilling data, temperature surveys, geophysical logs, LiDAR, resistivity, magnetic anomalies, microgravity and seismic studies. This collection of data has been interpreted, however, without application of a robust statistical analysis. In addition, in 2010, a 3D, three-component reflection seismic survey was carried out, which was integrated with existing well and precision gravity data (Echols *et al*., 2011). Applying three dimensional - three component reflection seismic techniques

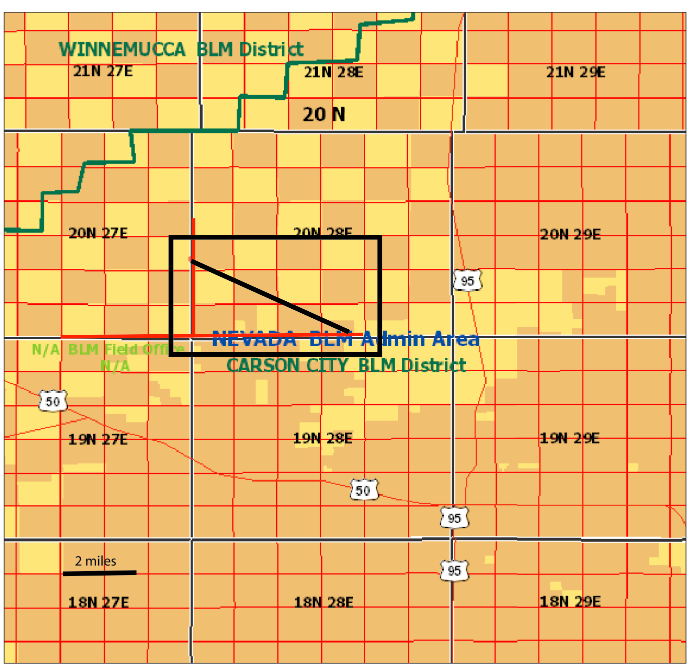

Figure 1. A view of the study area: the black rectangle shows the boundary of the larger aperture array (~ 300 m spacing) and the line shows the location of Line 1 of the 2010 active source reflection line deployed by Magma Energy Inc., line which we intend to duplicate.

to this data, to define transmisive geothermal structures at Soda Lake, has encountered difficulties. A method aiming to resolve the subsurface structure using *P*-to-*S* conversions at reflecting layers is under investigation, however, preliminary results are not encouraging. We are using a new, independent method to estimate 2D and 3D *P*- and *S*-velocity models and to identify faults along *2D* reflection profiles. Continuous data collected from the 3D-3C Magma active seismic survey in 2010 will be re-processed and its use to derive supplementary seismic information on geothermal reservoir parameters will be investigated.

Method

We are preparing to use existing and newly acquired seismic survey data to test and validate a cost-effective, non-invasive, seismic exploration method, based on seismic interferometry (Campillo and Paul, 2003; Halliday D. and A. Curtis, 2008; Stehli *et al*., 2008; Gouedard et al., 2008). This new seismic exploration method (Tibuleac *et al.*, 2010, 2011, 2012) has had promising results when used for fault definition and *P* and *S*- velocity model estimation. Green's Functions (GF) will be extracted from stacks of ambient noise and signal crosscorrelations and autocorrelations (Irie and Brown, 2010) from pairs of sensors and at the same sensor. The GF surface wave and *P* reflection components will be analyzed.

An initial P and S-velocity model of ~ 100 m resolution will be estimated using ambient noise analysis at arrays of sensors, as described below. By applying cross-correlation to ambient noise data recorded at pairs of closely spaced (~ tens of meters) seismic sensors along reflection lines, and stacking the results over a period of time, we will generate virtual shot gathers as if one of the sensors is generating seismic waves, i.e. we will retrieve the earth's reflection response (Draganov *et al*., 2009). The method also aims to characterize geothermal reservoir seismic spectral, stochastic and attenuation characteristics and to statistically evaluate the benefit for geothermal exploration of integration seismic and other geophysical results in a well-characterized area, near Soda Lake.

Algorithms for extracting ambient noise-derived Green's functions have been developed and are used at NSL (Tibuleac *et al*., 2011) to derive *P* and *S* velocity models in the Reno Basin, for inter-station distance from 0.5 to 60 km, for different sensor-types and to estimate the P/S reflection component of the Green's Functions extracted from waveform autocorrelations (Tibuleac *et al*, 2012). The algorithms are using spectral whitening and sign-bit normalization. Continuous waveform auto-correlation is also used to image the individual station substructure. Claerbout (1968) showed that for a horizontally layered medium the auto-correlation of the transmission response of a seismic noise source in the subsurface yields the reflection response.

We have encouraging preliminary results of testing the new method using two datasets collected in 2010:

1) The Soda Lake seismic survey. A pilot study to test the new exploration method was conducted by UNR and Imageair Inc., in 2010 (Tibuleac and Eneva, 2011). The deployment covered an area where depressurization of a shallow aquifer created a steam cap at Soda Lake. The array, consisting of 100 m spaced high-frequency vertical geophones deployed over an area of 1.3 km^2, recorded ambient seismic noise (and small earthquake waveforms) for two days. The survey was aimed at resolving lateral seismic parameter variations at a resolution of approximately 100 m. Although this preliminary demonstration of the method had encouraging results, the survey was limited in time and space, and sampled up to ~ 150 m deep. As shown in Tibuleac and Eneva, 2011, applying cross correlation to ambient noise data recorded at pairs of sensors, and stacking the results over the whole period of time, inter-station GF's were generated, with Rayleigh waves as dominant arrivals. The fundamental Rayleigh wave velocity (between 1-5 Hz) was higher at pairs of stations in a transect outside a steam cap than at inter-station paths inside the anomaly. More scattering (complex GF's) has also been observed for paths crossing the vapor cap.

2) A dataset collected in 2010 at a potential geothermal exploration site near Reno, NV by UNR with funding from Optim Inc. The Soda Lake survey was similar to an experiment conducted by UNR and Optim Inc., in 2010 which used the same short period sensors. During that experiment, waveforms have been collected by two co-located seismic reflection surveys (with

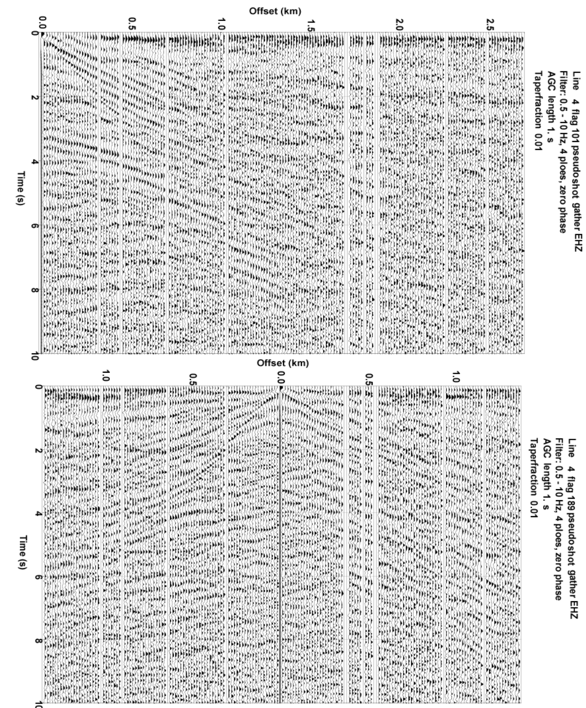

Figure 3. (from Tibuleac et al., 2010, AGU presentation). Experiment near Reno. Examples of ground roll and P arrivals resulting from ambient - noise crosscorrelation stacks on line 4 for flag 101 (upper plot) and flag 189 (lower plot). No data pre-filtering has been applied before cross-correlations. Average gain control (AGC) was applied on each waveform in 1 sec windows.

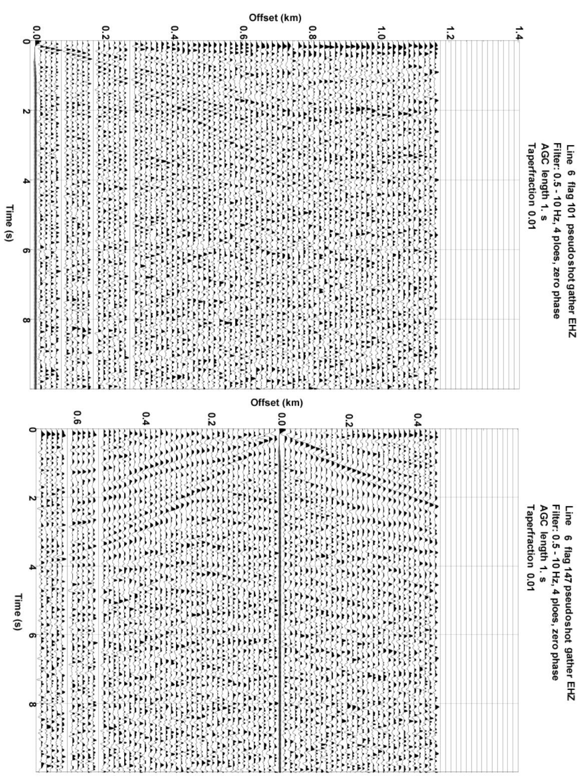

Figure 2. (from Tibuleac et al., 2010, AGU presentation). Experiment near Reno. Examples of ground roll resulting from ambient - noise crosscorrelation stacks on line 6 for flag 101 (upper plot) and flag 147 (lower plot). The null lines are for sensors which did not record. No data pre-filtering has been applied before cross-correlations. Average gain control (AGC) was applied on each waveform in 1 sec windows. Windows of 100 s were cross-correlated, however, only the first 10 s are shown.

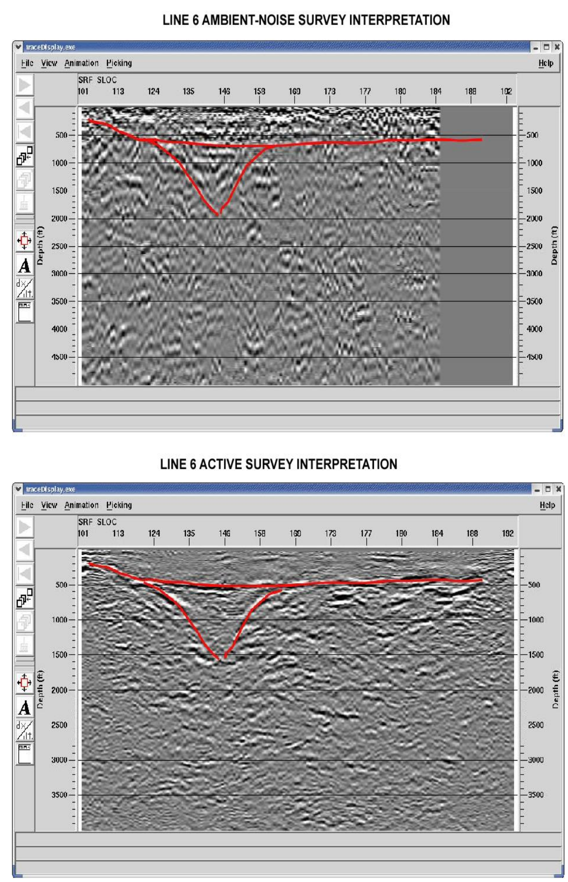

Figure 4. (from Tibuleac et al., 2010 AGU presentation). Experiment near Reno. Active source and ambient - noise result comparison for line 6. The noise records were processed with the same geometry as the active source records, were sorted according to CDP (common depth point), and put through the same depth migration process as the active source data, using the same velocity model. Note lower frequencies for the ambient noise survey.

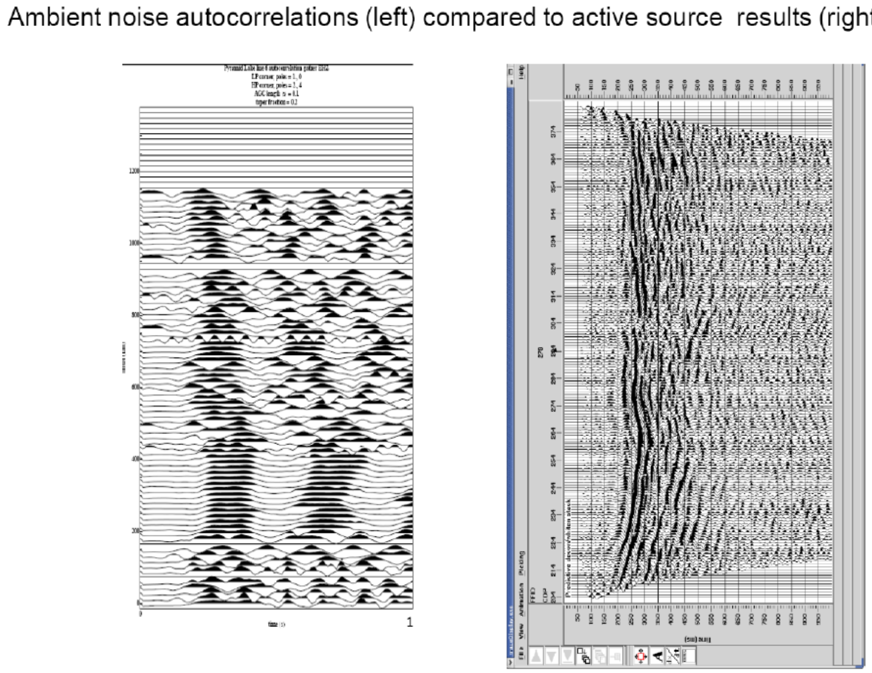

Figure 5. (from Tibuleac et al., 2010, AGU presentation). Experiment near Reno. Results of two co-located surveys near Reno: a passive geophone and "Texan" survey, recording ambient noise in the left plot and an active source survey in the right plot. One second of records is represented on the horizontal axis of each plot. Only ambient noise autocorrelations are shown here (left), as a first estimate of the experiment results. The autocorrelation is interpreted as the co-located source–receiver elastic wave Green's function (i.e. the Earth's reflection response). This is only a qualitative assessment of survey result similarity. Despite the difference in frequency content (lower frequency for the noise survey, which was filtered with a zero-phase high pass Butterworth filter at 2 Hz) the reflector at ~ 300 ms is resolved by both surveys and changes in autocorrelations (left) appear to follow the lateral variations shown by the active survey. Automatic gain control (AGC) in the left plot was applied in a window of 0.1 sec on each trace. Sensors in this line are 15 m apart. In the left plot, each trace is the stack of autocorrelations of ambient noise in one-hour windows for records during the three days of deployment. The plot on the right is a common depth point (CDP) stacked section of the active source reflection survey. A trace is shown for every CDP (spacing of approximately 7.5 m) and was derived after refraction statics.'

sensors 15 m apart), one active (by Optim, Inc.) and one passive (deployed by UNR), with a total of ~ 350 sensors. Preliminary results are encouraging; however, further investigations are necessary for the ambient noise method to be used as a stand-alone exploration technique. We have encouraging preliminary results (Figures 2-5, from Tibuleac *et al*., 2010, AGU poster) testing our ambient seismic noise exploration method on two reflection lines (line 4, parallel to a road, and line 6, perpendicular to a road) near Reno. We have determined that three-day noise surveys can produce similar results (although currently with less resolution) than active surveys for one reflection line which crosses a known fault (line 6), as shown in Figure 4, while the results do not match well for another line (not shown here). We have also determined that useful information for higher resolution preliminary velocity models can be extracted from ambient noise autocorrelations (Figure 5).

Technical Approach

We have organized our study into two phases (Figure 6), with a go/no go decision after Phase *I*.

Phase I – Proof of Concept: Method Development, Feasibility Assessment and Validation

Tasks 1 and *7* of this phase include administrative, experiment permitting, and reporting activities.

Task 2. Preliminary P/S seismic velocity model estimation using passive seismic arrays. Geophone arrays will be used to estimate *preliminary, lower resolution (~ 150 m)* 3D *P*- and *S*-velocity models from the ambient - noise extracted GF's and from existing active-survey information. First, we will invert the ambient-noise extracted GF Rayleigh wave dispersion for *S*-velocity models. Second, we will use of the GF *P* - reflection component resulted from passive array autocorrelations, crosscorrelations and waveform modeling to derive a preliminary P-velocity model. Third, we will invert existing, active reflection seismic survey ground roll dispersion to derive *S*-velocity models. Array processing techniques, such as *fk* analysis (frequency-wavenumber) (Tibuleac *et al*, 2011), will be used to estimate Rayleigh - wave phase velocity dispersion curves for ad-hoc sub-arrays of stations. Dispersion estimates will be inverted for surface wave velocity models using the Computer Programs in Seismology (CPS3.0) surf96 algorithm (Herrmann and Ammon, 2002).

Finally, all the above information will be used to estimate an initial velocity model. An accurate preliminary velocity model is essential for seismic survey interpretation. The lack of preliminary shear-wave velocity models has proved to be a problem for the current geothermal exploration studies. Existing and new seismic array deployments at Soda Lake will be used to apply seismic interferometry for GF extraction. We will determine whether the existing 3D active seismic surveys have potential value for the project.

Task 3. Reflection line deployment and ambient-noise analysis. Crosscorrelation and autocorrelation will be applied to the ambient seismic noise recorded by closely spaced (meters to tens of meters apart) sensors within passive seismic reflection lines, at the same locations as previous active reflection lines, to obtain virtual shot - gathers. The *P*- and *S*- velocity models derived at Task 2, in combination with information extracted from passive survey ground roll dispersion and from the passive survey *P*-reflection component of the GF's, resulted from autocorrelations, will provide the initial seismic velocity models. The expected results of this task are (1) a set of virtual shot gathers; (2) a starting model incorporating preliminary (from Task 2) and new seismic model information from ground roll and from the P-reflection component of the GF's at each line sensor.

Task 4. Analysis of New Geothermal Field Seismic Characteristics. We will analyze new, possible geothermal field seismic characteristics (further referred to as SP-SC-A parameters) in terms of ambient-noise spectral content, scattering and attenuation, using data recorded at all sensors (Pullammanappallil *et al.*, 1997; Saenger *et al.*, 2009; Schechinger, *et al.*, 2009) We will investigate the usefulness of stochastic heterogeneity, of spectral properties and of attenuation variations for detecting productive geothermal reservoirs, and faults. We will research possible fault indicators related to seismic scattering. We will also investigate variations in the seismic noise spectral content in a geothermal reservoir area (Georgsson et al. 2000).

Task 5. Assess Seismic Model Resolution and Accuracy. We will assess the resolution and accuracy of the ambient - noise survey-derived seismic models, when compared to active survey - derived models and will evaluate correlation of the SP-SC-A parameters and other existing geophysical information on productive geothermal fields. First, the correlation of array-estimated preliminary seismic velocity models to known geophysical features of the geothermal field will be evaluated. Second, the crosscorrelation stacks between each pair of stations, processed with the same geometry as the active source records, will be arranged into virtual shot gathers. Third, we will estimate the usefulness of the SP-SC-A parameters and compare the results to existing seismic and geophysical information, obtained by collaborating scientists in previous studies.

Task 6. Statistically Assess Geothermal Reservoir Favorability. We will assess productive geothermal reservoir favorability using geostatistics methods (Iovenitti *et al*, 2010), by integration of the newly obtained seismic information and existing geophysical data in the study area. First, we will develop initial geothermal reservoir favorability maps for each available geophysical dataset. Second, we will use geostatistics methods for pattern identification across multi-dimensional datasets to develop a final favorability map. Finally, we will assess the possibility of predicting productive geothermal reservoir favorability.

A go/no-go decision will be made prior to the beginning of Phase II.

PHASE II – Application of the Prototype Method to a New Area of Interest

After validation, the new seismic exploration method will be applied to another area of interest. The order of the tasks at Phase I will be repeated, however, with modifications to reflect the results of Phase I investigations (Figure 6). The success of the method in drilling target identification will be assessed.

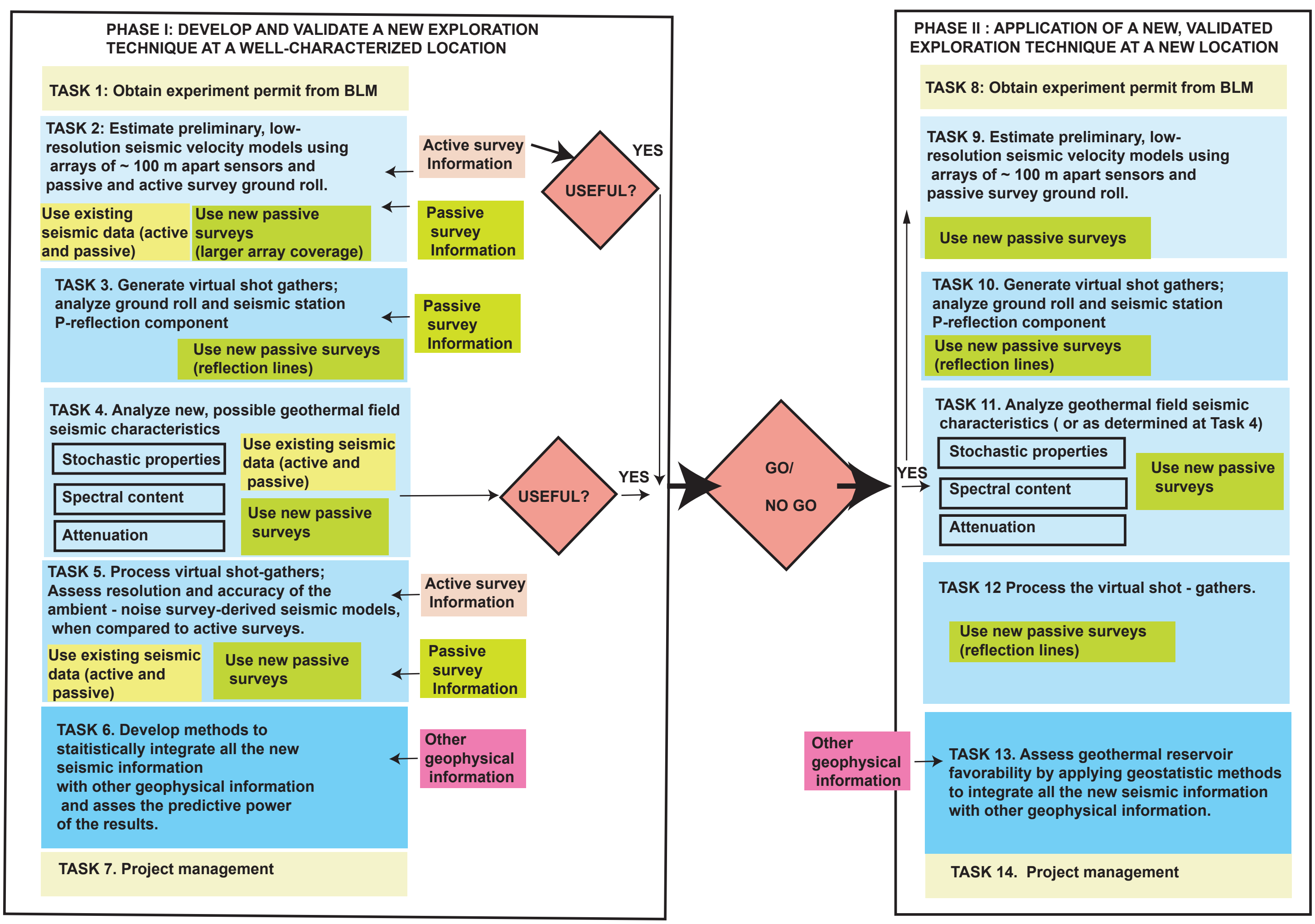

Figure 6. Project organization flow chart.

Summary

Scheduled to start in May 2012, this project will attempt demonstration and validation of a relatively inexpensive seismic exploration technique, using ambient seismic noise, as opposed to active sources recorded at arrays and reflection lines. At the time of the meeting, we hope to report on Tasks 1-3. The new method has the potential to provide knowledge of existing fault dips using ambient seismic noise processing, performance which has not been yet reported by other groups. Also, the method has the potential to estimate a preliminary shear velocity model which, unlike the *P*-velocity model, is not yet satisfactorily accomplished by conventional seismic reflection surveys and which has the potential to provide important independent information. Attenuation, spectral content and stochastic property analysis will be investigated as indicators of geothermal reservoir favorability. The project result will be a robust statistical evaluation, integration and synthesis of seismic and other geothermal favorability parameters.

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