Seismology and the Characterization of Lithospheric Heterogeneity

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Over the last 30 years seismologist have been moving away from a layer-cake Earth model toward a model that incorporates geologic heterogeneity at a variety of scales. Much of this work has been driven by the well recognized need to extract more of the information available in seismic data and by the increasing availability of high-speed computation as a tool for extracting that information. The need to characterize geologic heterogeneity at increasingly finer scales has spun off a number of interesting seismological issues, particularly in the realm of seismic scattering, but I suggest that there is a more fundamental reason for pursuing the characterization of heterogeneity. As a whole, geology and geophysics is undergoing a fundamental shift away from large-scale description (via plate tectonics) toward understanding and modeling Earth processes at the scales at which they occur, rather than through the low resolution mask of effective media. In order to make this transition we need to characterize the nature of geologic heterogeneity and how it varies and in particular we need quantitative scaling laws that can be applied to modeling a variety of geologic processes ranging from fluid flow, to the propagation of reaction fronts, to strain partitioning, to the interaction between Earth systems. Seismology will play a dominant role in characterizing heterogeneity and the derivation of scaling laws. To facilitate the inclusion of heterogeneity of all scales into our Earth models, we need to further develop and validate the range of techniques available for deriving heterogeneity parameters from seismic data.

Approaches to characterizing heterogeneity and scaling

The various approaches presently available to investigate heterogeneity are summarized in Table 1. The different approaches to heterogeneity characterization operate at different scales and have different strengths and limitations. In particular, all of the seismic techniques are limited by relatively narrow temporal and spatial bandwidths that are significantly less than the range of heterogeneity scales in the lithosphere. Because seismic scattering is most efficient when the seismic wavelength and scale of heterogeneity are similar, comparisons between techniques that employ different characteristic frequencies are difficult. Due to overlap in their frequency bands, successful comparison between lowpass filtered log data, map data and reflection seismic data is possible. Long range seismic experiments do not carry the overprint of data processing (stacking and migration) inherent in reflection seismic data, however, the long range experiments provide very limited information on the spatial distribution of variations in heterogeneity while reflection seismic data provide highly localized information. The differences in scale length sensitivity and localization of the various techniques of heterogeneity characterization present a significant challenge to the establishment of a standard heterogeneity model that would provide the basis for global comparisons.

TABLE 1

METHOD	CHARACTERISTICS
Borehole Logs	- High resolution - Generally limited to vertical sampling - Sense a variety of physical properties
Analysis of Geologic Maps	- Sensitive to descriptive lithologic variation - Limited spatial bandwidth - Mapping is generally interpretive
Seismic Techniques	- Sensitive to velocity / acoustic impedance fluctuations - Frequency dependent
Coda Analysis	- Dominantly sensitive to forward scattered field - Long travel paths (low resolution) - nonlocalized
Array analysis	- Sensitive to delay induced fluctuations in wave front coherence - Dominantly sensitive to forward scattered field but has been applied to strong specular reflections - Long travel paths (low resolution) - nonlocalized
Scattered wave imaging	- sensitive to relative strength of scattered field - localizes fields of scatterers but generally parameterized differently than other techniques
Reflection Analysis	- Sensitive to the spatial properties of back scattered field - High resolution with respect to other seismic techniques - High degree of localization - Standard processing techniques enhance coherence

The scattering regime and the scattered wave field

A significant portion of the heterogeneity information carried in seismic data is due to heterogeneity at or below the scale of the seismic wave length. As a result scattering plays a major role in both the kinematics and dynamics of the wave field. The nature of the scattered wave field depends on the strength and relative size of the heterogeneity in the media through which a wave propagates. In general, these parameters are represented by the scale and magnitude of fluctuations in the acoustic impedance field. Flatte et al. (1979) suggest a method of characterizing the scattering regime that identifies the dominant mechanism of scattering. To characterize the size and spatial extent of the heterogeneity they define a parameter Λ such that $\Lambda \propto \left(\frac{R_f}{L_H}\right)^2$,where R_f = radius of the first Fresnel zone and L_H = correlation length of the of the impedance field orthogonal to the direction of wave propagation. For $\Lambda<1$, specular processes dominate and for $\Lambda>1$ diffraction processes dominate. To characterize the strength of the fluctuation, they define Φ such that $\Phi^2 = q_0^2\left[\mu^2\right]RL_I$, where q_0 = wave number of the seismic pulse, μ = RMS fluctuation of acoustic impedance, R = distance traveled by the wave, L_{p} = the correlation length parallel to the direction of propagation and L_I is approximated by $0.4L_p$. They further suggest that the approximate boundary between the weak and strong scattering regimes is $\Lambda \Phi^2 = 1$ for small values of Λ and $\Phi = 1$ for large values of Λ. The bound between weak and strong scattering regimes essentially represents the boundary between wave fields dominated by single and multiple scattering respectively. Mapping of the relevant characteristics of typical crustal seismic experiments onto the proposed description of the scattering regime demonstrates that wave propagation in the crystalline crust is dominated by weak scattering but, for regions of the crust dominated by fluctuation between silicic and mafic compositions, strong scattering occurs for frequencies above about 10-15 Hz. Both theoretical and experimental work suggest that strong scattering has significant effects on the seismic wave field that will perturb attempts to invert the spatial properties of the wave field to characterize the heterogeneity of the acoustic impedance field.

Seismic reflections, heterogeneity mapping and scaling law estimation

Of the various seismic techniques, reflection seismic data offer the highest potential for resolution and localization of heterogeneity. Theoretical and experimental work demonstrate that the spatial statistics of the impedance field (geology) and the back-scattered wave field are correlated and for the special case of the ideal seismogram (represented by the primary reflectivity series), the spatial properties of the two fields are the same. Correlation between the wave field and the impedance field suggests that the wave field might be inverted to determine the spatial properties of the impedance geology.

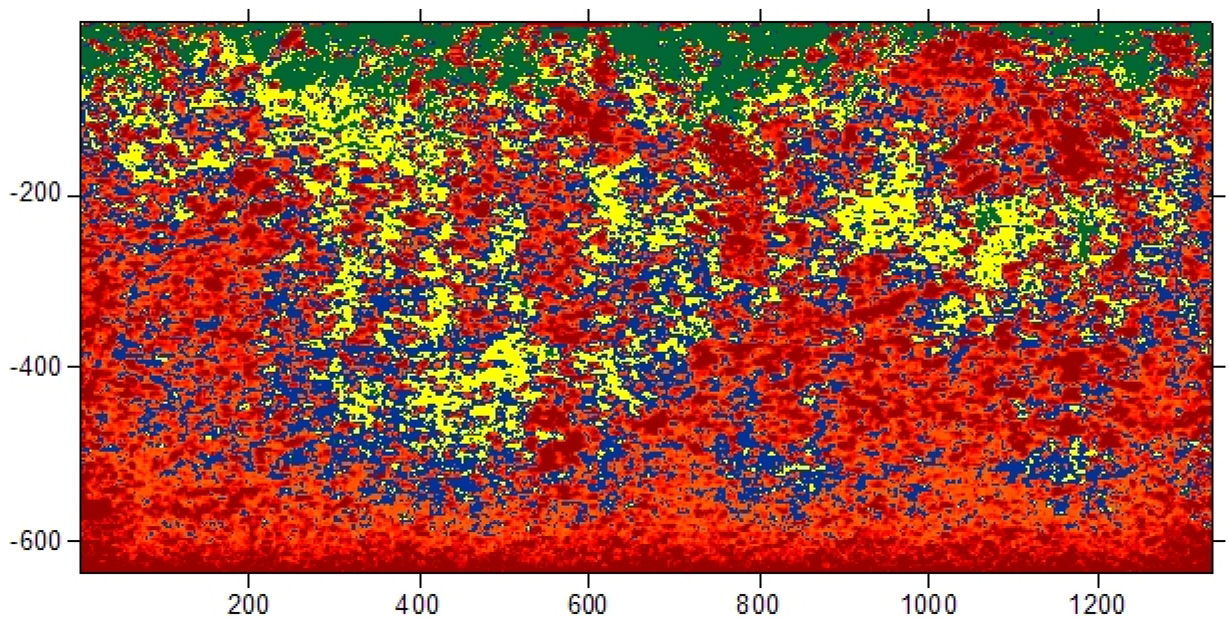
Analysis of the spatial statistics and physical property distributions of geologic maps over crustal terrains representing a variety of crustal levels demonstrates that geologic heterogeneity is typically discontinuous or modal with self-similar spatial properties. These observations have led to the use of the von Karman distribution, either in the form of a correlation function or power spectrum, to parameterize geologic heterogeneity. The von Karman distribution is described by a variance, characteristic correlation length and a Hurst number. The correlation length represents the largest scale for which the scaling is described by a power law and the Hurst number is the exponent of the power law. The Hurst number is directly related to the fractal dimension. The methodology for estimating the three parameters of the von Karman distribution from seismic reflection data is relatively straight forward involving trend removal, estimation of the 2-D power spectrum or correlation function and the an optimization procedure to determine the von Karman parameters.

Although several workers have reported von Karman parameters extracted from reflection data that are consistent with values reported for geologic maps, it is difficult to confirm the validity of the technique. Several arguments, including modification of coherence by stacking and migration, the limited temporal and spatial bandwidth of the seismic data, the contribution of strong scattering and contamination of the data by both correlated and uncorrelated noise and unresolved statics suggest that direct extraction of valid von Karman parameters may be difficult. The validity of the method remains an open question.

An alternative approach based on the premise that although the von Karman parameters extracted from the reflection wave field may be contaminated by a variety of problems, as long as the contamination process is stationary, variations in the von Karman parameters represent variations in the wave field which are a response to geologic heterogeneity. Support for this premise is found in seismic modeling studies and several examples in which geologic information can be confidently projected into seismic profiles. Based on this idea we have carried out fine-scale statistical mapping of crustal reflection data to determine relative variations in heterogeneity and then used the maps to estimate the von Karman parameters.

Figure 1 shows an example of heterogeneity mapping for a 220 km long seismic profile from the Grenville Province. In this case, the parameter mapped is a combination of the correlation length and Hurst Number. The power of the technique for localizing significant lateral and vertical variations are clearly demonstrated.

Figure 1. Heterogeneity mapping of a seismic profile from the Grenville Province in Eastern Quebec.



Outstanding Issues and Directions

To move ahead on the development of Earth models that include heterogeneity we need to move the techniques of extraction of heterogeneity information into a more routine part of seismic data analysis. Significant theoretical development, particularly in the realm of the back scattered wave field is required to deal with issues related to the frequency dependence of heterogeneity estimates. More comparisons between the various techniques are required, as is a common form of parameterization. Development of validated techniques for heterogeneity estimation will provide the tools for the investigation of recent exciting proposals that suggest multiple scaling populations in the lithosphere that are linked to specific processes of lithospheric evolution.