Regional Imaging of the Subsurface of Mars Using Teleseismic Events, Claudia M. Aprea, Douglas M. Alde, and James T. Rutledge, Los Alamos Seismic Research Center & EES-11, MS-D443, Los Alamos National Laboratory, Los Alamos, NM 87545

Introduction
We present a plausible method to map the subsurface structure of Mars using distant events (such as teleseismic marsquakes or distant meteor impacts) and a sparse distribution of recording stations. The goal is to obtain a computed reflectivity image of a localized region of Mars, a 3-D map of the locations of impedance changes within the crust and upper mantle. We have tested this method in the mapping of the crustal structure beneath the Jemez Volcanic Field in northern New Mexico quite successfully. The image was obtained by applying a novel adaptation of the Kirchhoff wavefield imaging method to digitally recorded teleseismic data. It could be also valuable for mapping the Mars subsurface as it is not very sensitive to station distribution and origin of sources.

Kirchhoff migration

The Kirchhoff migration method has been widely used to obtain high-resolution images of the shallow Earth's crust for petroleum exploration. It has recently been applied for basic research studies of deeper Earth structure [1][2]. Kirchhoff migration has also proven useful in the study of crustal scatterers near small-aperture arrays [3] and characterization of lower mantle heterogeneities [4]. We developed and used a modification of the classic Kirchhoff migration geometry to map the crustal structure beneath the Jemez Volcanic field quite successfully using teleseismic data (distant earthquakes) as sources.

In conventional migration applications, a source is initiated on or near the Earth's surface and the resulting seismic field propagates into the Earth. Velocity and density contrasts scatter portions of the wavefield back towards the surface where it is recorded by an array of receivers (Figure 1a). The field recorded at the surface can be extrapolated back into the interior of the Earth using one of various forms of the wave equation. This extrapolation requires an a-priori model for the Earth's velocities and density. Our modified version uses distant events as sources, and unlike the typical seismic exploration, the characteristics of the sources are unknown. However, the following assumptions can be made: the initial arrival is the direct path compressional wave. Plane-wavefronts from the source arrive at the base of the region being imaged as in the case of teleseismic travel time tomography [5], and the incident wavefront direction vector of the source pulse is nearly vertical near the Earth's surface. This implies the energy associated with the P (compressional) wave mode dominates the vertical component of motion. In order to separate the forward-scattered P-waves from the direct arrival the geometry of our imaging approach differs from the conventional (Figure 1b). We image using waves that are reflected first from the free surface, and after propagate down to a scattering location, where it is scattered back towards the surface where it is recorded.

Figure 1

Because high frequency wavefields can be well described by the asymptotic ray theory we need only the determination of the ray amplitudes and ray travel times, which are done by ray tracing on an initial velocity model. This model can be constructed from geophysical/geological information available and can be improved on through the process of migration, though sometimes this is not required as Kirchhoff migration has been shown to be robust in terms of the initial model, particularly in regions of only mildly heterogeneous velocity structure. The number and distribution of stations are important for the spatial resolution of the result, but they do not need to be uniformly distributed. The key is to work with a sufficiently large number of events to obtain a statistically robust image. The spatial resolution of the image is a function of both the station spacing and the frequency content of the data.

Each event (or group of events) will produce an independent reflectivity image. These images are then stacked together, in a well defined way, to produce an
average image. Finally, the result is tested statistically to assure us the procedure is correct.

Case study - Jemez volcanic field, NM
An example of the application of this method is the computation of a reflectivity image for the Earth beneath the Jemez volcanic field in northern New Mexico. The Jemez volcanic field (JVF), located at the intersection of the Jemez lineament and the western boundary of the Rio Grande Rift, is the home of one of the most famous giant resurgent calderas, and perhaps one of the most studied volcanic systems in the world. Volcanism in the JVF began as early as 16.5 Ma and continued in different ways and time spans until the most recent eruption occurred, at ~50 ka. Geology of the area has been extensively studied. The data come from the multidisciplinary Jemez Tomography Experiment (JTEX). It comprised both active and passive seismology, geology, gravity and electromagnetic data collection efforts conducted from 1993 to 1995 attempting to improve our geophysical knowledge of the region [6]. The active and passive seismic experiments, with different degrees of resolution, resulted in a three dimensional P velocity model and helped elucidate the heterogeneous structure of the JVF [7][8][9][10].

The resulting migrated 3-D image along with station locations (triangles) is shown in Figure 2. The figure shows zones of strong intensity with different polarity (cold colors and warm colors) distributed over a zero intensity background (green). The high-amplitude areas in the images indicate boundaries between media of different impedances. Significant features seen in the image include the base of the caldera fill; several reflectors in the crust associated with residuals coming from the mantle and or other crystallized chambers such as the chamber seen in tomographic images as a low velocity zone; two strong reflectors coincident with the crust-mantle interface, and a zone of layered reflections from the base of the crust consistent with basaltic underplating.

Conclusions
This adaptation of the conventional Kirchhoff migration algorithm appears to be a good candidate for future exploration of Mars’ structure. Some of the benefits this method presents are:

• An artificial seismic source is not required; regional crustal images could be derived passively using Martian teleseisms [11][12] or possibly distant meteor impacts [13];
• Little detailed information is required of the source characteristics;
• Although the spatial resolution of the image does depend on number and the distribution of stations, an acceptable image can be obtained from a reasonably uniform, but not necessarily regularly spaced, seismic array on the Mars surface.

References