Velocities of southern Basin and Range xenoliths: Insights on the nature of lower crustal reflectivity and composition

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ABSTRACT

To reconcile differences between the assessments of crustal composition in the southern Basin and Range province on the basis of seismic refraction and reflection data and lower-crustal xenoliths, we measured velocities of xenoliths from the Cima volcanic field in southern California. Lower-crustal samples studied included gabbro, microgabbro, and pyroxenite. We find that the mafic xenolith velocities are compatible with regional in situ measurements from seismic refraction studies, provided that a mixture of gabbro and pyroxenite is present in the lower crust. Supporting this model are observations that many of the lower-crustal xenoliths from the Cima volcanic field are composites of these rock types, with igneous contacts. Vertical incidence synthetic seismograms show that a gabbroic lower crust with occasional pyroxenite layering can produce a reflective lower crust that is similar in texture to that shown by seismic reflection data recorded nearby.

INTRODUCTION

In studies of the southwestern United States, a fundamental dispute has emerged between geologists who study xenoliths from the upper mantle and lower crust and geophysicists who measure bulk in situ properties of these regions with seismic waves. The dispute originates from the mismatch in results reported by these two communities. Those who study the actual rocks from the lower crust find them to be highly mafic in composition (e.g., Griffin and O'Reilly, 1987; Wilshire, 1990; Wilshire et al., 1991), whereas refraction seismologists have maintained that the low seismic velocities from the lower crust (typically <6.5 km/s) preclude it from being as mafic as the xenolith samples suggest (e.g., Goodwin and McCarthy, 1990; McCarthy et al., 1991; Parsons et al., 1995). In this paper we present laboratory velocity measurements on lower crustal xenoliths brought to the surface in recent (<7.5 Ma) basalt eruptions from the Cima volcanic field (Fig. 1); the measurements were carried out at high pressures equivalent to those of their deep-crustal origin, and we compare those direct measurements to in situ velocities measured from nearby seismic refraction experiments.

GEOLOGIC AND GEOPHYSICAL SETTING OF THE CIMA VOLCANIC FIELD AND SURROUNDINGS

The Cima volcanic field is one of many small alkalic basalt fields of late Tertiary–Quaternary age in the southern Basin and Range province (Luedke and Smith, 1981). Remnants of the Cima volcanic field are found within an area of ~300 km^2 in the Ivanpah highlands (Hewett, 1956) of the east-central Mojave Desert in southern California (Fig. 1). The Cima volcanic field is underlain by Proterozoic metamorphic and igneous rocks (DeWitt, 1980; Wooden and Miller, 1990), Proterozoic and lower Paleozoic sedimentary rocks (Calzia, 1991), Cretaceous granitic rocks and dike rocks of the Teutonia batholith (Beckerman et al., 1982), and Miocene terrestrial basin deposits (Reynolds and Nance, 1988). The presence of thin septa of Proterozoic rocks in the Teutonia in adjacent Proterozoic rocks indicates that rocks of the Teutonia batholith lie at a shallow depth throughout most of the Cima volcanic field. Gravity data (Wilshire et al., 1987) indicate the presence of Teutonia batholith rocks to depths of ~10 km (R. C. Jachens, 1991, oral commun.). The Cima volcanic field basaltic rocks, which range from late Miocene (~7.5 Ma) to Holocene (~100 ka or younger) (Turrin et al., 1985; Wells et al., 1991) were erupted from at least 71 vents. Eruptions occurred in two distinct episodes, one from ~7.5 to 3 Ma and the other from ~1 Ma to ~100 ka.

The nearest in situ characterization of the crust in the region comes from the U.S. Geological Survey Pacific to Arizona Crustal Experiment (PACE) seismic refraction profiles located to the south of the Cima volcanic field, extending to within 75–100 km of the Cima locality (Fig. 1). Modeling of these refraction data has determined a relatively uniform lower-crustal velocity of ~6.5–6.7 km/s (McCarthy et al., 1991). The 6.5–6.7 km/s lower-crustal velocities are typical of the southern Basin and Range crust and are also observed regionally beneath the Arizona transition zone of the Colorado Plateau (Goodwin and McCarthy, 1990; McCarthy et al., 1991; Parsons et al., 1995). The vertical-incidence seismic reflection data nearest to the Cima volcanic field were recorded ~75 km to the south by the California Consortium for Crustal Studies (CALCRUST) in Ward Valley, California (Frost and Okaya, 1986), and show a highly reflective lower crust.

CHARACTERIZATION OF CIMA XENOLITHS

Several cinder cones and lava flows of the Cima volcanic field contain abundant lower-crustal and upper-mantle xenoliths

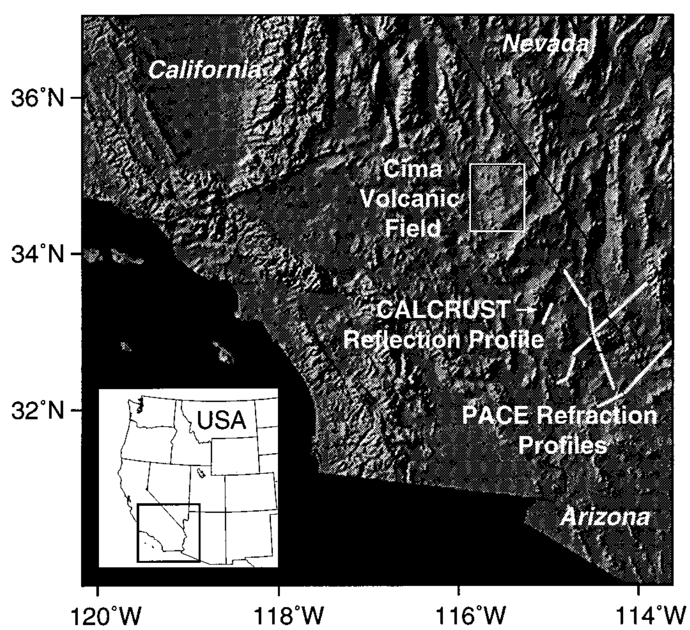

Figure 1. Locations of Cima volcanic field, U.S. Geological Survey Pacific to Arizona Crustal Experiment (PACE) refraction profiles (McCarthy et al., 1991), and CALCRUST deep-reflection profile (Frost and Okaya, 1986).

(Wilshire et al., 1991). Crustal rocks are gabbro, pyroxenite, and microgabbro, all with igneous textures. Mantle rocks include spinel peridotite and pyroxenite, all with metamorphic textures. The mantle xenoliths are commonly intruded by dikes that are lithologically identical to the igneous crustal xenoliths and are thought to be stagnated dikes related to feeders that supplied magma to the lower crust (Wilshire, 1990).

Approximately 60% of xenoliths of all types show incipient to extensive melting and/or magmatic infiltration features. Many of the pyroxenites and gabbros show partial melting features, generally with substantial parts of the melt having again crystallized before entrainment in the host basalt, as shown by two generations of newly crystallized minerals in glass, coarse grain size of new crystals, and oscillatory zoning of new plagioclase crystals. Partially melted crustal rocks generally have abundant cavities, believed to have formed by segregation of CO_2-rich fluids during crystallization or later melting, ranging from microscopic to as much as 2 cm across; macroscopic cavities 0.5 mm across make up as much as 10% of some xenoliths (Wilshire, 1990). The three major xenolith rock types are all found as composites in which one intrudes the other, forming an igneous contact. Both gabbros and pyroxenites are observed as composite with peridotites (Wilshire et al., 1991), indicating that these rocks are transitional from the upper mantle into the lower crust.

LABORATORY MEASUREMENTS OF SEISMIC VELOCITY AND DENSITY ON CIMA XENOLITHS

We chose to focus on Cima xenoliths because of the high quality and large size of the samples as well as their abundance. To measure velocities at high confining pressures, three orthogonal cores 2.54 cm in diameter and at least 2.5 cm in length were drilled from each sample. Three cores are necessary to check for seismic anisotropy in the samples, because in a strongly anisotropic rock, arbitrarily choosing a single core could affect the velocity results by 10%–20% or more. Thus, relatively large, unfractured xenolith samples are necessary. The cylindrical samples from the Cima xenoliths were polished on the ends and jacketed in copper. Sending and receiving piezoelectric transducers (~1 MHz natural resonance frequency) were mounted on the ends of the cores, which were then placed in a pressure vessel, and longitudinal and shear velocities were determined by dividing the measured sample length by the traveltime across the samples. Christensen (1985) provided a detailed description of the complete velocity-determination method. Velocities and densities were measured at 1000 MPa in three microgabbros, one coarse-grained gabbro, and four pyroxenite xenoliths. Also included in the measurements was a granite sample collected from a surface exposure of the Teutonia batholith. The measured velocities were corrected for temperatures that simulate low (~9 °C/km), average (~15 °C/km), and high (~26 °C/km) geotherms by using the temperature data of Christensen (1979).

None of the crustal rocks we investigated was strongly anisotropic; the average anisotropy was <4%. We report average velocities over the three directions for the nine crustal rocks investigated. The results of the velocity measurements as a function of pressure (converted to approximate depth) at an average geotherm (Sass et al., 1994) are summarized in Figure 2. Also shown in Figure 2 is an average velocity vs. depth profile derived for the nearest seismic refraction model of the crust (profile 3 of McCarthy et al., 1991; Fig. 1). The measured velocity of the Teutonia granite sample matches well with the average upper-crustal velocity from the seismic refraction modeling down to middle-crustal depths (~15 km). Many of the gabbroic xenoliths were found to have surprisingly low velocities (<6.5 km/s) for such mafic rocks and fall short of the average lower-crustal velocity from the seismic refraction modeling (Fig. 2), whereas one microgabbro sample did have a measured velocity high enough to match the in situ velocity for the lower crust. Since the pressure derivatives of the gabbro velocities measured at pressures equivalent to lower crustal depths are not abnormally high (Fig. 2), it is unlikely that open cracks are responsible for the low velocities. Two of the low-velocity gabbros, which contain up to 20% glass, have been partially melted and subsequently quenched in the lower crust. We attribute the glass to be the primary cause of the low velocities in these samples. The third low-velocity gabbro contains abundant (~18%) oxide, which is responsible for its relatively low velocity as well as its high density (Fig. 3).

In contrast to the gabbro samples, the four pyroxenite xenoliths investigated all had high velocities at lower-crustal pressures of 7.0–7.5 km/s, much higher than the in situ average lower-crustal velocity of 6.5–6.7 km/s. The velocity variations between the gabbro and pyroxenite xenoliths may have implications on the origin of lower-crustal reflectivity. In Figure 3, the measured velocities and densities of the samples are combined into acoustic impedance, and strong contrasts are observed between the pyroxenites and gabbros. From average velocities and densities of the gabbros and pyroxenites, we obtain a reflection coefficient of 0.1. Thus, subhorizontal interlayering of these lithologies should produce strong reflections to vertical-incidence seismic energy.

IMPLICATIONS FOR THE NATURE OF THE LOWER CRUST

The observation that gabbros and pyroxenites coexist in the upper mantle and lower crust, as evidenced by their common associations as composite xenoliths, is strongly suggestive that the lower crust in the region is composed of a mixture of these lithologies. The measured velocities of the gabbro xenoliths indicate that, apart from one sample, most are too slow to make up the entire lower crust as compared with the measured velocities from seismic refraction data. A similar comparison indicates that the measured velocities of the pyroxenites are too fast for such rocks to compose the entire lower crust. The lower crust could, however, be composed of a mixture of

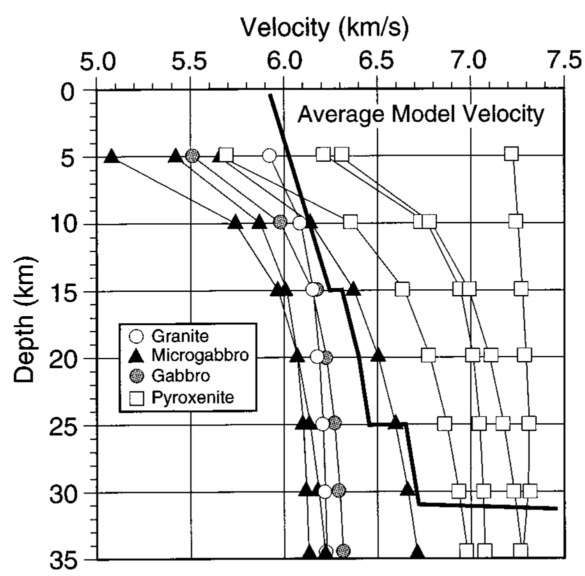

Figure 2. Average measured velocity with depth of gabbro, microgabbro, and pyroxenite xenoliths, and one surface granite sample corrected for average geotherm (Sass et al., 1994). Thick black line is velocity vs. depth average from model of McCarthy et al. (1991) that is nearest Cima volcanic field. In general, gabbro samples are too slow, and pyroxenite samples too fast to represent lower crust alone, but mixture of two lithologies could be reasonable representation of lower crust.

these two lithologies. If the gabbros with the lowest measured velocities make up most of the ~15-km-thick lower crust, then a cumulative layer thickness of ~4 km of pyroxenite would need to be mixed in with the gabbro to arrive at the in situ lower-crustal velocity as measured by the seismic refraction data. At the other limit, if the bulk of the lower crust is represented by the gabbro with the highest measured velocity, then a pyroxenite layer of <1 km cumulative thickness would be necessary to match the refraction model.

We modeled a lower crust as comprising the gabbro with the highest measured velocity and interspersed thin layers of pyroxenite (<1 km cumulative thickness) by using reflectivity modeling (after the method of Fuchs and Müller, 1971) and compared the result with deep-crustal vertical-incidence seismic data collected nearby in Ward Valley by CALCRUST (Frost and Okaya, 1986; Fig. 1). We were able to reproduce the general texture and density of lower-crustal reflectivity as observed on the deep-reflection data (Fig. 4) with six to ten 50- to 300-m-thick layers of pyroxenite interspersed in gabbro. These layers represent the sort of thicknesses resolvable with controlled-source vertical-incidence seismology, but clearly much thinner layers (and possibly thicker ones also) must exist because millimetre- to centimetre-scaled layering is observed in the Cima composite xenoliths (Wilshire et al., 1991). Layers of gabbro, pyroxenite, and peridotite (P-wave velocity of 8.0 km/s) were intermixed in the model to simulate a transitional Moho boundary, because all three lithologies are found as composite xenoliths. The genetic origins of ultramafic layering such as pyroxenite in the lower crust are uncertain, but lower-crustal ultramafic xenoliths are very common both locally (e.g., Wilshire, 1990) and worldwide (e.g., Rudnick, 1992) and could represent cumulates or restites associated with basaltic intrusions and/or extraction of silicic melts (Rudnick, 1992).

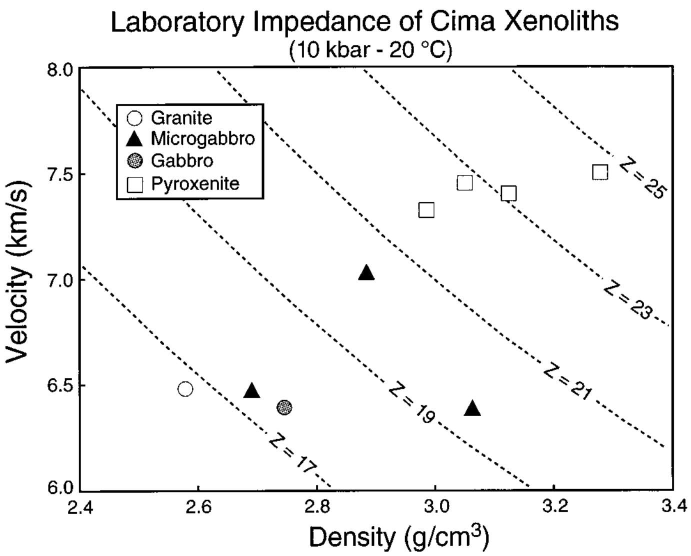

Figure 3. Measured acoustic impedance (product of density and velocity) of xenoliths investigated plotted with contours of equal impedance. Gabbro and pyroxenite xenoliths fall into two distinct fields of impedance and thus would be strong reflectors of seismic energy if rocks were in direct contact.

DISCUSSION

This paper presents velocity and density measurements on xenoliths from the Cima volcanic field and compares those results to velocities measured from seismic refraction and reflection data collected 75–100 km away from the Cima site. We have shown that the features of both long-offset and near-vertical seismic data can be matched by a lower crust composed of rocks similar to the gabbro and pyroxenite xenoliths measured. However, many uncertainties are inherent in this approach. The number of samples measured was small because of the requirement that the samples be large and intact; thus, either of the two apparent families of gabbro velocities might represent statistically insignificant outliers. The possibility that the xenoliths are in some way altered through the entrainment process also cannot be completely ruled out, and the role (if any) that the observed cavities and pores in the xenoliths play on either the in situ crustal velocity or the xenolith samples is uncertain. Also, the uniformly igneous textures of the mafic lower-crustal xenoliths may be an indication that these rocks are closely related to the magmatism that brings them to the surface and, thus, only locally represent lower-crustal composition.

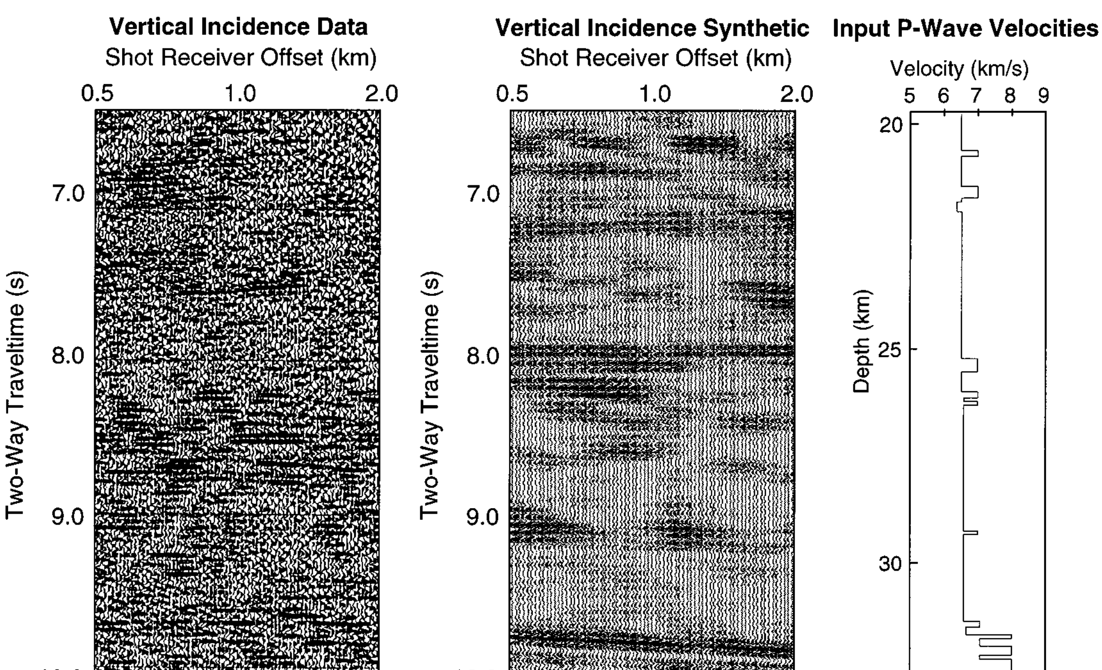

Figure 4. Window of CALCRUST (Frost and Okaya, 1986) lower-crustal vertical-incidence seismic data from Ward Valley, California (~75 km from Cima volcanic field), compared with full wavefield synthetic reflection data (after method of Fuchs and Müller, 1971) generated from one-dimensional velocity vs. depth curve shown. Reflective texture was reproduced reasonably well by modeling lower crust with background velocities of higher measured velocity gabbro xenolith and adding from six to 10 layers of pyroxenite (cumulative thickness <1 km).

Given the uncertainties in this approach, there still are appealing reasons to pursue it. That we can be certain that these xenoliths represent at least some fraction of the lower-crustal composition at any locality in the southern Basin and Range province cannot be ignored. The lower crust throughout the region is uniform in velocity within ~0.2 km/s (e.g., Prodehl, 1979; McCarthy et al., 1991; Parsons et al., 1995), which is an indication that compositions may be regionally similar. Gabbro and pyroxenite xenoliths with igneous textures are common in western U.S. localities (see, for example, Wilshire et al., 1988; Wilshire, 1990; McGuire, 1994), and analysis of gravity data (R. W. Simpson et al., unpublished data) supports wide distribution of gabbro in the subsurface along the Colorado River extensional corridor. These observations indicate that regionally, mafic magmatic intrusions have significantly altered the composition and structure of the southern Basin and Range lower crust. One implication of a primarily gabbroic lower crust is that the observed low velocities may not persist with time and could increase sharply as the gabbros convert to equilibrated granulites (e.g., Christensen and Fountain, 1975).

CONCLUSIONS

Our primary conclusion is that laboratory velocity and density measurements on lower-crustal xenoliths from the Cima volcanic field are consistent with the observed velocities from seismic refraction data if the lower crust represents a variable mix of gabbro and pyroxenite. Such a mixture can duplicate the reflective texture observed on vertical-incidence seismic data with a few (~6–10) 50–300-m-thick layers of pyroxenite within a primarily gabbroic lower crust.

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