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A 3-D SEISMIC MODELING STUDY OF THE LADRON HORST NEAR SOCORRRO, NEW MEXICO

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Abstract. Three-dimensional seismic modeling demonstrates that the intragraben horst-like feature imaged on COCORP's Socorro-Abo Pass survey in the Albuquerque Basin, New Mexico likely corresponds to the northeast-plunging continuation of the Ladron uplift. This accords with the original interpretation which was expounded with reservations that the feature might be a result of side reflections off a nearby exposed basement uplift. This domed feature on Socorro Line 1A, referred to hereafter as the Ladron horst, cannot be a consequence of side reflections from the nearby Ladron Mountains. Three-dimensional modeling defines a minimum northeastern extent of the Ladron uplift in the subsurface, confirms some aspects of previous interpretations, and offers a new interpretation of the apparent western boundary of the horst. Second-order discontinuities in the reflections off the horst are modeled as normal faults within the subsurface basement uplift.

Introduction

Line locations from part of the 1975/76 COCORP survey in the Rio Grande rift are shown on the generalized geological map in Figure 1. Prominent reflections in the shallow crust imaged a large apparent basement uplift. Also recorded were deep reflections, from approximately 20 km, interpreted as reflections off a mid-crustal magma body [Brown et al., 1979; Brown et al., 1980]. Figure 2 shows the Socorro Line 1A seismic section with both the prominent horst within the Albuquerque Basin and the deeper mid-crustal magma body.

de Voogd [1986a] stressed the importance of three-dimensional analysis of the COCORP data obtained in the Albuquerque Basin. A common assumption of the seismic reflection method is that reflections originate from within the plane of section, in other words, from directly beneath the seismic line. However, Brown et al. [1980] expressed concern that some of the reflections on Socorro Line 1A might have originated from well out of the plane of section. Specifically, side reflections, or sideswipe, off the nearby Ladron Mountains might have generated what appeared to be a domed feature in the shallow section, like the one observed on Line 1A. Three-dimensional modeling demonstrates, however, that the Ladron horst reflections are not sideswipe, and that they originated from almost directly beneath the seismic line.

Much of the attention drawn by the Socorro-Abo Pass survey has been directed toward the mid-crustal magma body. Nevertheless, several interpretations of the prominent shallow structure as imaged by COCORP have appeared in the literature. The first interpretation of this anomalous intrabasin mound was that it represents the internally faulted, down-plunge extension of the Ladron uplift to the southeast

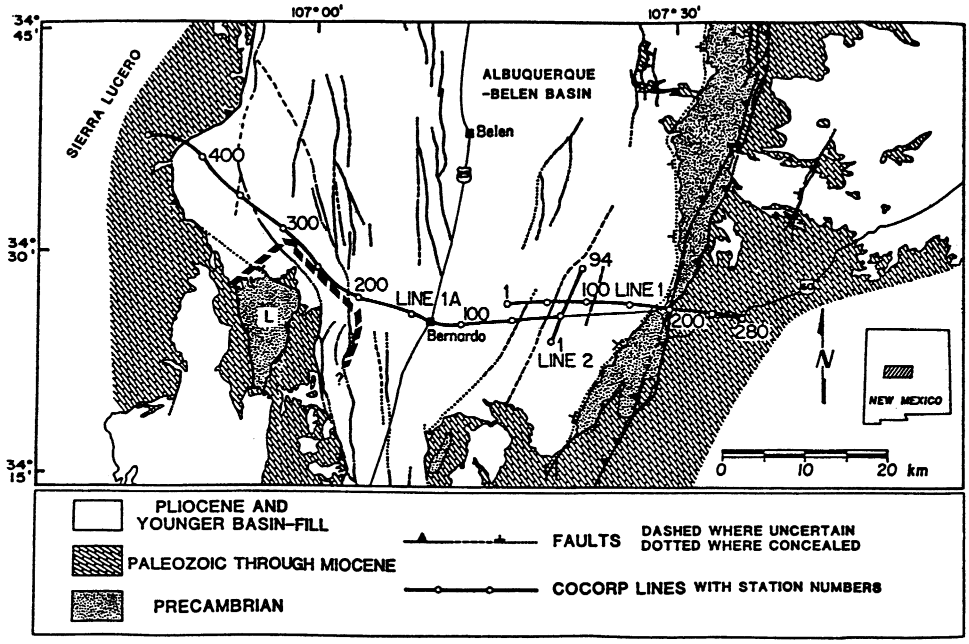

Fig. 1. Generalized geologic and tectonic map showing COCORP line locations in the Albuquerque-Belen Basin. Broad dashed line outlines minimum extent of the Ladron uplift, L, in the subsurface. Ladron uplift probably continues even farther to the northeast [after de Voogd et al., 1986b].

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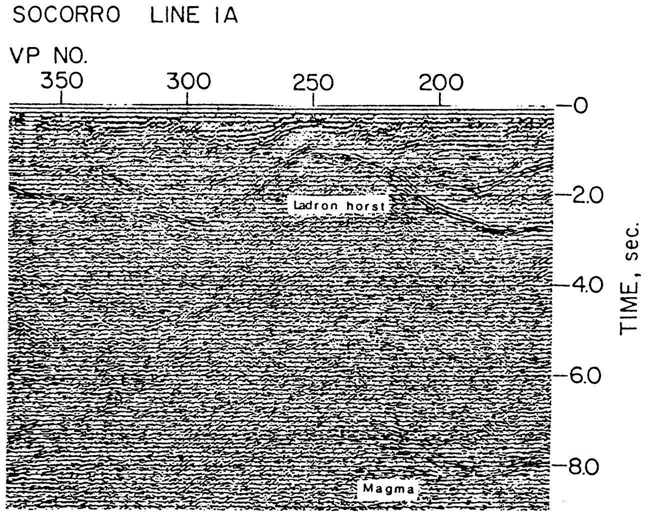

Fig. 2. Unmigrated Socorro Line 1A seismic section displayed at 1:1 scale for an average p-wave velocity of 6 km/sec.

[Brown et al., 1979]. Integral to this interpretation are the steep normal faults which bound and are contained within the horst. Later, Cape et al. [1983] interpreted migrated COCORP seismic sections to conclude that the steep basement reflections imaged on Line 1A and adjacent lines are listric normal faults. In contrast, Wu [1986] interpreted compressional features on Socorro Line 1A, attributing the intragraben horst to folding and reverse faulting. The nature of structure in the Albuquerque Basin is much debated. No one interpretation commands universal support, although each includes substantial faulting. This study lends support to previous interpretations of abundant intrarift normal faulting.

Between VP's 200 and 300 in Figure 2, imaged between one and three seconds two-way travel time, is an antiformal structure with over three kilometers relief, the Ladron horst. This study presents a simple, viable three-dimensional model of this feature which is consistent with previous interpretations of an extension of the Ladron uplift in the subsurface.

Geology

The Ladron uplift is a fault-bounded and complexly deformed uplift consisting mainly of Precambrian basement rocks and Paleozoic sedimentary rocks on the western edge of the southern Albuquerque Basin (see fig. 1). It has undergone several episodes of uplift, the most recent of which occurred in late Miocene and/or earliest Pliocene time [Chapin and Seager, 1975]. Granitic intrusives, quartzites, and metavolcanic rocks comprise most of the exposed Precambrian rocks in the Ladron Mountains [Foster and Stipp, 1961; Condie, 1976; Kelley, 1977], similar to the lithologies found on the opposite side of the basin.

The structure on the western border of the Albuquerque Basin differs markedly from that on the eastern border. The Ladron uplift stands alone "like a giant rivet driven up from below" [Kelley, 1977], but the uplifts to the east crop out in a fairly continuous north-trending line all along the eastern edge of the southern Albuquerque Basin. The numerous faults within the Ladron uplift have varied strikes, as do the faults which bound the uplift. Most of the faults in the uplifts to the east, however, parallel the axis of the basin.

Surface mapping of the Socorro area indicates that uplift of the Ladron Mountains may have been contemporaneous with uplift of the Lemitar-Socorro-Chupadera Mountains intrarift horst which extends southward 70 km from the Ladron Mountains [Chapin and Seager, 1975]. Three-dimensional seismic modeling of COCORP's Socorro Line 1A defines a minimum northeast extent of the Ladron uplift in the subsurface. The Ladron uplift extends at least 5 km northeast beneath the Phanerozoic sedimentary cover, consistent with the Bouguer gravity map of Keller [1983].

The Model

The first step in modeling the Ladron horst was to construct a three-dimensional model interface, constrained by the shape of the Ladron Mountain basement outcrop, which would generate a reflection horizon with the same gross asymmetric shape as the reflections on the real data. To construct a realistic model, the real seismic section was displayed at a two-to-one vertically exaggerated scale in order to accentuate the relief on the horizon of interest. Then, planes with different orientations were joined together to produce a relatively simple, yet realistic model. The preliminary model was later digitized with no vertical exaggeration, and second-order features, which are described later, were added.

The assumption was made that the continuous, high amplitude reflections in the shallow part of Line 1A correspond to top of Precambrian basement and, thus, represent similar acoustic impedance across the entire line. For each model trial, then, a constant velocity of 3.5 km/s was chosen for basin fill, based on average refraction [Jurdy and Brocher, 1980; Brocher, 1983] and reflection [Brown et al., 1980] velocities of the basin sediments. The half-space below the basin fill/basement interface was assigned a velocity of 6.0 km/s.

Many trial synthetic seismic lines were shot using a normal incidence ray tracing procedure, each time increasing the plunge of the horst, until the depth of the synthetic reflections matched those on the real data. Figure 3 shows several 3-D perspective views of the northeast-plunging Ladron horst models and their respective synthetic seismograms. Note how the amplitudes decrease in each successively deeper seismogram. This loss in amplitude is due to several effects, including spherical divergence and other geometric effects. Amplitude loss due to spherical divergence essentially reflects the attenuation due to the longer distance traveled by deeper penetrating energy. Geometric effects refer to the simple fact that the geophones used in this seismic reflection survey record only vertical ground motion. As the plunge of the model layer increases, reflection points move farther out of the plane, and the reflected energy returns at greater angles to the vertical. Thus, the greater the model plunge, the smaller the vertical component of seismic energy returned to the reciever. Based on the position and shape of the Ladron uplift outcrop, velocity of basin fill, and on depth in two way travel time, a model plunge of about 10° best fit the data (Figure 4).

The plunge of the model layer was incremented even further to nearly 90° in an attempt to simulate side reflections from the Ladron Mountains. If the Ladron uplift really were "like a...rivet driven up from below," that is, if in the subsurface it were steep-sided and areally limited, one might encounter severe sideswipe problems. Sub-horizontally propagating seismic energy could reflect off of such a feature and contaminate the seismic section. This was found not to be the case. In the nearly vertically plunging model no seismic energy returned to the seismic line within the 20 second recording period.

The Ladron horst as it appears on the seismic section is, therefore, not a result of sideswipe from the Ladron Mountains. Velocities of the basin fill as determined from seismic reflection [Brown, et al., 1980] and refraction [Jurdy

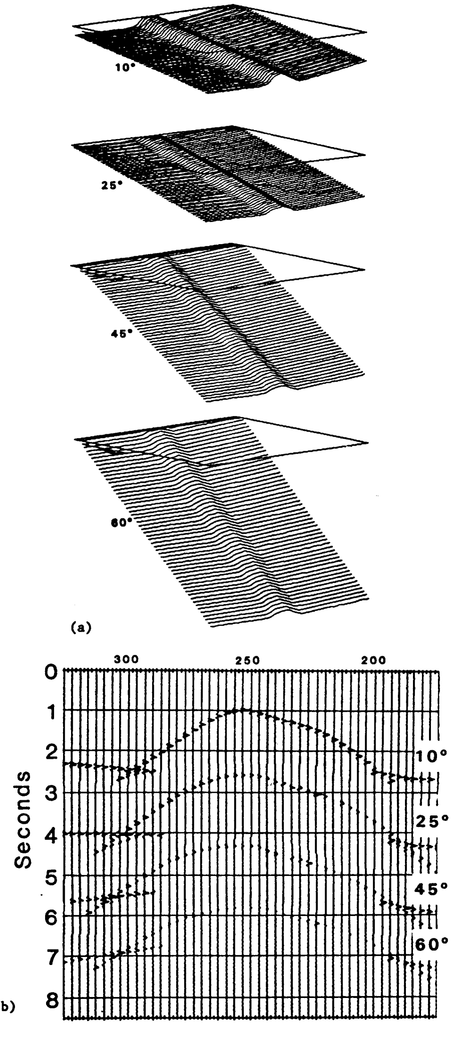

Fig. 3. (a) 3-D perspective views of four models, each with increasing plunge. (b) Synthetic seismograms corresponding to models shown in (a). Note increasing depth in time and decrease in amplitude with increasing plunge.

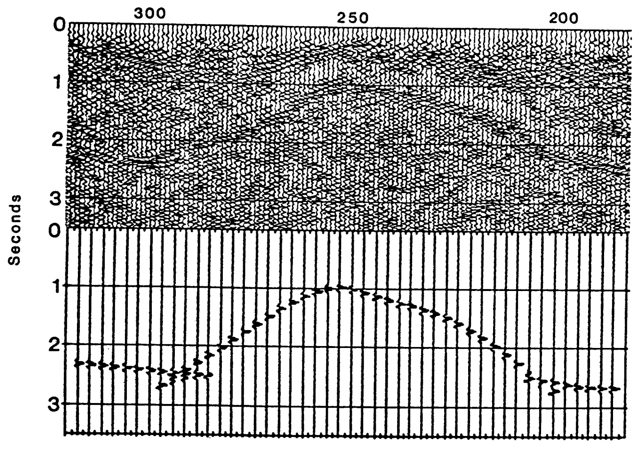

Fig. 4. Detail from Line 1A (top) and best fit synthetic seismogram (bottom). Both are displayed at a 1:1 scale for an average p-wave velocity of 3.5 km/sec.

and Brocher, 1980] methods are so low that were the Ladron Mountains to generate sideswipe, the first side reflections from them should arrive at around two to three seconds. That such reflections are observed in neither the synthetic nor the real data can be explained by either of two possibilities. Either no such horizontally propagating energy was reflected by the Ladron Mountains, or the vertical component of such energy was simply too low to be detected by the geophones used in the field.

The position of the Ladron horst beneath the seismic line is further confirmed by the change in dip of the underlying magma reflector. de Voogd [1986b] speculated that velocity pull up effects were responsible for this apparent change in dip. Where a flat-lying reflector, such as the Socorro magma body, underlies a relatively high velocity body, such as the Ladron basement uplift, one expects to see the deeper reflection horizon "pulled up" in time because of the high velocity rocks above. The portion of the magma body not directly overlain by the uplifted basement appears deeper in time, giving the entire magma body a false concave upward appearance. This velocity pull up effect would only occur if the Ladron horst were truly located beneath the seismic line. (compare Figures 2 and 5).

Once the correct plunge was determined and sideswipe ruled out, reflection points on the best fit model layer defined a minimum northeast extent of the Ladron uplift in the subsurface, shown in map view by the dashed line in Figure 1. Of course, it is unlikely that this basement uplift is truncated just to the northeast of this line. It, therefore, probably extends beyond this minimum. More seismic data are needed in order to define the maximum northeast bound of this feature.

Faults

If the interpretation presented in this paper is correct and the Ladron horst is fault-bounded, then the reflections defining the western slope of the subsurface Ladron horst represent a moderately-dipping (over 40°) northeast-trending fault which forms the southern margin of the Monte Largo embayment. That this west-dipping fault imaged on Line 1A is not expressed at the surface suggests that movement on that fault ceased prior to the deposition of the overlying upper Cenozoic sediments, indicating that this pre-Cenozoic fault was not reactivated during later Cenozoic extension.

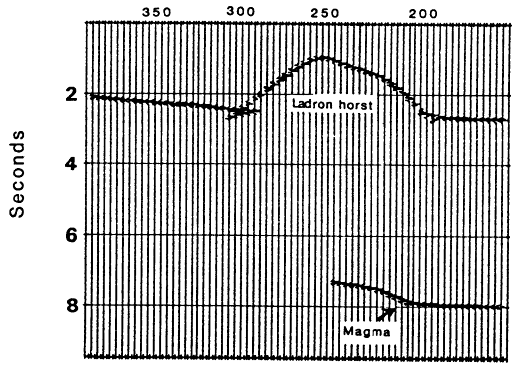

Fig. 5. Best fit synthetic seismogram showing velocity pull up of a horizontal reflector at 8 seconds two way travel time. Compare with real data in Figure 2.

Alternatively, the moderately steep reflections on the western slope of the subsurface Ladron horst could represent the dip slope of a west-tilted block. The Rio Grande rift consists mainly of asymmetric half grabens and tilted-block uplifts rather than true horsts and grabens [Chapin, in press].

The reflections defining the eastern slope of the horst represent a 25° southeast-dipping fault similar to the Jeter and Silver Creek faults which are low angle faults documented in outcrop and drill holes along the eastern flank of the Ladron uplift. The Jeter fault has some characteristics of regional detachments (e.g. its low angle and associated tectonic melange) and has been interpreted as such by J. F. Callender [Baldridge et al., 1984] and by Wu [1986].

In this model second-order discontinuities on the surface of the Ladron horst, modeled as minor normal faults, are essential in maintaining the subtle discontinuities observed on the reflection data. Small diffractions define the top and east side of the real Ladron Horst reflections (Figure 2). Small faults with throws of around 500 m were added to the Ladron horst model in order to simulate these discontinuities. Subtle discontinuities observed in the real data are preserved in the synthetic (Figure 6). Smoothing the apices on the model layer removes these discontinuities from the synthetic section, therefore the Ladron horst must be internally faulted.

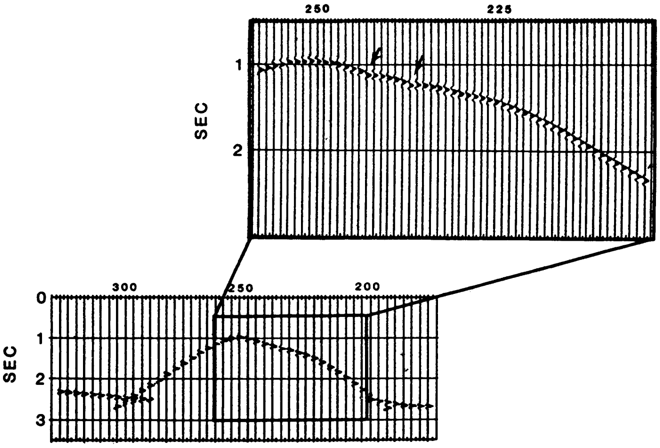

Fig. 6. Detail from synthetic seismic section. Arrows point to discontinuities resulting from small normal faults in model layer.

Conclusions

Three-dimensional structure must be considered in order to interpret the complex reflection patterns of Socorro Line 1A and of other seismic reflection surveys. This modeling study adds credence to the general interpretation of Brown et al. [1979]. It defines a minimum northeast extent of the subsurface nose of the Ladron uplift, and eliminates from consideration the possibility that the Ladron horst reflections originate from far out of the plane of the section. It also provides further support to the evidence of substantial intrarift normal faulting in the Albuquerque Basin. The questions of timing of faulting and of whether Cenozoic extension reacitvated older faults are still unresolved. Better and more seismic and well data in the area could best address these unsolved problems.

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