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STRUCTURE OF THE ESPAÑOLA BASIN, RIO GRANDE RIFT, NEW MEXICO, FROM SAGE SEISMIC AND GRAVITY DATA

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Abstract—Seismic and gravity data, acquired by the SAGE program over the past twelve years, are used to define the geometry of the Española basin and the extent of pre-Tertiary sedimentary rocks. The Paleozoic and Mesozoic units have been thinned and removed during Laramide uplift in an area now obscured by the younger rift basin. The Española basin is generally a shallow, asymmetric transitional structure between deeper, better developed basins to the northeast and southwest. The gravity data indicate the presence of three narrow but deep structural lows arrayed along the Embudo/Pajarito fault system. These sub-basins seem to be younger than the faults on the basin margins. This apparent focussing of deformation in the later history of the basin may be a response to changes in regional stress or more local accommodation of the rift extension. Future work is planned to develop seismic data over one of these sub-basins, the Velarde graben, and to better define the gravity map in order to facilitate three-dimensional modeling.

INTRODUCTION

Since 1983 the Summer of Applied Geophysical Experience (SAGE) program, sponsored by the Los Alamos National Laboratory branch of the University of California's Institute of Geophysics and Planetary Physics, has conducted geophysical field work in the Española basin of the Rio Grande rift (Fig. 1). Although primarily a "hands on" course for the teaching of geophysical field methods to undergraduate and graduate students, SAGE has also systematically pursued a program of research on the structure and stratigraphy of the basin. The goal of these studies is ultimately to understand better the kinematics of the Española basin, the role of the basin in the overall evolution of the Rio Grande rift, and the more general implications regarding the process of continental rifting.

The purpose of this paper is to offer interpretations of selected SAGE seismic sections, some as yet unpublished, to present a new gravity map of the basin, and to integrate and interpret the geophysical data to elucidate major structural features of the basin. In particular, we wish to focus on the Embudo/Pajarito fault system. Additional processing of many of the seismic lines shown here is in progress, hence the interpretations offered are preliminary.

GEOLOGIC SETTING AND PREVIOUS WORK

The Rio Grande rift extends as a series of interconnected, asymmetrical basins from central Colorado to Big Bend, Texas, and Chihuahua, Mexico, a distance of more than 1000 km (Fig. 1). The northern rift is a narrow physiographic and tectonic depression separating the Colorado Plateau from the Great Plains, part of the stable North American craton, on the east (Cordell, 1978; Baldridge et al., 1983, 1994; Olsen et al., 1987; Chapin and Cather, 1994). The Española basin in northern New Mexico is transitional between the larger and deeper San Luis (Kluth and Schaftenaar, 1994; Brister and Gries, 1994) and Albuquerque-Belen (Russell and Snelson, 1994; May and Russell, 1994) basins of the rift to the north and south, respectively (Fig. 1).

The general structure and asymmetrical geometry of the Española basin were known from geological mapping (Kelley, 1978; Manley, 1979) and from limited gravity and seismic reflection and refraction data (Cordell, 1979; Biehler et al., 1991). These results showed that the eastern and western sides of the basin are structurally different from each other. The eastern side is characterized by a basinward sloping Precambrian surface without major faulting along the margin of the basin. In contrast, the western edge of the basin is a northeast-trending zone of down-to-the-east faults, largely concealed beneath the Jemez volcanic field. A major zone of faulting (Embudo fault zone), trending obliquely across the basin, transfers extension laterally from the southern end of the San Luis basin to the west side of the Española basin (Fig. 1). The Embudo transfer fault effectively "decouples" the main Española basin to the south from the northern and northwestern part of the basin (including the Abiquiu embayment north of the Jemez volcanic field; Kelley, 1979). A narrow central graben (Velarde graben), aligned along the Embudo zone, is present near the northern end of the main Española basin (Manley, 1979). Previous SAGE results (Baldridge et al., 1994) showed that the Abiquiu embayment is essentially a shallow platform, and may preserve an early stage of development of the Española basin.

Proprietary seismic reflection data for parts of the Española basin have previously been published by Black (1984). Although these data offer important coverage of the southeastern part of the basin, no location map is provided for the seismic profiles. Other proprietary oil company data exist in the northern part of the basin as well, and efforts continue to secure their public release.

DATA AND RESULTS

Seismic reflection and refraction experiments have been performed during every summer of the SAGE program (Fig. 1). These experiments are usually co-located and hence complement each other in velocity and structural resolution. Gravity results generally conform to the seismic model, as both the sedimentary rock velocity and density are primarily controlled by porosity, confining pressure (depth), and degree of saturation. Various electromagnetic measurements are also made; in particular, a profile of magnetotelluric soundings has been constructed from the Nacimiento uplift, west of the Jemez Mountains, to the east side of the Sangre de Cristo Mountains. Only the seismic and gravity results will be discussed here due to their greater relevance to the Española basin structure, as opposed to the deep crust.

Seismic profiles

In most years the SAGE seismic experiments have been designed, with respect to recording aperture and source energy, to explore depths corresponding to basin structure (i. e., a few km). In 1986, 1987, 1988 and 1993, shallow targets were sought. Also, reflection efforts were hampered in some years by the presence of volcanic and volcaniclastic rocks, which degrade the data quality and limit the depth of penetration. Various recording systems, energy sources, and processing systems have been used. Since 1989, Vibroseis® recording and processing with Advance Geophysical's MicroMax® and ProMax® systems has been standard.

Four profiles (Fig. 2), representing six field seasons (about 8 km of line are acquired each summer) are discussed here. These profiles characterize the eastern basin margin, adjacent to the Sangre de Cristo Mountains and the shallow western and northwestern parts of the Española basin. The profiles document earlier inferences based on geological data (e. g., Kelley, 1978; Manley, 1979) that the Española basin is asymmetrical. More detailed descriptions of the field procedures for the Tesuque

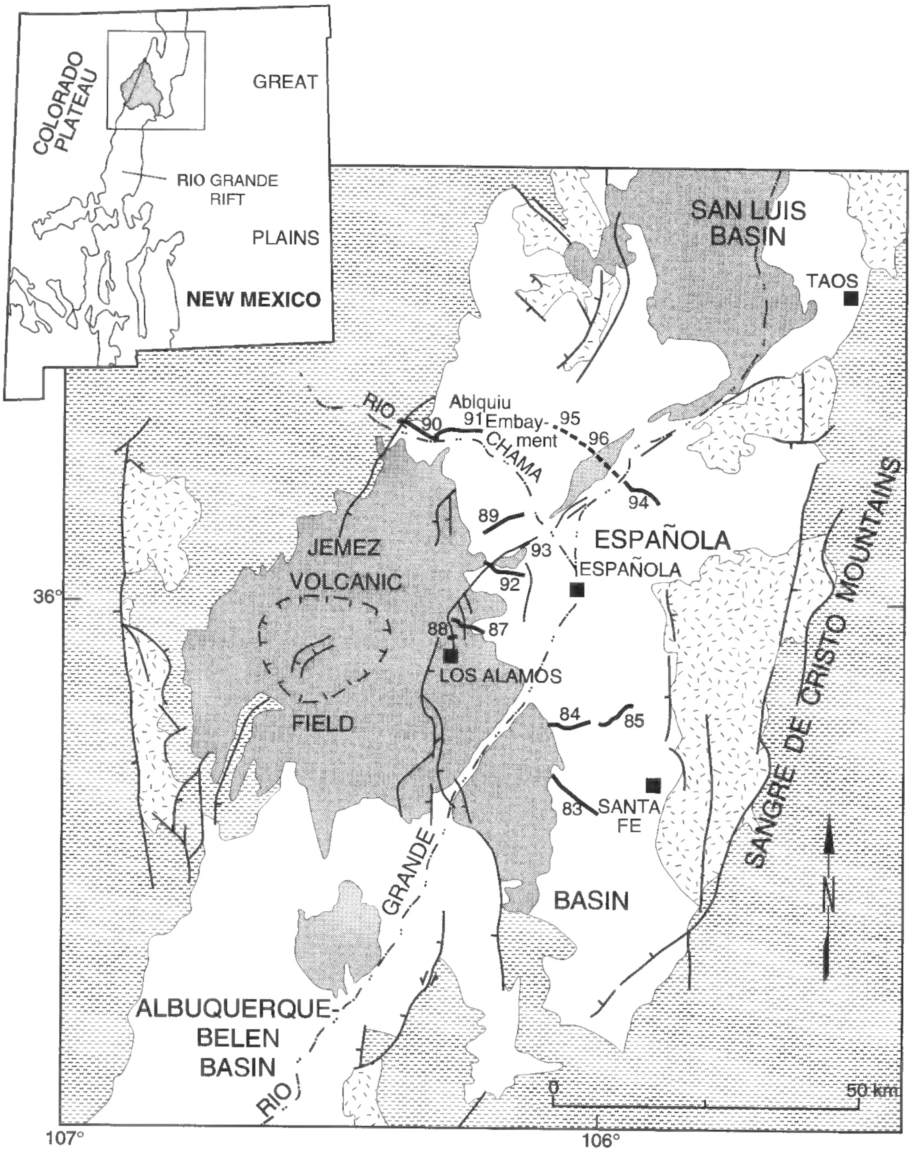

FIGURE 1. Index map, showing locations of all SAGE seismic profiles and the years in which the work was accomplished. Profiles discussed in this paper are as follows: Tesuque is 1984 and 1985, Rio del Oso is 1989, Abiquiu is 1990 and 1991, and Velarde is 1994. Seismic profiles planned for 1995 and 1996 (dashed line) are designed to complete a single transect across the Embudo fault zone. Hatchured pattern is Precambrian rocks, horizontally dashed pattern is pre-Tertiary rocks, shaded pattern is all volcanic rocks, white is Tertiary sediments and sedimentary rocks.

line can be found in Biehler et al. (1991) and for the Abiquiu line in Baldridge et al. (1994). The Rio del Oso line was recorded in a manner similar to the Abiquiu line, with the ARCO Field Acquisition Survey Team. The Velarde line was recorded with two vibrators and a 48 channel DFS IV system operated by the Colorado School of Mines. Field parameters were similar to the Abiquiu line, except for a smaller recording aperture.

The interpretations (Fig. 2) have been made with the aim of illustrating the major reflecting events in each common midpoint (CMP) stacked section. It was not practical to reproduce the actual sections in this format. The actual seismic sections for Tesuque and Abiquiu are available in Biehler et al. (1991) and Baldridge et al. (1994), and the Rio del Oso and Velarde sections will be published in the near future. The important elements of the four sections displayed include a thickness of Eocene to Holocene rocks and a package of pre-Tertiary sedimentary rocks, which include various thicknesses of Paleozoic and Mesozoic units. The Precambrian basement is usually devoid of geophysically characterizable structure, except in the Velarde profile. Proterozoic supracrustal rocks of the Hondo and Vadito Groups (Mawer et al., 1990) are likely responsible for the deeper reflecting events in that section. The Precambrian structures are not well oriented with respect to the Velarde survey line (Mawer et al., 1990), which was designed to map the shallower horizons.

The thickness of Paleozoic and Mesozoic rocks is of considerable importance. Prior to this work the effect of the Laramide uplift on the previously extensive Paleozoic and Mesozoic sedimentary rocks beneath the Española basin was nearly unknown. The extent of these rocks was first recognized in the subsurface by Black (1984), who inferred the presence of thrust sheets of presumed Laramide (early Tertiary) age to explain some of the seismic observations. Subsequently, based on SAGE data and on drill holes for hydrocarbon exploration, Biehler et al. (1991) reinterpreted subsurface relations in the Tesuque profile (southern part of the basin) to indicate that the Paleozoic/Mesozoic section was erosionally truncated and missing from the eastern two thirds of the profile and that Tertiary units directly overlie Precambrian. Only small, isolated remnants of Paleozoic and Mesozoic rocks crop out on the western flanks of the Sangre de Cristo Mountains. The Paleozoic and Mesozoic rocks are geophysically well characterized by higher velocities and densities. The maximum thickness observed is similar to measured sections in

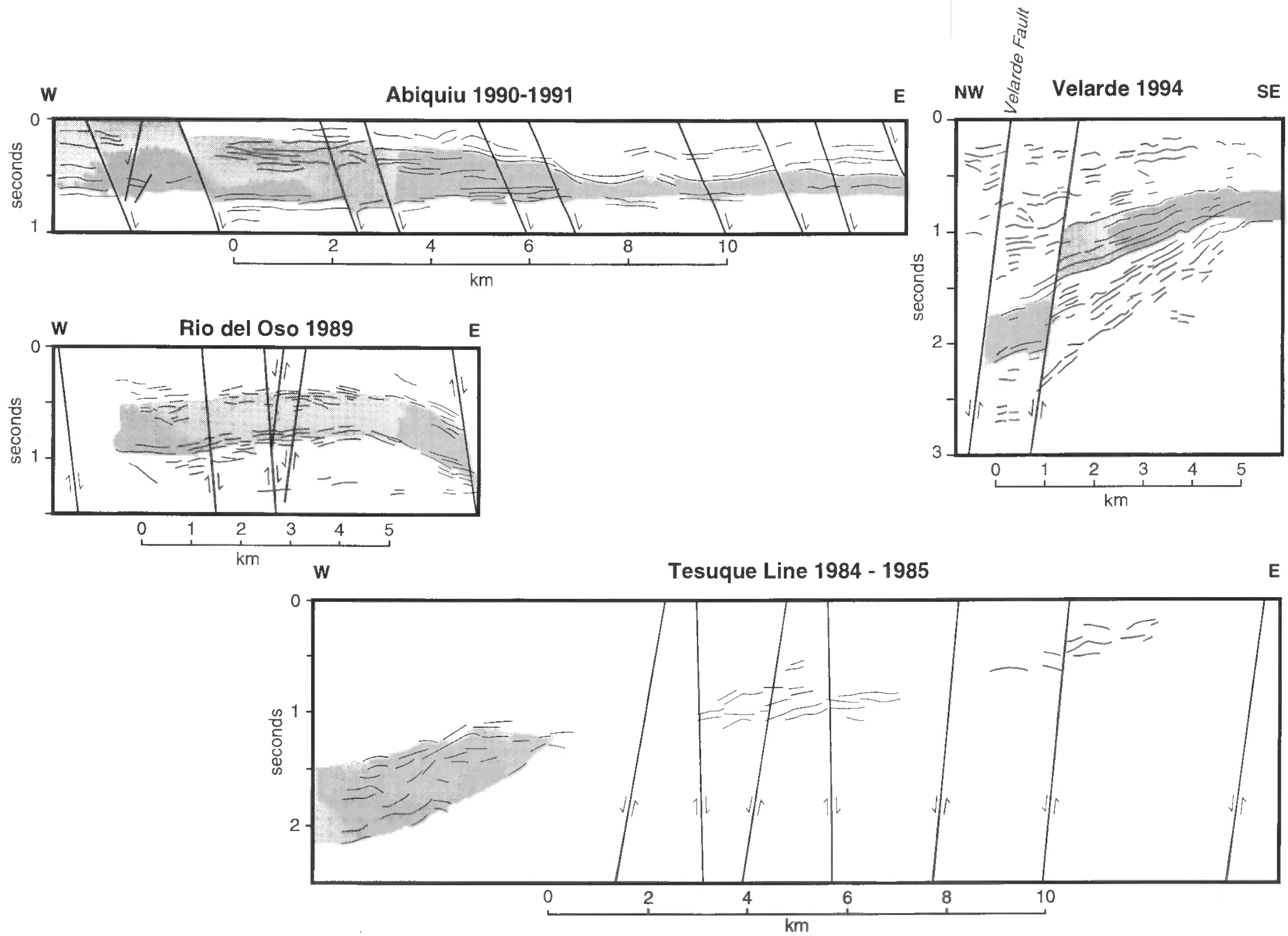

FIGURE 2. Interpreted common midpoint stacked reflection sections. All profiles are time sections. On each section, the upper unpatterned interval represents Tertiary sediments and sedimentary rocks, including rift fill. Shaded pattern indicates Paleozoic and Mesozoic sedimentary rocks. Underlying unpatterned interval is Precambrian. Major coherent reflecting events are indicated by black lines, heavy black lines indicate mapped faults. For most of the Tesuque line, Tertiary units are inferred to directly overlie Precambrian crystalline rocks; top of Precambrian is marked by subhorizontal reflectors.

nearby outcrop. The Tertiary unconformity in the Tesuque line displays a gentle dip to the west, with only minor (< 200 m) normal faulting. No major extensional features are recognizable.

The Abiquiu line was very significant in understanding the character of the Paleozoic and Mesozoic section (Baldridge et al., 1994). The western end of the seismic profile is on Mesozoic rocks of the Colorado Plateau, which can be continuously traced eastward into the subsurface. The lowermost reflecting event is due to the Madera limestone, which overlies the Precambrian basement. This event has a very characteristic "two-legged" wavelet, which can be identified in most of the seismic sections. The Laramide uplift has caused a thinning of the Paleozoic and Mesozoic section to the east at Abiquiu. The Tertiary rift basin at Abiquiu is rather shallow and lacks major extensional features.

Twenty kilometers southeast of Abiquiu, along the Rio del Oso, the Paleozoic/Mesozoic section is interpreted to underlie a similar thickness of Tertiary rocks, but does not thin eastward, thus placing the Laramide uplift to the east of this line. Instead, the eastern end of the Rio del Oso line shows a monoclinal warping and faulting downward to the east into the Velarde graben.

Paleozoic/Mesozoic rocks recognized in the Velarde line are interpreted to be erosionally thinned to the east, with a gentle dip of the unconformity, similar to the Tesuque profile 40 km to the south. The actual disappearance of the pre-Tertiary sedimentary rocks occurs east of the end of the seismic line. On the west end of the line, major, down-to-the-west, normal faulting is observed on the Velarde fault, stepping down into the Velarde graben.

Gravity map

The gravity map (Fig. 3) incorporates data gathered over the 12-year history of SAGE, as well as from older U. S. Geological Survey (Cordell, 1979) sources. The SAGE data consists primarily of dense transects near the seismic lines, although an attempt to acquire a better two-dimensional array of stations has been pursued as well. Starting in 1994, and to be continued over the next two summers, is the use of the Global Positioning System (GPS) for elevation control and a more aggressive filling of data gaps on the map. This effort will make possible a better three-dimensional model of the basin, when locally guided by interpretation of the seismic profiles. No other significant subsurface control (i. e., boreholes) is available in most of the Española basin.

The important conclusions reached from the gravity data are: (1) major extensional structures (fault-bounded sub-basins) are confined to the center of the main Española basin; (2) a gently basinward-dipping unconformity on the Precambrian is characteristic of the entire eastern margin of the Española basin from Santa Fe to Velarde; and (3) no major structural relief exists between Abiquiu and the Rio del Oso. Cordell (1979) reached a similar conclusion with regard to the central basin grabens. The amplitude of the associated gravity anomaly implies several kilometers of structural relief across the ten to twenty-kilometer wide zone.

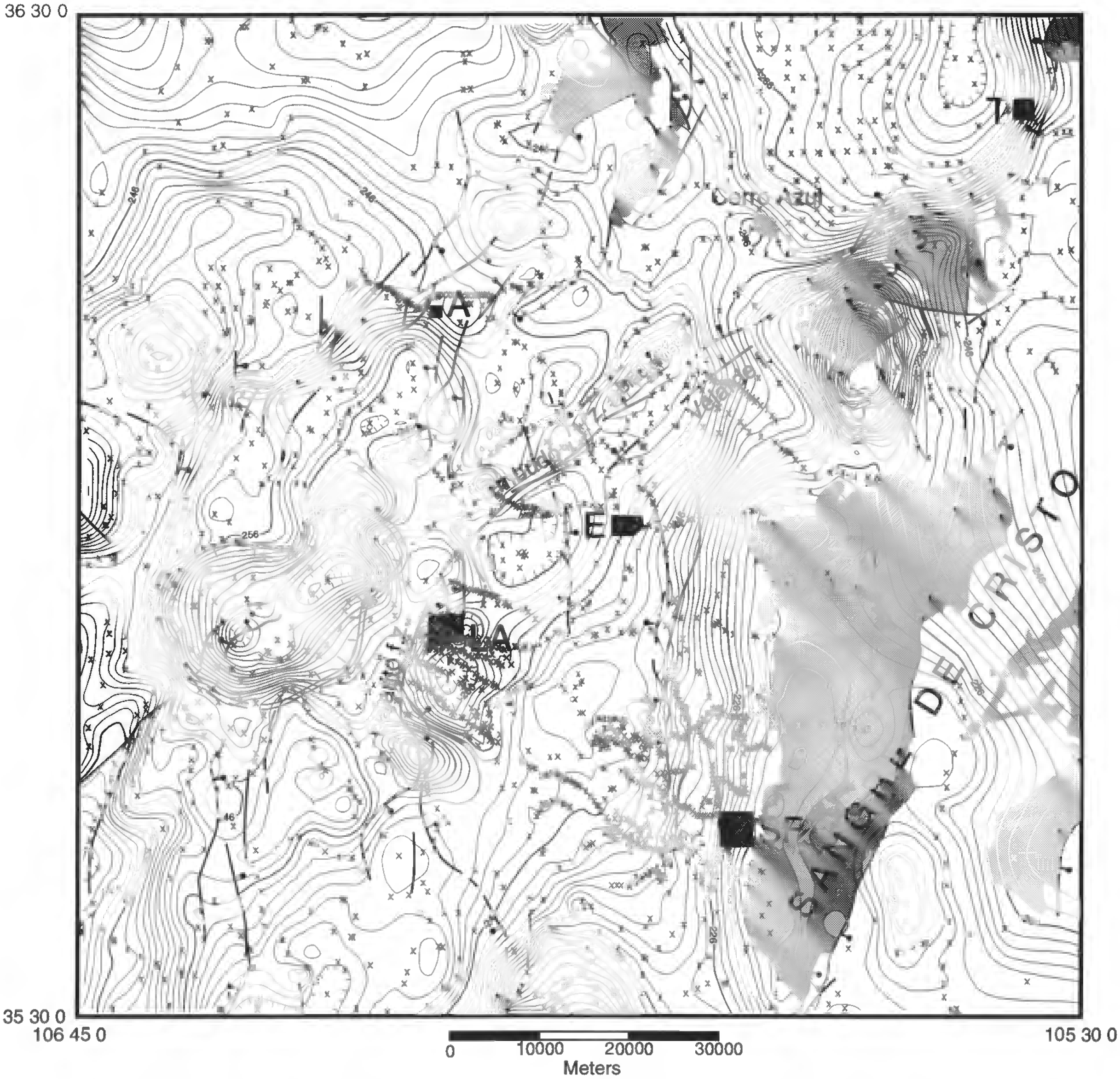

FIGURE 3. Gravity and tectonic map. Bouguer gravity is contoured at a 2 mGal interval. Station locations are indicated by small "X" symbols. Stippled pattern is exposed Precambrian rocks. Heavy lines are faults, with bar and ball on downthrown side. The tectonic base is abstracted from Kelley (1978) for interpretive purposes. A, Abiquiu; E, Española; LA, Los Alamos; SF, Santa Fe; and T, Taos.

Three closed gravity lows are situated along the surface trace of the Embudo/Pajarito fault system (Fig. 3). We infer that the lows result from structural sub-basins developed along the fault system. The north-easternmost of these, elongated east-northeasterly beneath Black Mesa, is bounded by faults along both sides. Thus, we infer that the gravity low results from a structural basin formed between these faults, the Velarde graben of Manley (1979). The Velarde seismic profile imaged the south side of the anomaly (Fig. 2). Two down-to-the-northwest faults extending from the boundary of the Picuris range are present (Manley, 1977). The northern of these faults is the Velarde fault of Manley (1979). Since it is so close to the end of the 1994 seismic line, we are not able to determine the amount of offset where the fault crosses our line. The southern of the two faults (unnamed) appears to have a vertical component of offset of 1 to 1.5 km. Gravity data indicate that the southwestern end of the Velarde graben does not continue west of the Rio Chama. The western end of the graben is bounded by the rollover of strata and by the fault inferred from the 1989 seismic data (Fig. 2) near the eastern end of the Rio del Oso.

A second closed gravity low is located south of the Embudo zone west of the Rio Grande. It is bounded on the north by the Embudo fault zone and on the east and west by north-trending faults, but appears to have no distinct bounding structures on the south or west. The steep gravity gradient associated with the Embudo fault zone suggests that a large down-to-the-south offset occurs across the fault at this location, which is compatible with the sense of offset derived from geological mapping (Dethier and Manley, 1985).

A third gravity low, bounded by the Pajarito fault zone on its west side, is situated beneath the Pajarito Plateau south and east of Los Alamos. Although no faults are present at the surface along the east side of the gravity low, we suggest that the basin may be bounded by faults in the subsurface that lie to the east of the southern projections of the Rendija Canyon and Guaje Mountain faults.

Over the next two summers reflection and wide-angle seismic data will be acquired to connect the Abiquiu and Velarde lines (Fig. 1) over the 25-km gap separating them across the northern gravity low. It is unlikely that seismic data will be acquired across the two southern gravity anomalies due to volcanic and volcaniclastic cover in the Pajarito Plateau area and to access restrictions.

DISCUSSION AND CONCLUSIONS

The Española basin consists of a series of narrow, deep, axial troughs (or sub-basins) arrayed along the Pajarito and Embudo fault zones in an otherwise relatively shallow basin. The eastern side of the Española basin dips gently westward and northwestward toward the Pajarito/Embudo fault system, with no major structural boundary apparent at its eastern margin (Baltz, 1978; Manley, 1979). The northwestern part of the basin, north of the Embudo fault zone, is primarily a shallow platform separated from the Colorado Plateau by a broad zone of faults with throw of 500 m (Baldridge et al., 1994). This shallow platform continues southward at least as far as the Rio del Oso with no major structural discontinuities, and is essentially "decoupled" from the rest of the Española basin by the Embudo zone. The Pajarito fault zone is a major down-to-the-east fault system. From gravity data we infer that the basin is shallow west of the Pajarito fault zone, but we have been unable to successfully determine basin geometry beneath the volcanic and volcaniclastic rocks of the Jemez volcanic field with seismic data.

We suggest, in agreement with Manley (1979), that the axial structural troughs may be younger than the faults bounding the margins of the Española basin, and thus that the troughs represent a relatively recent stage in the evolution of the Española basin. Along the margin of the Colorado Plateau near Abiquiu, faults do not appear to have undergone significant offset more recently than about 8 Ma (Baldridge et al., 1994). In contrast, both the Pajarito and the Embudo fault zones have been active in Pliocene to Holocene time. South of Los Alamos, up to 200 m of down-to-the-east offset has occurred on the Pajarito fault zone since the Bandelier Tuff was erupted (Smith et al., 1970; Carter and Gardner, this volume). Fault activity on the western segment of the Embudo fault zone (west of Española) may have been, in part, contemporaneous with that of the Abiquiu margin, but apparently continued until more recently (Aldrich and Dethier, 1990). Right-slip offset along this part of the fault zone commenced after deposition of the youngest sediments of the Santa Fe Group (Chamita Formation), about 6-4.5 Ma (Manley, 1979), but did not affect upper Puyé sediments, i.e., sediments younger than about 2.5 Ma (Dethier and Manley, 1985; Aldrich, 1986; Aldrich and Dethier, 1990). In contrast, Quaternary deformation along the eastern segment of the Embudo fault zone (Velarde graben segment) is recorded by fault scarps cutting alluvial fans along the base of the Picuris Mountains and by geomorphic evidence (Muehlberger, 1978, 1979; Dungan et al., 1984). Present seismicity indicates that deformation is continuing along this segment (House and Hartse, this volume).

If our inference is correct that the deep axial sub-basins are younger than the extension along the margins of the Española basin, and in essence that the active part of the basin has become narrower with time (Manley, 1984), then this shift in activity may correlate with a major reorientation of the direction of regional extension from east-northeast to west-northwest (Zoback et al., 1981; Aldrich et al., 1986) that occurred over a broad region of the western U. S. about 10 Ma. The narrowing of the basin may have occurred in response to the change in the regional stress field, assuming that the faults toward the center of the basin were more favorably oriented, or simply to the focussing of extension on specific fault zones as the rift basin continued to develop.

Finally, we are now better able to delineate the western extent of the massive Sangre de Cristo-Brazos uplift of Laramide (early Tertiary) age than has been possible from surface data alone. Along the western side of the basin, Paleozoic and Mesozoic sedimentary rocks are preserved beneath Tertiary basin-filling sediments, although in the Abiquiu line these units are observed to thin dramatically to the east beneath an Eocene unconformity (Baldridge et al., 1994). In the southeastern part of the basin (Tesuque line), the Paleozoic/Mesozoic section has been completely removed by erosion, allowing Tertiary basin fill to be deposited directly on Precambrian rocks (Biehler et al., 1991). However, if we have interpreted the Velarde section correctly, a thick section of Paleozoic/Mesozoic rocks is present, possibly indicating that this area lay in a reentrant in the western margin of the uplift.

In conclusion, the existence of limited, but strategically placed, seismic lines combined with more broadly ranging gravity coverage makes an integrated geological-geophysical model possible in three dimensions. As the SAGE plan for a complete east to west transect of the basin is completed in the next few field seasons, a quantitative geophysical-structural model will be produced. Gravity will be used to infer structural detail, by analogy to areas where seismic data exist. We believe that kinematics of the basin evolution can be deduced from a model of this type, under reasonable assumptions and geologic constraints.

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