Insights into the kinematic Cenozoic evolution of the Basin and Range–Colorado Plateau transition from coincident seismic refraction and reflection data

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ABSTRACT

Estimates of surface extension in the southern Basin and Range province and transition into the Colorado Plateau range from a few percent to several hundred percent locally, yet the crustal thickness varies perhaps only 10–15 km across these provinces. Within the southern Basin and Range and the metamorphic core complex belt, extremely extended crust is directly juxtaposed against equally thick (or thinner) crust that underwent far milder extension. Unless preextension crustal thickness varied dramatically over a short distance, the crust must have maintained its thickness during extension, through mechanisms that involve crustal flow and magmatism. We employ a 300-km-long profile of seismic refraction and coincident vertical-incidence reflection data to investigate the geophysical signature of these processes from the extended southern Basin and Range province to the unextended Colorado Plateau. By integrating the seismic velocity with the pattern of reflectivity along the profile, we estimate the amounts of Tertiary magmatism and flow that have occurred. We estimate an upper bound of 8 km of mafic material intruded beneath the metamorphic core complex belt and 4 and 5 km of intruded material beneath the Transition Zone and southern Basin and Range province, respectively. We emphasize that this 8-km estimate is strictly an upper bound, and that the actual amount of magmatism was probably less (3 to 4 km). We further speculate that several kilometers of silicic rock was added to the metamorphic core complex belt via ductile flow. As suggested by numerous numerical models of crustal extension, we conclude that a mobile, felsic midcrustal layer accommodated most of this crustal flow. This ductile midcrustal layer appears to be thickest beneath the most extended terranes and thinnest beneath the less extended Transition Zone and Colorado Plateau. In contrast, the lowermost crust appears to have thinned passively in an amount that corresponds more directly to the regional surface extension.

INTRODUCTION

In 1985, the U.S. Geological Survey (USGS) initiated a multidisciplinary program to study the geologic and tectonic evolution of the southwestern United States and to investigate the extensional processes controlling the Colorado Plateau–southern Basin and Range province transition. This program, referred to as the Pacific to Arizona Crustal Experiment (PACE), includes a wide range of geophysical and geologic studies, including seismic refraction, magnetotellurics, paleomagnetism, gravity, magnetics, geochronology, and geologic mapping. Central to the PACE program has been the use of seismic refraction methods to define crustal thickness, rock composition, and crustal structure. These seismic refraction profiles have been acquired along a transect that extends from the southern Basin and Range province in southeastern California onto the Colorado Plateau in northern Arizona. The refraction profiles are also complemented by coincident or nearly coincident seismic reflection studies conducted by Stanford University, the California Consortium for Crustal Studies (CALCRUST), and the Consortium for Continental Reflection Profiling (COCORP).

This paper integrates the results from the PACE seismic refraction/wide-angle reflection (from here on referred to simply as "refraction") studies with the results from vertical-incidence seismic reflection ("reflection") profiling. Our intent is to produce an interpretive model for the Tertiary geologic evolution across the transition from unextended to extended crust. We include recent geologic and geophysical results derived from PACE and other, independent studies conducted near the transect (for example, Howard and John, 1987; Anderson, 1988; Anderson and others, 1988; Klein, 1991; Sass and others, unpubl. data). Our discussion begins with an introduction to the study area, followed by an overview of the seismic refraction and reflection data bases. For a more detailed discussion of the seismic data sets, the reader is referred to: (refraction) Wilson and others, 1991; McCarthy and others, 1991; and (reflection) Hauser and others, 1987; Goodwin and others, 1989; Goodwin and McCarthy, 1990; Howie and others, 1991; and Parsons and others, 1992a.

BACKGROUND

The PACE transect extends in a northeast direction and crosses four distinct provinces: the southern Basin and Range province, the metamorphic core complex belt, the Transition Zone, and the Colorado Plateau (Fig. 1). These four provinces have contrasting geological, geophysical, and physiographic characteristics that reflect a varied tectonic history.

Southern Basin and Range Province

The southern Basin and Range province is a region of very complex geology resulting from deformation in Proterozoic, Mesozoic, and Tertiary time. During the Proterozoic, convergent tectonism, anorogenic magmatism, and crustal growth occurred, based on geologic and geochronologic studies (Anderson and Silver, 1976; Karlstrom and Conway, 1986; Conway and Karlstrom, 1986; Wooden and Miller, 1990). From Triassic through Late Cretaceous time, the southern Basin and Range province underwent uplift, thrusting, magmatism, and regional metamorphism (Burchfiel and Davis, 1981; Haxel and others, 1984; Spencer and Reynolds, 1990; Miller and others, 1982; Howard and others, 1982; Hamilton, 1982). During the Cenozoic Era,

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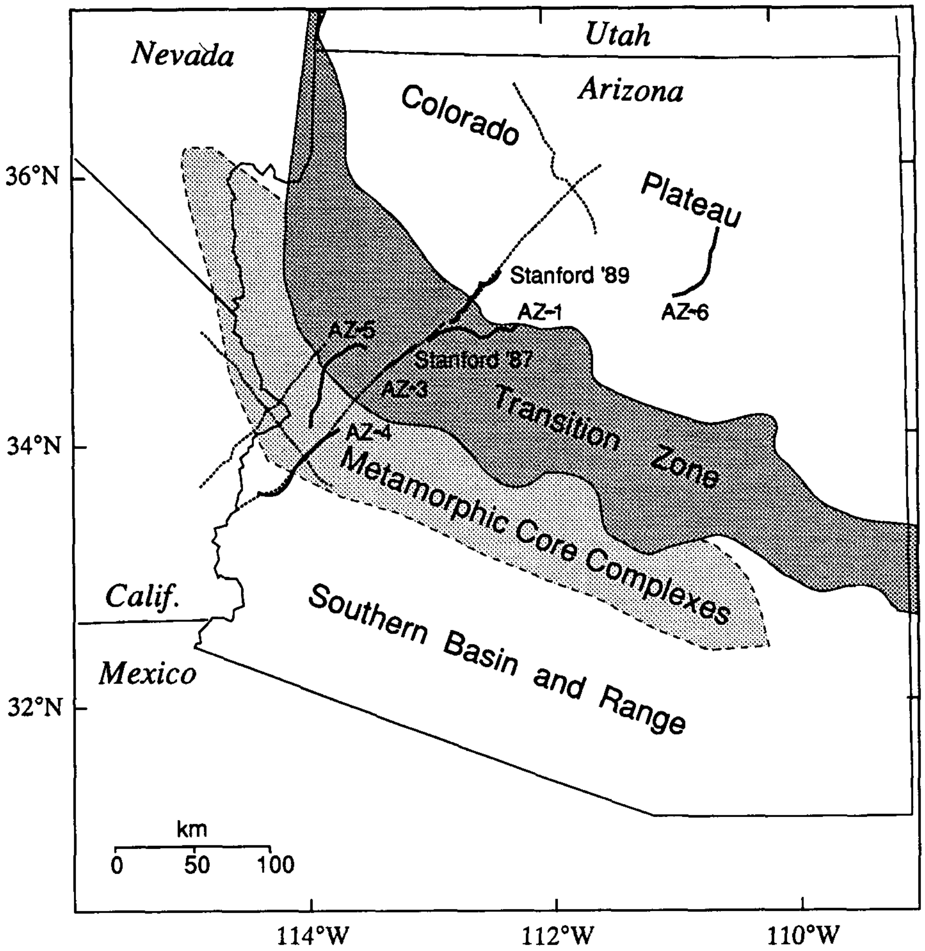
extensional tectonism occurred in two phases; the first phase began in the early Miocene (~22 Ma) and continued until middle Miocene time (~15 Ma) and was associated with hundreds of percent extension along low-angle normal faults (for example, Davis and others, 1980; Reynolds and Spencer, 1985; Howard and John, 1987; Davis, 1988). The second extensional phase ranged from middle Miocene time (~15 Ma) until the end of the Miocene (5 Ma) and was associated with less intense, high-angle normal faulting, which produced the well-known basin and range morphology. The southern Basin and Range province is generally quiescent today and is characterized by high heat flow (1.5–2.5 HFU), uniform upper-mantle velocities (7.8–8.0 km/s), low seismicity, and crustal thicknesses that range between 26 and 30 km (Hearn, 1984; Hearn and others, 1991; McCarthy and others, 1991).

Metamorphic Core Complex Belt

Northeast of the southern Basin and Range province is a narrow (50 to 100 km wide) northwest-southeast–trending belt characterized by unusually large extension during the early and middle Miocene (phase one described above). This belt, which at the latitude of the PACE transect is exposed in the Whipple and Buckskin-Rawhide Mountains, is known as the metamorphic core complex belt. Although this belt is usually considered to be part of the Basin and Range province, in this discussion we treat it as a separate geologic province to differentiate it from the less-extended Basin and Range province that bounds it to the southwest. Along the PACE corridor, volcanic activity was prevalent during core complex extension (Suneson and Lucchitta, 1983; Hazlett, 1986; Nielson, 1986; Nielson and Turner, 1986; Nielson and Beratan, 1990), as indicated by thick volcaniclastic deposits. Geologic and geobarometric studies document that the upper ~10 km of the crust has been structurally denuded since the early Tertiary, exposing midcrustal rocks at the surface (Howard and John, 1987; Anderson, 1988; Anderson and others, 1988). Significantly, despite the unusual amount of extension, elevations are high, averaging 0.3 to 1.0 km above sea level, and deep basins have not formed.



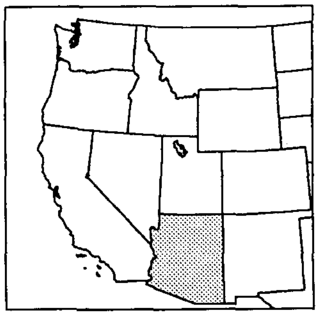


Figure 1. Locations of the U.S. Geological Survey Pacific to Arizona Crustal Experiment (PACE) refraction profiles (dashed lines) and the coincident COCORP reflection profiles (AZ-1, AZ-3, AZ-4, AZ-5, AZ-6) and reflection profiles recorded by Stanford University discussed in the text (solid lines). The profiles cross terranes of varied extension, from the highly extended metamorphic core complex belt and southern Basin and Range province, to the intermediate Transition Zone, into the nonextended Colorado Plateau.

Transition Zone

Bounding the metamorphic core complexes to the northeast is the ~100-km-wide Transition Zone. This region roughly coincides with the Mogollon Highlands (Lucchitta, 1990) and is characterized by widespread exposure of Early Proterozoic crystalline rocks. Approximately 1.0 to 1.5 km of Paleozoic strata (Stone and others, 1983) and an unknown thickness of Mesozoic strata are thought to have been stripped off the Proterozoic basement during a period of uplift, thrusting, and erosion at the end of the Mesozoic Era (Spencer and Reynolds, 1990; Foster and others, 1990; Howard, 1991). The Transition Zone has geophysical properties that are intermediate between those of the southern Basin and Range province and the Colorado Plateau. Like the Basin and Range, it is characterized by high heat flow (2.5 HFU) and Neogene volcanism. It is also actively extending, as suggested by present-day seismicity and young, fault-bounded basins. Stratal tilts within these basins are low, however, indicating only a small amount of extension. In addition, elevations within the Transition Zone are high (1 to 2 km above sea level), well above those of the southern Basin and Range, and in places exceeding those of the Colorado Plateau.

Colorado Plateau

In contrast to these extended regions, the Colorado Plateau is a relatively stable, coherent block that has resisted Mesozoic and Tertiary deformation. Approximately 1.5 km of flat-lying Paleozoic sedimentary rocks caps the Plateau in northern Arizona, but near the PACE transect, only scattered remnants of Mesozoic strata remain. The erosional event that stripped off the Mesozoic sedimentary rocks probably occurred during late Mesozoic or early Tertiary time. Eocene gravels, whose source was from the southwest, were deposited directly onto Paleozoic strata and indicate that the Plateau stood at a lower elevation than the bordering Basin and Range province in Eocene time. Today the Colorado Plateau is 1.5 to 2.0 km above sea level and is associated with thick crust; interpretations of crustal thickness range from 40–45 km (Roller, 1965; Warren, 1969) to >50 km (Hauser and Lundy, 1989). The Colorado Plateau is also associated with low heat flow (0.75 to 1.5 HFU, Lachenbruch and Sass, 1978; Morgan and Gosnold, 1989), although the thermal state of the upper mantle, estimated from Pn velocities, is widely debated. Pn velocities of 7.8 km/s were reported by Roller (1965) and Warren (1969) and were based on reversed refraction profiles. More recent estimates, derived from inversion of local seismicity, suggest Pn velocities of as much as 8.1 km/s (Beghoul and Barazangi, 1989).

SEISMIC REFRACTION DATA

The coincident parts of the PACE refraction profiles and Stanford and COCORP reflection profiles discussed in this manuscript begin in the southern Basin and Range province (near the California-Arizona border) and extend across the metamorphic core complex belt and the adjacent Transition Zone before ending >35 km inboard of the physiographic boundary of the Colorado Plateau (Fig. 1). The associated velocity model (Fig. 2) indicates significant variations in crustal structure laterally along the transect (see McCarthy and others, 1991, for a detailed discussion of analysis techniques, modeling assumptions, and error estimates). Most striking is a 9-km-thick midcrustal layer, characterized by 6.35 ± 0.15-km/s velocities, that is centered southwest of the metamorphic core complex belt. This velocity is intermediate between that of granite and gabbro (for example, Holbrook and others, 1992) and suggests a bulk composition of diorite. Actual rock types, however, may encompass a range of igneous and metamorphic compositions, including a mixture of silicic (granite) and mafic (gabbro) end members. The midcrustal layer pinches out in the direction of the Transition Zone and thus appears to be associated with core-complex extension.

Underlying the middle crust is a lower-crustal layer with velocities of 6.6 ± 0.15 km/s (Fig. 2). Although details of the geometry of this lowermost layer are not well known, the unit is believed to thin dramatically from the Transition Zone southwest into the southern Basin and Range province. The layer is only 3–5 km thick beneath the metamorphic core complex belt, whereas beneath the Transition Zone it exceeds 10 km in thickness. Velocities are best determined beneath the Transition Zone where the layer is thick. Beneath the southern Basin and Range province and metamorphic core complex belt, lower-crustal velocities may be higher than 6.6 km/s, but only where the layer is thin (≤3 km).

The base of the crust beneath the southern Basin and Range province and the Transition Zone coincides with a large increase in velocity from 6.6 to ~8.0 km/s. To a first-order approximation, the Moho appears to be nearly flat beneath the southern Basin and Range province and the metamorphic core complex belt (crustal thickness ranges from only 28 to 30 km), despite dramatic variations in the amount of extension evident at the surface. Northeast of the metamorphic core complex belt, the Moho dip increases to 4–7° and the crustal thickness increases gradually to ~40 km. Areas of greatest extension are not necessarily underlain by the thinnest crust, as one might expect if extension were accommodated by pure-shear necking of the entire crust. In fact, under the Whipple Mountains metamorphic core complex (100 km north of the PACE refraction profile discussed here), the crust actually thickens beneath the region of greatest extension (McCarthy and others, 1991; Wilson and others, 1991). These observations require that extension in the lower crust was decoupled from extension in the upper crust. Only to the northeast, in the Transition Zone, does decreasing extension appear to be matched by increasing crustal thickness.

Perhaps the most significant observation to come out of the refraction studies is the low seismic velocity recorded throughout the crust. Average crustal velocities are ≤6.3 km/s, with no velocity exceeding 6.6 ± 0.15 km/s. The prominent structure that defines the domed and thickened middle crust is associated with only a small (0.15 to 0.2 km/s) lateral velocity increase across it. The low seismic velocities are problematic in light of the numerous Proterozoic, Mesozoic, and Tertiary periods of magmatism that have affected much or all of the region.

SEISMIC REFLECTION DATA

The COCORP seismic reflection data (Hauser and others, 1987; Nelson, 1988) serve as the principal data set for our review of the reflection character of the southern Basin and Range province–Colorado Plateau transition. Four of the seven profiles that constitute the COCORP Arizona transect coincide approximately with the PACE refraction lines (Fig. 1); when these data sets are combined, they provide the long, regional control necessary for studies of the transition from unextended to extended crust. In addition to the COCORP reflection profiles, our discussion is supplemented by higher-resolution profiles acquired by Stanford University. The latter profiles are laterally more restricted but provide detail unavailable in many of the reconnaissance-style COCORP lines. We begin with a description of the reflection character of the Colorado Plateau and move southwest from there.

Colorado Plateau

The Colorado Plateau is the least reflective of all the provinces studied (Figs. 2 and 3). COCORP Arizona line 6 provides one of the best images of the crust across the Plateau (Hauser and Lundy, 1989). Although some events occur throughout the crust, most of these are diffractive and lack lateral continuity. The Stanford 1989 reflection profile, which crossed the physiographic boundary between the Colorado Plateau and Transition Zone and coincides with the PACE refraction profile (Fig. 1), provides an additional glimpse into the reflection character of the Colorado Plateau. The data recorded on the northern end of this study are similar in appearance to those displayed on COCORP line 6 (Figs. 2 and 4). Southwest toward the physiographic boundary, the Stanford data gradually become more reflective and are highly reflective within the Transition Zone (Fig. 2, kilometers 230–290; Howie and others, 1991). No clear reflection from the Moho is evident on either the COCORP or Stanford profiles (Figs. 2 and 4). On the basis of both a weak die-out in reflective energy at 16 s and the reinterpretation of pre-PACE refraction data, Hauser and Lundy (1989) postulated

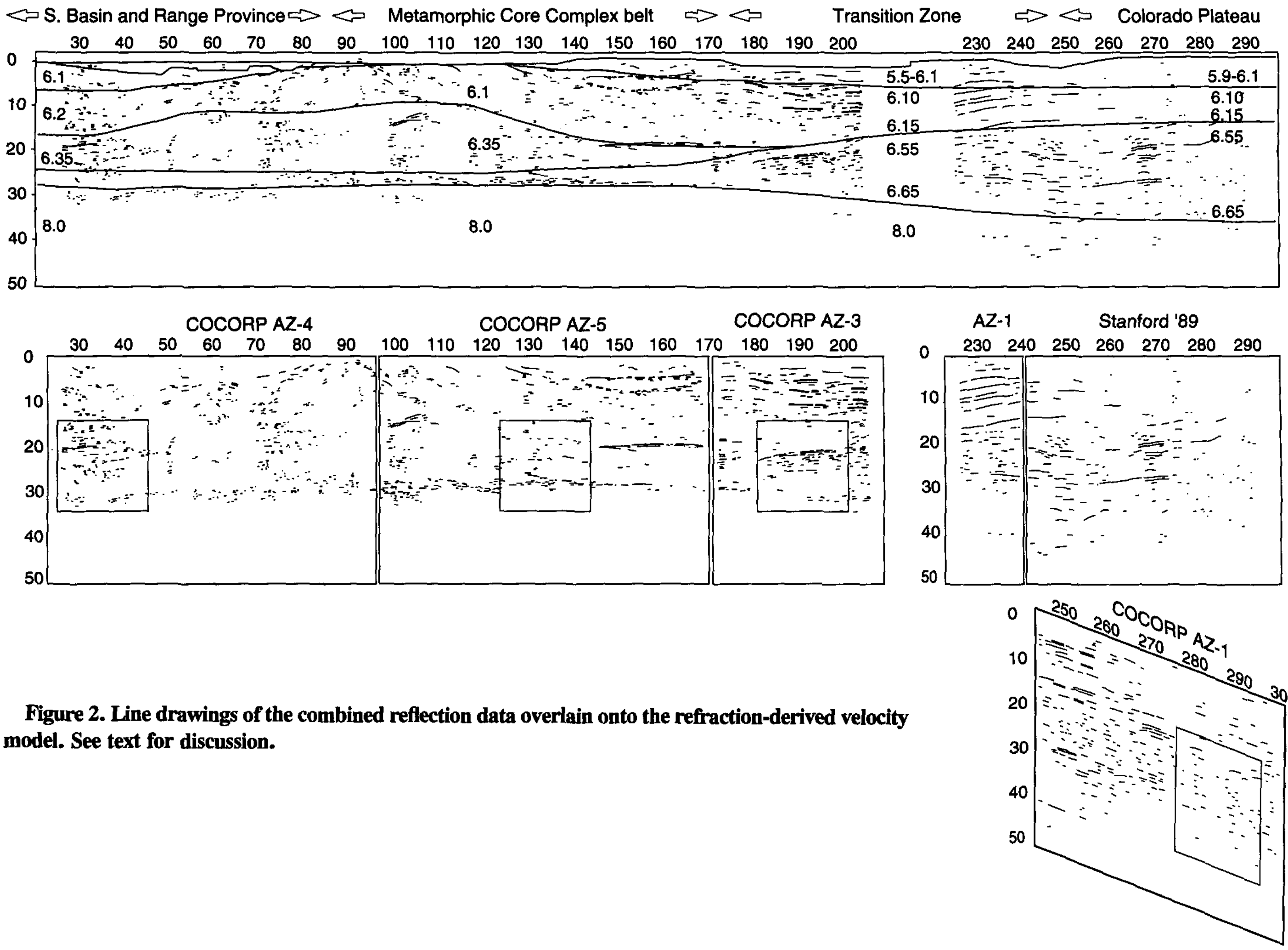


Figure 2. Line drawings of the combined reflection data overlain onto the refraction-derived velocity model. See text for discussion.

that the crust was at least 50 km thick. Analysis of the PACE refraction profile, however, suggests that the crust is ≤40 km thick (Fig. 2). The observation that the reflection Moho is not a sharp, well-defined event is significant and may account for this discrepancy, indicating a transitional crust-mantle boundary at wavelengths observed in vertical-incidence reflection studies.

Transition Zone

The Transition Zone is characterized by a sequence of discrete, subhorizontal reflections, several of which are laterally continuous for as much as 15 km. These reflections, collectively known as the Bagdad reflection sequence (Galvan and Frost, 1985; Hauser and others, 1987; Goodwin and others, 1989), originate in Proterozoic crystalline crust. They extend down to ~12-km depth and define a broad synform >100 km across (Fig. 2, kilometers 130–240).

In addition to the Bagdad reflection sequence, an equally impressive zone of reflectivity is observed at 20- to 22-km depth and is associated with the top of the lower crust (as determined from the refraction analysis). This prominent event is apparent on COCORP line 3 (Fig. 2, kilometers 180–200) but is perhaps best imaged on the Stanford/CALCRUST 1987 reflection profile recorded concurrent with PACE (Goodwin and others, 1989; Goodwin and McCarthy, 1990) (Fig. 5). On these profiles the event is characterized by a 1-s-thick (TWTT) zone of laminated reflections above a more transparent lower crust (to P waves). Shear-wave profiles (Goodwin and McCarthy, 1990), however, show less-dramatic reflectivity associated with the top of the lower crust and more persistent S-wave reflections continuing down to the Moho rather than dying out. From an integrated analysis of these P- and S-wave data, a strongly laminated mafic-felsic layer may be inferred at the top of the lower crust, succeeded below by a decrease in layering. From velocity data, the bulk composition of the lower crust is intermediate (a range of rock types, from metapelite to felsic granulite is permitted by the seismic velocities), whereas the high-amplitude reflection (Fig. 5) that marks the top of this layer may indicate increased gabbro or amphibolite layering (Goodwin and McCarthy, 1990). The zone of midcrustal reflectivity is thicker on the 1989 Stanford profile in the northeast portion of the Transition Zone, where it ranges between 21- and 28-km depth (Howie and others, 1991). Parsons and others investigated these reflections in detail (1992a) and determined that the polarity, P- versus S-wave response, and amplitude-versus-offset character of these reflections were most consistent with a mafic layering origin.

The Moho is a weakly reflective boundary in the Transition Zone (Figs. 2, 3, and 5). It can only be observed as scattered reflections between 30- and 32-km depth beneath the

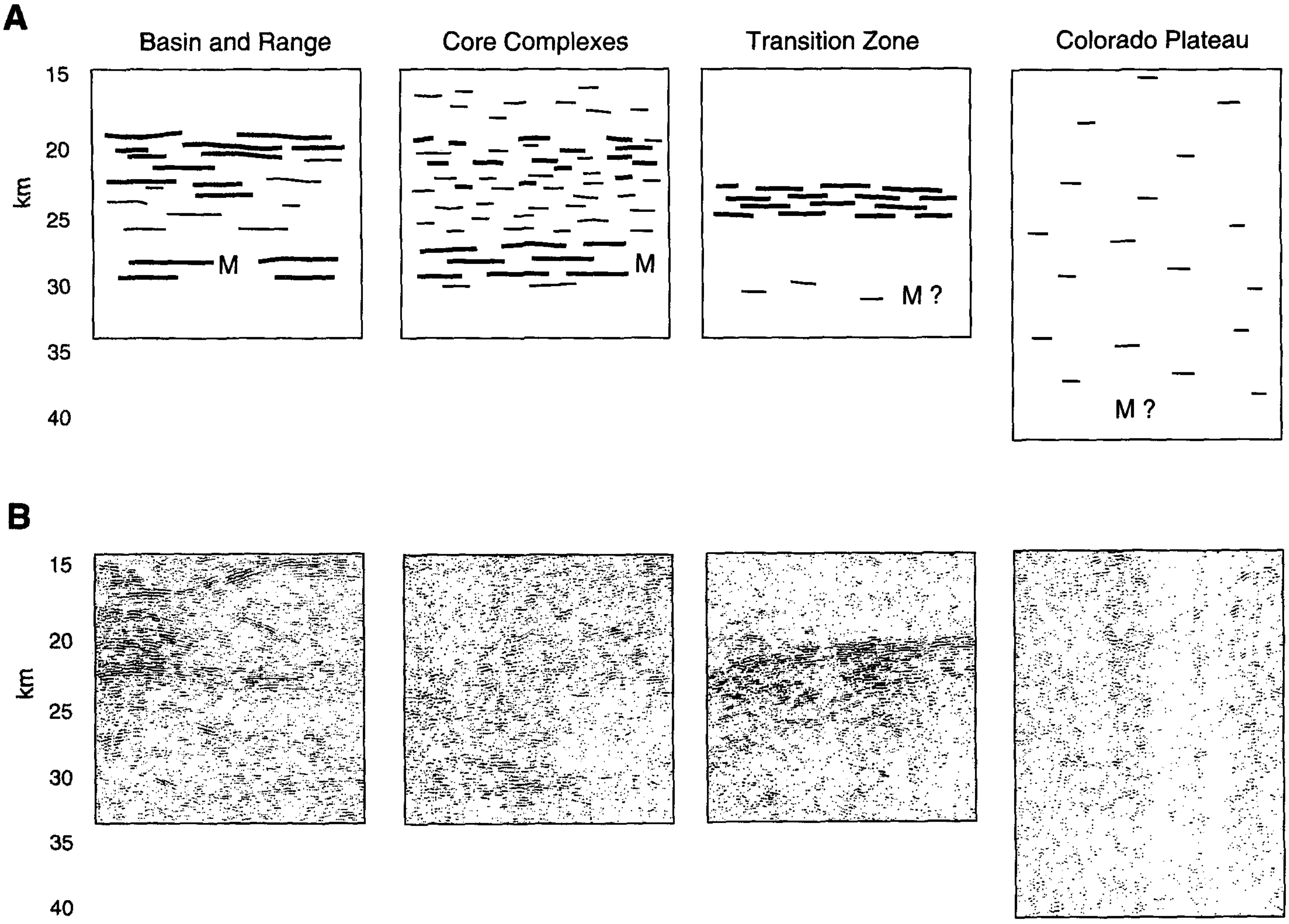


Figure 3. (A) Schematic representation of the reflectivity patterns that characterize the provinces crossed by the PACE profiles. (B) Windows of COCORP reflection data recorded in the four physiographic provinces (Nelson, 1988). The data acquisition and processing parameters are identical for these four windows. Location of data windows is indicated by corresponding boxes in Figure 2. Note that there is not a one-to-one correlation between the line drawings and data examples, because the line drawings are intended to be schematic and more representative of the province as a whole. See text for more discussion.

western end of the Transition Zone, increasing to about 36 km deep beneath the central Transition Zone. These scattered Moho reflections define a gently northeast-dipping boundary that corresponds closely with the refraction-defined Moho. The decreasing amplitude of the Moho arrivals to the northeast coincides with the decreasing amount of extension observed at the surface (Hauser and others, 1987; Howie and others, 1991; McCarthy and others, 1991); stronger Moho arrivals are evident beneath the highly extended southern Basin and Range and metamorphic core complex belt, whereas clear Moho reflections are not observed beneath the unextended Colorado Plateau.

Metamorphic Core Complex Belt

The reflective character of the crust changes dramatically in the vicinity of the metamorphic core complexes. The eastern half of COCORP line 4 and the western half of COCORP line 5 together provide a complete crossing of the core complex belt (Figs. 1, 2, and 6). These profiles show a complex pattern of dipping reflections in the upper crust, weak and diffuse reflectivity throughout the middle and lower crust, and a clear reflection Moho at about 28- to 30-km depth. No prominent events can be observed on the COCORP profiles that might correspond to either the Bagdad reflections or the top of the lower crust that were imaged in the Transition Zone. Instead the crust appears to be reflective mostly on a fine scale (Fig. 3).

This first-order picture of the reflective character of the metamorphic core complexes can be further refined based on a network of industry seismic profiles crossing the core complexes and the adjacent Transition Zone. Clayton (1993) observed a medium-amplitude reflection that regionally underlies the metamorphic core complex belt at ~4 s TWTT (~11 km). He interpreted this reflective zone as deepening to the northeast and merging with the higher-amplitude 7-s reflector in the Transition Zone. Although this 4-s event does not stand out on the COCORP

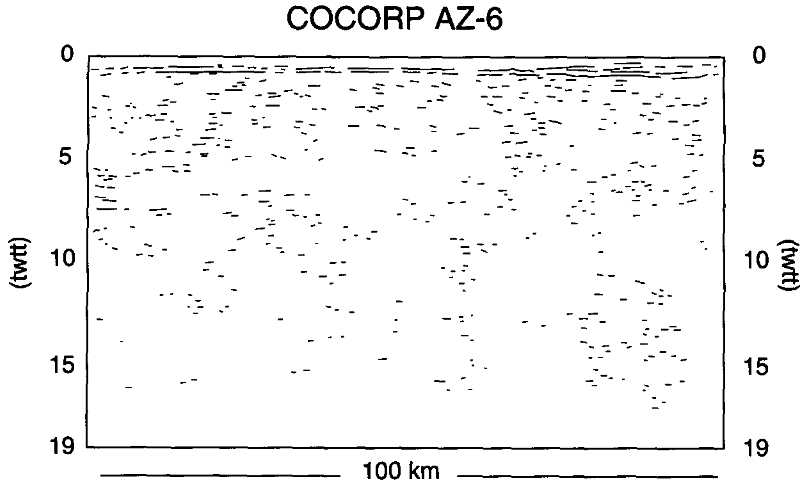


Figure 4. Line drawing (time section) of COCORP profile AZ-6 recorded on the Colorado Plateau (see Fig. 1 for location). This profile lacks the strong mid- to lower-crustal reflectivity of the reflection data recorded in the southern Basin and Range province and Transition Zone. Horizontal scale is the same as the line drawings in Figure 2.

profiles, its presence is supported by the analysis of PACE wide-angle reflection data, which contain a prominent reflector at approximately this same depth beneath the Buckskin-Rawhide metamorphic core complex.

Despite these differences between the COCORP and industry data sets, the former do adequately portray the two principal reflection characteristics of the metamorphic core complex crust: (1) a prominent ~10-s (28 to 30 km) Moho reflection and (2) a pervasive, weakly reflective and laterally discontinuous reflective fabric present throughout the crust (Figs. 2, 3, and 6). The abundant fine-scale layering is characteristic of many metamorphic core complexes (Reif and Robinson, 1981; Goodwin and Thompson, 1988) and has been interpreted as evidence for pervasive ductile deformation of the crust (for example, Goodwin and Thompson, 1988), as we discuss below.

Southern Basin and Range Province

The southern Basin and Range province displays a fourth reflective pattern, distinct from that of the metamorphic core complexes, the Transition Zone, and the Colorado Plateau. The western part of COCORP line 4 (Figs. 2 and 6) extends southwest, beyond the metamorphic core complex belt into a less-extended region more typical of the southern Basin and Range province as a whole. In this area, the COCORP profile contains a strong zone of reflections between 18- and 23-km depth, followed by a well-defined reflection Moho at about 28-km depth (Figs. 2, 3, and 6). The midcrustal reflectivity is at approximately the same depth as that observed at the top of the lower crust in the Transition Zone and may have a similar origin. Superposed on much of the middle and lower crust (below 8- to 10-km depth) is a weaker, pervasive reflection character (Fig. 3).

ASSESSMENT OF MAGMATISM AND DUCTILE DEFORMATION

Before developing an interpretive model for the evolution of the Colorado Plateau–southern Basin and Range province transition, we must first estimate the relative roles of magmatism and ductile deformation in the crust. This cannot be done directly and requires two critical assumptions. Our first assumption is that the above-described seismic patterns for the Colorado Plateau, Transition Zone, metamorphic core complexes, and the southern Basin and Range province are valid representations of the crust in these regions. Second, we assume that these reflection patterns are of Tertiary age and owe their origin to extension (we do not include in this the pattern from the Colorado Plateau, where there has been effectively no Cenozoic extension). Clearly this is not realistic; several workers have argued, for example, that the Bagdad reflection sequence may correspond to Proterozoic mafic intrusions (for example, Howard, 1991; Litak and Hauser, 1992). In addition, magmatism, ductile deformation, and uplift during the Mesozoic must have left some signature on the present-day crustal structure. By making this assumption, however, we may estimate an upper bound to the amount of Tertiary magmatism that has occurred.

Crustal Magmatism

There is a well-established correlation between Tertiary crustal extension and magmatism in the Basin and Range province and metamorphic core complex belt (for example, Gans and others, 1989). In addition to the present-day high heat flow (Lachenbruch and Sass, 1978; Sass and others, unpubl. data), Tertiary volcanic activity is also abundant along the PACE transect (Suneson and Lucchitta, 1983; Hazlett, 1986; Nielson, 1986; Nielson and Turner, 1986; Moyer and Nealey, 1989; Nielson and Beratan, 1990). Thick volcaniclastic deposits are exposed in tilted Tertiary fault blocks, and Tertiary dike swarms mostly oriented normal to the northeast-southwest direction of extension are exposed in the metamorphic core complex belt (Davis and others, 1982; Nakata, 1982; John, 1982; Spencer, 1985). Moreover, elevations also have remained high despite the large amount of extension. This requires either an unusually thick pre-extension crust (for example, ~60 km; Coney and Harms, 1984) or an addition of material (of crustal density) to inflate the crust, such as mantle-derived intrusions (Okaya and Thompson, 1986; McCarthy and Thompson, 1988; Gans and others, 1989; Thompson and McCarthy, 1990). The question is not whether magmatism has occurred, but how much as occurred, and can we identify mafic layering on seismic reflection profiles?

The best indication of mafic layering along the PACE transect is the Bagdad reflection sequence. Goodwin and others (1989) modeled the polarity and waveform of this laterally continuous, high-amplitude sequence of events and demonstrated that the reflections resulted from positive impedance contrasts. They thus proposed that the reflections result from high-velocity mafic sills intruding lower-velocity granitic country rock. (Note that in this manuscript we use the term *sill* to represent a subhorizontal intrusion into crystalline rock.) A zone of reflections that is strikingly similar to the Bagdad reflection sequence has been drilled in Sweden (Juhlin, 1990), where diabase intrusions into Proterozoic granite have been confirmed. The deeper reflection that underlies the Bagdad reflection sequence, referred to here as the top of the

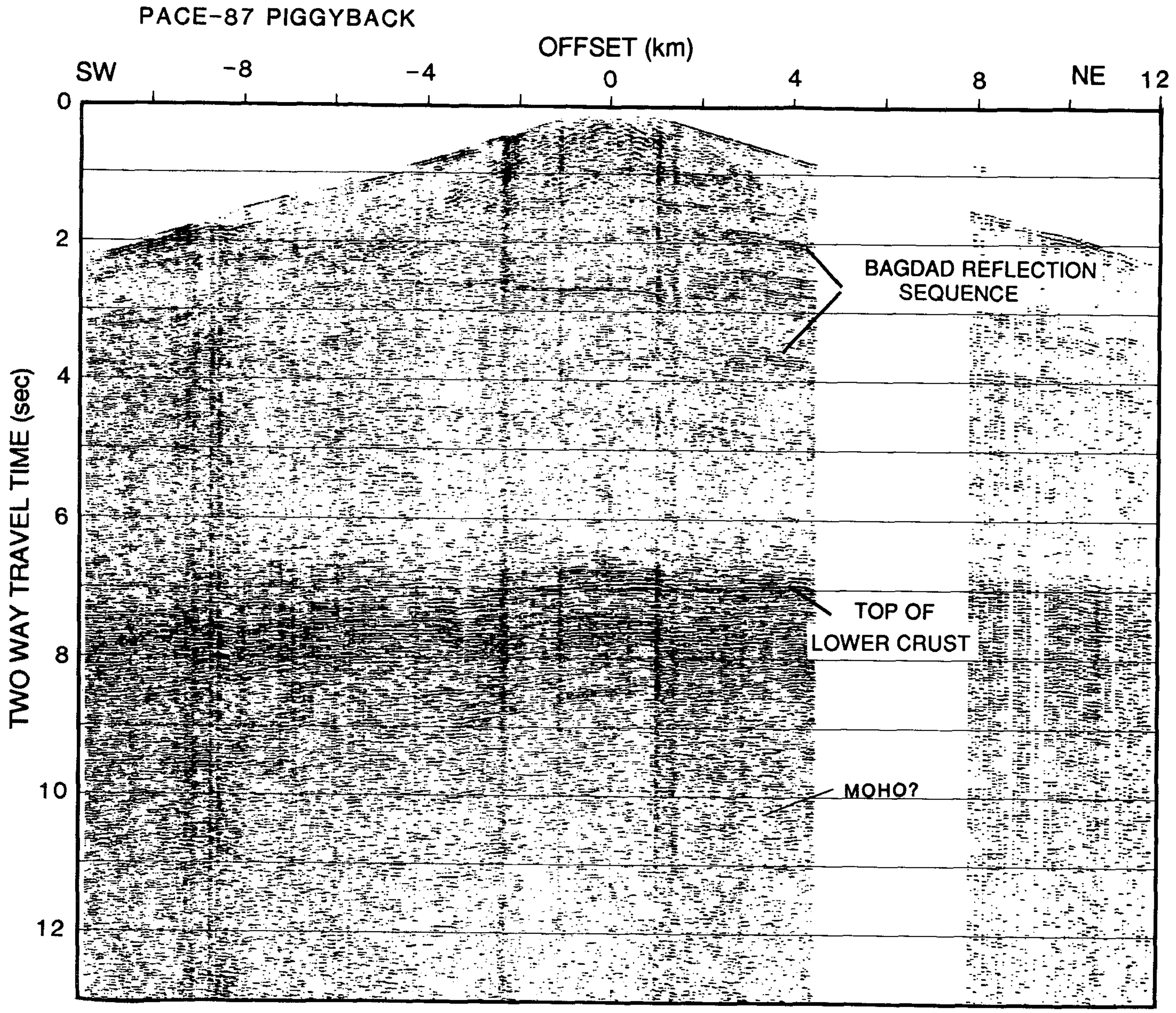


Figure 5. A shot gather from the 1987 Stanford-CALCRUST experiment recorded in the southern Transition Zone. These data depict the highly layered sequence at the top of the lower crust in detail; the reflectors are thought to be thin, horizontal mafic intrusions that have clustered near the top of the ductile middle crust (Goodwin and McCarthy, 1990; Parsons and others, 1992a). The southwestern portion of the data shows the pervasive fine-scale reflectivity that typifies Basin and Range sections. The probable Proterozoic mafic intrusions that cause the Bagdad reflection sequence are imaged in the upper few seconds of the gather.

lower crust, is also believed to be the result of mafic intrusions (Goodwin and McCarthy, 1990; Parsons and others, 1992a). This argument is based on the observation that the high-amplitude reflections from the top of the lower crust have positive polarity, a positive amplitude-versus-offset trend, and a positive step in velocity to 6.6 km/s (as determined from the refraction analysis). P- and S-wave modeling suggests that the most likely rock types for this 3-km-thick zone are gabbroic sills or their metamorphic equivalents (high Vp and Poisson's ratio) interlayered with intermediate-composition rocks (lower Vp and Poisson's ratio) (Goodwin and McCarthy, 1990; Howie and others, 1991).

The only other region where similar high-amplitude reflections are recorded on the PACE transect is the southern Basin and Range province, on the southwestern edge of the survey. Here an equally bright zone of reflectivity is present between 18- and 23-km depth (Fig. 6). Although little information is available to indicate the origin of this reflective zone, it is similar to the top of the lower crust beneath the Transition Zone in terms of its depth, amplitude, and laminated character. Furthermore, as in the Transition Zone, this zone of reflectivity is associated with a pronounced wide-angle reflection resulting from a first-order velocity discontinuity at its top (the magnitude of this velocity contrast is not well determined due to the presence of

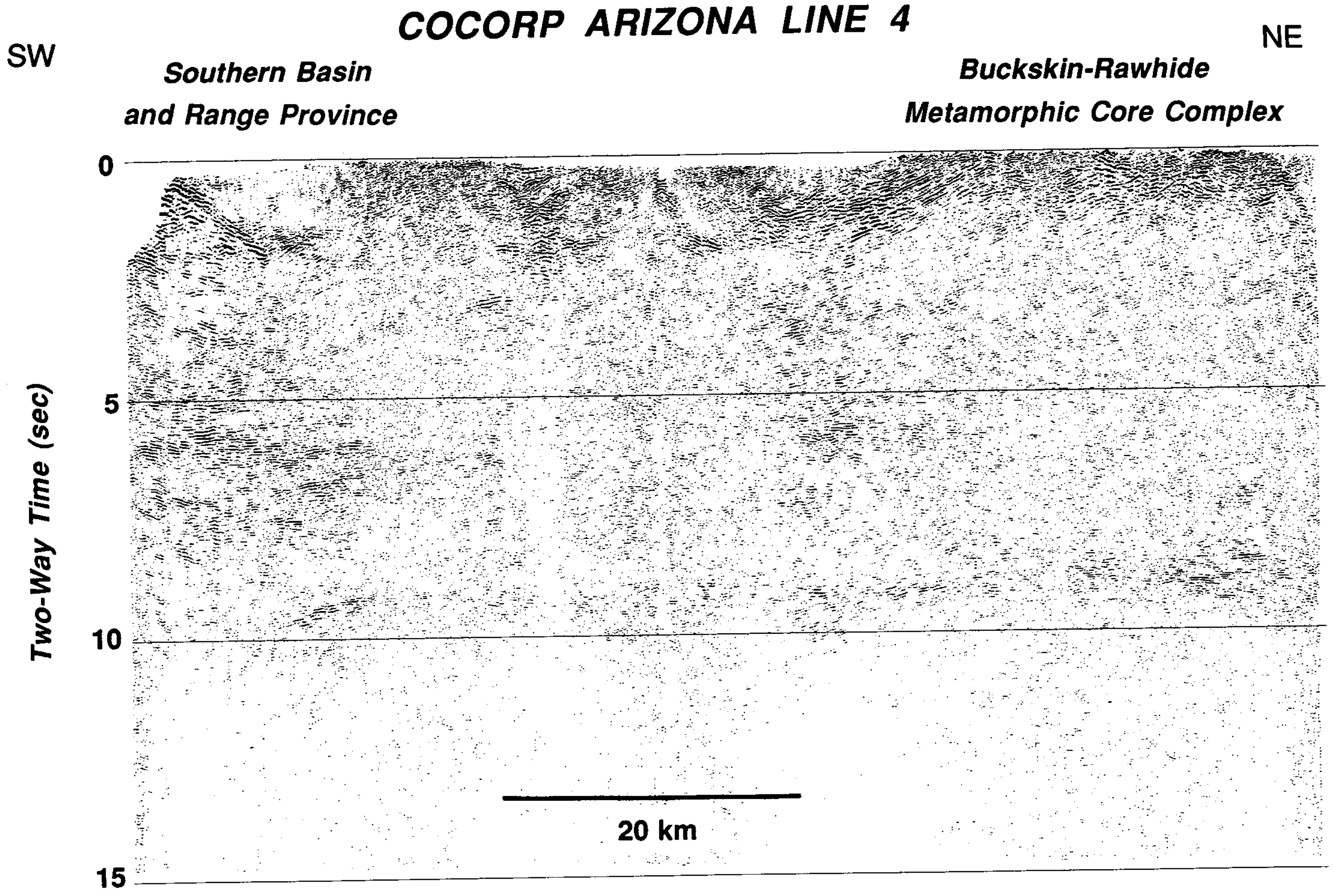


Figure 6. COCORP Arizona Line 4 seismic reflection profile recorded across the southern Basin and Range province and the Buckskin-Rawhide metamorphic core complex (kilometers 30 to 100 in Fig. 2). The prominent reflectivity on the western (left) portion of the figure is representative of the southern Basin and Range province and consists both of a strong zone of reflectivity in the middle crust (6- to 7-sec TWTT or 20- to 23-km depth) and pervasive fine-scale reflectivity throughout the middle and lower crust. In contrast, only the fine-scale reflectivity is visible across the metamorphic core complex belt (eastern two-thirds of the plot). See Figure 3 for enlarged windows displaying these different reflective fabrics.

this event near the edge of the refraction survey). We thus propose that both the Transition Zone and the southern Basin and Range province are characterized by a 3- to 5-km-thick zone of mafic intrusions interlayered with intermediate-composition rocks at the top of the lower crust.

Magmatic Underplating of the Crust

Recent studies by Wilshire (1990) of lower-crustal xenoliths in Neogene basalts suggest that the lower crust in southeastern California and western Arizona is characterized by underplated mafic and ultramafic rocks derived from peridotite melts. These xenoliths consist primarily of two-pyroxene gabbro, pyroxenite, wehrlite, and websterite. One of Wilshire's (1990) xenolith localities is in the western Transition Zone, very near the PACE transect. Two other localities that display a similar suite of rocks are situated in southeastern California within 100 km of the refraction and reflection profiles.

Despite this xenolith evidence for a mafic, underplated lower crust, support from *in situ* seismic refraction studies is lacking. Estimates of expected seismic velocities for underplated mantle-derived rocks as a function of temperature and depth of intrusion have been computed by Furlong and Fountain (1986), who concluded that, at 30-km depth and at a heat flow of 1.5 HFU, underplated mafic material would have a velocity of 7.2 to 7.8 km/s. A similar conclusion may be obtained from an estimate of seismic velocities from the crustal xenoliths (Wilshire, 1990). The densities of the xenoliths range between 3.05 g/cm^3 and 3.34 g/cm^3, averaging 3.2 g/cm^3. An estimate of seismic velocity from these densities and compositions, taking into account the elevated temperatures, yields an average seismic velocity of 7.2 km/s. These velocities are much higher than the 6.6-km/s refraction velocity measured for the lower crust along the PACE transect. Similarly, a comparison of the refraction velocities with velocities measured in the laboratory for a range of rock types (for example, Holbrook, 1988; Holbrook and others, 1992) reveals that the mafic and ultramafic compositions are poor matches for the observed seismic velocities (Fig. 7). Pyroxenite, metagabbro, and mafic granulite all have temperature-corrected velocities well above those determined for the lower crust in the southwestern United States.

The apparent inconsistency between the velocities inferred from the xenoliths and the lower-crustal velocities can be resolved if the

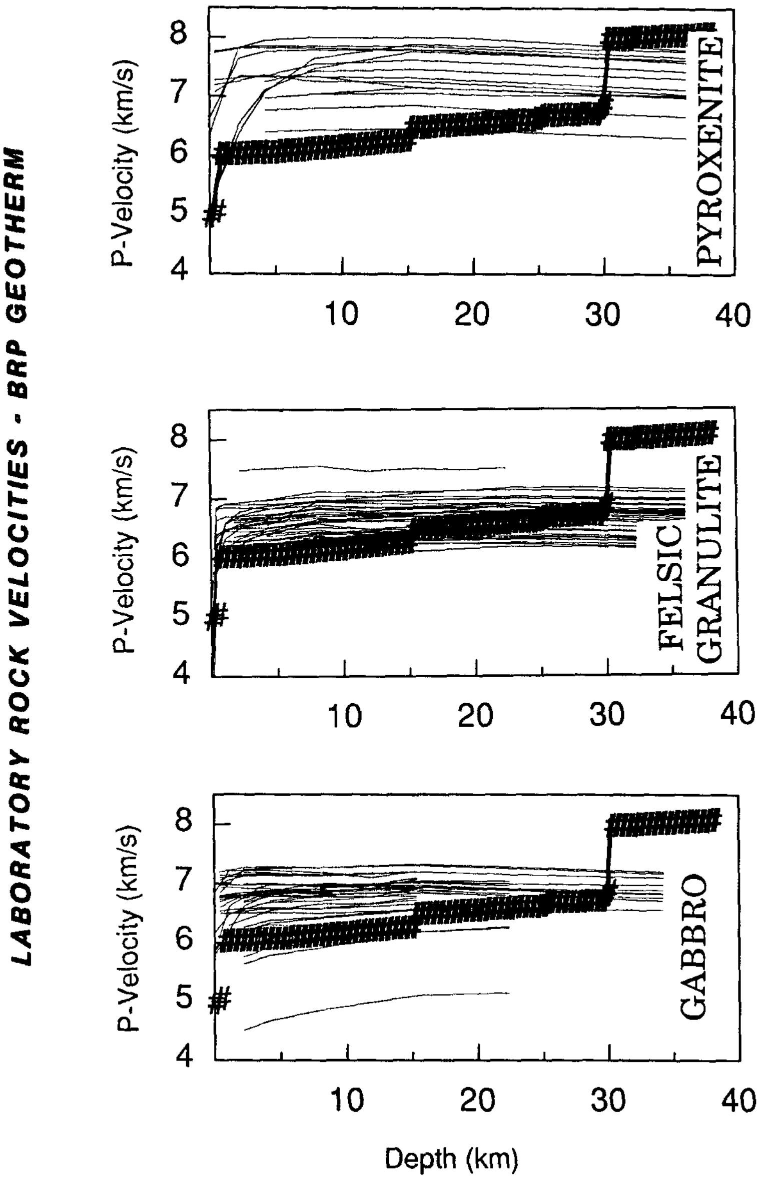


Figure 7. Observed laboratory velocities of a variety of lower-crustal rocks (after Holbrook, 1988) superposed on an average velocity-depth curve for the PACE transect. The more mafic gabbros and pyroxenites are on average faster than *in situ* velocities derived from the refraction data.

xenoliths were derived from the upper mantle (Goodwin and McCarthy, 1990; McCarthy and others, 1991). This proposal is consistent with a definition of the crust-mantle boundary based on P-wave velocity (Mohorovičić, 1909), rather than mineralogy (compare with Griffin and O'Reilly, 1987). Most of the xenoliths have densities and inferred P-wave velocities that are virtually indistinguishable from upper-mantle peridotite. Thus, the source of the mafic xenoliths could reside at or below the Moho without being identified seismically. In effect, we view the dense mafic melts as "overplating" the top of the upper mantle, rather than underplating the base of the crust.

Ductile Deformation

In addition to compositional layering, ductile deformation also has an identifiable reflection signature. Weak, laminated, and discontinuous reflections prevail on the seismic reflection profiles acquired across the Whipple and Buckskin-Rawhide metamorphic core complexes (for example, Frost and others, 1987). A similar pattern has been noted across other metamorphic core complexes, including the Snake Range (McCarthy, 1986), the Kettle Dome (Hurich and others, 1985), the Ruby Range (Valasek and others, 1989), and the Picacho Mountains (Goodwin and Thompson, 1988). Where these reflections have been projected to the surface or sampled in deep drill holes, they correlate with metamorphosed crystalline rocks, commonly ductilely deformed or mylonitized (for example, Reif and Robinson, 1981; Hurich and others, 1985; Goodwin and Thompson, 1988; Christensen, 1989; Wang and others, 1989). Waveform modeling studies in conjunction with laboratory velocity and density measurements have shown that laminated reflections may be produced by constructive interference through a stack of many thin layers (tens of meters thick on average) of varying composition and texture (for example, Hale and Thompson, 1982; Jones and Nur, 1984; Hurich and Smithson, 1987; Goodwin and Thompson, 1988; Christensen and Szymanski, 1988; Wang and others, 1989). Large contrasts in seismic velocity are not needed, although velocity anisotropy, common in foliated rocks, has been shown to be important in enhancing the reflectivity (Christensen and Szymanski, 1988). The laterally discontinuous character of the reflections is attributed to the complex structure of the rock units themselves; these bodies are typically discontinuous horizontally on a scale of hundreds of meters (Goodwin and Thompson, 1988; Wang and others, 1989).

This weak, discontinuous reflection character extends from the metamorphic core complex belt southwest into the Basin and Range province and is interpreted here as evidence of ductile deformation at varying depths in the crust (Fig. 6). Where extension is extreme, as in the core complexes, this fabric extends from the Moho up to the surface, effectively overprinting much of the preexisting reflectivity in the crust. Away from the metamorphic core complexes, crustal extension is less, and the ductile fabric is evident only at deeper levels in the crust (Frost and others, 1987).

Based on these two reflection patterns, we have interpreted the relative distribution of magmatism and ductile deformation along the PACE transect in southeastern California and western Arizona (Fig. 3). Beneath the Colorado Plateau only scattered reflectivity is observed, which probably indicates a lack of both mafic layering and ductile deformation. The Transition Zone, however, reveals abundant reflectivity, most of which is high in amplitude and laterally continuous; for reasons outlined above, we believe that most of this reflectivity is of magmatic origin. In contrast, mostly discontinuous subhorizontal reflections are observed beneath the metamorphic core complex belt, suggesting that much of the mafic layering once present may have been overprinted by ductile deformation. Finally, the southern Basin and Range province has high-amplitude reflections disrupted and overprinted by a pervasive fabric of weak, discontinuous, subhorizontal reflectivity. We interpret this to indicate that both magmatism and ductile deformation have been active crustal processes in that region.

ESTIMATES OF MAFIC MAGMATISM

From the seismic velocities, we can estimate the *maximum amount* of mafic, mantle-derived magma intruded into the crust during Tertiary extension. In general, there are no resolvable high-velocity (≥6.8 km/s) layers that could indicate contiguous units of mafic intrusions (several kilometers thick and tens of kilometers long). If sizable quantities of basalt were intruded into the crust, then the intrusions were apparently either initially distributed randomly in thin layers, or were homogenized by subsequent crustal flow or magma mixing. The Transition Zone provides perhaps the more clear indication, as its reflection pattern is apparently not overprinted by ductile deformation. Very little mafic material is believed to have been added to the lower crust in the Transition Zone, given the relatively low velocities (6.6 km/s) of this deepest layer (Goodwin and McCarthy, 1990; McCarthy and others, 1991). Instead, most of the mafic melt intruded at the top of the lower crust, possibly as the result of ponding of the magma below a rheologically weak, quartz-rich middle crust (Howie and others, 1991; Parsons and others, 1992b). Goodwin and McCarthy (1990) estimated that only 30% gabbro interlayered with intermediate rocks was necessary to generate the high-amplitude reflections in the lower crust of the Transition Zone. This corresponds to a maximum of 3 km of mafic additions to the crust at this level. Small amounts (<0.5 km) of mafic additions are estimated at shallower levels in the Transition Zone, where individual mafic sills associated with the Bagdad reflection sequence are thin (~25 to 30 m thick; Goodwin and others, 1989). In total then, we estimate that a maximum of ~4 km of mafic rock has been added to the crust in the Transition Zone.

A similar, but slightly higher amount of mafic magmatism is estimated in the southern Basin and Range province. By analogy with the Transition Zone, we estimate that 3 km of mafic rock may have been intruded at ~20-km depth, thereby producing the high-amplitude zone of reflections identified on COCORP Line 4 (Fig. 6). In addition, velocities are higher in the top 10 km of the crust (as much as 6.2 km/s; McCarthy and others, 1991) and permit the intrusion of 1 to 2 km of mafic rock in this portion of the crust. In total then, we estimate a maximum of ~5 km of mafic additions to the entire crust in the southern Basin and Range province.

Potentially the greatest amount of mafic intrusion and crustal inflation has occurred in the metamorphic core complex belt. Although the velocity of the lower crust does not exceed 6.6 km/s and the average crustal velocity is low (6.2 to 6.3 km/s), there still is room for the intrusion of as much as 8 km of mafic material into the crust along this highly extended part of the transect, as explained below. Like the southern Basin and Range province to the southwest, high velocity gradients, high upper-crustal densities, and exposed Tertiary plutons suggest that as much as 2 km of mafic material may have intruded into the upper 10 km of the crust. At deeper levels, the intermediate 6.35-km/s velocity for the midcrustal layer may represent a thick zone of gabbroic sills intruded and mixed with silicic host rock. For a 14-km-thick middle crust with an average velocity of 6.35 km/s (Fig. 2), a maximum of 6 km of this lens could consist of gabbroic (6.8 km/s) additions to the crust if it were mixed with silicic country rock with a bulk velocity of 6.1 km/s. As noted earlier, Clayton (1991) has identified a regionally continuous, moderate-amplitude reflection at ~4 s TWTT beneath the metamorphic core complexes. This reflection correlates with the top of the refraction-defined midcrustal layer at 11-km depth and dips to the northeast, where it may ultimately tie with the 20-km-deep high-amplitude reflection at the top of the lower crust in the Transition Zone (Clayton, 1991). Based on this correlation, and drawing from estimates presented above for amounts of mafic material intruded at the top of the lower crust in the Transition Zone, we speculate that this 11-km-deep event is the most likely site for intrusion of mafic sills within the core complex crust. One to 2 km of mafic material could be preferentially ponded at this level. The absence of any other continuous reflectors in the midcrustal layer suggests that if this layer is a result of mixing of mafic intrusions with silicic host rock, the mafic intrusions have been broadly distributed throughout the middle crust in thin, discontinuous layers, rather than intruded as thick, concentrated horizons. The prevalence of laminated, discontinuous reflections throughout the crust and the weaker reflection amplitudes for the 11-km-deep reflector in comparison to its down-dip Transition Zone equivalent suggest that the crust has been homogenized by ductile flow. Magma mixing and crustal anatexis may also contribute to this reflection character. All totaled, we estimate that a maximum of 8 km of mafic material could have been added to the metamorphic core complexes during extension. We emphasize, however, that this is an upper-bound estimate, and it is more likely that at least some of the mafic material identified in the crust beneath the metamorphic core complexes is Mesozoic or older in age.

INTERPRETIVE MODEL

In accordance with these interpretations of the reflection and refraction profiles, we may now use the seismic observations to build a kinematic model for the development of extension in the southwestern United States. At the end of the Laramide orogeny, the crust in the southwestern United States was hot, thermally weakened, and overthickened (for example, Wernicke and others, 1987; Sonder and others, 1987). Plutonism, thrusting, and crustal thickening were concentrated in the southern Basin and Range province, whereas the Colorado Plateau experienced only moderate deformation. In the Eocene epoch, gravels were shed onto the Plateau from highlands to the southwest (Young, 1966, 1970), suggesting that the southern Basin and Range province had a thicker crust than the Colorado Plateau prior to Miocene extension. Although poorly constrained, we assign crustal thicknesses of 45 km to the southern Basin and Range province and 40 km to the Colorado Plateau (Fig. 8A), assuming that the Plateau crustal thickness has remained fairly constant since the Laramide and that the southern Basin and Range crust was only marginally thicker than that of the Colorado Plateau.

After a period of quiescence, extension began in early Miocene (~22 Ma). The early stages of this extension were marked by brittle faulting in the upper crust and intrusion of basaltic melt at deeper levels (Fig. 8B). We

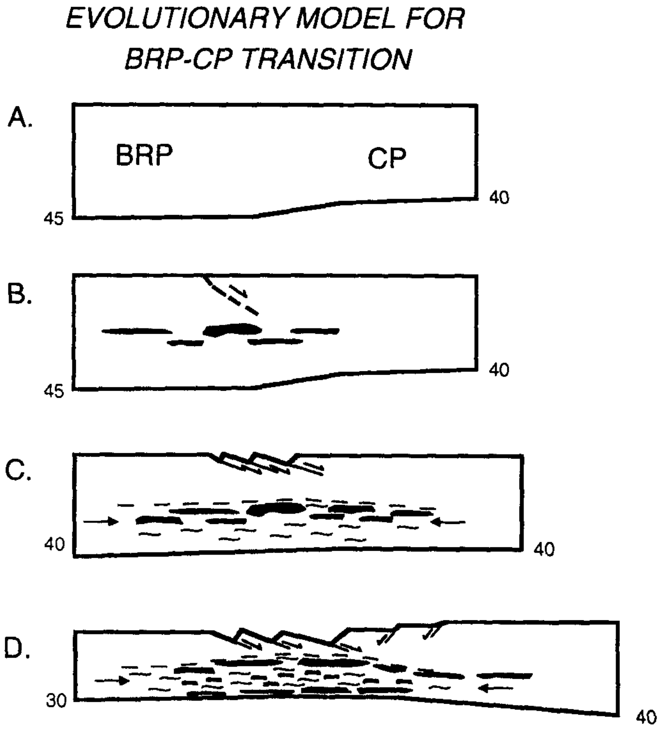


Figure 8. Model for the Cenozoic evolution of the Basin and Range (BRP)–Colorado Plateau (CP) transition. (A) Following the Laramide, but prior to extension, the initial crustal thickness is assumed to be 45 km. (B) At ca. 22 Ma, faulting and magmatism begin. (C) As extension and faulting continue (ca. 20 to 22 Ma), the middle crust begins to deform ductilely, and isostatic doming initiates. (D) During the peak extensional phase (ca. 18 and 20 Ma), extension thins the crust dramatically while isostatic doming elevates midcrustal rocks to shallow, upper-crustal levels. Throughout this period of metamorphic core complex extension (22 to 15 Ma), the thinning of the crust due to extension is partially offset by magmatism and ductile flow, which combine to inflate the crust and maintain crustal thickness at ~28 km beneath the metamorphic core complex belt and southern Basin and Range province. Decreasing extension to the northeast results in a 40-km-thick crust beneath the Colorado Plateau. Age constraints taken from Frost and Martin (1982), Suneson and Lucchitta (1983), Nielson (1986), Nielson and Turner (1986), Reynolds and others (1986), Spencer and others (1986), Bryant and Naeser (1987), Davis (1988), and Foster and others (1990).

believe that much of this melt intruded at the rheologic contrast that marks the top of the lower crust (~20-km depth), whereas smaller amounts intruded the upper and lower crust. The estimates of 4, 5, and 8 km of mafic material added to the Transition Zone, southern Basin and Range province, and metamorphic core complex crust, respectively, are considered to be maxima, because they do not take into account any preextension high-velocity material in the crust. Smaller amounts of intrusions, particularly beneath the core complexes, are likely. We believe, however, that magmatism did result in the addition of enough advected heat to allow the crust to behave ductilely; the more felsic middle crust may even have undergone partial melting.

As extension continued, brittle deformation in the upper crust was accompanied by ductile deformation and continued magmatism at depth (Fig. 8C). For reasons that are unclear, extension was greatest along the metamorphic core complex belt, perhaps due to underlying horizontally directed magmatic inflation (Lister and Baldwin, 1993; Parsons and Thompson, 1993). Rather than the crust thinning in a pure-shear fashion beneath this area, hot, mobile felsic material from adjacent, less-extended regions flowed into the middle crust to fill the evolving "void" (Gans, 1987; Block and Royden, 1990; Kruse and others, 1991; McCarthy and others, 1991). The middle crust was weakest and most susceptible to this lateral flow because of its felsic compositions and high temperatures. Lateral variations in the amount of upper-crustal extension were thus accommodated in the middle crust by flow of material from less extended regions into areas of greater extension, with the middle crust acting as a zone of compensation (McCarthy and others, 1991). Denudation of the upper crust along low-angle faults resulted in isostatic doming and uplift (Spencer, 1984), thereby pulling in new middle and lower crustal material from the sides (Fig. 8D; Block and Royden, 1990). In this way, the top of the lower crust, once at 20-km depth, was elevated to ~11-km depth, while being overprinted by contemporaneous ductile deformation. We believe that mafic magmatism, ductile deformation, and possibly crustal anatexis combined to yield a mixed and homogenized middle crust, as suggested by the 6.35 km/s lens and the pervasively laminated reflection pattern that characterizes the metamorphic core complex belt today.

The concept of lateral ductile flow is critical to our model; not only is it a way of suppressing the seismic velocities in the middle crust, it also allows crustal accommodation of the variable amounts of extension recorded at the surface, thereby maintaining a uniform crustal thickness throughout the southern Basin and Range province (for example, Kruse and others, 1991). As Gans (1987) noted in eastern Nevada, to maintain a constant crustal thickness, the less extended areas must provide material to areas that are more highly extended. A similar model incorporating isostatic uplift has been endorsed by Block and Royden (1990) to account for the flat Moho observed beneath several of the core complexes.

We postulate that during ductile flow of the middle crust, the lower crust thinned passively and necked; this interpretation is based on the observation that in the Transition Zone where extension was small, the lower crust is still thick. A progressive thinning of the lower crust in association with increased extension is recorded to the southwest in the direction of the southern Basin and Range province and the metamorphic core complex belt. Our model thus predicts brittle simple-shear deformation in the upper crust and pure-shear deformation in the lower crust, separated by an intervening zone of ductile flow and magmatic intrusions (McCarthy and others, 1991).

Although some mafic magma undoubtedly intruded the lower crust during extension, the low seismic velocities indicate that most of the magmatic activity was confined to the top of the upper mantle. The sharp nature of the crust-mantle boundary beneath the southern Basin and Range province and metamorphic core complexes (as seen in vertical-incidence and wide-angle studies) is undoubtedly affected by magmatism. However, the decreasing amplitude of the Moho reflection in the direction of the Colorado Plateau, despite xenolith evidence for continued magmatism, suggests that other processes such as ductile deformation also affected the evolution of this boundary.

CONCLUSIONS

By employing seismic velocities and reflectivity patterns across terranes of greatly varying extension we have estimated the maximum, end-member amount of crustal addition by mantle-derived magmatism to be a cumulative 8 km beneath the metamorphic core complex belt, 5 km beneath the southern Basin and Range province, and 4 km beneath the less-extended Transition Zone. From these estimates we can make some general statements concerning the amount of ductile flow that has occurred contemporaneous with extension.

Estimates of 50–70 km of extension in the 100-km-wide region surrounding the metamorphic core complex belt (>40 to 45 km [Davis, 1988]; 50 km [Howard and John, 1987]; 50 km [Reynolds and Spencer, 1985]; 55 to 75 ± 20 km [Spencer and Reynolds, 1989]) imply ≥100% crustal extension. If this extension were accomplished by simple thinning without any accompanying magmatism or lateral ductile flow, then the preextension crustal thickness would have been 60–100 km. This excessive thickness cannot be ruled out, but we think it unlikely. If instead the preextensional crustal thickness were ~45 km, as proposed here, then the 100% extension would thin the crust to ~22 km, requiring an additional 6 to 8 km of material from magmatism and/or ductile flow to achieve the 28- to 30-km crustal thicknesses present today. It is thus possible that no ductile flow occurred at all, given the seismic evidence for as much as 8 km of mafic additions to the crust. However, because multiple magmatic episodes have occurred in this region prior to Tertiary time, we think it likely that only one-half to one-third (3 to 4 km) of the seismically inferred mafic material beneath the metamorphic core complex belt is Tertiary in age. This leaves room for 2 to 4 km of rock added via crustal flow. Moreover, if extension exceeded 100%, or if the preextension crustal thickness were <45 km, the amount of additions to the crust via ductile flow would be greater. These estimates cannot be constrained any further without a better understanding of the preextension crustal thickness and the amount of pre-Tertiary mafic material in the crust.

Based on the seismic reflection character evident in the COCORP reflection profiles, we believe that the middle crust was the locus of most of the magmatism and crustal flow. We also propose that these two processes were responsible for crustal isostatic compensation of the short-wavelength basin-range-basin topography. Acting in concert, magmatism and ductile flow homogenized the crust, mixing mafic intrusions with the more silicic host rock and forming an intermediate-composition midcrustal lens. On a more regional scale, the Moho varies smoothly, dipping gradually to the north beneath the topographically higher Transition Zone and Colorado Plateau, suggesting that only the broadest variations in elevation are isostatically compensated below midcrustal levels.

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