NATURE AND ORIGIN OF SEISMIC REFLECTION
FABRIC, RUBY-EAST HUMBOLDT METAMORPHIC CORE
COMPLEX, NEVADA

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Abstract. Seismic reflection profiling across exposed upper and middle crustal rocks of the Ruby-East Humboldt metamorphic core complex delineates important characteristics of the crustal structure developed during Tertiary extensional deformation. The goals of this study were to trace a Tertiary extensional shear zone from mylonitic surface outcrops into a seismic section and to characterize the deeper crustal fabric associated with the polyphase deformational history of the complex. Reflections in the shallow surface correlate with a plastic to brittle shear zone that formed during the tectonic unroofing of the middle crustal rocks. Constructive interference from strong planar layering in the mylonitic shear zone is considered chiefly responsible for generating the reflections. East and

southwest dipping reflectors in the seismic section appear to correlate with exposed, opposing dipping mylonitic foliation domains. The opposing dips of the mylonitic layering may reflect warping of the normal-sense shear zone during tectonic exhumation coupled with an overall anastomosing character. Deeper in the section, a heterogeneous reflection character correlates with increases in velocity shown from wide-angle measurements in this region and is interpreted as penetrative fabric originating from extensional flow facilitated by broad-scale pure shear and localized simple shear. Lower crustal rocks apparently achieved granulite facies metamorphism during extension. A maximum of 6-8 km of mafic material could have been added to the crust during Cenozoic extension. The Moho reflection has such a high amplitude that it may be caused by partially molten rocks interleaved with peridotite. Reflections from the Moho show no significant upwarping of the base of the crust beneath the core complex. This suggests that the lower-crustal configuration is at least as young as the period of extensional activity that lasted from approximately 40 to 20 Ma which was responsible for the exhumation of the metamorphic core complex.

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INTRODUCTION

The origin of metamorphic core complexes and the interrelationship between Cordilleran crustal compression and superposed extension still remain major questions in the tectonic history of western North America. A characteristic feature of Cordilleran metamorphic core complexes is a shallowly dipping mylonitic foliation with a pervasive stretching lineation that records the azimuth of the slip line during extension [e.g., Davis, 1980; Snoke and Lush, 1984]. The origin of the foliation may be composite in some cases, but commonly its formation occurred during Tertiary crustal extension along normal-sense, plastic shear zones. These zones appear to be the midcrustal continuations of upper crustal normal fault systems. The geometry of these plastic to brittle fault zones has been chiefly documented with areal geologic mapping, structural analysis, and the preparation of cross sections. Seismic reflection studies offer another technique to explore the geometry of fault zones associated with metamorphic core complexes as well as the crustal fabric of the middle and lower crust beneath them. Several regional seismic reflection studies [Reif and Robinson, 1981; Allmendinger et al., 1987; Hauser et al., 1987; Frost et al., 1987; McCarthy and Thompson, 1988] have provided some important insights into this problem, but detailed seismic studies closely coordinated with geologic and structural mapping are still few [e.g., Gans et al., 1985; Hurich et al., 1985; McCarthy, 1986]. Combined geologic, vertical-incidence, and wide-angle reflection profiles directly across an exposed metamorphic core complex were virtually nonexistent prior to this study.

An extensive seismic survey was conducted by the University of Wyoming seismograph crew during the summers of 1984 and 1985. The survey line was approximately 15 km long and traversed a complex structural zone that exposes various elements of a low-angle, plastic to brittle fault zone that contains unmetamorphosed upper Paleozoic and Tertiary rocks in the hanging wall and mylonitic lower Paleozoic and late

Proterozoic metasedimentary rocks and intercalated granitic rocks in the footwall (Plates 1 and 2). The seismic reflection traverse was complemented by a high-resolution seismic survey for shallowest structure and wide-angle recording for deep crustal and Moho structure.

The topics upon which the survey focused were: (1) the three-dimensional geometry of the fault zone, (2) the reflectivity of the mylonitic rocks, and (3) the character of the middle and lower crustal fabric including the Moho.

GEOLOGIC FRAMEWORK

The Ruby Mountains-East Humboldt Range (RM-EHR) is a north-northeast system of horsts in the late Cenozoic Basin and Range province of northeast Nevada (Figure 1). To a first approximation the pre-Quaternary rocks of the Ruby Mountains-East Humboldt Range are divisible into three structural terranes (deep to shallow): migmatitic core, mylonitic zone, and cover (Figure 1).

In the southern Ruby Mountains (south of Harrison Pass) Cambrian to Carboniferous low-grade to nonmetamorphosed, miogeoclinal sedimentary rocks form a generally eastward dipping sequence structurally overlain on the west flank by the west dipping Mitchell Creek klippe [Willden and Kistler, 1979; Howard et al., 1979] (Figure 1). The remainder of the northern Ruby Mountains and much of the East Humboldt Range is an extensive metamorphic complex pervasively intruded by igneous rocks. The transition between these contrasting structural levels is presently being investigated (M.R. Hudec, work in progress, 1988), but in a nutshell, it appears to be a steeply inclined Mesozoic metamorphic gradation intruded by an Oligocene granitic pluton (see Figure 1).

The intrusive plutonic rocks that ubiquitously invaded the metamorphic complex display a wide compositional range from quartz gabbro to granite. However, the most conspicuous intrusive rock is leucocratic, commonly coarse-grained to pegmatitic, consisting dominantly of alkali-feldspar, sodic plagioclase, and quartz; modal variations span the granite to trondhjemite fields. Muscovite and biotite are commonly present; whereas

Fig. 1. Generalized geologic map of the Ruby Mountains and East Humboldt Range, Nevada, [after Howard et al. 1979; Snoke and Miller, 1988; and Lush et al., 1988]. A.L. is Angel Lake. The area of Plate 1 is outlined.

garnet, sillimanite, zircon, and monazite occur as sporadic accessory minerals. The intrusive rocks vary from crosscutting dikes to concordant sheets complexly interlayered with adjacent metamorphic rocks.

The RM-EHR record a complex polyphase Mesozoic-Cenozoic deformational history. The earliest inferred Mesozoic event is premetamorphic thrust faulting. Howard [1966] recognized a duplication of late Precambrian to Ordovician miogeoclinal strata which he considered best explained by premetamorphic thrust faulting (Ogilvie thrust fault of Smith and Howard [1977]). Likewise, in the northern East Humboldt Range, Lush et al. [1988] have argued that Archean basement rocks were faulted into the miogeoclinal supracrustal sequence prior to metamorphism and associated polyphase plastic deformation.

The development of a pervasive foliation (S_1) coupled with transposition of original bedding in the metasedimentary rocks is the most obvious effect of the first phase of Mesozoic penetrative deformation. This S_1 foliation and associated compositional layering were subsequently folded by numerous F_2 folds ranging from huge nappes to microfolds [Howard, 1966; Snoke and Lush, 1984]. Various late to postmetamorphic folds are locally developed on these earlier structures.

Superposed on the Mesozoic polyphase deformation is a locally pervasive, mylonitic shear zone deformation (Figure 1). This deformation is interpreted as a low-angle brittle to plastic, normal-sense shear zone, as described by Wernicke [1981]. Physical conditions of mylonitization varied from upper greenschist to upper amphibolite facies [Snoke and Lush, 1984; Hurlow, 1988]. Apparently, as the shear zone evolved and ambient physical conditions changed (i.e., via uplift and tectonic denudation of cover rocks), the character of the extensional deformation changed from plastic to brittle, and low-angle normal faults were localized in the mylonitic shear zone [Snoke and Lush, 1984]. These low-angle faults further reworked and dismembered early macroscopic folds related to the Mesozoic compressional regime and juxtaposed upper crustal, unmetamorphosed

to low-grade metamorphic rocks and midcrustal rocks (Plate 2).

A domical aspect is characteristic of portions of the RM-EHR, especially along the western flanks of the range system. The domical geometry is especially complex near Secret Valley, a topographic and structural low that separates the northern end of the Ruby Mountains from the southwestern terminus of the East Humboldt Range. In this area, the site of our seismic reflection traverse, mylonitic foliation exposed in the southwestern East Humboldt Range dips to the south or southwest, whereas the mylonitic foliation in the northern Ruby Mountains dips eastward. This situation of opposing dip domains in the mylonitic zone is a geometry somewhat atypical of the RM-EHR complex. The mylonitic shear zone south of Soldier Creek Canyon dips consistently westward; in the East Humboldt Range the shear zone also dips westward until its termination near Wells, Nevada, at the north end of the range. The eastward dip of mylonitic foliation in the northern Ruby Mountains therefore appears to be a manifestation of footwall deformation during mid-Tertiary tectonic exhumation along an originally westward dipping plastic to brittle low-angle normal fault zone. The undulating nature of master detachment fault zones has been well documented in southeastern California and western Arizona [Howard and John, 1987] and the Death Valley region [Hamilton, 1988].

SEISMIC DATA ACQUISITION

Approximately 15 km of seismic data were acquired by the University of Wyoming across the exposed middle crustal terrane of the RM-EHR (Plate 1) as part of an ongoing seismic reflection study of Cordilleran metamorphic core complexes. The data include both high-resolution and wide-angle measurements. The vibroseis method was used as a source for the reflection survey. Table 1 summarizes the recording parameters employed for the Common Depth Point (CDP) profiling. Dense source and receiver spacings and multiple-input sweeps coupled with wide-angle recording were employed to obtain high-resolution data and deep crustal velocities in lieu of line

STRUCTURAL GEOLOGIC MAP OF THE NORTHERN RUBY MOUNTAINS— SOUTHWESTERN EAST HUMBOLDT RANGE, NEVADA

EXPLANATION

- Qs Surficial deposits, undivided (Quaternary)
- Tsv Sedimentary and volcanic rocks (Miocene)
- €Zqs Biotite-muscovite granite orthogneiss (Oligocene)
- €Zqs Limestone (Triassic to Pennsylvanian)
- €Zqs Diamond Peak Formation (Pennsylvanian and Mississippian)
- €Zqs Calcite and dolomite marble (Devonian to Ordovician)
- €Zqs Eureka metaquartzite (Ordovician)
- €Zqs Marble of Verdi Peak (Ordovician and Cambrian) and granite rocks
- €Zqs Horse Creek assemblage - calcite marble, calc-silicate paragneiss, metadolomite, calc-silicate metaquartzite (Ordovician and Cambrian); pegmatitic granite, mafic to felsic orthogneiss
- €Zqs Impure metaquartzite and schist (Cambrian and Late Proterozoic) and granite rocks

SYMBOLS

- Contact, dotted where covered
- Low-angle fault, chiefly brittle; dotted where covered
- Low-angle fault, plastic to brittle; dotted where covered
- High-angle fault, dotted where covered
- Anticline (left), Overturned anticline (center), Overturned syncline (right)
- General strike and dip direction of foliation in €Zqs

Plate 1. Structural geologic map of the northern Ruby Mountains and southwestern East Humboldt Range, Nevada. Cross section lines are labeled: AA', BB', CC'. Based on geologic field work of A.W. Snoke (unpublished data, 1988) and Howard (1966).

TABLE 1. Northern Ruby Mountains -- East Humboldt Range CDP Data Acquisition Parameters

Parameter	Description
<u>Recording</u>	
Instrument	MDS-10 recording system
Number of channels	96
Coverage	48-fold nominal
Recording time	23 and 28 s
Correlated record length	8 s
Sample rate	4 ms
<u>Source</u>	
Source type	Vibroseis
Number of vibrators	4
Number of sweeps	8 and 12
Sweep frequencies	10-57 Hz
	upsweep
Sweep length	23 and 28 s
Source interval	30.5 m
Configuration	off-end
<u>Receiver</u>	
Geophone type	10 Hz Geosource MD81
Receiver interval	30.5 m
Geophone array	12 phones spaced 2.8 m
Near-group distance	152.4 m
Far-group distance	3078.5 m

kilometers of coverage. The 8 to 12 sweeps used to build up each vibration point of "shot" gather were individually recorded, as opposed to using vertical summation in the field. This led to an improved signal-to-noise ratio because noisy traces that would otherwise have degraded the stack could be eliminated. The CDP data were complemented by wide-angle recording offsets of 4 to 40 km to obtain velocity information from the deep crust.

Because the seismic profiles were located to tie in with mapped geologic features of the core complex, the main survey was conducted downdip from the 1.5- to 2.0-km-thick exposed mylonite zone that separates the core of the RM-EHR metamorphic core complex from its cover sequences. From east to west the survey

first sampled the southward dipping mylonite zone exposed along the southwest flank of the East Humboldt Range, crossed downfaulted Secret Valley, and ended up in the east dipping mylonite zone exposed in the Secret Creek gorge area (Plate 1). The change in line direction from N75°W to N40°W near CDP 1030 resulted in some crossline control.

DATA PROCESSING

A conventional processing sequence was used for the reduction of the vibroseis CDP data with the exception of prestack velocity filtering (Table 2). Because a large part of the survey was conducted directly above the detachment system, most of the reflected wave field from the fault zone was received at travel times less than 0.5 s. This important information, obscured by first-arrival noise, would have been lost by muting functions prior to stacking the data. This problem was overcome by F-k filtering, which was designed to attenuate coherent noise based on its unique apparent velocity. Effective removal of multicyclic noise was achieved, and shallow reflections were clearly identifiable following velocity filtering (Figure 2). F-k filtering can produce artifacts, especially if strong

TABLE 2. Velocity Structure of the Crust

Discontinuity	Depth	Velocity	T-Corrected
	0.0		
		3.80	
	1.5	5.50	
A	3.0	6.10	6.20
B	12.5	6.35	6.4-6.5
C	19.5	6.6	6.7-6.8
X	28.0	7.2-7.5	7.4-7.8
M	31.0	7.8	7.9-8.1

Fig. 2. (a) Shot gather prior to F-k velocity filtering and (b) the same shot gather after application of the velocity filter. Note the abundant shallow reflections in the first second of data in the filtered shot gather.

discontinuities exist in the targeted noise field; however, comparison of filtered and unfiltered sections demonstrates that artifacts are minimal. In some cases, residual first arrivals and events that could not be partially recognized in the unfiltered data were treated as artifacts and eliminated by prestack muting. This approach led to enhanced imaging of the shallow mylonite zone.

DATA DESCRIPTION

The RM-EHR seismic profile is displayed at approximately 1:1 vertical-to-horizontal scale (Figure 3). The section is unmigrated, but an average velocity of 5.5 km/s can be used for the depth conversion for the first 2 s of data, and a velocity of 6.0 km/s is appropriate for greater travel times. A line drawing interpretation is presented in Figure 4. Recorrelation of the data with a shorter sweep [Okaya, 1986] provides information down to 12 s. The seismic profile displays an overall highly reflective signature at

all crustal levels defined by discrete bands of reflections at 0.5, 1.7, 2.7, 4.0, and 6.0 s. The near-surface crustal fabric is characterized by the pronounced bands of multicyclic reflections B and C (Figure 4). A high-resolution section (Figure 5), centered on CDP 1000 in Figure 3, images the mylonite zone at shallow depth and shows that reflections from the mylonite zone are laterally discontinuous. In the western part of the section (Figure 4), reflection C dips gently eastward beneath a more acoustically transparent region between the CDPs 1050 and 1300. On the eastern half of the section, reflection B appears as a set of oppositely dipping events which trend toward the eastward dipping reflection C between 0.4 s and 1.2 s near the line bend at CDP 1030.

Beneath these near-surface events a marked loss in coherent energy is observed across the entire profile between 1.0 and 1.6 s. This transparent zone is interrupted near 1.3 s on the western edge of the profile by a band of somewhat diffuse but continuous reflections, D1,

Fig. 3. CDP 48-fold seismic section from the northern Ruby Mountains-southwestern East Humboldt Range (Plate 1). M is mylonite zone reflection. N is reflection interpreted as coming from a Mesozoic fold nappe.

that dip southeastward and merge with a well-defined subhorizontal zone of reflections, D2, on the eastern edge of the profile between 2.5 and 2.8 s. This reflection geometry roughly outlines a wedge-shaped feature about 3 km in thickness thinning to the southeast. Below

this apparent wedge a package of prominent high-amplitude events, E, are observed between 4.0 and 4.5 s across most of the section. At 6 s a set of multicyclic events, F, appears and is also present in our unpublished data at two other localities 15 and 70 km to the south. On

Fig. 4. Line drawing of seismic section from Figure 3. Reflections discussed in text are labeled B through F.

the remainder of the section, short reflective segments define a layered seismic fabric.

On a section recorrelated to extend it to Moho depth [Okaya, 1986] (Figure 6) the multicyclic reflection fabric continues below 8 s. Near the expected crust-mantle transition at approximately 30 km a set of events at 9.6 and 10.5 s exhibit variable strength and continuity across most of the profile. This bimodal reflection geometry is similar to the findings on the Consortium for Continental Reflection Profiling (COCORP) Basin-Range transect [Klemperer et al., 1986] and correspond with events in our wide-angle data (Figure 7).

INTERPRETATION

Because the seismic profile is located downplunge from well-mapped geologic

structures, the seismic wave field can be correlated with specific geologic features. In the near surface the prominent dipping reflection zones B and C can be traced to surface outcrops that are part of the 1.5- to 2-km-thick mylonite zone that forms a distinct zone of intense plastic strain between unmetamorphosed to low-grade cover rocks and upper amphibolite facies rocks of the migmatitic core. The mylonite zone is characterized by modest compositional variation (i.e., interlayered impure quartzite, marble, and pelitic schist with granitic gneiss and pegmatitic leucogranite). Across the western edge of the profile the multicyclic reflections, C, correlate with the mylonite zone exposed in Secret Creek gorge. The reflections correlated with the mylonitic zone have a southeastern apparent dip of approximately 15° which is near the average dip of

Fig. 5. High-resolution seismic section showing shallow mylonite zone reflections. Centered on CDP 1000 in Figure 3. Note discontinuous character of mylonite reflections. Approximately 8:1 horizontal exaggeration.

mylonitic foliation in surface exposures [Snoke and Lush, 1984]. The B set of reflections appears to correlate with the south to southwest dipping mylonitic shear zone exposed in the southwestern East Humboldt Range, although the dip of these reflections is somewhat steeper than expected from foliation measurements in surface exposures (Plate 1, A.W. Snoke, unpublished data, 1988).

Younger normal faulting has offset the mylonite zone (Plate 2). The offset of the mylonite reflection C beneath CDP 1300 by approximately 0.3 s correlates with the surface trace of the Poison Canyon fault, the northern extension of an inferred range-bounding fault system. The mylonite zone continues to dip southeast beneath Secret Valley until it is further faulted down at the southeastern margin of Secret Valley by several normal faults of small displacement. Beyond this point its continuation becomes weaker.

Upper Plate

Most of the survey was conducted directly above or along the detachment system, thus the seismic section contains limited sampling of the upper plate. The low-frequency reflections (Figures 4 and 5) above the southwest dipping shear zone (i.e., reflection B) image the upper parts of the detachment system but have little lateral or vertical extent. Across Secret Valley, however, the survey provides a more detailed sampling of the features above the detachment surface. The subsurface extent of Secret Valley is recognized on the seismic section largely because of its striking reflection contrast with the surrounding higher-frequency mylonite reflections. The lateral limits of this anomalous reflection fabric correlate with mapped normal faults that offset Tertiary and upper Paleozoic sedimentary rocks. Down-dip displacement on the west bounding,

Fig. 6. A representative shot gather recorded during CDP acquisition in the northern RM-EHR and recorrelated to 12 s in order to extend the data to the Moho. The record, collected within Secret Valley, shows the distribution and character of the midcrustal and lower crustal events B, C, M, and X, which correspond to the same boundaries recognized on the wide-angle data.

east dipping Poison Canyon fault is interpreted as about 1.0 km, on the basis of the correlation of the valley-flooring reflections C with the surface exposures of the mylonitic footwall west of CDP 1395. The magnitude of the offset of reflection zone C across the east bounding fault is much less, probably less than 0.2 km.

The internal reflection character from rocks that underlie the thin Quaternary fill of the valley consists primarily of events which dip westerly between 10° and 50°. Surface measurements reveal that

nearby Tertiary sedimentary rocks dip only moderately, commonly less than 30°, therefore some of these events probably represent reflections from steeply inclined upper Paleozoic sedimentary rocks which are extensively exposed in hills north and south of the west side of Secret Valley (see Plate 1). Alternatively, these events may be reflections generated between blocks of contrasting rock type that were faulted and rotated during extension along the underlying detachment fault. The orientation of these reflections was

Fig. 7. Examples of "wide-angle" shot gathers used to determine crustal velocity in core complex. (a) is offset of 20 km and (b) is offset of 26 km. Events A through M used to determine interval velocities in Table 2. M is Moho.

probably also affected by the postdetachment normal faulting which offset parts of the plastic to brittle, low-angle normal-fault system.

Lower Plate

In the northern Ruby Mountains and southwestern East Humboldt Range the transition into the migmatitic core terrane is a gradational contact from strongly foliated mylonitic rocks near the base of the 1.5- to 2-km-thick mylonite zone to more massive, but compositionally similar, lithologies within the migmatitic core [Howard, 1980; Snoke and Lush, 1984]. On the seismic profile the transition to the migmatitic core is recognized by a loss in coherent energy below the mylonite reflections B and C. The homogeneous reflection fabric is attributed to loss of the pervasive layered and planar mylonitic fabric and to a more massive character, manifested by complex intrusive contacts within much folded metasedimentary rocks. This transparent zone in the lower plate is interrupted near depths of 5 km (1.5-2.0 s)

by the wedgelike pattern outlined by reflection bands D1 and D2. Geologic and structural mapping of the migmatitic core reveals important large-scale recumbent folds. The juxtaposition of metacarbonate rocks against migmatitic quartzofeldspathic gneisses in these folds is a possible source for the observed reflections. Alternatively, the wedgelike pattern could be a manifestation of a massive rock unit partitioned by an anastomosing shear zone.

Deep Crust

The present-day middle crust is dominated at 4 and 6 s by subhorizontal events E and F (Figure 4) which are prominent across the RM-EHR traverse and which are also present in the COCORP Nevada Line 4 profile, 70 km to the south. Between these reflections a higher concentration of discontinuous events is recognized compared to shallower levels, and similar reflections are also particularly common below 7.0 s. The primary reflections, E and F, could

Fig. 8. Geotherms calculated for the Basin and Range Province [from Lachenbruch and Sass, 1978] and superposed petrogenetic grid. Garnet stability in mafic rocks from Newton and Hansen [1983]. Hornblende stability from Binns [1969]. A, B, C, X, and M represent approximate depths of reflectors from which interval velocities were calculated. And, andalusite; Ky, kyanite; Sil, sillimanite; Ho, hornblende; Q, quartz; Opx, orthopyroxene; Pl, plagioclase; Di, diopside; Ab, albite; Jd, jadeite.

represent fundamental midcrustal boundaries because each marks an increase in velocity on the basis of wide-angle data [Valasek et al., 1987]. Recorrelated data also show evidence for a pair of multicyclic lower-crustal reflections similar in character and separation to the X and M reflections identified on COCORP data [Klemperer et al., 1986]. This reflection character is interpreted as indicating strong heterogeneity in this region of the crust. Because of the pervasive overprint of crustal extension, both during core complex development and Basin-Range faulting, this deep crustal fabric may have an extensional origin.

Recording at offsets of 18 to 40 km [Valasek et al., 1987, Figure 1] to determine interval velocities provides an opportunity to better constrain the character of the deep crust and can consequently be used to develop a detailed crustal model (Table 2 and Figure 7).

Events at 5 through 11 s have adequate move-out to determine crustal velocities to within ± 0.13 km/s [Valasek et al., 1987], and the temperature-corrected velocity structure is plotted next to the line drawing (Figure 4). The long-wavelength velocity structure of the crust has been determined; however, the abundant multicyclic reflections through each interval also indicate the importance of small-scale layering (tens to hundreds of meters) within each interval. To allow for three dimensionality, several crossing wide-angle profiles were incorporated into a seismic model that matches the travel time and move-out of the various reflections, although the model does not attempt to match the detailed layering implied by the multicyclic character within the bands. This velocity model was tested against reflections on four other shot gathers and proved consistent for different offsets [Valasek et al., 1987].

The strong layering demonstrated by many seismic reflection sections suggests that much of the crust is strongly anisotropic; and the amount and type of anisotropy depend on the modal mineral content and overall fabric of the rock units. This anisotropy must be considered when interpreting velocities. Because of the strong multicyclic reflections (Figures 3 and 7), interval velocities (Table 2 and Figure 4) must be averages for interlayered zones of high and low velocities. On the basis of laboratory velocity determinations [Christensen, 1982], velocities of 6.1–6.2 km/s correspond to quartzo-feldspathic rocks; this agrees with observations of interlayered quartzites, schists, marbles, and layered to lenticular granitoid rocks in the upper crust. Velocities of 6.4 to 6.5 km/s correspond to quartzo-feldspathic rocks (deformed granitic and metasedimentary rocks) combined with about one-third mafic material, possibly intrusive. The next zone from a depth of 20 to 28 km has model velocities of 6.7 to 6.8 km/s. This should have a granulite-facies assemblage [Sandiford and Powell, 1986, Figure 8], and may therefore be more felsic than gabbro, possibly about one-third granitic material. If underplating by gabbroic magma is an important process for crustal development, this zone could have been a primary locus for underplating accompanied by partial melting of more felsic rocks to produce granitic magmas that invaded the upper crust. The lowermost 3 km in the crust (the zone between the "X" reflection and the Moho) has a relatively high velocity of 7.4 to 7.8 km/s that lies between normal velocities for lower crust and upper mantle. This zone may consist of mafic residuum or deformed layered cumulates from the overlying gabbroic layer and thus could also be the result of underplating.

DISCUSSION

Mylonitic Fault Zone Reflectivity

Seismic reflection profiling across exhumed, originally deep crustal terranes is one approach for determining the causes of lower crustal reflectivity. Previous studies of this nature have successfully

demonstrated mylonite reflectivity [Hurich et al., 1985; Ratcliffe et al., 1986; Cook et al., 1988] and confirmed some of the theoretical and laboratory conclusions regarding source of the reflectivity [Fountain et al., 1984, 1987; Jones and Nur, 1984]. These studies indicate that the controlling factors are a combination of the degree of compositional heterogeneity, the relatively planar nature of the layering, and finally anisotropy, which was recently verified by Christensen and Szymanski [1988].

In the above studies, differences in velocities and densities of rocks within the imaged, highly layered fault zones yielded reflection coefficients (~ 0.1) that approach the maximum for crystalline rocks. In the RM-EHR core complex, laboratory measurements are predominantly from quartzo-feldspathic rocks sampled from the exposed shear zone updip from the seismic profile. These samples collected from the mylonite zone show low V_p near 6.2 km/s, low seismic anisotropy of about 6%, and small reflection coefficients of 0.03 [McDonough et al., 1985; Fountain et al., 1987]; yet reflections from the mylonite zone are clearly observed, although weaker than deeper reflections (Figures 3 and 5). To explain this contradiction, we suggest that (1) marble fold lenticules (i.e., "tectonic fish") similar to those widely exposed in the northern Ruby Mountains (Plates 1 and 2) are present in the subsurface beneath the seismic line, providing important compositional heterogeneity, and/or (2) biotite and biotite-sillimanite schists common in the mylonite zone are underrepresented in the laboratory studies because of difficulty in obtaining fresh, oriented samples.

We therefore propose that a combination of planar geometry, layering, composition (marble versus quartzo-feldspathic rocks), and possibly anisotropy cause the mylonite reflections. That layering increases reflection amplitudes in sequences characterized by low-reflection coefficients has been demonstrated [Fuchs, 1969; Smithson et al., 1977; Hurich and Smithson, 1987], and this principle has been advanced to model mylonitic fault zone reflectivity [Wong et al., 1982; Fountain et al., 1984; Jones and Nur, 1984]. Hurich

and Smithson [1987] showed that amplitudes recovered from laminated zones can be up to 3 times those generated from a single interface. Furthermore, modeling of relationships common to plastic fault zones reveals that the effects of focusing, tuning, and interference of reflections and diffractions gives rise to a complex wave field similar to that observed in the RM-EHR profile [Hurich and Smithson, 1987]. In the RM-EHR core complex this layering is observed at scales appropriate for increased signal amplitude through resonance. Furthermore, even 6% anisotropy will contribute to reflectivity. Thus anisotropy possibly could be a more significant factor than the laboratory-measured reflection coefficients indicate if, for example, sillimanite-bearing pelitic schist, a difficult rock type to collect from the mylonite zone, had been represented in the laboratory sample suite [e.g., McDonough et al., 1985]. Finally, much more marble may be present in the subsurface than apparent from the surface exposures; it is a common component of fold lenticles in the northern Ruby Mountains mylonitic zone. In contrast to more contorted gneissic terranes, principal features of mylonite fault zones are their extensive planar geometry and laminated internal character; these characteristics are independently favorable for generating relatively continuous reflections.

Extensional Fault Zone Geometry

The prominent reflections correlated with the exposed RM-EHR mylonite zone as well as deeper reflections provide an unusual opportunity to evaluate the geometric aspects of crustal extension during core complex exhumation. The most striking aspect of these reflections is their opposing dips, as demonstrated by comparing shallow reflections east and west of CDP 1020.

The mylonitic shear zone is well exposed along the west flank of the RM-EHR for approximately 100 km from south of the Oligocene Harrison Pass pluton [M.R. Hudec, personal communication, 1988] to the northern end of the East Humboldt Range (Figure 1). Surface geologic mapping indicates that most of the shear zone dips

to the west; and seismic reflection data, as reported by Effimoff and Pinezich [1981], reveal that the shear zone continues to dip westward in the subsurface. Sense of shear criteria indicate top to the west-northwest [Snoke and Lush, 1984; Lister and Snoke, 1984]. In the northern Ruby Mountains, eastward dips of the mylonitic foliation are common (Plate 1), and consequently, the direction of the sense of shear is commonly up the plunge of the stretching lineation for this part of the extensional shear zone. These geometric observations suggest that the extensional shear zone has been warped after its formation during top to the west-northwest plastic to brittle extension. Interestingly, the new seismic reflection data (Figures 3 and 4) indicate that the eastward dip of the reflectors continues beneath the westward dipping segment, suggesting a younger age for the eastward dipping zone. How these conflicting geometries, indicated by the seismic reflection data, can be reconciled with surface geologic mapping and sense of shear criteria is uncertain. Two aspects of the inferred history of the shear zone may be an explanation for opposing dips of the reflectors: (1) the footwall of the plastic to brittle low-angle fault zone has been deformed during tectonic exhumation, and (2) the shear zone is composed of anastomosing zones that truncated each other during noncoaxial deformation (e.g., see Bell and Hammond [1984, Figure 4] for a small-scale example of this phenomenon). Given the inherent complexities of shear zones, these geometric complications may plausibly happen synchronously during shear zone development. During rapid exhumation along an extensional, low-angle normal fault, Davis and Lister [1988] have suggested that a shear zone may be warped and abandoned as more favorably oriented splays develop. The consequence of such a structural history would be a braided shear zone consisting of locally opposing dipping segments that are, nevertheless, the product of a single plastic deformational history. The opposing dips of the reflectors recorded on the seismic profile may therefore simply be the product of progressive inhomogeneous simple shear coupled with synchronous deformation of the footwall.

Crustal Signature

The dominant feature in the crust in the RM-EHR core complex is strong subhorizontal layering observed in the reflection wave field. Numerous discontinuous events alternate with the more continuous, high-amplitude bands of reflections D, E, and F near travel times of 2, 4, and 6 s, respectively. This laminated signature demonstrates that the crust is heterogeneous and subhorizontally layered, which seems to be a diagnostic feature of these highly extended complexes [Hurich et al., 1985]. On a global basis it has been suggested that extensional tectonics commonly yield a consistent reflection character described as a transparent upper crust overlying a high density of lower crustal reflections. Locally, in the Basin-Range province, COCORP seismic data indicate this type of reflection character along their 40°N transect which was approximately 70 km south of the RM-EHR profile [Allmendinger et al., 1987]. However, in the RM-EHR complex the entire crust appears reflective, and lower crustal reflections are the strongest. Similar findings have been reported in three other metamorphic core complexes: the Kettle Dome of NE Washington [Hurich et al., 1985], the Picacho Mountains of SE Arizona [Reif and Robinson, 1981; Goodwin and Thompson, 1988], and the Albion Mountains of Idaho (S.B. Smithson, unpublished data, 1988). The variation in reflection response between our data in the northern Ruby Mountains-southwest East Humboldt Range and both COCORP data and our data in the southern Ruby Mountains is probably a result of recording problems in the southern Ruby Mountains caused by loose, low-velocity surface material. In any case the generalization of transparent upper crust-reflective lower crust for extensional terrains does not appear to apply to highly extended Cordilleran metamorphic core complexes. However, we emphasize that middle crustal rocks are exposed at the Earth's surface in the RM-EHR core complex as well as in some other core complexes [Anderson et al., 1988] because of extreme extension; and consequently, a direct comparison with less extended terrains may be misleading.

Deep Reflections

The interpretation of the deep crustal structure of the RM-EHR is based on surface geology, isotopic data, character of the deep reflectors, correlation of velocity data with possible rock types, and a comparison with other areas. Structural analysis and geochronological data indicate that late Eocene to Oligocene granitic rocks were strongly deformed during mid-Tertiary crustal extension [Wright and Snoke, 1986]. These granitoids have isotopic patterns characteristic of crustal anatexis, and they may have been generated during the emplacement of high-temperature mafic magmas into the lower crust. The abundance of flat, very prominent lower-crustal reflectors is unusual on a global scale and is most common in areas that have undergone crustal extension [Hurich et al., 1985]. This characteristic is in direct contrast to the weaker, more complex reflection wave fields associated with terranes that have undergone compression as a final tectonic event [Smithson and Johnson, 1989].

We propose that during mid-Tertiary extension the lower crust behaved plastically and was extended by a combination of coaxial and noncoaxial deformation mechanisms. The deep crust as a whole has deformed by coaxial stretching, while on a local scale noncoaxial deformation was concentrated along anastomosing mylonite zones superposed on a heterogeneous rock suite. The starting materials included structurally and compositionally complex Archean crust [Lush et al., 1988] supplemented by additions of mantle-derived mafic magma. Crustal extension by a combination of coaxial and noncoaxial deformation causes rotation of complex structures toward horizontal, an enhancement of layering, and an attenuation of rock bodies. The mafic-ultramafic intrusive component inferred to be present was most likely sheared and recrystallized during intrusion and probably is characterized by deformation textures similar to those reported by Moore [1973] for the deep-seated Giles complex, Musgrave Ranges, central Australia. The seismic reflection data from the RM-EHR therefore provide a unique view of the deep crustal

fabric of a Tertiary extended orogen and its attended igneous and metamorphic overprint. The strong subhorizontal layering characteristic of the deep crustal part of the seismic profile is thus interpreted to be an expression of extensional metamorphism.

Strong midcrustal reflections present on a regional scale are interpreted as mylonites that may represent extensive midcrustal decoupling zones. These zones could have been formed during either Mesozoic compression or Cenozoic extension.

Geothermal profiles from Lachenbruch and Sass [1978] superposed on a petrogenetic grid (Figure 8) are a useful aid in the interpretation of velocity structure and petrologic history. The characteristic Basin and Range geothermal profiles are used for estimates of present temperatures. However, for the magmatic peak during the late Eocene-Oligocene, the higher temperatures shown by the Battle Mountain High profiles are employed as a upper temperature limit; they encompass the temperature ranges calculated by Lachenbruch and Sass [1978, pp. 233, 234 and 241] for combinations of extended, intruded and underplated Basin and Range lithospheric models.

The petrogenetic grid (Figure 8) indicates that, for the highest geotherm, hornblende would be unstable at about 20 km depth and garnet would appear in mafic rocks at about 23 km, but the appearance of garnet depends rather critically on the actual slopes of the geotherm and garnet field boundary (Smithson, 1989). Granodiorite would begin to melt at about 16 km and be completely molten at about 25 km. These depths do not correlate exactly with present crustal depths because of the dynamic interaction of crustal extension, intrusion, and uplift, but they do provide some useful first approximations. Velocity anisotropy can range from 5 to 15% [Birch, 1960; Christensen, 1982]; the amount of anisotropy expected will be controlled by minerals present of which micas and amphiboles will show the greatest effects [Alexandrov and Rhyzova, 1961; Christensen, 1982]. The disappearance of hornblende at lower crustal depths suggests that mafic rocks would be recrystallized chiefly to pyroxene granulites with relatively small

anisotropy (3-6%), and this granulite facies metamorphism would be attained during extension. Furthermore, the possible occurrence of garnet in pyroxene granulite (Figure 8) indicates that the inferred seismic velocity could be higher by several tenths of a kilometer/second for a given mafic composition. Such a change in seismic velocity, for example, from $V_p = 6.9-7.1$ km/s to $7.0-7.4$ km/s, would cause some overestimation of the amount of mafic rocks in the lower crust.

To better infer rock types the velocity profile (Figure 4 and Table 2) has been temperature corrected in light of the geotherm and petrogenetic grid (Figure 8). From surface exposures and velocity the 6.2-km/s zone is predominantly quartzofeldspathic rocks interlayered with scattered deformed mafic rocks (biotite-hornblende quartz dioritic orthogneisses and amphibolites in Archean gneiss) which contribute to reflectivity. The 6.5-km/s zone is about one third mafic rocks that could range from amphibolite to pyroxene granulite interlayered with quartzofeldspathic rocks. The interlayering of extreme compositions rather than more uniform dioritic rocks is inferred from the abundant multicyclic reflections (Figures 3 and 7). Given a velocity of 7.0 km/s for normal gabbroic rocks at lower crustal depths and higher for garnet-pyroxene granulite, the 6.8 km/s zone in the lower crust consists of about one-third granitic rocks and two thirds mafic rocks and is also consistent with the high reflectivity of the lower crust caused by interlayering of these compositions. The 3-km-thick, high-velocity (7.4-7.8 km/s) zone at the base of the crust indicates a composition intermediate between mafic and ultramafic such as pyroxene-rich and possibly garnet-rich rocks. This zone, which contains numerous discontinuous layers, could consist of a residuum from partial melting or a cumulate zone from crustal underplating.

The amount of mafic material in the crust is a critical parameter because numerous models for Basin and Range development rely on mafic intrusion and/or underplating [Lachenbruch and Sass, 1978; Klemperer et al., 1986; Thompson and McCarthy, 1986; Gans, 1987]. The above

estimates indicate that at most 50% of the present crust consists of mafic material. If a thick crust was developed by the stacking of crustal flakes during Mesozoic continental A-type subduction [Mattauer et al., 1983; Lush et al., 1988], it might have had a thickness of 50–60 km. The proportion of felsic to mafic rocks would have been determined by the character of the preexisting Archean and Proterozoic crust plus mafic magmas derived from the mantle during Mesozoic crustal shortening and metamorphism. Although the uncertainties are considerable, mafic material probably accounted for 25 to 50% of the imbricated crust during the late Mesozoic, prior to the initiation of mid-Tertiary crustal extension. Homogeneous extension would result in essentially the same amount of mafic material in the crust after it was thinned to 31 km. This leaves little room for mafic intrusion or crustal underplating. If we allow for variability in geologic assumptions and use the minimum value of 25% original mafic material, we postulate that a plausible maximum of about 25% of the Basin and Range crust might have been added through intrusion and/or underplating, that is, 6–8 km (Valasek et al., 1987; Smithson, 1989).

Deformed late Eocene–Oligocene granitic rocks in the present upper crust have a crustal isotopic signature [Kistler et al., 1981; Wright and Snoke, 1986; Snoke and Miller, 1988]. These were generated in the deep crust and separated from a solid residuum as the temperature rose due to intrusion and lithospheric thinning, therefore some of the layered material in the 6.8-km/s zone is probably a restite (i.e., similar to the stronalites of the Ivrea zone) and some is injected mafic material (now garnet-pyroxene granulite). As modest amounts of mafic material were added to the deep crust, granites separated out and moved upward to form much of the 6.2-km/s zone. Granitic and gabbroic intrusions together with country rocks were drawn out into subhorizontal layers and metamorphosed up to granulite facies during the strong Cenozoic extension.

The amplitude of Moho reflections [Klemperer et al., 1986] (Figure 9) is very strong in the Basin and Range. The multicyclic character of Moho reflections

MOHO AMPLITUDE ANALYSIS

Fig. 9. True amplitude plot of trace 34 from the 26.3-km wide-angle gather. Based on summing 10 adjacent traces and correcting for spherical divergence with the crustal velocity function, the large-amplitude Moho event at 11.0 s is 13 dB above the basement reflection A at 5.4 s.

(Figure 7) demonstrates that the Moho is a layered zone, and the duration of these events (0.3–0.4 s) indicates that the zone is 1.2 to 1.5 km thick. Variability in reflections indicates a laterally discontinuous layering or large-scale lensing (possibly boudinage) marking the Moho zone. The amplitude of the reflection indicates a large velocity contrast such as the interlayering of peridotite with more felsic material. Thus gneissic rocks ranging from granite to diorite in composition might be required to generate such large amplitude reflections; however, the petrogenetic grid (Figure 8) shows that rocks as felsic as granite would be at least partially melted at today's probable range of PT conditions. This suggests that the high-amplitude Moho reflection is either caused by intermediate rocks (compositionally dioritic) interlayered with peridotite and/or possibly the presence of some melt in the lower-velocity layers. This melt could be from granites melted in place or basaltic magma that had ponded at the Moho as discontinuous sills (Smithson, 1989).

If the lowermost event is correlated to the Moho, the lack of any offset in depth from the regional findings [Klemperer et al., 1986; McCarthy and Thompson, 1988] suggests that the Moho has reequilibrated from a Mesozoic crustal thickness estimated

at over 50 km [Coney and Harms, 1984; Gans, 1987] to a province-wide 30 to 35-km-depth during the Tertiary.

Gibson and Levander [1988] used a seismic model of discontinuous diffractors, similar to that of Hurich and Smithson [1987], to point out that point diffractors at wide angles could give a seismic response that could be confused with layering and consequently lead to an erroneous velocity analysis. In this study, vertical incidence data show the presence of continuous layers (or more particularly zones because individual cycles of reflections often lack continuity in many different areas), and the "wide-angle" data [Valasek et al., 1987] is in the precritical range where confusion of layers with diffractors is unlikely. In any case we suggest that individual layers are not continuous over great distances (about 10 km or more) but "come and go" within zones as a result of intrusion and deformation.

CONCLUSIONS

The highly reflective profile obtained from the RM-EHR metamorphic core complex is interpreted as delineating dominantly Tertiary extensional features. With the exception of a possible relict Mesozoic fold in the upper crust or the inferred decoupling zones of uncertain age in the midcrust, much of the preexisting crustal fabric was thoroughly transposed during the protracted history of Tertiary extension. Downplunge correlation of the plastic to brittle shear zone that developed during the exhumation of the core complex provides a direct link between present crustal reflectivity and extensional deformation in the upper crust. The mylonitic zone is reflective despite lacking strong measured velocity contrasts. The recovery of significant reflections from a mylonite zone under these conditions confirms conclusions [Smithson et al., 1979; Wong et al., 1982; Fountain et al., 1984; Christensen and Szymanski, 1988] regarding the importance of the special properties of plastic fault zones in forming relatively continuous reflectors.

Overall, the mylonite zone demonstrates a complex structure in the subsurface

data. Both east and southwest dipping domains of mylonitic foliation appear to continue in the subsurface as separate zones. These opposing dipping mylonitic zones may be the product of a single progressive inhomogeneous simple shear deformation that involved warping of the shear zone and truncation of earlier segments.

Prominent deep crustal reflections recognized in the profile mark significant compositional boundaries as defined by wide-angle measurements within the core complex. This crustal fabric is interpreted as being of extensional origin and probably partially represents deformed mafic igneous intrusions (Precambrian to Cenozoic) and complex Precambrian basement because of the high-velocity structure as well as the close temporal and spatial association of Tertiary magmatism with extension [Gans, 1987]. Tectonic layering must also play an important role in explaining this reflection wave field. The successful imaging of the shallower mylonite zone(s) seems to indicate that their favorable layering and lateral continuity would enable these zones to be detected at any level in the crust, even in the absence of strong acoustic contrasts. In general, though, this principle can be applied to any planar layered structure in the crust.

The reflection Moho was not found to be disturbed beneath the core complex but seems to conform to the rather constant depth found throughout the northern Basin and Range [Klemperer et al., 1986]. The similarity of the Moho in character and depth to adjacent less-extended regions also supports conclusions of Klemperer et al. [1986] that the crust in the Basin-Range province has recently reequilibrated. This restructuring has occurred at least since the period of 40 to 20 Ma when the core complex was exhumed via low-angle normal faulting [Snoke and Lush, 1984; Dallmeyer et al., 1986; Dokka et al., 1986]. The strong plastic flow associated with the protracted history of this extension is responsible for producing the highly reflective signature observed throughout the entire crust of the core complex.

The crustal cross section (Figure 10)

Fig. 10. Interpretative crustal cross section for the northern Ruby Mountains-East Humboldt Range, eastern Great Basin. Upper plate cover rocks overlie a detachment fault system and a mylonitic shear zone. Recumbent fold nappes of the migmatitic core (infrastructure) are underlain by granitic intrusions and a midcrustal decoupling zone (mylonitic shear zone). This zone passes downward into highly deformed Precambrian crystalline rocks intruded by gabbroic bodies that have been sheared and rotated toward horizontality during middle to lower crustal extensional deformation, resulting in a granulite facies metamorphism. Large-scale pure shear is accommodated by simple shear concentrated along midcrustal and lower crustal shear zones. The layered Moho is accentuated by shear accompanying extension and/or intrusion. Magma may be ponded at the Moho. Although this diagrammatic model is not drawn to scale, it would represent the essential elements of a crustal cross section approximately 30 km thick, as envisioned for the RM-EHR core complex.

consists of relatively unmetamorphosed rocks of the upper plate overlying a gently westward dipping mylonite zone, which contains large-scale splays of reverse dip. Mesozoic nappes consisting of deformed granitoids, metasedimentary rocks, and Archean gneissic basement are preserved structurally below the mylonite zone. Strong widespread multicyclic reflections in the midcrust are attributed to mylonitic zones that accommodated foreland thrust belt shortening in the hinterland and/or represent zones of localized plastic extensional Tertiary strain. The lower

crust is postulated to consist of a preexisting mixture of felsic and mafic rocks intruded by an undetermined but limited amount of Cenozoic mafic magma that triggered deep-seated anatexis and granitic magmatism. Some of this Cenozoic granitic magma migrated upward and forms part of the present-day migmatitic upper crust. In this case some of the interlayered mafic rocks causing reflections are probably garnet-pyroxene restites with velocities higher than gabbro. Any gabbroic intrusions causing lower crustal anatexis must have been emplaced just before or

during the late Eocene-Oligocene extension that deformed the granitic rocks. The lower crust attained granulite facies conditions during this plastic extension. As a result, the lower crust is depicted as a mixture of various preexisting rocks and deformed gabbroic (granulite facies) intrusions (Figure 10), all of which have been thinned and rotated toward the horizontal by overall coaxial deformation with localized noncoaxial deformation zones. Lowermost crust, the ~ 7.6-km/s zone between the "X" and Moho reflections, is interpreted as either a mafic residuum or cumulate because of the velocity (intermediate between gabbroic and peridotitic rocks), the layering, and the extensive magmatic history in the Basin and Range. The high-amplitude Moho reflection may be an indication of magma mixed with peridotite because gabbroic rocks intermixed would not give adequate acoustic impedance contrast to yield the reflection characteristics. This magma could be ponded basalt intruded from the mantle or partially molten more silicic rocks.

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REFERENCES

- Alexandrov, K.S., and T.V. Rhyzhova, Elastic properties of rock forming minerals 2, Layered silicates, Bull. Acad. Sci. USSR, Geophys. Ser., 9, 1165-1168, 1961.
- Allmendinger, R.W., T.A. Hauge, E.C. Hauser, C.J. Potter, S.L. Klemperer, K.D. Nelson, P. Knuepfer, and J. Oliver, Overview of the COCORP 40° N Transect, western United States: The fabric of an orogenic belt, Geol. Soc. Am. Bull., 98, 308-319, 1987.
- Anderson, J.L., A.P. Barth, and E.D. Young, Mid-crustal Cretaceous roots of Cordilleran metamorphic core complexes, Geology, 16, 366-369, 1988.
- Bell, T.H., and R.L. Hammond, On the internal geometry of mylonite zones, J. Geol., 92, 667-686, 1984.
- Binns, R.A., Hydrothermal investigations of the amphibole-granulite facies boundary, Spec. Publ. 2, Geol. Soc. Aust., 341-344, 1969.
- Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 1, J. Geophys. Res., 65, 1083-1102, 1960.
- Christensen, N.I., Seismic velocities, in Handbook of Physical Properties of Rocks, vol. 2, edited by R.S. Carmichael, pp. 2-228, CRC Press, Boca Raton, Fla., 1982.
- Christensen, N.I., and D.L. Szymanski, Origin of Reflections from the Brevard fault zone, J. Geophys. Res., 93, 1087-1102, 1988.
- Coney, P.J., and T.A. Harms, Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression, Geology, 12, 550-555, 1984.
- Cook, F.A., A.G. Green, P.S. Simony, R.A. Price, R.R. Parrish, B. Milkereit, P.L. Gordy, R.B. Brown, K.C. Coffin, and C. Patenoude, Lithoprobe seismic reflection structure of the southeastern Canadian Cordillera: Initial results, Tectonics, 7, 157-180, 1988.
- Dallmeyer, R.D., A.W. Snoke, and E.H. McKee, The Mesozoic-Cenozoic tectonothermal evolution of the Ruby Mountains, East Humboldt Range, Nevada: A Cordilleran metamorphic core complex, Tectonics, 5, 931-945, 1986.
- Davis, G.A., and G.S. Lister, Detachment faulting in continental extension: perspectives from the southwestern U.S. Cordillera, John Rodgers Symposium Volume, Spec. Pap., Geol. Soc. Am., 281, 133-159, 1988.
- Davis, G.H., Structural characteristics of metamorphic core complexes, southern Arizona, in Cordilleran Metamorphic Core

- Complexes, edited by M.D. Crittenden, Jr., P.J. Coney, and G.H. Davis, Mem. Geol. Soc. Am., 153, 35-77, 1980.
- Dokka, R.K., M.J. Mahaffie, and A.W. Snoke, Thermochronologic evidence of major tectonic denudation associated with detachment faulting, northern Ruby Mountains-East Humboldt Range, Nevada, Tectonics, 5, 995-1006, 1986.
- Effimoff, I., and A.R. Pinezich, Tertiary structural development of selected valleys based on seismic data: Basin and Range Province, northeastern Nevada, Philos. Trans. R. Soc. London, Ser. A, 300, (1454), 435-442, 1981.
- Fountain, D.M., C.A. Hurich, and S.B. Smithson, Seismic reflectivity of mylonite zones in the crust, Geology, 12, 195-198, 1984.
- Fountain, D.M., D.T. McDonough, and J.M. Gorham, Seismic reflection models of the continental crust based on metamorphic terrains, Geophys. J. R. Astron. Soc., 89, 61-67, 1987.
- Frost, E.G., D.A. Okaya, T.V. McEvilly, E.C. Hauser, G.S. Galvan, J. McCarthy, G.S. Fuis, C.M. Conway, R.G. Blom, and T.L. Heidrick, Crustal Transect: Colorado Plateau-detachment terrane-Salton trough, in Geologic Diversity of Arizona and its Margins: Excursions to Choice Areas, Spec. Pap. 5, edited by G.H. Davis and E.M. VandenDolder, pp. 398-422, Arizona Bureau of Geology and Mineral Technology, Tucson, Az., 1987.
- Fuchs, K., On the properties of deep crustal reflectors, J. Geophys., 35, 133-149, 1969.
- Gans, P.B., An open-system, two-layer crustal stretching model from the eastern Great Basin, Tectonics, 6, 1-12, 1987.
- Gans, P.B., E.L. Miller, J. McCarthy, and M.L. Ouldcott, Tertiary extensional faulting and evolving ductile-brittle transition zones in the northern Snake Range and vicinity: New insights from seismic data, Geology, 13, 189-193, 1985.
- Gibson, B.S., and A.R. Levander, Lower crustal reflectivity patterns in wide-angle seismic recordings, Geophys. Res. Lett., 15, 617-620, 1988.
- Goodwin, E.B., and G.A. Thompson, The seismically reflective crust beneath highly extended terrains: Evidence for its origin in extension, Geol. Soc. Am. Bull., 100, 1616-1626, 1988.
- Hamilton, W.B., Death Valley tectonics -- Hingeline between active and inactivated parts of a rising and flattening master normal fault, Guideb., South Coast Geological Society, Santa Ana, Calif., in press, 1988.
- Hauser, E., C. Potter, T. Hauge, S. Burgess, S. Burtch, J. Mutschler, R. Allmendinger, L. Brown, S. Kaufman, and J. Oliver, Crustal structure of eastern Nevada from COCORP deep seismic reflection data, Geol. Soc. Am. Bull., 99, 833-844, 1987.
- Howard, K.A., Structure of the metamorphic rocks of the northern Ruby Mountains, Nevada, Ph. D. thesis, 170 pp., Yale Univ., New Haven, Conn., 1966.
- Howard, K.A., Metamorphic infrastructure in the northern Ruby Mountains, Nevada, in Cordilleran Metamorphic Core Complexes, edited by M. D. Crittenden, Jr., P. J. Coney, and G. H. Davis, Mem. Geol. Soc. Am., 153, 335-347, 1980.
- Howard, K.A., and B.E. John, Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona, in Continental Extensional Tectonics, edited by M.P. Coward, J.F. Dewey, and P.L. Hancock, Spec. Publ. Geol. Soc. of London, 28, 299-311, 1987.
- Howard, K.A., R.W. Kistler, A.W. Snoke, and R. Willden, Geologic map of the Ruby Mountains, Nevada, scale 1:125,000, U.S. Geol. Surv. Misc. Geol. Inv. Map I-1136, 1979.
- Hurich, C.A., and S.B. Smithson, Compositional variation and origin of deep crustal reflections, Earth Planet. Sci. Lett., 85, 416-426, 1987.
- Hurich, C.A., S.B. Smithson, D.M. Fountain, and M.C. Humphreys, Seismic evidence of mylonite reflectivity and deep structure in the Kettle dome metamorphic core complex, Washington, Geology, 13, 577-580, 1985.
- Hurlow, H.A., P-T conditions of mylonitization in a Tertiary extensional shear zone, Ruby Mountains-East Humboldt Range, Nevada, Geol. Soc. Am. Abstr. Programs, 20, 170, 1988.
- Jones, T.D. and A. Nur, The nature of seismic reflections from deep crustal

- fault zones, J. Geophys. Res., **89**, 3153-3171, 1984.
- Kistler, R.W., E.D. Ghent, and J.R. O'Neil, Petrogenesis of garnet two-mica granites in the Ruby Mountains, Nevada, J. Geophys. Res., **86**, 10,591-10,606, 1981.
- Klemperer, S.L., T.A. Hauge, E.C. Hauser, J.E. Oliver, and C.J. Potter, The Moho in the northern Basin and Range province, Nevada, along the COCORP 40°N seismic-reflection transect, Geol. Soc. Am. Bull., **97**, 603-618, 1986.
- Lachenbruch, A.H., and J.H. Sass, Models of an extending lithosphere and heat flow in the Basin and Range province, in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R.B. Smith and G.P. Eaton, Mem. Geol. Soc. Am., **152**, 209-250, 1978.
- Lister, G.S., and A.W. Snoke, S-C mylonites, J. Struct. Geol., **6**, 617-638, 1984.
- Lush, A.P., A.J. McGrew, A. W. Snoke, and J.E. Wright, Allochthonous Archean basement in the northern East Humboldt Range, Nevada, Geology, **16**, 349-353, 1988.
- Mattauer, M., B. Collot, and J. Van der Driessche, Alpine model for the internal metamorphic zones of the North American Cordillera, Geology, **11**, 11-15, 1983.
- McCarthy, J., Reflection profiles from the Snake Range metamorphic core complex: A window into the mid-crust, in Reflection Seismology: The Continental Crust, Geodyn. Ser., vol. 14, edited by M. Barazangi and L. Brown, pp. 281-292, AGU, Washington, D.C., 1986.
- McCarthy, J., and G.A. Thompson, Seismic imaging of extended crust with emphasis on the western United States, Geol. Soc. Am. Bull., **100**, 1451-1465, 1988.
- McDonough, D.T., D.M. Fountain, and C.A. Hurich, Seismic properties of rocks from metamorphic core complexes: Implications for crustal reflections, Eos Trans. AGU, **66**, 1088, 1985.
- Moore, A.C., Studies of igneous and tectonic textures and layering in the rocks of the Gosse Pile Intrusion, Central Australia, J. Petrol., **14** (I), 49-79, 1973.
- Newton, R.C., and E.C. Hansen, The origin of Proterozoic and late Archean charnockites; evidence from field relations and experimental petrology, Mem. Geol. Soc. Am., **161**, 167-179, 1983.
- Okaya, D.A., Seismic profiling of the lower crust: Dixie Valley, Nevada, in Reflection Seismology: The Continental Crust, Geodyn. Ser., vol. 14, edited by M. Barazangi and L. Brown, pp. 269-281, AGU, Washington, D.C., 1986.
- Ratcliffe, N.M., W.C. Burton, R.M. D'Angelo, and J.K. Costain, Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark basin margin in eastern Pennsylvania, Geology, **14**, 766-770, 1986.
- Reif, D.M., and J.P. Robinson, Geophysical, geochemical, and petrographic data and regional correlation from the Arizona state A-1 well, Pinal County, Arizona, Ariz. Geol. Soc. Dig., **13**, 99-109, 1981.
- Sandiford, M., and R. Powell, Deep crustal metamorphism during continental extension: Modern and ancient examples, Earth Planet. Sci. Lett., **79**, 151-159, 1986.
- Smith, J.F., Jr., and K.A. Howard, Geologic map of the Lee 15-minute quadrangle, Elko County, Nevada, scale 1:62,500, U. S. Geol. Surv., Map GQ-1393, 1977.
- Smithson, S.B., Contrasting lower crust, in Lower Crust: Properties and Processes, AGU, IUGG U7 Symposium Volume, edited by R.F. Mereu, et al., in press, 1989.
- Smithson, S.B., and R.A. Johnson, Crustal structure of the western U.S. based on reflection seismology, in Geophysical Framework of the U.S., edited by W. Mooney and L. Pakiser, Mem. Geol. Soc. Am., **172**, in press, 1989.
- Smithson, S.B., P.N. Shive, and S.K. Brown, Seismic velocity, reflections, and structure of the crystalline crust, in The Earth's Crust, Its Nature and Physical Properties, Geophys. Monogr. Ser., vol. 20, edited by J.G. Heacock, pp. 254-270, AGU, Washington D.C., 1977.
- Smithson, S.B., J.A. Brewer, S. Kaufman, J.E. Oliver, and C.A. Hurich, Structure of the Laramide Wind River uplift, Wyoming from COCORP deep reflection data and from gravity data, J. Geophys. Res., **84**, 5955-5972, 1979.
- Smithson, S.B., R.A. Johnson, and C.A. Hurich, Crustal reflections and crustal structure, in Reflection Seismology: The

- Continental Crust, Geodyn. Ser., vol. 14, edited by M. Barazangi and L. Brown, pp. 21-33, AGU, Washington, D.C., 1986.
- Snoke, A.W., and A.P. Lush, Polyphase Mesozoic-Cenozoic deformational history of the northern Ruby Mountains-East Humboldt Range, Nevada, in Western Geological Excursions, vol. 4, edited by Joseph Lintz, Jr., pp. 232-260, Geological Society of America Annual Meeting, MacKay School of Mines, Reno, Nev., 1984.
- Snoke, A.W., and D.M. Miller, Metamorphic and tectonic history of the northeastern Great Basin, in Metamorphic and crustal evolution of the Western United States, edited by W.G. Ernst, pp. 606-648, Prentice-Hall, Englewood Cliffs, N.J., 1988.
- Thompson, G., and J. McCarthy, Geophysical evidence for igneous inflation of the crust in highly extended terraines (abstract) Eos Trans. AGU, 67, 1184, 1986.
- Valasek, P.A., R.B. Hawman, R.A. Johnson, and S.B. Smithson, Nature of the lower crust and Moho in eastern Nevada from "wide-angle" reflection measurements, Geophys. Res. Lett., 14, 1111-1114, 1987.
- Wernicke, B., Low-angle normal faults in the Basin and Range province -- Nappe tectonics in an extending orogen, Nature, 291, 645-648, 1981.
- Willden, R., and R.W. Kistler, Precambrian and Paleozoic stratigraphy in central Ruby Mountains, Elko County, Nevada, in Basin and Range Symposium and Great Basin Field Conference, edited by G.W. Newman and H.D. Goode, pp. 221-243, Colorado, Rocky Mountain Association of Geologists and Utah Geological Association, Denver, Colo., 1979.
- Wong, Y.K., S.B. Smithson, and R.L. Zawislak, The role of seismic modeling in deep crustal reflection interpretation. Part I, Contr. to Geol., 20, 91-109, 1982.
- Wright, J. E., and A. W. Snoke, Mid-Tertiary mylonitization in the Ruby Mountain-East Humboldt Range metamorphic core complex, Nevada, Geol. Soc. Am. Abstr. Programs, 18, 795, 1986.
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