Paper 3:

Coincident Seismic Reflection/Refraction Studies of the Continental Lithosphere: A Global Review

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Abstract

Nearly 50 coincident seismic reflection/refraction studies to depths of at least the Moho provide an improved understanding of the continental lithosphere. Some conclusions include the following: (1) A transparent upper crust, a common observation on vertical reflection profiles, cannot generally be correlated with velocity gradients or low-velocity zones. Rather, a commonly transparent upper crust may be explained by short-wavelength, steeply dipping features in the brittle upper crust and to a lesser degree by signal contamination from source-generated noise. (2) The reflective lower crust in extensional terranes appears to be characterized by a high average seismic velocity (6.6-7.3 km/s) and to consist of laminated high- and low-velocity layers with typical thicknesses of 100-200 m. (3) Landward dipping reflectors observed in the middle to lower crusts of convergent zones have been identified as paired high- and low-velocity slabs which represent oceanic crust and mantle accreted via underplating to the continental margin. (4) The crust-mantle boundary may differ sufficiently when imaged with vertical incidence and wide-angle data to justify the retention, for the present, of the concept of separate reflection and refraction Mohos. While there is good evidence that these features are coincident within measurement uncertainties in most regions, recently recorded data from the Basin and Range admit the possibility for non-coincidence in that area. (5) Upper mantle reflections which cannot be migrated into the lower crust remain rare, despite isolated unequivocal examples. Thus the upper mantle appears to be relatively homogeneous at seismic reflection wavelengths and to lack the laminations inferred for the lower crust. The wide-angle method will likely provide the most reliable information on the velocity structure and physical state of this portion of the lithosphere for some years to come. (6) There appear to be clear and consistent basic differences between convergent and extensional terranes which have been identified from coincident experiments; these differences may be sufficiently universal to infer the tectonic history of poorly exposed terranes. (7) No truly three-dimensional coincident experiment (i.e.,

including three-dimensional migration) has been conducted, but some three-dimensional data have been collected using both methods. Measurements of attenuation, Poisson's ratio, and anisotropy within the crust using coincident data sets remain frontiers.

Introduction

Vertical incidence reflection profiling has identified a number of characteristic features of the continental lithosphere. Features which are characteristic (but certainly not universal) include a commonly transparent upper crust, inferred low-angle faulting in the middle to lower crust, a reflective lower crust, a discontinuous set of reflections from the crust-mantle boundary, and a generally transparent upper mantle. The ability of the reflection profiling method to provide high-resolution images of the geometry of these crustal reflectors has been critical to inferences concerning the evolution of the continental crust but has been unable to define what physical properties produce these reflections. This review summarizes the additional information which has been brought to bear on the physical properties of these characteristic crustal structures through the use of coincident wide-angle refraction profiling. More specifically, it is our intent to demonstrate the unique ability to coincident seismic reflection/refraction experiments to not only image lithospheric structure but also to provide information necessary to infer the composition and physical state of the continental crust.

A number of recent review articles concerning deep continental reflection profiling in West Germany [Meissner et al., 1983], Canada [Green and Clowes, 1983], the United States [Phinney and Odom, 1983], and the world [Brewer and Oliver, 1980] (see articles in the work edited by Barazangi and Brown [1986]) have summarized state-of-the-art techniques and results. Similarly, a recent global compilation of crustal refraction studies has been prepared by Prodehl [1984], and Soviet deep seismic sounding (DSS) studies have been summarized by Davydova [1975]. Although the advantages of combined reflection/refraction studies have been pointed out in comparisons of the two methods [Berry and Mair, 1980; Meissner et al., 1983; Braile and Chiang, 1986], no previous compilation of coincident field studies have been published.

Owing to the extreme heterogeneity of the earth's crust, we have, with a few exceptions, generally restricted our review to only those studies where truly coincident (not just proximal) deep penetration reflection and refraction profiles were obtained on continental lithosphere. These criteria also excluded a number of shallow crustal experiments as well as a number of high-quality coincident experiments conducted on oceanic lithosphere [e.g., NATStudy Group, 1985; Watts et al., 1985; Detrick et al., 1986]. While all known experiments which met these restrictive conditions were included, there are probably unknown seismic experiments which fulfill our criteria and which have been unknowingly omitted. In particular, the authors have restricted their literature search to the English language, and it was not possible for them to read untranslated Soviet literature on DSS profiling. DSS studies of the crust in the USSR and eastern Europe and elsewhere have been carried out for many years, mostly through wide-angle reflection and refraction. Pre-critical reflections from the lower crust during DSS profiling are often obscured by low-velocity arrivals out to 40 km, but Davydova [1975] reviewed six special experiments where these pre-critical arrivals were observed

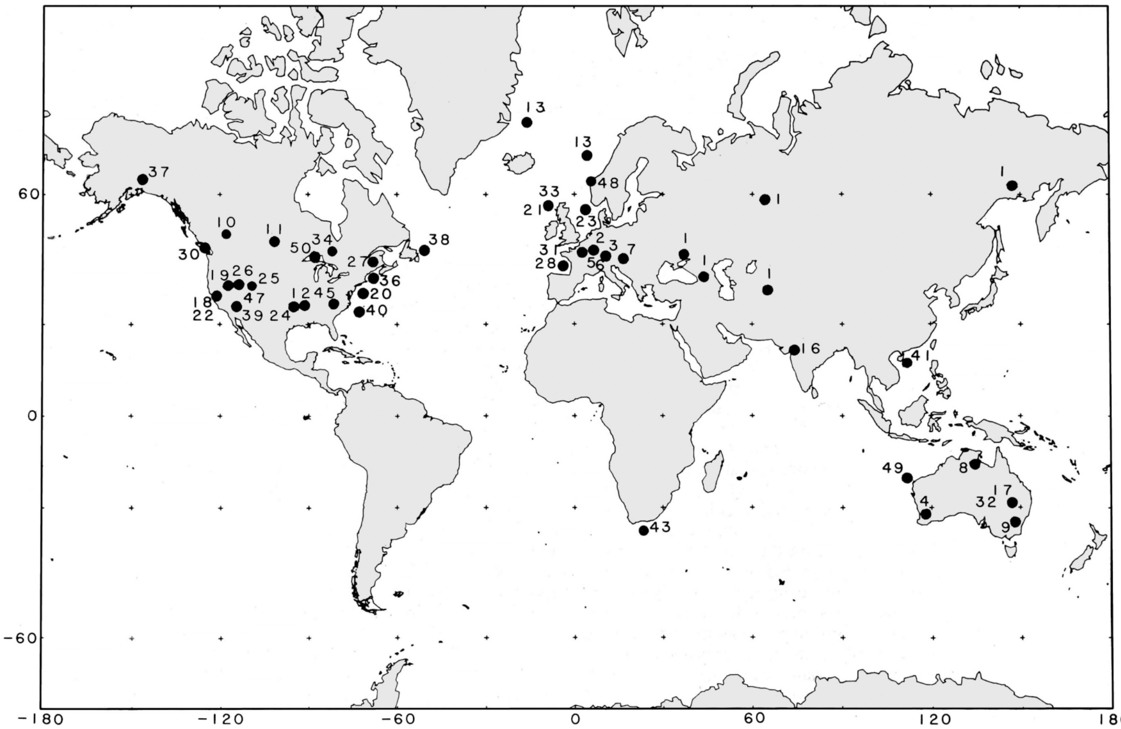


Fig. 1. World map showing locations of coincident seismic reflection/refraction experiments (large solid dots) performed as of the end of 1986. Numbers refer to experiments listed in Table 1. Note that in order to simplify the presentation of the map, not every experiment in western Europe and the western United States given in Table 1 has been identified on the map. Crosses indicate latitude and longitude in 30° intervals.

as well as the wide-angle events.

Figure 1 shows the location of 46 coincident seismic reflection/refraction experiments of the middle to lower continental crust. The narrow geographical distribution of these experiments to within the northern hemisphere, and the concentration on extensional regimes, with a few exceptions, is striking. A summary of the acquisition parameters used during these experiments is provided in Table 1, where the experiments are ordered chronologically. Additional information concerning the data acquisition during the experiments can be obtained from the reference in the far right-hand column on Table 1. Many of these experiments have only recently been completed, and results are currently unavailable.

Note that in Table 1 each study region is classified as occurring in either a convergent or extensional terrane. While this binary classification scheme is undoubtedly unduly simplified, it reflects the commonly held view that these two processes are the most fundamental tectonic processes affecting the continental lithosphere. Each experiment is classified according to the style of the most recent tectonism to occur in the study region. In some cases the assignment to extensional terranes, which includes extended continental margins, continental rifts, and continental rift basins, is not wholly satisfactory. In such cases this assignment is made primarily on the basis of the lack of convincing evidence for convergence. Similarly, classifying some regions as convergent

TABLE 1. Field Acquisition Parameters for Coincident Reflection/Refraction Experiments

Experiment	Year Conducted	Geographic Location	Tectonic Framework	CDP Aperture, km	CDP Fold	CDP Source Type	Receiver Aperture, km	Receiver Interval, km	Shot Point Interval, km	Source Type	References
1	1964–1966	various studies in the USSR	convergent and rift	40	1–2	explosive	40–120	0.1	30–60	explosive	*Davydova et al.* [1975]
2	1968	Rhinegraben, West Germany	rift		1	explosive	180	0.3	20	explosive	*Glocke and Meissner* [1976], *Meissner et al.* [1976]
3	1968	Ries Crater, West Germany	rift	1.38	3	explosive	38	0.3	38	explosive	*Angenheister and Pohl* [1976], *Meissner et al.* [1976]
4	1969	SW Australia	rift			explosive	>300	>10	200	explosive	*Mathur* [1974]
5	1973	Hunsruck, West Germany	rift	2.4	3–4	explosive	120	5		explosive	*Meissner et al.* [1980]
6	1975	Rhine Graben, West Germany	rift	3.2	4–6	explosive	120	5		explosive	*Meissner et al.* [1980]
7	1975	Hungary	convergent	2.4–3.0	12–24	explosive	100	0.1–0.25	40	explosive	*Posgay et al.* [1986], *Sollogub et al.* [1973]
8	1976–1978	McArthur Basin, Australia	rift			explosive				explosive	*Mathur* [1983], *Finlayson and Mathur* [1984]
9	1976–1978	Lachlan Fold Belt, Australia	rift			explosive				explosive	*Mathur* [1983], *Finlayson and Mathur* [1984]
10	1976–1985	cordillera, Alberta, Canada	convergent	12	30	Vibroseis					*Green and Clowes* [1983]
11	1977–1981	Manitoba-Saskatchewan, Canada	rift	9.6	4	explosive	300	7.7	>200	explosive	*Hajnal* [1986], *Green et al.* [1980]
12	1978	Mississippi Embayment	rift	2.9	24–48	Vibroseis	200	2	60–100	explosive	*Crone et al.* [1985], *Mooney et al.* [1983]
13	1978–1984	Norway-Greenland	rift	3.6	24	airgun	50–60	0.05?	0.15	airgun	*Mutter et al.* [1982 1985], *Zehnder et al.* [1985]
14	1978	Aachen, West Germany	convergent	23	8	explosive	90	0.08	1.3	explosive	*Meissner et al.* [1983]
15	1978	Urach, West Germany	rift	23	8	explosive	90	0.08	1.3	explosive	*Bartelsen et al.* [1982], *Gajewski and Prodehl* [1985], *Walther et al.* [1986]
16	1980(?)	Narmada-San, India	rift	11.6	6	explosive	200	0.2	20–40	explosive	*Kaila* [1986]
17	1980–1982	Eromanga Basin, Australia	rift (?)	2	6	explosive	300	12.5	37.5	explosive	*Mathur* [1983], *Finlayson et al.* [1984]
18	1980–1982	Central California	convergent	3.6	24	Vibroseis	90	0.6	30	explosive	*Wentworth et al.* [1984], *Walter* [1985]
19	1980–1982	Western Mojave Basin, California	rift	9.6	48	Vibroseis	100	2–3	100	explosive	*Fuis et al.* [1986], *Cheadle et al.* [1986]
20	1981	New Jersey	rift	13	142	airgun	65	0.05	0.3–3	airgun, explosive	*LASE Study Group* [1986]
21	1981	Western Scotland	rift	3	30	airgun	70	0.1	1.3	explosive	*Hughes et al.* [1984], *Jones et al.* [1984]
22	1981–1982	Central California	transpressional	3.6	24	Vibroseis	100	1.0	25	explosive	*Wentworth et al.* [1984], *Trehu and Wheeler* [1987]
23	1981–1984	North Sea	rift	3	30	airgun	530	7	18–80	explosive	*Barton et al.* [1984], *Barton and Wood* [1984]
24	1981–1986	Oklahoma	convergent	9.6	24	Vibroseis	175	0.0625	10–20	explosive	*Lillie et al.* [1983], *Nelson et al.* [1982], *McMechan and Keller* [1985]
25	1982	Utah	rift	9.6	48	Vibroseis	31.6	0.1	2	Vibroseis	*Liu et al.* [1986]
26	1982–1986	Central Nevada	rift	10	48	Vibroseis	240	1	45	explosive	*Hauge et al.* [1987], *Catchings et al.* [1986]
27	1983–1984	Quebec, Canada–Maine	convergent	12	133	Vibroseis	100	0.8	20	explosive	*Stewart et al.* [1986], *Luetgert et al.* [1987]
28	1983	Aquitaine Shelf, Western France	rift	7.5		airgun	130	0.025		airgun	*Patriat et al.* [1986], *Pinet et al.* [1986]
29	1984	Variscides, West Germany	convergent	16	25	explosive	>90	0.08	0.32?	explosive	*Bortfeld et al.* [1985]
30	1984	Vancouver Island, Western Canada	convergent	11	30	Vibroseis	400	25	4	explosive	*Clowes et al.* [1987], *Ellis et al.* [1983]
31	1984	NW France	convergent	7.6	96	Vibroseis	105	0.08	15	explosive	*Bois et al.* [1986], *Hirn et al.* [1987]
32	1984	Eromanga-Surat Basin, Australia	rift	2	6	explosive	192	2.5?	48	explosive	*Wake-Dyster et al.* [1987], *Finlayson and Collins* [1987]
33	1984	outer Hebrides	rift			airgun				airgun	*Powell and Sinha* [1987]
34	1984	Ontario, Canada	shield	9.6	24	airgun	300	3–6	150	explosive	*Cook* [1985], *Northey and West* [1985]
35	1984–1985	Rhinegraben, West Germany	rift	8	80–100	Vibroseis	190	2.1	20–30	explosive	*Fuchs et al.* [1987], *Gajewski and Prodehl* [1987]
36	1984–1985	Maine	rift	3.3	30	airgun	110	20	0.15	airgun	*Hutchinson et al.* [1986]
37	1984–1986	Alaska	convergent	15	128	Vibroseis	120	1	10–30	explosive	*Fuis et al.* [1986], *Page et al.* [1986]
38	1984–1986	Newfoundland, eastern Canada	rift	3	30	airgun	100–150	10–20	0.20	airgun	I. Reid (personal communication, 1986)
39	1985	California-Arizona	rift	2.5	32	Vibroseis	120	0.5	10–21	explosive	*Henyey et al.* [1985], *McCarthy et al.* [1986, 1987]
40	1985	Carolina Trough,	rift	3.8	36	airgun	160	25–70	1	explosive	*Grow et al.* [1980], *Trehu et al.* [1986], *NAT Study Group* [1985]
41	1985	China	rift	2.4	24	airgun	65?	0.05	0.15–3	airgun, explosive	J. Diebold (personal communication, 1986)
42	1985	Hatton Bank, United Kingdom	rift			airgun				airgun	*White et al.* [1987]
43	1985	Agulhas Bank, South Africa	rift			airgun				explosive	*Durrheim* [1987]
44	1985?	northern Switzerland								explosive	*Sierro et al.* [1987]
45	1985–1986	Appalachians	convergent	8.0		Vibroseis	80–90	0.066		Vibroseis	*Phinney and Roy-Chowdhury* [1985], *Diebold* [1987]
46	1985–1987	southern Nevada	rift	10–15	48–125	Vibroseis	120	1	20–30	explosive	this paper
47	1985–1986	Arizona	rift	10	48	Vibroseis	120	0.5	10–20	explosive	*Fuis et al.* [1986], *Hauser et al.* [1986]
48	1985–1986	Norway	rift?			airgun				airgun	*Hurich et al.* [1987]
49	1986	Australia	rift	2.4	24	airgun	60–70	0.05	2.4	explosive, airgun	J. C. Mutter (personal communication, 1986)
50	1986	Great Lakes, North America	rift	3	24–30	airgun	300	5–40	0.05–0.3	airgun	*Behrendt et al.* [1986]
51	1987	Tanzania/Zaire	rift	1	48	airgun	120	0.01	1	explosive	this paper

when they actually are obliquely convergent (for example, Alaska and northern California) may also be somewhat unsatisfactory. Finally, we recognize that in some cases the relative effects of spatially overlapping compressional and extensional events is not accounted for by this classification.

With the advent of large cooperative national projects in Australia, Canada, France, Great Britain, the United States, and West Germany, and the increasing usage of marine multi-channel techniques, the number of coincident experiments has increased exponentially since 1964 (Figure 2). By assuming, perhaps optimistically, the current growth rate, the number of coincident experiments will be doubled by 1990. In part this rapid growth rate is being accomplished by the reoccupation of existing reflection or refraction lines by the other type of coverage, thus minimizing new expenses and more importantly, investigating identified problems. Several more experiments are planned for the next 2 years; in Table 1 we have listed those experiments having a known source of funding and that will be completed in 1987.

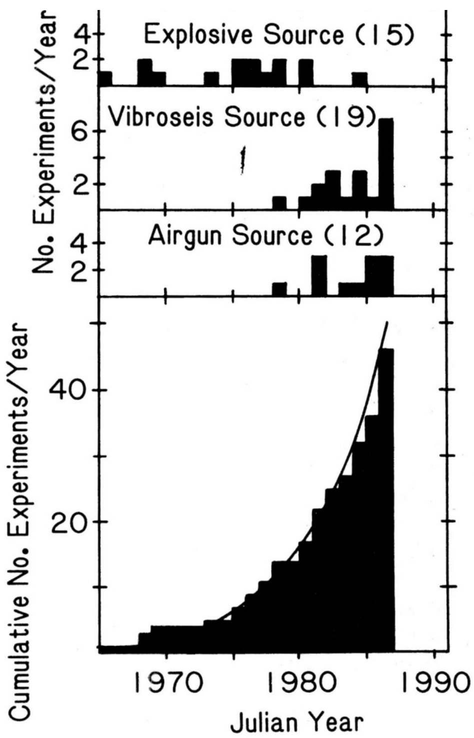


Fig. 2. (Top) Comparison of the number of seismic reflection experiments having coincident seismic refraction data performed since 1965 using explosives, Vibroseis, and airgun sources. (Bottom) Cumulative number of coincident reflection/refraction experiments initiated since 1965. The thin solid line shows the fit to the cumulative curve of exp [0.1823(1-1965)] where *t* is the Julian year.

After a brief review of typical field parameters used in these experiments, we address seven different current problems in the seismic imaging of the crust: these problems are (1) the commonly transparent upper crust, (2) the reflective lower crust in extensional terranes, (3) landward dipping reflections in the middle to lower crust of convergent terranes, (4) crustal faults of variable dips, (5) the crust-mantle boundary, (6) the upper mantle, and (7) magmatic conduits and reservoirs in continental lithosphere. Following this review, we summarize differences between convergent and extensional terranes. Our goal is to describe what coincident reflection/refraction profiles have determined to date about these problems and to indicate what future work seems to us to be the most likely to provide answers in the future.

Data acquisition methods in coincident parameters

Reflection Profiling

In the 1980s the general trend in onshore reflection profiling has been to increase the aperture of the common depth point (CDP) gathers, whereas offshore reflection profiling has been restricted to CDP apertures less than 4 km, apart from the Large-Aperture Seismic Experiment (LASE)

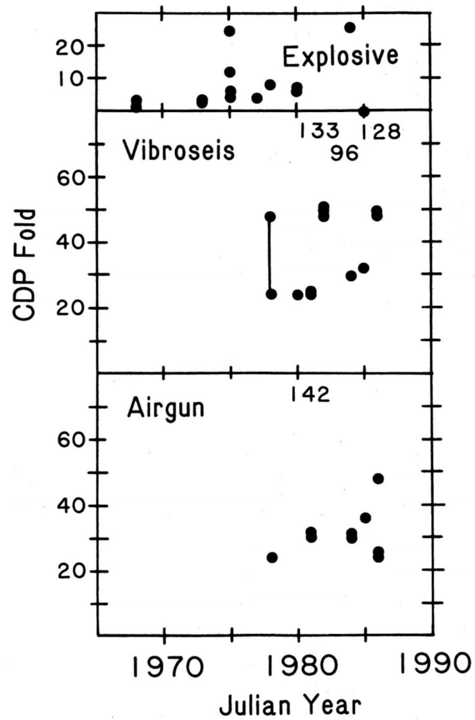


Fig. 3. Comparison of the CDP fold achieved in coincident reflection /refraction experiments since 1965 for explosive, Vibroseis, and airgun sources. Note that higher folds were achieved using 800-channel and larger signbit recording systems.

conducted off- shore New Jersey [LASE Study Group, 1986] and the Etude de la Croute Continentale et Oceanique par Réflexion et Refraction Sismique (ECORS) marine profiling [Pinet et al., 1986]. The LASE exemplifies the flexibility available in marine studies of continental structure. Three ships, two towing multi-channel streamers, were used to artificially magnify the length of the CDP gathers in order to provide high resolution of the stacking velocities [Buhl et al., 1982].

CDP folds are typically 25-48, both onshore and offshore (Figure 3), with a corresponding large receiver interval of the order of 100 m, which spatially aliases steeply dipping arrivals and noise. Larger CDP folds, between 96 and 250, have been achieved in SE Alaska, California, and Maine, using 800-channel and larger sign bit recording systems, which minimizes spatial aliasing by decreasing the receiver group interval to about 30 m while maintaining a 12- to 15-km aperture. Virtually all early onshore reflection profiling in the USSR, West Germany, Canada, and Australia utilized explosive sources in boreholes and low-fold (3-8) CDP coverage, while workers in the United States have generally used large (4-5 truck) *Vibroseis* arrays and higher-fold (24) coverage. In Australia, standard industry parameters are generally used, including an explosive source of 8-40 kg every 333 m, group intervals of 83.3 m in a split spread (+- 1.92 km), for six-fold coverage to 20 s [Mathur, 1983; Johnstone et al., 1985; Wake-Dyster et al., 1985].

Advances in source array technology have dramatically altered the typical field experiment in recent years. Recent offshore reflection profiling has utilized increasingly large volume (98.3 L (6000 cubic inches)) airgun arrays having source energy levels comparable to small explosive sources (Table 2). By assuming ideal coupling, the sum of 10 sweeps from a large *Vibroseis*

Type Source	Source Size	Energy, foot-pounds	Energy, J
Airgun array*	2000 cubic inches (32.8 L)	2.2×10^6	3.0×10^6
	4000 cubic inches (65.5 L)	4.4×10^6	6.0×10^6
	6000 cubic inches (98.3 L)	6.6×10^6	8.9×10^6
Vibroseis	5 trucks each	9.1×10^6/ sweep†	1.2×10^7/ sweep
	27,500 peak force		
60% dynamite‡	1.36 kg	4.3×10^6	5.8×10^6
	36.2 kg	1.1×10^8	1.5×10^8

* From *Dobrin* [1976, p. 130].
† Calculated assuming a 10.2-cm displacement at 10 Hz for 20 s.
‡ Assuming ideal coupling, i.e., for marine shots [from *Dobrin*, 1976, p. 130].

Table 1. Comparison of source energetics.

array provides energy levels comparable to the 20- to 30-kg shots used in explosive reflection profiling (Table 2); thus the more flexible *Vibroseis* sources now predominate on land (Figure 2). Offshore deep seismic profiling, however, owing to its relatively low cost per mile and its more uniform source coupling, is rapidly overtaking onshore reflection profiling both in the number of experiments performed and in the mileage obtained each year. A growing number of experiments, such as the Great Lakes experiment and the Vancouver Island experiment, are using both onshore and offshore recording of the signals from large airgun source arrays.

Perhaps one of the more significant innovations in field acquisition methods is near-real-time field processing to monitor data quality. Real-time plots of all common shot gathers were used to monitor data quality for the 1024-channel sign bit data collected during early 1986 in SE Alaska. Field brute stacks were available about 1 week after data acquisition: the principal delay in obtaining the brute stacks was introduced by the completion of the geodetic survey of the CDP line's coordinates. Field processing capability proved invaluable to the successful acquisition of high-quality reflection records in the eastern Mojave Basin, California, by the Consortium of California Universities named CALCRUST (T. V. McEvilly and D. A. Okaya, personal communication, 1986). This capability during noise testing leads to the recognition and suppression of a strong *Vibroseis*-earth resonance which significantly degraded the record from the lower crust.

While perhaps not a recent innovation, the design of seismic reflection experiments based on the results from coincident high-quality seismic refraction data sets is becoming increasingly important. These refraction data help define more complex two-dimensional velocity models than is permissible from any other geophysical methods. From these detailed models, detailed synthetic seismic reflection profiles can be constructed. Although this refraction model need not always shed light on a reflection survey to be collected, for the SE Alaskan seismic reflection fieldwork, such forward modeling provided surprisingly accurate stacking velocities used to generate brute stacks in the field. These refraction studies can provide useful constraints on depth to important targets such as the Moho, the laminated lower crust, and other crustal features. This is not to say that the collection of high-quality wide-angle reflection data ensures that a study area is likely to yield high-quality vertical reflection data, or visa versa. Indeed, experience shows that "success" or "failure" with one method is a poor indicator of what the other method will yield. Differences in acquisition methodology and frequency bandwidth appear to be the main reasons for these differences.

Refraction Profiling

Apart from a few marine expanding spread profiles (ESP) and ocean bottom seismometer (OBS) experiments, large explosive sources are used almost exclusively for wide-angle profiling (Table 1). Recent ESP studies in Utah [Liu et al., 1986] and at the deep drill site in South Carolina have used *Vibroseis* sources [Diebold, 1987], and the possibility of using *Vibroseis* for wide-angle refraction profiling has been investigated in the USSR [Yushin, 1982]. Large-volume airgun arrays (6000 cubic inches) have been used on continental margins for both ESP and OBS experiments [LASE Study Group, 1986; Trehu et al., 1986; Behrendt et al., 1986].

Although receiver and shot point intervals remained nearly constant at 5 km and

100 km, respectively, from the 1960s through the 1970s, the typical receiver and shot point intervals both have now been reduced to below 1 km and 10-20 km, respectively (Figure 4), resulting in finer horizontal sampling of the crust and great resolution of lithospheric heterogeneity. The typical onshore wide-angle profile now approaches the level of spatial resolution obtained in DSS profiling over 20 years ago (Table 1). ESPs are increasingly being used both onshore and offshore to acquire laterally restricted estimates of crustal properties along CDP lines and to offer receiver intervals as low as 50 m.

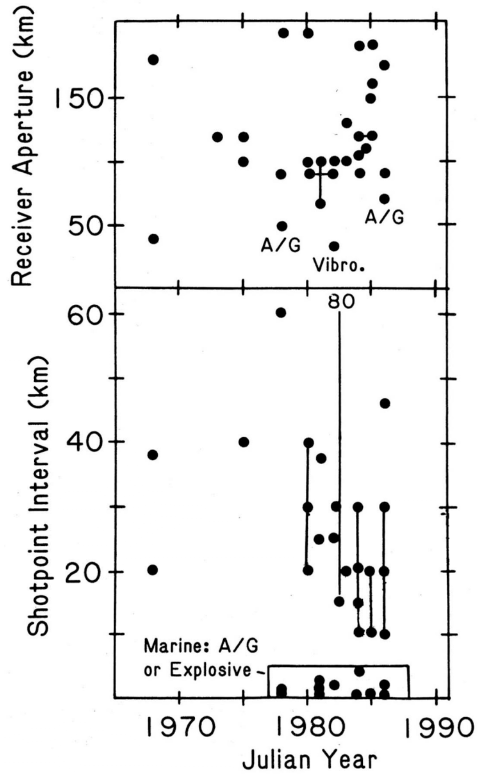


Fig. 4. Comparison of the receiver aperture and shot point (SP) intervals used in the refraction portion of coincident seismic reflection/refraction profiling since 1965. Note the extremely small SP intervals utilized by marine studies.

Three-Dimensional Experiments

Although detailed three-dimensional work is increasingly attempted in industry reflection and academic refraction profiling, relatively few of the coincident experiments reviewed here have included significant efforts to explore the third dimension of the lower crust. While individual cross lines do provide some three-dimensional control, no truly three-dimensional vertical incidence reflection experiments, which permit the three-dimensional migration of reflection amplitudes from the lower crust have yet been attempted, largely because of the large expense involved. Fan shooting during wide-angle refraction profiling has been performed in Canada, France, West Germany, and several locations in the United States, including Alaska, California, Maine, and Mississippi Embayment, and Oklahoma. These results generally provide evidence for short-wavelength heterogeneity of the continental crust, as relatively closely spaced shot points produce drastically different wide-angle reflection records between *Pg* and *PmP*. In SE Alaska and Ontario and Quebec, Canada, fan shooting indicates that abrupt differences in signal propagation, corresponding to major changes in crustal structure, exist at the terrane boundaries [Fuis and Ambos, 1986; Mereu et al., 1986]. In Maine, fan shots provide the best control on the three-dimensional geometry on the Moho through observations of *PmP* travel times [Luetgert, 1985; Luetgert et al., 1987]. Fan shooting in southern Saskatchewan, Canada, has revealed large offsets in *PmP* travel time which may represent faults of the Moho [Green et al., 1986b].

An ambitious program of off-line profiling was attempted in south-central West Germany by the Deutsches Kontinentales Reflexionsseismisches Programm (DEKORP) [Bortfeld et al., 1985]. Approximately 3400 three-component seismograms were obtained at the critical Moho distance of 70 km. The 10- to 15-Hz signals point to a strong crustal heterogeneity; common receiver sections for receivers only 8 km apart differ dramatically in signals received between *Pg* and *PmP*. Short, generally SE dipping reflectors in the middle and lower crust are inferred, in agreement with reflection results from the main profile.

Q, Poisson's Ratio, and Crustal Anisotropy

Very few measurements bearing on either the apparent or intrinsic attenuation (*Q*), the Poisson's ratio, or the velocity anisotropy of the crust have been reported from the coincident experiments reviewed here. In part, the absence of these measurements reflects the difficulty of recording useful shear wave energy on vertical seismometers and the preservation of relative amplitudes.

Gajewski et al. [1987b] report a coincident reflection/refraction profile in SW Germany wherein the S-wave velocity structure was obtained from horizontal-component recordings of the shot data. Their results provide a two- dimensional model of Poisson's ratio for the entire crust and the upper 10 km of the mantle. Poisson's ratio has significant variations: (1) approximately 0.25 in the shallow uppermost crust; (2) 0.22-0.24 in the middle crust; (3) 0.26-0.30 in the lower crust; and (4) an increase from 0.25 to 0.30 in the upper 10 km of the mantle. Only the whole crustal average is 0.25, the value typically assumed.

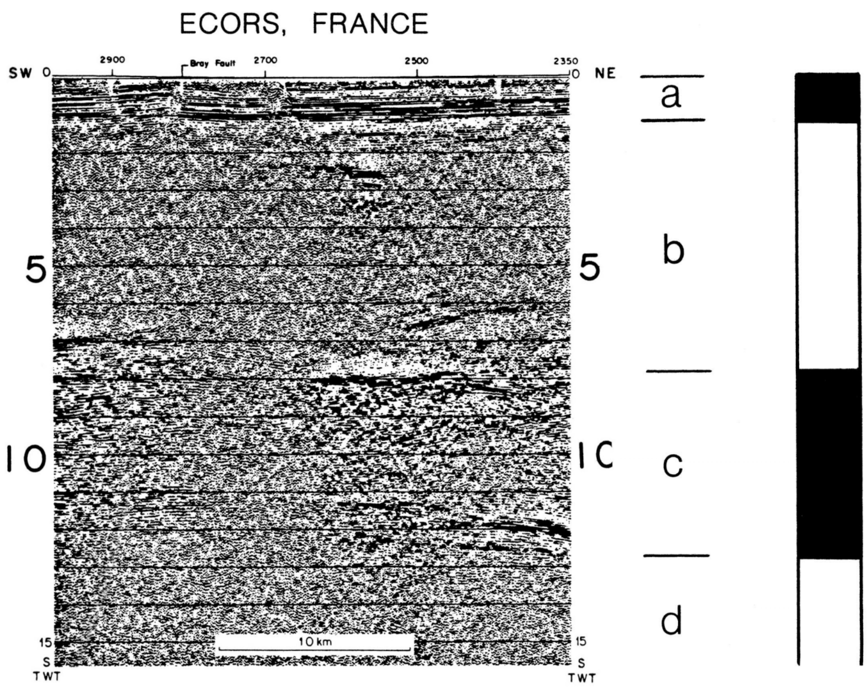
An innovative attempt to use shear wave *Vibroseis* in the USSR resulted in the examination of the petrology of the upper to middle crust of the Urals [Druzhinin et al., 1985]. The lack of wide-angle shear wave energy was used to suggest the presence of partial melt at the Urach geothermal anomaly of southwest Germany [Gajewski and Prodehl, 1985]. *PmP* and *SmS* phases were used to derive an average Poisson's ratio of 0.25 for the crust in Maine [Luetgert et al., 1987]. Reflectivity modeling of wide-angle lower-crustal reflections from the Rhinegraben by varying the Poisson's ratio in lower-crustal lamellae led Fuchs et al. [1987] to argue that the low-velocity lamellae do not represent dominantly fluid layers (although some fluids are possible).

In agreement with teleseismic studies, a high crustal Q in Maine is evident from the larger than usual energy above 15 Hz in the wide-angle reflections. Shear wave splitting of *SmS*. indicative of crustal anisotropy, has been observed in western France [Hirn et al., 1987]. Anisotropy of the *Pg* arrival in Maine is also evident and is explained by the strong structural foliations in central Maine [Klemperer and Luetgert, 1987]. Although small, both structural anisotropy and fabric anisotropy may be expected in several of the locations examined by these experiments, only the Maine and SE California experiments have reported a significant anisotropy consistent with structural fabric [McCarthy et al., 1986]. Given the importance of these parameters to the determination of the physical properties and structural orientation of the lower crust, however, it would seem likely that future experiments will address these parameters.

Problems in Crustal Seismology

In the following seven sections we discuss current issues in our understanding of the continental lithosphere and how refraction data supplement the geometrical relationships illuminated by reflection profiling. We have attempted to discuss only a few

Fig. 5. (Left) Deep seismic reflection profile collected by ECORS in northern France [Bois et al., 1986] showing several of the characteristic features of the continental crust and uppermost mantle: (a) a well-imaged sedimentary cover, (b) a reflection poor or "transparent" upper crust, (c) a laminated, reflective lower crust, and (d) a transparent upper mantle. These and several other features are discussed in the text. (Right) Generalization of the reflectivity of the seismic section at left; reflective portions are solid areas, and transparent portions are open areas. The same process has been applied to compile Figures 6 and 7. The variability in reflectivity across the 25 km of the section displayed here illustrates the caution that must be used when characterizing portions of the crust as simply "reflective" or transparent.



representative experiments, with the understanding that many other studies support these conclusions. Figure 5 illustrates several of the commonly observed characteristics of the continental lithosphere.

Transparent Upper Crust

Seismic reflection profiling is highly effective in imaging the structure of sedimentary basins which locally cover the crystalline crust; however, few reflections at frequencies between 10 and 30 Hz are generally observed in the upper 4- to 5-s two-way time (TWT) of the crust beneath the sediment cover. Important exceptions include reflections from inferred low-angle faults commonly observed in the upper crust (as described below), reflections from the upper crust in highly extended terranes with core complexes, and occasional reflections from the base of exposed plutons. Otherwise, the upper crust in many regions appears to be acoustically transparent. Our compilation of coincident reflection/refraction experiments shown in Figures 6 and 7 does not reveal a systematic relationship between the velocity-depth functions and the apparent transparency of the upper crust as observed on seismic reflection profiles. In particular, although refraction profiles on the southwestern flank of the Rhinegraben and in the Urach geothermal area provide evidence favoring a prominent low-velocity zone (LVZ) in the upper crust (7-14 km) which in turn has been correlated with an acoustically transparent zone in a coincident reflection profile [Bartelsen et al., 1982; Walther et al., 1986; Gajewski and Prodehl, 1987; Fuchs et al., 1987], this is not a general observation. Counter examples are readily found: in Maine, reflection profiles indicate a generally

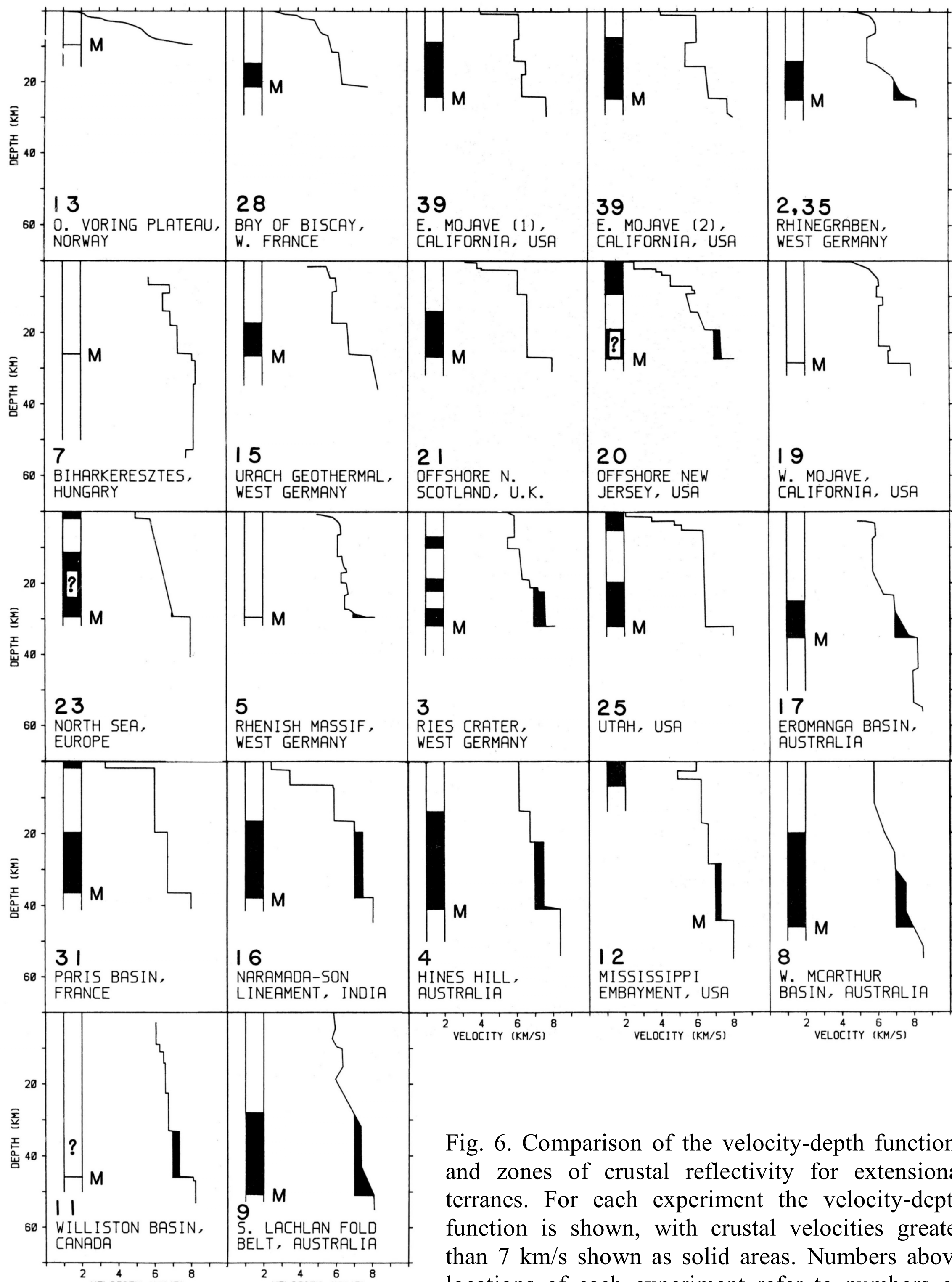


Fig. 6. Comparison of the velocity-depth functions and zones of crustal reflectivity for extensional terranes. For each experiment the velocity-depth function is shown, with crustal velocities greater than 7 km/s shown as solid areas. Numbers above locations of each experiment refer to numbers on Table 1. The refraction Moho is indicated by an M. On the left of each velocity-depth function is a column indicating reflective zones in the crust as solid areas. Transparent zones are shown as open areas. Question marks indicate that the reflectivity estimate is taken from a proximal, non-coincident profile.

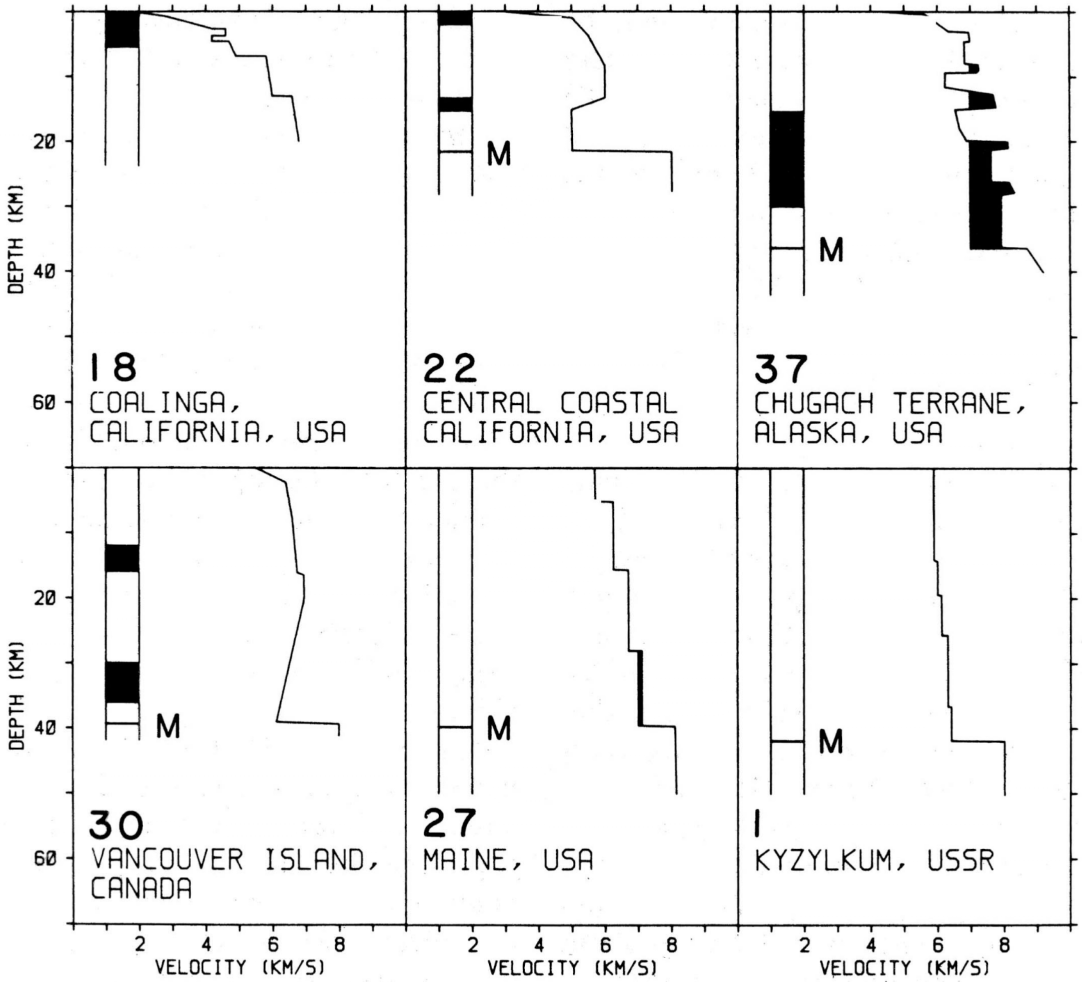


Fig. 7. Comparison of the velocity-depth functions and zones of crustal reflectivity for convergent terranes. The format of the figure is the same as that for Figure 6.

transparent upper crust, and refraction data indicate a positive velocity gradient [Stewart et al., 1986; Luetgert et al., 1987] .Velocities were similarly constrained using ESPs to indicate positive velocity gradients in the Paris Basin, France, where the upper crust is also apparently transparent [Bois et al., 1986, Figure 5]. Thus despite a wide variety of velocity-depth functions, ranging from LVZs to positive velocity gradients, seismic reflection profiles are often characterized by an apparently transparent upper crust.

The common observation of a transparent upper crust presents a paradox. Beneath the sedimentary cover the refraction velocities commonly reported for the upper crust, 5.5 to 6.5 km/s, are consistent with a metamorphic and/or igneous lithology. Fuchs [1969] , Hale and Thompson [1982] , and many others have shown that relatively small perturbations in a well-laminated velocity structure at length scales of tens of meters produce large-amplitude reflections. Well logs from the crystalline portion of the upper crust display velocity perturbations of the proper wavelength and magnitude to produce such reflections [Goodwin, 1985]. Why then does the upper crust commonly appear to be transparent?

Two possible explanations are proposed for this paradox. First, it is important to remember that the reflection strength is a strong function of a reflector's geometry and scale length as well as the reflector's impedance contrast. The velocity perturbations in the upper crust are probably neither well laminated nor of long scale length because this portion of the crust behaves non-ductilely; extension and compression are accomplished brittlely by cataclasis and folding, producing short features with steep dips not well imaged using conventional seismic profiling methods. If, in the limiting case of non-laminated structure, the upper crust is conceived of as a region of random point scatterers or spherical velocity perturbations, it is apparent why, after CDP stacking and conventional processing, the reflection sections will be transparent.

A second, and non-mutually exclusive explanation, is that the transparency of the upper crust may be at least partially an artifact of the seismic reflection method itself. After first arrivals are muted, CDP folds are significantly lower for the upper 5 s of the section than they are below 5 s, resulting in lower S/N improvements during stacking. Furthermore, it is the near-source data which provide information on the upper crust; it is these data that are most frequently contaminated by source-generated noise and/or low-velocity surface and shear wave energy. These source-generated noises adversely affect the data quality most significantly in the upper crust. In view of the rapid onset of the reflective lower crust at 5-6 s, and the success with which sedimentary basins are imaged in the upper crust, we view reflector geometry and scale length as the more important of the two explanations of the transparent upper crust. This view is also supported by the fact that marine studies are less hampered from surface noise problems (for example, British Institutions Reflection Profiling Syndicate (BIRPS) data), but these regions also show a transparent upper crust.

Refraction data can help resolve between these hypotheses through an examination of the body wave scattering properties of the upper crust. Frankel and Clayton [1986] have shown, through finite difference modeling of random velocity perturbations, how to quantitatively examine coda waves for these scattering losses. In the future it will be possible to quantify the scale lengths and velocity contrasts of crustal scatterers and to compare this structure with observed and theoretical (synthetic) seismic reflection data.

Finally, we emphasize that a transparent upper crust is not a universal feature, and we caution against over-application of the concept of a two-layer crust (upper transparent and lower reflective); as more data are collected over geologically different regions, this division appears more and more an overgeneralization, and the concept should only be applied where warranted by a substantial data base. We note that in several cases the middle crust is reflective. In the eastern Mojave Basin, California, for instance, laminated reflections are present at a depth of only 3 s (9 km) [Okaya, 1986]. Recent models for the extension in the Basin and Range suggest that these reflections may correspond to blocks of uplifted lower crust [McCarthy, 1986]; the reasons for the generally high reflectivity of the lower crust are reviewed in the next section.

Reflective Lower Crust

In obvious contrast to the upper crust, most seismic reflection studies from extensional terranes report that the lower 5 s of the crust is strongly reflective over a large depth range (Figures 6 and 7). The depth to the top of the reflective crust varies between

3 and 9 s TWT (9 and 27 km) (Figure 6) but typically is found between 5 to 7 s (15 and 21 km depth). In the Eromanga Basin, Australia, the lower crust is highly reflective; the reflective zone corresponds to a lower crust having velocities between 7.1 and 7. 7 km/s. The top of the lower crust is distinguished by a prominent wide-angle reflection indicative of a sharp discontinuity (the Conrad?). A weak Moho reflection is in keeping with the refraction results which suggest that a 4-km-thick velocity gradient marks the base of the crust. The reflective, high-velocity lower crust is cited as evidence favoring the intrusion into the crust of mafic igneous rocks, perhaps during a thermal or rifting event [Finlayson and Mathur, 1984].

Because of the unusually thick and acoustically reflective sediment cover, the reflection profiles collected during the LASE experiment offshore New Jersey resolve the lower crust only faintly. However, the refraction data provide evidence for the presence of a 7.2 km/s lower crustal layer that is continuous across the ocean-continental boundary. This mafic layer may correspond to an extended lower crust penetratively intruded by mafic intrusions [LASE Study Group, 1986].

In western Uzbekistan, USSR, crustal velocities down to 30-35 km are constrained to be between 5.9 and 6.4 km/s, and two prominent lower-crustal arrivals are observed at depths of about 25 and 30-35 km [Davydova et al., 1975]. Moho is at about 40 km depth and is extremely variable in reflectivity: in most places it is the strongest crustal reflection; in a few places it is considerably weaker than the reflection from 33 km depth. The lower crustal arrivals appear to be generated from laminated interfaces.

Evidence for a laminated lower crust on the east flank of the Rhinegraben (Black Forest) is present in a coincident reflection/refraction data set; near-vertical reflections are abundant, and wide-angle reflections between *Pg* and *PmP* are prominent and numerous. Sandmeier and Wenzel [1986] demonstrate, using reflectivity synthetic seismograms, that the band-limited wide-angle reflection data in their study area are best modeled with a laminated lower crust consisting of alternating high-velocity (7.2 km/s) and low-velocity (6.2 km/s) layers, each with an average thickness of 120 +- 30 m. The average velocity within the laminated stack increases from 6.0 km/s at the top to 6.8 km/s at the bottom. Synthetic seismogram modeling shows that although narrow-angle reflections from the lower-crustal laminations are not sensitive to Poisson's ratio, the wide-angle reflections provide greater constraints [Sandmeier and Wenzel, 1986]. The refraction data also show that the reflective lower crust corresponds to a relatively high-velocity (6.6 to 6.8 km/s) zone on the average.

Gajewski et al. [1987a] propose that in southwest Germany the lower crust may be divided into two types: type 1 has a high average velocity (greater than 6.6 km/s), has a greater thickness (more than 10 km), and is highly reflective because of intense lamination. Type 2 lower crust has a low average velocity (less than 6.6 km/s), lesser thickness (less than 10 km), and lower reflectivity.

Several workers have suggested that the reflective lower crust corresponds to the ductile portion of the crust; if so, the depth to the top of the lower crust corresponds to the isotherm at which lower crustal rocks become ductile (which also is dependent on the composition of the lower crust). Variations in the depth of the top of the lower crust should therefore reflect differences in either the present or pre-existing geotherms [Klemperer, 1987] or lower crustal compositions.

Fuchs et al. [1987] and Louie and Clayton [1987] document that reflections recorded over abroad range of incident angles (near vertical to wide angle) provide more information regarding the physical properties of reflectors than does conventional near-vertical incidence reflection profiling. Specifically, wide-angle reflections are sensitive to the shear wave properties of reflectors and provide investigators with angle-dependent reflection coefficients from which strong inferences concerning layer thickness can be made. For instance, a large number of energetic wide-angle reflections from the lower crust between *Pg* and *PmP* in the Rhinegraben were best modeled as being generated by solid-solid (but not solid-liquid) laminations having thick- nesses of approximately 100 m [Sandmeier and Wenzel, 1986; Fuchs et al., 1987]; near-vertical incidence data could not distinquish between these solid-solid and solid-liquid laminations. In a second example, in the eastern Mojave Desert, California, Louie and Clayton [1987] provide evidence from the range dependence of reflection spectra that many reflectors in the lower crust are also produced by such lamellae. The method of Louie and Clayton [1987] can be applied to either wide-angle data or near-vertical data with long (greater than 10 km) apertures.

In extensional environments, "average" refraction velocities for the lower crust are often above 7.0 km/s (Figure 6); velocities above 7.0 km/s may correspond to a zone which is intruded by mafic and ultramafic rocks during crustal extension. Thus a laminated, intruded, lower crust is also in accord with the average refraction velocities. Where evident, the thickness of this zone generally increases with crustal thickness, in keeping with isostatic considerations. Note that it is possible that the high-velocity lower crust in some regions (such as the Basin and Range) may be mistaken as the upper mantle and thus would be mistakenly interpreted as evidence for a thin crust.

In convergent terranes there is less evidence for a high- velocity lower crust correlative to a reflective lower crust (Figure 7). The velocity model for the Chugach Terrane in southeastern Alaska is a notable exception (Figure 7) ; the field brute stacks of COP profiles display prominent and continuous reflectors in the middle to lower crust (5 to 10.5 s). As is discussed below, the higher velocities in the lower crust in southeastern Alaska are explained by the underplating of the continental crust by mafic and ultramafic fragments of the oceanic lithosphere [Page et al., 1986]. Elsewhere, as in Vancouver Island, the accretion of relatively old and cold oceanic plates may depress the geotherm and reduce the ductility of the lower crust, inhibiting the creation of a reflective and laminated lower crust.

Landward Dipping Reflectors

Seismic reflection data collected landward of the accretionary prism in several convergent zones of western North America have identified landward dipping reflectors that are presumably the product of the accretionary process at these presently or recently active margins. Coincident seismic reflection/refraction data sets from British Columbia, Alaska, and central California provide the best information on the interpretation of the structures responsible for these reflections. Although landward dipping reflections are also observed in eastern Australia [Wake-Dysler et al. 1987], the lack of coincident refraction data makes the interpretation of these reflections difficult.

Figure 8 summarizes the character of the reflection sections from these three regions and compares the seismic velocities derived from the coincident refraction data as a function of TWT. The Vancouver Island, Canada, experiment is described by Clowes et al. [1987] and Yoralh et al. [1985]. The seismic reflection data indicate prominent landward dipping reflections; Figure 8a shows a line drawing of a portion of one line with clear reflection events between 4 and 8 s which are separated by a seismically transparent zone. This transparent zone correlates with a high seismic velocity (7.7 km/s) and is identified as mantle material, while highly reflective zones characterized by intermediate velocities are interpreted as subducted sedimentary and igneous rocks. Thus the deeper reflective horizon is interpreted to be oceanic crustal material at the top of the actively subducting plate, underlain by seismically transparent mantle [Green et al., 1986a, b]. Clowes et al. [1987] and Green et al. [1986a, b] interpret the upper reflective and transparent zones as an underplated oceanic slab associated with an earlier phase of subduction. Thus coincident reflection/refraction data present a strong case that the crust

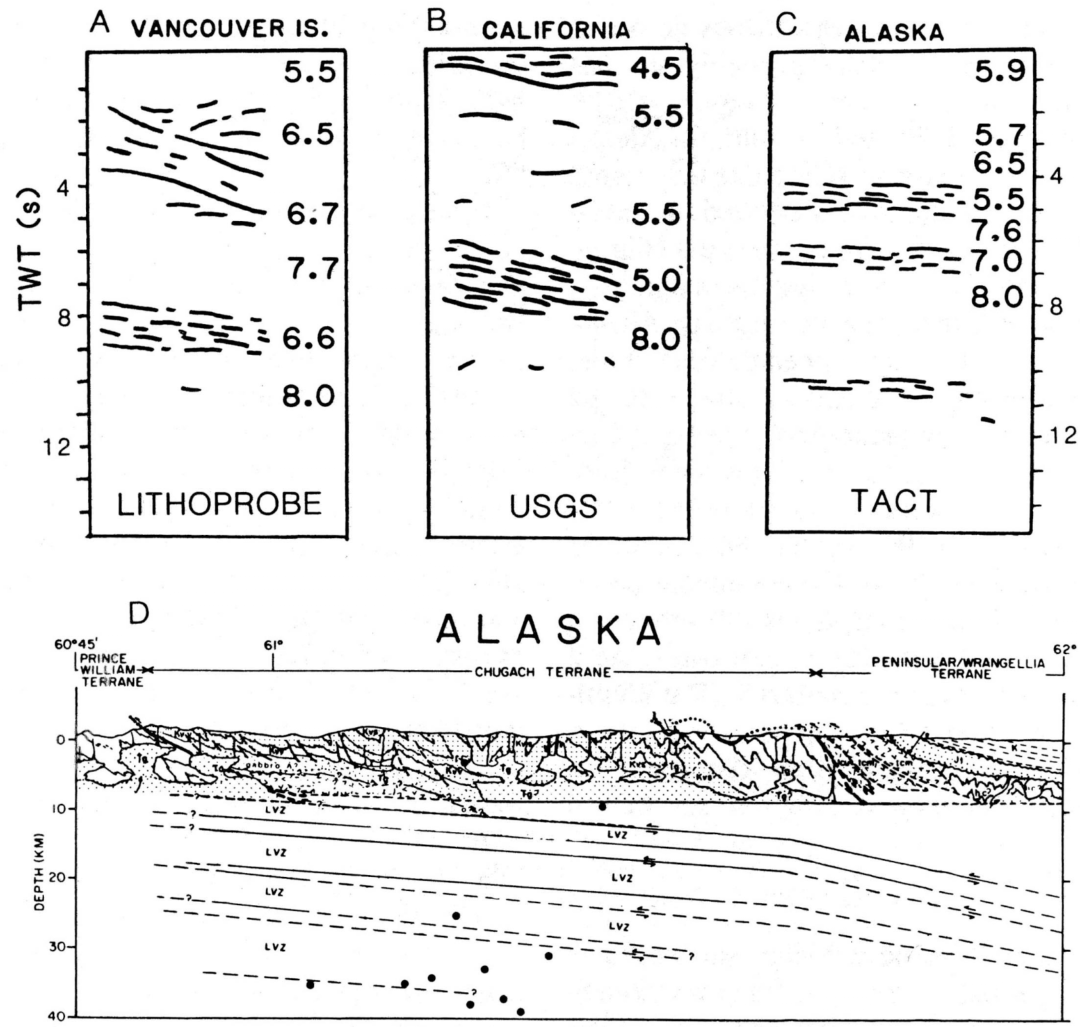


Fig. 8. Comparison of line drawings of landward dipping reflections from (a) Vancouver Island [Clowes et al., 1987], (b) central California [Trehu and Wheeler, 1987], and (c) SE Alaska [Fuis et al., 1986] with seismic velocities (in kilometers per second) from coincident refraction profiling. Figure 8d shows the assemblage of landward dipping accreted oceanic lithospheric fragments inferred from the velocity model for the Chugach Terrane in SE Alaska [from Page et al., 1986].

of Vancouver Island has been built by the underplating of marine sedimentary and igneous rocks during the subduction process.

In central California, commercial seismic reflection data collected in the Coast Ranges west of the San Andreas Fault were reprocessed to 12 s using a truncated correlation sweep [c.f. Okaya, 1986]. The reprocessed section shows a prominent set of landward dipping reflectors at 5-7 s [Trehu and Wheeler, 1987, Figure 8b]. Coincident seismic refraction data, interpreted independently by Mereu [1987] and Trehu and Wheeler [1987], indicate a pronounced seismic low-velocity zone at the base of the crust, at the same depth as the landward dipping reflections. Trehu and Wheeler [1987] interpret the coincident reflection/refraction data as indicating that the lower crust contains a package of deeply buried sediments that was subducted at the presently inactive trench, approximately 150 km offshore. Unlike the Vancouver Island study, there is no indication in the seismic refraction data of high-velocity material (7.6 km/s or greater) within the crust. Thus although transparent zones do occur in the California reflection data, these probably do not represent underplated oceanic mantle.

Seismic refraction data were collected in southern Alaska in 1983 and 1984. Coincident seismic reflection data were added in 1986. The refraction data have identified an imbricate stack of high and low velocities within the crust (Figure 8c). The landward dip of these boundaries indicates that as in the case of Vancouver Island, the crust of southern Alaska has been built up by the underplating of oceanic crustal and upper mantle rocks (Figure 8d). Preliminary stacks of the 1986 seismic reflection data indicate landward dipping reflections which correspond to the refraction-determined low-velocity layers (Figure 8c). In actively accreting areas the expected high pore pressures in the subducted sediments may explain both the lower velocity of the subducted material and the higher reflectivity. Just as is observed on Vancouver Island, the high-velocity layers are transparent and are presumed to consist of mantle material. The identification and interpretation of landward dipping reflectors in convergent terranes may have application elsewhere on continents where ancient convergent margins are buried under cover rocks.

Fault Zones

Seismic reflection profiles have been highly successful in identifying reflection events with shallow to steep dips which are interpreted to be deep crustal faults on the basis of their spatial correlation to mapped faults, or on the basis of the tectonic setting. Why many faults are characterized by high reflectivity has been studied with field and laboratory data by Hurich et al. [1985] and Jones and Nur [1984], respectively. High-quality coincident reflection/refraction studies of faults are rare because fault zones tend to be thin, and only high-resolution refraction data will detect the presence of the fault unless it is wide and has a large velocity contrast with respect to the surrounding rocks. Thus coincident reflection/refraction studies of fault zones are one of the least developed aspects of crustal seismology.

We divide our discussion of faults into vertical and non-vertical faults. Strike-slip faults are generally vertical, and consequently, they are difficult to image with near-vertical incidence reflection profiles. The San Andreas Fault has been examined with a seismic reflection profile that has proximal seismic refraction data and with a coincident reflection/refraction data set. Feng and McEvilly [1983] present a detailed interpretation of a seismic reflection profile across the San Andreas at a location where proximal seismic refraction data are available. They conclude that the fault zone is actually 3-5 km wide with pronounced low velocities. This width is consistent with proximal earthquake refraction data which indicate a 3-km-wide seismic low- velocity zone (3.0 to 4.5 km/s) which extends to a depth of 12 km [Healy and Peake, 1975]. Seismic velocities adjacent to the fault range from 5.2 to 6.6 km/s. Unfortunately, the refraction data is of low resolution, and we do not know whether the low average velocities determined within the fault zone actually represent the velocity throughout the entire zone. It is possible that high-resolution refraction measurements, as are made for groundwater surveys [Sjogren, 1984], would indicate that the LVZ medium actually consists of narrow zones with velocities of 3.0 km/s alternating with largely unfractured rocks with velocities approaching 6.0 km/s. These two models of strike-slip faults, one filled exclusively with low-velocity fault gouge, the other with gouge alternating with unfractured rocks, can be expected to have distinct mechanical properties in terms of faulting.

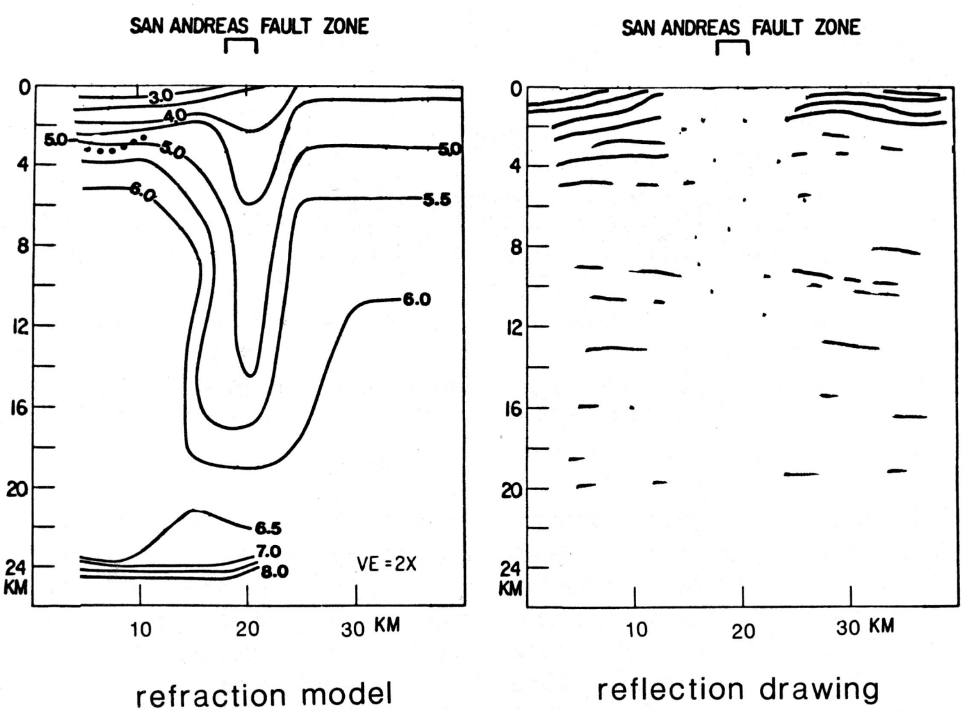


Fig. 9. Schematic line drawings of the reflection line SJ-6 across the San Andreas Fault south of Coalinga, California, with velocities (in kilometers per second) inferred from a coincident refraction model [Trehu and Wheeler, 1987]. Note the prominent low-velocity zone associated with the San Andreas Fault.

A coincident reflection/refraction profile was recently recorded across the San Andreas Fault south of the town of Parkfield, California. The commercial seismic reflection data show a 5-km-wide zone of nonreflective crust at the fault, which is flanked to the east and west by clear midcrustal reflections. The coincident seismic refraction data have been interpreted by Mereu [1987] and Trehu and Wheeler [1987]. Both interpretations show a 5- to 10-km-wide seismic LVZ coincident with the fault (Figure 9) and are consistent with interpretations 30 km to the north by Feng and

McEvilly [1983]. The LVZ is a product of severe fracturing of the rock and the production of fault gouge. The clearly demonstrated existence of an LVZ on the San Andreas Fault suggests that similar, although less major, LVZs will occur on other minor faults [Mooney and Ginzburg, 1986].

Seismic reflection data were recorded in the Basin and Range Province of western Utah by industry [McDonald, 1976] and by the Consortium for Continental Reflection Profiling (COCORP) in 1982. These data imaged the Sevier Desert detachment over a distance of some 100 km [Allmendinger et al., 1983]. The detachment fault can be traced from the near surface to a TWT of 5 s, or approximately 15 km depth. Two coincident seismic refraction data sets are available to examine the velocity structure of the crust along these reflection profiles: a proximal (40 km to the north) refraction profile (Delta-West) recorded by the U.S. Geological Survey (U.S.G.S.) in the early 1960s and a coincident ESP collected by COCORP [Liu et al., 1986]. Although the Delta-West refraction profile provides clear evidence for a midcrustal low-velocity zone [Mueller and Landisman, 1971; Muller and Mueller, 1979], the COCORP ESP does not. Gants [1985] has reexamined the Delta-West profile in light of the recent seismic reflection data and concludes that the high-amplitude reflections from the Sevier detachment most likely correlate with a high acoustic impedance at the base of the crustal LVZ determined from refraction data. The spatial variation in crustal velocities and reflectivities suggests the local presence of mylonite anisotropy and high pore pressure due to dehydration and greenschist metamorphism [Gants, 1985] on the detachment fault. The Sevier detachment occurs at a depth of about 12 km over some 60 km of its image in the reflection data, which suggests that it is associated with the brittle-ductile transition in the Basin and Range [Smith and Bruhn, 1984].

It is interesting to note that some major faults at the surface (i.e., core complex detachment faults) are not strong reflectors even through they are deep enough for the formation of mylonites and are at a low angle and therefore have a favorable geometry for seismic imaging. Other low-angle faults which have strong seismic velocity contrasts across them are clearly identified by coincident reflection and refraction data. One example is in the Quebec-Maine transect, where the shallowly dipping detachment along the Grenville terrane has been mapped using both vertical incidence reflection and wide-angle refraction data [Luetgert, 1985]. Another example is the U.S.G.S. study of western California where (presumed) oceanic crust beneath the Great Valley underthrusts the marine metasedimentary rocks of the Coast Ranges. In this study, commercial reflection data were complemented by detailed refraction data, and the coincident data were jointly interpreted [Wentworth et al., 1984; Walter, 1985]. After the reflection data were processed to provide the best image of the structure, the probable composition of each major structural unit was determined from its seismic velocity. For example, the underthrusting mafic oceanic crust is identified on the basis of its high seismic velocity (6.4-6.55 km/s). Above the fault plane, refraction velocities were reliably correlated with individual reflection events and, including the identification of seismic LVZs within some stratigraphic horizons, were indicative of anomalously high pore pressures within the sedimentary column.

Crust-Mantle Boundary

The nature of the crust-mantle boundary, a fundamental crustal feature, has interested seismologists since it was first identified by A. Mohorovicic in 1909. For years it was defined, on the basis of seismic refraction measurements, as that boundary below which the seismic velocity reached 7.6 km/s to 8.6 km/s [Steinhart, 1967]. Since then, there has been increasing interest in the definition of the Moho and in determining its spatial variability with seismic reflection data [Meissner, 1967,1973; Fuchs, 1969,1970; Kosminskaya and Kapustian, 1979; Hale and Thompson, 1982; Braile and Chiang, 1986]. These studies demonstrated that the crust- mantle boundary is not a simple first-order discontinuity but instead consists of a complex interlayered zone of high- and low-velocity material. A consensus emerged from the comparison of seismic reflection data with proximal refraction data that the "reflection Moho" consists of a package of nearly continuous reflections at TWT of 8-12 s that are underlain by a seismically transparent zone [e.g., Barton et al., 1984]. The base of the reflective zone can generally be correlated with the "refraction Moho," although there may be important exceptions; for example, Phinney [1986] argues on the basis of non-coincident data sets that the refraction Moho is several kilometers deeper than the reflection Moho in the continental crust offshore New York.

The coincident reflection/refraction investigation in Quebec, Canada, and Maine provides strong evidence that the base of the reflective zone corresponds to the refraction Moho in that area. The reflection data are presented by Stewart et al. [1986], and the correlation of the refraction Moho with the reflection Moho is discussed by Luetgert [1985] and Stewart et al. [1986], who conclude that over a 300-km-long segment the two methods are seeing, within measurement errors, the same feature as Moho. A similar close correlation was noted by Barton et al. [1984] in the North Sea with sparser refraction data.

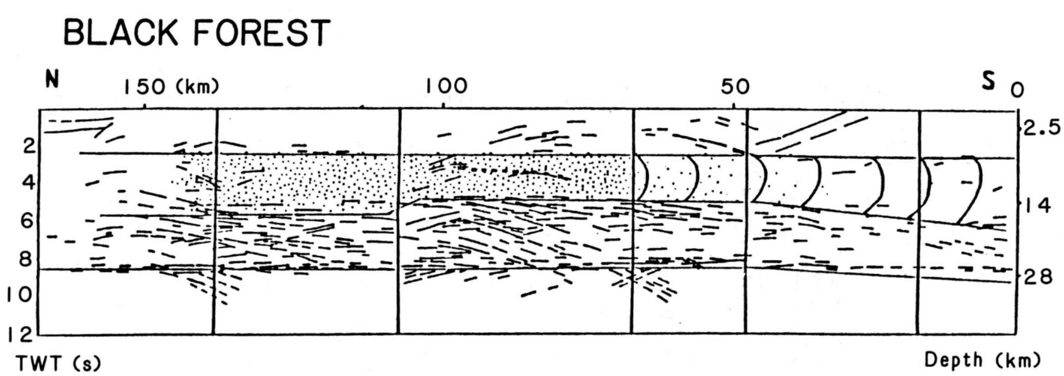


Fig. 10. Line drawing of the reflection section along the Black Forest, West Germany, with isovelocity contours from a refraction model superimposed and an upper crustal low-velocity zone shown as the dotted region [Gajewski and Prodehl, 1987].

Coincident reflection/refraction profiles on the east flank of the Rhinegraben in southwestern Germany have been used to examine the correlation between the reflection and refraction Moho. Gajewski and Prodehl [1987] interpreted the crustal velocity structure from refraction data and then used their velocity model to calculate TWT for vertical incidence data. When compared with a line drawing of the coincident reflection data (Figure 10), the observed and predicted times are in excellent agreement: the refraction Moho times occur at the base of the reflective zone in the lower crust.

The seismic velocity model derived for southwestern Germany from the refraction data shows a lower crustal structure consisting of laminated high and low velocities (6.2 to 7.4 km/s) and a step increase at the Moho (7.4 to 8.0 km/s) [Sandmeier and Wenzel, 1986; Gajewski and Prodehl, 1987]. This velocity model implies that the deepest reflection from the lower crust (i.e., the reflection Moho) will not necessarily be the highest-amplitude reflection, since constructive interference within the lower crust will amplify near-vertical reflections. It is in fact a common observation on seismic reflection sections that reflections up to several seconds above Moho depth are stronger than the Moho reflection. In contrast, Braile and Chiang [1986] show that wide-angle Moho reflections are significantly less sensitive to a laminated velocity structure if that structure is thinner than 5 km.

Klemperer et al. [1986] presented evidence for the correspondence between the reflection and refraction Moho across Nevada at 40°N. Their comparison showed that along a 450-km transect the Moho topography inferred from TWT was only 50% of that previously inferred from refraction data and showed a maximum discrepancy of about 1.0 s TWT between reflection and refraction Mohos. High-quality, truly coincident refraction data have recently been acquired along this transect to resolve whether or not this discrepancy is real [Catchings et al., 1986].

CALCRUST seismic reflection data collected in the highly extended terrane of the eastern Mojave Desert of southern California show strong reflections from the lower crust which abruptly terminate below 9 to 10 s (the reflection Moho), yielding an estimated crustal thickness of 27-30 km [Okaya et al., 1985]. Proximal (12 km south and parallel) U.S.G.S. seismic refraction data recorded for the Pacific - Arizona Crustal Experiment (PACE) program define the velocity structure and crustal thickness with a high degree of accuracy owing to the use of multiple shot points and 500-m recording spacing. This data indicates a crustal thickness of 26-27 km [McCarthy et al., 1986] and a vertical incidence TWT of 9.5 +- 0.5 s to the refraction Moho. Thus the reflection Moho and refraction Moho appear to differ by only 1-2 km in this study.

Finally, we note that in some convergent terranes (southern Alaska and Vancouver Island) the concept of "the Moho" , is blurred owing to the underplating of the continent by oceanic crustal and upper mantle slabs. Double and higher multiple Mohos are reported [e.g., Page et al., 1986], an observation which suggests that caution should be exercised when correlating the reflection and refraction Mohos in such terranes.

Transparent Upper Mantle

Unequivocal wide-angle reflections from the upper mantle have been reported in a number of refraction experiments summarized by Prodehl [1984] and Fuchs [1986]. It has been suggested that these reflections are generated by fine-scale laminations produced by ductile shear flow in the upper mantle and/or by a velocity anisotropy introduced by the preferred orientation of olivine crystals [Fuchs, 1986]. Encouraged by the success of these wide-angle experiments, reflection seismologists have attempted to identify near-vertical reflections from the continental upper mantle. Short reflection segments beneath the Moho event in the Rhinegraben are cited as possible near-vertical incidence reflections from the upper mantle [Dohr, 1970]. The BIRPS MOIST profile, which currently lacks complementary wide-angle reflection data, has also reported a prominent lower crustal and upper mantle reflection to 24 s, referred to as the Flannan

Fault [Brewer et al., 1983; McGeary and Warner, 1985; Peddy et al., 1986]. Although there is a strong dip on this reflection event, line segment migrations indicate that this event does not migrate into the crust using crustal velocities. More recent BIRPS data along the ORUM profile, also currently lacking wide-angle coverage, shows very strong, horizontal reflections at 13-15 s [Warner et al., 1987]; these are the clearest, most unequivocal subhorizontal near-vertical reflections recorded to date.

Elsewhere, the evidence for unequivocal upper mantle reflections at near-vertical incidence is less conclusive. In at least one coincident seismic reflection/refraction experiment in Hungary [Posgay et al., 1986], a low-frequency near-vertical reflection from 15 s, well beneath the continental crust, is reported. The velocity control from this profile is provided by stacking velocity analyses, and the reproduced section is narrowly band-pass filtered, and so the published data does not provide unequivocal evidence for upper mantle reflections. Most dipping upper mantle reflection events in COP data from the Gulf of Maine migrate into the crust during line segment migration [Hutchinson et al., 1986]. The same is true for dipping events recorded onshore Maine [Unger et al., 1987]. Wide-angle reflection events with TWT of 15 sand greater observed from onshore Maine have been shown to correspond in terms of TWT to converted crustal phases and their multiples [Luetgert et al., 1987].

The preponderance of the available data thus favors the general homogeneity of the upper mantle at seismic reflection wavelengths. In no sense can the upper mantle be similar to the reflective lower crust: too many high-quality reflection experiments have been performed in which no upper mantle laminations are observed. If the reflectivity of the lower crust is related to its ductility, as shown in Figure 11, the transparency of the upper mantle may best be related to the decreased ductility of the upper mantle as

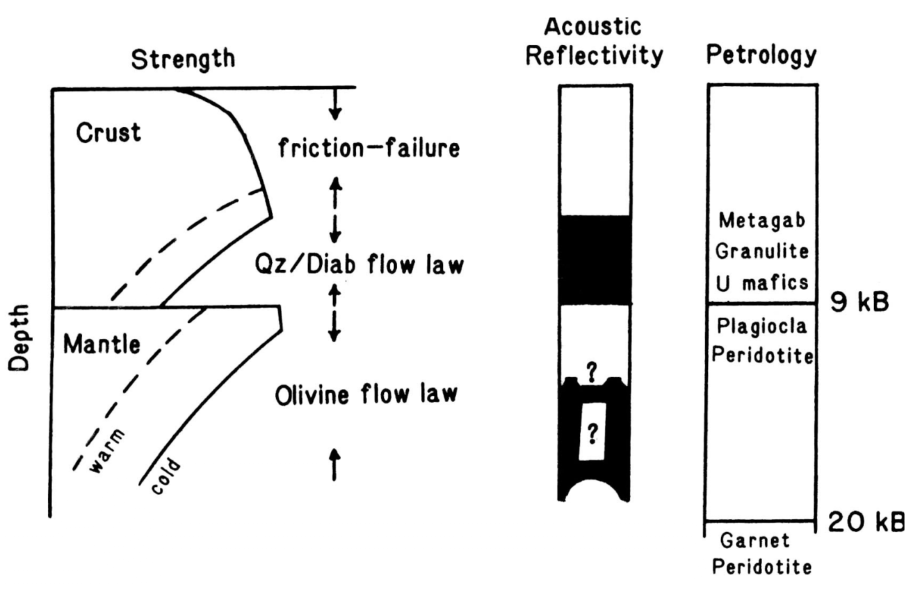


Fig. 11. (Left) Schematic diagram of the variation of the mechanical strength of the crust and uppermost mantle with respect to depth for cold (solid curve) and warm (dashed curve) geotherms from Chen and Molnar [1983]; see also Meissner and Wever [1986] and Meissner [1986] for a discussion of strength-depth curves. The upper part of the crust represents brittle behavior and is based on a linear relationship between the shear stress and normal stress, and the upper mantle is controlled by flow laws of crustal and upper mantle. (Middle) The zones of high reflectivity in the continental lithosphere (solid region) correspond to low-strength regions. (Right) The generally agreed upon petrology of the lower crust and upper mantle [Wilshire, 1987] are shown.

inferred from rheological studies [Chen and Molnar, 1983]. Seismic reflectivity in the continental lithosphere may thus be a strong function of its ability to form laminations and anisotropy through shear flow. According to the strength curve of Figure 11, we can hypothesize increased reflectivity with depth in the upper mantle owing to increased shear flow, yet deep seismic lines collected by BIRPS do not show such a systematic pattern [Warner et al., 1987; McGeary and Warner, 1985]. Studies of upper mantle reflections are currently in their infancy, however, and more combined reflection/refraction studies will be required before the heterogeneity of the upper mantle can be more fully appreciated.

Magmatic Processes

The transport and emplacement of magma into the lithosphere is a fundamental mechanism for the alteration and evolution of the continental lithosphere. While there have been a number of coincident studies of inferred active and inactive magmatic plutons and intrusions in both extensional and convergent terranes, there remains room for significant contributions to our understanding of igneous plutonism through coincident profiling. For a variety of reason, discussed below, these magmatic intrusions are difficult to image well.

Inferred midcrustal magma chambers in extensional terranes are reported from seismic reflection surveys in the Rio Grande rift and Death Valley [Brown et al., 1980; de Voogd et al., 1986]. In both cases, near-vertical reflections between 6 and 7 s TWT (18-21 km) are observed which, on the basis of their extremely high amplitude and complexity, can best be explained by a set of thin low-velocity (magma?) sills [Brocher, 1981; de Voogd et al., 1986]. The lack of high-quality coincident refraction profiles along these surveys is particularly regrettable in view of Fuchs et al.'s [1986] observation that only wide-angle reflections can provide useful constraints on a reflector's shear wave properties, constraints required to uniquely determine the presence of magma.

A coincident reflection/refraction experiment was performed in a convergent setting in Long Valley, California, in an attempt to image a proposed midcrustal magma chamber (5 to 7 km deep). The existence of the magma chamber had been inferred primarily from wide-angle reflections [Hill, 1976; Hill et al., 1985], p-wave delays [Steeples and Iyer, 1976], and s-wave attenuation [Sanders, 1984]. Although the reflection experiment was well designed and included both compressional and shear wave profiling, severe coupling and statics problems introduced by a highly variable surficial geology significantly degraded the data quality and did not permit the unambiguous identification of either a narrow- or wide-angle reflection from the postulated magma chamber [Deemer, 1985; Rundle et al., 1985]. Reflection studies of active rhyolitic volcanos will in general be impaired by the presence of highly attenuating and scattering tuffs and an extremely variable superficial geology.

Seismic reflection profiles over frozen granitic plutons generally reveal that the plutons themselves are acoustically transparent for seismic frequencies less than 45 Hz [Lynn et al., 1981; Jurdy and Phinney, 1983; BIRPS and ECORS, 1986; Stewart et al., 1986]. Internal reflections are observed at higher frequencies from a major granitic batholith in Manitoba, Canada, even though it appears transparent at lower frequencies [Mair and Green, 1981; Green and Mair, 1983]. Wide-angle profiling thus provides an effective means of inferring the seismic properties of the plutons themselves with lower frequencies: seismic velocities measured for the Coast Range batholith, California [Walter and Mooney, 1982], and the Devonian plutons in Maine (C. E. Mann, personal communication, 1986) and elsewhere are between 5.5 and 6.3 km/s. Reflector geometries indicate that the base of the plutons can be of several origins: thrust related as for the Elberton granite, in Georgia [Jurdy and Phinney, 1983], cumulate in origin as in Texas and western Nevada [Lynn et al., 1981], or underlain by metavolcanics as in Maine [Stewart et al., 1986]. To date, no wide-angle experiment specifically designed to resolve the nature of the bases of plutons has been attempted. Wide-angle profiling is required in some cases, such as in the Southwestern Approaches and the English Channel, because the sides of the batholiths are not imaged by reflection profiling [BIRPS and ECORS, 1986].

Summary

Coincident seismic reflection/refraction experiments provide complementary insights into the structure, composition, and evolution of the continental lithosphere. Although reflection profiles provide the highest resolution images of crustal reflectors, there are a number of regions in the crust which are not reflective. Where the upper crust is transparent, in most granitic plutons, in transparent zones between landward dipping reflections, and where the upper mantle is transparent, wide-angle data sets provide the only useful constraints on the constituency of the continental lithosphere. Where reflectors do exist, reflection profiles allow us to refine our simplistic refraction models, and these refraction models allow us to better constrain the geometric interpretations of reflection models. The identification of a double Moho reflection, for instance, is problematic without coincident refraction control to confirm the presence of multiple high-velocity layers separated by lower velocities as in southern Alaska (Figure 8d).

Wide-angle seismic data also provide the best constraints on the physical properties of a reflector, even when the reflector is too thin to produce a refraction response. Thus detailed wide-angle studies will be useful in making further inferences concerning the laminations in the lower crust and the fine structure of crustal detachment and decollement faults.

Fundamental differences in velocity-depth relations as well as reflectivity between extensional and convergent terranes underscore the seismic contrasts between the penetrative intrusion and ductile deformation produced during extension and tectonic underplating produced during convergence. Figures 6 and 7 indicate these possible systematic differences between convergent and extensional terranes. In convergent terranes the lower crust is typically reflective with weak velocity gradients (Figure 7). The lower crustal reflectors appear to be discrete; they are inferred to be generated by horizons well separated (by over a wavelength) in depth. In extensional terranes the lower crust is usually highly reflective with a strongly laminated appearance; this reflective zone is frequently correlated to velocities between 6.5 and 7.3 km/s (Figure 6), thought to correspond to a mixture of mafic and ultramafic rocks. The combination of a high velocity and a transparent lower crust may be sufficiently unique to convergent zones that it could be used to guide the interpretation of older lithosphere. Likewise, the laminated lower crust is sometimes still reflective even when uplifted (as in the case of some core complexes), suggesting that extensional terranes may also be recognized long after extension has ended. If these generalizations are correct, it may be possible to better infer the tectonic history and setting of poorly exposed terranes using coincident seismic reflection/refraction profiling. We emphasize two points regarding this hypothesis. First, extensional versus convergent terranes will not be distinguished from the analysis of either reflection or refraction data alone. Second, a binary division of terranes into extensional and convergent will often not reflect the true complex evolution of a region.

Further refinements in this emerging picture await the results of recently performed experiments and future experiments designed to address the physical properties of the lower crust as well as its geometry. By attempting to record and model useful shear wave energy and wide-angle data in many azimuths and to obtain estimates of Q, many more constraints may be placed on the porosity, fluid content, petrology, and perhaps the degree of alteration of the lower crust than do most experiments performed to date. It must be kept in mind, however, that although limitations in our resolution of the lower crust imposed by spatial and temporal sampling can be minimized, the inherent inhomogeneity of the crust acts to defocus our image of it. We believe that investigations within the next few years will remove the man-made limitations for imaging the continental lithosphere and will allow us to see more clearly how to circumvent those imposed by the earth itself.

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