CHAPTER 1

Deep Seismic Reflection Profiling: How Long Does the COCORP Line Have To Be? or Dip Limitations on Migrated Sections As Imposed by Recording Geometry

ABSTRACT

The length of a seismic profile and the recording time available as input to migration govern simple equations relating dip observable on migrated profiles to the spatial location of the reflector. This relationship is particularly important in COCORP seismic reflection profiles of the continental crust, commonly 50 to 200 km and 16 to 20 sec long, which must be migrated to obtain a focused image and extract the maximum amount of information. A certain amount of the observed decrease of dip with depth and on the edges of migrated sections can be related to the size of the input, as shown in a real data example; any ***further*** decrease in dip with depth may have geologic significance. Crooked profiles complicate the migration: either linear segments are migrated separately (which drastically decreases the dip resolution obtained on the section as a whole), or the "straightened" line is migrated as a unit (which involves 2-D assumptions about the crust). Both seismic profile planners and interpreters must consider the dip limitations. Seismic planners may need to resolve dips up to 30 degrees to depths of 30 km: a lead-in (or step-in) of 17 km on both ends of the line and a recording time of 16 sec will yield that resolution on the migrated profiles. For 45-degree resolution to 30 km depth, a 30-km lead-in is required. The inhomogeneity of the crystalline crust can be estimated by the number, length, and degree of dip of reflectors; however, interpreters of migrated data must not assign geologic significance to limitations caused by recording or migration procedures.

INTRODUCTION

COCORP, Consortium for Continental Reflection Profiling, has been gathering seismic reflection data in order to learn more about the nature of the continental crust. Specific locations are chosen for the geologic question posed therein: *e.g.*, the extensional structure of the Rio Grande Rift, the Wind River thrust, Wyo., the Brevard Zone in the southern Appalachians (Schilt *et al.*, 1979). To wring the *maximum* amount of information from the seismic profiles, migration is absolutely necessary to collapse diffractions which obscure the underlying signal, to display dipping energy in its true spatial and temporal location, to remove the distortions caused by lateral velocity variation (Wind River, Wyo., see Chapter 3), and to improve the signal/noise ratio. It is a well-known property of migrated seismic profiles that the observed range of dips decreases with the migrated depth of the event. In this paper we identify two independent geometrical causes for the loss of dipping events.

The decrease of dipping events with depth on migrated sections influences both planners of field work and interpreters of migrated seismic data. The planners should ask: for the given geologic investigation what should the field parameters be to see, for example, up to 30 degrees of dip at 30 km depth? Specifically, as will be discussed herein, how long should the recording time and the line be? The interpreter should ask, is the loss of south-dipping events on the north end of the line, for example, and the general decrease of dipping events with depth, due to recording parameters, or to geologic reality? How inhomogeneous is the continental crust, based upon the length, the degree of dip, and the number of deep reflectors?

THEORY

This paper uses the geometrical model in Figure 1.1 for the derivations of the simple equations. Assumed are straight raypaths and that the midpoint of the shot/receiver pair is the recipient of the normally reflected ray. The latter is true only at zero offset and approximately true for offsets which are small compared with reflector depth.

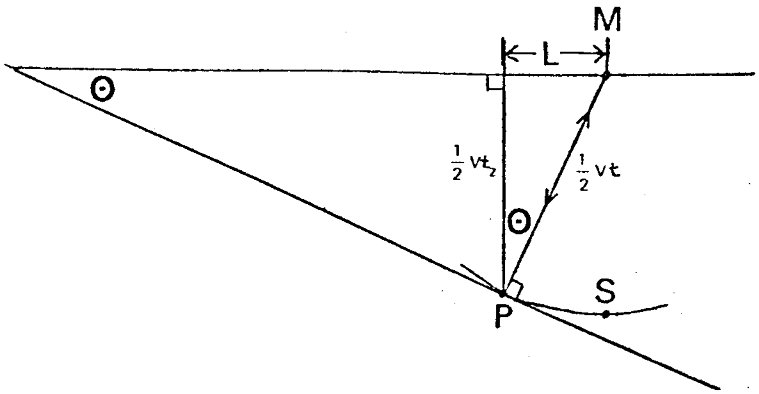


FIG. 1.1. Dip limitation imposed by line extent. where M = midpoint of the shot/receiver pair; S = unmigrated location of the dip segment, P ; t_z = two-way time on migrated section; V = velocity; L = lateral displacement of event; θ = dip angle; and t = two-way time on unmigrated section.

Dip Limitation Imposed By Recording Time

Let t_{rec} be the time interval over which a record is made after the shot goes off, and t be the unmigrated two-way time of an event. The only events recorded from point P are those with dips small enough for $t \leq t_{rec}$ (Figure 1.2).

Using Figure 1.1's geometry,

$$\cos \theta = \frac{t_z}{t} \tag{1.1}$$

or

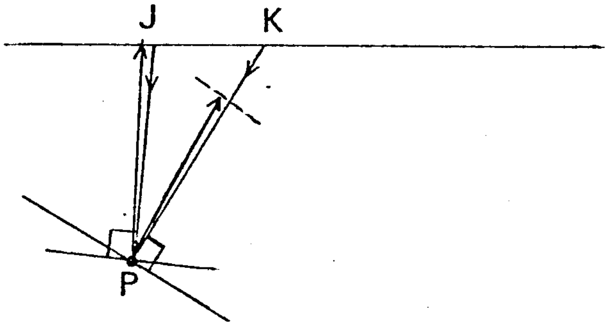


FIG. 1.2. Dip limitation imposed by recording time. At J, the reflection from the shallowly dipping horizon arrives in time to be recorded. At K, the recorders are turned off before the reflection from the steeply dipping reflector arrives. The gently dipping reflector will be seen below location J; the steep reflector will not be seen, even though it may exist in the earth.

$$\theta = \cos^{-1} \frac{t_z}{t} \qquad (1.2)$$

The finite recording time implies

$$\theta_{max} = \cos^{-1} \frac{t_z}{t_{rec}} \qquad (1.3)$$

and so in general

$$\theta \le \cos^{-1} \frac{t_z}{t_{rec}} \quad ; \quad t_z \le t_{rec} \qquad (1.4)$$

Dip Limitation Imposed By Line Extent

The "instep," P, of an event is defined as the lateral position of the event from the appropriate edge of the section, the appropriate edge being the ***downdip edge*** of the section (Figure 1.3).

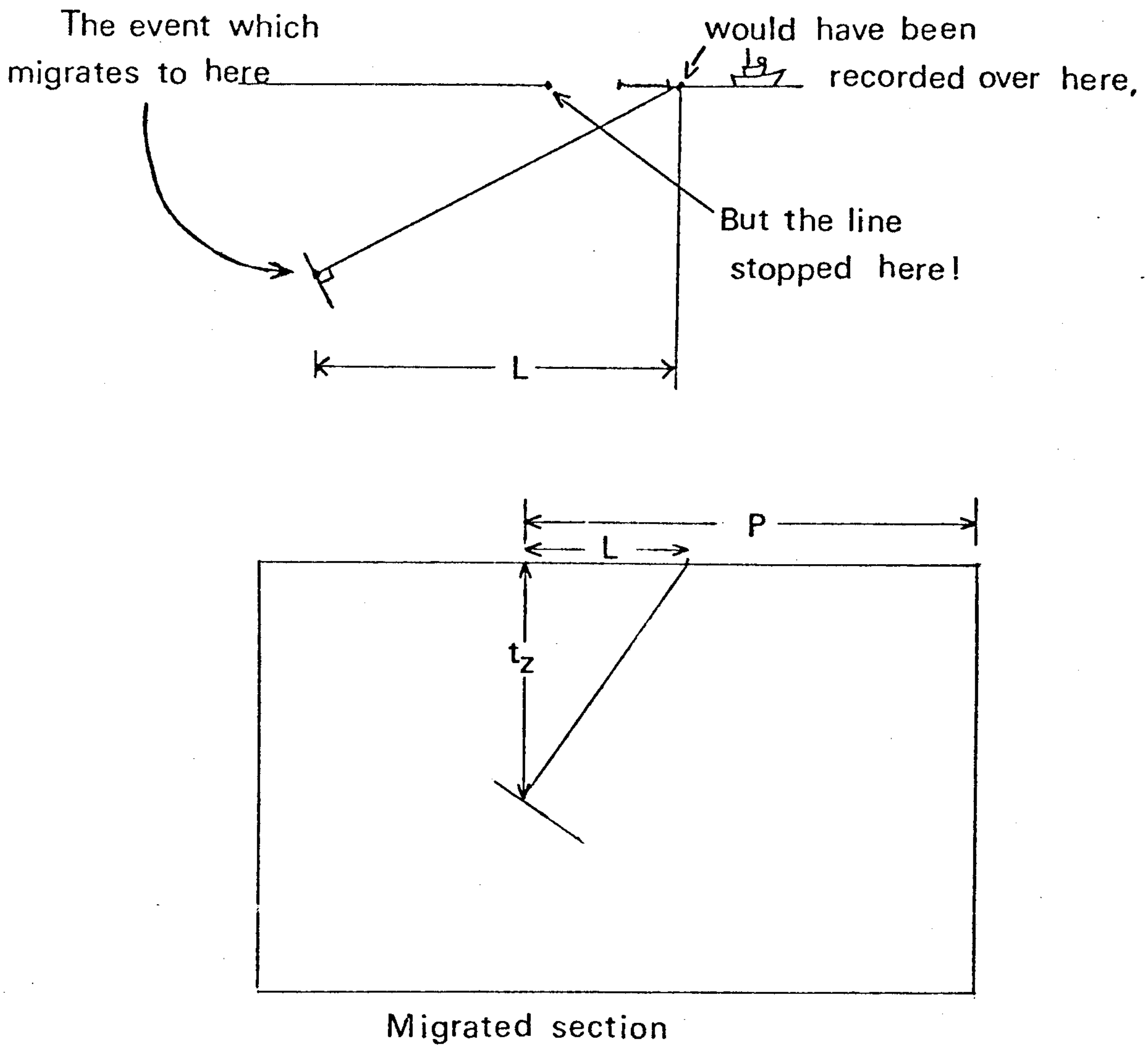


FIG. 1.3. Dip limitation imposed by line extent.

The only events to be recorded are those with

$$L \leq P \tag{1.5}$$

Using Figure 1.1, this may be rewritten as

$$\frac{Vt_z}{2} \tan \theta \leq P \tag{1.6}$$

$$\theta_{max} \leq \tan^{-1}\left[\frac{P}{\frac{1}{2} Vt_z}\right] \quad (1.7)$$

Form of Limitations

Equations (1.4) and (1.7) permit the maximum dip recorded as a function of either recording time limit or line length to be graphically determined, as shown in Figure 1.4. Figure 1.4 is the most important figure in the paper. It yields the instep (on both sides) and maximum recording time required to see up to a given dip at a given depth. To interpret the curves in Figure I.4 for a generalized migrated section is straightforward and shown in Figure 1.5.

Perhaps the easiest way to view the dip limitations is by contouring the maximum dip allowable for a given line length and recording time: Figure 1.6 illustrates the dip limitations for a typical COCORP migration (50 km, 16 sec input). The placement of the slanting lines originating at (0,0) in the upper right corner is governed by the distance from the edge of the line, *i.e.*, the instep. The flat lines (lower left) represent the recording time limitation.

The edge effect observed on migrated sections, that north dips are not seen on the north end of the line and vice versa, is shown in the region of slanted lines. If north is hypothetically to the right, then south dips may be seen right up to the north edge, but not north dips. This dip selectivity as observed on migrated sections can affect the interpretation. Dips of either sense are seen in the areas with horizontal lines (flip the figure on its vertical axis at the 50 km mark). For a seismic experiment designed to image the crust to 30 km with up to 30-degree dips, Figure 1.6 indicates that a step-in of 17 km is needed (on both sides). (To convert sec to km, assuming an average crustal velocity of 6 km/s, multiply by 3.) To image with up to 45-degree dips at 30 km depth, a step-in of 28 km is necessary (which implies that the migrated section is considerably longer than twice 28 km, or 56 km). To remove edge effects (the area of slanted lines), the step-in necessary

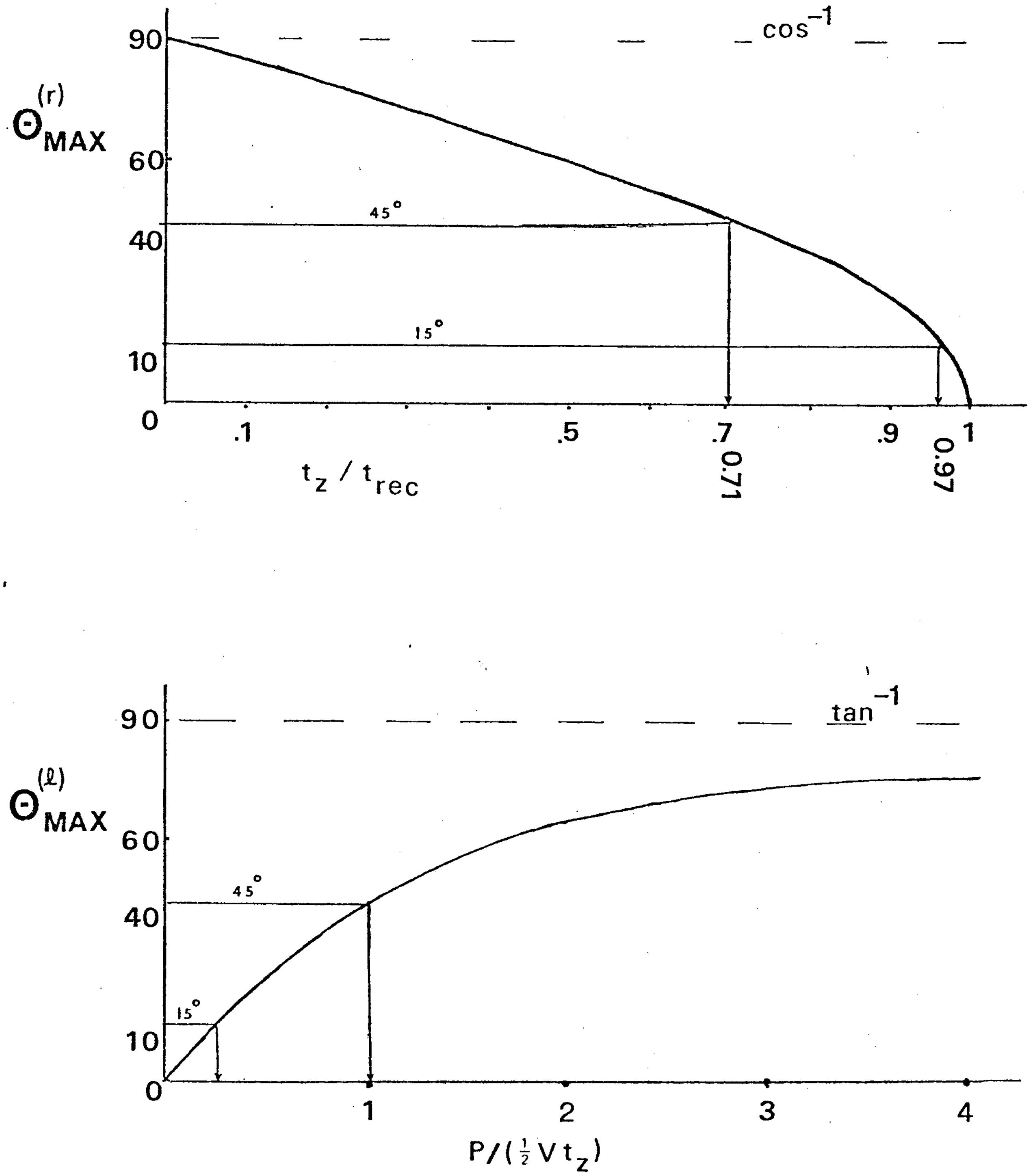
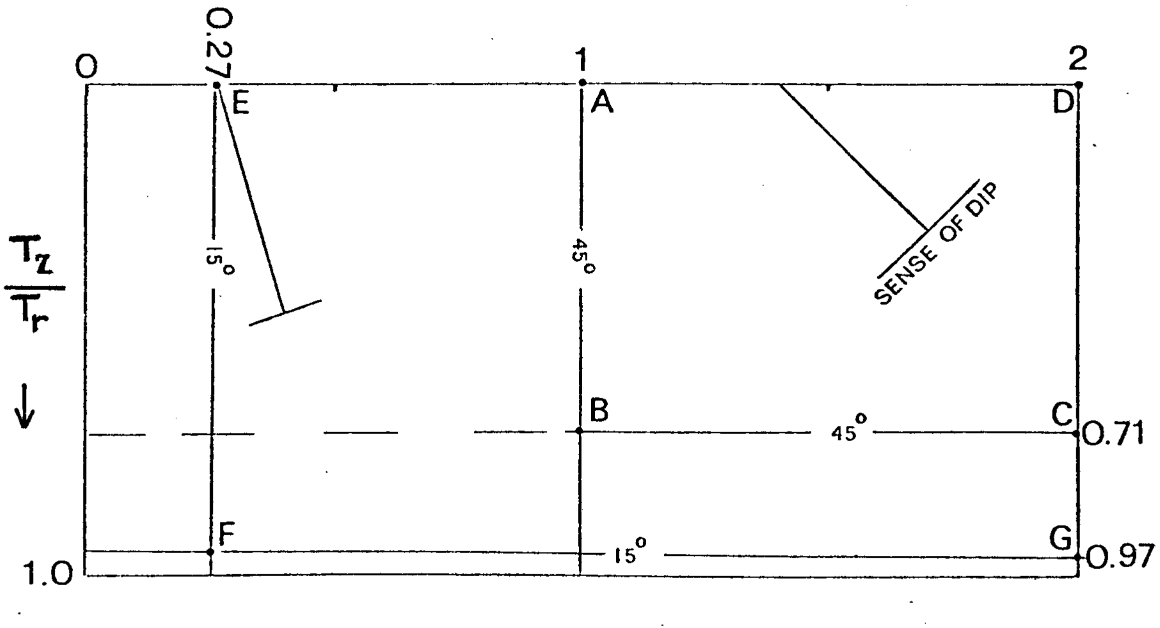


FIG. 1.4. Maximum dip obtainable on a migrated section as functions of recording time $\left[\frac{t_z}{t_{rec}}\right]$, $\theta^{(r)}_{max}$, and line length $\left[\frac{\text{instep} = P}{\text{true depth}}\right]$, $\theta^{(1)}_{max}$. Analysis applicable to depths where offset is negligible compared to distance traveled and assumes straight raypaths.



MIGRATED DEPTH SECTION

FIG. 1.5. Dip limitations on a migrated depth section. Rectangle ABCD represents the only region in which real dips greater than 45 degrees may be observed (dipping down from right to left). Rectangle EFGD is the corresponding one for 15-degree dips. For dips in the opposite sense, simply flip the figure about the vertical axis. If dips up to 45 degrees are desired at a certain depth, then a lead-in equal to prospect depth must be obtained on both sides, as well as record for at least 40% more time than the vertical traveltime to that depth.

for 15 degrees is 12 km, which allows imaging with that resolution to 45 km depth; for 30 degrees is 23.5 km, which allows imaging to 40 km; for 45 degrees, the step-in is 33.3 km, which allows imaging to 30 km.

Note that two approximations were made in this analysis of dip limitation. The two approximations have opposite effects: one underestimates the dip recordable, and one overestimates the dip recordable. The straight ray approximation yields a pessimistic view of the dips recordable. Due to the bending of the rays when velocity increases downwards, it will be possible to see steeper dips on the edges of migrated sections than here indicated. The zero-offset approximation, *i.e.*, offset is much less than the distance traveled, yields an optimistic view of the dips recordable at the line's edges when depths are approximately equal to offsets. With non-zero offsets, the maximum dip calculated in this analysis would be greater than that actually seen at the line's

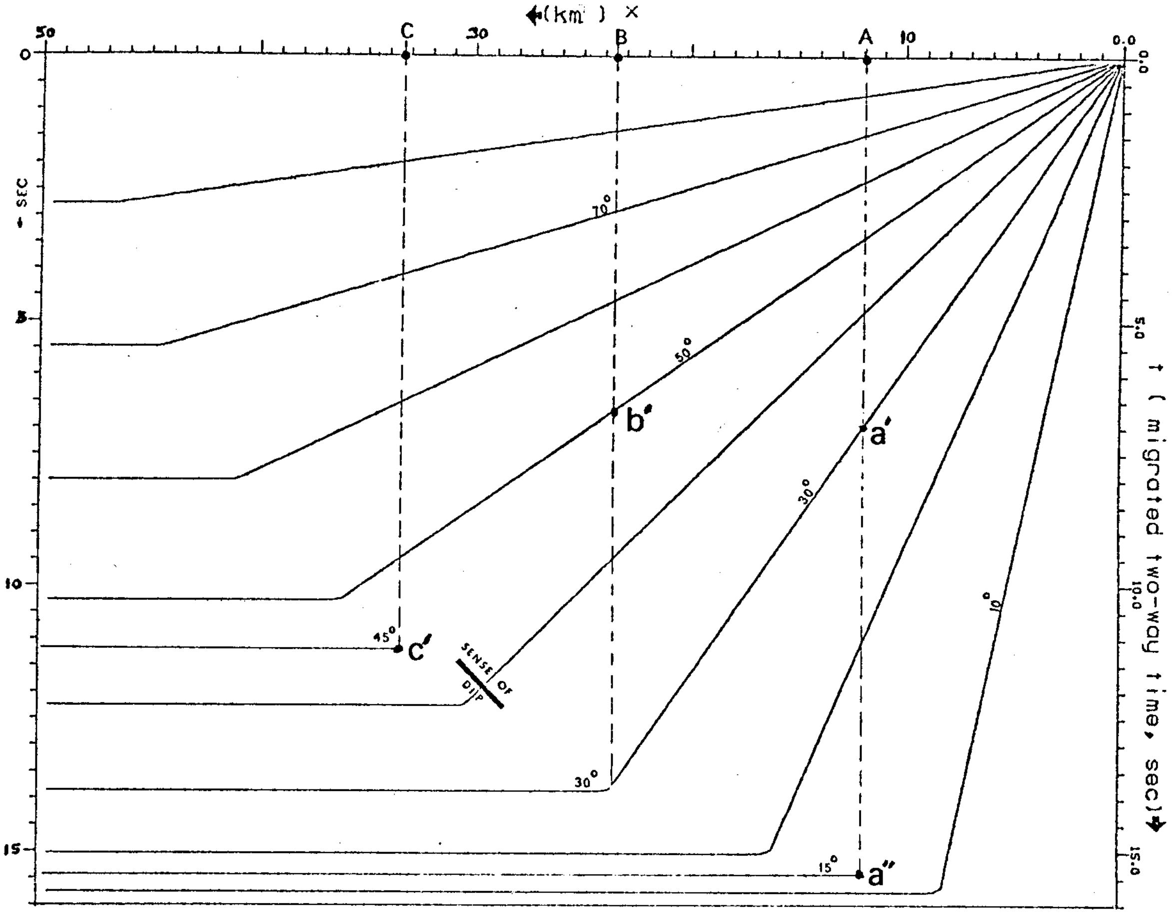


FIG. 1.6. Contours of maximum dip recordable for a migrated line (50 km by 16 sec). Pt. A is the 12 km step-in necessary to see 30-degree dips to 21 km (7 sec), pt. a', and 15-degree dips to 46 km (15.5 sec), pt. a''. Pt. B is the 23.5 km step-in need to see 50-degree dips to 21 km (7 sec), at b', and 15-degree dips at 46 km. To see 45-degree dips at 33 km (11 sec) a 33.3 km step-in (Pt. C) is needed as shown at c'. To obtain the limitations for dips of the other sense, flip the figure on its central vertical axis.

edges (Figure 1.7). The limitations of recordable dips when offsets are approximately equal to depths are governed by other factors, such as geophone group spacing, frequency content of input signal, cable length, maximum depth of interest, and velocity structure of area, as discussed by French (1977), and others. More validity is lent to this analysis by the one approximation underestimating and the other overestimating the maximum dip recordable.

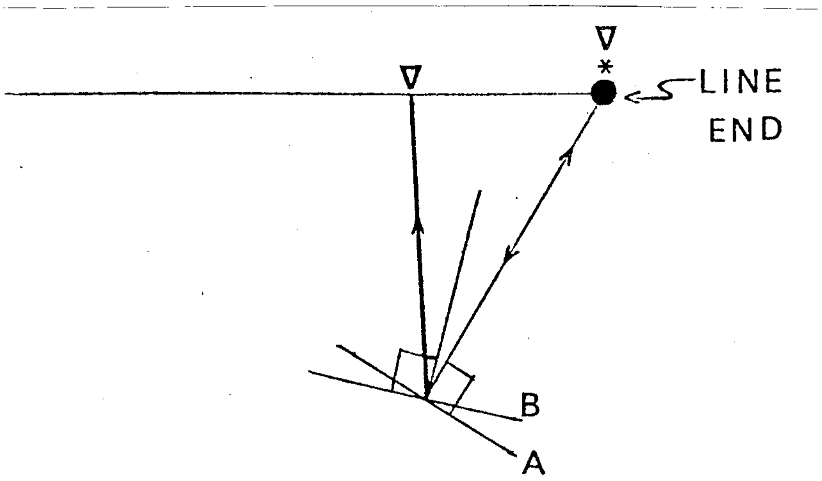


FIG. 1.7. At the edges of the line, there is a decrease in maximum dip recordable as offset increases. Zero offset is an optimistic assumption when calculating the maximum dip recordable (reflector A) at the edge of a line. Non-zero offsets reduce the maximum dip recordable (reflector B).

APPLICATIONS

General Deep-Crustal Migrations

Typical COCORP profiles are 50-200 km in extent and 16-20 sec long. The crookedness of some profiles complicates their migration considerably. When the line significantly deviates from linearity, two possible options are: 1) divide the line into linear portions, and migrate the segments, which drastically lowers the imaging power (degree of dip observable) on the migrated profiles, or 2) straighten the line such that the feature(s) of interest are made approximately true dip in the plane of the section. This second technique assumes the feature(s) of interest to be 2-D, and was used to image the Wind River (WR) thrust to 32 km depth (Chapter 3). Not particularly straight 200 km - 20 sec lines have been gathered, but a 50 km - 16 sec line is the maximum amount we currently migrate in one piece. The dip limitations for this size dataset are shown in Figure 1.6. The edge effects on deep-crustal migrated data were circumvented by having ~20 km (40%) overlap on the migrated sections and using only the middle sections of a migrated dataset for interpretation.

The Migration of a Segment of COCORP Data

The depth migration of a 31.4 km (19.5 miles), 6 sec, dataset (Figure 1.8) was used to help interpret the nature of the WR thrust in the upper crust (see Chapter 3). This input size is comparable to that of petroleum-industry migrations. The migrated data shows the last NE dipping reflection from the WR fault to be at Pt. A, ~11.5 km (~3.8 sec), ~6.4 km from the NE side of the section. Is the lack of NE dips in the lower right corner due to geology, or to the data recording limitations?

Figure 1.9 graphically provides the answer: 28 degrees (and lower) is the maximum dip obtainable given the length of the input profile (which had NE dipping reflectors all the way to the edge of the section). The average dip of the WR thrust is 35-30 degrees, and so NE from pt. A (Figure 1.8), the lack of WR thrust reflection is due to the shortness of the input to migration. On the longer migrated lines over this same region, reflections with apparent dips of 30-35 degrees off the WR thrust were seen from 0-32 km depth.

Hardeman Cty., Texas COCORP Data

The test site for the COCORP experiment was at Hardeman Cty. Two lines 11 km long, and one line 17 km long were shot. The time migrations of those lines are presented and discussed in Chapter 2. Figure 1.10 shows the distribution of south dips obtainable on the migrated

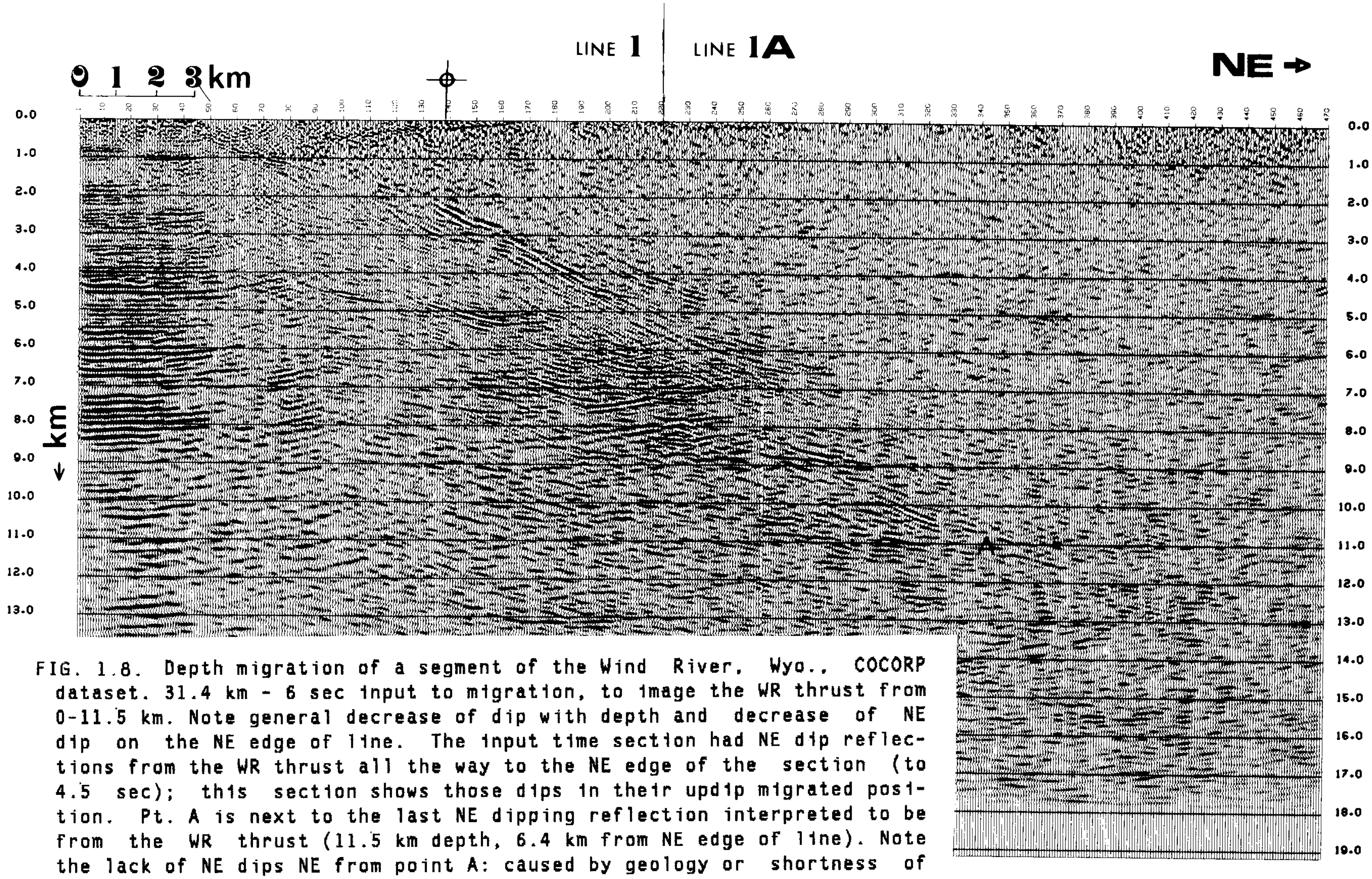


FIG. 1.8. Depth migration of a segment of the Wind River, Wyo., COCORP dataset. 31.4 km - 6 sec input to migration, to image the WR thrust from 0-11.5 km. Note general decrease of dip with depth and decrease of NE dip on the NE edge of line. The input time section had NE dip reflections from the WR thrust all the way to the NE edge of the section (to 4.5 sec); this section shows those dips in their updip migrated position. Pt. A is next to the last NE dipping reflection interpreted to be from the WR thrust (11.5 km depth, 6.4 km from NE edge of line). Note the lack of NE dips NE from point A: caused by geology or shortness of input?

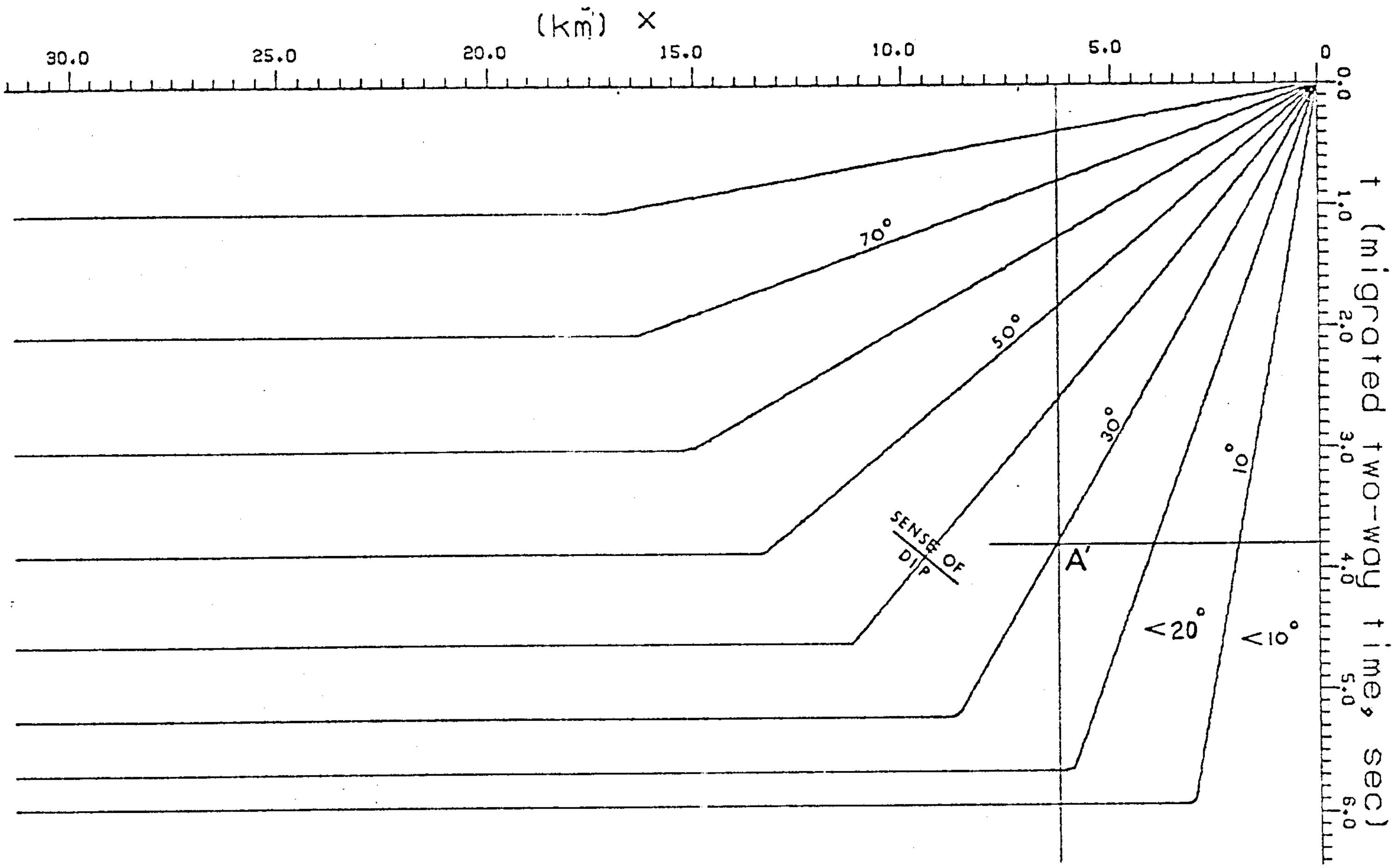


FIG. 1.9. Maximum dip contours (in 10-degree increments) given the input of 31.4 km, 6 sec to the migration, for the sense of dip illustrated. Pt. A' lies at the boundary where 30-degree dips begin to be non-recordable. The shortness of the input is causing the termination of WR thrust reflections northeastward of Pt. A, Figure 1.8.

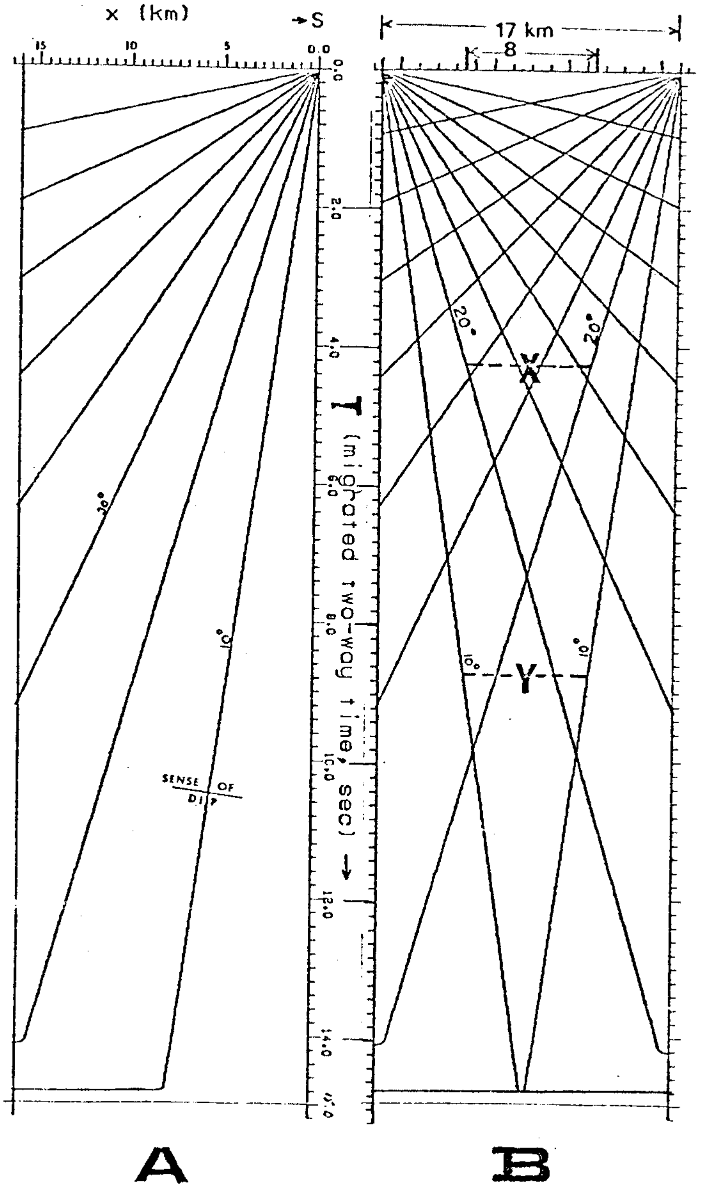


FIG. 1.10. A. A 1:1 representation of migrated Hardeman line 1, assuming an average 6 km/sec crustal velocity. The contours, 10-degree increments, are maximum south dip recordable on the migrated time section. The 0-degree dip contour is the southern edge of the section. This analysis assumes straight raypaths and depths >> offset.

B. Contours for dips of both senses, for Hardeman line 1. A dip segment drawn perpendicular to a contour indicates the sense of dip for which that contour applies (as shown in 1.9A). In the center 8 km, 20-degree dip in either sense is obtainable to 4.2 sec (dashed line at X), and 10-degree dip in either sense to 8.7 sec (dashed line at Y). The known dip limitations influence the seismic interpretation of the deep crust.

sections (10A) and the maximum dip of both orientations (10B). In the Hardeman dataset the length of line is the limiting parameter, not recording time, which is not surprising. Figure 1.10B shows that most of the line suffers from edge effects. From Figure 1.10B, we observe that in the center 8 km of line 1, 20-degree dip (either sense) is obtainable to 4.2 sec (~12 km), 10-degree dip (either sense) is obtainable to 8.7 sec (~26 km) and 5-degree dip (either sense) to 14.8 sec (~44 km). The middle 8 km of line 1 can be used to describe the seismic nature of the continental crust at Hardeman Cty., knowing the dip limitations imposed. The shortness of lines 2 and 3 so severely limits the dip recordable that their migrated sections are essentially useful for flat events directly under the line, and for dipping events on the sides of the line as qualitatively indicated by Figure 1.10B.

CONCLUSIONS

Seismic reflection data, especially deep-crustal data, need migration to portray dipping energy in its true location, collapse diffractions, remove distortions due to lateral velocity variations, and improve the signal/noise ratio. Migrated sections show a decrease of dip with depth and on the edges; a simple geometrical analysis shows that lateral extent of line and length of recording time limit the dips observable on a migrated section. The analysis assumes straight raypaths and offsets << reflector depth.

Both seismic profile planners and interpreters must consider these dip limitations. If profile planners wish to investigate the continental crust with resolution up to 30-degree dip at 30 km depth, and 16 sec is input to the migration, then a 17-km step-in (from the edge of the section) is needed on both edges. If resolution up to 45 degrees dip at 30 km depth is desired, a step-in of 28 km on both sides is necessary. Crustal seismic interpreters try to assign geologic significance to the length, degree of dip, and number of deep reflectors (or lack thereof); the interpretable signal on migrated sections can be only those dips allowed by the line length and recording time. 50 km--16 sec migrated

COCORP profiles image the earth with dips from 0-15 degrees to 46 km depth in the center 26 km of the section. The center 28 km of the migrated section will portray 0-20-degree dips to 30 km depth. The applications of this paper to hydrocarbon exploration are obvious and straightforward.

Among all geophysical methods, seismic reflection profiling offers the most resolution for investigating the continental crust. Processing, including migration, focuses this detailed picture of the crust; when the recording and processing limitations are known, the interpreter can assign geologic significance to the reflections which are geologically generated.

ACKNOWLEDGMENTS

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REFERENCES

French, William S., 1977, Migration and three-dimensional interpretation: Modeling and Migration, symposium of Dallas Geophys. Soc., February.

Phinney, R.A., and Jurdy, D.M., 1979, Seismic imaging of deep crust: Geophysics, v. 1979, p. 1637-1660.

Schilt, S., Oliver, J., Brown, L., Kaufman, S., Albaugh, D., Brewer, J., Cook, F., Jensen, L., Krumhansl, P., Long, G., and Steiner, D., 1979, The heterogeneity of the continental crust: results from deep crustal seismic profiling using the VIBROSEIS technique: Rev. Geophy. and Space Phy., v. 17, no. 2, p. 354-368.