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Velocity Gradients in the Continental Crust from Head-Wave Amplitudes[1]

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Abstract. Small velocity gradients in a refracting horizon have a pronounced effect on the spectral amplitudes of head waves. Negative velocity gradients and anelasticity (Q^{-1}) result in a similar amplitude decay with distance for narrow-bandwidth data. Positive velocity gradients result in a net amplitude gain with distance compared with the head wave from a homogeneous, perfectly elastic refractor. Wave-theoretical expressions for these effects applied to published amplitude data for the major crustal refraction branches, P_g and P^*, suggest that the 'granitic' crust in the Basin and Range province has either negative velocity gradients of the order of 10^{-2} km/sec/km or an anelastic Q of the order of 400, whereas the 'granitic' crust in the eastern United States and on the California coast has slightly positive velocity gradients. Similarly, the 'basaltic' intermediate layer appears to have a negative gradient of the order of 10^{-2} sec^{-1} under the Snake River plain and null or slightly positive gradients under Lake Superior and Mississippi. Velocity gradients inferred from laboratory measurements on granite and basic igneous rocks, together with published geothermal gradients, are generally consistent with the gradients inferred from amplitude data.

VELOCITY GRADIENTS AND AMPLITUDES

Recent wave-theoretical studies show that the spectral amplitudes of critically refracted waves (head waves) are quite sensitive to small velocity gradients in the refracting horizon [*Červený and Janský*, 1967; *Hill*, 1971]. Negative gradients and anelasticity (Q^{-1}) result in a similar amplitude decay with distance for narrow bandwidth data; positive gradients result in a net amplitude gain with distance with respect to theoretical amplitudes for head waves refracted from a homogeneous medium with infinite Q. These theoretical effects of velocity gradients on head-wave amplitudes are illustrated in Figure 1. The negative gradient case is based on asymptotic solutions obtained by *Hill* [1971]; the positive gradient case is adapted from *Červený and Janský* [1967].

In a preliminary attempt to determine the existence and distribution of velocity gradients in well-established crustal horizons, these theoretical results have been applied to published amplitude data for the major crustal travel time branches P_g and P^*. In this study, only first-arrival data for these branches are included.

RELATION BETWEEN Q' AND VELOCITY GRADIENTS

Effective Q values (hereafter referred to as Q') were computed for each amplitude data set by determining in a least squares sense the net gain ($-Q'$) or decay ($+Q'$) of the observed data with respect to theoretical head-wave amplitudes from homogeneous, infinite Q refractors. The results are interpreted in terms of negative velocity gradients for Q' values smaller than 10^3, null gradients for Q' values greater than 10^3, and positive gradients for negative Q' values as summarized in Table 1. Four examples of the amplitude data showing the least squares fit for Q' are given in Figure 2.

Q' VERSUS REGIONAL HEAT FLOW

The distribution of Q' values for the data considered is shown in Figure 3, together with regional heat flow contours presented by *Archambeau et al.* [1968]. From the figure, we see that

[1] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, Contribution 1914. Publication authorized by the Director, U. S. Geological Survey.

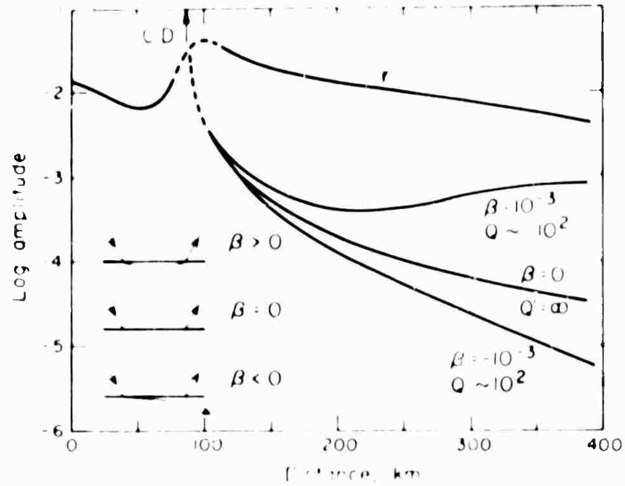

Fig. 1. Amplitude curves illustrating effect of positive ($\beta = 10^{-3}$ sec^{-1}), null ($\beta = 0$), and negative ($\beta = -10^{-3}$ sec^{-1}) velocity gradients on head-wave amplitudes, together with effective Q values (Q') with respect to the $\beta = 0$, $Q = \infty$ case. The reflected wave amplitude r, which is insensitive to small gradients in the refracting medium, is shown for reference. The arrow at C.D. indicates the ray-theoretical critical point. These curves were generated for 6-Hz waves in a 6.4-km/sec layer 30 km thick over an 8.0-km/sec half-space. The positive gradient case is adapted from *Červený and Jansky* [1967].

there is a general inverse correlation between Q' values and heat flow. Q' values in the 'normal' heat flow provinces of the eastern United States and west coast are greater than 10^3 or are negative; these values imply null or small positive velocity gradients for both the upper portions of the crystalline crust ('granitic layer') and the intermediate layer in these regions. Q' values in the Basin and Range high heat-flow province, which probably includes the Snake River plain, are generally smaller than 10^3. These low Q' values common to the Basin and Range province may be due to: 1, scattering of the critically refracted waves by relief on the refractor associated with Basin and Range faulting; 2, a temperature-dependent anelastic Q; or 3, negative velocity gradients in the upper portions of the crystalline crust associated with high geothermal gradients.

Available information is insufficient to quantitatively assess effects of the first two factors, and they remain as possible contributing factors. The third factor can be assessed quantitatively and is found to be consistent with the correlation between Q' and heat flow mentioned above. Heat flow studies suggest that the crustal geothermal gradients in the Basin and Range heat flow province is 30°/km or possibly somewhat higher [*Roy et al.*, 1968; *Lachenbruch*, 1970; *Minster and Archambeau*, 1970]. This geothermal gradient, together with partial derivative data for P-wave velocities in granites with respect to pressure, $(\partial V_p/\partial P)_T$, and temperature, $(\partial V_p/\partial T)_P$, measured in the laboratory [*Hughes and Maurette*, 1956], suggests negative velocity gradients of

$$\beta \sim -0.8 \times 10^{-2} \text{ km/sec/km}$$

in the 6.0-km/sec 'granitic' horizon of the Basin and Range province. The lower geothermal gradients (about 15°/km) that are associated with the 'normal' heat flow province, when combined with the same partial derivative data, suggest positive velocity gradients of

$$\beta \sim 0.5 \times 10^{-2} \text{ km/sec/km}$$

in the upper crystalline crust. Thus, the differences in velocity gradients in the upper part of the crystalline crust (P_g refractor) between the Basin and Range and eastern United States-west coast heat flow provinces inferred separately from P_g amplitudes and geothermal gradients are reasonably consistent.

Similar calculations using the partial derivative data for P waves in basic igneous rocks reported by *Hughes and Maurette* [1957] indicate that the 'basaltic' 6.7-km/sec intermediate layer has negative velocity gradients of

$$\beta \sim -1.6 \times 10^{-3} \text{ km/sec/km}$$

beneath the Snake River plain and

$$\beta \sim -0.3 \times 10^{-2} \text{ km/sec/km}$$

beneath Lake Superior and Mississippi. As before, a geothermal gradient of 30°/km is assumed for the high heat flow region (the Snake River plain) and 15°/km is assumed for the 'normal' heat flow regions (Lake Superior and Mississippi). These velocity gradients inferred from geothermal data are more negative than those implied by the Q' values obtained from P^* amplitude data in these regions (Table 1). If we accept this result at face value, then a compositional gradient (increasingly mafic with depth) is required in the upper parts of these intermediate layers to bring the velocity gradient estimated from the geothermal gradient

TABLE 1. Summary of Q' and Velocity Gradients from Crustal Amplitudes Data
Standard error refers to Q'^{-1} fit to amplitude data, β is velocity gradient, and 'null' and '+' β indicate zero and positive gradients, respectively.

Region and Profile	Phase	Q'	Q'^{-1a}	Std. Error in Q'^{-1a}	$\beta(\text{sec}^{-1})^a$	Source
Basin and Range						
Fallon-Eureka	P_g	471	2.10	0.91	−15	*Eaton* [1963]
Fallon-S.F.	P_g	760	1.22	0.36	− 9.7	*Eaton* [1963]
Fallon-Owens V.	P_g	−446	−2.2	1.16	+	*Eaton* [1963]
Eureka-Fallon	P_g	972	1.03	0.47	− 7.5	*Eaton* [1963]
Eureka-North	P_g	−1290	−0.77	0.88	+	*Hill & Pakiser* [1966]
Mt. City-South	P_g	403	2.48	3.71	−18	*Hill & Pakiser* [1966]
NTS-East	P_g	117	8.50	0.87	−26	*Ryall & Stuart* [1963]
California						
S.F.-Fallon	P_g	3810	0.262	0.076	null	*Eaton* [1963]
S.F.-S. Monica	P_g	−1580	−0.63	1.13	+	*Healy* [1963]
Camp Roberts	P_g	2860	0.349	0.87	null	*Healy* [1963]
S. Monica-L. Mead	P_g	230	4.34	2.17	−15	*Roller & Healy* [1963]
San Juan (6.06)	P_g	−47	−21.	4.9	+	*Stewart* [1968*b*]
San Juan (6.35)	P_g?	54	18.	3.7	−20	*Stewart* [1968*b*]
Colorado Plateau						
Hanksville	P_g	1260	0.795	1.02	null	*Roller* [1965]
Chinle	P_g	221	4.53	1.33	−16	*Roller* [1965]
Missouri						
Hannibal	P_g	−613	−1.63	0.86	+	*Stewart* [1968*a*]
Swan L.-Hannibal	P_g	−549	−1.82	0.54	+	*Stewart* [1968*a*]
Swan L.-St. Joseph	P_g	−1960	−0.511	0.633	+	*Stewart* [1968*a*]
St. Joseph	P_g	−475	−2.10	0.63	+	*Stewart* [1968*a*]
Mississippi	P^*	−382	−2.62	0.92	+	*Warren et al.* [1966]
Lake Superior	P^*	31,700	0.0315	0.604	null	*O'Brien* [1968]
Snake River plain						
Boise-South	P^*	337	2.97	0.84	− 4.4	*Hill & Pakiser* [1966]

^{a} 1 × 10^{-3}.

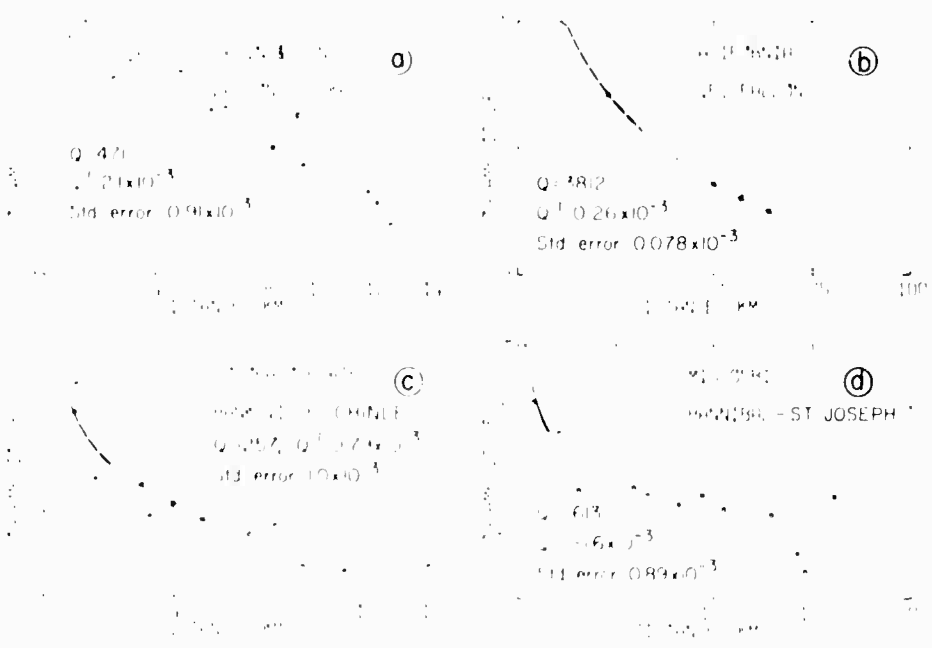

Fig. 2. Examples of P_g amplitude data in four regions: *a*, Fallon toward Eureka in the Basin and Range [*Eaton*, 1963]; *b*, San Francisco east in California [*Eaton*, 1963]; *c*, Hanksville north in the Colorado Plateau [*Roller*, 1965]; and *d*, Hannibal west in Missouri [*Stewart*, 1968*a*]. Continuous line is least squares fit for Q' through the amplitude data. Broken line shows amplitude decay with $Q' = \infty$ for comparison.

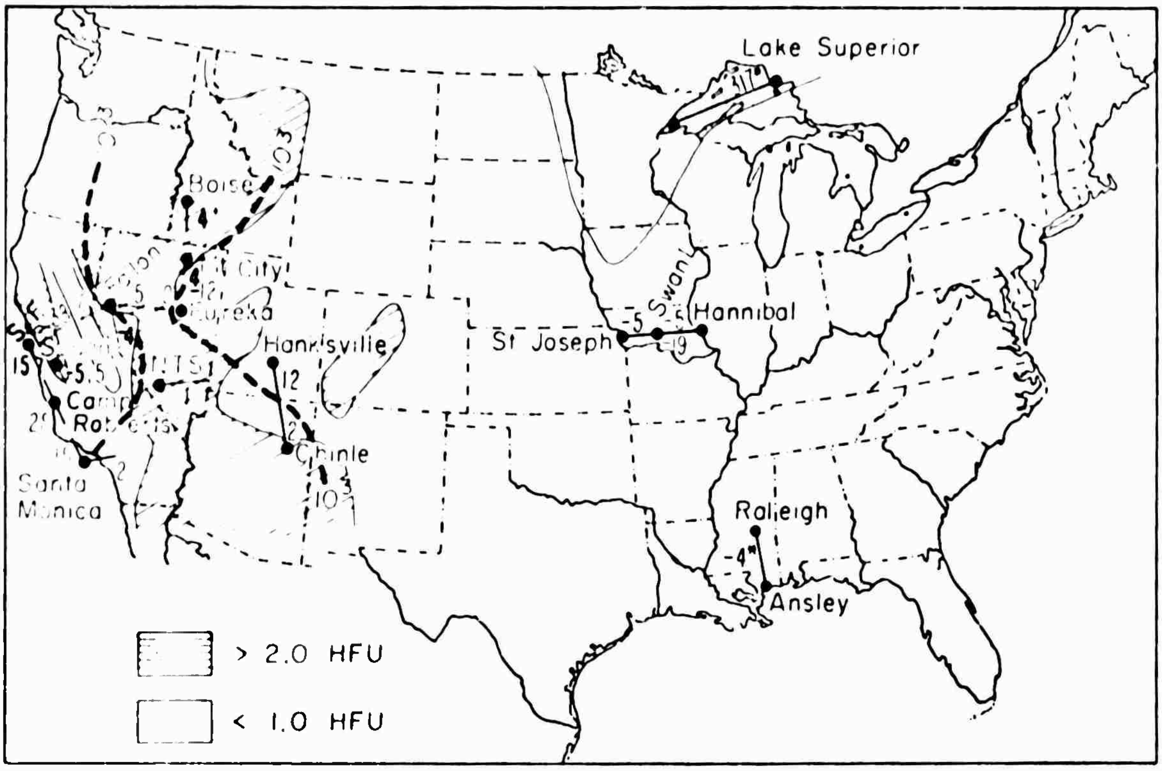

Fig. 3. Location of seismic profiles and the relation of Q' to heat flow. Number beside each profile is $Q' \times 10^{-2}$. The dark broken contour line separates the region in which Q' is less than 10^3 from that in which it is either greater than 10^3 or negative. Regional heat flow patterns are adapted from *Archambeau et al.* [1968]. Numbers associated with heat flow contours have units μcal/cm²/sec.

(e.g., -16×10^{-3} sec^{-1} in the Snake River plain) to the level of the velocity gradient estimated from Q' (4×10^{-3} sec^{-1} in the Snake River plain). However, neither the amplitude nor the thermal data are of sufficient accuracy to provide much confidence for this suggested compositional gradient in the intermediate layers.

CONCLUSIONS

Thus, on the basis of P_g amplitudes and thermal data, we conclude that a slight P-wave low velocity zone may exist in the upper crystalline crust in the Basin and Range high heat flow province and that such zones are unlikely in the eastern United States and west coast normal heat flow provinces. In the Basin and Range province, the crustal low velocity zone would have the form of a gradual decrease in velocity from the top of the crystalline crust downward (at a maximum rate of about 1×10^{-3} km/sec km) and would terminate rather abruptly at the top of the intermediate layer. The abrupt, pronounced crustal low velocity zone at depths of about 10 km of the type proposed by *Mueller and Landisman* [1966] could be present in either the Basin and Range province or the eastern United States, but such a zone would be difficult to detect using the data and methods described in this paper.

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DISCUSSION

Porath: You have a uniform 6.4-km/sec velocity for the Columbia plateau. Might you not expect a lower velocity at depth because the plateau basalts probably cover an ancient granitic crust?

Hill: The data only give the time it takes a *P* wave to travel from the Moho to the surface; there is no way of dividing the crust up into layers, so this is just an average velocity.

Meyer: Did you consider using a lower *Q* and positive gradient in the Lake Superior region?

Hill: All I did was to fit the homogeneous head-wave potential, derived from the amplitude data published by O'Brien, and make a least square solution for *Q*. This gives an estimate of the lower limit for the gradient and an upper limit for *Q*.

Higgins: What is the physical significance of a negative *Q*?

Hill: That is an artifact; in reality there must be a positive *Q* and a positive velocity gradient to give the amplitude increase.