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RECONSIDERATION OF THE RELATIONS BETWEEN S AND P STATION ANOMALIES IN NORTH AMERICA

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Abstract. The relation between S and P station anomalies is classically assumed to be linear. We reconsider this relation in the light of recent surface and body wave studies concerning the U.S., which suggest lateral variations of more than one independent physical parameter, such as thickness of a layer, in the first 200 to 300 km of the mantle. This implies breaking up the travel time data into provinces within which only one parameter can be assumed to vary. We apply this to U.S. data from ISC bulletins for the period 1964-73, and find that the new correlations are more easily interpreted in terms of known physical processes in the upper mantle.

Introduction

The correlation of S and P station anomalies across the U.S. has long been recognized, both P and S data yielding systematically early arrivals in the Central and Eastern parts of the continent and late arrivals in the West (Hales and Doyle, 1967; Hales and Roberts, 1970; Hales and Herrin, 1972). The (S) versus (P) correlation line has a slope of about 4, very high compared to the slope of $\sqrt{3}$ expected for a Poisson's ratio of $\sigma = 0.25$ and to the slopes obtained in other parts of the world (Kaila et al., 1968; Jeffreys and Singh, 1973). Such a high slope implies lateral variations of the ratio $k = \alpha/\beta$ of average P to average S velocities in the first 200-300 km of the Earth (or equivalently of the average Poisson's ratio) between the Western and Central U.S.. The lateral variations required are, however, too high to be explained satisfactorily in terms of known physical processes, even if a mechanism involving partial melting in the mantle is introduced (Hales and Herrin, 1972).

In this paper, we examine the relation between S and P station anomalies across the U.S., as obtained from the ISC bulletins for the period 1964-73, and as described in an earlier paper (Romanowicz, 1979a). We review the classical approach of determining the correlation between S and P station anomalies, which implicitly implies that the ratio of relative variations of P and S velocity $(\delta\alpha/\alpha)/(\delta\beta/\beta)$ is constant (Hales and Herrin, 1972). In this case, only one independent parameter is allowed to vary laterally. In view of the results from the inversion of surface wave data (Biswas and Knopoff, 1974; Cara, 1979) and P wave data (Romanowicz, 1979a), across the U.S., we investigate the consequences on the S versus P relations, when more than one parameter is allowed to vary laterally. We then apply the new relations to our data and discuss their physical meaning.

Theoretical Relations between (S) and (P) station anomalies

In what follows, we shall assume that the low velocity zones coincide in depth for S and P waves. We shall then discuss this assumption.

It is generally assumed that the relation of S to P station anomalies is linear. The problem is classically expressed in terms of average P and S wave velocities in the first 200-300 km of the mantle (Hales and Herrin, 1972). If H is the thickness over which the heterogeneities occur, and (α,β) are respectively the average P and S velocities in a reference model and (α',β') in another province, then if :

$$\alpha' = \alpha + \delta\alpha \qquad \text{and} \qquad \beta' = \beta + \delta\beta$$

the vertical travel time anomalies in the primed region will be :

$$\delta t_p = -\frac{H}{\alpha^2}\delta\alpha \qquad \text{for P waves, and}$$

$$\delta t_s = -\frac{H}{\beta^2}\delta\beta \qquad \text{for S waves,}$$

and thus :

$$\frac{\delta t_s}{\delta t_p} = \left(\frac{\alpha}{\beta}\right)^2 \frac{\delta\beta}{\delta\alpha} \qquad (1)$$

This ratio is constant if α/β is constant. In this case, the curve relating S to P station anomalies is a straight line whose intercept will be zero if the reference model is chosen adequately.

A simple one-parameter model illustrating this case, based on observations of variations of thickness of the lvz across the U.S. (Green and Hales, 1968; Biswas and Knopoff, 1974), would be to consider a two layer medium with velocities $(\alpha_1\ \beta_1)$ in the first layer, $(\alpha_2\ \beta_2)$ in the second, and an undulating interface, as depicted in Fig.1. Layer (1) could for instance represent the lid and layer (2) the lvz. Let z_0 be the depth to the lvz in the radially symmetric reference model with respect to which travel time anomalies are calculated, which is supposed to consist of two layers of constant thickness. Let us consider two regions A and B, for which we can define depth differences h_A and h_B between the interface and the reference level z_0 (see Fig.1.). Then, in region A :

$$\delta t_p = h_A(\alpha_2^{-1} - \alpha_1^{-1}); \quad \delta t_s = h_A(\beta_2^{-1} - \beta_1^{-1})$$

and in region B :

$$\delta t_p = h_B(\alpha_2^{1} - \alpha_1^{1}); \quad \delta t_s = h_B(\beta_2^{1} - \beta_1^{1})$$

so that $$\left(\frac{\delta t_s}{\delta t_p}\right)_A = \left(\frac{\delta t_s}{\delta t_p}\right)_B = \text{constant} \qquad (2)$$

which is a straight line passing through the origin , as in equation (1).

Now, a model involving the lateral variation of at least one more parameter is suggested by the comparison of results for Western and Central U.S. obtained by inversion of higher mode surface wave data (Cara, 1979) and P arrival data (Roma-

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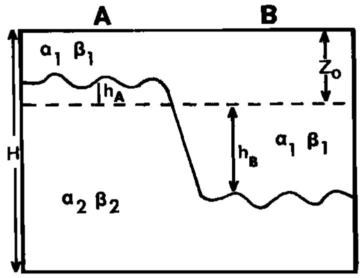

Fig. 1. Two layer model representing Western (A) and Eastern (B) U.S. when only one parameter, here depth to the mantle lvz, varies. The broken line represents the boundary between the two layers in the reference radially symmetric model.

nowicz, 1979a). The surface wave models are presented in Fig. 2a, and show that the lvz is much thicker and more pronounced in the West for S waves, while it is found that for P waves the velocity contrasts between the two provinces are much smaller. A simplified model is presented in Fig.2b. For P waves, the model is the same as in Fig. 1. For S waves, a lvz of average velocity $\beta_3 < \beta_2$ is introduced in the West (region A). The bottom limit of this additionnal layer is taken to be of fixed depth . Let us choose the reference model so that, in region B : when $t_p^B = 0$, then $t_S^B = 0$. Then, as previously :

$$\left(\frac{\delta t_s}{\delta t_p}\right)_B = \frac{(\beta_2^{-1} - \beta_1^{-1})}{(\alpha_2^{-1} - \alpha_1^{-1})} \quad (3)$$

Since $\beta_2 \neq \beta_3$, in region A, when $\delta t_p^A = 0$, then $\delta t_S^A = \delta t_s^A(0) \neq 0$. In fact :

$$\delta t_s^A(0) = D(\beta_3^{-1} - \beta_2^{-1}) \quad (4)$$

Also :

$$\delta t_p^A = h_A(\alpha_2^{1} - \alpha_1^{1})$$

$$\delta t_s^A = h_A(\beta_3^{1} - \beta_1^{1}) + D(\beta_3^{1} - \beta_2^{1}) \quad \text{or}$$

$$\delta t_s^A = \delta t_p^A(\beta_3^{1} - \beta_1^{1})/(\alpha_2^{1} - \alpha_1^{1}) + \delta t_s^A(0)$$

Comparing equations (3) and (5) we see that we obtain two different correlation lines for regions A and B, with slopes and intercepts depending on the value of β_3. As can be seen from equation (4), if $\beta_3 < \beta_2$, which is the case in the U.S., then $\delta t_S^A(0) > 0$. If one assumes that D is ≈ 100 km, with $\beta_2 \approx 4.5$ km/s and $\beta_3 \approx 4.1$ km/s, then the difference in intercepts $\delta t_s^A(0)$ will be ≈ 2s.

We have assumed here that the lvz for S and P waves coincide. If it were not the case, this would imply a further decoupling between S and P lateral variations of velocity at a given depth. For our purposes, we can adjust the average level of the boundaries of the lvz by adequately defining the average velocities α and β in each layer.

Application to Station Anomalies in North America

The data used are teleseismic P and S arrival times to U.S. stations, as read in the ISC bulletins for the ten years 1964-73. Among other considerations, we were careful to select events and stations for which averaging over a large set of data could compensate for the loss of accuracy when reading is not personnally done. A detailed account of the selection was given in a previous paper (Romanowicz, 1979a), in which Fig. 2 gives the distribution of events used, showing good azimuthal coverage around North America. Relative travel time anomalies were calculated with respect to the Jeffreys-Bullen Tables, "relative" meaning taking out the average, for each event , over all stations. To make sure such an average is meaningful, only those events were kept that were observed by at least 20 stations for P waves and 10 stations for S waves. Consideration of relative anomalies eliminates the problem of origin time versus depth uncertainty, and, to a large extent, subtracts contribution of source region structure. Station anomalies were calculated as the average of the relative anomalies over all events observed at the station. Table 1 lists S station anomalies, number of events and standard deviations of the mean. For P station anomalies, the reader is refered to Romanowicz (1979a). The correlation (S) = a(P) + b has been calculated by minimizing the sum of squares of distances to the line (York, 1965), with all stations listed in Table 1, except PHI, which has exceptionnally large P and S anomalies. The correlation is shown in Figure 3a :

$$a = 4.75 \pm 1.0 \quad ; \quad b = -0.25 \pm 0.14 \quad (6)$$

These values are in agreement with previous study of station anomalies across the U.S. (Hales and Roberts, 1970; Hales and Herrin, 1972). In order to interpret such a high slope, different processes including partial melting in the lvz have been suggested (Hales and Herrin, 1972). However, with the current knowledge about temperature and pressure dependence of upper mantle materials and the influence of cracks filled with liquid, it is very hard still, to account for a slope as high as 4-5.

In view of the theoretical considerations of the preceding section, it is interesting to introduce some regionalization in the area studied. One is naturally suggested by the distribution of P and S station anomalies, as well as other geophysical data, which suggest large lateral variations between Western and Central U.S. (to the East of 105°W, roughly, Romanowicz, 1979a). The results obtained when we distinguish western stations from others is shown in Fig. #b. The data distinctly separate into two oblate clusters whose axes are

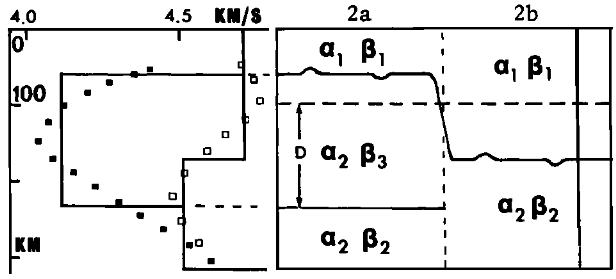

Fig. 2a. S velocity models for the Central (□) and Western (■) United States as obtained from a surface wave study by Cara (1979).

Fig. 2b. Simplified model corresponding to fig.2a. Notations are as in Figure 1.

not aligned. In fact, calculating the two correlations, we obtain, for the Western province :

$$a = 2.54 \pm 0.8 \quad ; \quad b = 0.6 \pm 0.07 \qquad (7)$$

for the Central-Eastern province :

$$a = 2.33 \pm 1.1 \quad ; \quad b = -1.1 \pm 0.10 \qquad (8)$$

These results show that the P and S station anomalies in North America are compatible with a model in which there is lateral variation of more than one independent parameter, as discussed above. The regionalization considered here reflects only the crudest large scale lateral variations in properties across the continent. Smaller scale variations of the elastic parameters may also exist, but there are too few data to reasonably distinguish scatter due to such variations from errors in the data. The simple, two layer model presented in Fig. 2b is well suited to explain our observations; it is however not unique, and could well be replaced by a model involving lateral variation of two other parameters. Other factors can contribute to the dispersion of data points around the correlation lines, such as non-coincidence of lvz, as mentioned previously, or azimuthal variations of travel time anomalies at stations. Such effects can be expected, in particular, for stations in or near a region of rapidly varying structure, such as GOL and LUB, or LON (Romanowicz, 1979b). Moreover, S readings from ISC bulletins are highly inaccurate, and may introduce serious bias. We have therefore investigated other data sets, from previous studies. The correlation lines obtained are presented in Fig. 4. Stations whose names are on the figure are excluded from the calculation; GOL and LON, among them, have just been discussed. The slopes obtained in each region are of the order of 2.5 and the difference in intercepts is ≃ 1.2 sec, which is compatible with our results.

Table 1. Relative S and P station anomalies in North America With Corresponding Number of Events Used and Standard Deviations of the Mean

Sta.	δt_s	N_s	σ_s	Sta.	δt_s	N_s	σ_s
AAM	-2.41	34	0.36	MRG	-0.25	29	0.40
ATL	-1.53	13	0.52	NEW	0.84	5	0.55
BKS	1.21	96	0.29	ORV	1.32	31	0.47
BLA	-0.51	45	0.21	OXF	-1.13	7	0.38
BMO	1.45	36	0.39	PAL	-1.61	74	0.30
CLE	-2.22	96	0.23	PAS	0.64	65	0.28
COR	1.13	8	0.86	PHI	1.35	13	0.77
CPO	-1.21	64	0.33	RCD	-1.19	17	0.61
CHI	-3.28	7	0.86	SLC	0.96	27	0.41
DUG	0.62	11	0.36	SLD	2.36	29	0.54
FAV	-1.82	4	0.32	SLM	-3.10	8	0.74
FAY	-1.49	25	0.47	SPO	1.50	16	0.59
FGU	1.29	11	0.66	TFO	1.95	71	0.26
FLO	-2.50	20	0.42	TUC	0.70	96	0.23
GEO	-0.93	44	0.33	TUL	-1.50	52	0.32
GOL	0.64	70	0.26	UBO	0.61	84	0.23
JAS	1.27	38	0.41	UKI	3.63	9	0.40
LUB	0.43	74	0.22	WES	-0.52	40	0.43
LON	0.98	27	0.37	WSC	-2.09	5	0.80

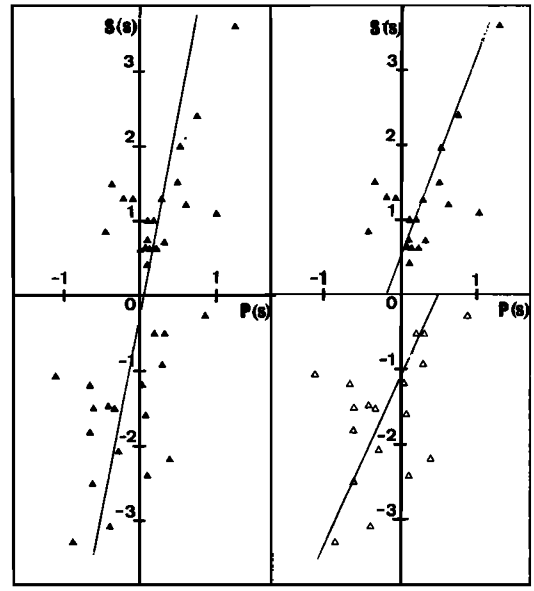

Fig. 3. S versus P relative station anomalies across North America. a) Correlation using all data (except station PHI). b) Correlation when separating Central (Δ) from Western (▲) data.

Discussion

The slopes obtained for the correlation lines can be discussed in the framework used by Hales and Herrin (1972). If one considers an initial model (α_0, β_0) corresponding to $\sigma = 0.25$, then the slopes obtained imply relative variations of P and S average velocities such that :

$$\frac{\delta\beta}{\beta_0} \simeq 1.5 \frac{\delta\alpha}{\alpha_0}$$

Such a value falls, in particular, into the range obtained for models involving the presence of liquid basalt in the form of partial melt in the lvz, as studied by Birch (1969), while Hales and Herrin (1972) found that such a mechanism was insufficient to explain a slope of $\delta t_s/\delta t_p$ of ≃4. The new interpretation thus permits to reconcile the data with possible physical processes responsible for them. In view of the models shown in Fig 3a and in equations (3) and (5), we would expect a smaller slope for the Central U.S., pointing out to a difference in anture of the lvz in the two regions. However , such a difference is not resolvable by the data, while the difference in intercepts is. It is compatible with the existence of a stronger relative contrast in S velocity than in P velocity between the two regions, in the upper 250 km of the Earth, as is shown by the studies of Romanowicz (1979a) for P and Cara (1979) for S.

We must now address the question of the physical meaning of such stronger lateral variations in S velocity. A large decrease in β while α remains approximately constant implies that the shear modulus decreases while the incompressibility modulus K increases, in view of the relations: $\alpha^2=(4K+3\mu)$; $\beta^2=\mu/\rho$, where ρ is density. For any ordinary solid, this seems difficult to achieve, and a model involving cracks partially filled with liquids (O'Connell and Budiansky,1974)

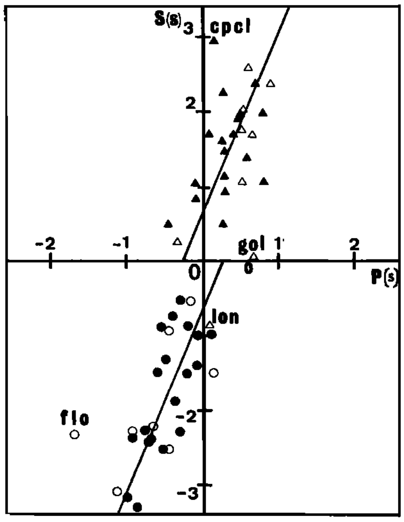

Fig. 4. S versus P station anomalies across the U.S. from previous studies :
- Sengupta and Julian (1978) West △ Center ○
- Cleary and Hales (1966) for P West ▲
- Hales and Roberts (1970) for S Center ●

is not pertinent here due to the high pressures involved. One possibility would be to investigate the behavior of the modulus K for mantle material with some assumptions about lateral variations in chemistry, such as the basalt depletion hypothesis for the lithosphere in old shield areas, as proposed by Jordan (1978). Also, while it seems difficult to account for 1-2 sec of time difference (intercepts separation of the two lines), by lateral variation of attenuation in the period range 1-10 sec, the emergent form of S waves in a region of high attenuation might be the cause of systematic errors in picking up travel times, which could increase the effect of attenuation.

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