Geol. Bull. Univ. Peshawar, 1985, Vol. 18, pp. 65–73

SHEAR WAVES PROVIDE AN EXTRA CONTROL ON SEISMIC INTERPRETATIONS

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ABSTRACT

Interpretation of shear wave arrivals in 40 km refraction line (LUST), by ray-tracing procedure, gives good correlation between Vs distribution and laterally varied lithology in the Precambrian Lewisian metamorphic complex of NW Britain. It provides an explanation for the Vp–spike detected in the uniform velocity environments of quartz-feldspathic gneisses of the northern belt, and Vp/Vs sheds more light on rapid velocity decrease in the retrogressed equivalents of pyroxene-granulites of the central belt. No evidence is found for shallow existence of pyroxene-granulites under the northern belt.

INTRODUCTION

In recent years shear waves have been commonly used in seismic work for the exploration of hydrocarbons, earthquake predictions, and crustal seismology. These waves differing from P-waves in physical nature and characteristics respond differently to varied conditions of porosity, saturation, saturating fluids, and lithology. For example, porosity of a rock reduces both velocities (Vp, Vs) but Vs appears to be more sensitive to pore aspect ratio (Tatham, 1982), under-saturation causes Vp to decrease more than Vs (O'Connell and Budiansky, 1974; Toksoz, *et al.*, 1976), and an increased amount of quartz in a rock would enhance Vs but suppress Vp. This differential behaviour of Vs is of great significance in explaining situation like Vp-over laps in different lithology. The Vp/Vs which fluctuates abnormally in such anomalous situations is likely to provide an invaluable tool for earthquake predictions (Aggarwal, *et al.*, 1975), the detection of gas saturaton from the zones where reflection amplitudes are unreliable (Tatham, 1976).

The emphasis in this paper is on the contribution of shear waves in solving lithologic problems which may not be solved by Vp alone. For that study the LUST (Lewisian Units Seismic Traverse) data are taken into account; LUST is a 40 km long refraction profile (Fig. 1) across laterally varied lithology of (central and northern belts) the Lewisian metamorphic complex of NW Britain,

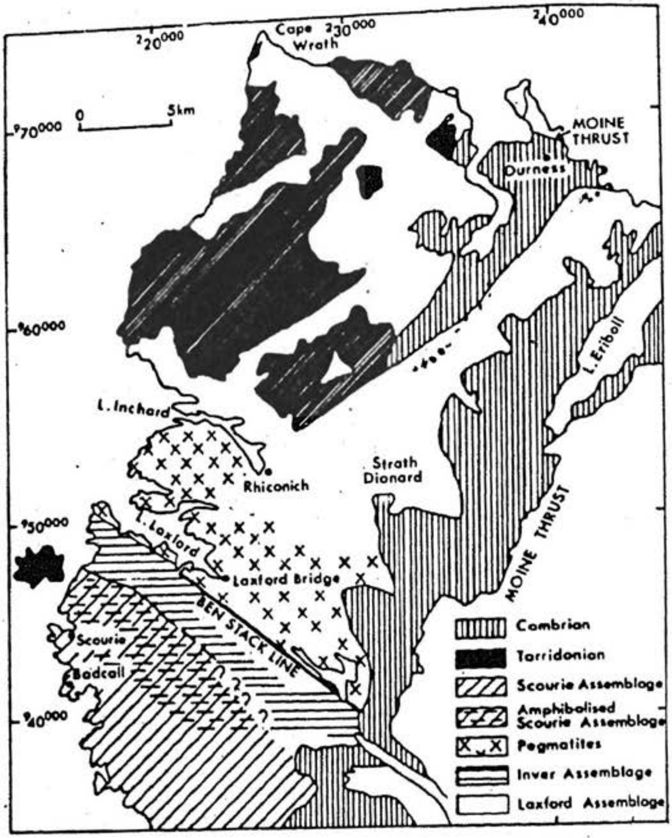

Fig. 1. Map showing refraction line (dotted) across different lithological units of the Lewisian Complex.
Laxford assemblage = Quartz-feldspathic gneisses
Scourie assemblage = Pyroxene-granulites
Amphibolised Scourie assemblage +
Inver assemblage = Retrogressed equivalents of Pyroxene-granulites.

and shot (underwater) from both ends (Badcall and Durness) and on two intermediate positions (Laxford and Inchard). Lithologically, the northern belt of the complex predominates in quartz-feldspathic gneisses (acidic composition) and contains some concordant amphibolite layers; the central belt comprises mainly pyroxene-granulites (andesitic composition) and retrogressed equivalents. The boundary between these two assemblages referred to as the Ben Stack Line, forms a crustal lineament and contains a concentration of granites and pegmatites (Pecah, *et al.*, 1907; Holland and Lambert, 1973; Bowes, 1978).

SHEAR WAVE VELOCITY MODEL

As the experiment was conducted with a conventional explosive source, the recorded shear waves are mode converted ones (P to S–waves), generated at only one interface, possibly the water bottom. The mode conversion in all the four shots is variable depending upon the angle of incidence and physical properties of the sea-bed sediments. The normalised, filtered shear wave (SV) data of one shot (Loch Laxford) is presented in Fig. 2 on reduced time scale, using reduction velocity 3.5 km/s. The time section shows the difficulty of picking S–arrivals as the quality of these waves is quite affected by the surrounding noise. The estimated (r.m.s.) error associated with the picking in all the four shots is ± 0.038s.

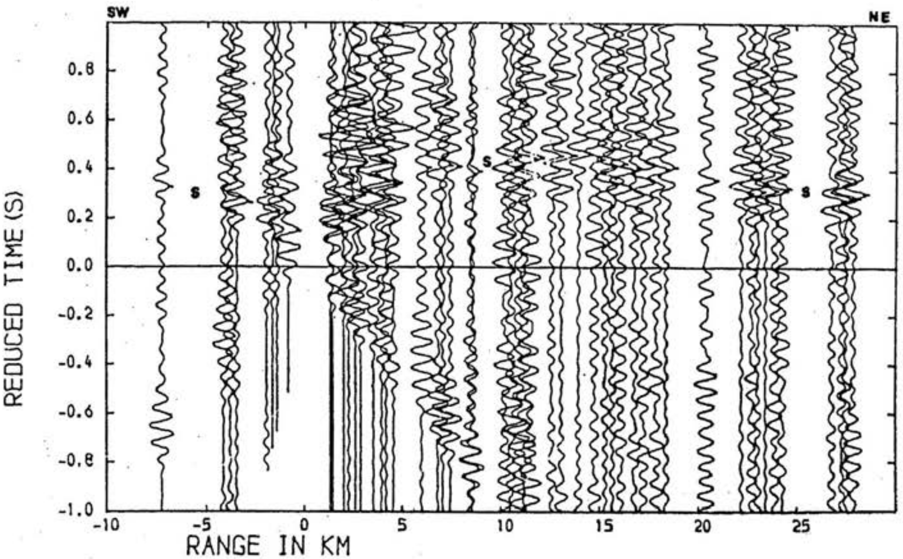

Fig. 2. Normalised, filtered, reduced time section of Laxford shot, showing S-arrivals.

The picked data presented in Fig. 3 on reduced time scale (reduction velocity 3.5 km/s) are corrected for the time delay (0.08s) of near-shot very low velocity sea-bed sediments.

It is to be noted that the T–X curves of all the four shots are smooth and continuous and characterise a continuous velocity variation in the area as a function of depth and range. Therefore, velocity modelling was done by ray tracing technique (Cerveny, *et al.,* 1974) using a set of velocity depth functions descriptive of lateral as well as vertical velocity changes without any discontinuity. The continuous lines of Fig. 3 passing through the observed data represent model curves computed iteratively by the programme for an optimised velocity distribution (Fig. 4) in the area. The apparent misfits at certain places (between 5 to 7 km range in Badcall shot, between 35 to 40 km range in Laxford shot, and between 15 to 20 km in Inchard shot) could be the result of wrong pickings, because every attempt to model them produced magnified misfits at other places. The observed data scatter around the model curves approaches zero-mean and a devia-

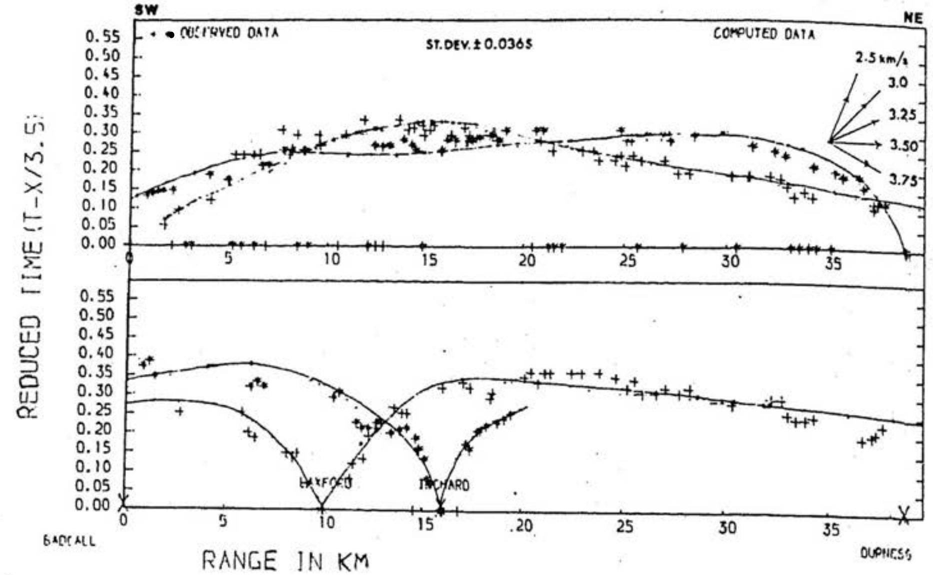

Fig. 3. Picked S-arrival times from the four shots, and fitted model curves computed by ray-tracing technique.

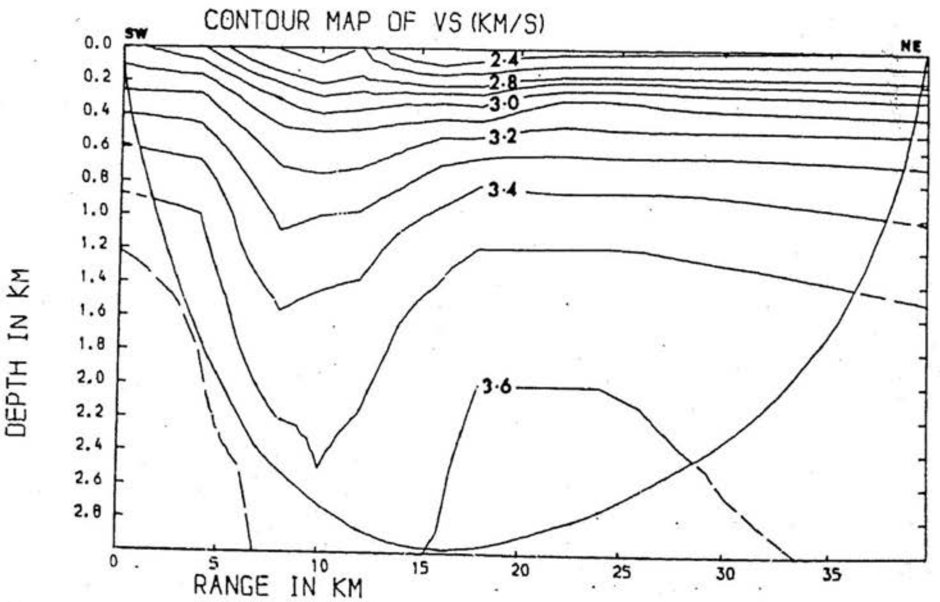

Fig. 4. Shear wave velocity (Vs) distribution showing lateral and vertical changes.

tion of ± 0.036s equivalent to an uncertainty associated with the pickings (0.038s). If the model is recommended on the basis of these observations, then the long wave-length variations in the computed curves are likely to represent real velocity variations in the Earth. The resulting shear wave velocity distribution of Fig. 4 is marked by a boundary which represents the path of deepest ray penetration (3 km depth), and separates sampled estimates (inside the boundary) from unsampled ones.

INTERPRETATION

The Vs-distribution in the area (Fig. 4) shows clearly the lateral as well as vertical velocity variations. The continuous increase of velocity with depth in vertical column is attributed to the closing of cracks in rocks due to overburden pressure (Toksoz, *et al.,* 1976), whereas the lateral change is associated with varied lithology. Over pyroxene-granulites of the central belt Vs appears high, but at 5 km to the south (across Scourie) it decreases rapidly in retrogressed schists and then progressively reaches a minimum over granites and pegmatites (Ben Stack Line). Further north, it rises and gives almost uniform estimates in quartz-feldspathic gneisses, relatively lower than those pyroxene-granulites. This correlation between Vs–distribution and lithology shows the sensitivity of shear waves to compositional changes. If this distribution is compared with Vp model of the area (Fig. 5) designed from P–arrivals data (LUST) using ray tracing (Hall, 1978), it becomes clear that the general pattern in both cases is almost similar except for the following differences :

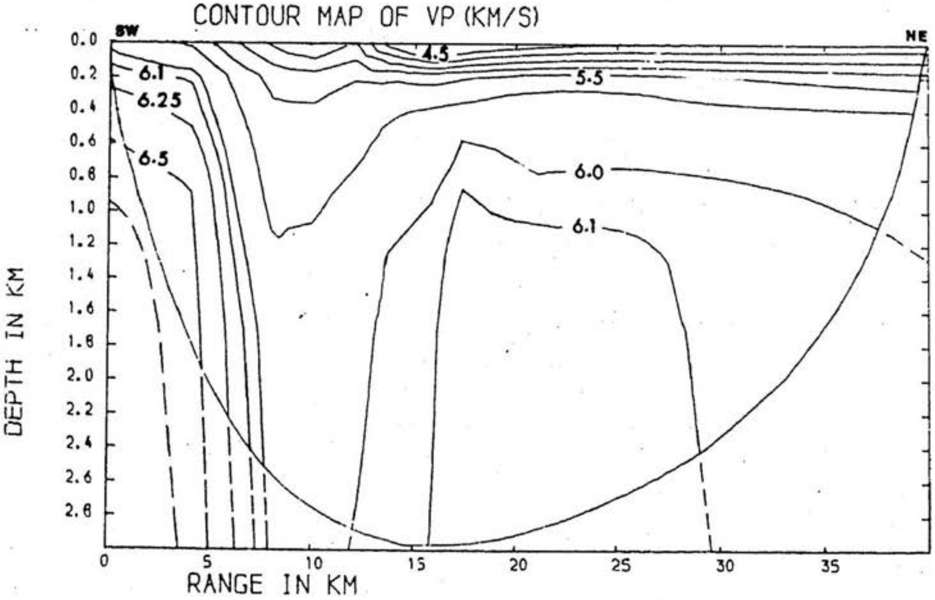

Fig. 5. Compressional wave velocity (Vp) distribution (after Hall, 1978).

i) Vs decreases more gently than Vp in retrogressed equivalents of pyroxene-granulites.

ii) Vs does not show a high velocity spike as exposed by Vp near Loch Inchard at a depth of 1 km.

It is obvious that Vp spiking is caused by a local compositional change in more acidic environments of quartz-feldspathic gneisses, this could be due to pyroxene-granulites or amphibolites. Because both being of high velocity can produce a velocity jump. The acceptable candidate would be that which satisfies conditions imposed by Vp and Vs, i.e., Vp should be much higher than that of quartz-feldspathic gneisses but Vs similar. For that finding the problem is treated quantitatively.

If rocks are defined, by a five mineral assemblage (quartz, plagioclase, k-feldspar, amphibole and pyroxene), and effective velocities (Vp, Vs) for these minerals are known, then the aggregate velocities (Vp, Vs) can be estimated for different rocks on the basis of Birch (1943) model given below.

$$V = 1 / \sum_{i=1}^{n} X_i / V_i$$

Where Xi is the volume percentage of ith mineral occupying the rock, and Vi is the effective velocity in that mineral. With the use of estimated effective velocities (Hall and Al-Haddad, 1979; Ali, 1983) and mean composition in the above mentioned treatment the aggregate velocities for different lithologies are given in Table–1.

TABLE–1 PREDICTED AGGREGATE VELOCITIES OF ROCK UNITS FOR THE MEAN COMPOSITION.

	Quartz	Plagio-clase	K-feld-spar	Amphi-bole	Pyro-xene	Predicted rock velocities		
Vp (km/s)	6.21	5.70	5.25	7.25	7.50			
Vs (km/s)	4.20	3.09	2.89	3.94	4.55			
Vp/Vs	1.48	1.84	1.82	1.84	1.65			
	% volumes of minerals					Vp (km/s)	Vs (km/s)	Vp/Vs
Quartz-feldspathic gneisses	30	25	20	20	5	6.10	3.53	1.73
Amphibolite	—	40	—	60	—	6.54	3.55	1.84
Pyroxene-granulites	10	35	10	10	35	6.50	3.64	1.77
Retrogressed equivalents	25	30	15	25	5	6.15	7.75	1.74

It can be noticed from Table–1 that Vp for amphibolitic composition is much higher than that of quartz-feldspathic gneisses but Vs is similar. Pyroxene granulites, on the other hand, offer higher Vp as well as Vs. In the view of this estimation the most probable explanation for Vp-spike in the zone of almost flat Vs is the existence of concealed amphibolite body (not pyroxene-granulites) below the acidic gneisses which may have a link with the exposed amphibolite complex. This confirms Hall's (1978) view that there is no evidence for shallow (upto 2 km depth) existence of a substantial body of pyroxene-granulites under the northern belt. It is interesting to note that Vp and Vs for retrogressed rocks are very similar to those of acidic gneisses (Table–1). This suggests that if retrogressed rocks underlie the gneisses the detection of the interface would not be possible by seismic methods.

As far as retrogressed equivalents of pyroxene-granulites in the central belt are concerned, it appears from Table–1 that (in reconstitution of minerals in retrogressive metamorphism) the reduction in velocities (Vp, Vs) are due to increased contents of quartz and amphibole at the expense of pyroxene. The Vp/Vs distribution (Fig. 6) obtained from the combination of Vp and Vs models gives a

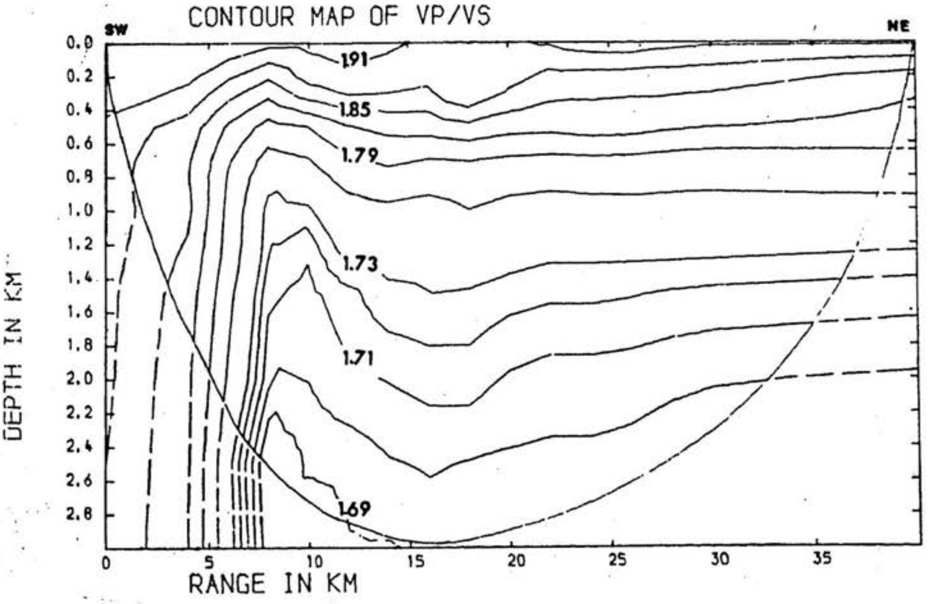

Fig. 6. Distribution of Vp/Vs in laterally varied lithology.

resolved picture of the area, the dominant lateral and vertical variational trends in central and northern belts, and shows a progressive lateral decrease (north wards) in these rocks. If replacement of pyroxene by amphibole is supposed to be the only mineralogic change in retrogression then theoretically Vp/Vs should give a gradual increase. But the observation is opposite. This suggests that quartz would be the other variable whose extremely low Vp/Vs (1.48) overshadows the effect of amphibole increase. The situation is clarified in Table–1, i.e., the increased volume percentage of amphibole when counteracted by the addition of similar amounts of quartz in the composition of retrogressed rocks, the Vp/Vs is decreased. The small interchange in feldspars as compared to feldspars component of pyroxene-granulites causes negligible effect on Vp/Vs. It is, therefore, inferred that retrogressed rocks are subjected to gradual increase of quartz alongwith amphibole (northwards) at the expense of pyroxene content.

CONCLUSIONS

1– The correlation between lateral lithological changes and shear wave velocities suggests a potential of shear waves to enhance geological modelling.

2– Near Loch Inchard, the detected Vp–spike is probably due to a concealed amphibolite mass instead of pyroxene-granulite masses.

3– The progressive decrease in Vp/Vs (northwards) in retrogressed rocks seems to be the result of an increased component of quartz in retrogression.

4– The possibility of shallow existence of pyroxene-granulites under quartz-feldspathic gneisses of the northern belt does not apply.

5– If retrogressed rocks exist under quartz-feldspathic gneisses, the detection of the interface, seismically, is not possible.

Acknowledgements: The author is thankful to Dr. J. Hall (Glasgow University, U.K.) for invaluable suggestions in the course of work, to Dr. Altan Necioglu and Mushtaq A. Khan (Department of Earth Sciences) for critical review, and M. Nazir for giving typing help.

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