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RECORD No. 1963/38

SEISMIC WAVE VELOCITIES IN THE NEW GUINEA/SOLOMON ISLANDS REGION

by

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CONTENTS

ILLUSTRATIONS

SUMMARY

Independent values of the velocity of P waves have been determined to a depth of 500 km below the New Guinea/Solomon Islands region from an empirical study of the arrival times at the surface from 185 earthquakes.

The existence of a low-velocity channel with an axis at a depth of 150 km, where P waves may be transmitted at a velocity of 7.6 km/sec, is inferred.

The use of USCGS preliminary earthquake epicentres, origin times, and depths has confirmed that the reliability of these data have increased since they were determined by electronic computer.

1. INTRODUCTION

The velocity distribution of both P and S waves, particularly in the upper 500 km of the Earth's mantle, is a fundamental seismological problem. Its solution has been complicated by suggestions of the existence of a low-velocity channel in the upper mantle (Gutenberg, 1948, 1953, and 1959b; later studies of surface-wave dispersion by many authors). In the upper part of the mantle, where earthquakes occur, velocity variations with depth can be studied by direct observation of P and S wave arrival times.

Although the area of the Pacific that contains the arcuate structures of New Guinea, New Britain, and the Solomon Islands (Plate 1) is one of the most active seismic areas of the world, there has been little opportunity owing to a shortage of local seismic stations, for a detailed study to be made of its seismicity and tectonic features as revealed by seismological records. The seismic stations now operating in the area (see Plate 2) are Rabaul (commenced in 1939), Charters Towers (1957), Port Moresby (1958), Honiara (1960), and Darwin (1961). The station density over the area (35 degrees of longitude by 10 degrees of latitude) is still inadequate and offers only limited scope for quantitative examination by seismological methods of any physical characteristics of the area; the scope is further limited by the capabilities of the instruments at some of the above stations.

Nevertheless, sufficient data have accumulated from recordings of earthquakes that occurred in the area between July 1960 and May 1961 (Plate 2) to allow investigation of the velocity/depth relation for P waves. This has been facilitated by the high frequency of earthquake occurrence, together with a very wide range of focal depths encountered in the area.

Relative seismicity of different areas is not necessarily indicated by Plate 2, as no account is taken of earthquake magnitude and the period of observation is short.

The substance of this Record was presented at the Tenth Pacific Science Congress, Honolulu 1961.

2. OBSERVATIONAL DATA

The observational data used in this investigation are conveniently summarised in a series of graphs showing travel time as a function of distance (Plate 3). These graphs were plotted from P wave arrival times listed in preliminary station bulletins together with pertinent data extracted from USCGS 'Preliminary Determination of Epicentre' cards, which had been compiled with an IBM 650 computer since July 1960. Epicentral distances were individually calculated using direction cosines. Owing to the high frequency of earthquake occurrence, it has been possible to group 185 shocks, having focal depths from 13 to 516 km, into 10 depth ranges. By using results from four stations, the epicentral distance range 0 to 25 degrees (over which the form of the curve, arrival time against distance, must be ascertained) has been covered for each group of shocks.

The graphs use a vertical scale of the form $t - k\Delta$ to accentuate the change in slope of the travel-time curve on each side of the point of inflection, and this allows a more accurate interpretation to be made of the slope of the adopted curve at this point. The value of k is chosen so that the portion of the travel time curve in the vicinity of the point of inflection, is nearly horizontal.

For this investigation, data relating to all the earthquakes, listed on the USCGS cards have been given equal weights regardless of magnitude.

Some uncertainty is involved in assessing a curve of best fit for each group of plotted points (travel-time curve) but the uncertainty is reduced by the fact that the two shoulders of each graph (e.g. the h=65 km graph) are in general more clearly defined than the central section and thus give a guide to the limits of slope of the critcal centre section (which contains the point of inflection). To minimise errors in such interpretation, each group of points was plotted three times, using a slightly different value of k in the y-axis scale in each case, to ensure a variation in the relative positions of these shoulders. The resulting three velocity values agreed to within 0.1 km/sec for most groups (Table 1).

3. INTERPRETATION

A method first suggested by Gutenberg (1953) has been applied to deduce values of velocity at the nominal depths representing each group of shocks. Its validity depends firstly on the ray theory to explain the propagation of energy from earthquake foci, secondly on the fact that the wave velocity is a function of focal depth, but remains constant in the horizontal plane at a given depth, and thirdly on the continuity of the travel-time curve observed at the surface over the range of epicentral distances considered, at least as far as its point of inflection.

Briefly, Gutenberg showed that under these conditions the velocity (V_h) of P or S waves at depth h is simply related to the minimum value of the apparent velocity (V_{min}) observed at the surface.

$$V_h = V_{min} \cdot r_h / r_o$$

where r_h = distance from depth h to centre of Earth

r_o = Earth radius (6378 km)

He determined a velocity/depth relation for both P and S waves by examining the reported arrival times of P and S waves at a large number of stations for about 80 earthquakes of varying focal depths.

In the current investigation, Gutenberg's method has been applied with slight modification to earthquakes in the New Guinea/Solomon Islands region to determine whether his general results apply to such a restricted area as this. From the mean minimum apparent velocity estimated from the graphs for each nominal depth, the velocity of the ray leaving the focus horizontally has been calculated. The reduced results for P waves are illustrated by Plate 4 and those for S waves by Plate 5. S wave velocities are presented for the sake of completeness only and are considered much less reliable than the P wave velocities.

In Plates 4 and 5, a comparison is made between the velocity distribution inferred for the New Guinea/Solomon region and distributions suggested by Bullen (1947) and Gutenberg (1953). These plates also compare Bullen's theoretically determined velocity distribution with that obtained by treating the standard tables (Jeffreys and Bullen, 1948) as a series of actual observations and computing a velocity distribution using the graphical method described above.

4. DISCUSSION

Only the data representing P wave arrivals will be discussed because they are more comprehensive and therefore can be more reliably interpreted than those for S waves.

It appears (Plate 4) that the region of low velocity in the New Guinea/Solomon region may be thicker and have a lower minimum value of velocity (which is reached at a greater depth) than found by Gutenberg. Also, it may be noted that the rate of decrease in velocity is greatest for the depth range 75 to 150 km and exceeds the critical rate $(-dV/dr = v/r)$ of 0.1 km/sec per 100-km depth, which is sufficient to cause a ray entering such a region to be refracted downwards (i.e. with a radius of curvature less than the radius of that depth). A shadow zone could thus be produced at the surface, and consequently, a discontinuous travel-time curve having two branches (Bullen, 1947; Gutenberg, 1959a and b). It is therefore probable that the inflection points (corresponding to V_{min}) on the 90, 115, and 135-km graphs lie in shadow zones and the values of V_{min} are in fact interpolated. Nevertheless the resulting V_h values should still be close to the actual value of velocity at the depth concerned (Gutenberg, 1959b, p.442). Certainly it is difficult to concede that V_h values would be much higher, as the outer sections of the corresponding travel-time curves would then not fit the observed data.

Gutenberg's method of analysis allows V_h values at different depths to be derived independently of each other. This is an advantage over the classical theoretical method of determination (Bullen, 1947 and 1956, p.99) which requires that the travel-time curve be continuous over the range of epicentral distances covered by the ray paths being analysed. If not, assumptions that may seriously affect the resultant velocities obtained for various depths must be made.

However, values of V_h here obtained are subject to error, which may be caused by a number of factors, the most important being:

(a) errors of interpretation of the form of the adopted travel-time curve, owing to the scatter of plotted points,

(b) errors in the determination of V_{min} at distances where there are no first arrivals, owing to the presence of a shadow zone. These would be due to the condition $-dV/dr \geq V/r$ in the low velocity channel.

Quantitative estimates of the accuracy of V_h values cannot be made at this stage other than the indications given by Table 1. The values depend entirely on the graphical interpretations in Plate 3 and the minimum velocity inferred may, in fact, be somewhat higher. However, it would be difficult to reconcile with the observed data a velocity distribution having no diminution with depth.

It is suggested that these data do, at least, imply the existence of a low-velocity channel such that the maximum velocity gradient ($-dV/dr$) between 0 and 150-km depth is not very much less than v/r, if it does not in fact exceed v/r. If $-dV/dr < v/r$, errors of type (b) above would not be expected and continuity of the travel-time curves (Plate 3), leading to a more reliable interpretation of V_h, could then be inferred.

Therefore it is considered that the data summarised in Plate 4 suggest the presence of a low-velocity channel and a different velocity distribution from those found by other investigators. It is interesting to speculate that this difference may be caused by features or conditions peculiar to the New Guinea/Solomon Islands region.

A rather novel means of estimating the accuracy of the USCGS epicentre determinations is provided by the graphs of Plate 3. It is usual to find considerable scatter in any such set of observations consisting of preliminary data. Estimates have been made of the r.m.s. deviation of the plotted points vertically displaced from the adopted travel-time curves (Plate 3; Table 1). It is found to be highest for the 25-km and 40-km groups of shocks and roughly constant thereafter, with a small increase for the 115, 135, and 175-km graphs. Three causes of this scatter are suggested:

(a) errors in the calculated epicentral distances, which will be transferred to the graph by the k factor in the vertical scale. Such errors would produce a random scatter,

(b) incorrectly identified P onsets, which in most cases would be late, not early, and which would cause a scatter predominantly in a positive vertical direction,

(c) definite initial onsets which do not represent the arrival of the direct wave, e.g. at a station within the shadow zone for a particular shock, would again cause a predominantly positive vertical scatter in the middle portion of the graph.

As the average difference between computed and observed arrival times for shocks in all depth ranges is only about 1½ sec, it is suggested that errors in epicentral distance may therefore be the main cause. If so, the r.m.s. values indicate an equivalent mean error of between 0.2 and 0.3 degrees for most depths; this seems surprisingly small for preliminary epicentre determinations. Nevertheless, it is clear from the appearance of the graphs that it would have been extremely difficult to fit the curve to each set of points had the scatter been much greater than this value.

At depths less than 50 km the second assumption, viz. that there are no significant horizontal variations of velocity, would be violated if the complex tectonics of the area extend well into this depth range. Moreover, any shocks in the 25-km group having epicentres above the Mohorovicic Discontinuity will lie in a region where wave velocities are lower and possibly have a wide range. These conditions would lead to additional scatter.

Below 50-km depth the scatter is roughly the same in each graph, but a small increase occurs for shocks between 100 and 200-km depth. It can be seen on Plate 4 that the difference between any of the previously published velocity/depth curves and the curve determined in this investigation is greatest for this depth range. Many earthquakes used for this study were small and the corresponding epicentre data were consequently available only from the closest stations. The increased scatter noted may be due to errors in distance calculated from epicentres using standard travel-time data, if these are incorrect in this region.

5. CONCLUSIONS

Evidence has been presented to support the contention that there is a layer of low velocity for seismic waves under the New Guinea/Solomon Islands region. The minimum velocity reached may be as low as 7.6 km/sec at a depth of about 150 km. The decrease in velocity found is much more pronounced than hitherto reported and suggests that shadow zones for the arrival of direct P waves exist in the area.

The successful use of USCGS preliminary epicentre data is demonstrated, and the average error in epicentral positions, determined for earthquakes in the New Guinea/Solomon Islands region since July 1960 by computer methods, appears to be about ¼ degree. This is a favourable comment on the accuracy of such data.

Improvement in the quality of this kind of data will be possible in due course through more selective use of the results of earthquakes, and by distinguishing between different ray paths in terms of regional geology. This was not possible in the present preliminary investigation; the number of events available was too limited to permit more than a general analysis.

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NEW GUINEA / SOLOMON ISLANDS REGION

TABLE I

VELOCITY OF P WAVES — VARIATION WITH DEPTH

DEPTH RANGE (km)	NOMINAL DEPTH (km)	$\bar{V}$ min. k = 14·0 (km/sec)	$\bar{V}$ min. k = 14·2 (km/sec)	$\bar{V}$ min. k = 14·4 (km/sec)	MEAN $\bar{v}$ min (km/sec)	$\frac{r_h}{r_0}$	V_h (km/sec)	NUMBER OF OBS.	R.M.S DEVIATION Time (Seconds)	R.M.S DEVIATION Distance (Degrees)
0-31	25	7·97	7·94	7·92	7·95	0·998	7·93	67	6·5	0·5
32-49	40	8·01	7·94	7·96	7·97	0·994	7·92	59	5·4	0·4
50-79	65	7·94	7·94	8·00	7·96	0·990	7·88	113	3·0	0·2
80-101	90	7·94	7·90	7·96	7·93	0·986	7·82	74	3·3	0·2
102-125	115	7·7	7·7	7·5	7·6	0·982	7·5	69	3·4	0·2
126-150	135	7·83	7·83	7·79	7·82	0·979	7·66	48	3·4	0·2
151-199	175	7·94	8·00	7·88	7·94	0·973	7·73	45	3·8	0·3
200-250	225	k = 13·0 8·55			8·55	0·965	8·25	28	2·0	0·1
350-410	380	k = 11·0 (9·8)			(9·8)	0·94	(9·2)	13		
450-520	480	(10·2)			(10·2)	0·92	(9·4)	17		

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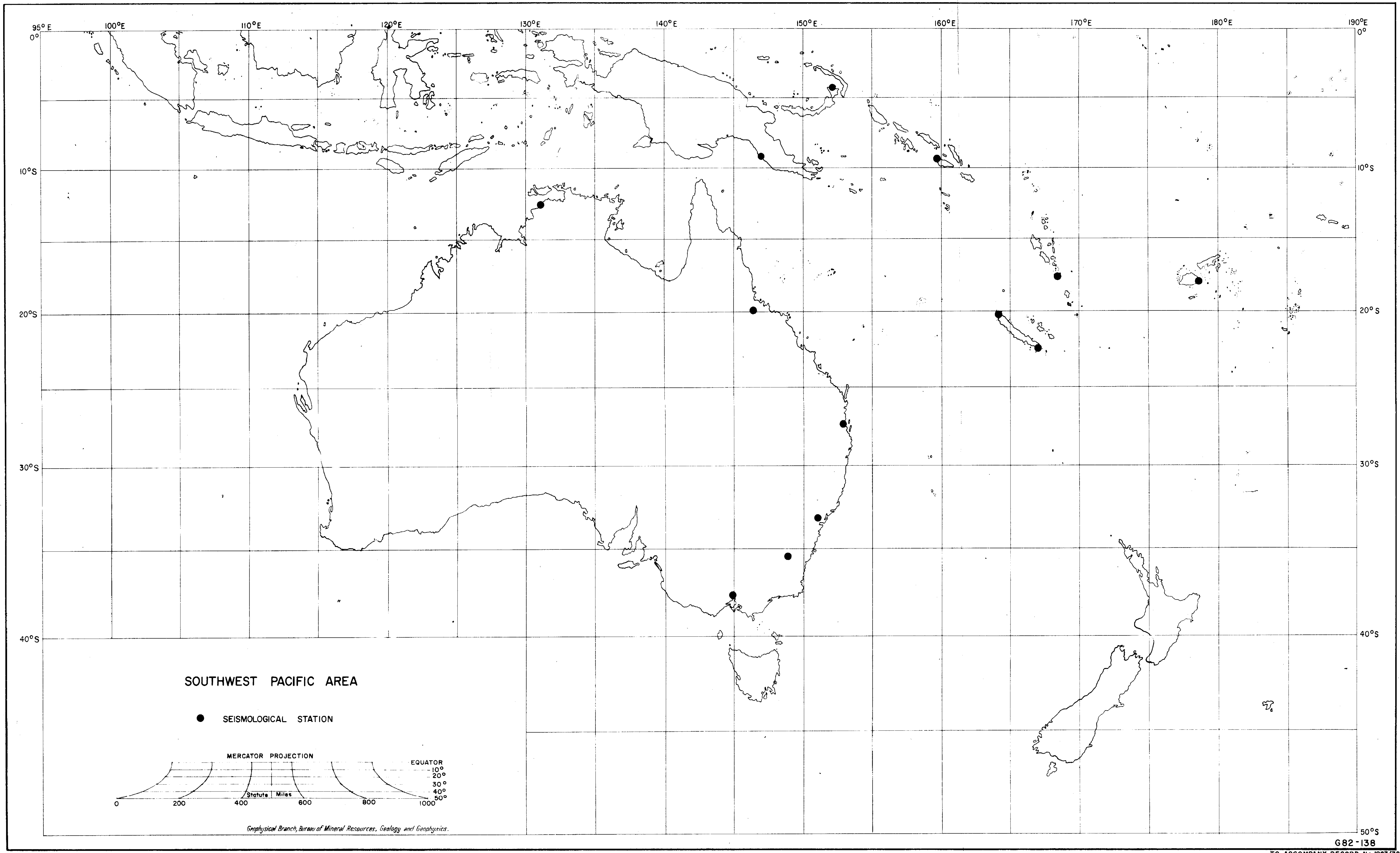

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SEISMIC WAVE VELOCITIES, NEW GUINEA/SOLOMONS

PLATE 2

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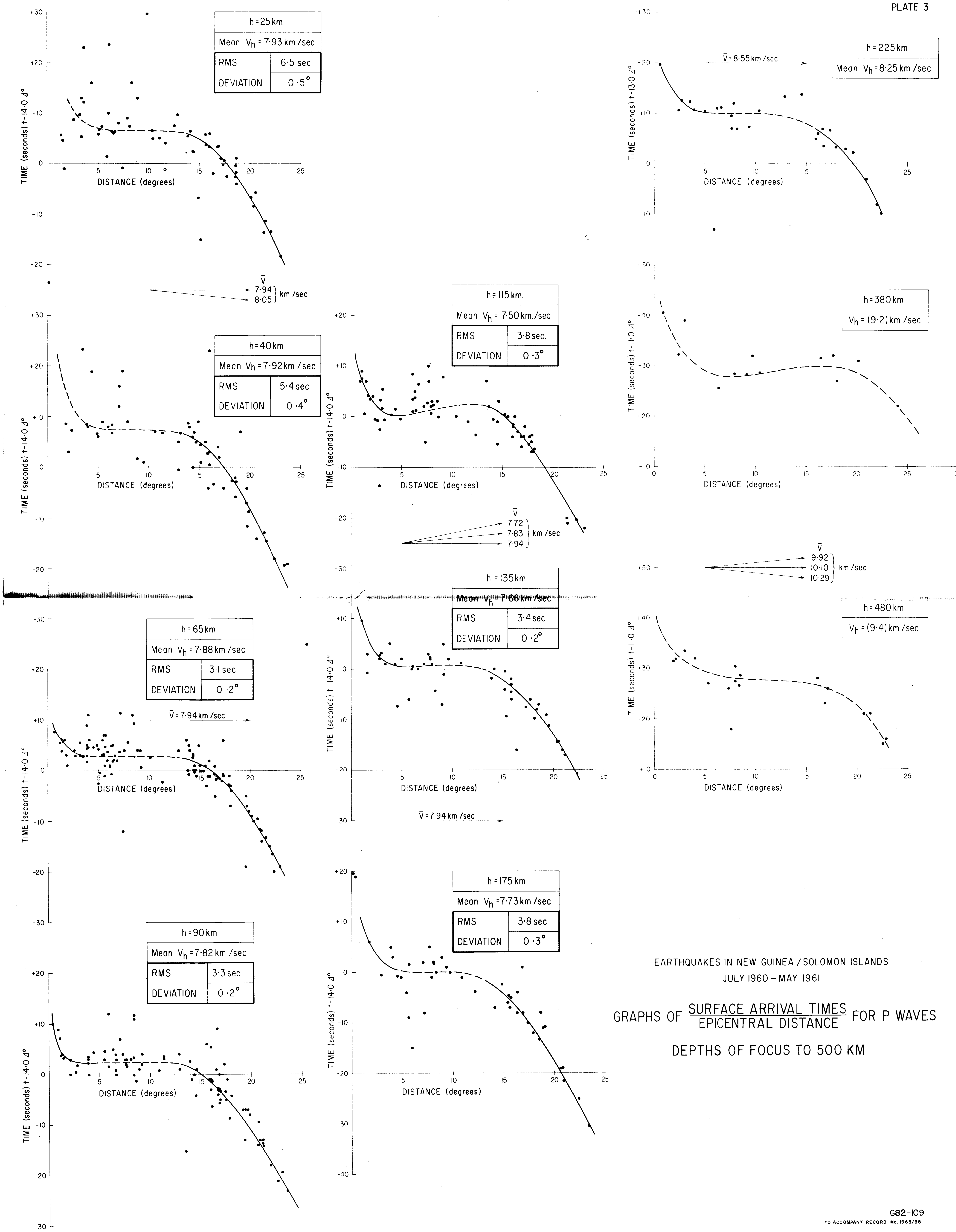

EARTHQUAKES IN NEW GUINEA / SOLOMON ISLANDS

JULY 1960 – MAY 1961

GRAPHS OF $\frac{\text{SURFACE ARRIVAL TIMES}}{\text{EPICENTRAL DISTANCE}}$ FOR P WAVES

DEPTHS OF FOCUS TO 500 KM

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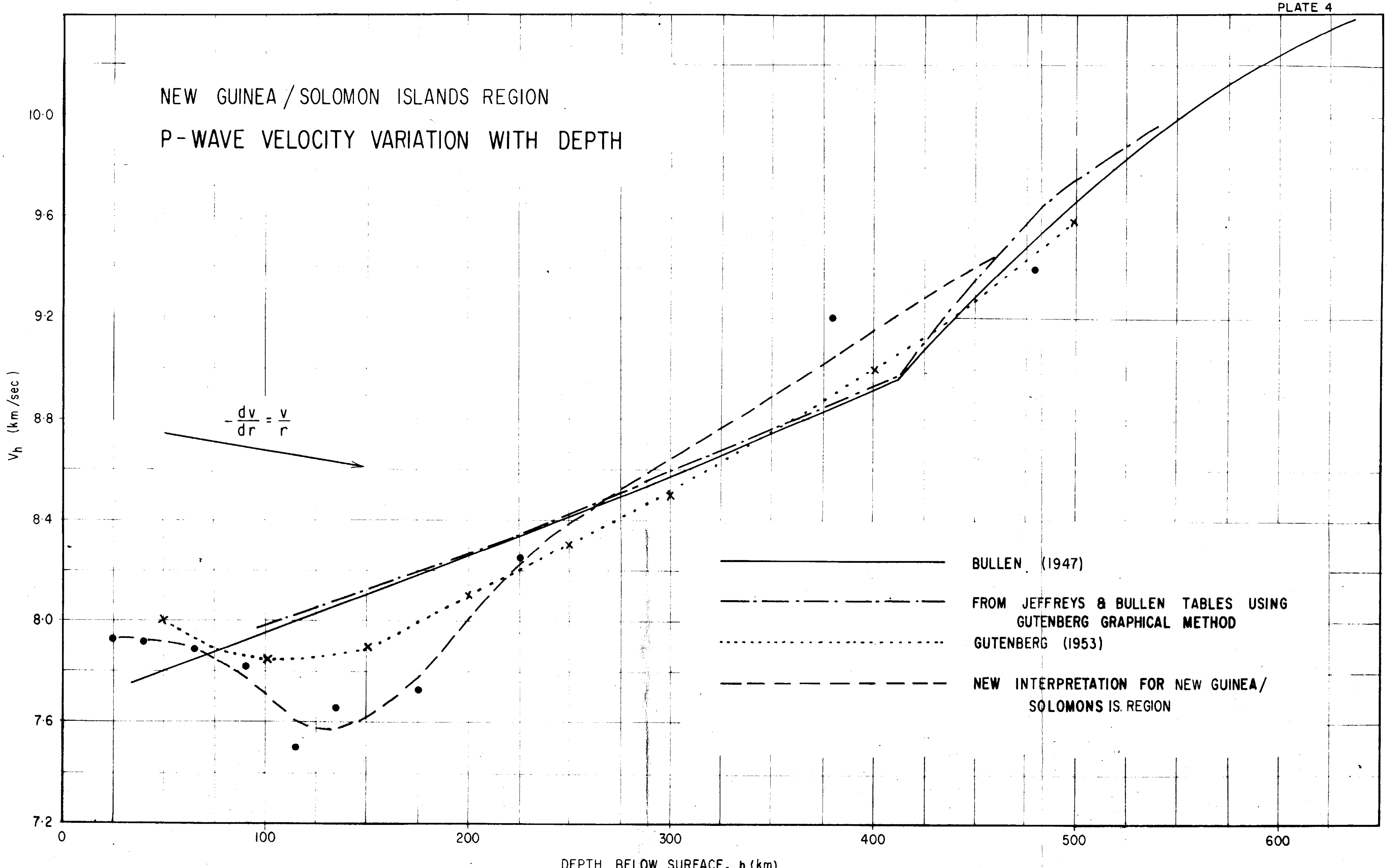

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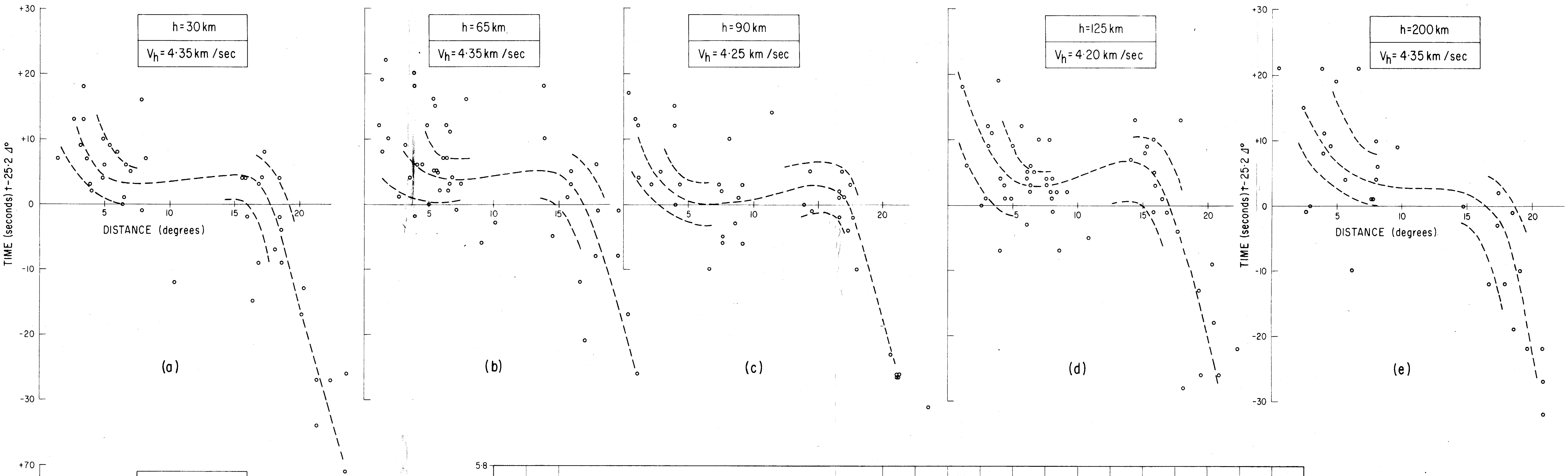
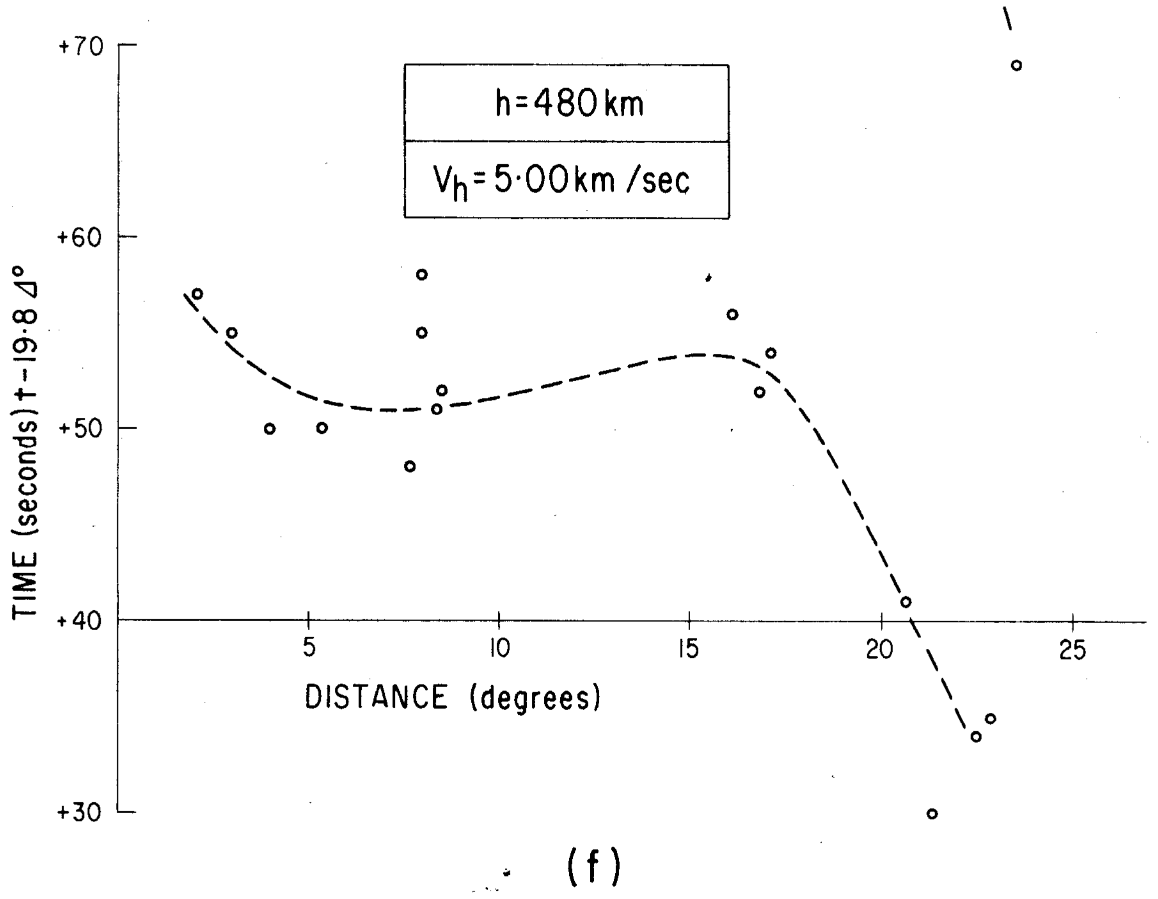
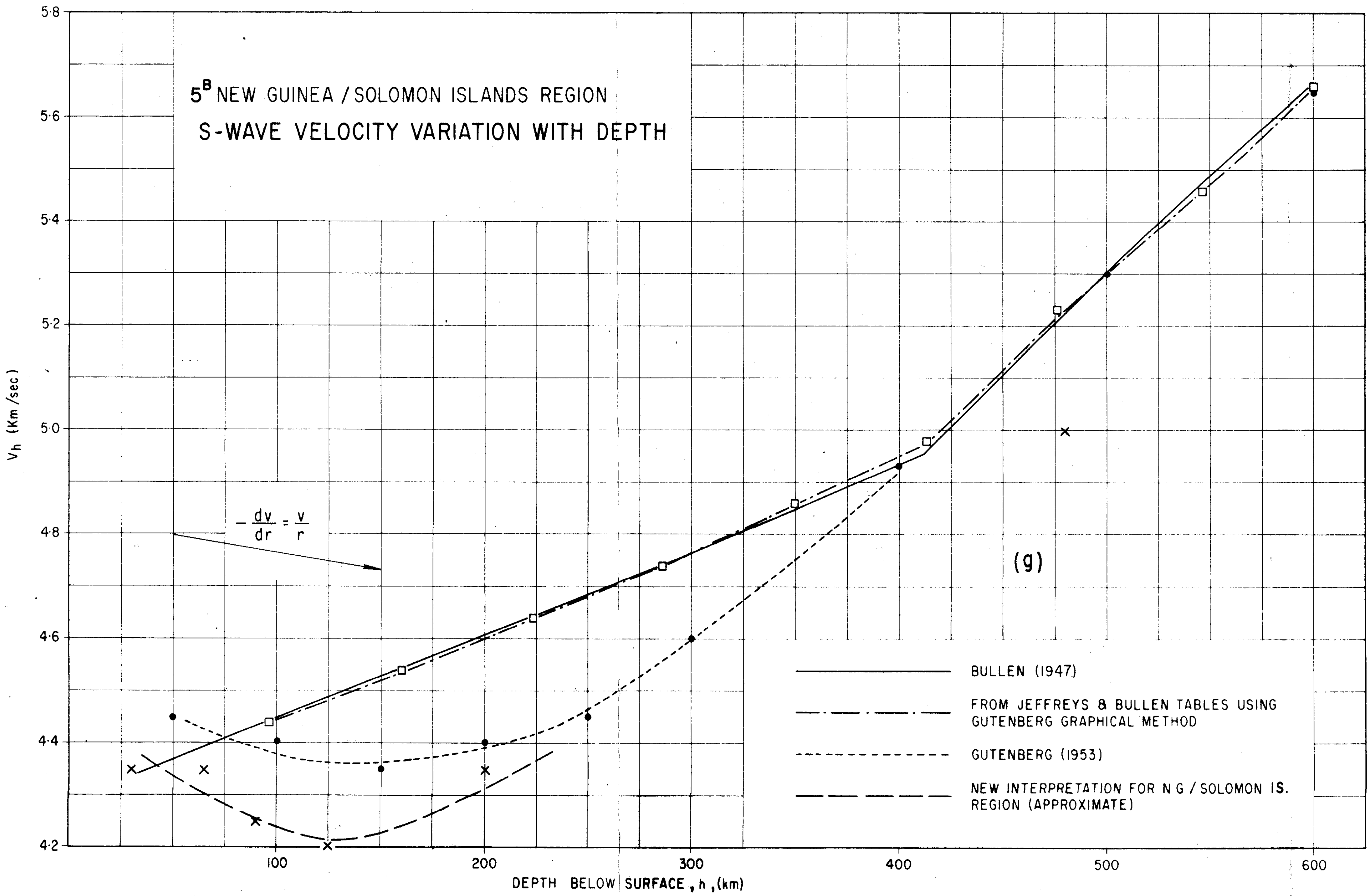
5A S-WAVE SURFACE ARRIVAL TIME / DISTANCE PLOTS (INTERPRETATION DOUBTFUL; V_h VALUES VERY UNCERTAIN)





NEW GUINEA / SOLOMON ISLANDS REGION

VELOCITY OF S-WAVES



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