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USE OF MICROCOMPUTER IN MAPPING DEPTH OF STRATIGRAPHIC HORIZONS IN NATIONAL PETROLEUM RESERVE IN ALASKA

By

Thomas G. Payne

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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ABSTRACT

REGIONAL MAPPER is a menu-driven system in the BASIC language for computing and plotting (1) time, depth, and average velocity to geologic horizons, (2) interval time, thickness, and interval velocity of stratigraphic intervals, and (3) subcropping and onlapping intervals at unconformities. The system consists of three programs: FILER, TRAVERSER, and PLOTTER. A control point is a shot point with velocity analysis or a shot point at or near a well with velocity check-shot survey. Reflection time to and code number of seismic horizons are filed by digitizing tablet from record sections. TRAVERSER starts at a point of geologic control and, in traversing to another, parallels seismic events, records loss of horizons by onlap and truncation, and stores reflection time for geologic horizons at traversed shot points. TRAVERSER is basically a phantoming procedure.

Permafrost thickness and velocity variations, buried canyons with low-velocity fill, and error in seismically derived velocity cause velocity anomalies that complicate depth mapping. Two depths to the top of the pebble shale are computed for each control point. One depth, designated Z_s is based on seismically derived velocity. The other (Z_w) is based on interval velocity interpolated linearly between wells and multiplied by interval time (isochron) to give interval thickness. Z_w is computed for all geologic horizons by downward summation of interval thickness.

Unknown true depth (Z) to the pebble shale may be expressed as

$$Z = Z_s + e_s \qquad \text{and} \qquad Z = Z_w + e_w$$

where the e terms represent error. Equating the two expressions gives the depth difference:

$$D = Z_s - Z_w = e_w - e_s.$$

A plot of D for the top of the pebble shale is readily contourable but smoothing is required to produce a reasonably simple surface.

Seismically derived velocity used in computing Z_S includes the effect of velocity anomalies but is subject to some large randomly distributed errors resulting in depth errors (e_S). Well-derived velocity used in computing Z_W does not include the effect of velocity anomalies, but the error (e_w) should reflect these anomalies and should be contourable (non-random). The D surface as contoured with smoothing is assumed to represent e_w, that is, the depth effect of variations in permafrost thickness and velocity and buried canyon depth.

Estimated depth (Z_{est}) to each geologic horizon is the sum of Z_w for that horizon and a constant e_w as contoured for the pebble shale, which is the first highly continuous seismic horizon below the zone of anomalous velocity. Results of this "depthing" procedure are compared with those of Tetra Tech, Inc., the subcontractor responsible for geologic and geophysical interpretation and mapping.

INTRODUCTION

Mapping System

To aid in defining possible traps for oil and gas in NPR-A north of the 70th parallel a system called REGIONAL MAPPER, consisting of three programs for microcomputer, has been developed and tested. Under menu control the system computes and plots (1) reflection time, depth, and average velocity to geologic horizons, (2) interval time, thickness, and interval velocity of stratigraphic intervals, and (3) code letters for stratigraphic intervals subcropping and onlapping at unconformities. A description of the system and programs is the subject of a later report.

Contouring of maps is by hand from machine plotted data positioned according to a rectangular coordinate system on panels that are joined to form maps. Depths as plotted are all subsea depths. Minus signs are omitted to reduce clutter. A depth of zero for the Colville Group or Nanushuk/Torok Group (Table 1) means that the unit directly underlies the Gubik Formation (Pleistocene) and has been truncated. The assignment of zero depth is an approximation. In all wells north of the 70th parallel, except J. W. Dalton 1 and Inigok 1, the base of the Gubik ranges in depth, relative to sea level, from -73 to +23 feet. In Dalton it is -173 feet and in Inigok it is +63 feet.

A well location map of the northeastern part of NPRA (Fig. 1) gives well names. On the other maps (Figs. 2-9) the wells are shown by dots but the names are not given.

Seismically derived depth (Zs) and depth based on well data (Zw) are zero or negative relative to sealevel but are computed, stored on disks, and plotted as positive values. In contouring depth maps the negative sign is used.

Purpose of Depth Report

Variation in thickness and velocity of permafrost, buried canyons, and errors in seismically derived average velocity cause velocity problems in depth mapping. The present report describes a procedure for estimating depth of stratigraphic horizons at seismic shot points based on seismically derived velocity and on velocity from check shot surveys of wells. The procedure is different from that used by Tetra Tech, Inc., the subcontractor responsible for mapping.

Tetra Tech's maps are by seismic horizons, so another purpose of the report is to provide a means of mapping geologic horizons (Table 1).

Table 1. - Map Units

	TERTIARY SYSTEM.
CO -	COLVILLE GROUP. Late Cretaceous. (Cenomanian to Maestrichtian).
NA -	NANUSHUK/TOROK GROUP. Early and Late Cretaceous. (Aptian to Cenomanian)
PS -	PEBBLE SHALE UNIT. Early Cretaceous (Neocomian).
UN -	(Pebble shale unconformity).
	KINGAK FORMATION.
KA -	Late Jurassic (Kimmeridgian to Tithonian) and Early Cretaceous (Neocomian).
KB -	Late Jurassic (Oxfordian to Kimmeridgian).
KC -	Early to Middle Jurassic.

SR - SAG RIVER SANDSTONE. Late Triassic to Early Jurassic.

SB - SHUBLIK FORMATION. Middle and Late Triassic.

SD - SADLEROCHIT GROUP. Late Permian and Early Triassic.

LS - LISBURNE GROUP. Late Mississippian to Early Permian.

EN - ENDICOTT GROUP. Early to Late Mississippian (Meramecian).

BA - ACOUSTIC BASEMENT.

The interval time, thickness, and interval velocity of the Tertiary System are the same as the time, depth, and average velocity to the top of the Colville Group. The parts of the Kingak Formation are informal units based on paleontologic zones.

Until the recently issued FY '74-'81 Final Report 1/, Tetra Tech has submitted mainly reflection time maps of seismic horizons. Because of the huge volume of work, depth and thickness maps of potential reservoirs and onlap and truncation (subcrop) maps required in defining stratigraphic prospects have not been available. Tetra Tech's recently released depth maps are highly smoothed and show few structural anomalies.

The USGS depth mapping procedure that is the subject of this report produces depth maps that, although similar in regional average depth, show considerable variance from and more structural anomalies than those by Tetra Tech. In view of the high cost and significance of the data collected by the NPR-A project and the interpretive uncertainties involved, it seems desirable to provide alternative interpretations to those of the subcontractor.

1/ Tetra Tech, Inc., 1982, Petroleum Exploration of National Petroleum Reserve in Alaska, 1974-1981, (Final Report),

TETRA TECH'S SYSTEM FOR MAPPING DEPTH OF SEISMIC HORIZONS

Tetra Tech has developed a computerized system for mapping time, velocity, depth, and thickness of seismic horizons and intervals. The Tetra Tech Interpreted Seismic Database for NPR-A consists of eight computer listings, one for each of eight NPR quadrangles. The data listings and the depth maps became available late in 1981 in the draft of the FY '74-'81 Final Report. The procedure for mapping depth of a given seismic horizon as described in the report (pp. 59-84) consists of the following steps:

(1) Reflection time (ms) to Horizon 0700, the approximate top of the pebble shale, is measured on record sections at approximately every third shot point. To facilitate seismic interpretation Horizon 0700 is picked at the trough above a strong peak generated by the top of the pebble shale. Therefore, a time value of 15 ms (about one-half cycle) is added to Horizon 0700 to better tie with the wells.

(2) Section lag (ms) is subtracted from raw time. The lag is 50 ms for 1974-1977 land lines, 20 ms for 1978 and 1979 lines, and 70 ms for 1977 marine lines.

(3) In the vicinity of short-wave anomalies (rapid lateral velocity variations) a time value based on time sag is subtracted from reflection time so that the anomalies appear similar to the normal regional values.

(4) Seismic stacking velocity data are analyzed. About half of GSI analyses are of the "Velscan" type; most of the others are of the less precise "Velpak" type.

(5) Analyses are disregarded in areas of discordant dip, short-wave anomalies, or faults.

(6) Because of bias in the velocity data, the Dix equation is inadequate to reduce stacking velocity to average velocity. Therefore, an empirically derived correction factor of 0.94 is used. This factor gives the best fit to average velocity derived from well survey data.

(7) Interval velocity values are obtained from the Dix equation for shot points with velocity analyses.

(8) For Horizon 0700 a regional velocity map is drawn by hand, based mainly on well data and secondarily on seismically derived velocity. With the exception of a velocity high south of Barrow, the surface in the onshore area slopes rather uniformally to the south and southwest.

(9) The regional velocity surface for the 0700 Horizon is described by three polynomial models fitted by the least-squares method for three subdivisions of the coastal plain. The models allow computation of average velocity at any given point for which x and y are defined. The highest order polynomial is an 8th order.

(10) For the 0700 Horizon, depth is calculated for every third shot point from adjusted time and the regional average velocity models.

(11) Depth and thickness values for Horizon 0700 and older horizons and intervals are calculated using the "layer cake" method. Thickness values for intervals between seismic horizons are obtained from isochrons based on adjusted times and from interval velocity. Depth values for older horizons are determined by summation of thickness values and the Horizon 0700 depth value.

(12) An interpolation scheme is used to calculate depth values of horizons above 0700. The relationship between average velocity and time is determined at every third shot point from (a) surface velocity data, (b) Torok clinothem time and average velocity, and (c) Horizon 0700 time and average velocity. Depth of horizons between the surface and 0700 are determined from this relationship by interpolation.

(13) Depth and thickness are machine contoured for each seismic horizon by a contouring package by which the surfaces are smoothed.

USGS MICROCOMPUTER SYSTEM FOR MAPPING DEPTH OF STRATIGRAPHIC HORIZONS

The USGS procedure for mapping depth is part of the mapping system described in the Introduction. In correcting for shallow velocity anomalies the procedure uses the top of the pebble shale as the base horizon because this is the first regionally continuous horizon below the zone of velocity anomalies. The procedure consists of steps as follows:

(1) The area north of the 70th parallel is divided into eight panels (A-H), each eight inches in width. The plot scale is 1:250,000 or 1 inch = 4 miles. The area selected for demonstration in this report is in the northeastern part of the Reserve and consists of parts of panels E, F, G, and H (fig. 2).

(2) By use of the program FILER a sequential file (Table 2) is established for each shot point with velocity analysis, including three-letter file name, location by printer column and row, seismic line, shot point, and time lag. The first letter of the file name is the panel letter and is not printed on the map panel (fig. 2). An alphabetic listing of file names with section, township and range and seismic line numbers and shot point numbers will be available in open-file form on completion of the files.

Table 2. Example of file at control point FAS

FILENAME	NUMHRZ	COLUMN	ROW
FAS	34	55	139
LINE	SHOT PT	LAG	DC
D102-77	38	50	-76

NUM	HOR		TIME(MS)		VELOCITY(RMS)
1			3		7021
2			341		7170
3			873		7878
4			1166		9131
5			1359		9472
6	(From Velscan and Velpak data, entered from keyboard)		1552		9646
7			1703		9763
8			1811		9803
9			1967		9995
10			2028		9990
11			2191		10141
12			2662		11521
13			0		0
14			0		0
15			0		0
16			0		0
17	22		572		
18	24		790		
19	1		1465		
20	2		1485		
21	8		1521		
22	3		1615		
23	7		1658		
24	16	SEISMIC	1760	FROM	
25	9		1818		
26	20	HORIZONS	1918	DIGITIZER	
27	10		1980		
28	6		2038		
29	13		2120		
30	5		2205		
31	4		2300		
32	23		2425		
33	18		2475		
34	30		2560		
35			0		
36			0		DEPTH (FT)
37	CO		0		0
38	NA		65		261
39	PS		1476		7178
40	UN		1522		7428
41	KA	GEOLOGIC	1522	FROM	7428
42	KB		1646		8073
43	KC	HORIZONS	1803	TRAVERSER	8981
44	SR		1939		9793
45	SB		1961		9958
46	SD		2013		10343
47	LS		2153		11393
48	EN		2477		14498
49	BA		2563		15268

(3) A printer is used rather than a plotter because of the large number of points and number of maps to be produced, and the fact that minor error in location can be tolerated because of the reconnaissance nature of the maps. The printer is set at eight lines per inch (y) and ten characters per inch (x). An asterisk locates a point and is forced to the nearest print position. The maximum error of location is 1/16th of an inch in y and 1/20th of an inch in x. Where overlap of printed data occurs, one of the points is dropped.

(4) Tables of stacking velocity versus time are entered in the sequential file (Table 2) by the program FILER. Tetra Tech's printout of raw stacking velocity versus time is used for horizons below and including the pebble shale (0700). For shallower horizons interpretations by Tetra Tech are not available, and GSI tables are used, as printed on the record sections.

(5) The stacking velocities are reduced to average velocity by multiplying by 0.94, a factor derived independently by the writer and by Tetra Tech. The factor was obtained by comparing, for all horizons, seismically derived velocities at or near wells with those from well check shot surveys.

(6) On each record section a strip of paper about one-half inch in width is mounted at each shot point with velocity analysis.

(7) The more laterally persistent seismic horizons are marked by ticks on the strips at peaks.

(8) The seismic horizons are given a two-digit code number at random except that correlative peaks on adjacent strips must bear the same number and non-correlative peaks on adjacent strips must bear different numbers.

(9) The paper strips and a horizon code menu are mounted on a digitizing tablet and the raw time value (ms) to each marked seismic horizon and its code number are entered by FILER into the sequential file by touching the ticks and code menu squares with the indicator pen. Times of zero and 2,000 ms also are entered by pen for scaling.

(10) By program, section lag (L) is subtracted from raw time as in step 2 of Tetra Tech's procedure, to yield adjusted time (T).

(11) For each well a file code and location are entered. Reflection time and depth are entered for each geologic horizon. Depth is from log picks by Bird (1982) 2 / and corresponding time is from the check shot survey. Wells in the demonstration area include Simpson 1, East Simpson 1, East Simpson 2, South Simpson 1, Topagoruk 1, Ikpikpuk 1, Drew Point 1, J. W. Dalton 1, W. T. Foran 1, Cape Halkett 1, and East Teshekpuk 1 (fig. 10). In addition, Inigok 1 (T. 8 N., R. 5 W.) was used as the starting well in the traverse grid.

(12) The TRAVERSER program is run. It reads sequential files starting at a point of geologic control, initially a well, and traverses a set of specified shot points having velocity analyses to close in the time

2 / Bird, Kenneth, J., 1982, Rock-unit reports of 228 wells drilled on the North slope, Alaska: U.S. Geological Survey Open-File Report 82-278, Menlo Park, California, 106 p.

domain on another point of geologic control. In tracing (phantoming) each geologic horizon the program parallels the set of predefined seismic events, records loss of horizons by onlap or truncation, and stores reflection time for each traversed shot point. This procedure does not apply to the acoustic basement, which is identified by inspection and assigned a code number of 30. Some traverses extend a short distance outside the area of geologic control and do not have a well on which to close. In such cases the average velocity and interval velocity of all geologic intervals are assumed to remain constant and equal to their values in the starting well. If TRAVERSER is unable to trace the top of the Nanushuk/Torok Group in areas of paleocanyons that cut into the Group, reflection time is stored from the keyboard by inspection of record sections.

(13) Traverse misclosure may be due to error in log or paleontologic correlation. After correcting such errors TRAVERSER is rerun. If the misclosure is less than 30 ms, closure is forced by prorating the error back to the starting point, checking to assure that the geologic horizon being traced does not cross a seismic event. Otherwise, the results of the traverse are printed out and the operator must review the record section to make the necessary correction in seismic horizon correlations. When errors have been corrected, TRAVERSER is rerun and time to geologic horizons is stored in the sequential file for each traversed shot point. Those points then become points of geologic control and can be starting points for other traverses.

(14) In the TRAVERSER program interval velocity V_{int} of each geologic interval is obtained by linear interpolation between points of geologic

control, initially from check shot surveys in wells. Interval time T_{int} or isochron value is calculated by subtraction of stored horizon times. Interval thickness for each interval at a control point is

$$H_{int} = \frac{V_{int} \times T_{int}}{2000} .$$

(15) For each geologic horizon at each control point depth, in positive values from sealevel base, is computed by downward summation of interval thickness. Depth derived in this way, based on time values and velocities derived entirely from well data, is designated Z_W (see map, fig. 3). It is not necessary that Z_w be plotted and contoured.

(16) Seismically derived average velocity (V_S) to the top of the pebble shale at each control point is derived by interpolation in the tables of time versus average velocity (step 4).

(17) Seismically derived depth (Z_s) to the top of the pebble shale, in positive values from sealevel base, is stored as the product of reflection time (T) and average velocity (V_s) divided by 2,000 (see map, fig. 4). It is not necessary that Z_s be plotted and contoured. The contours on the map are from Tetra Tech's map whereas the plotted values are Z_s values calculated as indicated above and plotted by PLOTTER without the minus sign. Note the degree of difference between contouring and plotted values.

(18) Unknown, true depth (Z) to the pebble shale may be expressed as

$$Z = Z_s + e_s \qquad \text{and} \qquad Z = Z_w + e_w$$

where the e terms represent error. Equating the two expressions gives the depth difference (D).

$$D = Z_s - Z_w = e_w - e_s$$

A map of D values (fig. 5) prepared by PLOTTER shows lines separating positive and negative values. Only about three percent of the values are misfits, that is, positive values in negative areas or negative values in positive areas. Therefore, the depth difference (D) is strongly systematic or non-random in areal distribution. Note that although depths are to be contoured in negative values from sealevel base, they are computed, filed, and plotted as positive values. Therefore, D and the error terms as mapped (figs. 5, 6, 7) have signs opposite from their true signs.

(19) A plot of D for the top of the pebble shale (fig. 5) is readily contourable but smoothing is required to produce a reasonably simple surface. Seismically derived velocity used in computing Z_s includes the effect of velocity anomalies but is subject to some large areally random errors resulting in depth errors (e_s). Well-derived velocity used in computing Z_w does not include the effect of velocity anomalies. The error (e_w) should reflect these anomalies and should be contourable (non-random). The contoured D surface is smoothed and assumed to represent e_w, that is, variations in permafrost thickness and velocity and buried canyon depth. The goal is to contour D with just enough smoothing to randomize e_s. If the D surface is overly smoothed, then e_s is nonrandom and contourable and e_w will not properly

correct for velocity anomalies. There is no reason for believing error in seismically derived velocity (e_s) is areally systematic. If the contouring of D is too detailed and D values are mostly honored, then e_s approaches zero and Z_{est} approaches depth based on seismically derived velocity, which is undesirable because Z_s involves large random errors at some shot points.

(20) Values are read from the contoured surface at control points, stored by FILER as e_w values, and plotted by PLOTTER (fig. 6).

(21) Random error is assumed to be represented by e_s and is calculated as (e_w - D). As shown by a plot (fig. 7), e_s is indeed areally random.

(22) Estimated depth to the top of the pebble shale is

$$Z_{est} = Z_w + e_w.$$

Estimated depth to each geologic horizon is the sum of Z_w for that horizon and a constant e_w as contoured for the pebble shale.

(23) The shallowest depth of the pebble shale is on the structural high south of Barrow, where it is about 1,200 feet. At control points where Z_w for a given horizon is shallower than the depth to the base of the zone of anomalous velocity, the full value of the adjustment e_w should not be added and the following scheme is used.

$$Z_{est} = Z_w + \frac{Z_w e_w}{Z_b} \qquad \text{(Used only where } Z_w \text{ is less than 1,000 feet)}$$

Z_b is depth to the base of the zone of anomalous velocity. Inasmuch as Z_b rarely is known, an arbitrary value of 1,000 feet is assumed.

(24) Average velocity to each geologic horizon is obtained by dividing the appropriate Z_{est} values by reflection time and multiplying by 2,000. The USGS average velocity to the top of the pebble shale is shown together with Tetra Tech's average velocity model (fig. 8).

(25) An option of the program FILER reads all sequential files on a given map panel and writes the data needed in mapping into a random-access file for that panel, which is used by the program PLOTTER to plot map values for hand contouring.

COMPARISON OF RESULTS OF DEPTHING SYSTEMS

Computed Depth versus Well Depth of Pebble Shale

Tetra Tech's regional velocity model (dashed lines, fig. 8) is very simple and drawn mainly to fit well data. Even so, at J. W. Dalton 1, for example, the depth to the pebble shale, as computed from adjusted time and average velocity, is in error by almost 300 feet compared with well depth.

$$-\frac{1.725 \text{ sec} \times 8967 \text{ ft/sec}}{2} = -7734$$

True depth as posted by the well is -7,446 feet. This type of error probably is due to the hand-drawn regional average velocity map and its description by polynomial models.

Depth Interpolated from Contouring versus Well Depth of Pebble Shale

Tetra Tech's contoured depth to the top of the pebble shale at East Simpson 2 (FY '74-'81, Final Report) is about -6,085 feet, whereas the true depth as posted by the well is -6,287 feet. The contoured depth at W. T. Foran 1 is -7,550 feet, whereas the true depth as posted is -7,299 feet. This type of error probably is due to the regional average velocity map and its conversion to polynomial models, as well as to smoothing in machine contouring of depth.

For the 11 wells in the demonstration area the USGS average error of this type, irrespective of sign is 39.5 feet with maximum of 79 feet. Tetra Tech's average error is 83.7 feet with maximum of 251 feet.

Computed Depth versus Depth Interpolated from Contouring

At W. T. Foran 1 Tetra Tech's computed depth to the pebble shale is

$$-\frac{1.690 \text{ sec} \times 8600 \text{ ft/sec}}{2} = -7267 \text{ feet,}$$

whereas depth as contoured is -7,550 feet. At Inigok 1 computed depth is

$$-\frac{1.695 \text{ sec} \times 10200 \text{ ft/sec}}{2} = -8645 \text{ feet.}$$

whereas depth as contoured is -9,000 feet. For 100 randomly selected points, depth to the top of the pebble shale was computed from values read from Tetra Tech's time and average velocity maps and was compared with depth read from the contoured depth map. The former was subtracted from the latter and the difference between computed depth and depth as contoured has a nearly normal distribution and standard deviation of 135 feet. This type of error must be due to smoothing by the machine contouring program.

The USGS depth maps (figs. 9 and 10) show plotted (computed) depth values that can be compared readily with the contouring. With contour interval of 200 feet all or nearly all plotted depth values are properly located between contours. For the pebble shale the difference between depth values interpolated between contours and those depth values as plotted form a normal distribution, truncated at $\pm$ 200 feet, with near zero mean and standard deviation of 51 feet.

Depth Estimated by "Depthing" Procedures Compared with Seismically Derived Depth

Tetra Tech's depthing procedure violates seismically derived average velocity to the top of the pebble shale to a much greater extent than does the USGS procedure. This is shown below in the depth domain.

$$Z_S = \frac{0.94\ V_S\ T}{2000}\ \text{(ft)}$$

V_S - stacking velocity (ft/sec)

T - reflection time (ms)

Z_{tt} - depth to top of pebble shale by Tetra Tech's procedure

Z_{gs} - depth to top of pebble shale by Geological Survey procedure

$Z_s - Z_{tt}$

Percent of points for which depth difference is between:

(%)	(ft)
18	$\pm$ 50
34	$\pm$ 100
63	$\pm$ 200
84	$\pm$ 300
92	$\pm$ 400
97	$\pm$ 500
98.6	$\pm$ 600

$Z_s - Z_{gs}$

Percent of points for which depth difference is between:

(%)	(ft)
60	$\pm$ 50
75	$\pm$ 100
90	$\pm$ 200
97	$\pm$ 300
98.6	$\pm$ 400

A map (fig. 4) shows Tetra Tech's depth contours (Z_{tt}) on top of the pebble shale, whereas plotted values are depth values (Z_s) based on seismically derived velocity. Their final report states (p. 71) "Most of the NPRA seismic data were acquired with a spread length of 8,000 to 10,000 ft (2,440 to 3,050 m). Therefore, accurate velocity information is available only to depths of 12,000 to 15,000 ft (3,660 to 4,575 m)." For the top of the pebble shale the maximum depth in the demonstration area is only about 8,000 feet, so the velocity data are well within the accuracy range.

In view of the above statements it is surprising that Tetra Tech's depth values to the pebble shale differ so greatly from Z_s. The difference is partly valid and represents random error but must be due largely to smoothing in eliminating short-wave anomalies, in contouring a regional velocity surface, fitting polynomial models, and in use of the depth contouring package.

Difference in Depth to Pebble Shale Due to Difference in Seismic- and Well-Derived Velocity

The difference (D) has a distribution as follows:

D $(Z_s - Z_w)$	
Percent of points for which depth difference is between:	
(%)	(ft)
24	$\pm$ 50
40	$\pm$ 100
68	$\pm$ 200
86	$\pm$ 300
95	$\pm$ 400
98.3	$\pm$ 500
100	$\pm$ 600

Random Error Distribution

In the demonstration area random error (e_s) in depth to top of the pebble shale is distributed as follows:

$\underline{(e_w - D)}$

Percent of points for which error is between: (%)	(ft)
62	$\pm$ 50
76	$\pm$ 100
91	$\pm$ 200
97.4	$\pm$ 300
98.6	$\pm$ 400
99.8	$\pm$ 500
100	$\pm$ 600

Difference in Tetra Tech and USGS Depth Estimates

The difference ($Z_{gs} - Z_{tt}$) to the top of the pebble shale forms nearly a normal distribution with standard deviation of 210 feet. The distribution is as follows.

$\underline{Z_{gs} - Z_{tt}}$

Percent of points for which depth difference is between:	
(%)	(ft)
20	± 50
38	± 100
66	± 200
85	± 300
95	± 400
98	± 500
99.5	± 600

Stated the other way, for 34 percent of the points the depth difference is more than 200 feet, for 15 percent it is more than 300 feet, for 5 percent it is more than 400 feet, and for 2 percent it is more than 500 feet. If USGS depths are valid, then the Tetra Tech smoothing procedures could wipe out closures and possible prospects.

Areas of Closure on Pebble Shale

The USGS depth map (fig. 9) shows six areas of closure on top of the pebble shale with 150 to 250 feet of vertical closure. They are as follows:

(1) South Simpson 1 is just north of a closure of about 16 square miles. The Simpson Sand is stratigraphically about 150 feet below the top of

the pebble shale and is truncated by the pebble shale unconformity. Possibly at the crest of the structure two miles south of the well the sand body is less deeply truncated and may include younger sand of better reservoir quality. The sand tested 75,000 CFGPD but there is some question about the adequacy of the test. There is a good possibility of a gas field in this closure. South Simpson 1 is also at the edge of closed areas on the Sag River Sand and the Sadlerochit Group. The feature appears on Tetra Tech's reflection time map of Horizon 0700 as a strong eastward nosing containing a small closure and south of a time sag (reentrant from the north). This feature does not show on their depth map.

(2) East Simpson 1 is in a closure on top of the pebble shale and has minor shows of gas and oil in the basal Torok, the pebble shale, Sag River Sand, Shublik Formation, and the Sadlerochit Group. This well is also in a small closed area on the Sag River Sand and on the Sadlerochit Group. On Tetra Tech's reflection time map of the top of the pebble shale it shows as a strong eastward nosing with reentrant northwest of the well, but does not show on their depth map.

(3) On the USGS map Drew Point is in a closed area on the pebble shale. It is also in a small closure on the Sag River Sand, and on a southwestward nosing on the Sadlerochit Group. The well had minor gas and oil shows in the basal Torok, Sag River Sand, and Sadlerochit Group. On Tetra Tech's reflection time map the well is on a northeastward nosing not shown on the depth map.

(4) An offshore closure centering about 8 miles northeast from Drew Point 1 has not been tested. The Sadlerochit Group and Shublik Formation underlie the pebble shale unconformity in the area of closure. The feature is within a large stratigraphic closure extending at least to -7,400 feet on the Sadlerochit Group. This feature is not shown on Tetra Tech's time map and the depth map does not extend offshore.

(5) A large closure centering 12 miles south-southwest from J. W. Dalton 1 has not been tested. The main hope for a reservoir in this area is the pebble shale sand, which is 35 feet in the Foran and Halkett wells, 10 feet at Dalton, 15 feet at East Teshekpuk, 0 at Drew Point, and 45 feet thick at Ikpikpuk. This feature is represented on the Sag River depth map by a broad southeastward projecting nose. Tetra Tech's time map shows a small closure in the southern part of this area but there is no anomaly on their depth map.

(6) A large area in the vicinity of East Teshekpuk 1 is closed to a depth of about -6,800 feet to the north, west, and south and must extend eastward to the truncation of the pebble shale (not shown) just east of the map border. This area coincides approximately with two areas of closure at -6,800 feet shown on Tetra Tech's depth map. Again the main hope for a reservoir is the pebble shale sand, which probably is thin as described under (5) above. There is no closure on top of the Sag River Sand or on the Sadlerochit Group.

Reproducibility

The only step in the USGS procedure that involves a question of reproducibility is step 19, the contouring of the difference (D) between depth based on well velocity and depth based on seismically derived velocity. D values are plotted on figure 5 but the contour interpretation is shown in figure 6 on which the plotted values are e_w values read from the contoured surface and stored back in the file. The problem of reproducibility involves the degree of smoothing in contouring the D surface to define e_w. The smoothing criterion is the randomization of e_s, which is the error in depth caused by errors in seismically derived velocity. Over-smoothing causes nonrandom e_s distribution. Under-smoothing reduces e_s so that the depth estimate Z_{est} approaches Z_s.

Two geologists and an engineer contoured the D surface with quite similar overall results. The version presented (fig. 6) is by the writer.

Four steps of Tetra Tech's procedure involve the question of reproducibility. Step 3, the elimination of short-wave anomalies, raises the question of the maximum wave length of anomalies that are "regionalized". The ground rules are not given.

In Tetra Tech's step 8 regional average velocity is contoured by hand, and the surface grossly violates the plotted velocity values (fig. 8). Their step 9 involves a selection as to how the map area is to be subdivided and the order of polynomial models to be fitted to average velocity in each subdivision. The coefficients of the models are not given and the areal subdivisions are not shown in the final report. Tetra Tech's step 13 could produce quite different depth results depending on the machine contouring package used and the degree of smoothing.

Permafrost Anomalies

Large areas of abnormally thin or no permafrost should correspond with large areas of abnormally slow average velocity compensated by long reflection time. Conversely, large areas of abnormally thick permafrost should correspond with large areas of abnormally fast average velocity compensated by short reflection time. The accuracy of Tetra Tech's highly smoothed regional average velocity map and their depth map depends on uniformity of thickness and velocity of the permafrost zone and the absence of buried canyons with low-velocity fill. Canyons are known to be present from seismic sections and from well data. Likewise, variation in permafrost velocity and thickness is known. Tetra Tech's reflection time map of Horizon 0700 (final report) is quite detailed and does not seem compatible with the ultra-simple regional average velocity map (heavy lines, fig. 8).

Example of Difference in Depth between $\overline{V}_{tt}$ and $\overline{V}_{gs}$ Related to Permafrost Thickness

Points A and B (figs. 8 and 9) lie on Tetra Tech's 9,000 ft/sec regional velocity contour for the top of the pebble shale. Point A (T. 19 N., R. 11 W.) is on land and one mile northeast of East Simpson 2, at a point where V_{tt} of 9,000 intersects V_{gs} of 9,200 ft/sec. Point B (T. 18 N., R. 10 W.) is 7 miles to the southeast and offshore, where V_{tt} of 9,000 intersects V_{gs} of 8,800 ft/sec. Point B is 5 miles due east of East Simpson 1.

Point A	Point B
$\overline{V}_{gs}$ = 9200 ft/sec	$\overline{V}_{gs}$ = 8800 ft/sec
$\overline{V}_{tt}$ = 9000 ft/sec	$\overline{V}_{tt}$ = 9000 ft/sec
T_{tt} = 1.375 sec	T_{tt} = 1.465 sec

$$Z_{gs} = \frac{1.375 \times 9200}{2} = 6325 \text{ ft} \qquad Z_{gs} = \frac{1.465 \times 8800}{2} = 6446 \text{ ft}$$

$$Z_{tt} = \frac{1.375 \times 9000}{2} = 6187 \text{ ft} \qquad Z_{tt} = \frac{1.465 \times 9000}{2} = 6592 \text{ ft}$$

Note that the slope of the pebble shale from A to B is -121 feet (6,325 - 6,446) according to the USGS interpretation but is -405 feet (6,187 - 6,592) according to Tetra Tech's interpretation. Note also that the depth of 6,325 feet (Z_{gs}) at Point A agrees with the top of the pebble shale in East Simpson 2 and that Z_{tt} is too shallow by -138 feet. In the opinion of the writer the permafrost is thin or absent at Point B, under Smith Bay, and is relatively thick at Point A. $\bar{V}_{gs}$ takes into account this probable difference in permafrost thickness, whereas $\bar{V}_{tt}$ does not. The sharp increase in reflection time from A to B is compensated by offshore decrease in velocity (9,200 to 8,800 ft/sec) in the USGS system.

CONCLUSIONS

Seismic work and drilling by the U.S. Navy in the 40's showed that the coastal plain north of the 70th parallel is primarily an area of stratigraphic plays. This was confirmed by industry activity in the state area east of the National Petroleum Reserve leading to discovery of Prudhoe Bay field. Between 1972 and 1982 Tetra Tech, Inc., the subcontractor responsible for geophysical and geological interpretation in the Reserve, produced a set of detailed reflection time maps of seismic horizons. These excellent maps show character, including positive and negative time closures, noses, and reentrants. They were the only maps available when most of the well site decisions were made for coastal plain drilling in the Reserve.

The writer rejoined the Geological Survey in October 1978 and, working about half time, tried to define stratigraphic prospects by making maps of prospective reservoirs showing contoured depth, thickness, paleostructure, lines of pinchout by onlap and truncation, and other features, based on both seismic and geologic data. This work went very slowly and, in the hope of developing some prospects before termination of the program, the writer developed the mapping system described in the Introduction. Only about one-third of the files have been completed and the federal exploration program has been terminated, thus this system has been of limited use to the Office of National Petroleum Reserve (Alaska) in making decisions for future drilling. However, the system and its application in NPR-A should be of interest to explorationists in the Reserve and elsewhere.

In their FY '74-'81 Final Report Tetra Tech has presented time, depth, and thickness maps of seismic horizons and intervals. Unlike the time maps, the depth maps are essentially featureless and present a very generalized regional picture of the structure and are of little use in defining prospects. The question arises as to whether the relatively featureless nature of the depth maps is a figment of the mapping technique or represents the true structure of the horizons. Judging from the time maps, the former interpretation is assumed. The problem lies in the velocity models used and the depth smoothing performed by the machine contouring package. The great disparity between depth from seismically derived velocity and depth read from the Tetra Tech maps further suggests that the depth maps are over-smoothed.

The USGS mapping procedure is an attempt by the writer to solve the velocity problem by what may be a novel procedure of (1) computing two depths Z_s and Z_w for the base horizon, the top of the pebble shale, (2) contouring the difference (D) with smoothing, and (3) considering the contoured component of the difference as the systematic or non-random depth response to velocity variations related to permafrost thickness and velocity and to thickness of fill in paleocanyons.

It is hoped that the "depthing" scheme will prove to be relatively accurate, and that the mapping system described in the Introduction will be of value in defining stratigraphic prospects for oil and gas and will aid Geological Survey geologists in preparing various types of geologic maps of the coastal plain.

FIGURE 1. WELL LOCATION MAP, NORTHEASTERN PART OF NPRA.

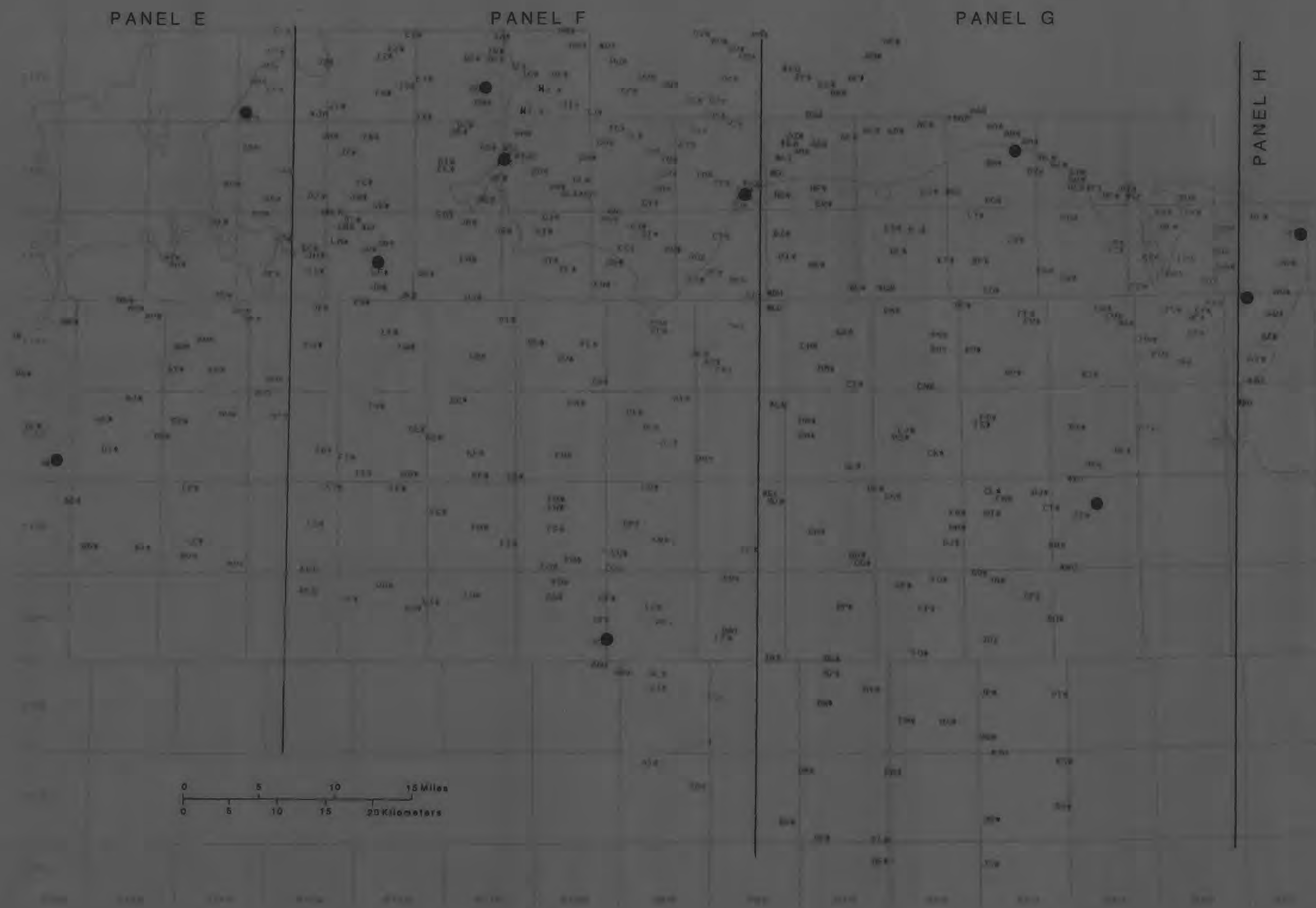

FIGURE 2. COMPUTER FILE NAMES BY PANELS NORTHEASTERN PART OF NPR-A

FIGURE 3. DEPTH (FT) TO TOP OF PEBBLE SHALE, BASED ON SUMMATION OF THICKNESS OF OVERLYING INTERVALS. THICKNESS OF INTERVALS IS DERIVED FROM INTERVAL TIME AT CONTROL POINTS AND FROM INTERVAL VELOCITY INTERPOLATED BETWEN WELLS. DEPTH IS DESIGNATED Zp. PLOTTED VALUES ARE NEGATIVE (SUBSEA). MINUS SIGN OMITTED TO REDUCE CLUTTER.

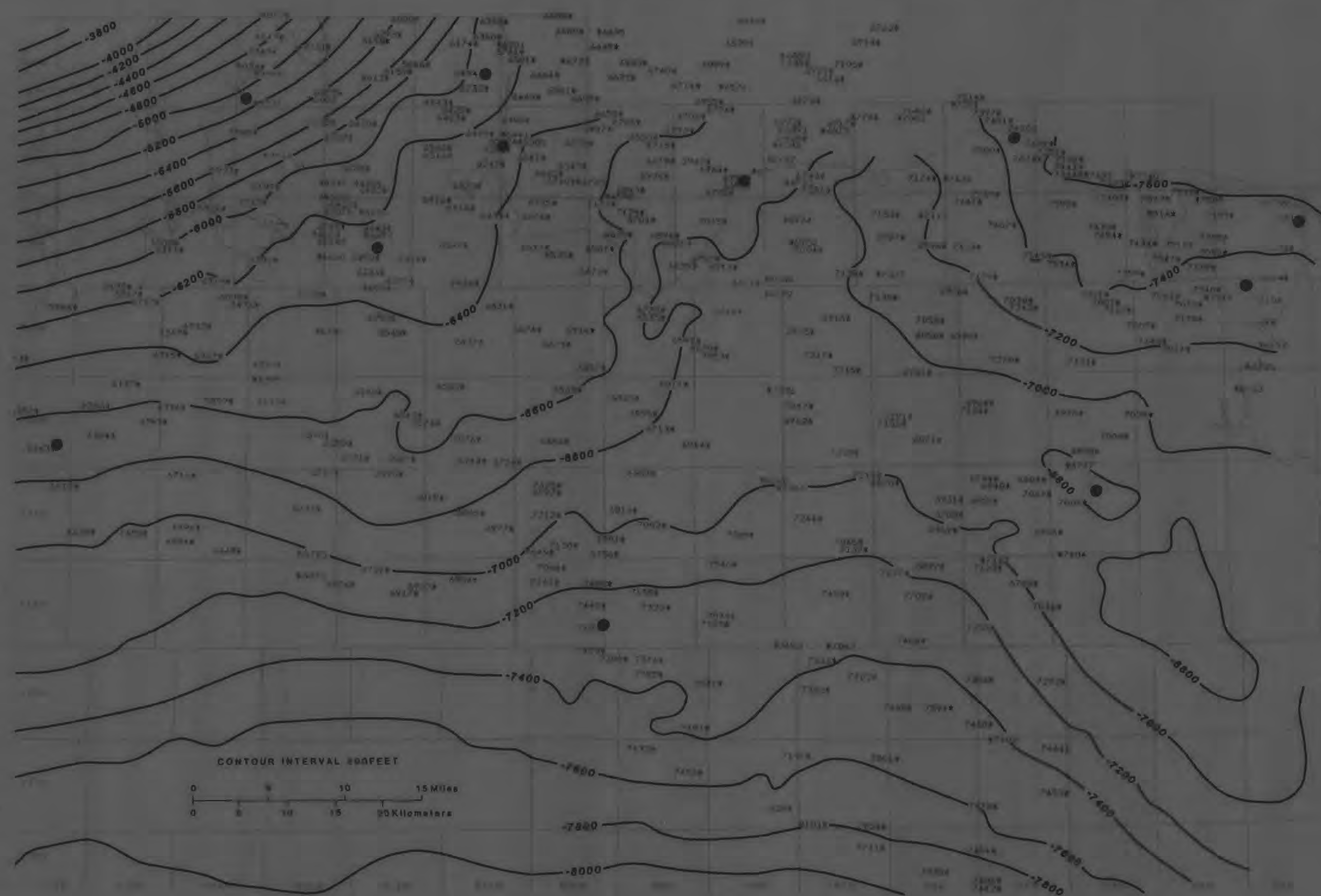

FIGURE 4. ESTIMATED DEPTH (FT) TO TOP OF "PEBBLE SHALE" BY TETRA TECH SYSTEM (Z_{tt}), AS CONTOURED. PLOTTED VALUES ARE DEPTH BASED ON SEISMICALLY DERIVED VELOCITY (Z_s) AND ARE NEGATIVE (SUBSEA).

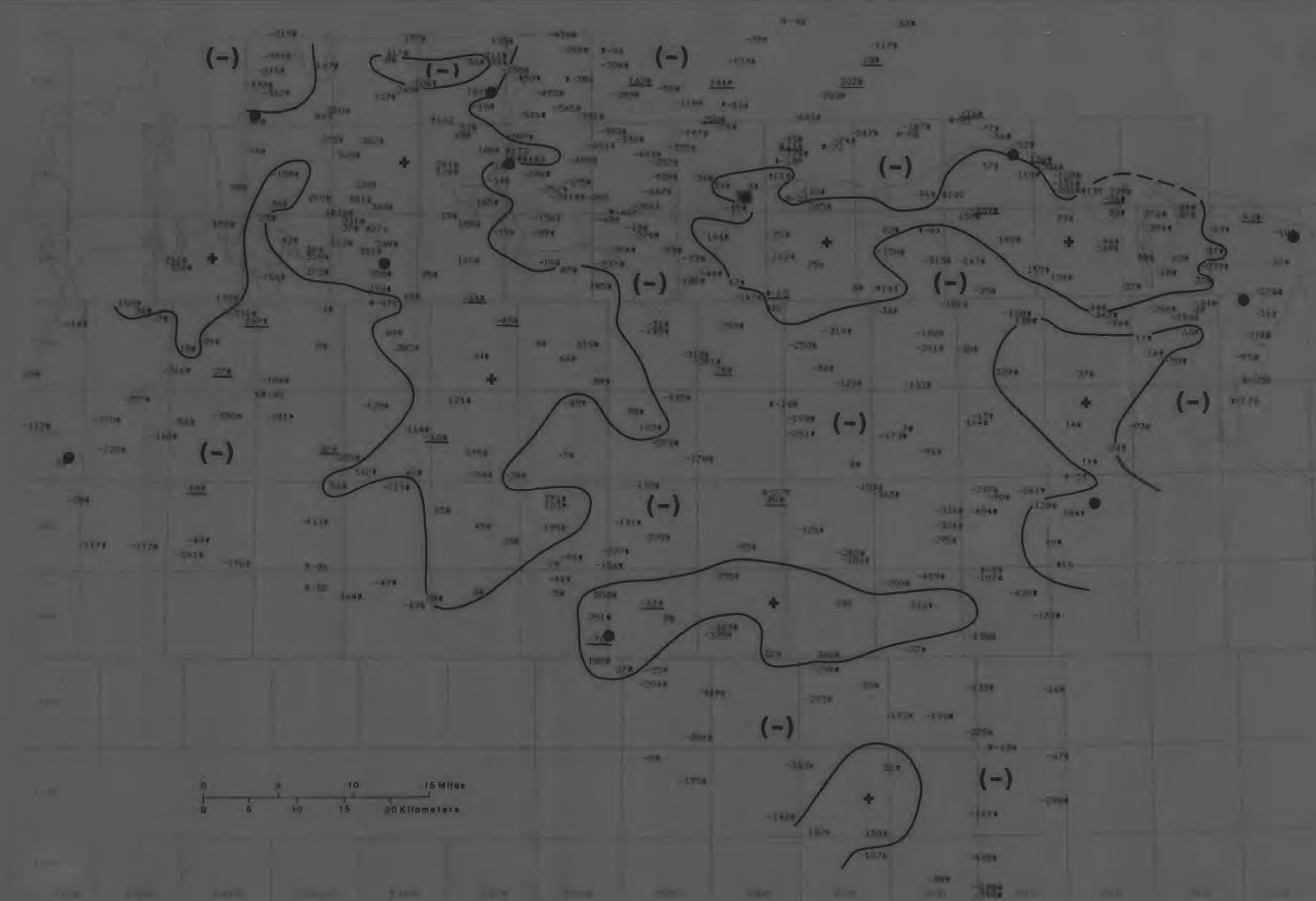

FIGURE 5. DIFFERENCE (D) BETWEEN DEPTH BASED ON SEISMICALLY DERIVED VELOCITY AND DEPTH BASED ON WELL DERIVED VELOCITY. LINES REPRESESENT ZERO DIFFERENCE. UNDERLINED NUMBERS ARE MISFITS.

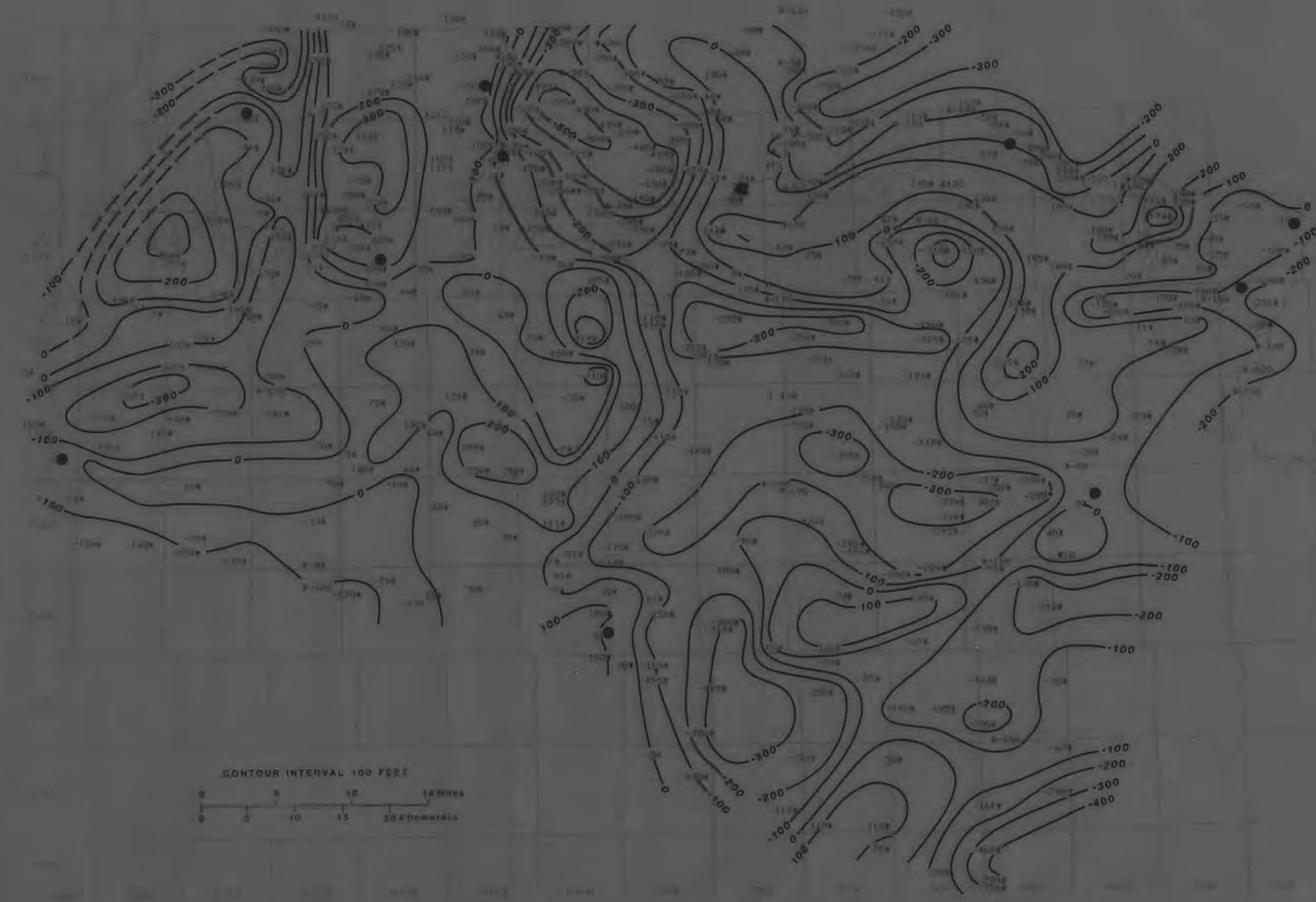

FIGURE 6 NON-RANDOM COMPONENT OF DIFFERENCE (D) BETWEEN DEPTH BASED ON SEISMICALLY DERIVED VELOCITY (Z_s) AND DEPTH BASED ON WELL-DERIVED VELOCITY (Z_w).

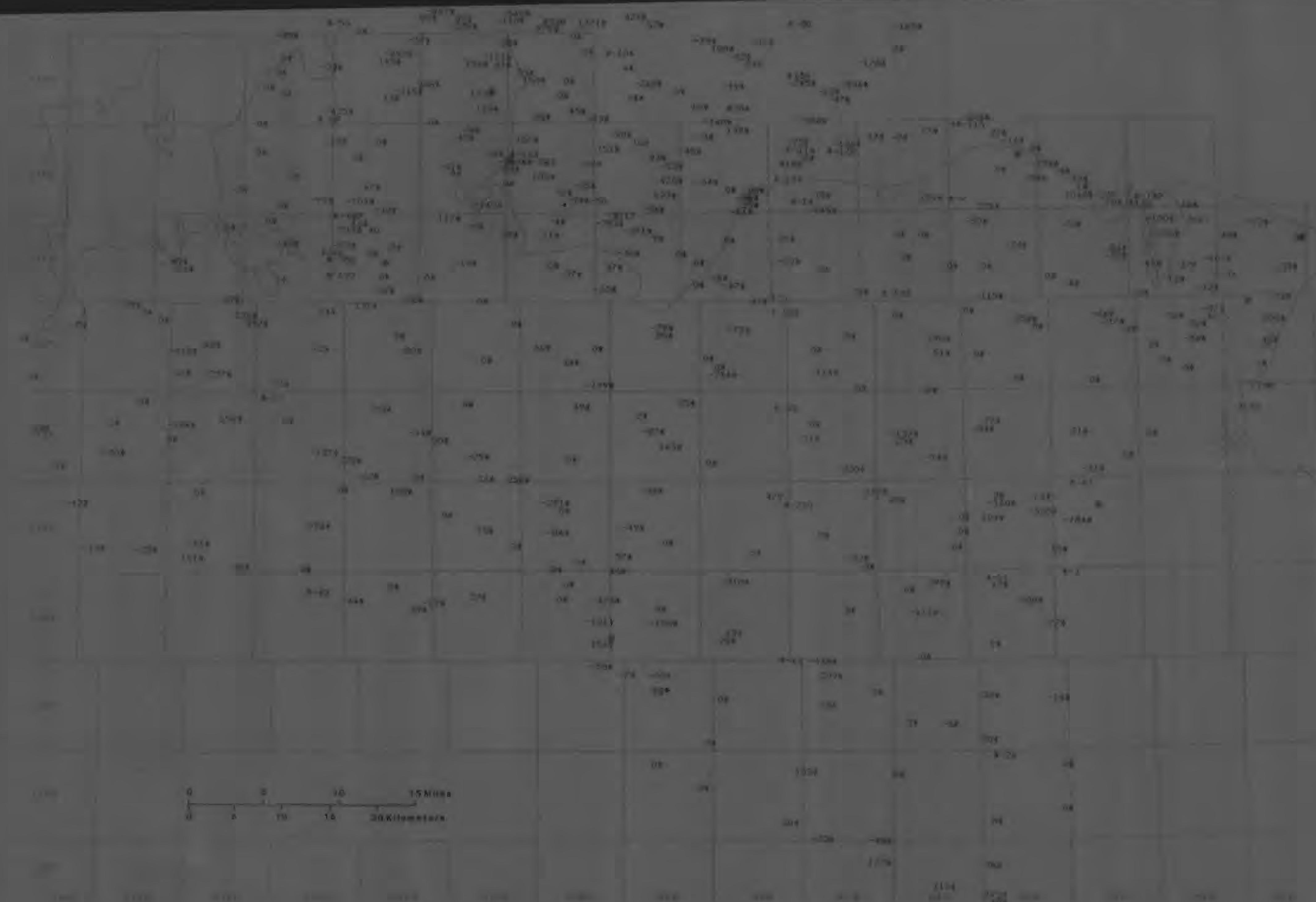

FIGURE 7. RANDOM ERROR IN DEPTH DIFFERENCE (D) TO TOP OF "PEBBLE SHALE" REPRESENTS MAINLY ERROR IN SEISMICALLY DERIVED VELOCITY

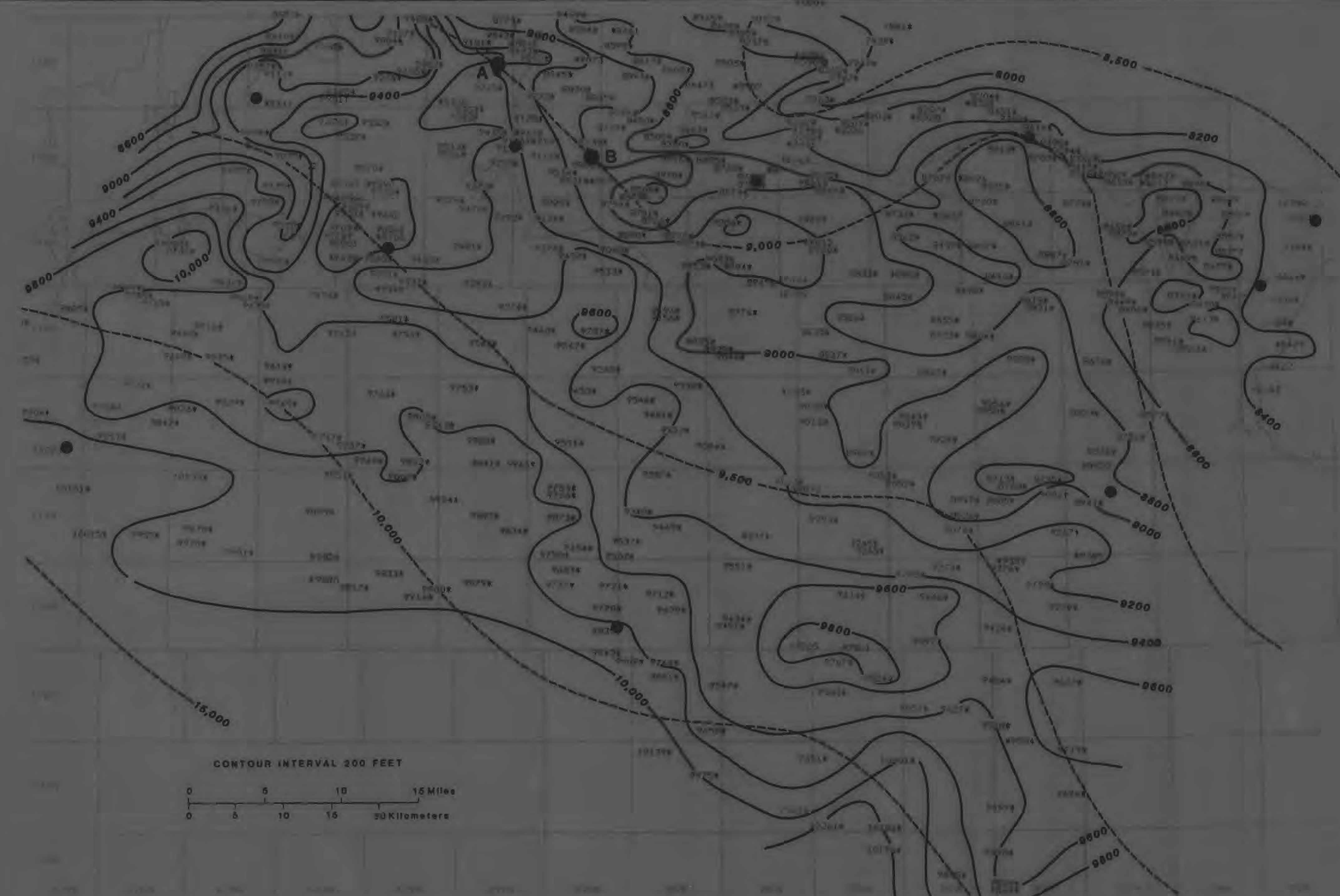

FIGURE 8. AVERAGE VELOCITY TO TOP OF "PEBBLE SHALE" IN FT/SEC. SOLID CONTOUR LINES ARE FROM USGS MODEL BASED ON PLOTTED VALUES.
DASHED LINES FROM TETRA TECH'S MODEL.

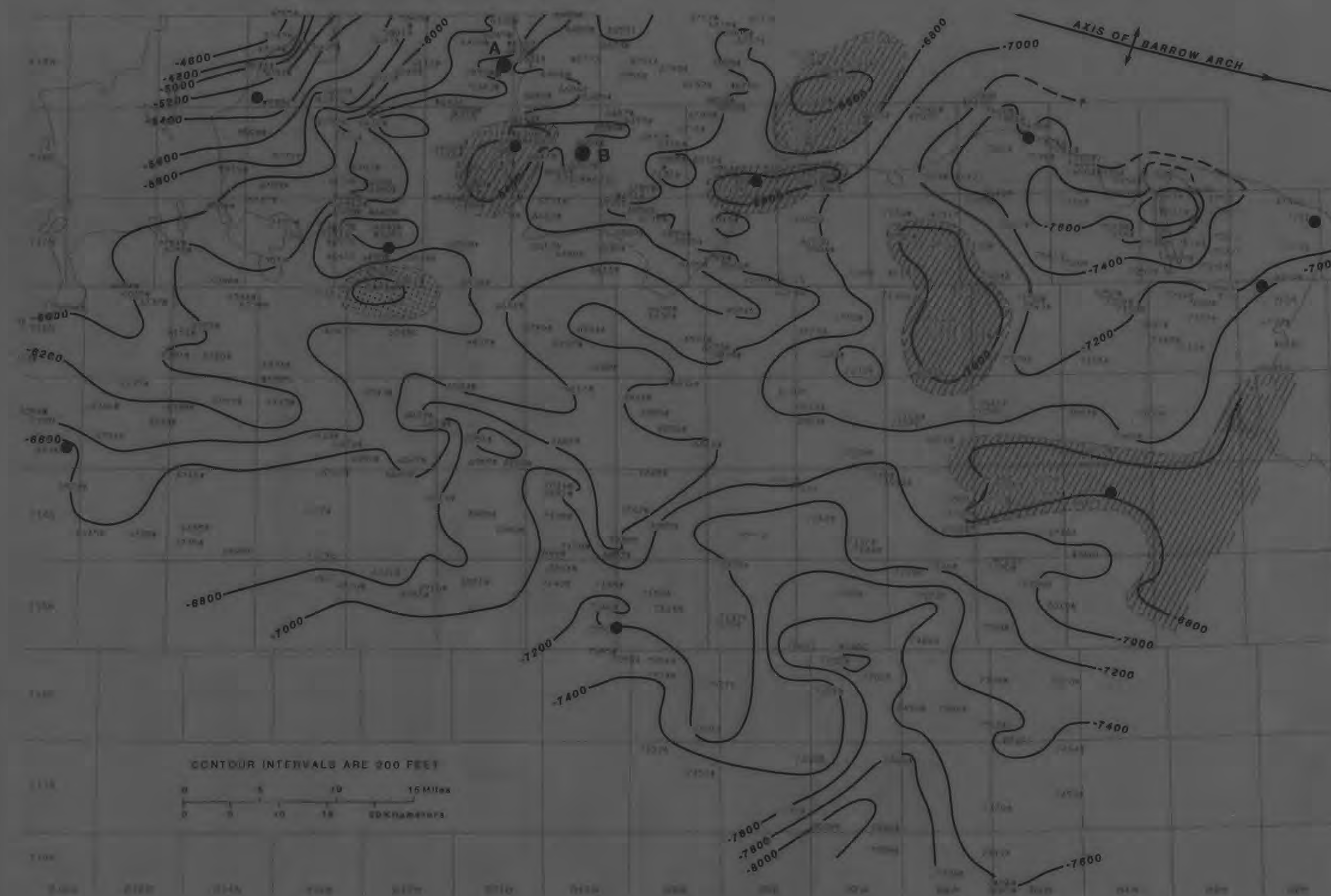

FIGURE 9. ESTIMATED DEPTH (FT) TO TOP OF "PEBBLE SHALE" BY USGS SYSTEM (Z_{gs}). STIPPLED AREA IS HYPOTHETICAL GAS FIELD. SLANT LINED AREAS ARE INDICATED CLOSURES THAT MIGHT CONTAIN OIL OR GAS IF RESERVOIR IS PRESENT NEAR CONTOURED HORIZON