USGS
science for a changing world

DENSITY AND VELOCITY RELATIONSHIPS FOR DIGITAL SONIC AND DENSITY LOGS FROM COASTAL WASHINGTON AND LABORATORY MEASUREMENTS OF OLYMPIC PENINSULA MAFIC ROCKS AND GREYWACKES

by Thomas M. Brocher[1] and Nikolas I. Christensen[2]

US GEOLOGICAL SURVEY
LIBRARY
OCT 15 2001
RESTON, VA

Open-File Report 01-264

2001

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

[1] U.S. Geological Survey, 345 Middlefield Road, M/S 977, Menlo Park, CA 94025
[2] Dept. of Geology and Geophysics, 1215 W. Dayton St., University of Wisconsin, Madison, WI 53706

ABSTRACT

Three-dimensional velocity models for the basins along the coast of Washington and in Puget Lowland provide a means for better understanding the lateral variations in strong ground motions recorded there. We have compiled 16 sonic and 18 density logs from 22 oil test wells to help us determine the geometry and physical properties of the Cenozoic basins along coastal Washington. The depth ranges sampled by the test well logs fall between 0.3 and 2.1 km. These well logs sample Quaternary to middle Eocene sedimentary rocks of the Quinault Formation, Montesano Formation, and Hoh rock assemblage. Most (18 or 82%) of the wells are from Grays Harbor County, many of these are from the Ocean City area. These Grays Harbor County wells sample the Quinault Formation, Montesano Formation, and frequently bottom in the Hoh rock assemblage. These wells show that the sonic velocity and density normally increase significantly across the contacts between the Quinault or the Montesano Formations and the Hoh rock assemblage. Reflection coefficients calculated for vertically traveling compressional waves from the average velocities and densities for these units suggest that the top of the Hoh rock assemblage is a strong reflector of downward propagating seismic waves: these reflection coefficients lie between 11 and 20%. Thus this boundary may reflect seismic energy upward and trap a substantial portion of the seismic energy generated by future earthquakes within the Miocene and younger sedimentary basins found along the Washington coast.

Three wells from Jefferson County provide data for the Hoh rock assemblage for the entire length of the logs. One well (Eastern Petroleum Sniffer Forks #1), from the Forks area in Clallam County, also exclusively samples the Hoh rock assemblage. This report presents the locations, elevations, depths, stratigraphic and other information for all the oil test wells, and provides plots showing the density and sonic velocities as a function of depth for each well log. We also present two-way travel times for 15 of the wells calculated from the sonic velocities. Average velocities and densities for the wells having both logs can be reasonably well related using a modified Gardner's rule, with $\rho = 1825v^{1/4}$, where ρ is density in kg/m^3 and v is the sonic velocity in km/s. In contrast, a similar analysis of published well logs from Puget Lowland is best matched by a Gardner's rule of $\rho = 1730v^{1/4}$, close to the $\rho = 1740v^{1/4}$ proposed by Gardner et al. (1974).

Finally, we present laboratory measurements of compressional-wave velocity, shear-wave velocity, and density for 11 greywackes and 29 mafic rocks from the Olympic Peninsula and Puget Lowland. These units have significance for earthquake hazard investigations in Puget Lowland as they dip eastward beneath the Lowland, forming the "bedrock" beneath much of the lowland. Average Vp/Vs ratios for the mafic rocks, mainly Crescent Formation volcanics, lie between 1.81 and 1.86. Average Vp/Vs ratios for the greywackes from the accretionary core complex in the Olympic Peninsula show greater scatter but lie between 1.77 and 1.88. Both the Olympic Peninsula mafic rocks and greywackes have lower shear-wave velocities than would be expected for a Poisson solid (Vp/Vs=1.732). Although the P-wave velocities and densities in the greywackes can be related by a Gardner's rule of $\rho = 1720v^{1/4}$, close to the $\rho = 1740v^{1/4}$ proposed by Gardner et al. (1974), the velocities and densities of the mafic rocks are best related by a Gardner's rule of $\rho = 1840v^{1/4}$. Thus, the density/velocity relations are similar for the Puget Lowland well logs and greywackes from the Olympic Peninsula. Density/velocity relations are similar for the Washington coastal well logs and mafic rocks from the Olympic Peninsula, but differ from those of the Puget Lowland well logs and greywackes from the Olympic Peninsula.

CONTENTS

TABLE

FIGURES

INTRODUCTION

We present data from 16 sonic and 18 density logs from 22 oil test wells to categorize the sonic velocities and densities of Cenozoic sedimentary basins in coastal Washington (Fig. 1).

We also present laboratory measurements of compressional-wave and shear-wave velocities for 40 basement rocks outcropping in the Olympic Peninsula and Puget Lowland. These measurements were made on twenty-nine mafic rocks (mainly Crescent Formation volcanics) and eleven greywackes at room temperatures and confining pressures up to 1000 MPa (10 Kbar). These measurements represent the first laboratory measurements of the shear-wave velocities for these important bedrock units.

We use these well log and laboratory measurements to examine velocity-density relationships for rock suites found in coastal Washington, the Olympic Peninsula, and Puget Lowland. For two of the suites of rocks investigated here, we note significant departures of these measurements from the density/velocity relationship proposed for sedimentary rocks by Gardner et al. (1974).

Finally, we use the average velocity and densities determined for sedimentary units in coastal Washington (the Quinault and Montesano Formations and the Hoh rock assemblage) to obtain estimates of the average seismic reflection coefficients in the sedimentary basins found along the coast of Washington. These estimates suggest that seismic waves might be efficiently trapped in the basins during future large earthquakes in the Pacific Northwest, enhancing the ground motions for the basins relative to nearby bedrock sites.

WELL LOG ANALYSIS

We first report the new sonic and density logs for the 22 oil test wells along coastal Washington. The locations, elevations, and depths of the wells, as well as the operator, lease name, well number, and completion year are presented in Table 1: the wells in this table are ordered by latitude from south to north. The well information in Table 1 is taken from the Well History Control System (WHCS) One-line File, an on-line digital well-log database leased from Petroleum Information by the USGS Office of Energy Resources at Denver. Table 1 provides information on the type of sonic and density tool used to make the log, as well as the other tools which were run simultaneously with these tools (normally caliper, spontaneous potential, and gamma-ray). Only a few of the sonic logs were made with older, short tools, with short spans between the source and receivers. Stratigraphic control is available for 21 of the 22 wells [Rau and McFarland, 1982; Palmer and Lingley, 1989].

Sonic and density logs were hand digitized at non-uniform intervals between 0.3 and 30 m to capture the significant variations of the logs with depth for frequencies up to 20 Hz. The average sampling interval was 1 to 3 m. The sampling interval was adequate to estimate linear trends in the data over these intervals. We note that our sampling interval was not intended and is not sufficiently dense for the calculation of high-frequency (say >50 Hz) synthetic seismograms. For higher-frequency synthetics, it will be necessary to redigitize the logs with a finer sampling interval.

For the sonic logs, we picked transit times (μs/ft) as a function of depth down the well. For the gamma-gamma density logs, we picked bulk density in kg/m^3 as a function of depth down the well. For the neutron density porosity logs, we converted the logged density porosity (ϕ) to formation density (ρ_{fd}) using $\rho_{fd} = \rho_m + (\rho_f - \rho_m)\phi$, where the matrix density $\rho_m = 2650$ kg/m^3, and the fluid density $\rho_f = 1000$ kg/m^3 [Ellis, 1987]. All of the logs analyzed here are plotted at a scale of 30.49 m:5.08 cm (100 feet:2.5 inches) or 30.49 m:2.54 cm (100 feet:1 inch). Depths are measured from an arbitrary reference datum, normally the Kelley Bushing (KB), located 3.65 m (12 feet) above ground level. The downhole depths reported here have not been corrected for this small upward shift. Cased intervals of the wells and sections identified on the logs as having cycle skipping problems were not digitized. In some cases data from the logs were ignored: these data were associated with washouts, thick mudcake, invasion of drill fluids or large deviations from the general trend of density and sonic values having very limited depth extent, generally less than a few meters [Ellis, 1987]. The digitized sonic log data were converted from transit times to velocities (m/s) and depths from feet to meters for both the sonic and density logs. Plots are presented in Figures 2 to 11 showing seismic velocities and densities as a function of depth for each well.

We have calculated two-way travel times from the sonic logs and displayed these in Figures 12 to 15. This calculation required us to extrapolate sonic velocities to the surface. In one case, Belco Petroleum Corp. Milwaukee Land 1-1, the depth to the first measured sonic velocity was judged to be too great to extrapolate the sonic velocity to the surface.

BOREHOLE LITHOLOGIES

The following discussion of the borehole lithologies (Table 2) is summarized from Rau and McFarland (1982) and Palmer and Lingley (1989), who described the lithologies in the wells reported here. The reader is referred to these references for a more detailed discussion of the units sampled in the boreholes.

Hoh rock assemblage

The Hoh rock assemblage is composed of middle Eocene to middle Miocene, deep-water marine rocks thought to have been accreted to North America during the subduction process. Many of these rocks are turbidites and are mainly greywacke clastic sedimentary rocks. In the Forks area, most of the Hoh rock assemblage consists of thick sequences of siltstone, claystone, and sandstone. Alternations of these lithologies may explain the undulations observed in sonic and density logs of this formation.

Quinault and Montesano Formations

The Quinault Formation rests unconformably on the Hoh rock assemblage. Rau and McFarland (1982) discuss the uncertainty in the age of this unit, which includes late Miocene and Pliocene members. Rau and McFarland (1982) use the Quinault Formation for the sedimentary rocks of this age lying unconformably on the Hoh rock assemblage. Bergen and Bird (1972) and Palmer and Lingley (1989) believe most of these rocks to be late Miocene in age and refer to them as the Montesano Formation. Palmer and Lingley (1989) group rocks above the Montesano Formation and call them undifferentiated Quaternary deposits and Quinault Formation. For four of the Ocean City wells studied here we show the Montesano Formation as described by Palmer and Lingley (1989); for the remainder of the 22 wells we follow the formation identification provided by Rau and McFarland (1982).

From top to bottom the Montesano Formation contains a thick siltstone, sandstone, and claystone member. Similarly, the Quinault Formation identified by Rau and McFarland (1982) has claystone, sandstone, and siltstone members, which have fairly distinctive signatures in the sonic and density logs.

Quaternary Deposits

Few, if any, of the well logs sample Quaternary deposits, which are inferred to overlie the sampled units. The Shell John's 1-15 and Shell Sampson Johns OCA 2-15 wells may sample Quaternary deposits at the tops of the logs, but the available formation identifications are not definitive (Table 2).

COMMENTS ON THE WELL LOG DATA

We superimposed the formation tops from Table 2 onto the well logs shown in this report. Often these formation contacts correspond to significant changes in the sonic velocity and density, and/or in the character of these logs.

In Table 3 we show average velocities and linear regressions over intervals corresponding to known or inferred formations. Similar averages and linear regressions on the density log data are shown in Table 4. As anticipated, average sonic velocities (generally 1400 to 2000 m/s) and densities (2000 kg/m^3) in the Quaternary deposits are significantly lower than those of underlying Tertiary sedimentary rocks (Tables 3 and 4). The contact between the Hoh rock assemblage and overlying Tertiary sedimentary rocks represents a large (about 0.3 km/s) increase in sonic velocity (Table 3).

Hoh rock assemblage

Long sections of the Hoh rock assemblage were logged at three wells near Joe Creek in Greys Harbor County as well as at four northernmost wells analyzed in this study (Figures 1, 10, and 11). In the Joe Creek area (Figure 1; T20N, R12W), the well logs show a substantial decrease in density and sonic velocity at a depth of about 1000 m (3280 ft). The logs for the four northernmost wells in Jefferson and Clallam Counties (Figure 10) show more minor variations with depth, particularly with respect to the density. The high scatter in sonic velocities in the Belco Petroleum Milwaukee Land 1-1 well (Figure 10) are due to cyclic skipping. Density logs for the El Paso Lacey No. 22-1 and Belco Petroleum Milwaukee Land 1-1 wells show a well-defined increase in density with depth (Figure 10).

Quinault and Montesano Formations

The Quinault Formation is characterized by low sonic velocities and densities. Sonic velocities generally lie between 2 and 2.5 km/s; densities generally lie between 2100 and 2300 kg/m^3. In many of the wells there is a distinctive unit within the Quinault Formation that is typified by rapid fluctuations in sonic velocity and density. This unit contains pebbles in a sandstone matrix. The rapid fluctuations in the logs are caused by sampling the higher sonic velocities and densities of the pebbles versus the lower-velocity and lower density matrix. This conglomeratic unit is especially well developed in Shell OCA Hogan #1-13 (Figure 2), but is also seen in the Shell Hogan #1-8 (Fig. 2), Shell Grays Harbor Co. OCA #1-11 (Fig. 3), Shell Ocean City Land Development Co. #1-14 (Fig. 3), Shell Sampson Johns OCA #2-15 (in the Montesano Formation) (Fig. 4), Shell Luse #1-23 (Fig. 5), and Shell Grays Harbor Co. #1-35 (Fig. 7) wells.

Within the Quinault and Montesano Formations, the claystone member generally has the lowest velocities and densities and the sandstone member generally has the highest velocities and densities. The low densities and sonic velocities of the claystone member of the Quinault Formation are well displayed at the Shell Ocean City Land Development Co. #1-14 well (Figure 3). The higher seismic velocities and densities of the sandstone member are typified by the Shell John's #1-15 and Shell Sampson Johns OCA #2-15 wells (Figure 4).

Quaternary Deposits

Only the Shell John's 1-15 and Shell Sampson Johns OCA 2-15 wells may sample Quaternary deposits at the tops of the logs (Figure 4). In these wells undifferentiated Quaternary deposits and Quinault Formation have velocities between 1.5 and 2.0 km/s (Figure 4). The higher velocities in the John's #1-15 well at about 300 m depth correspond to a pebbly sandstone member, most likely of the Quinault Formation (Rau and McFarland, 1982). No density logs were made for these intervals.

TRAVEL TIME CURVES

Individual travel time curves calculated for the wells having sonic well logs are shown in Figures 12 to 15. The calculated travel time curves are summarized in Figure 15. For the majority of the wells the curves plot closely together and nearly intersect the 1 second mark at a depth of 1000 m, consistent with an average velocity of 2 km/s to this depth. One curve, for the Shell-Minard 1-34 well, yields consistently larger travel times, consistent with its lower velocity (Figure 15). Both the travel time curve and sonic velocities are anomalous at the Shell-Minard 1-34 relative to nearby sites. The sonic log at Shell-Minard 1-34 was not compensated, and it may be possible that the sonic velocities measured there are systematically too low. [An alternative explanation is that the interval transit time scale was incorrectly read for this well.]

In contrast to these wells in Grays Harbor County, the travel time curves calculated for the Hoh River Barlow No. 1 (Figure 15) and Humble Oil Ollar State No. 1 (Figure 14) wells yield smaller travel times at all depths sampled. These smaller travel times are consistent with the higher sonic velocities found in the wells associated with the Hoh rock assemblage.

LABORATORY MEASUREMENTS

Laboratory determined velocities for 40 basement rocks outcropping in the Olympic Peninsula and Puget Lowland provide the first measurements of shear wave velocities for the Crescent Formation volcanics and greywackes in the Olympic accretionary core complex (Figure 16). Brocher et al. [2001] showed the compressional-wave velocity as a function of confining pressure for these rocks, but did not present the shear-wave velocity information, nor did they describe the variability of the measurements (summarized by Tables 5 to 12).

The eleven greywackes were taken from the accretionary wedge of the Olympic core complex; the 29 mafic samples are mainly basalts from the Crescent Formation (Figure 16). Mafic samples OL-10 and OL-15 represent gabbros within the Crescent Formation; the other mafic samples are basalts. Samples were field oriented by their bedding and flow structure. Velocities were measured in a hydrostatic pressure apparatus at room temperature using a pulse transmission technique described by Christensen [1985]. The laboratory data in Tables 5-12 and Figures 17 and 18 are uncorrected for increasing temperature in the crust, which can significantly lower the velocities in the lower crust (corrections are approximately –0.02 to –0.06 km/s per 100°C increase in temperature [Christensen, 1979]). Mean P-wave velocities for the two different rock suites at almost all confining pressures differ by at least 1 km/s: even the standard deviations of the velocities for the two suites are distinct (Figures 17 and 18). Mean S-wave velocities for the mafic rocks and greywackes differ less significantly. We have also plotted Vp/Vs and Poisson's ration as a function of confining pressure for the two rock suites.

The Vp/Vs ratio for both the Olympic mafic rocks and greywackes are higher than average than would be expected for a Poisson solid (Vp/Vs=1.732). Thus, the shear wave velocities expected for these lithologies are lower than might be predicted from their P-wave velocity assuming a Poisson's ratio of 0.25. The Vp/Vs ratio shows relatively little sensitivity to confining pressure for the mafic rocks, but increases more significantly for the greywackes.

DENSITY AND VELOCITY RELATIONSHIP

Gardner et al. (1974) proposed an empirical relationship, based on borehole measurements, between sonic velocity and density in sedimentary rocks. The rule proposed by Gardner et al. (1974) is $\rho = 1740v^{1/4}$, where ρ is density in kg/m^3 and v is the sonic velocity in km/s. For the purpose of discussion, we will refer to the coefficient multiplying the factor of $v^{1/4}$ as Gardner's coefficient.

In Figure 19 we plot average compressional-wave velocities and densities for the laboratory measurements of Olympic Peninsula greywackes and mafic rocks at 100 MPa (Tables 5 and 9), for the wells in Coastal Washington reported here, and in Puget Lowland as reported by Brocher and Ruebel (1998) are plotted in Figure 19. We determined the Gardner's coefficient for each suite of rocks by minimizing the misfit between the observed and calculated density (Figure 20). For each suite of rocks the Gardner's coefficient was determined from a well-defined minima in the root-mean-square (RMS) curves of misfit versus Gardner's coefficient (Figure 20).

P-wave velocities and densities of the Olympic Peninsula greywackes and well log data sampling sedimentary rocks in the Puget Lowland (Brocher and Ruebel, 1998) are best fit by Gardner's coefficients of 1720 and 1730, respectively (Figure 20). These values are very close to the coefficient of 1740 proposed for sedimentary rocks by Gardner et al. (1974).

In contrast, the velocities and densities for the Washington Coast wells and Olympic Peninsula mafic rocks are best fit by much higher Gardner's coefficients of 1835 and 1840, respectively (Figures 19 and 20). These coefficients are significantly higher than the value of 1740 determined by Gardner et al. (1974) for sedimentary rocks.

Figure 20 demonstrates that there are significant differences between the Olympic Peninsula greywackes and mafic rocks and between the Puget Lowland and the Coastal Washington sedimentary rocks measured in the sonic and density logs.

To what can we ascribe the high Gardner's coefficient needed for the sedimentary rocks sampled in the coastal Washington well logs? Figure 20 suggests that the high Gardner's coefficient required for the coastal Washington wells may result from the inclusion of Olympic mafic rocks within the Quinault and Montesano Formations and in the Hoh rock assemblage.

EARTHQUAKE HAZARDS IMPLICATIONS

The low sonic velocities and densities within the Quinault and Montesano Formations and the abrupt increase of these parameters in the underlying Hoh rock assemblage suggest that strong ground motions along the coast will be amplified due to the presence of these formations.

Reflection coefficients calculated for vertically traveling compressional waves were calculated from

$$Rpp = (v_2\rho_2 - v_1\rho_1)/(v_2\rho_2 + v_1\rho_1) \qquad (1)$$

where v is the sonic velocity and ρ is the density, and 1 represents the upper layer and 2 the bottom layer.

Reflection coefficients (Table 14) calculated from the average velocities and densities for these units (Table 13) suggest that the top of the Hoh rock assemblage is a strong reflector of downward propagating seismic waves: these reflection coefficients lie between 11 and 20%. The magnitudes of these coefficients are all consistent with strong seismic reflectors. Thus this boundary may reflect upwards and trap a substantial portion of the seismic energy generated by future earthquakes within the Miocene and younger sedimentary basins found along the Washington coast. The largest reflection coefficients (20%) would be expected for the case when Quaternary deposits directly overlie the Hoh rock assemblage.

Although we have calculated compressional-wave reflection coefficients, we believe that these are appropriate for shear-waves as well. If the Vp/Vs ratio is constant for these rocks, then Rss should be identical to Rpp. If Vp/Vs increases with formation age and/or depth, then Rss would be higher than the Rpp calculated here.

DATA AVAILABILITY

The densities, seismic velocities, and two-way travel times shown in Figures 2 to 15 and Tables 5 to 12 are available in Excel5 spreadsheets using anonymous ftp (swave.wr.usgs.gov at /pub/outgoing/brocher)

ACKNOWLEDGEMENTS

Zenon Valin, USGS, kindly performed a search of a digital database providing well locations and other well information. Larry Beyer, USGS, made many useful suggestions for digitizing the well log data. Rick Blakely, USGS, reviewed an earlier version of this report. Pat McCrory provided a copy of Figure 1, modified here.

This work was supported by the National Earthquake Hazards Reduction Program.

REFERENCES CITED

Bergen, F.W., and Bird, K.J., 1972, The biostratigraphy of the Ocean City area, Washington: Proceedings of the Pacific Coast Miocene Biostratigraphic Symposium: presented at the 47th Annual Pacific Section S.E.P.M. convention, March 9-10, 1972, Bakersfield, California, p. 173-191.

Brocher, T.M. and Ruebel, A.L., 1998, Compilation of 29 sonic and density logs from 23 oil test wells in western Washington State, U.S. Geological Survey Open-File Report 98-249, 41 p.

Brocher, T.M., T. Parsons, R.A. Blakely, N.I. Christensen, M.A. Fisher, R.E. Wells, and the SHIPS Working Group, 2001, Upper crustal structure in Puget Lowland, Washington: Results from 1998 Seismic Hazards Investigation in Puget Sound, *J. Geophy. Res.*, 106, 13,541-13,564.

Christensen, N.I., 1979, Compressional wave velocities in rocks at high temperature and pressures, critical thermal gradients and crustal low-velocity zones, *J. Geophys. Res.*, 84, 6849-6857.

Christensen, N.I., 1985, Measurements of dynamic properties of rock at elevated pressures and temperatures, in *Measurements of Rock Properties at Elevated Pressures and Temperatures*, edited by H. J. Pincus and E. R. Hoskins, pp. 93-107, American Society for Testing and Materials, Philadelphia, Pa.

Ellis, D.V., 1987, Well Logging for Earth Scientists, Elsevier, New York, 532 p.

Gardner, G.H.F., L.W. Gardner, and A.R. Gregory, 1974, Formation velocity and density; the diagnostic basics for stratigraphic traps, *Geophysics, 39*, 770–780.

Johnson, S.Y.,Tennyson, M.E., Lingley, W.S., and Law, B.E., 1993, Petroleum geology of the State of Washington: U.S. Geological Survey, Professional Paper 1582, 40 pp.

McFarland, C.R., 1983, Oil and gas exploration in Washington, 1900-1982, Washington (State), Dept. of Natural Resources, Div. Geology and Earth Resources, Information Circular 75, 119 p.

Palmer, S.P., and W.S. Lingley, 1989, An assessment of the oil and gas potential of the Washington outer continental shelf, Washington State & Offshore Oil and Gas, Washington Sea Grant Program, Univ. of Wash., Seattle, 83 p., 12 plates.

Rau, W.W., and McFarland, C.R., 1982, Coastal wells of Washington: Washington Division of Geology and Earth Resources Report of Investigations 26, 4 plates.

Table 1. Oil test well location and logging history.

Operator	Leasename	No.	County	Latitude	Longitude	Depth (ft)	Depth (m)	T	R	S	Elev. (ft)	Elev. (m)	Year	Sonic Log	Density Log	Other Logs
Shell Oil	Shell-Minard	1-34	Grays Harbor	47.01294	-124.15234	4600	1402	18 N	12 W	34	27	8	1970	T3R	CFD gg	Cal., GR, SP
Shell Oil	Luse	1-23	Grays Harbor	47.04164	-124.14824	3602	1098	18 N	12 W	23	8	2	1970	BHC T3R2R	CFD gg	Cal., GR, SP
Shell Oil	Sampson Johns	2-15	Grays Harbor	47.04555	-124.16222	2390	729	18 N	12 W	15	13	4	1970	BHC T3R2R		Cal., SP
Shell Oil	Shell-Sampson J	1-15	Grays Harbor	47.04732	-124.15396	2795	852	18 N	12 W	15	20	6	1970	BHC T3R2R	CFD gg	Cal., GR
Shell Oil	Ocean City LD C	1-14	Grays Harbor	47.04738	-124.13805	4268	1301	18 N	12 W	14	30	9	1970	BHC T3R2R	CFD gg	Cal., GR, SP
Shell Oil	Hogan	1-13	Grays Harbor	47.05186	-124.12610	2922	891	18 N	12 W	13	45	14	1970	BHC T3R2R	CFD gg	Cal., SP
Shell Oil	Hogan	1-8	Grays Harbor	47.05762	-124.07370	1395	425	18 N	11 W	8	35	11	1970	BHC T3R2R	CFD gg	Cal., GR, SP
Shell Oil	Grays Harbor County	1-11	Grays Harbor	47.06535	-124.13080	3240	988	18 N	12 W	11	20	6	1970	BHC T3R2R	CNFD	Cal., GR, SP
Shell Oil	Grays Harbor County	1-35	Grays Harbor	47.09222	-124.14999	2527	770	19 N	12 W	35	60	18	1970	BHC T3R2R	CFD gg	Cal., GR, SP
El Paso Product.	Grays Harbor Community	27-1	Grays Harbor	47.09741	-123.78906	4600	1402	19 N	9 W	27	411	125	1975		CFD gg	Cal., GR
El Paso Product.	Grays Harbor County	36-1	Grays Harbor	47.09778	-124.12517	2769	844	19 N	12 W	36	65	20	1974		CFD gg	Cal., GR
Shell Oil	Shell Trambites	1-28	Grays Harbor	47.10477	-124.17253	3111	948	19 N	12 W	28	12	4	1970	BHC T3R2R	CFD gg	Cal., GR, SP
Shell Oil	Grays Harbor County LHA	1-15	Grays Harbor	47.13101	-124.15640	2032	620	19 N	12 W	15	45	14	1970	BHC T3R2R	CFD gg	Cal., GR, SP
Shell Oil	Shell-McCleave	1-33	Grays Harbor	47.18498	-124.18867	1344	410	20 N	12 W	33	132	40	1970	T3R2R	CFD gg	Cal., GR, SP
Development Assoc.	M A Baker	1-30	Grays Harbor	47.19826	-124.10410	4000	1220	20 N	11 W	30	460	140	1973		Sidewall NFD	Cal., GR
Humble Oil & Ref.	Ollar State	1	Grays Harbor	47.20285	-124.12630	5000	1524	20 N	12 W	24	450	137	1961	T3R1R		Cal., SP
Humble Oil & Ref.	Everett Trust and Savings	B-1	Grays Harbor	47.20285	-124.12630	5000	1524	20 N	12 W	24	450	137	1961	T3R1R		Cal.
Development Assoc.	Carlisle	1-23	Grays Harbor	47.20645	-124.13293	4100	1250	20 N	12 W	23	284	87	1974		CFD gg, CNFD	Cal., GR
Hoh River Oil Co.	Barlow	1	Jefferson	47.74931	-124.40286	5015	1529	25 N	12 W	20	20	6	1965	T3R3R?		Cal., SP
El Paso Product.	Lacey	22-1	Jefferson	47.74689	-124.36052	5700	1738	26 N	13 W	22	261	80	1974		CFD gg	Cal., GR
Belco Petr. Corp.	Milwaukee Land	1-1	Jefferson	47.88261	-124.43869	6880	2098	27 N	14 W	1	140	43	1966	BHC T3R2R	CFD gg	Cal., GR, SP
Eastern Petr. Serv.	Sniffer Forks	1	Clallam	47.93750	-124.38028	3095	944	28 N	13 W	16	533	163	1973		CFD gg	Cal., GR

Abbreviations:

BHC - Borehole Compensated Sonic Log
CFD gg - Compensated Formation Density (gamma-gamma)*
SP - Spontaneous Potential
T3R3R - Sonic tool spacing (in feet) between transmitter (T) and receivers (R)

CNFD - Compensated Neutron Formation Density*
Cal. – Caliper
GR - Gamma Ray

*All density logging tools employ the backscattered gamma-ray technique, commonly called "gamma-gamma". The different names used here are either from different vendors or from different generations (having different trademark names).

Table 2. Stratigraphy in oil test wells

Well Name	Formation	Depth (ft)	Depth (m)
Shell Hogan No. 1-8	Quaternary deposits	0-800?	0-244?
	Quinault (?) Fm.	450-1300	137-396
	Hoh rock assemblage (?)	1300-TD	396-TD
Shell Hogan No. 1-13	No data	0-503	0-153
	Quinault Fm.	503-TD	153-TD
Shell Grays Harbor Co. No. 1-11	Quaternary (?) sediments	0-300	0-92
	Quinault Fm.	300-2850	92-869
	Hoh rock assemblage	2850-TD	869-TD
Shell Ocean City Land Co. No. 1-14	No data	0-919	0-280
	Quinault Fm.	919-3690	280-1125
	Hoh rock assemblage	3690-TD	1125-TD
Shell Sampson Johns No. 1-15	Undiff. Quat. Deposits and Quinault Fm.	0-1150	0-351
	Montesano Fm. – siltstone member	1150-1935	351-590
	Montesano Fm. – sandstone member	1935-2650	590-808
Shell Sampson Johns No. 2-15	Undiff. Quat. Deposits and Quinault Fm.	0-925	0-282
	Montesano Fm. – siltstone member	925-1410	282-430
	Montesano Fm. – sandstone member	1410-2125	430-648
Shell Luse No. 1-23	Undiff. Quat. Deposits and Quinault Fm.	0-1820	0-555
	Montesano Fm. – siltstone member	1820-2650	555-808
	Montesano Fm. – sandstone member	2650-2725	808-831
	Montesano Fm. – claystone member	2725-TD	831-TD
Shell Minard No. 1-34	No data	0-520	0-159
	Quinault Fm.	520-4450	159-1357
	Hoh rock assemblage	4450-TD	1357-TD
Shell Grays Harbor LHA No. 1-15	No data	0-500	0-152
	Quinault Fm.	500-1800	152-549
	Hoh rock assemblage	1800-TD	549-TD
Shell Trambitas No. 1-28	No data	0-1000	0-305
	Quinault Fm.	1000-2900	305-892
	Hoh rock assemblage	2925-TD	892-TD
Shell Grays Harbor Co. No. 1-35	Quinault Fm.	0-2500	0-762
	Hoh rocks (?)	2500-TD	762-TD
El Paso Grays Harbor Co. No. 36-1	No data	0-514	0-157
	Quinault Fm.	514-1740	157-530
	Hoh River assemblage	1740-TD	530-TD
Devel. Assoc. M A Baker No. 1-30	Post Miocene hiatus	0-280	0-85
	Hoh rock assemblage	280-TD	85-TD
Devel. Assoc. Carlisle No. 1-23	Quaternary (?) sediments	0-540	0-165
	Late Eocene	540-TD	165-TD
Humble Ollar State No. 1	Quaternary (?) sediments	0-380	0-116
	Hoh rock assemblage	380-TD	116-TD
Humble Everett Trust and Savings Bank ETR et al. B-1	Quaternary (?) sediments		
	Hoh rock assemblage?	1210-TD	369-TD
Shell McLeave No. 1-33	Quaternary sediments	0-450	0-137
	Quinault Fm.	450-1130	137-345
	Hoh rock assemblage	1130-1344	345-910
Hoh River Oil Barlow No. 1	Hoh rock assemblage	0-TD	0-TD
El Paso Lacey No. 22-1	Quaternary deposits	0-220	0-67
	Hoh rock assemblage	220-TD	67-TD
Belco Milwaukee Land No. 1-1	Hoh rock assemblage	615-TD	188-TD
Eastern Petrol. Sniffer Forks No. 1	Hoh rock assemblage	0-TD	0-TD

Sources: Rau and McFarland (1982), Palmer and Lingley (1989)

Table 3. Linear regression of sonic velocities in oil test well log

Wellname and number	Formation Name	Depth Interval (m)	Average Velocity (km/s)	Intercept Velocity (km/s)	Velocity Gradient (km/s/km)	R^2
Shell Hogan No. 1-8	Quinault (?) Fm.	137-396	2.460			
	Hoh rock assemblage (?)	396-TD	2.105			
Shell Hogan No. 1-13	Quinault Fm. – pebbly sand or sandstone	153-625	2.218			
	Quinault Fm. - siltstone	625-793	2.383			
	Quinault Fm. - claystone	793-891	2.097			
Shell Grays Harbor Co. No. 1-11	Quinault Fm. – sand and conglomerate	294-438	2.218			
	Quinault Fm. - claystone	438-869	2.047			
	Hoh rock assemblage	869-TD	2.035			
Shell Ocean City Land Co. No. 1-14	Quinault Fm. – sand and conglomerate	280-650	2.292			
	Quinault Fm. - claystone	650-1125	1.969			
	Hoh rock assemblage	1125-TD	2.096			
Shell Sampson Johns No. 1-15	Undiff. Quat. Deposits and Quinault Fm.	133-351	1.720			
	Montesano Fm. – siltstone member	351-590	2.018			
	Montesano Fm. – sandstone member	590-808	2.248			
	Montesano Fm. – claystone member	808-852	2.028			
Shell Sampson Johns No. 2-15	Undiff. Quat. Deposits and Quinault Fm.	0-282	1.642			
	Montesano Fm. – siltstone member	282-430	2.294			
	Montesano Fm. – sandstone member	430-648	2.629			
	Montesano Fm. – claystone member	648-TD	2.184			
Shell Luse No. 1-23	Undiff. Quat. Deposits and Quinault Fm.	263-555	2.241			
	Montesano Fm. – siltstone member	555-808	2.366			
	Montesano Fm. – sandstone member	808-831	2.334			
	Montesano Fm. – claystone member	831-TD	2.147			
Shell Minard OCA No. 1-34	Quinault Fm. – sand and gravel	159-290	1.584			
	Quinault Fm. – sandstone and silty sandstone	290-762	1.775			
	Quinault Fm. - claystone	762-1357	1.810			
	Hoh rock assemblage	1357-TD	2.243			
Shell Grays Harbor LHA No. 1-15	Undiff. Plio-Pleistocene	285-305	1.978			
	Quinault Fm.	305-549	2.090			
	Hoh rock assemblage	549-TD	3.339			
Shell Trambitas No. 1-28	Quinault Fm. - sandstone	347-488	2.061			
	Quinault Fm. – claystone and siltstone	488-892	2.251			
	Hoh rock assemblage	892-TD	2.871			
Shell Grays Harbor Co. No. 1-35	Quinault Fm. - sandstone	316-518	2.165			
	Quinault Fm. – siltstone with sandstone	518-701	2.246			
	Quinault Fm. - claystone	701-762	2.186			
	Hoh rocks (?)	762-TD	2.480			

Humble Ollar State No. 1	Hoh rock assemblage	116-TD	2.676	2.423	0.3551	0.0696
Humble Everett Trust and Savings Bank ETR et al. B-1	Hoh rock assemblage	369-TD	2.497	2.136	0.479	0.1609
Shell McLeave No. 1-33	Quinault Fm.	137-345	2.039			
	Hoh rock assemblage	345-405	2.713			
Hoh River Oil Barlow No. 1	Hoh rock assemblage	0-TD	2.574	1.757	1.2909	0.5501
Belco Milwaukee Land No. 1-1	Hoh rock assemblage	188-TD	3.243	1.561	1.2319	0.2755

Table 4. Linear regression of densities in oil test well logs

Wellname and number	Formation Name	Depth Interval (m)	Average Density (kg/m³)	Intercept Density (kg/m³)	Density Gradient (kg/m³/m)	R^2
Shell Hogan No. 1-8	Quinault (?) Fm. – sand and conglomerate	286-396	2335.1			
	Hoh rock assemblage (?)	396-TD	2167.1			
Shell Hogan No. 1-13	Quinault Fm. – pebbly sand or sandstone	153-625	2271			
	Quinault Fm. - siltstone	625-793	2218.9			
	Quinault Fm. - claystone	793-891	2155.6			
Shell Grays Harbor Co. No. 1-11	Quinault Fm. – sandstone and conglomerate	294-438	2270.3			
	Quinault Fm. - claystone	438-869	2162.8			
	Hoh rock assemblage	869-TD	2206.8			
Shell Ocean City Land Co. No. 1-14	Quinault Fm. – sandstone and conglomerate	280-650	2297.8			
	Quinault Fm. - claystone	650-1125	2120.0			
	Hoh rock assemblage	1125-TD	2345.6			
Shell Sampson Johns No. 1-15	Montesano Fm. – siltstone member	381-590	2155.9			
	Montesano Fm. – sandstone member	590-808	2287.0			
	Montesano Fm. – claystone member	808-852	2240.6			
Shell Luse No. 1-23	Undiff. Quat. Deposits and Quinault Fm.	231-555	2242.4			
	Montesano Fm. – siltstone member	555-808	2108.3			
	Montesano Fm. – sandstone member	808-831	2173.6			
	Montesano Fm. – claystone member	831-TD	2134.5			
Shell Minard No. 1-34	Quinault Fm. – sand and gravel	159-290	2037.0			
	Quinault Fm. – sandstone and silty sandstone	290-762	2182.0			
	Quinault Fm. - claystone	762-1357	2212.3			
	Hoh rock assemblage	1357-TD	2400.7			
Shell Grays Harbor LHA No. 1-15	Quinault Fm. – Undiff. Plio-Pleistocene	158-305	2103.4			
	Quinault Fm.	305-549	2185.9			
	Hoh rock assemblage	549-TD	2528.9			
Shell Trambitas No. 1-28	Quinault Fm. - sandstone	305-488	2167.2			
	Quinault Fm. – claystone and siltstone	488-892	2199.1			
	Hoh rock assemblage	892-TD	2478.1			
Shell Grays Harbor Co. No. 1-35	Quinault Fm. - sandstone	316-518	2188.4			
	Quinault Fm. – siltstone with sandstone	518-701	2226.7			
	Quinault Fm. - claystone	701-762	2183.3			

	Hoh rocks (?)	762-TD	2401.0			
El Paso Grays Harbor Co. No. 36-1	Quinault Fm.	157-530	2145.2			
	Hoh River assemblage	530-TD	2399.5			
El Paso Grays Harbor Co. No. 27-1	No data	No data	2193.6	2191.9	0.002	$7x10^{-5}$
Devel. Assoc. M A Baker No. 1-30	Hoh rock assemblage	85-TD	2335.0	2354	-0.02	0.0049
Devel. Assoc. Carlisle No. 1-23	Late Eocene	165-TD	2280.0	2424	-0.2	0.2987
Shell McLeave No. 1-33	Quinault Fm.	137-345	2120.0			
	Hoh rock assemblage	345-910	2453.0			
El Paso Lacey No. 22-1	Hoh rock assemblage	67-TD	2384.0	2313	0.08	0.38
Belco Milwaukee Land No. 1-1	Hoh rock assemblage	188-TD	2415.0	2264	-0.006	0.5963
Eastern Petrol. Sniffer Forks No. 1	Hoh rock assemblage	0-TD	2345.0	2348	-0.02	0.0049

Table 5. Laboratory measurements of compressional-wave velocities in Olympic mafic rocks

Vp km/s)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OL-1	2831	4.65	4.85	4.99	5.09	5.17	5.40	5.59	5.68	5.74	5.79
OL-2	2871	5.21	5.40	5.52	5.60	5.66	5.82	5.95	6.02	6.07	6.11
OL-4	2935	6.15	6.29	6.37	6.43	6.47	6.58	6.67	6.72	6.75	6.78
OL-5	2800	5.73	5.87	5.96	6.04	6.09	6.24	6.33	6.36	6.38	6.39
OL-7	2852	4.87	5.33	5.55	5.68	5.75	5.90	6.03	6.11	6.17	6.21
OL-8	2841	5.03	5.30	5.46	5.57	5.64	5.85	6.04	6.15	6.23	6.29
OL-9	2861	5.43	5.57	5.68	5.75	5.82	6.01	6.16	6.21	6.25	6.28
OL-10	3046	6.59	6.66	6.69	6.72	6.74	6.81	6.88	6.93	6.96	6.99
OL-11	3026	6.45	6.51	6.54	6.57	6.59	6.66	6.73	6.78	6.81	6.84
OL-12	2943	6.13	6.20	6.23	6.26	6.28	6.35	6.44	6.50	6.54	6.57
OL-13	2959	6.08	6.18	6.23	6.26	6.29	6.39	6.52	6.60	6.66	6.70
OL-14	2821	5.04	5.23	5.34	5.42	5.49	5.69	5.89	6.02	6.10	6.17
OL-15	2952	6.62	6.68	6.72	6.75	6.77	6.84	6.90	6.94	6.97	6.99
OL-16	2759	6.01	6.04	6.06	6.08	6.10	6.16	6.24	6.30	6.34	6.37
OL-17	2949	6.23	6.29	6.33	6.35	6.37	6.46	6.56	6.63	6.68	6.71
OL-18	2918	5.88	5.94	5.98	6.01	6.04	6.13	6.25	6.33	6.39	6.43
OL-19	2977	6.26	6.36	6.42	6.46	6.49	6.61	6.73	6.81	6.86	6.91
OL-20	2886	5.81	5.89	5.93	5.96	5.99	6.09	6.20	6.27	6.32	6.36
OL-21	2866	6.26	6.33	6.37	6.41	6.44	6.53	6.61	6.65	6.68	6.69
OL-22	2914	6.05	6.13	6.17	6.20	6.22	6.31	6.42	6.49	6.54	6.57
OL-23	2947	5.90	5.99	6.04	6.08	6.11	6.22	6.34	6.42	6.47	6.52
OL-24	2694	5.76	5.80	5.84	5.86	5.88	5.94	6.00	6.02	6.04	6.05
OL-25	2872	5.98	6.03	6.05	6.07	6.08	6.13	6.20	6.25	6.28	6.31
OL-26	2834	6.06	6.14	6.18	6.22	6.24	6.33	6.44	6.51	6.56	6.59
OL-27	2951	5.83	5.92	5.98	6.02	6.05	6.17	6.32	6.41	6.47	6.52
OL-28	2922	5.58	5.69	5.75	5.80	5.84	5.96	6.10	6.19	6.25	6.30
OL-29	2692	5.09	5.15	5.20	5.24	5.27	5.39	5.52	5.59	5.64	5.66
OL-30	2899	5.78	5.83	5.87	5.90	5.93	6.02	6.14	6.22	6.28	6.33
OL-31	2999	6.19	6.24	6.27	6.29	6.31	6.35	6.38	6.40	6.42	6.43
Aver.	2890	5.81	5.92	5.99	6.04	6.07	6.18	6.30	6.36	6.41	6.44

Table 6. Laboratory measurements of shear-wave velocity in Olympic mafic rocks

Vs (km/s)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OL-1	2831	2.85	2.95	3.02	3.06	3.09	3.17	3.23	3.27	3.30	3.32
OL-2	2871	2.94	3.04	3.10	3.14	3.17	3.25	3.29	3.31	3.33	3.34
OL-4	2935	3.22	3.33	3.41	3.46	3.49	3.58	3.62	3.64	3.65	3.66
OL-5	2800	3.28	3.35	3.39	3.43	3.45	3.50	3.53	3.54	3.54	3.55
OL-7	2852	2.93	3.02	3.08	3.11	3.14	3.21	3.27	3.31	3.33	3.35
OL-8	2841	3.01	3.06	3.10	3.12	3.14	3.20	3.26	3.30	3.33	3.35
OL-9	2861	3.07	3.13	3.16	3.18	3.20	3.26	3.33	3.36	3.39	3.41
OL-10	3046	3.64	3.66	3.67	3.68	3.69	3.71	3.74	3.76	3.77	3.78
OL-11	3026	3.52	3.54	3.55	3.56	3.57	3.59	3.62	3.64	3.65	3.66
OL-12	2943	3.65	3.39	3.40	3.41	3.42	3.45	3.48	3.51	3.53	3.54
OL-13	2959	3.36	3.39	3.40	3.41	3.42	3.47	3.52	3.56	3.58	3.60
OL-14	2821	2.55	2.63	2.69	2.72	2.75	2.86	2.99	3.08	3.15	3.21
OL-15	2952	3.59	3.62	3.63	3.64	3.65	3.68	3.70	3.71	3.72	3.73
OL-16	2759	3.08	3.10	3.11	3.12	3.12	3.15	3.17	3.18	3.19	3.20
OL-17	2949	3.34	3.38	3.39	3.41	3.42	3.45	3.49	3.52	3.54	3.55
OL-18	2918	3.25	3.28	3.29	3.30	3.31	3.35	3.39	3.42	3.44	3.45
OL-19	2977	3.37	3.40	3.42	3.44	3.45	3.50	3.54	3.57	3.58	3.60
OL-20	2886	3.21	3.24	3.26	3.27	3.28	3.31	3.34	3.36	3.37	3.38
OL-21	2866	3.42	3.46	3.47	3.49	3.50	3.54	3.58	3.61	3.63	3.65
OL-22	2914	3.29	3.32	3.34	3.35	3.36	3.39	3.45	3.49	3.51	3.53
OL-23	2947	3.29	3.32	3.34	3.35	3.36	3.40	3.44	3.47	3.49	3.50
OL-24	2694	3.05	3.07	3.09	3.10	3.11	3.13	3.15	3.16	3.17	3.17
OL-25	2872	3.23	3.26	3.27	3.28	3.29	3.32	3.35	3.37	3.38	3.39
OL-26	2834	3.22	3.26	3.28	3.30	3.31	3.36	3.41	3.44	3.46	3.48

OL-27	2951	3.21	3.26	3.29	3.31	3.33	3.38	3.45	3.49	3.52	3.54
OL-28	2922	3.14	3.19	3.22	3.24	3.26	3.33	3.39	3.41	3.43	3.44
OL-29	2692	2.67	2.72	2.75	2.77	2.79	2.86	2.91	2.93	2.95	2.96
OL-30	2899	3.24	3.26	3.28	3.29	3.30	3.33	3.39	3.42	3.44	3.46
OL-31	2999	3.38	3.46	3.50	3.52	3.53	3.55	3.55	3.55	3.55	3.55
Aver.	2890	3.21	3.24	3.27	3.29	3.31	3.35	3.40	3.43	3.45	3.46

Table 7. Laboratory derived Vp/Vs ratios for Olympic mafic rocks.

(Vp/Vs)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OL-1	2831	1.63	1.64	1.65	1.66	1.67	1.70	1.73	1.74	1.74	1.75
OL-2	2871	1.77	1.78	1.78	1.78	1.78	1.79	1.81	1.82	1.82	1.83
OL-4	2935	1.91	1.89	1.87	1.86	1.85	1.84	1.84	1.85	1.85	1.85
OL-5	2800	1.75	1.75	1.76	1.76	1.77	1.78	1.79	1.80	1.80	1.80
OL-7	2852	1.66	1.76	1.81	1.82	1.83	1.84	1.84	1.85	1.85	1.86
OL-8	2841	1.67	1.73	1.76	1.78	1.80	1.83	1.85	1.86	1.87	1.88
OL-9	2861	1.77	1.78	1.80	1.81	1.82	1.84	1.85	1.85	1.84	1.84
OL-10	3046	1.81	1.82	1.82	1.83	1.83	1.83	1.84	1.84	1.85	1.85
OL-11	3026	1.83	1.84	1.84	1.84	1.85	1.85	1.86	1.86	1.86	1.87
OL-12	2943	1.68	1.83	1.83	1.84	1.84	1.84	1.85	1.85	1.86	1.86
OL-13	2959	1.81	1.82	1.83	1.83	1.84	1.84	1.85	1.85	1.86	1.86
OL-14	2821	1.97	1.98	1.99	1.99	1.99	1.99	1.97	1.95	1.94	1.92
OL-15	2952	1.84	1.85	1.85	1.85	1.85	1.86	1.87	1.87	1.87	1.88
OL-16	2759	1.95	1.95	1.95	1.95	1.95	1.96	1.97	1.98	1.99	1.99
OL-17	2949	1.86	1.86	1.86	1.86	1.87	1.87	1.88	1.88	1.89	1.89
OL-18	2918	1.81	1.81	1.82	1.82	1.82	1.83	1.84	1.85	1.86	1.86
OL-19	2977	1.86	1.87	1.87	1.88	1.88	1.89	1.90	1.91	1.92	1.92
OL-20	2886	1.81	1.82	1.82	1.82	1.83	1.84	1.86	1.87	1.87	1.88
OL-21	2866	1.83	1.83	1.84	1.84	1.84	1.85	1.85	1.84	1.84	1.84
OL-22	2914	1.84	1.84	1.85	1.85	1.85	1.86	1.86	1.86	1.86	1.86
OL-23	2947	1.79	1.80	1.81	1.81	1.82	1.83	1.84	1.85	1.86	1.86
OL-24	2694	1.89	1.89	1.89	1.89	1.89	1.90	1.90	1.91	1.91	1.91
OL-25	2872	1.85	1.85	1.85	1.85	1.85	1.85	1.85	1.86	1.86	1.86
OL-26	2834	1.88	1.88	1.88	1.88	1.88	1.88	1.89	1.89	1.89	1.90
OL-27	2951	1.82	1.82	1.82	1.82	1.82	1.82	1.83	1.84	1.84	1.84
OL-28	2922	1.78	1.78	1.79	1.79	1.79	1.79	1.80	1.81	1.82	1.83
OL-29	2692	1.91	1.90	1.89	1.89	1.89	1.89	1.90	1.91	1.91	1.91
OL-30	2899	1.78	1.79	1.79	1.79	1.80	1.81	1.81	1.82	1.83	1.83
OL-31	2999	1.83	1.80	1.79	1.79	1.79	1.79	1.80	1.80	1.81	1.81
Aver.	2890	1.81	1.83	1.83	1.83	1.84	1.84	1.85	1.86	1.86	1.86

Table 8. Laboratory derived Poisson's ratio for Olympic mafic rocks

(σ)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OL-1	2831	0.199	0.206	0.212	0.217	0.222	0.237	0.248	0.252	0.255	0.256
OL-2	2871	0.267	0.269	0.270	0.271	0.271	0.274	0.279	0.282	0.285	0.287
OL-4	2935	0.310	0.304	0.300	0.297	0.294	0.290	0.291	0.292	0.293	0.294
OL-5	2800	0.257	0.259	0.261	0.263	0.265	0.270	0.275	0.276	0.277	0.278
OL-7	2852	0.216	0.263	0.279	0.285	0.287	0.289	0.292	0.293	0.295	0.296
OL-8	2841	0.222	0.249	0.263	0.271	0.276	0.287	0.294	0.297	0.300	0.302
OL-9	2861	0.265	0.271	0.276	0.279	0.283	0.291	0.294	0.293	0.292	0.291
OL-10	3046	0.282	0.284	0.285	0.285	0.286	0.288	0.290	0.291	0.292	0.293
OL-11	3026	0.288	0.290	0.291	0.292	0.292	0.295	0.297	0.298	0.298	0.299
OL-12	2943	0.226	0.287	0.288	0.289	0.290	0.291	0.293	0.294	0.295	0.296
OL-13	2959	0.281	0.285	0.287	0.289	0.290	0.292	0.293	0.295	0.296	0.297
OL-14	2821	0.327	0.330	0.331	0.332	0.332	0.331	0.327	0.322	0.318	0.314
OL-15	2952	0.292	0.293	0.294	0.294	0.295	0.296	0.298	0.300	0.301	0.302
OL-16	2759	0.322	0.322	0.322	0.322	0.322	0.323	0.327	0.329	0.330	0.331

OL-17	2949	0.297	0.298	0.298	0.298	0.298	0.300	0.302	0.304	0.305	0.306
OL-18	2918	0.280	0.281	0.282	0.283	0.284	0.287	0.291	0.294	0.296	0.297
OL-19	2977	0.297	0.300	0.301	0.302	0.303	0.305	0.308	0.311	0.313	0.314
OL-20	2886	0.280	0.282	0.284	0.284	0.285	0.290	0.295	0.299	0.301	0.303
OL-21	2866	0.286	0.287	0.289	0.290	0.291	0.293	0.292	0.291	0.290	0.289
OL-22	2914	0.290	0.292	0.293	0.294	0.295	0.297	0.297	0.297	0.297	0.297
OL-23	2947	0.275	0.278	0.280	0.281	0.282	0.287	0.291	0.294	0.296	0.297
OL-24	2694	0.305	0.305	0.306	0.306	0.306	0.308	0.309	0.310	0.310	0.310
OL-25	2872	0.294	0.294	0.293	0.293	0.293	0.292	0.294	0.295	0.296	0.297
OL-26	2834	0.303	0.304	0.304	0.304	0.304	0.304	0.305	0.306	0.307	0.307
OL-27	2951	0.282	0.282	0.283	0.283	0.284	0.285	0.287	0.289	0.290	0.291
OL-28	2922	0.268	0.271	0.272	0.272	0.272	0.274	0.278	0.282	0.285	0.288
OL-29	2692	0.310	0.308	0.306	0.306	0.305	0.305	0.308	0.310	0.312	0.312
OL-30	2899	0.271	0.272	0.274	0.275	0.276	0.279	0.282	0.284	0.286	0.287
OL-31	2999	0.287	0.278	0.274	0.272	0.272	0.273	0.276	0.278	0.280	0.280
Aver.	2890	0.279	0.284	0.286	0.287	0.288	0.291	0.294	0.295	0.296	0.297

Table 9. Laboratory measurements of compressional wave velocity of Olympic greywackes

Vp (km/s)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OLG-1	2480	4.03	4.10	4.15	4.18	4.20					
OLG-2	2440	4.04	4.18	4.27	4.34	4.39	4.60	4.86	5.03		
OLG-3	2340	4.62	4.76	4.84	4.91	4.96	5.16	5.40	5.56		
OLG-5	2640	5.41	5.50	5.57	5.61	5.65	5.79	5.94	6.02		
OLG-6	2660	5.30	5.33	5.36	5.38	5.39					
OLG-7	2630	5.21	5.29	5.34	5.38	5.41	5.53	5.69	5.80		
OLG-8	2610	4.98	5.00	5.02	5.04	5.06	5.15	5.34	5.53		
OLG-9	2520	3.77	3.90	3.99	4.05	4.11	4.31	4.57	4.76		
OLG-10	2580	4.84	4.96	5.06	5.14	5.20					
OLG-11	2410	4.15	4.21	4.29	4.33	4.37	4.61	4.88	5.07		
OLG-12	2843	4.47	4.89	5.18	5.39	5.55	5.93	6.14	6.24	6.31	6.36
Aver.	2559	4.62	4.74	4.82	4.89	4.94	5.13	5.35	5.50	6.31	6.36

Table 10. Laboratory measurements of shear wave velocity of Olympic greywackes

Vs (km/s)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OLG-1	2480	2.28	2.32	2.37	2.41	2.44					
OLG-5	2640	3.00	3.03	3.05	3.07	3.08	3.14	3.20	3.24		
OLG-6	2660	3.02	3.04	3.06	3.08	3.10					
OLG-8	2610	2.58	2.64	2.67	2.69	2.71	2.78	2.86	2.91		
OLG-10	2580	2.79	2.83	2.86	2.87	2.88					
OLG-12	2843	2.75	2.94	3.05	3.12	3.16	3.25	3.30	3.33	3.35	3.37
Aver.	2636	2.74	2.80	2.84	2.87	2.90	3.06	3.12	3.16	3.35	3.37

Table 11. Laboratory derived Vp/Vs ratios for Olympic greywackes

Vp/Vs

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OLG-1	2480	1.77	1.77	1.75	1.73	1.72					
OLG-5	2640	1.80	1.82	1.83	1.83	1.83	1.84	1.86	1.86		
OLG-6	2660	1.75	1.75	1.75	1.75	1.74					
OLG-8	2610	1.93	1.89	1.88	1.87	1.87	1.85	1.87	1.90		
OLG-10	2580	1.73	1.75	1.77	1.79	1.81					

OLG-12	2843	1.62	1.67	1.70	1.73	1.75	1.82	1.86	1.87	1.88	1.89
Aver.	2636	1.77	1.77	1.78	1.78	1.79	1.84	1.86	1.88	1.88	1.89

Table 12. Laboratory derived Poisson's ratios for Olympic greywackes

(σ)

Sample	Density	Pressure (MPa)									
	kg/m3	20	40	60	80	100	200	400	600	800	1000
OLG-1	2480	0.26	0.26	0.26	0.25	0.25					
OLG-5	2640	0.28	0.28	0.29	0.29	0.29	0.29	0.30	0.30		
OLG-6	2660	0.26	0.26	0.26	0.26	0.25					
OLG-8	2610	0.32	0.31	0.30	0.30	0.30	0.29	0.30	0.31		
OLG-10	2580	0.25	0.26	0.27	0.27	0.28					
OLG-12	2843	0.20	0.22	0.24	0.25	0.26	0.29	0.30	0.30	0.30	0.31
Aver.	2636	0.26	0.26	0.27	0.27	0.27	0.29	0.30	0.30	0.30	0.31

Table 13. Average Formation sonic velocities and densities.

Formation/Lithology	No.	Average velocity (km/s)	Average density (kg/m^3)
Undiff. Quaternary and Quinault Fm.	4	1.895	2173
Quinault Fm. - undifferentiated	4	2.196	2153
Quinault Fm. - claystone member	6	2.060	2172
Quinault Fm. - sand/sandstone member	7	2.045	2202
Quinault Fm. - siltstone member	3	2.315	2223
Quinault Fm. - all units, all wells	19	2.105	2194
Montesano Fm. - all units, all wells	9	2.250	2183
Montesano Fm. - claystone member	3	2.120	2188
Montesano Fm. - sandstone member	3	2.404	2230
Montesano Fm. - siltstone member	3	2.226	2132
Hoh rock assemblage	17	2.573	2376

Table 14. Compressional-Wave Reflection Coefficients[1]

Formation 1/Formation 2	Rpp	Rpp (%)
Montesano Fm./Hoh rock assemblage	0.111	11.1
Quinault Fm.*/Hoh rock assemblage	0.139	13.9
Undiff. Quat. & Quinault Fm./Hoh rock assemb.	0.195	19.5
Montesano Fm./Quinault Fm.*	0.029	2.9
Undiff. Quat. & Quinault Fm./Montesano Fm.	0.086	8.6
Undiff. Quat. & Quinault Fm./Quinault Fm.	0.057	5.7

[1]Rpp calculated from equation 1.

*Used values for Quinault Fm. – all units, all wells.

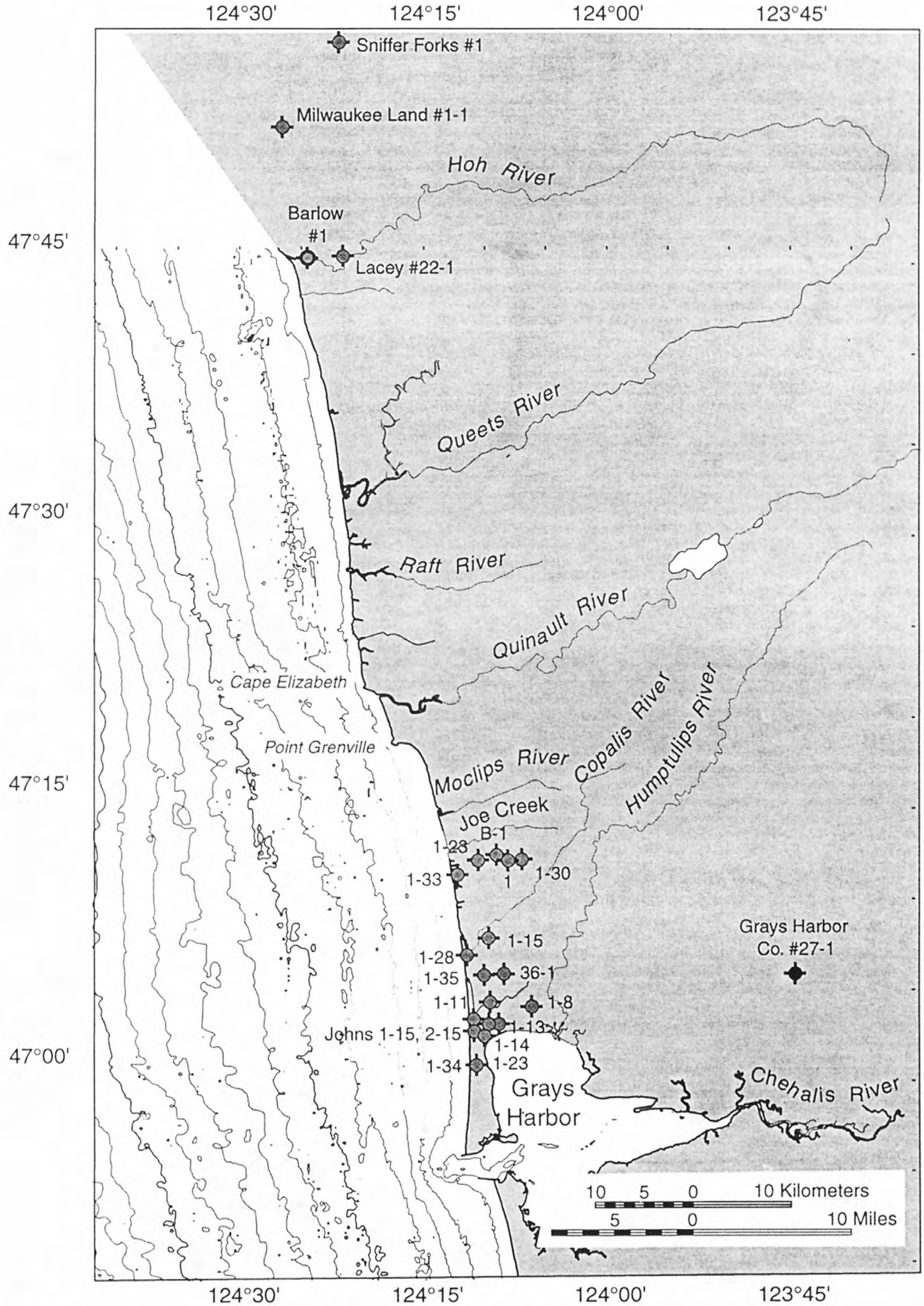

Figure 1. Map showing locations of oil test wells (circles with ticks) analyzed in this report. Bathymetric contours generated from NOAA-NOS hydrographic soundings.

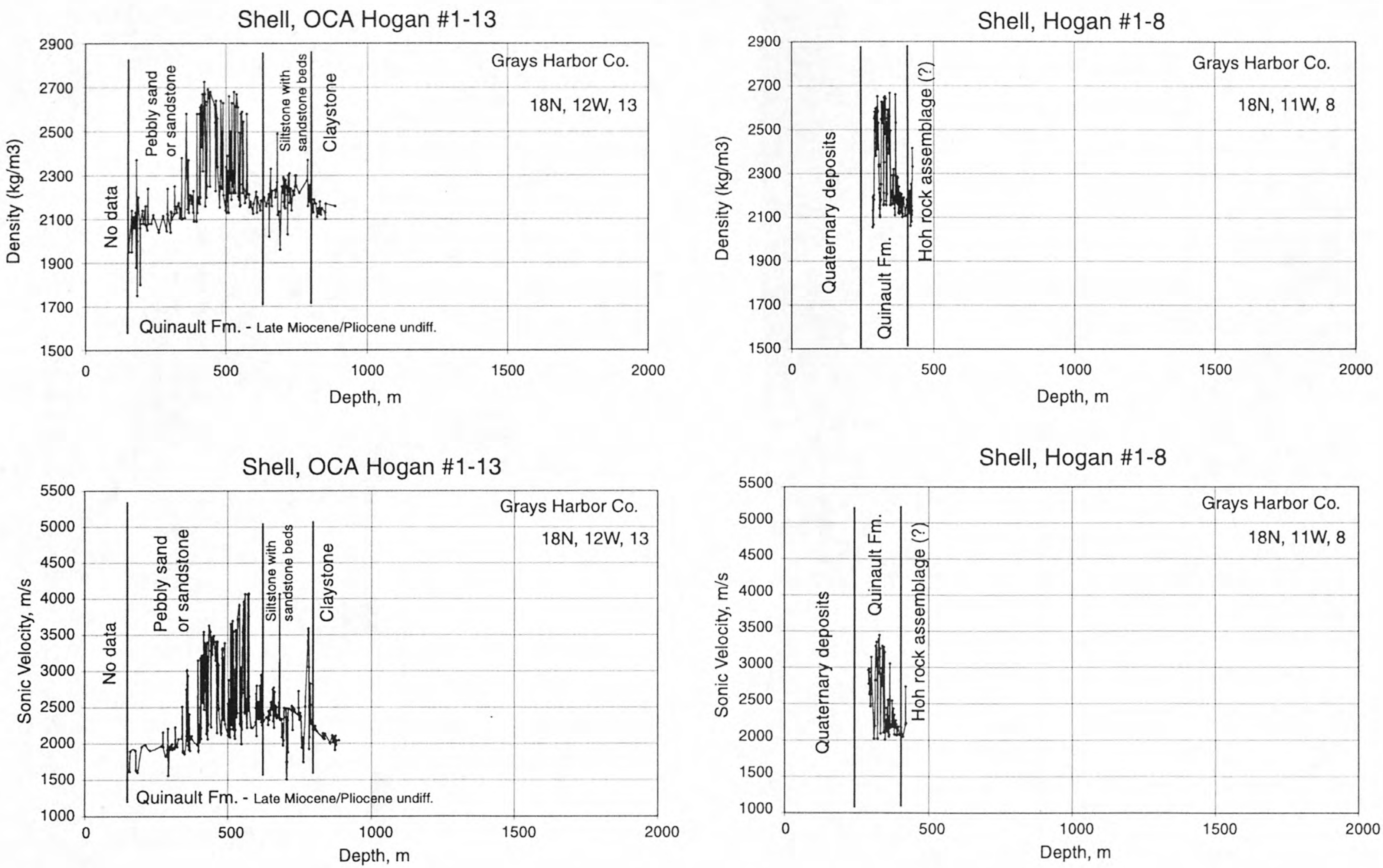

Figure 2. Sonic velocities and densities for the Shell Oil OCA Hogan 1-13 and Hogan 1-8 wells.

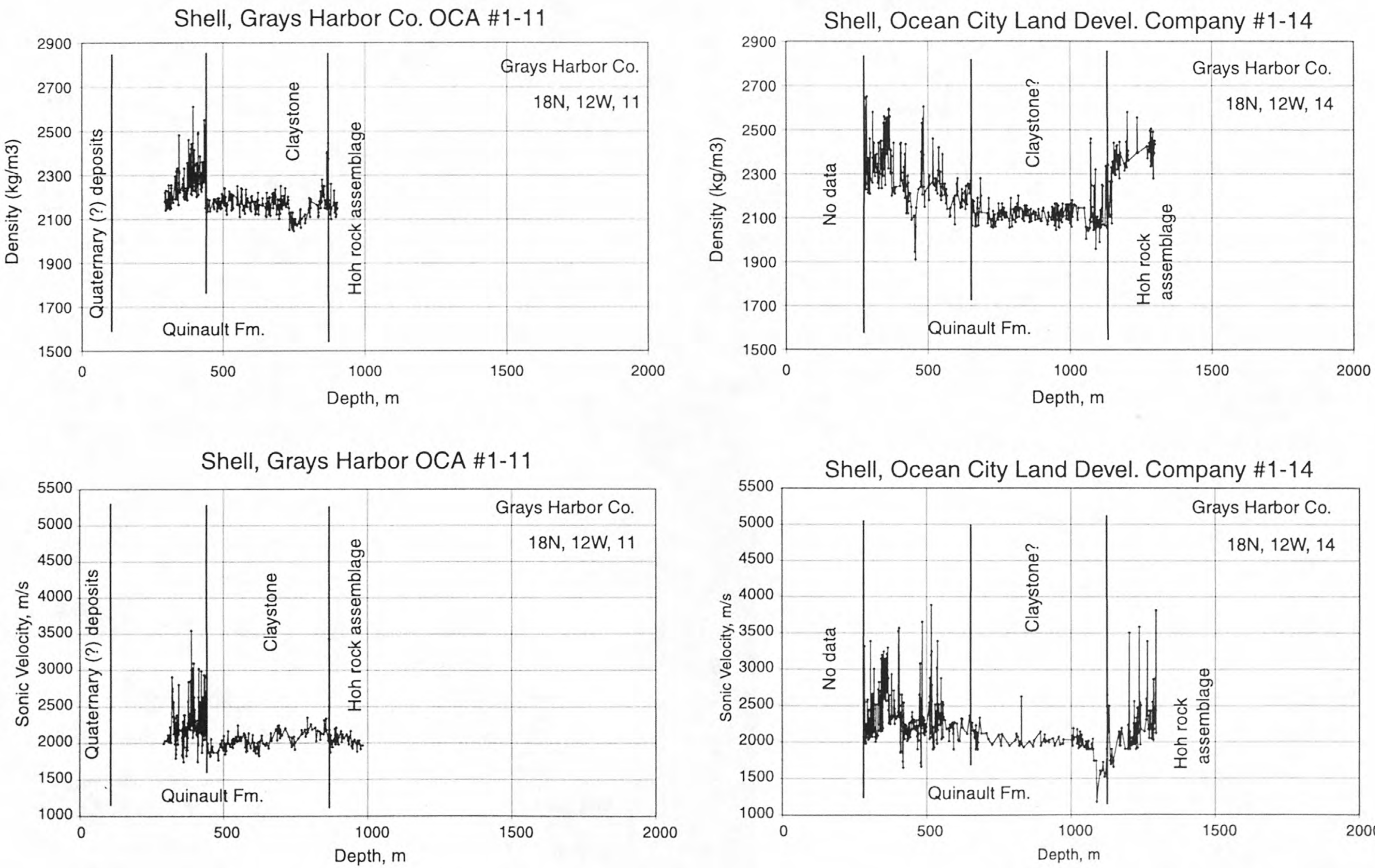

Figure 3. Sonic velocities and densities for the Shell Oil Grays Harbor County OCA 1-11 and Ocean City Land Development Co. 1-14 wells.

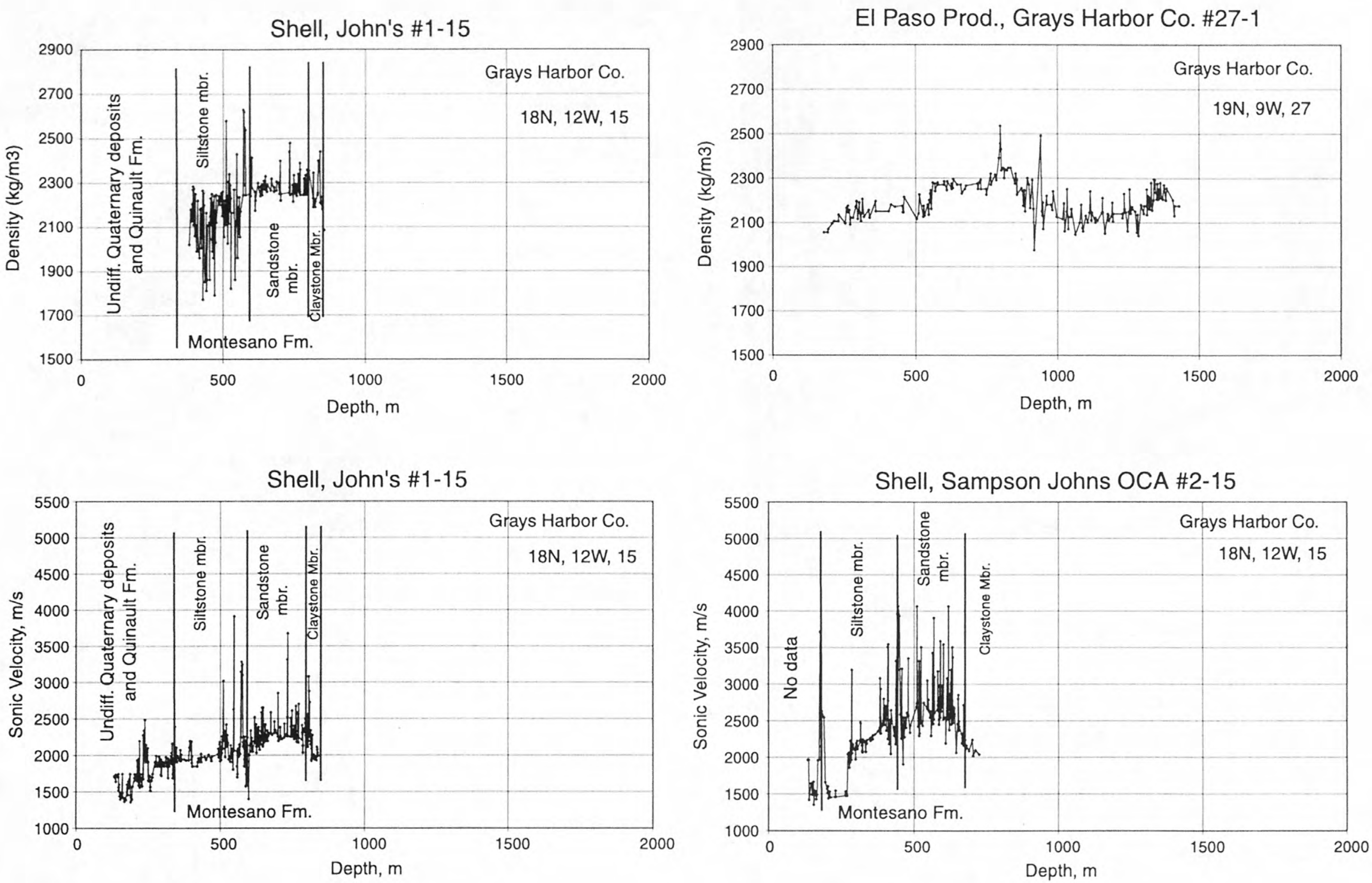

Figure 4. Sonic velocities and densities for the Shell Oil Johnson Sampson 1-15 and 2-15 and the El Paso Prod. Grays Harbor County 27-1 wells.

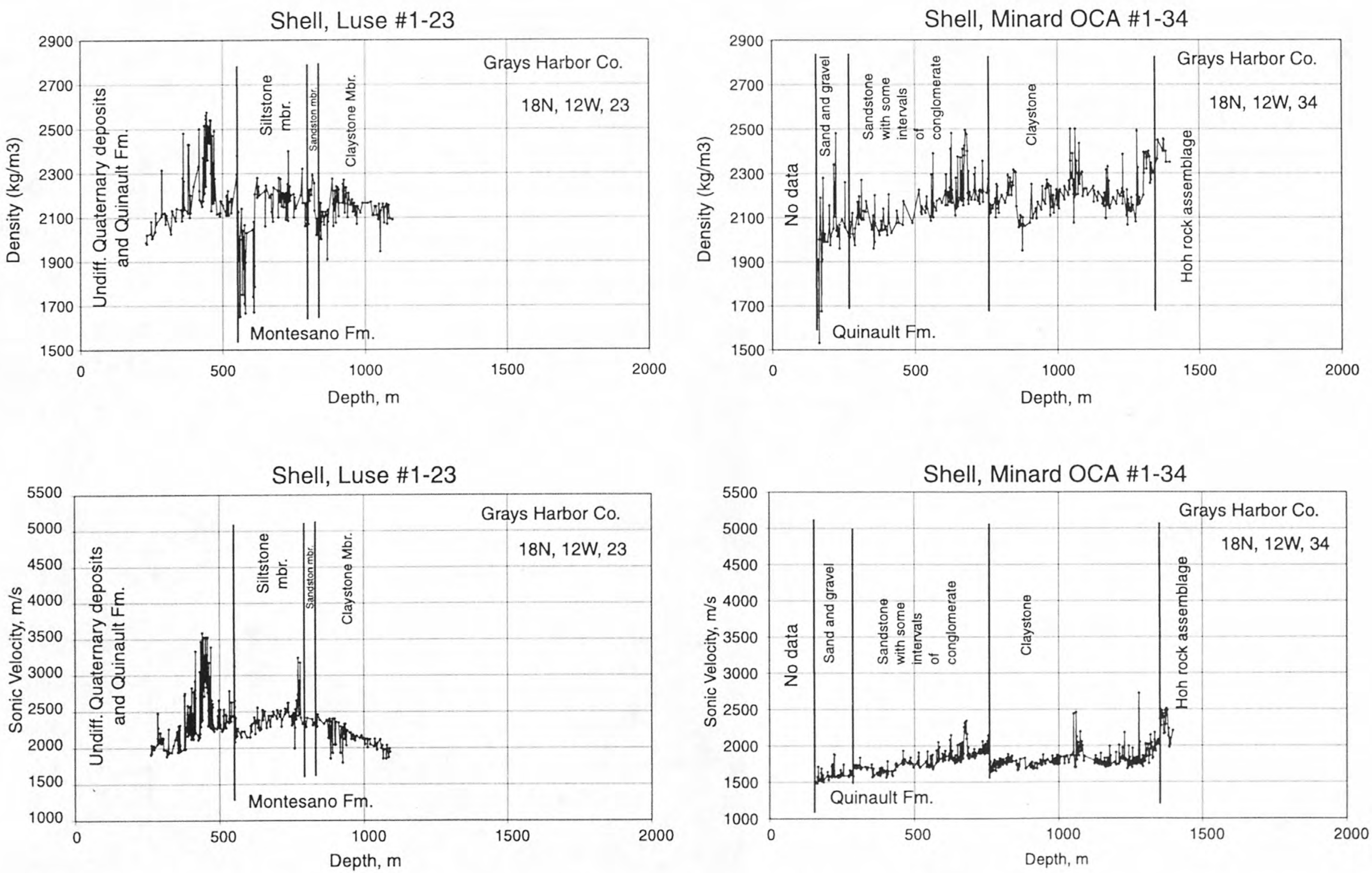

Figure 5. Sonic velocities and densities for the Shell Oil Luse 1-23 and Minard OCA 1-34 wells.

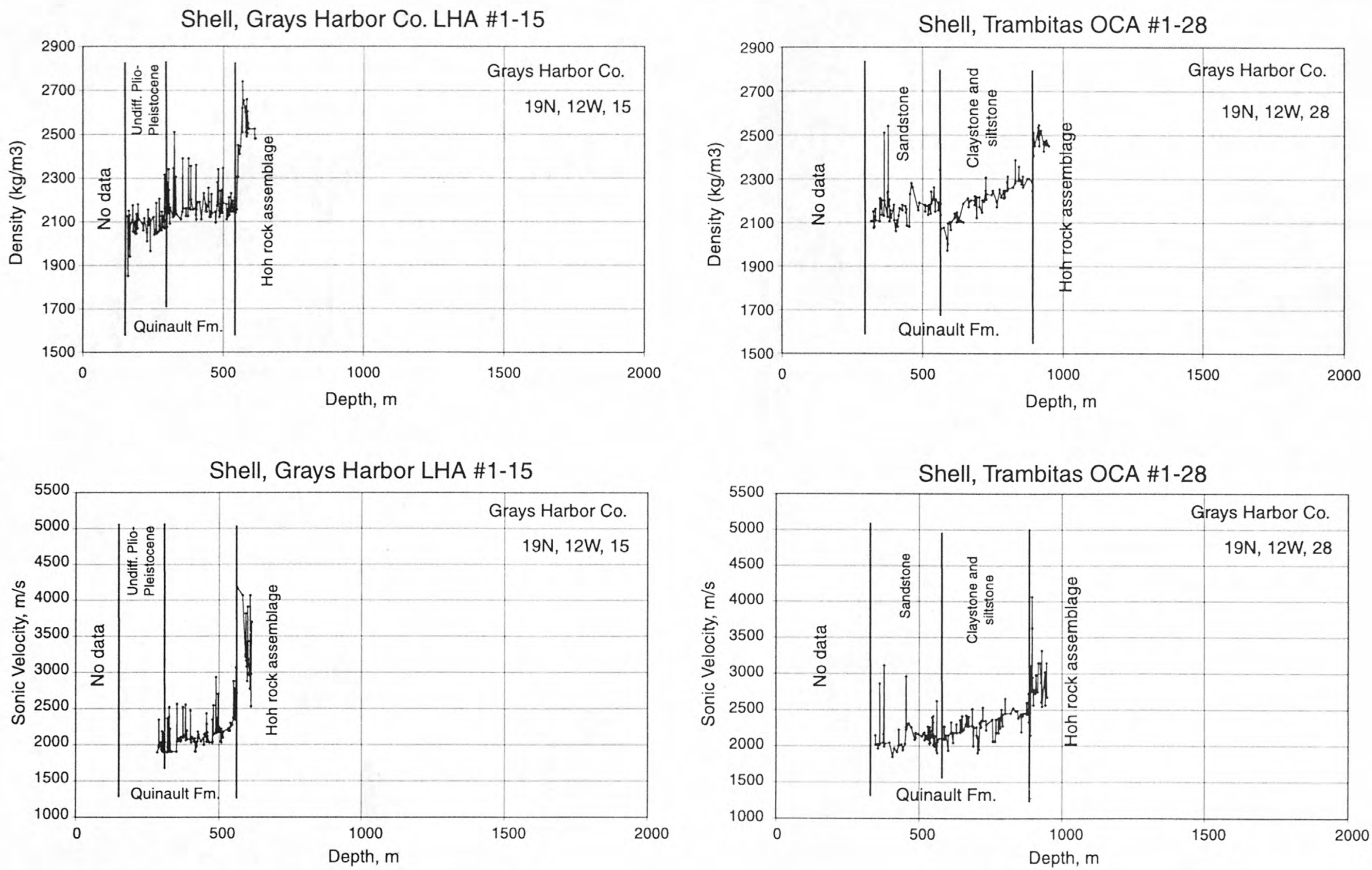

Figure 6. Sonic velocities and densities for the Shell Oil Grays Harbor County LHA 1-15 and Trambitas OCA 1-28 wells.

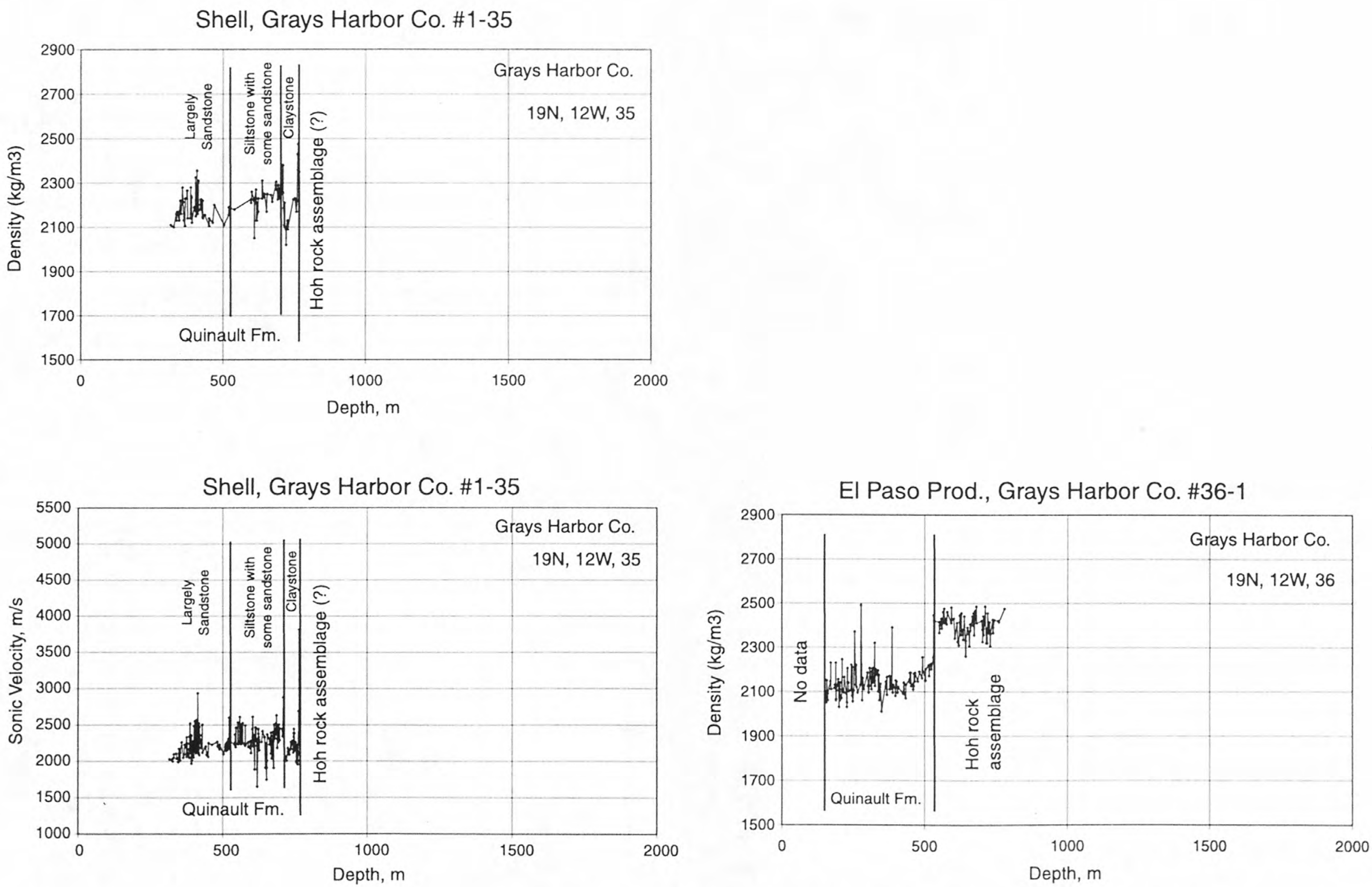

Figure 7. Sonic velocities and densities for the Shell Oil Grays Harbor County 1-35 and El Paso Prod., Grays Harbor County 36-1 wells.

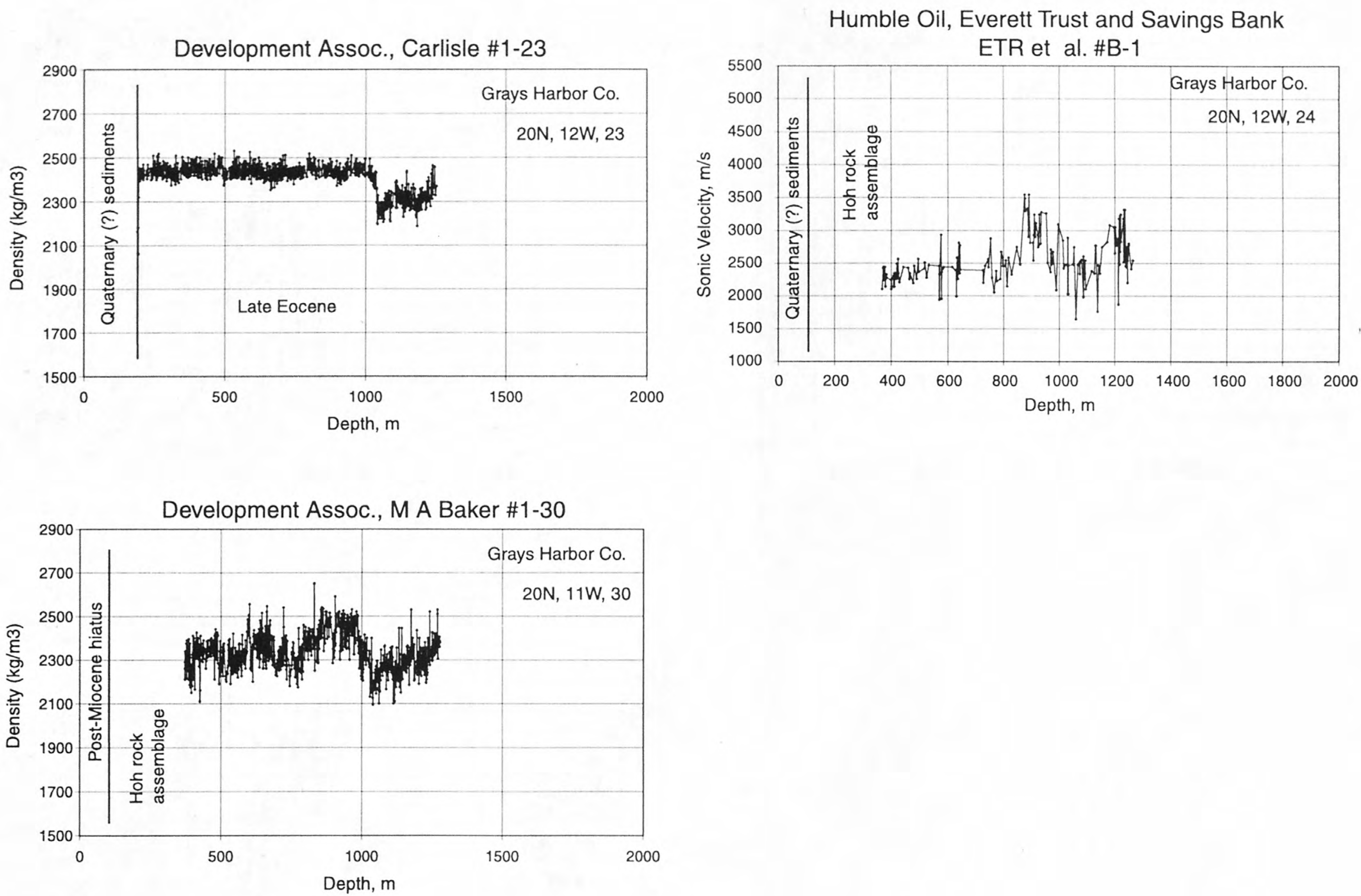

Figure 8. Sonic velocities and densities for the Development Assoc. M A Baker 1-20 and Carlisle 1-23 wells and Humble Oil Everett Trust and Savings Bank ETR et al. B-1 well.

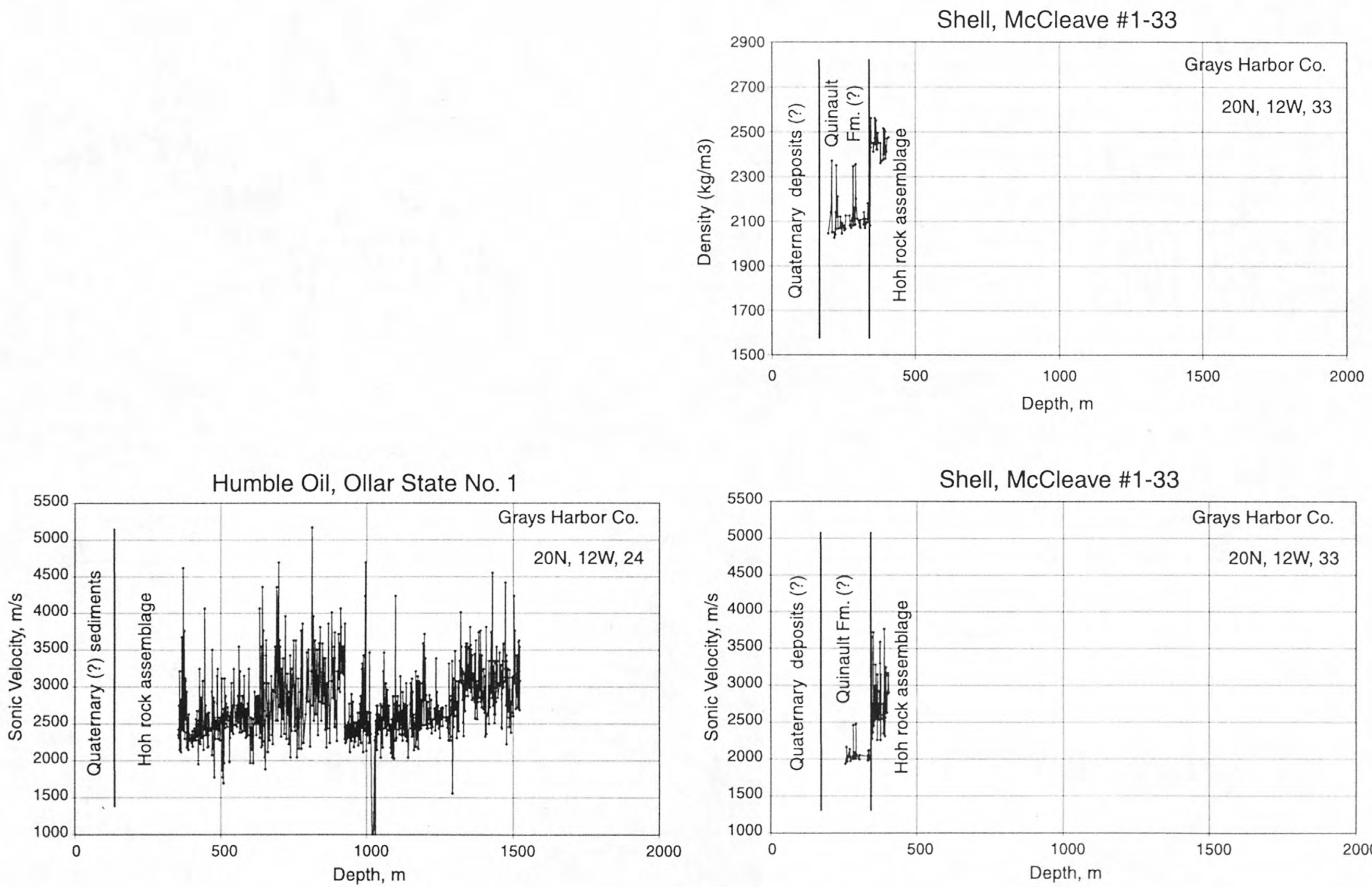

Figure 9. Sonic velocities and densities for the Humble Oil Ollar State 1 and Shell Oil McCleave 1-33 wells.

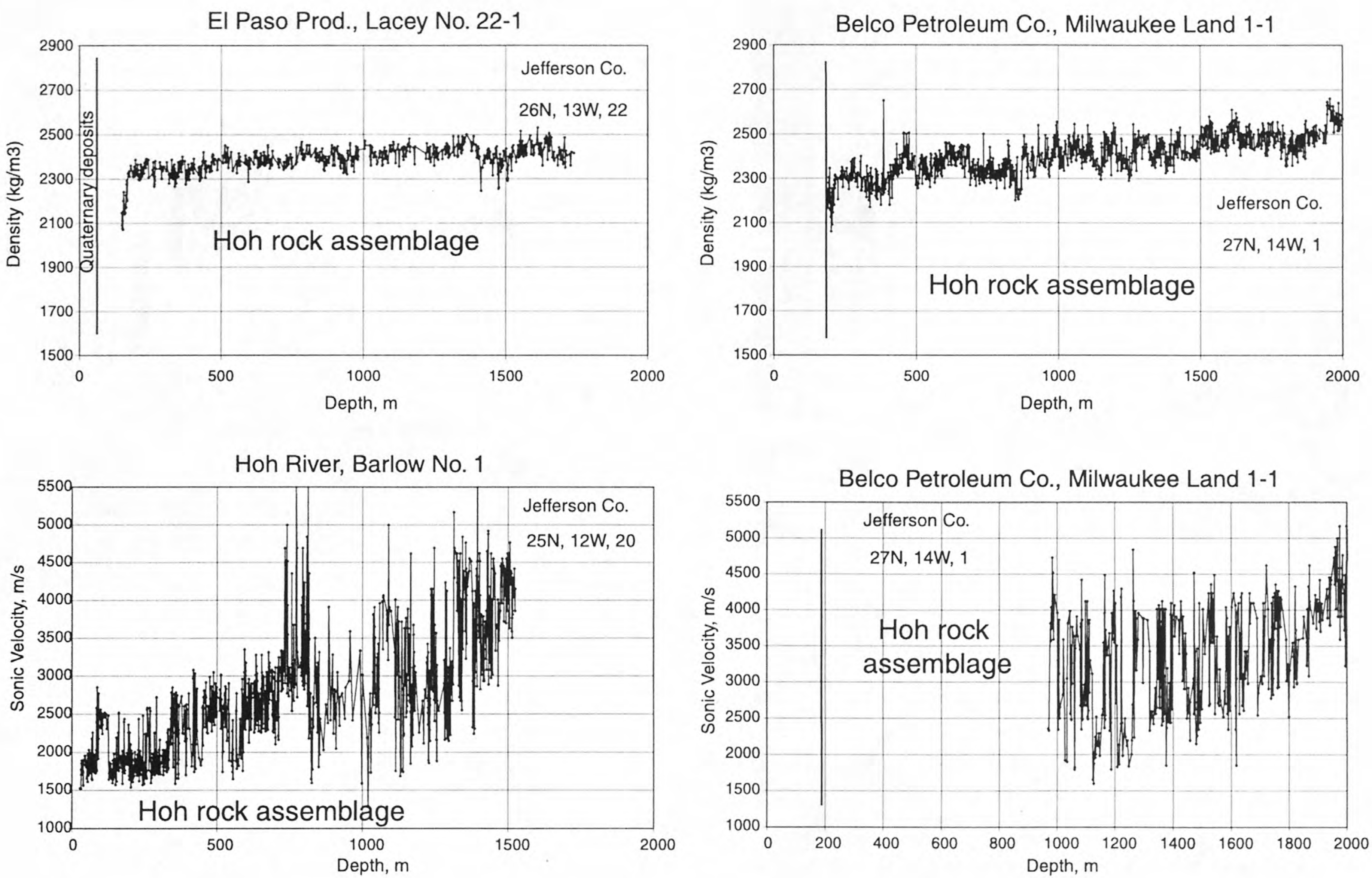

Figure 10. Sonic velocities and densities for the Hoh River Oil Barlow 1, El Paso Prod. Lacey 22-1, and Belco Petroleum Corp. Milwaukee Land 1-1 wells.

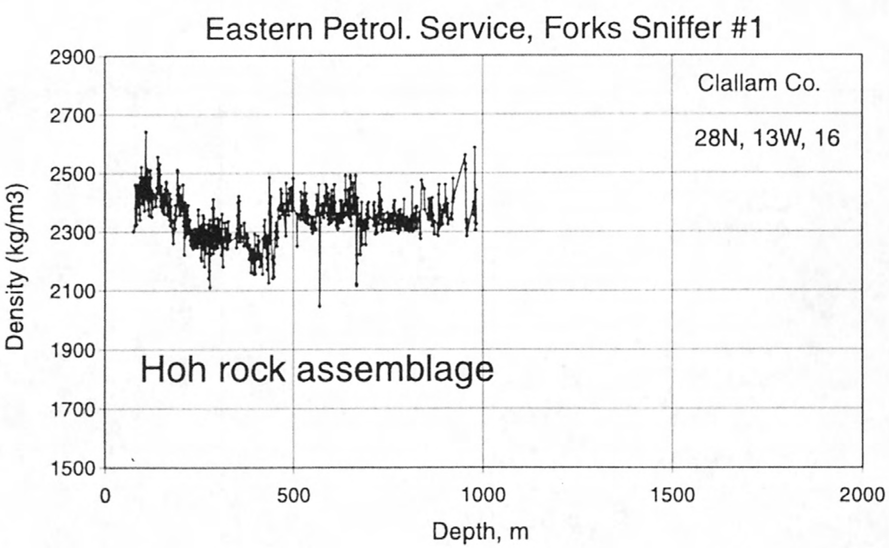

Figure 11. Densities for the Eastern Petroleum Services Sniffer Forks 1 well.

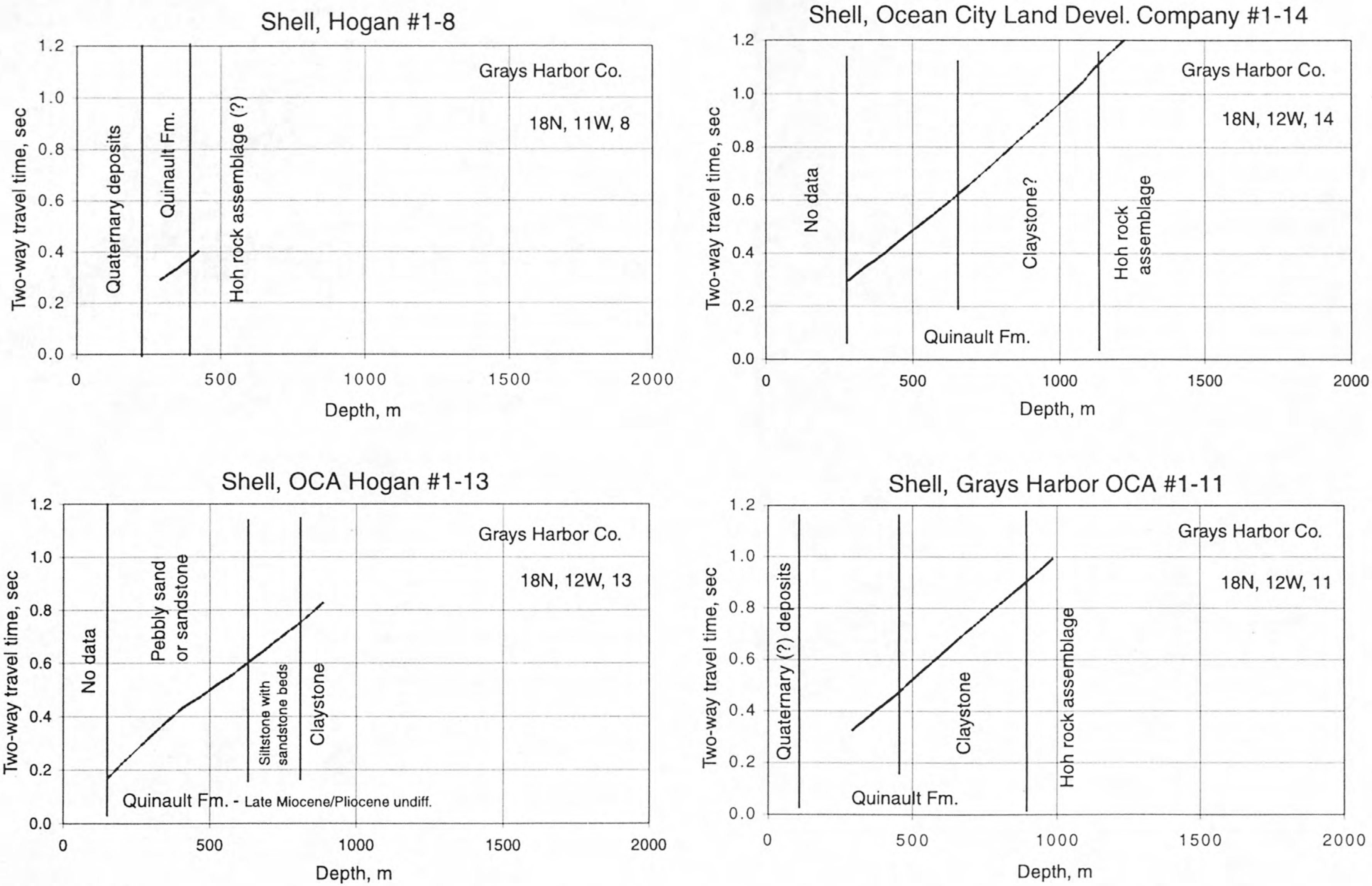

Figure 12. Calculated two-way travel times for the Shell Oil OCA Hogan 1-13, Hogan 1-8, Grays Harbor County 1-11, and Ocean City LDC 1-14 wells.

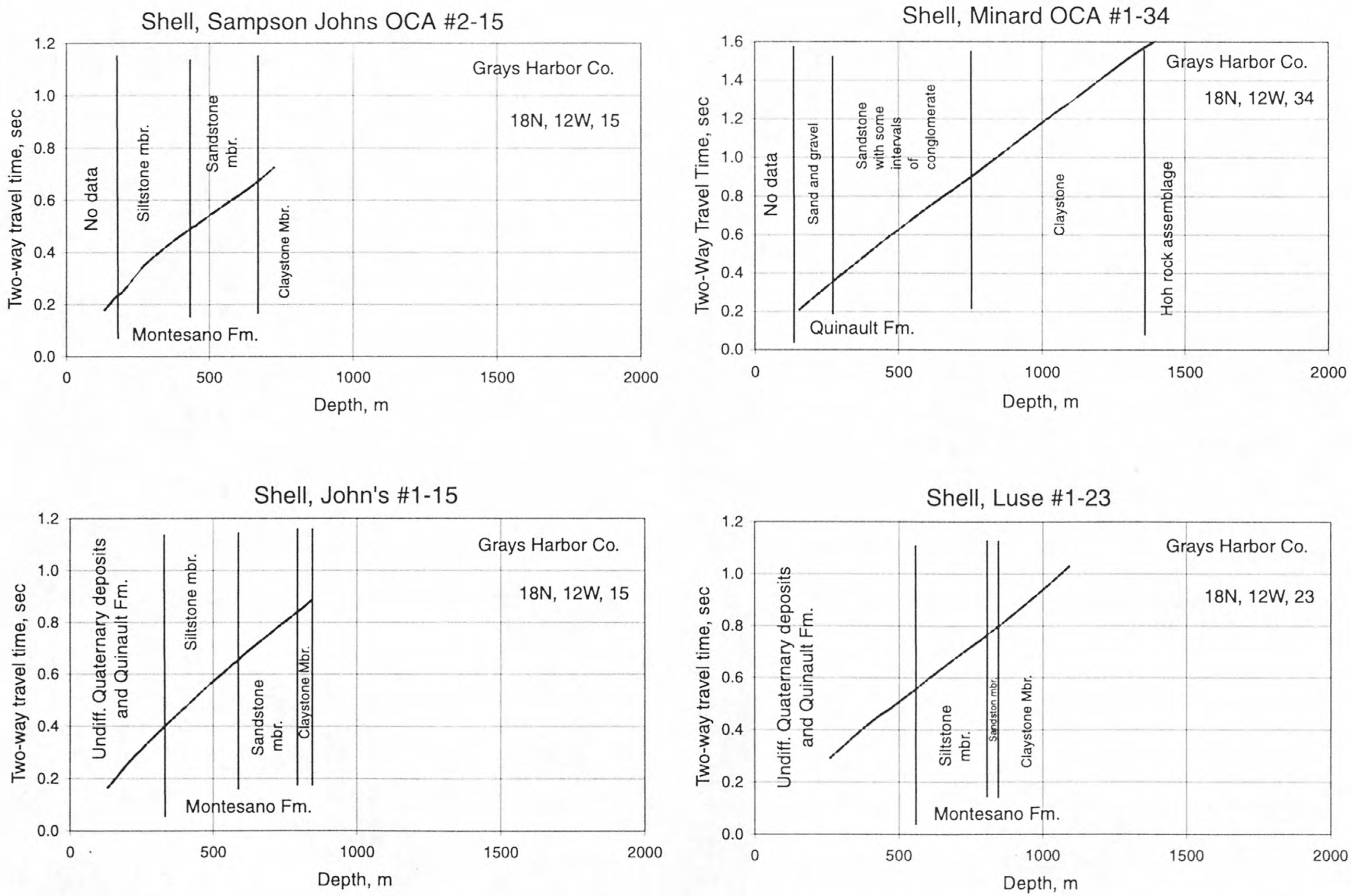

Figure 13. Calculated two-way travel times for the Shell Oil John Sampson 1-15, John Sampson OCA 2-15, Luse 1-23, and Minard OCA 1-34 wells.

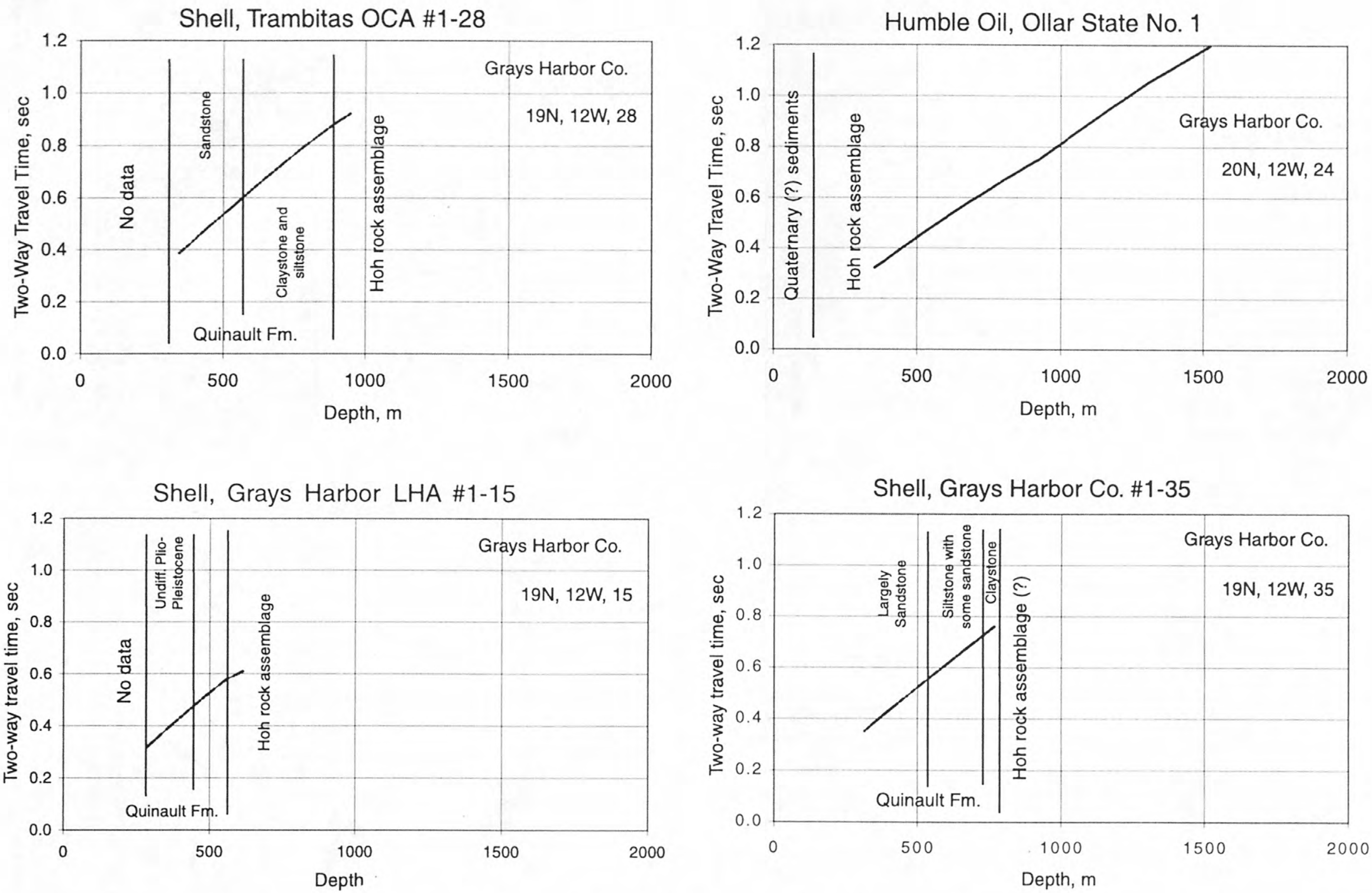

Figure 14. Calculated two-way travel times for the Shell Oil Grays Harbor County LHA 1-15, Trambitas OCA 1-28, Grays Harbor County 1-35, and Humble Oil Ollar State 1 wells.

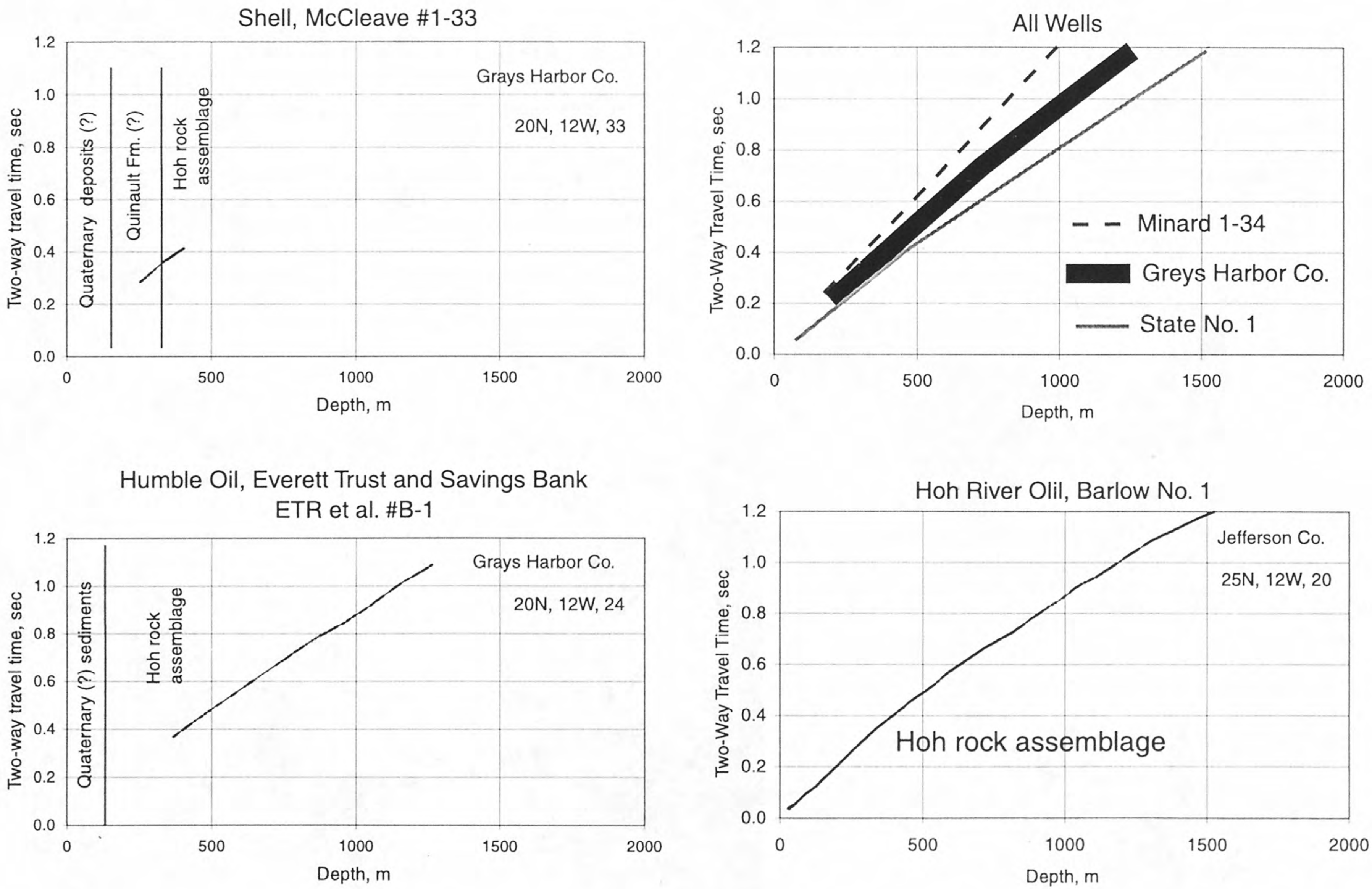

Figure 15. Calculated two-way travel times for the Humble Oil State B-1, Shell Oil McCleave 1-33, and Hoh River Oil Barlow 1 wells. Figure in upper right hand corner summarizes the calculated two way travel times for all the wells.

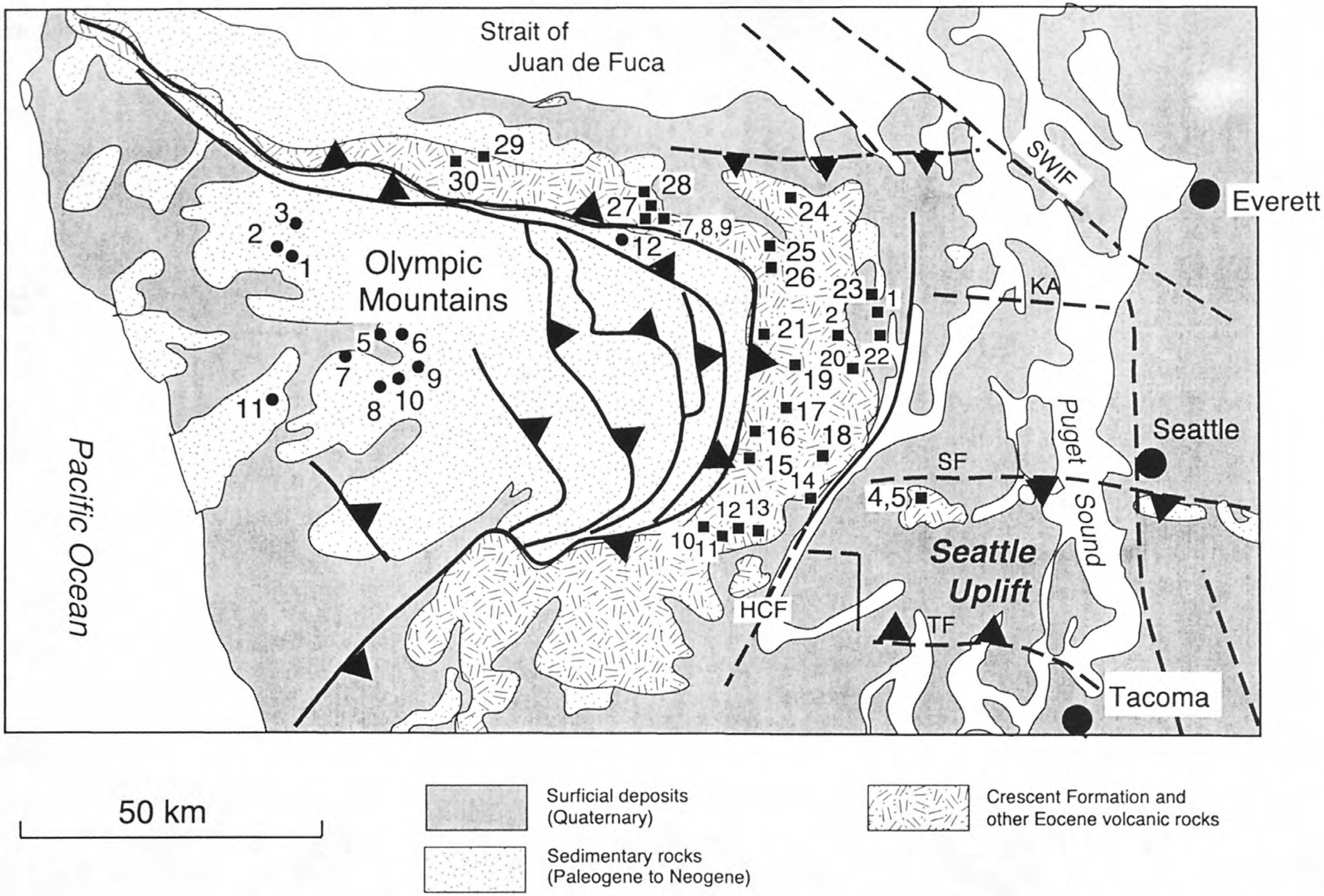

Figure 16. Map of the Olympic Peninsula showing the rock samples whose compressional and shear waves were measured in the laboratory. Abbreviations: HCF-Hood Canal fault, KA-Kingston Arch, SF-Seattle fault, TF-Tacoma fault. Figure modified from Brocher et al. (2001).

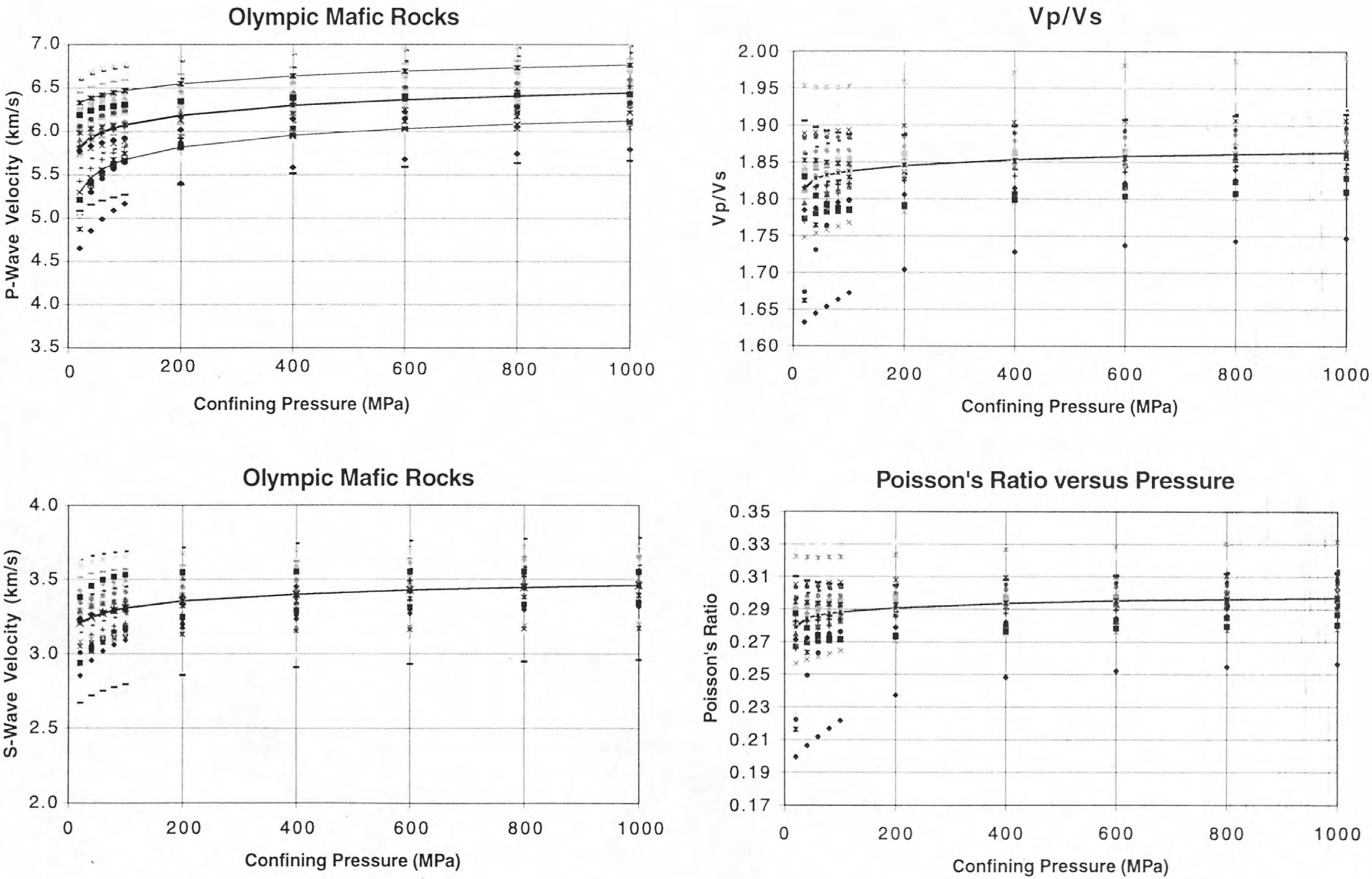

Figure 17. Compresional-wave, shear-wave, Vp/Vs ratio, and Poisson's ratio versus confining pressure for Olympic Peninsula mafic rocks (mainly Crescent Formation volcanics).

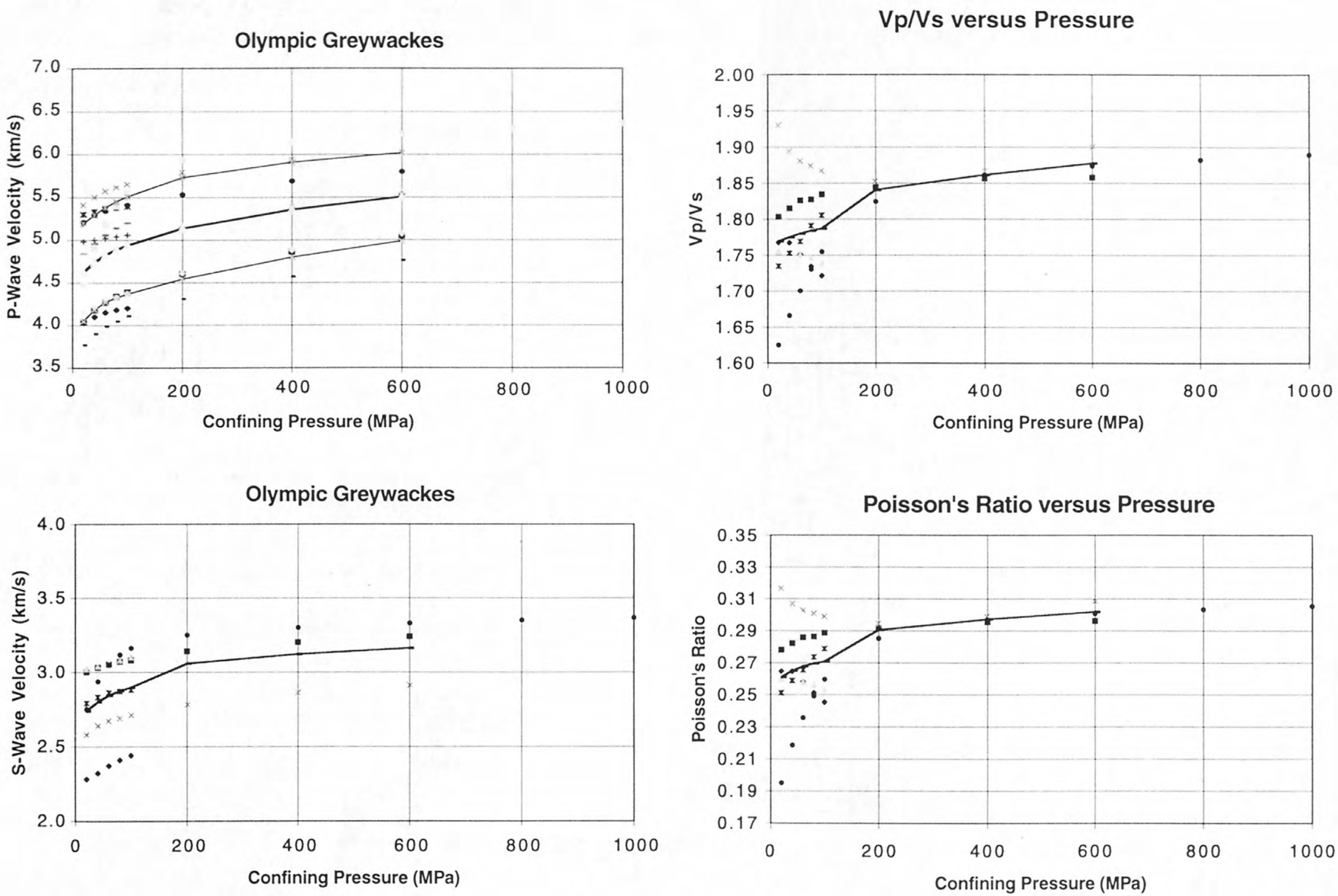

Figure 18. Compresional-wave, shear-wave, Vp/Vs ratio, and Poisson's ratio versus confining pressure for Olympic Peninsula greywackes.

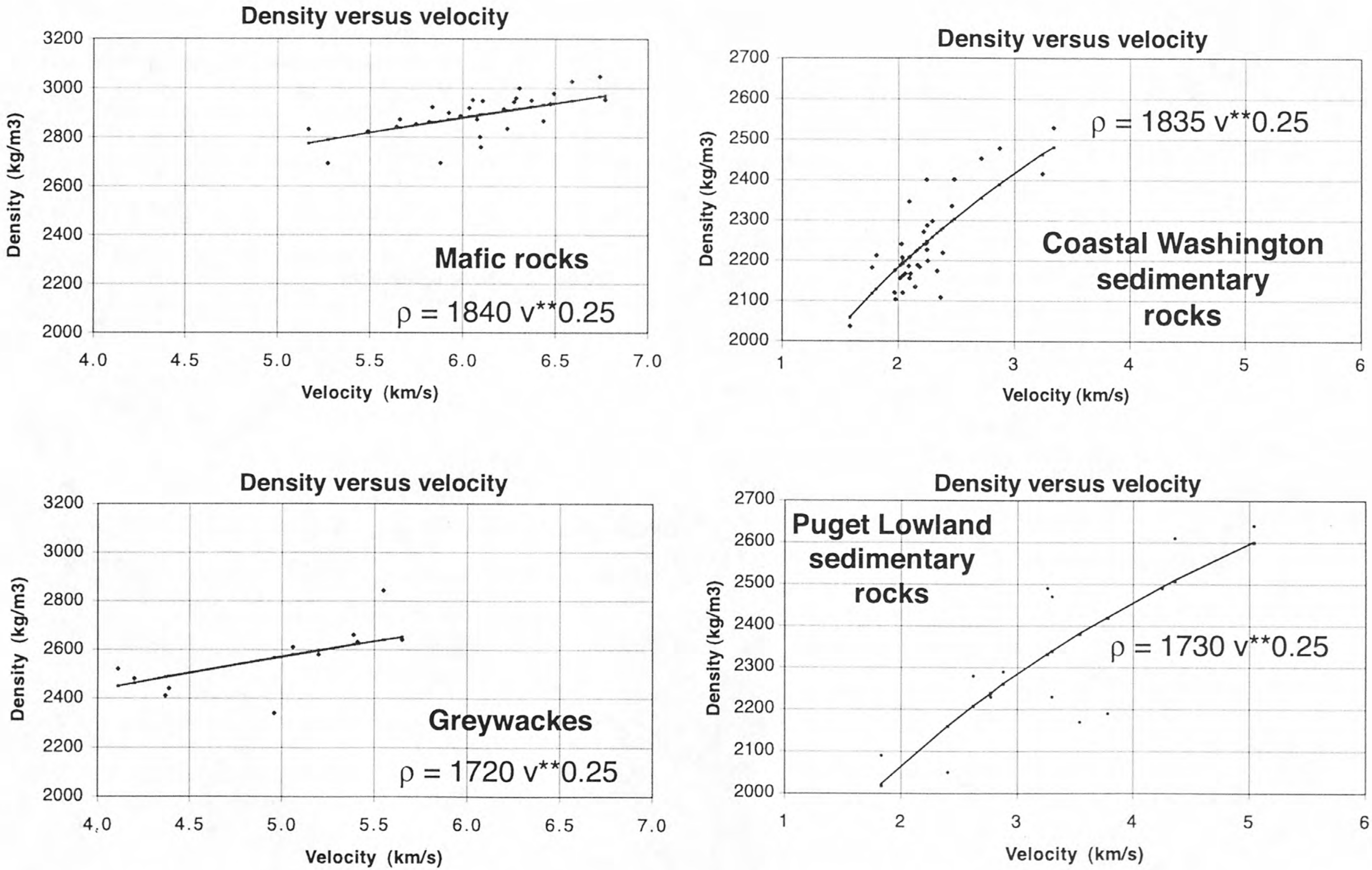

Figure 19. Density and velocity relationships for the Olympic Peninsula mafic and greywackes (left side), as well as for average sonic velocities and densities for the borehole logs presented here for coastal Washington, and for the Puget Lowland by Brocher and Ruebel (1998).

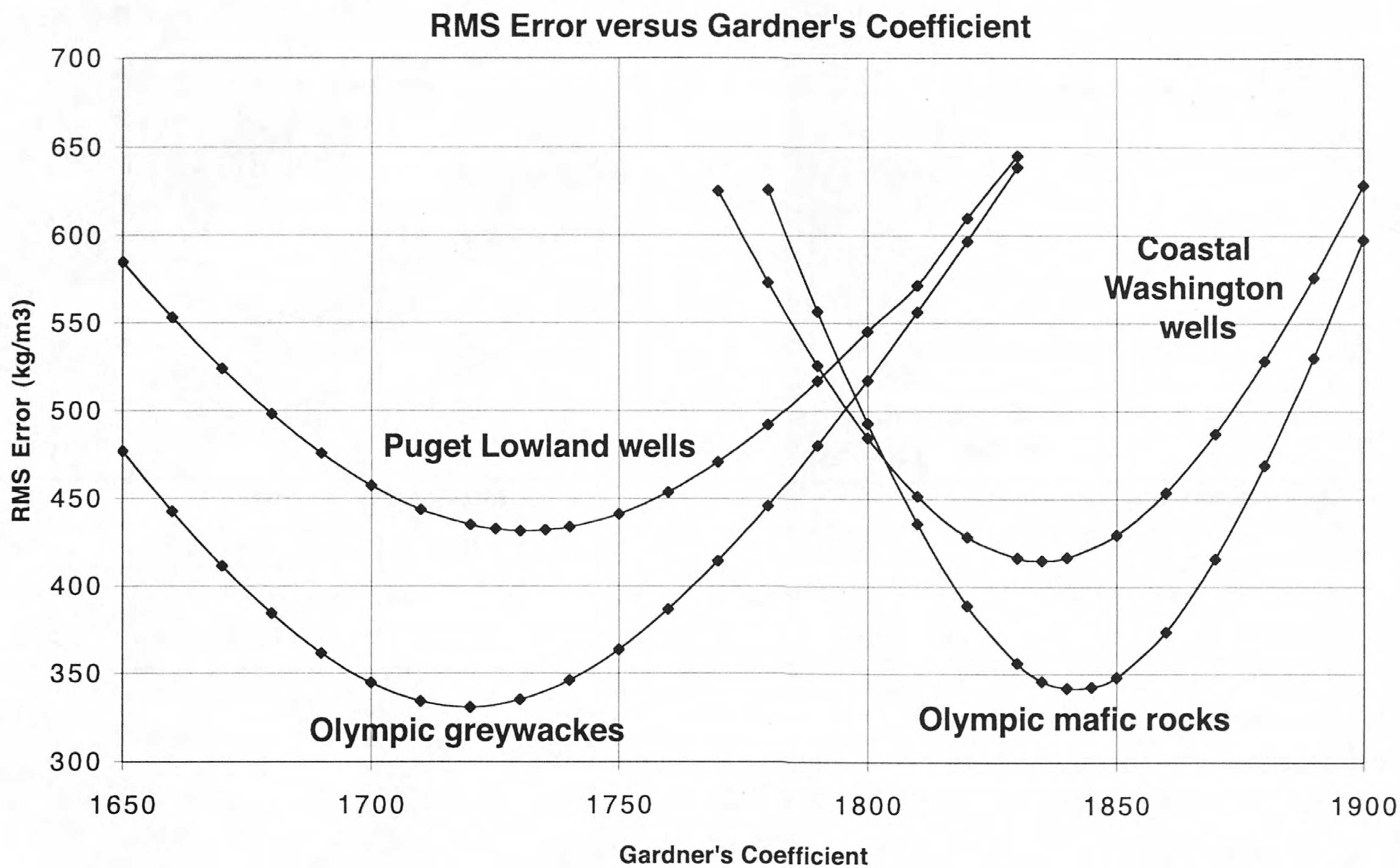

Figure 20. Graphs showing RMS misfit of the relationship ρ=Gardner's coefficient * v**0.25 for the various suites of rocks studied here and in Brocher and Ruebel (1998).

USGS LIBRARY - RESTON
3 1818 00329014 3