Carbonate reservoirs in Western Canada: An update

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ABSTRACT

Devonian Carbonate Reservoirs types in the Western Canada Sedimentary Basin are presented. A review of the reservoir parameters: geometry, lithology, porosity, fluid content, pressure, stress and their seismic estimation with compressional and shear waves velocities introduce the seismic method as a powerfull tool in carbonate reservoir characterization.

INTRODUCTION

In Western Canada the carbonate rock reservoirs of Devonian age host large reserves of hydrocarbons (GSC, 1989; 1993). As these reserves depletes production optimization is a expensive and strategic goal for the oil companies.

The Devonian deposition history in the Western Canada Sedimentary Basin (WCSB) is that of a dominant carbonate-evaporite sedimentation province. The carbonate reservoir types recognized and their seismic characterization are discussed. The sensitivity of compressional V_p and shear V_s wave velocities to structure, lithology, porosity, permeability, fluid content, temperature, stress and anisotropy variations confirm the seismic method as a principal tool in reservoir characterization. As the reservoir rock parameters are independent variables, specific geological constrains at the well control points are necessary to resolve the inverse problem: from wave seismic velocity measurements to the reservoir parameters.

3-D seismic, well-to-well tomography, amplitude, multicomponent, seismic borehole studies enhanced by innovative processing are promising tools to improve the geophysical abilities in imaging the subtle carbonate reservoirs.

THE WESTERN CANADA SEDIMENTARY BASIN

THE DEVONIAN SYSTEM

The Western Canada Sedimentary Basin (Fig. 1) through time is a product of two major tectonic settings:

1). From Late Paleozoic to Middle Jurassic the basin acting as a passive continental margin, was filled eastward in a series of episodic transgressive events,

2). From Late Jurassic to Tertiary, the Colombian and Laramide orogenesis controlled the sedimentation in the Foreland Basin.

The Phanerozoic Time Scale records six major unconformities as a result of sporadic epirogenic and orogenic movements.

During the Devonian, Western Canada was situated in equatorial latitudes. Five major transgressive-regressive sequences separated by unconformities are identified by Moore (1988; 1989) The relatively thick epeiric sea sediment complexes were deposited during eastward pulsatory transgression over the craton. Seven associated depositional cycles are correlated with the eustatic fluctuations of the sea level in North America as is proposed by Johnson et all (1985) are discussed and shown in Fig 2

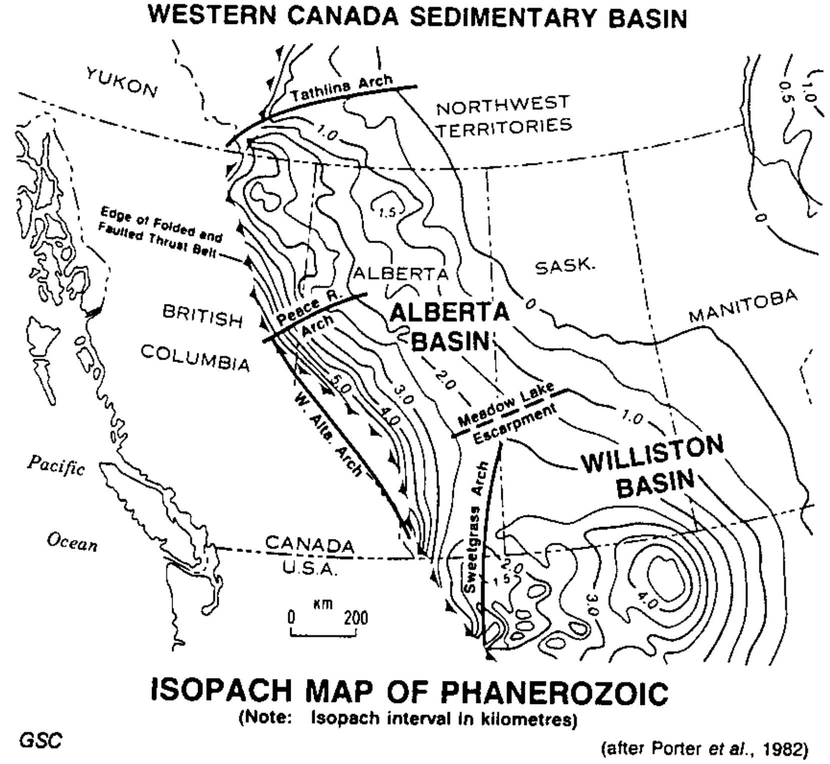


Figure 1. Basin Fill Map, Western Canada Sedimentary Basin.

Lower Elk Point (Cycle C1 and Cycle C2)

From Basal Red Beds to Upper Chinchaga a succession of redbeds, evaporites and carbonates was deposited within a restricted epicontinental sea. These strata have a maximum thickness of 300m and pinchout over the Tathlina, Peace River and Western Alberta arches.

Upper Elk Point (Cycle C3)

A major transgression is marked by ramp-to platform carbonates of Lower Keg River Formation. As the subsidence of the basin continued, the Upper Keg River barrier reef complex developed toward the northern limit of the basin. Isolated pinnacle reefs and reef mounds, (60m to 250m thick) within the central part of the basins.

The Muskeg-Prairie Evaporite Formations deposited in evaporitic conditions cover the entire basin with the exceptions of the north region of the Presquile' Barrier Complex where the normal marine sedimentation continued.

At the end of the Elk Point Cycle during a minor marine incursion peritidal to shallow-marine carbonates of Sulphur Point Formation covered the Northeastern Alberta.

Coastal marine and continental shale and sandstones of the Watt Mountain Formation terminates this cycle as the sea level drops.

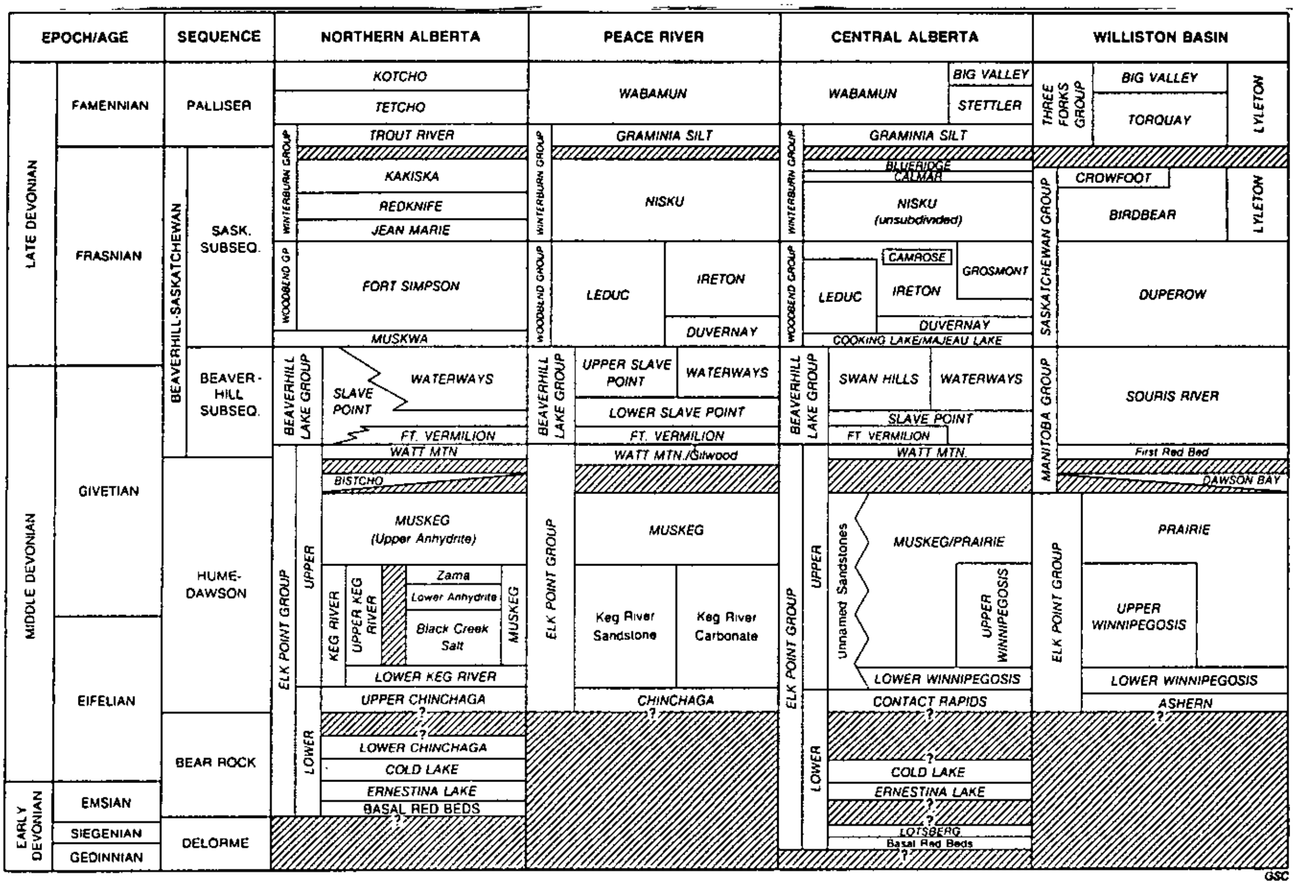


Figure 2. Table of Formations, Devonian, Western Canada Sedimentary Basin

Beaverhill Lake Group (Cycle 4).

Peritidal anhydrites and carbonates of Fort Vermilion Formation overlain during a gradual marine transgression the relatively flat surface of the Watt Mountain Formation. The sedimentation continued with the open-marine platform carbonates of the Slave Point Formation ranging from 20 m along the flanks of Alberta Ridge and the Peace River Arch to 150m near the Presquile' Barrier Complex. An extensive reef rimmed carbonate platform and the atoll like reef complex of the Swan Hills Formation developed in west-central Alberta. Basinal shales and argilaceous limestones of

Waterway Formation overlie the Swan Hills reef-complexes. In northern Alberta, the Waterways strata overlap the Slave Point reef complexes and in the southern Alberta interfinger with the shelf complex.

Woodbend Groups (Cycle 5)

In the deep water condition created by a renewed marine transgression and continuum deepening of the entire basin organic rich limestone and shale were deposited within the Duverney, Majeau Lake and Muskwa Formations. South and Southeast Alberta platform carbonates of Cooking Lake Formation were deposited in shallow waters. Leduc Formation and equivalents developed as reef-rimmed complex (Southern Alberta Shelf Complex).

In the Deep Basin area isolated Leduc reef complexes up to 250 m thick overlay direct Cooking Lake or Beaverhill platforms. Leduc reefs also developed in an arcuate fringe around Peace River Arch. The thick Ireton - Fort Simpson shales close the Woodbend Cycle as the Central Alberta basin was nearly filled.

Winterburn Group (Cycle 6)

The regressive sedimentation started in cycle 5 continued with the shelf carbonates of the Nisku Formation. A major regression terminated the Nisku sedimentation. The terigenous Calcar Formation deposits interfinger with shelf carbonates of Blue Ridge Member deposited during a shallow marine incursion.

At the end of the cycle the Gramina Silt was deposited as a second regression occurred.

Wabamun Group (Cycle 7)

A trangressive prograding carbonate ramp was initiated over central and northern Alberta and northeastern British Columbia. In southeastern Alberta the Nisku carbonates interfinger with the evaporitic deposits of the Stetller Formation. In northeastern British Columbia, the equivalent deeper water shales belong to the Besa River Formation.

DEVONIAN CARBONATE RESERVOIRS

The Carbonate reservoirs in The Devonian System in Western Canada Sedimentary Basin follow standard carbonate depositional models. In the Geological Survey of Canada (GSC) classification the typical Devonian carbonate reservoirs and their associated traps are illustrated in Figures 3 ,6 , 7 and 8.

Barrier Reef

A belt of transgressive phase reefs which separates deep seaward deposition of landward sedimentation. Open marine circulation was restricted behind the barrier reef.

Reef Complex

A large transgressive phase reef with complex facies surrounded by deeper-water deposits.

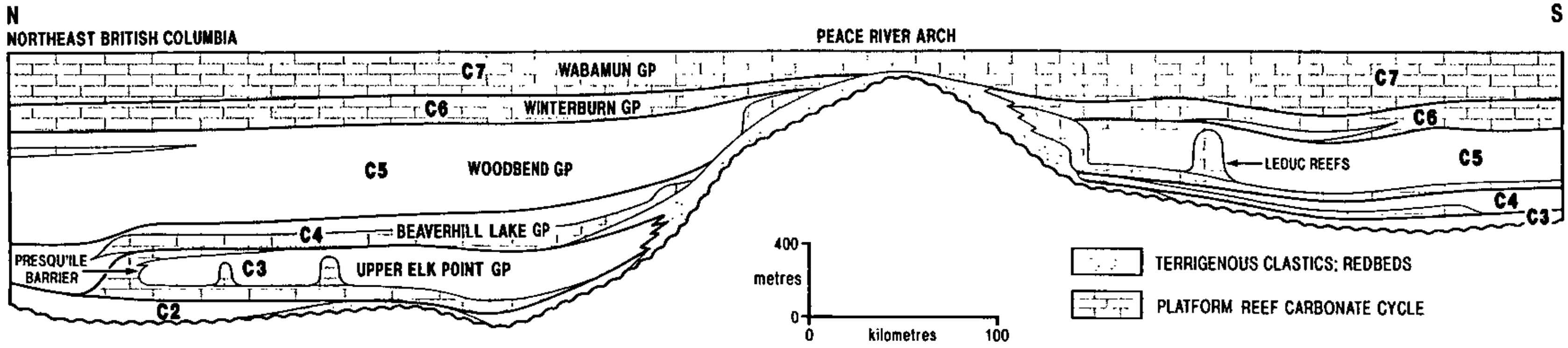


Figure 3. North-south cross section illustrating the major cycles in the Devonian of the Western Canada Sedimentary Basin. (Modified from Moore, 1989.)

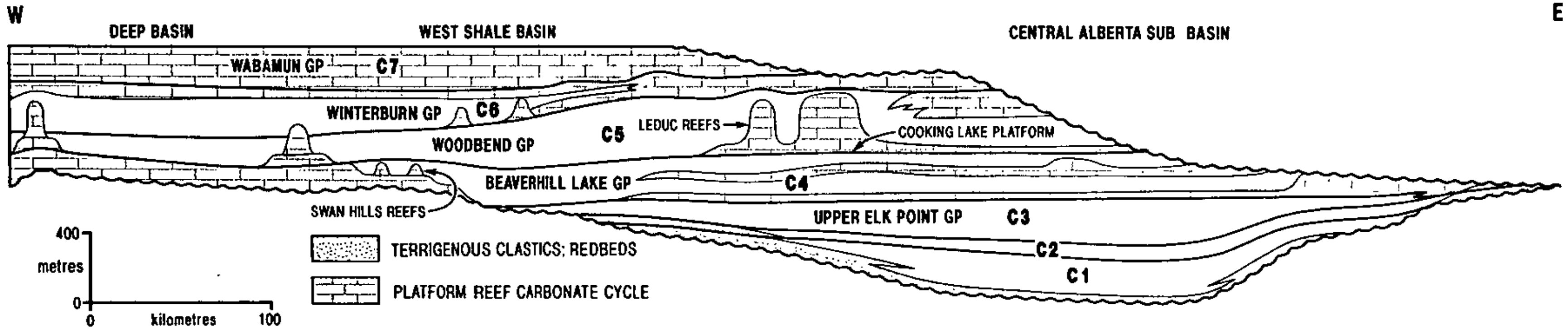


Figure 3. East-west cross section illustrating the major cycles in the Devonian of the Western Canada Sedimentary Basin. (Modified from Moore, 1989)

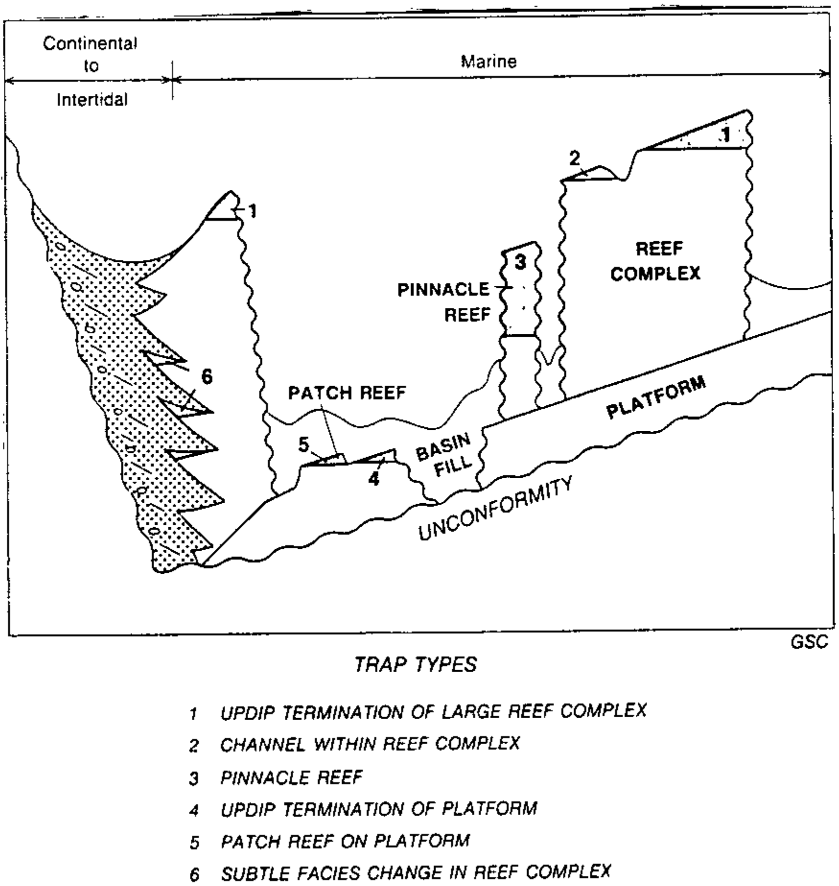


Figure 5. Trap Styles, Devonian transgresive phases (GSC)

Pinnacle Reef

A transgressive phase reef with a simple facies distribution and an areal extent less than a half square kilometer. Its thickness is larger than its diameter.

Patch Reef

A transgressive phase reef with less than three square kilometer in area with complex internal facies.

Platform Carbonate

Extensive, carbonate strata deposited during the first stages of marine transgression.

Shelf Carbonate

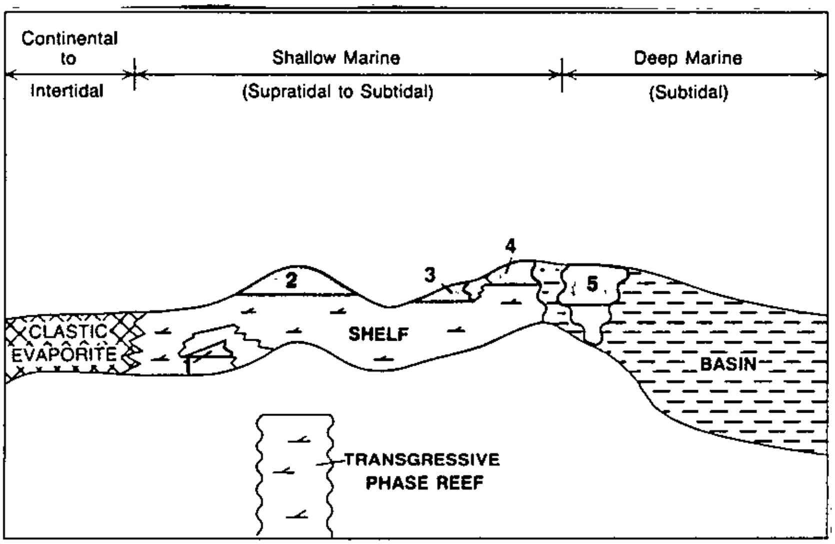
A sequence of thin, cyclic carbonate and evapotite sediments deposited in shallow marine waters.

Shelf Margin Reefs

Thinner barrier reefs with little impact on water circulation.

Shelf Interior Reefs

Regressive phase patch reefs that are surrounded by shelf carbonate and evaporite units.

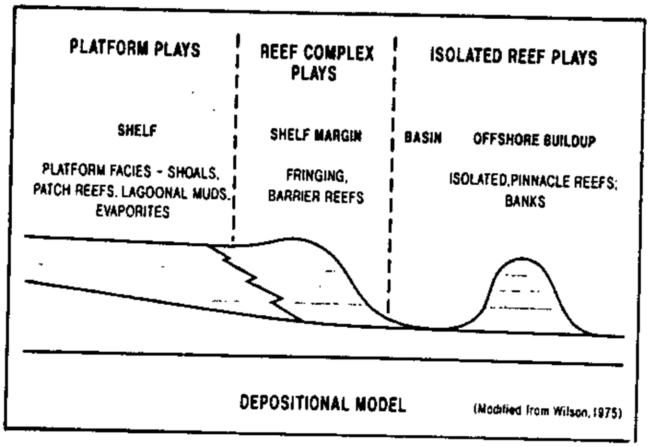


GSC

TRAP TYPES

1 LOCAL FACIES CHANGE
2 DRAPE OVER OLDER REEF
3 CHANNEL IN SHELF MARGIN
4 UPDIP TERMINATION OF SHELF MARGIN
5 PATCH REEF IN BASIN

Figure 6. Trap Styles, Devonian regressive phases (GCS).



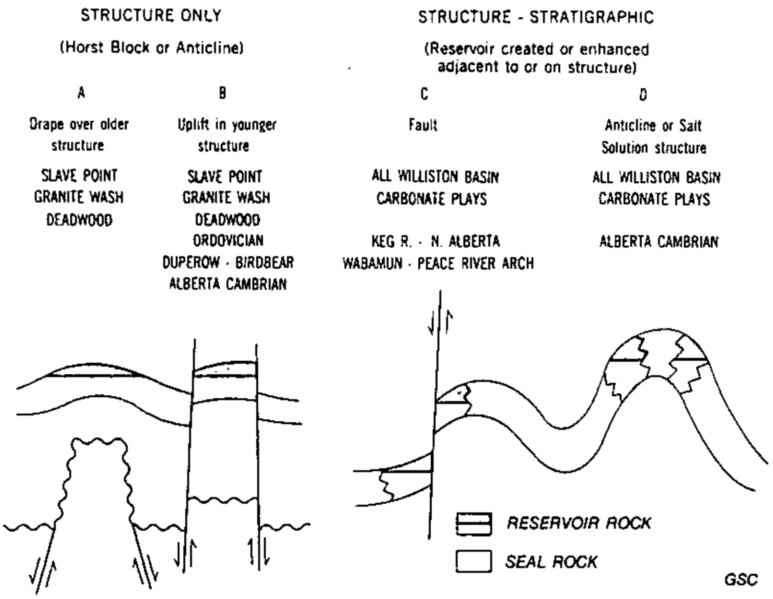


Figure 7. Structural and Structural-stratigraphic traps, Devonian (GSC).

SEISMIC VELOCITIES IN SEDIMENTARY ROCKS

In the laboratory and in situ, seismic velocities and densities for typical rock forming minerals (Table 1) and for typical sedimentary rocks (Table 2) have been measured as outlined below:

Table 1. Seismic Velocities and Densities in Typical Rock-Forming Minerals. (After Anderson & all, 1966)

	Vp (km/s)	Vs (km/s)	Vp/Vs	ρ (k/m³)
Quartz	6.057	4.153	1.46	2.65
Calcite	6.259	3.243	1.93	2.71
Dolomite	4.689	2.720	1.73	2.87
Halite	4.525	2.616	1.73	2.16

Table 2. Seismic Velocities and Densities in Typical Sedimentary Rocks. (After Domenico, 1984)

	Vp/Vs
Sandstone	1.46 - 1.76
Calc Sandstone	1.67 - 1.76
Dolomite	1.78 - 1.84
Limestone	1.84 - 1.99
Shale	1.70 - 3.00

It is evident that each mineral or rock has a set of values (Vp, Vs, Vp/Vs) which in particular conditions could identify with accuracy that material. Ideal these conditions will be determined by the medium in which the measurements are made, only. Based on these facts researchers over the last fifty years were trying to establish equations which will increase the probability of a realistic identification of these rocks.

RESERVOIR PARAMETERS

Gassman (1951) calculated the bulk modulus K of a fluid-saturated porous medium from the known bulk moduli of the solid matrix K_m, the frame dry K_d,, and the pore fluid K_f. The shear modulus of the rock is not affected by fluid saturation.

$$K = K_d + \frac{\left(1 - \frac{K_d}{K_m}\right)^2}{\frac{\varphi}{K_f} + \frac{1-\varphi}{K_m} - \frac{K_d}{K_m^2}} \qquad (1)$$

In Figure 8 and 9, from Wang and Nur (1992), Gassman calculated compressional and shear velocities versus measured velocities for typical carbonates are displayed. The deviation between observed and calculated velocities recommends caution in any use of Gassman equation when predicting saturating fluids.

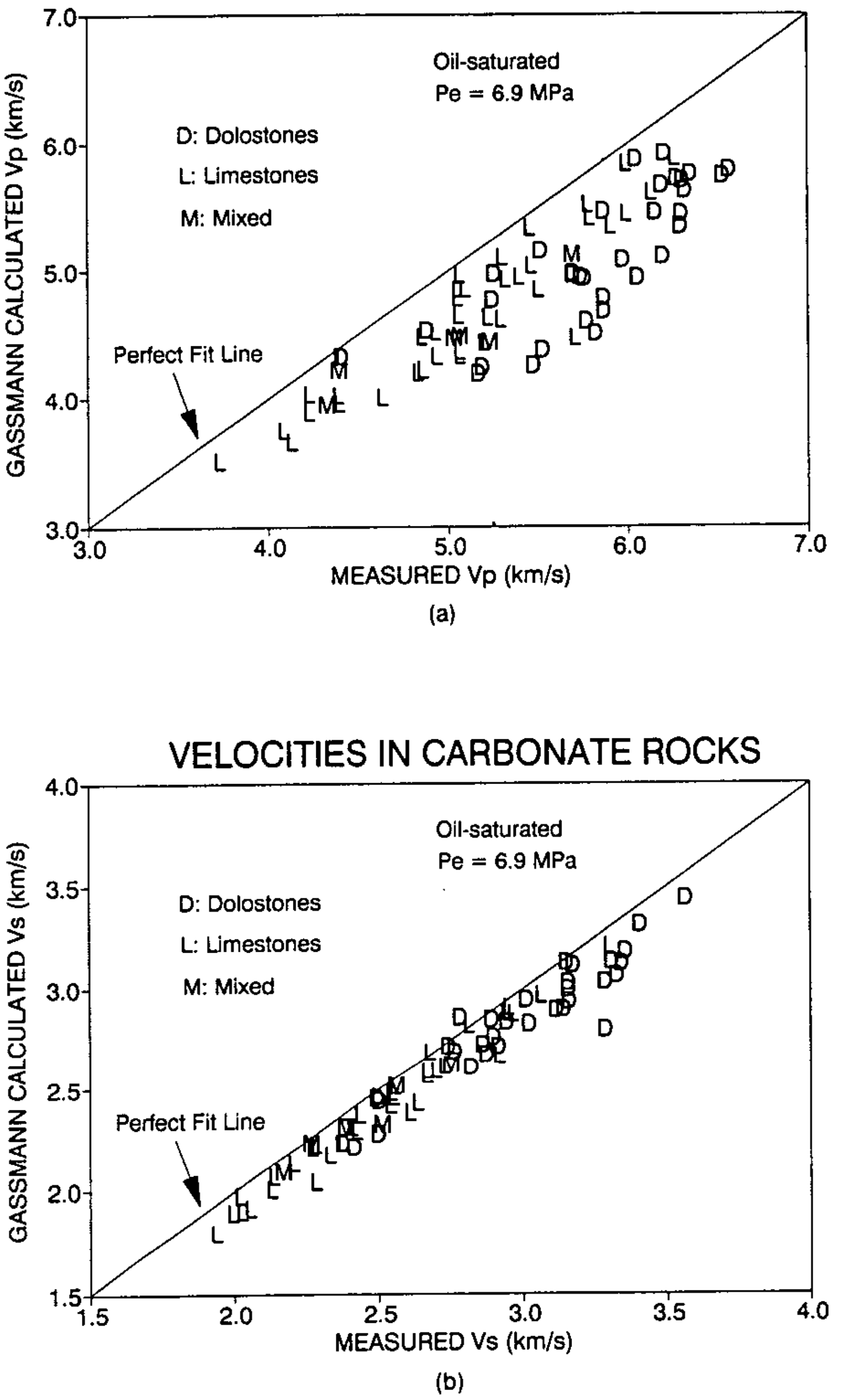


Figure 8. Comparison of laboratory measured compressional (a) and shear (b) wave velocities with those calculated using the Gassman equation at lower pressure (6.9 MPa).(after Wang and Nur. 1992).

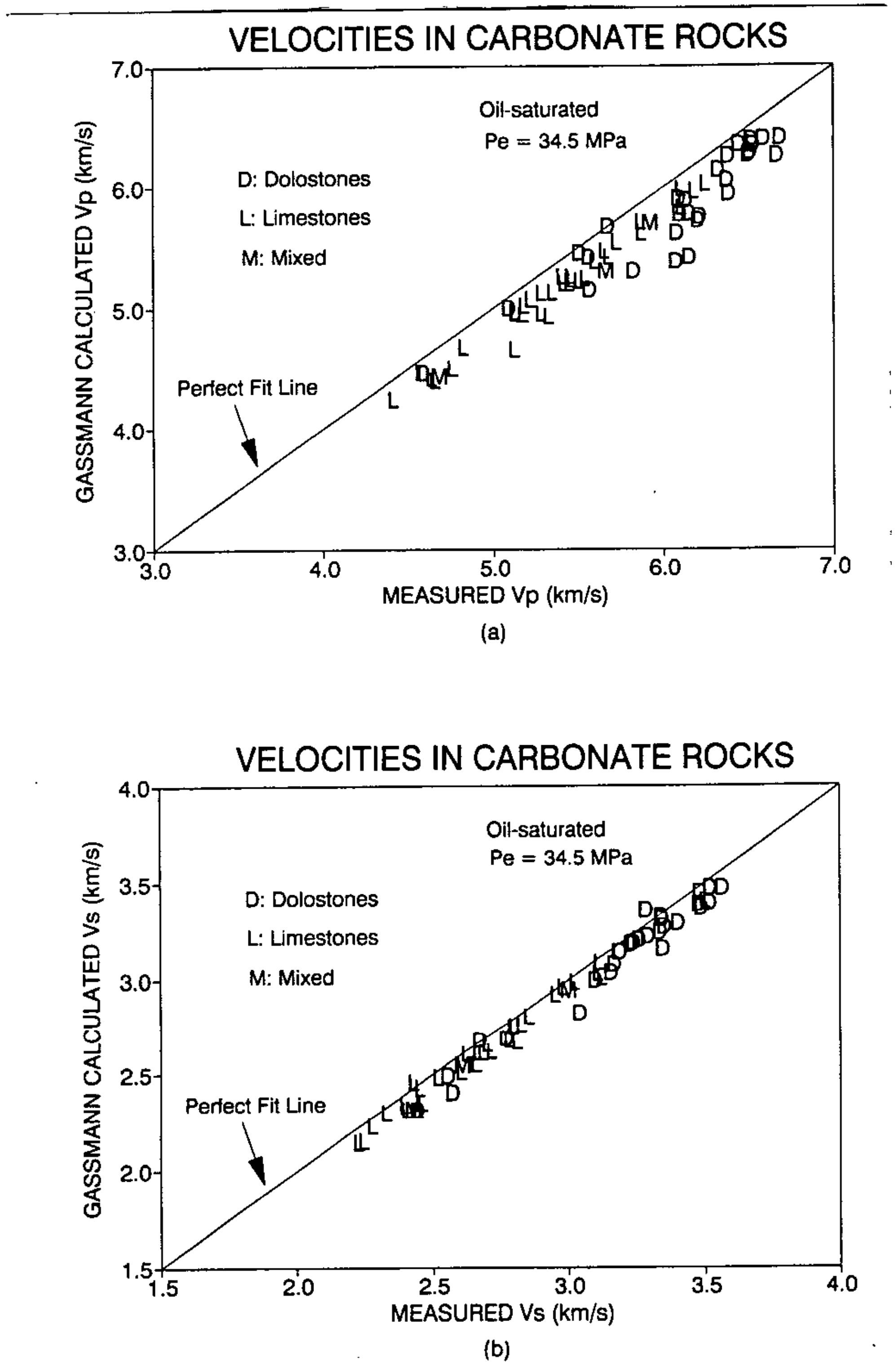


Figure 9. Comparison of laboratory measured compressional (a) and shear (b) wave velocities with those calculated using the Gassman equation at lower pressure (34.5 MPa).(after Wang and Nur. 1992).

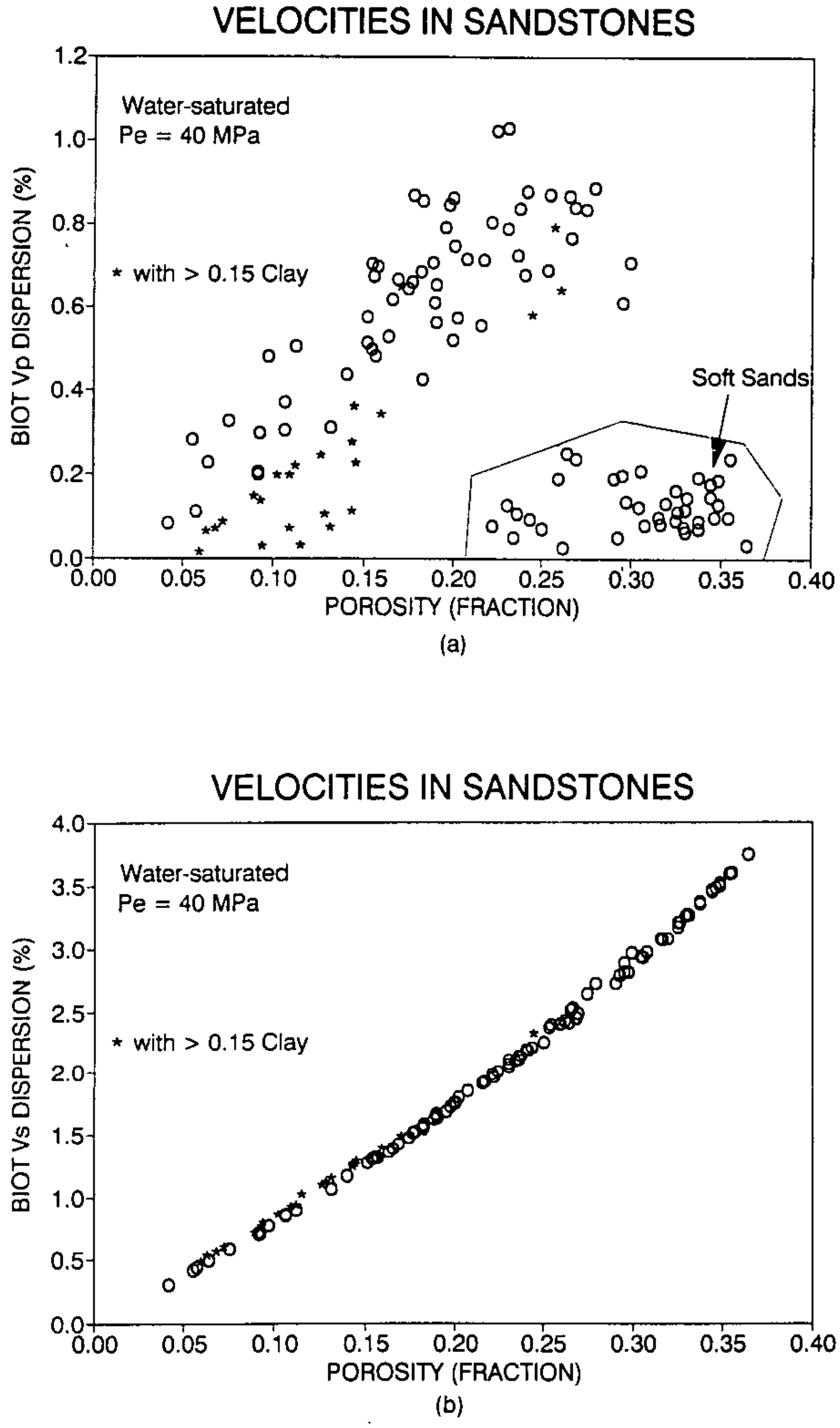
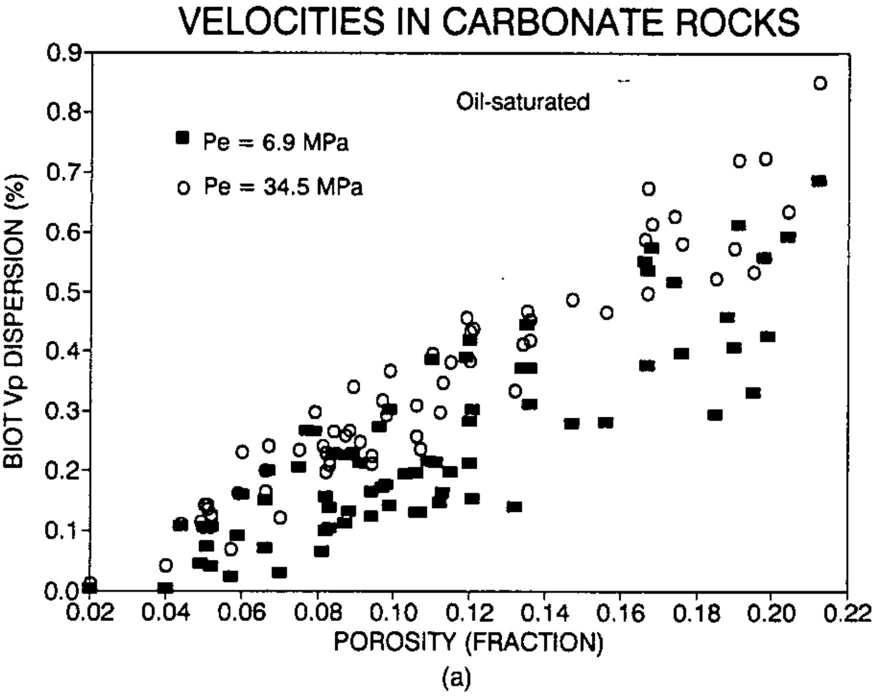
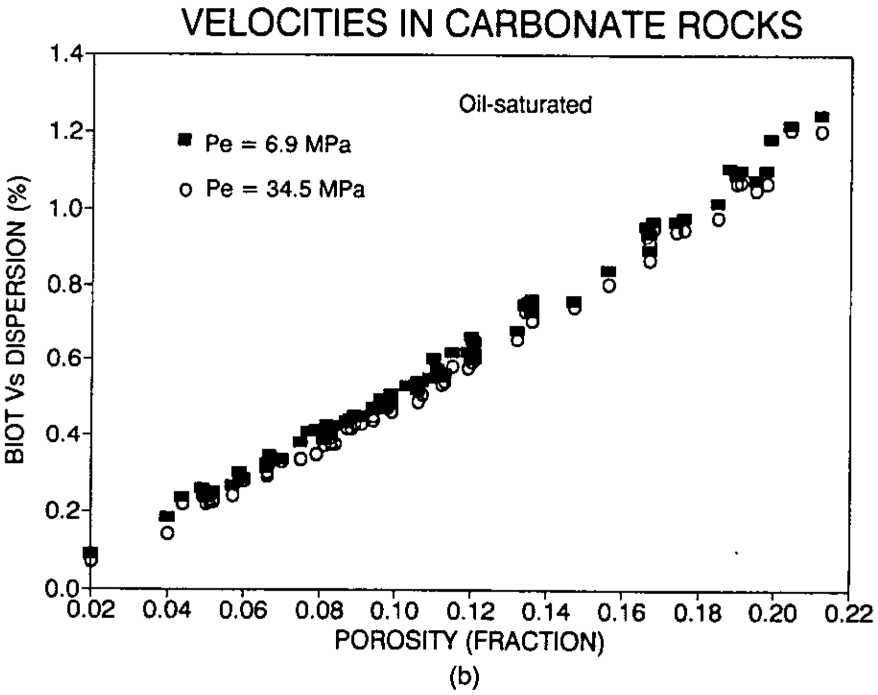


Figure 10. Maximum Biot dispersions of compressional (a) and shear (b) wave velocities in sandstone and samples saturated with water. (After Wang and al.,1992)



(a)



(b)

Figure 11. Maximum Biot dispersions of compressional (a) and shear (b) wave velocities in carbonate samples saturated with oil. (After Wang and al.,1992)

Wyllie et al. (1956) from experimental data discovered that in a rock of porosity φ the compression wave velocity V_p, the velocity in the matrix V_m ,and the velocity in the saturating fluid V_f fit the equation

$$\frac{1}{V_p} = \frac{\varphi}{V_f} + \frac{1-\varphi}{V_m} \tag{2}$$

Since its beginning this formula has been used to derive porosity from the sonic log. It has to be mentioned that this equation should not be used for carbonates as stated in Wyllie et al (1958).

Biot (1956; 1962) developed a theory for elastic wave propagation in porous media. The equations derived interrelates the compressional and shear velocities with the elastic constants of the rock and saturating fluid. In Figure 10 and Figure 11 from Wang et al. (1992) compressional and shear wave velocities calculated by the Gassman V_G and Biot V_B equations are compared for sandstones and carbonates.

$$\text{Biot Dispersion} = \frac{V_B - V_G}{V_g} \tag{3}$$

Lithology

Picket (1966) from laboratory measurements stated that Vp/Vs discriminates between clean sandstone, carbonates and limestones (fig. 12). Later other researchers confirmed this result with new measurements: Hamilton (1979), Domenico (1984),, Robertson (1987).

$$\sigma = \frac{0.5\left(\frac{V_P}{V_s}\right)^2}{\frac{V_P^2}{V_s} - 1} \tag{4}$$

The possibility of mapping lithologies throughout elastic wave velocities measurements has very important value for reservoir evaluation. Recording S- and P-wave seismic data on the surface in optimum conditions of S/N information from the subsurface can be derived accurately.

Porosity

Gregory (1976) studied the variation of elastic wave velocities with porosity in dry and saturated sedimentary rocks at low and high pressure as illustrated in Figure 13 and 14. A remarkable conclusion is that for a given lithology and porosity V_p/V_s can discriminate between liquid and gas pore.

Fluid Content

Pore fluids consist of oil, water mixtures and gases. Identification of pore fluids cannot be made with confidence based on V_p/V_s alone. To reduce the ambiguity detailed litological information is critical.

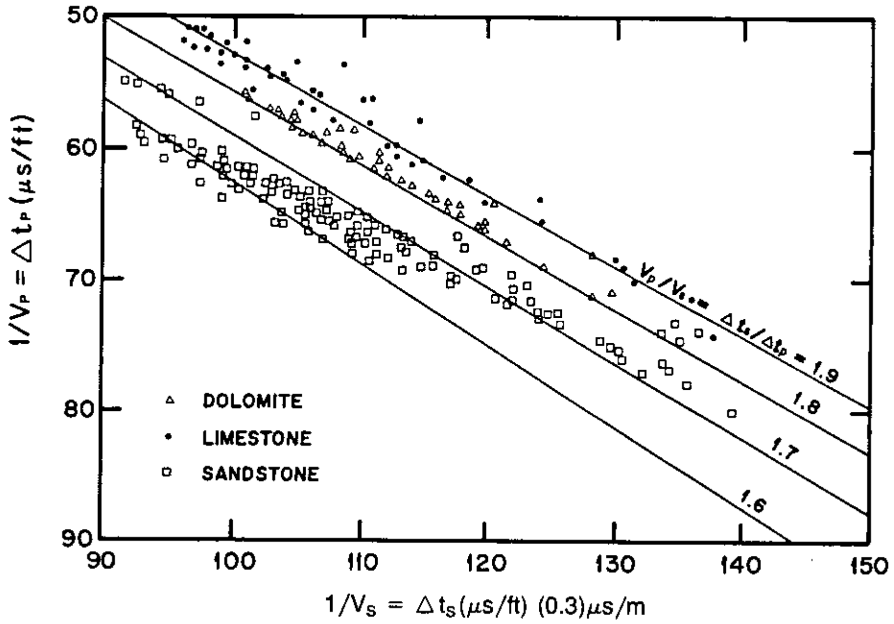


Figure 12. Separation of lithology types (after Pickett,1963).

Pore Shape

Kuster and Toksoz (1974) and Toksoz et al. (1976) developed a model for the propagation of elastic waves in porous media that considers the effect of pore shape on V_p and V_s.

Pressure, Depth of Burial.

The variations of V_p and V_s in carbonate rocks with pressure/depth is larger for the first 1000 m and is mainly due to the closure of the elongated pores.

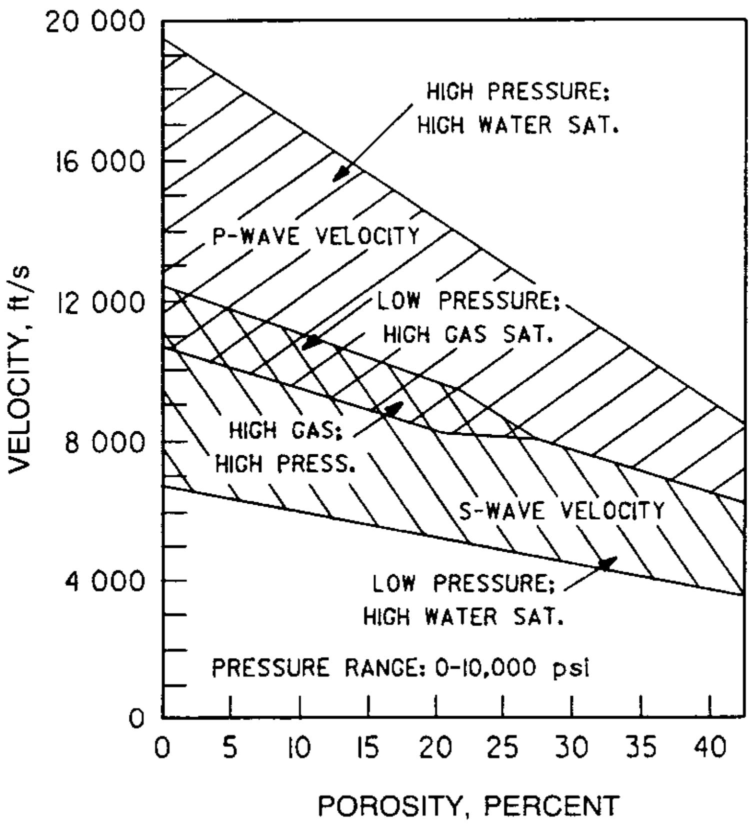


Figure 13. The ranges of Vp/Vs for dry and saturated rocks versus porosity.
(After Gregory, 1976)

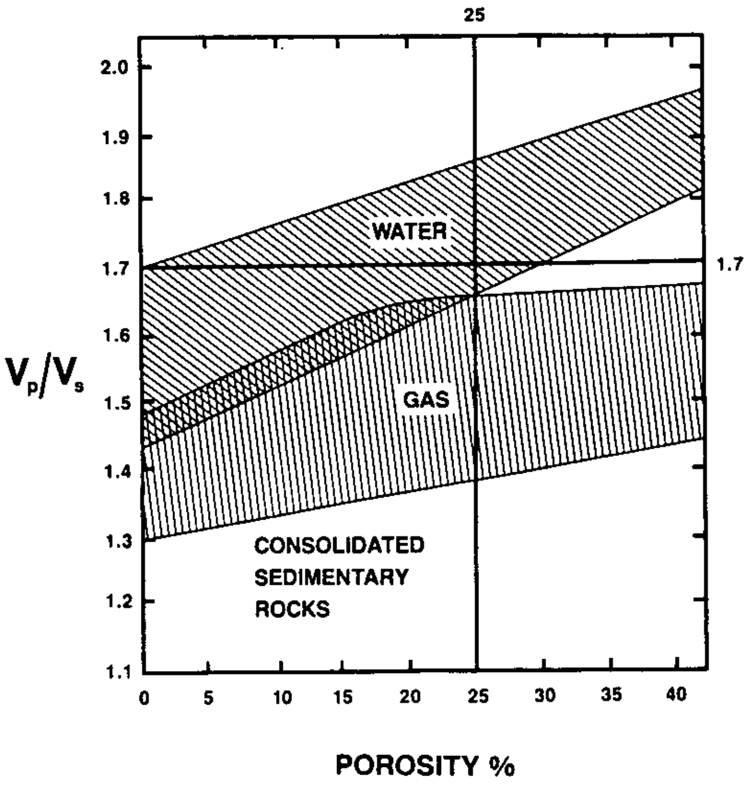


Figure 14. Location of P- and S-wave velocities plotted versus porosity for different pressures and water saturation. (After Gregory, 1976)

Temperature

The relation between elastic wave velocities and the temperature are less studied but from the reported studies, Timur (1977), the nature of the pore fluids is driving the bulk of the variations. For a brine-oil mixture a decrease in both V- and S- wave velocities are recorded.

Anisotropy

The anisotropy of carbonate rocks is controlled by factors as pore shape, pore and crack orientation, pressure, stress. The Devonian carbonates in Western Canada had a history of intense mechanical deformations. It is very likely that in the field, accurate anisotropy measurements will add to the techniques of reservoir description.

SEISMIC IMAGING THE CARBONATE RESERVOIR

The reflection seismic method for reef identification is well established for transgressive reef complexes. patch, and pinnacle reefs. These reefs present lateral velocities contrasts as well as differential compaction. Their seismic identification as structure anomalies appears easy but in many cases such structure tested dry. Criteria for reservoir characterization do not follow standards and is the geophysicists chalange to predict reservoir properties.

We have seen that compressional and shear wave velocities together carry pertinent data to predict reservoir parameters. Theoretical and field studies recommend multicomponent seismic as the method for detailed reservoir characterization.

The daily problem the geophysicist is facing is that only seismic compressional reflection is available for interpretation. Through innovative modeling with geological and well information it is possible to calibrate the seismic data to extract from the seismic amplitude the missing Vs value. AVO measurements and amplitude calibration might be adequate to properly assess the reservoir.

Seismic inversion plays an important role in assessing the carbonate reservoir. Theoretical models and direct application to real data fit the best case histories but care is recommended in drawing general conclusions.

Meckel and al (1977) have modeled two carbonate reservoirs: a Carbonate Shelf Margin (Figure 15) and a Carbonate Platform (Figure 16). For the first case the morphological appearance of the reservoir makes possible its identification. In favorable situation amplitudes can be calibrated for reservoir characterization (). In the second case due to the low acoustic impedance contrast the reservoir is seismically transparent (Fig. 13). These are the extreme cases for the vast field of the carbonate settings as they are encountered in all the geological times.

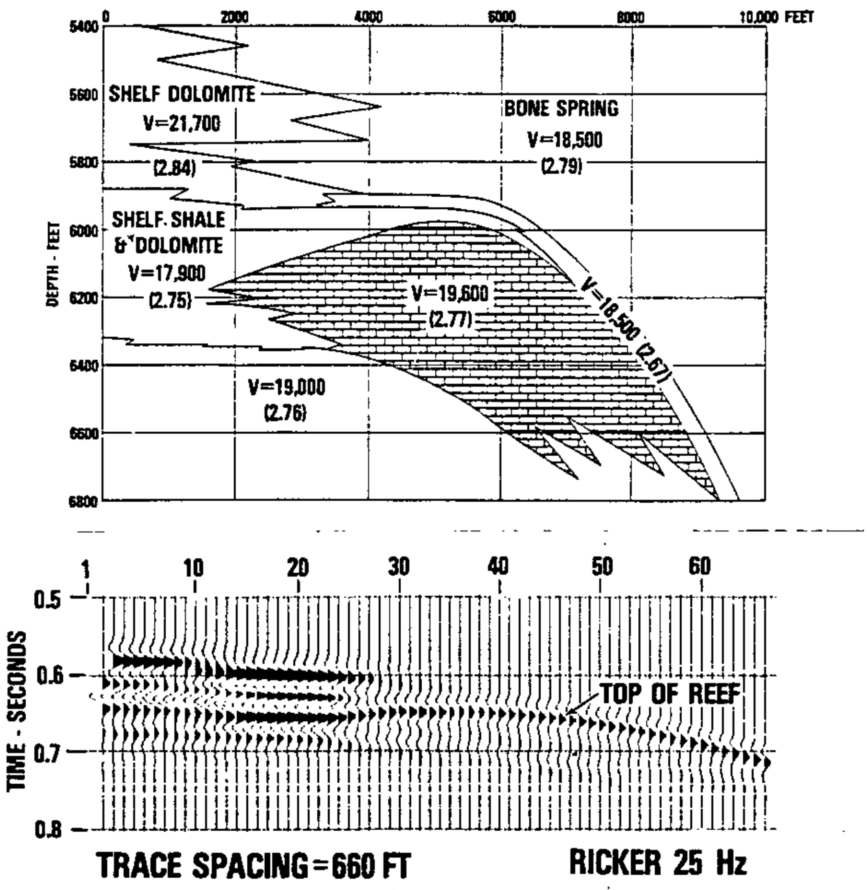


Figure 15. Seismic model of carbonate shelf margin (after Meckel and al., 1976)

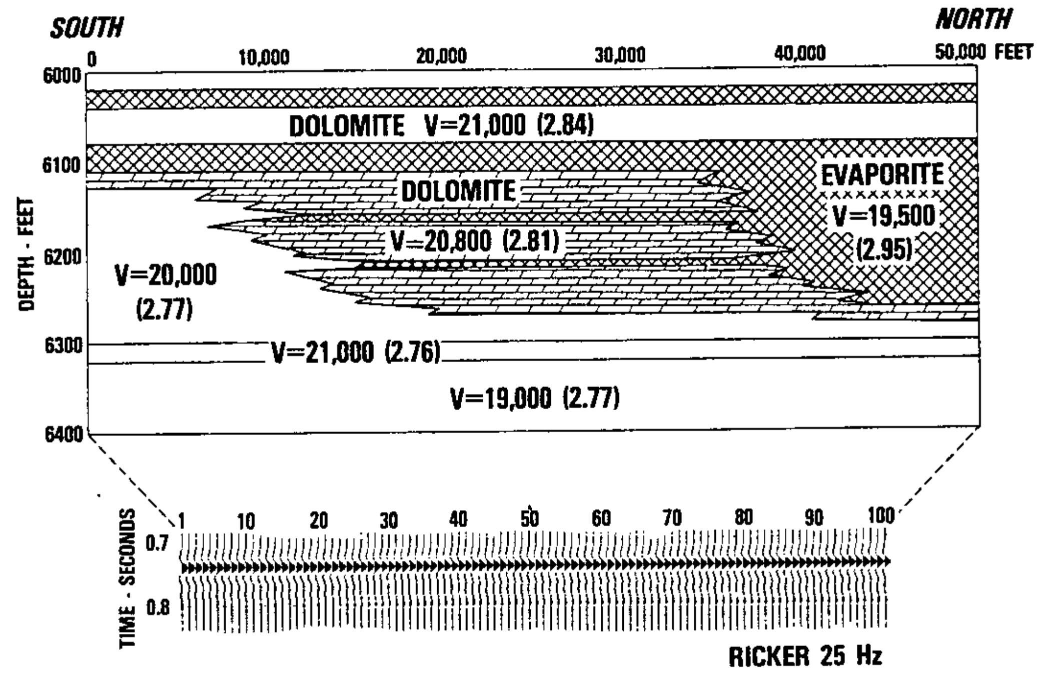


Figure 16. Seismic model of tidal-flat margin reservoir (after Meckel an al., 1976).

CONCLUSIONS

The reflection seismic method, the most used geophysical method in geoscience studies, is finding applications in reservoir characterization. The Devonian carbonate reservoirs in WCSB represented by a multitude of structural and stratigraphyc types are the target of intense exploration and development effort. To make this effort more efficient, the quality of these reservoirs have to be well known prior to new investments.

Today, the 3-D seismic method, sophisticated computer technologies and in depth knowledge of the petrophysical properties of the reservoir rocks open new domains in hydrocarbon reservoir studies.

Lithological calibration of the 3-D seismic amplitudes, acquisition of VSP and multicomponent (V, SV, SH) surveys, seismic anisotropy measurements, AVO studies, etc. expand the geophysicist potential to describe the subsurface, to make critical contributions in reservoir evaluation. Reservoir characterization is today an multidisciplinary effort of significant economic importance in the oil industry.

REFERENCES

Acheson, C. H., 1963, Time-depth and velocity-depth relations in Western Canada: Geophysics **28**, 894-909.

Ahmed Hassan, 1989, Application of mode-converted shear waves to rock-property estimation from vertical seismic profiling data: Geophysics **54**, 478-485.

Aki, K., and Richards, P. G., 1980, Quantitative seismology, Theory and methods: W. H. Freeman and Company.

Anderson, N. L., R. J. Brown, R. C. Hinds, L. V. Hills, 1989, Seismic signature of a Swan Hills (Frasnian) reef reservoir, Snipe Lake, Alberta: Geophysics **54**, 148-157.

Anderson, E. K. N. L., Franseen, 1991, Differential compaction of Winnipegosis reefs: A seismic perspective: Geophysics **56**, 142-147.

Andrew, John A., Duncan M. Edwards, Robert J. Graf, Richard J. Wold, 1991, Empirical observations relating near-surface magnetic anomalies to high-frequency seismic data and Landsat data in eastern Sheridan County, Montana: Geophysics **56**, 1553-1570.

Ass'ad, J. M., Tatham, R. T., and McDonald, J. A., 1992, A physical model study of microcrack-induced anisotropy: Geophysics, **57**, 1562-1570.

Birch, F., 1960, The velocity of compressional waves in rocks to 10 kilobars, Part 1 J. Geophys. Res., **65**, 1083-1102.

Birch, F., 1960, The velocity of compressional waves in minerals to 10 kilobars, Part 2: J. Geophys. Res., **66**, 2199-2224.

Stephan J. Bless, Thomas J. Ahrens, 1977, Measurements of the longitudinal modulus of Pierre clay shale at varying strain rates: Geophysics **42**, 34-40.

Bloy Graeme R., Charest Marc, 1988, Principles and Concepts for the Exploration of Reefs in the Western Canada Basin: CSPG.

Brundage, Harrison T., 1964, Making geophysics meaningful to geologists: Geophysics **29**, 985-991.

Carlson R. L., Schaftenaar, C. H., R. P. Moore, 1984, Causes of compressional-wave anisotropy in carbonate-bearing, deep-sea sediments: Geophysics **49**, 525-532.

Castagna, J. P.,. Batzle, M. L, Eastwood, R. L., 1985, Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks: Geophysics **50**, 571-581.

Caughlin, W. G.,Lucia, F. J., McIver, N. L., 1976, The detection and development of Silurian Reefs in Northern Michigan: Geophysics **41**, 646-658.

Chacko, S,. 1989, Porosity identification using amplitude variations with offset: Examples from South Sumatra: Geophysics **54**, 942-951.

Cheng, C. H., Jinzhong, Zhang, Burns, Daniel R., 1987, Effects of in-situ permeability on the propagation of Stoneley (tube) waves in a borehole: Geophysics **52**, 1279-1289.

Christensen, N. I., Wang, H. F., 1985, The influence of pore pressure and confining pressure on dynamic elastic properties of Berea sandstone: Geophysics **50**, 207-213.

Conklin, G. M., 1953, Problem areas for the seismologist: Geophysics **18**, 827-843.

Connelly, D. L., Ferris, B. J., Trembly, L. D., 1991, Northwestern Williston Basin case histories with 3-D seismic data: Geophysics **56**, 1849-1874.

A. Correia, F. W. Jones, A. Fricker, 1990, Terrestrial heat-flow density estimates for the Jeanne D'Arc Basin, offshore eastern Canada: Geophysics **55**, 1625-1633.

Crampin, S., 1981, A review of wave motion in anisotropic and cracked elastic-media: Wave Motion, **3**, 343-391.

__________ 1986, Anisotropy and transverse isotropy: Geophysical Prospecting, **34**, 94- 99.

Crampin, S., and McGonigle, R., 1981, The variation of delays in stress-induced anisotropic polarization anomalies: Geophys. J. R. ¬. Soc., **64**, 115-131.

Davis, T. L., 1972, Velocity variations around Leduc Reefs, Alberta: Geophysics **37**, 584-604.

Davis, T. L., Jackson, G. M., 1988, Seismic stratigraphy study of algal mound reservoirs, Patterson and Nancy fields, Paradox basin, San Juan, County, Utah: Geophysics **53**, 875-880.

Doyen, P. M. ,1988, Porosity from seismic data: A geostatistical approach: Geophysics **53**, 1263-1275.

Dumay, J., Fournier, F., 1988, Multivariate statistical analyses applied to seismic facies recognition: Geophysics **53**, 1151-1159.

Geis, W. T., Stewart, R. R., Jones, M. J., Katopodis, P. E., 1990, Processing, correlating, and interpreting converted shear waves from borehole data in southern Alberta: CASE HISTORY: Geophysics **55**, 660-669.

Goldberg, D. Gant, W. T., 1988, Shear-wave processing of sonic log waveforms in a limestone reservoir: Geophysics **53**, 668-676.

Gretener, P. E. F., 1961, An analysis of the observed time discrepancies between continuous and conventional well velocity surveys: Geophysics **26**, 1-11.

Hamilton, E. L., 1972, Compressional-wave attenuation in marine sediments: Geophysics **37**, 620-646.

Jones, T. D. ,1986, Pore fluids and frequency-dependent wave propagation in rocks: Geophysics **51**, 1939-1953.

Kisslinger, C., 1953, The effect of variations in chemical composition on the velocity of seismic waves in carbonate rocks: Geophysics **18**, 104-115.

Laster, S. J., 1985, The present state of seismic data acquisition: One view: Geophysics **50**, 2443-2451.

Lindseth, R. O., 1979, Synthetic sonic logs--a process for stratigraphic interpretation: Geophysics **44**, 3-26.

Lortzer, G. J. M., Berkhout, A. J., 1992, An integrated approach to lithologic inversion--Part I: Theory: Geophysics **57**, 233-244.

Lucet, N., Zinszner, B., 1992, Effects of heterogeneities and anisotropy on sonic and ultrasonic attenuation in rocks: Geophysics **57**, 1018-1026.

Mabey, D. R., 1956, Geophysical studies in the Intermontane Basins in Southern California: Geophysics **21**, 839-853.

Marr, J. D., 1971, Seismic stratigraphic exploration -- Part I: Geophysics **36**, 311-329

Mathisen, M. E., Budny, M., 1990, Seismic lithostratigraphy of deep subsalt Permo-Carboniferous gas reservoirs, Northwest German Basin: Geophysics **55**, 1357-1365.

Maureau,G. T. F. R., Wijhe, D. H. van, 1979, The prediction of porosity in the Permian (Zechstein 2) carbonate of eastern Netherlands using seismic data: Geophysics **44**, 1502-1517.

Meckel Jr., L. D., Nath, A. K., 1977, Geologic considerations for stratigraphic modeling and interpretation: AAPG Memoir **26**, 417-438.

McCormack, M. D., Dunbar, J. A., Sharp, W. W., 1984, A case study of stratigraphic interpretation using shear and compressional seismic data: Geophysics **49**, 509-520.

McDonald, J. A., F. Gardner, G. H., Kotcher, J. S., 1981, Areal seismic methods for determining the extent of acoustic discontinuities: Geophysics **46**, 2-16.

McGinnis, L. D., Otis, R. M., 1979, Compressional velocities from multichannel refraction arrivals on Georges Bank--northwest Atlantic Ocean: Geophysics **44**, 1022-1033.

Middleton, M. F., 1984, Seismic geohistory analysis--A case history from the Canning Basin, Western Australia: Geophysics **49**, 333-343.

Nur, A. and Simmons, G., Stress induced anisotropy in rock: An experimental study: Journal of Geophysical Research, **74**, 6667-6674.

Neff, D. B., 1990, Estimated pay mapping using three-dimensional seismic data and incremental pay thickness modeling: Geophysics **55**, 567-575.

Phipps, G. G., 1989, Exploring for dolomitized Slave Point carbonates in Northeastern British Columbia: Geophysics **54**, 806-814.

Pickett, G. R., 1970, Applications for borehole geophysics in exploration: Geophysics **35**, 81-92.

Podruski, J. A., Barclay, J. E., Hamblin, A. P., Lee, P. J., Osadetz, K. G., Procter, R. M., Taylor, G. C., 1988, Conventional Oil Resources of Western Canada: GSC **87-26**.

Rafavich, F., Kendall, C. H. St. C., Todd, T. P., 1984, The relationship between acoustic properties and the petrographic character of carbonate rocks: Geophysics **49**, 1622-1636.

Rai, C. S., Hanson, K. E., 1988, Shear-wave velocity anisotropy in sedimentary rocks: A laboratory study: Geophysics **53**, 800-806.

Reinson, G.E., Lee, P. J., Warters, W., Osadetz, K. G., Bell, L. L., Price, P. R., Trollope, F., Campbell, R. I., Barclay, J. E., Devonian gas resources of Western Canada Sedimentary Basin: GSC **452**.

Rene, R. M., Fitter, J. L., Murray, D. J., Walters, J. K., 1988, Reflection and refraction seismic studies in the Great Salt Lake Desert, Utah: Geophysics **53**, 431-443.

Renick, Jr. H, Gunn, R. D., 1989, Triangle Ranch Headquarters field development using shallow core holes and high-resolution seismic data: Geophysics **54**, 1384-1396.

Robertson, J. D., 1987, Carbonate porosity from S/P traveltime ratios: Geophysics **52**, 1346-1354

Scholle, P. A., Bebour, D. G., Moore, C. H., 1983, Carbonate Depositional Environments: AAPG.

Sengbush, R. L., 1962, Stratigraphic trap study in Cottonwood Creek Field, Big Horn Basin, Wyoming: Geophysics **27**, 427-444.

Sheriff, R. E., 1970, Glossary of terms used in well logging: Geophysics **35**, 1116-1139.

Stewart, R. R., 1989, Integrated seismic analysis: Kidney area, Northern Alberta, Canada: Geophysics **54**, 1240-1248.

Smith, G. C., Gidlow, P. M., Weighted stacking for rock property estimation and detection of gas: Geophysical Prospecting, **35**, 993-1014.

Sutton, G. H., Berckhemer, H., Nafe, J. E., 1957, Physical analysis of deep sea sediments: Geophysics **22**, 779-812.

Tatham, R. H., and McCormack, M. D., 1982, Multichannel seismology in petroleum exploration: Investigations in Geophysics Series, **6**, SEG.

Thomasson, M. R., Kettle,R. W., Lloyd, R. M., McCormack, R. K., Lindsey, J. P., 1989, Seismic detection and interpretation of porosity in Carboniferous age rocks of Kansas and Oklahoma: Geophysics **54**, 1371-1383.

Aytekin Timur, 1977, Temperature dependence of compressional and shear wave velocities in rocks: Geophysics **42**, 950-956.

Tucker, P. M., 1988, Seismic contouring: A unique skill: Geophysics **53**, 741-749.

Tuman, V. S., 1961, Refraction and reflection of sonic energy in velocity logging: Geophysics **26**, 588-600.

Tyce, R. C., 1981, Estimating acoustic attenuation from a quantitative seismic profiler: Geophysics **46**, 1364-1378.

Vo-Thanh, D., 1990, Effects of fluid viscosity on shear-wave attenuation in saturated sandstones: Geophysics **55**, 712-722.

Vo-Thanh, D., 1991, Effects of fluid viscosity on shear-wave attenuation in partially saturated sandstone: Geophysics **56**, 1252-1258.

Tatham, R. H., 1982, V_p/V_S and lithology: Geophysics, **47**, 336-344.

Wang, Z., Nur, A., 1992, Elastic wave velocities in porous media: a theoretical recipe:, Geophysics reprint series, **10**, 1-35.

Wang, Z., Hirsche, W. K., Sedgwick, G., 1991, Seismic monitoring of water floods?--A petrophysical study: Geophysics **56**, 1614-1623.

Wilkens, R., Simmons, G., Caruso, L., 1984, The ratio V<inf/p//V<inf/s/ as a discriminant of composition for siliceous limestones: Geophysics **49**, 1850-1860

Wu, X., Nyland, E.,1987, Automated stratigraphic interpretation of well-log data: Geophysics **52**, 1665-1676

Wyllie, M. R. J., Gregory, A. R., Gardner, G. H. F., 1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics **23**, 459-493

Wyllie, M. R. J., Gregory, A. R., Gardner, G. H. F., 1956, Elastic wave velocities in hetergeneous and porous media: Geophysics **21**, 41-70

Yale, D. P., 1985, Recent advances in rock physics: Geophysics **50**, 2480-2491

Yungul, S. H., 1961, Gravity prospecting for reefs: effects of sedimentation and differential compaction: Geophysics **26**, 45-56