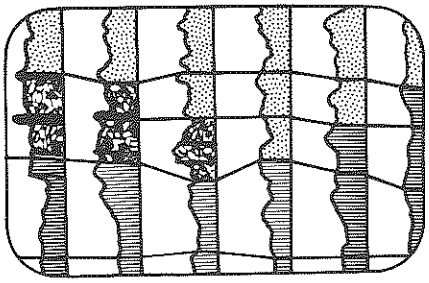

Subsurface Facies Analysis

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INTRODUCTION

This article will attempt to bridge the gap between "academic" sedimentology based largely on outcrop and modern sediment studies and the techniques of resource geologists who investigate sedimentary rocks in the subsurface. It is written for an audience which is unfamiliar with subsurface techniques, and is intended to be an introduction to subsurface data and procedures, particularly 1) geophysical logs, 2) cores and cuttings, 3) correlation, 4) facies analysis. Seismic methods are reviewed elsewhere in this volume; readers interested in these methods are also referred to the American Association of Petroleum Geologists Memoir 26 (Payton, 1977), a collection of papers which summarizes a great deal of information about seismic stratigraphic analysis.

Subsurface studies will probably become more important in academic facies modelling in the future. Many details of individual facies have been worked out, but we know relatively little about stacking of individual facies, or the migration of facies through time. One specific example of this is the very small number of studies documenting how fluvial point bar sequences (see "Sandy Fluvial Systems", this volume) are stacked together into meander belt sands, and how meander belt sands relate to one another. This kind of study is impossible to carry out in most outcrop areas, but a subsurface study in an appropriate unit may succeed.

DIFFERENCES FROM SURFACE WORK

In many ways, subsurface data differs from the kinds of data collected from outcrops and modern sediments. Most fundamentally, subsurface data provides a differently-biased sample of the characteristics of a rock unit than does outcrop data. Drill holes and cores are concentrated in localities and zones of economic interest while outcrops preferentially expose harder, more resistent rocks occurring near the margin of a basin. Drill holes "sample" a complete section while outcrops rarely do. Some common sedimentological techniques such as paleocurrent analysis are much less applicable in the subsurface because of difficulties in obtaining data. No matter how closely spaced wells may be, data from 3 to 20 cm diameter holes cannot provide as much local information as an outcrop. However, because outcrops are in most cases two-dimensional and restricted in size, subsurface data from an extensively drilled unit may be superior for larger scale or regional studies. For example, the sizes and shapes of offshore bars are known entirely from subsurface studies (see "Shelf and Shallow Marine Sands", this volume). The variation in the most appropriate scale of investigation may be the most important difference between the two situations.

GEOLOGICAL USES OF WELL LOGS

Well logs are extensively used in the petroleum industry for the evaluation of fluids in rocks, but this aspect will not be covered here. The interested reader is referred to the numerous logging company manuals or other manuals such as Merkel (1979) or Asquith (1982). In most subsurface studies, geophysical logs are the fundamental source of data because virtually every oil and gas well is logged from near the top to the bottom. Coal and mineral exploration drill

Table 1
Log types, properties measured, and geologic uses

Log	Property Measured	Units	Geologic Uses
Spontaneous potential	Natural electric potential (compared to drilling mud)	Millivolts	Lithology (in some cases), correlation, curve shape analysis, identification of porous zones
Resistivity	Resistance to electric current flow	Ohm-metres	Identification of coals, bentonites, fluid evaluation
Gamma-ray	Natural radioactivity - related to K, Th, U	API units	Lithology (shaliness), correlation, curve shape analysis
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, coal, tightly cemented zones
Caliper	Size of hole	Centimetres	Evaluate hole conditions and reliability of other logs
Neutron	Concentrations of hydrogen (water and hydrocarbons) in pores	Per cent porosity	Identification of porous zones, crossplots with sonic, density logs for empirical separation of lithologies
Density	Bulk density (electron density) includes pore fluid in measurement	Kilograms per cubic metre (gm/cm^3)	Identification of some lithologies such as anhydrite, halite, non-porous carbonates
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (and direction)	Structural analysis, stratigraphic analysis

Table 2
Lithology as determined by well logs

Lithology	Primary Log(s) Used	Important Property	Notes
Limestone	Gamma-ray	Low radioactive K-content	Porous limestone best distinguished from sandstone in cores or cuttings
Dolomite	Gamma-ray Density	Low radioactivity Density of 2.87	Best distinguished from limestone in cores or cuttings
Sandstone	Gamma-ray (SP)	Low radioactive K-content	Arkosic sandstone may not be identified
Shale	Gamma-ray	High radioactivity	
Conglomerate	Gamma-ray	Low radioactivity	Best distinguished from sandstone in cores or cuttings
Anhydrite	Density	Density of 2.96	
Halite	Density	Density of 2.03	
Sylvite (and other K-bearing evaporites)	Gamma-ray	Very high radioactivity	
Coal	Gamma-ray and sonic or density	Low radioactivity, long sonic travel time, low density	Argillaceous material in coal may raise radioactivity
Bentonite	Resistivity	Low resistivity	Impure ones may have high radioactivity

holes may provide well log data on shallow rock units. Other relevant information about subsurface methods and procedures can be found in Rees (1972), Allen (1975), Jageler and Matuszak (1972) and Krumbein and Sloss (1963).

Types of Logs

Different types of logs, with the properties they measure and their geological uses are shown in Table 1 and discussed below.

1) Spontaneous Potential (SP) Log. This log measures the electric potential between an electrode pulled up the hole in contact with the rocks and a reference (zero) electrode on the surface. The log is measured in millivolts on a relative scale only (Fig. 1) because the absolute value of the potential depends not only

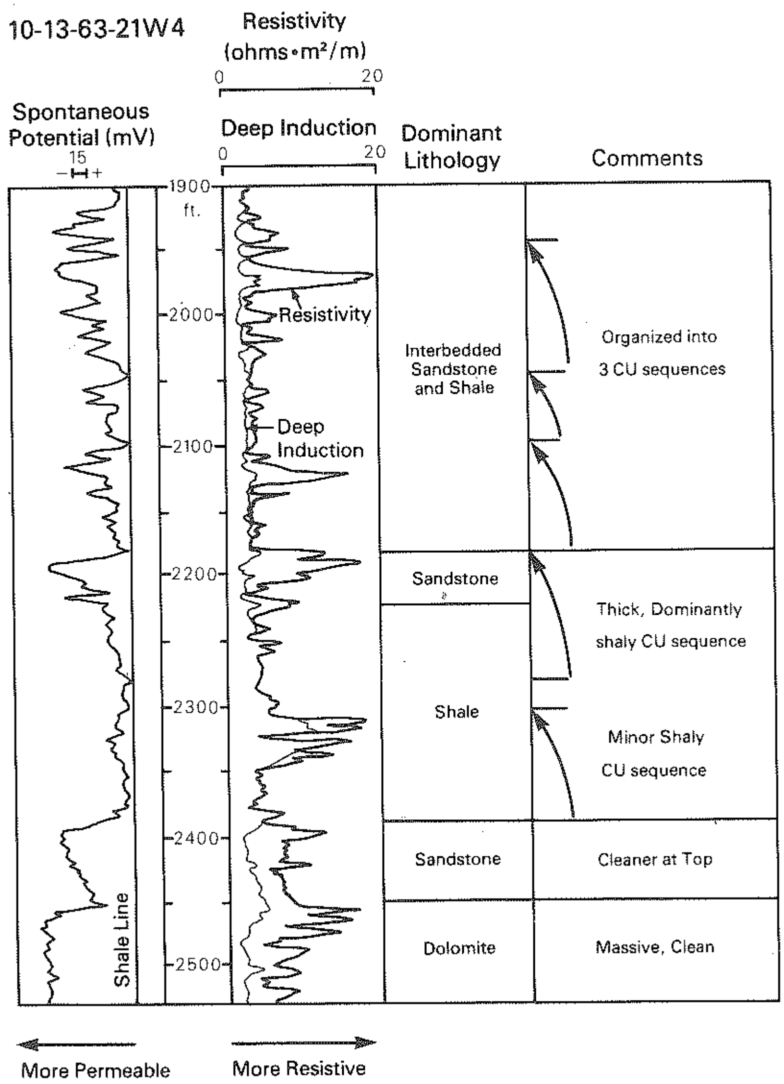


Figure 1 ▶
Example of SP and resistivity logs. A shale line, or line of zero deflection is shown on the SP log – any deviation from this reflects porous rock. Two resistivity curves are shown, one of medium depth, and one which reads deep into the formation beyond the influence of fluids from the drilling mud. The deep induction tool reads lower resistivity in porous zones, probably indicating salt water saturation. The coarsening-upward (C-U) sandstones and shales are Cretaceous Mannville Group rocks, lying unconformably on Devonian Winterburn dolomite (from core).

on the properties of the rock and interstitial fluid, but also on the properties of the drilling mud. In shaly sections, the SP response is relatively constant, and it can be used to define a "shale line" (Fig. 1). Zones of permeable rock containing interstitial fluid with a salinity contrast to the drilling mud are indicated by deflections from this line.

The SP log is run in most wells, and while it is not a good lithologic indicator in many areas, in others it provides the only available data which can be used. In areas of low-permeability rock such as the Deep Basin of Alberta, or the bitumen-saturated Athabasca Oil Sand it is useless for lithologic interpretation. In freshwater-bearing units such as many Upper Cretaceous formations in Alberta, SP deflection is suppressed where low salinity drilling mud is used. However, in other areas such as the Ventura basin in California, the sandstones are all permeable and saturated with salt water (or hydrocarbons), with the result that the SP log delineates them very well (Hsu, 1977). Experience in an area, and calibration against cores and cuttings are the best criteria for the reliability of the SP log as a lithologic indicator. In Figure 1, the coarsening-upward sequences are shown by progressively increasing deflection from the shale line of the SP curve, indicating more porosity/permeability upward.

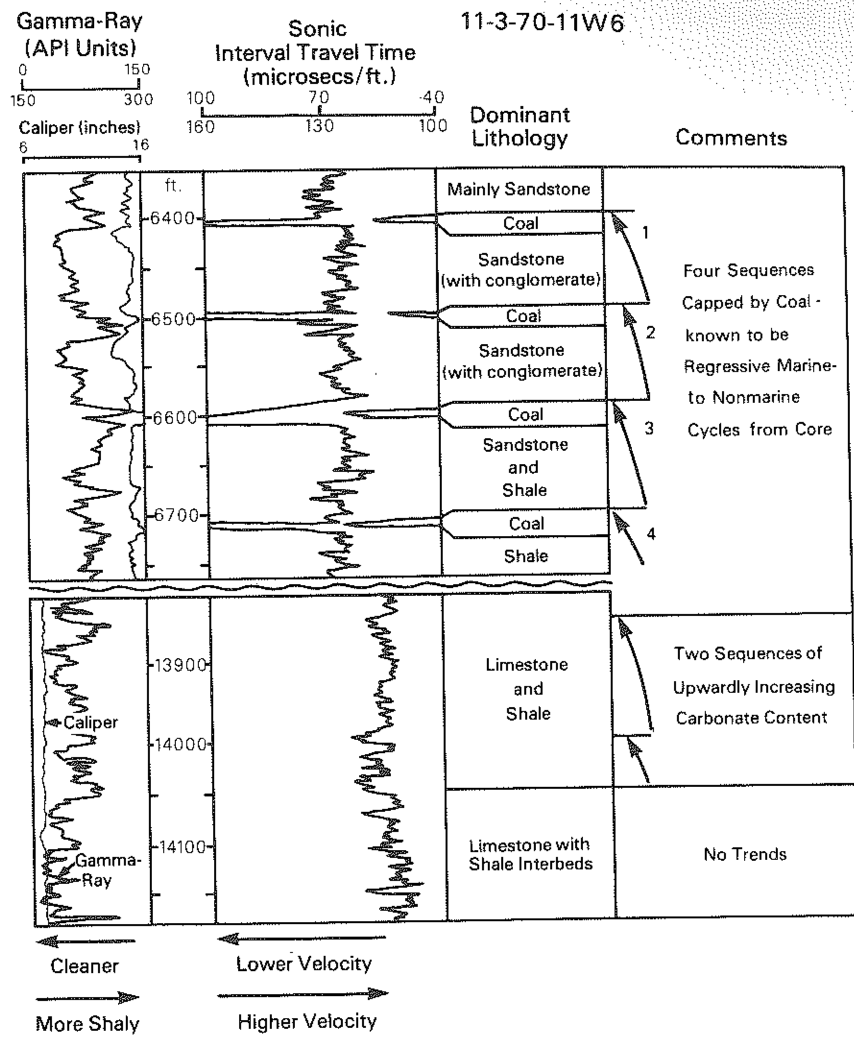


Figure 2

Example of gamma-ray and sonic logs. Siliciclastic (Lower Cretaceous Spirit River Formation) and carbonate-dominated (Devonian Ireton and Leduc Formations) sections are shown. Because of space limitations in the diagram, coaly shales (with higher gamma-ray readings) are also labelled as coals. In these carbonaceous rocks, the sonic log has gone off-scale to the left and re-appeared on the right. The arrows at the bottom of the logs show the directions of variation of the important rock properties. Sequences 1 and 2 coarsen upward while sequence 3 shows no real pattern because the well is very close to the limit of this transgression.

2) *Resistivity Logs.* These logs measure resistance of the interstitial fluid to flow of electric current. The current flow is created either directly by electrode contact, or indirectly by passing alternating currents through transmitting coils, thus inducing a magnetic field and secondary currents in the rock (induction log). By varying the length of the tool and focussing the current, resistivities can be measured at different distances from the hole. Several resistivity measurements are commonly shown on the same track (Fig. 1) with the scale in ohm-metres, increasing to the right. Resistivity logs are used mainly for evaluation of the fluid content of the rocks, but are also useful for identifying coals (high resistivity), thin limestones in shaly sequences (high resistivity), and bentonites (low resistivity) (Table 2). In areas where only SP and resistivity logs are available, resistivity logs are used for "picking" or identifying formations and correlation. Freshwater-saturated porous rocks (usually very shallow) have high resistivities. Resistivity logs are therefore useful in near-surface units for separating shales from porous sandstones or carbonates.

3) *Gamma-Ray Log.* This is probably the single most useful log for geological purposes (Fig. 2). It measures the natural gamma emissions of the rock, a property which is closely related to the content of potassium, thorium, and uranium. Because these elements (particularly potassium) are most common in clay minerals, the log reflects the "cleanness" or conversely the "shaliness" of the rock. This property is very useful because gamma-ray patterns in many cases mimic vertical grain-size trends of sedimentary sequences. This will be discussed in more detail later in the paper. Gamma-ray logs are calibrated in API units, with radioactivity increasing to the right (Fig. 2). It should be emphasized, however, that a gamma-ray reading is *not* a function of grain size; that is, a clean, well sorted, fine sandstone composed of quartz grains will give a similar gamma-ray reading to a coarse sandstone of the

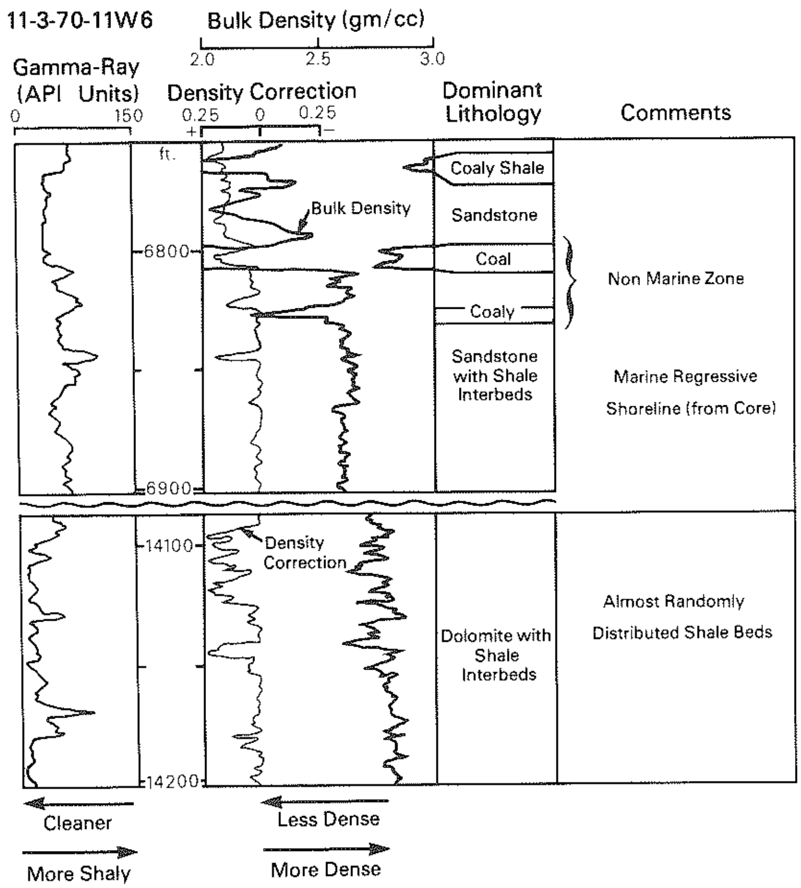


Figure 3
Example of density (along with gamma-ray) log from the Spirit River and Leduc Formations. The bulk density and density correction curves are shown. The density correction is calculated from the caliper log and is designed to compensate for mud cake build-up on the side of the hole. It has already been applied to the density value, and gives an indication of its reliability. Where density corrections are greater than .1gm/cm³, the density values are suspect. Because of the very low density of coaly material, the density log has gone off-scale to the left and reappeared on the right. Direction of rock property changes are shown at the bottom of the log.

same mineralogy. Clean lime mudstone also gives the same low gamma-ray response as a much coarser grained limestone.

The log can be affected by diagenetic clay minerals precipitated in the pores of rocks. Different clay types affect the log by different amounts because of their composition. Shales rich in illite (higher K) are more radioactive, on average, than those rich in montmorillonite or chlorite (low K).

4) Sonic Log. This is run with the gamma-ray log and measures the travel time of compressional sound waves through the formation (Fig. 2). The velocity of the sound depends on: 1) the lithology of the rock, 2) the amount of interconnected pore space, and 3) the type of fluid in the pores. This log is useful for delineating beds of low-velocity material such as coal or very porous rock, or high velocity material such as tightly cemented carbonate or sandstone, or igneous basement. The interval travel time is measured in time per unit length (microsecond/m) with longer travel times to the left (Fig. 2).

5) Density Log. This log is again run with a gamma-ray log (Fig. 3). The density tool emits gamma radiation which is scattered back to a detector in amounts proportional to the electron density of the formation. Electron density is directly related to density of the rock (except in evaporites) and the amount and density of pore-filling fluids. The log is plotted in gm/cm³ or kg/m³ with higher densities to the right (Fig. 3). Because the major classes of sedimentary rocks have somewhat different densities, this log is useful where porosities are known for lithologic identification.

6) Neutron Log. This log is used primarily to estimate porosities (Fig. 4) because it measures the concentration of hydrogen (in water or hydrocarbons) in the rock. The tool emits neutrons of a known energy level which collide with atomic nuclei in the formation, and the detector measures the energies of returning neutrons. Because energy is transferred most readily to particles of similar mass, energy loss is a function of hydrogen ion concentration. The log is useful in many cases in conjunction with other logs for empirical calibration of rock type against log response. Neutron porosity is commonly shown in the same track as a porosity calculated from the density log by assuming a density of the rock material (2650 kg/m³ for sandstone, 2710 kg/m³ for limestone) and fluid (1000 kg/m³ for water) (Fig. 4). Higher porosities are on the left.

7) Caliper Log. This log records the diameter of the well bore measured with a caliper device. It gives an indication of the conditions of the borehole. A very large hole indicates that a great deal of caving or falling in of the rock has occured. While most logging tools are designed to compensate for the size of the hole, anomalous or unreliable readings can occur where a very much enlarged hole has developed. A hole size smaller than the drill bit results because the fluid fraction of the drilling mud invades very permeable zones leaving the solid fraction (mud or filter cake) plastered to the inside of the well bore. The caliper log is usually plotted on the same track as the gamma-ray log (Fig. 2), with hole size increasing from left to right.

8) Dipmeter Log. This log is made by a resistivity tool with 3 or 4 electrodes, each capable of detecting changes in lithology, mounted on separate arms with a common centre point (Fig. 5). The orientation of the tool in the hole is also continuously recorded. Where a dipping bed is encountered, the response to the lithologic change occurs at slightly different elevations for each electrode. Because the orientations of the electrodes are known, correlation of the resistivity records yields the magnitude and direction of dip.

The tool can measure structural dip or fractures in the rock, but can also detect various types of sedimentary dips such as compaction drape over a reef, a mud drape on a point bar surface, and even some cross-stratification. In many cases it is difficult to determine the nature of a dipping surface unless a core has been taken of the interval. Dipmeter results are shown in "tadpole plots" which indicate the magnitude (0 to 90 degrees) laterally, and the direction of dip by the small tail (Fig. 5).

INTERPRETATION OF LITHOLOGY FROM LOGS

Interpretation of lithologies in the subsurface from logs, without any other data, is very difficult. In sections where lithologies are known in general, lithologic interpretation can be made with much more confidence, based on the properties measured by each log. It should be emphasized however, that the interpretation procedure is somewhat subjective because of 1) unusual minerals in the rock, 2) anomalously high or low porosity, 3) thinly interbedded lithologies, 4) poor hole condition, and 5) poor log quality. A few specific problems will be discussed.

1) Sandstone vs. Carbonate. Many sedimentary units contain either one or the other, so discrimination is not a problem in thsese cases. However, where they are mixed, distinguishing them solely on the basis of logs can be difficult. Because carbonates have higher densities, the density log can be successful; however, it should be noted that this log records bulk density so it will read values less than pure carbonate where porosity is present. The density log should be checked against other data.

2) Sandstone vs. Shale. The gamma-ray discriminates clearly in most cases. The log can be calibrated by establishing minimum and maximum readings corresponding to sandstone and shale end members (Fig. 6), and scaled between. Where a thick section is being considered, several estimates of the position of the maximum "shale" end member should be obtained over the entire depth range under study. As shales compact, the amount of radioactive material per unit volume increases, so the shale line will drift to the right on the gamma-ray log with increasing depth. The tool response is non-linear (Fig. 7). A cutoff can be established by drawing a line at some appropriate value (Fig. 6). This calibration works well for thick beds, but log response in thin beds (less than 2 m) is affected by surrounding lithologies and registers an intermediate value. It is extremely difficult to distinguish thinly interbedded sandstone and shale from shaly sand-

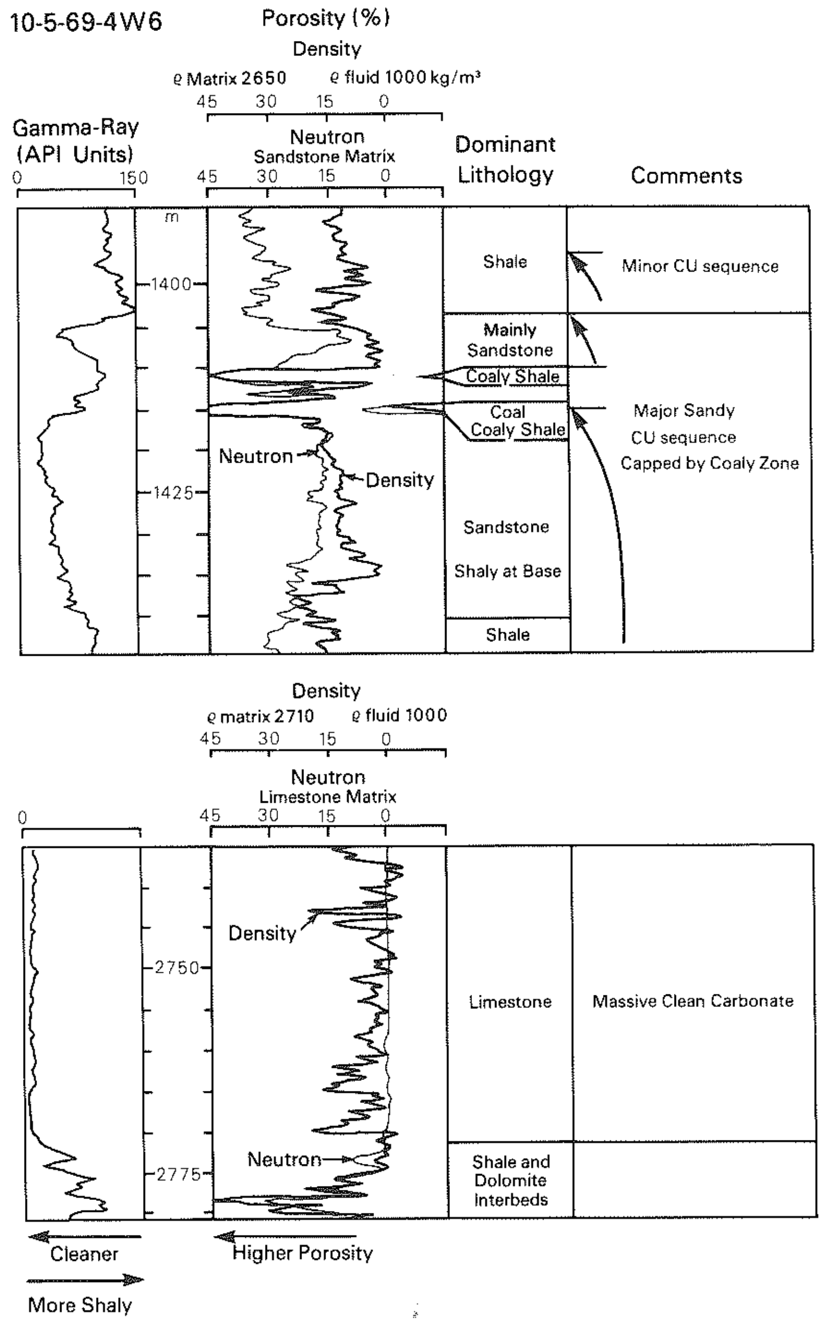


Figure 4
Example of neutron-porosity and density-porosity logs. In shales, the neutron-porosity log reads anomalously high because of water bound into the clay minerals. In the limestone (Mississippian Pekisko Formation), the density log records higher porosity because of light natural gas in the pores, and the neutron log records low porosity because of low concentrations of hydrogen in the gas (compared to water or oil). Porosities in coals (Spirit River Formation) are anomalously high because of its low density compared to the reference matrix material. Readings in the coaly material go off-scale to the left and reappear on the right.

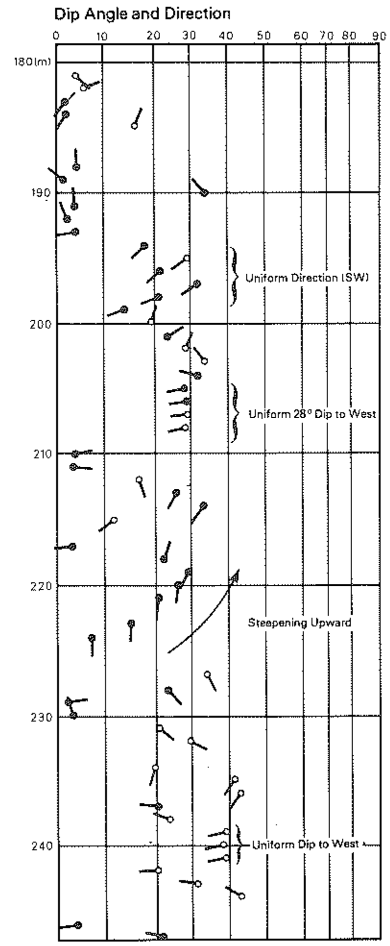


Figure 5
Example of a dipmeter log from the Paleocene Paskapoo Formation of Alberta indicating direction and magnitude of dip. Vertical tails mean northward dip. Zones with clear dip patterns are indicated. On some dipmeter logs, regional dip can be identified by (a) a consistent minimum dip, (b) a consistently recurring dip separated by zones with other dips.

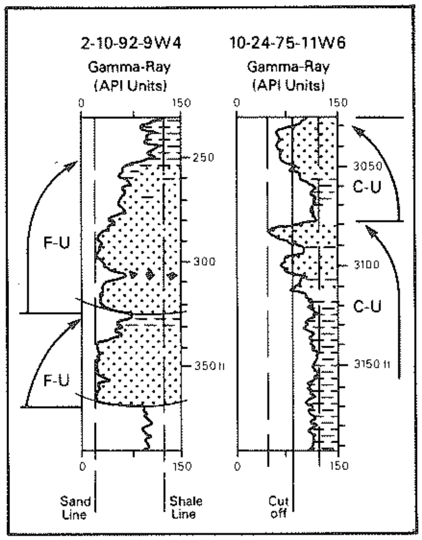


Figure 6
Examples of fining-upward (F-U) and coarsening-upward (C-U) sequences (actually upwardly increasing shaliness and upwardly decreasing shaliness). A clean sand line and shale line is drawn on each. Note the difference in spacing of these on the two logs. On the 10-24 log, a cutoff halfway between the sand and shale lines is drawn. The 2-10 well shows meandering stream sand bodies (with intraclast zone) of the Lower Cretaceous Athabasca Oil Sands. The 10-24 well shows shallow marine sequences from the Spirit River Formation of Alberta.

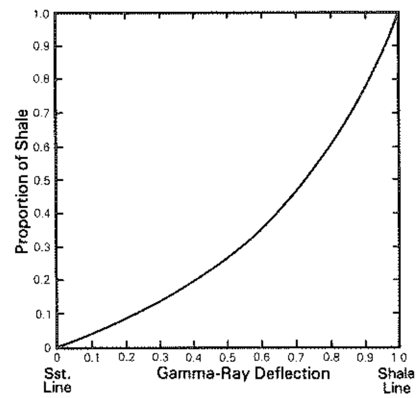


Figure 7
The relationship between gamma-ray reading and the proportion of shale. A reading half-way between maximum and minimum log values corresponds to about 28 per cent shale. Modified from Schlumberger basic manual.

stone or siltstone. The gamma-ray log run with the density log may provide slightly better resolution of thin beds because it is run at a slower logging speed. Another problem is that the gamma-ray log does not satisfactorily separate sandstone and shale where the sandstone contains much K-bearing feldspar or granite fragments. If this is known from cores or cuttings, the SP log can be used in some cases to discriminate between sandstone and shale. This has proved successful in evaluating lithologies in the so-called "Granite Wash", a wedge of porous Devonian arkoses and conglomerates shed from the Peace River Arch in northwestern Alberta. In this case, checking against cores showed that SP logs are more reliable for lithologic interpretation than gamma-ray logs.

3) Sandstone vs. Conglomerate. No general method is available to discriminate between these two rock types, especially for conglomerates with a sandy matrix. In local areas, by calibration from cores or cuttings, some differences in log response can be found. For example, in some cases conglomerates show a "cleaner" gamma-ray log signature. An empirical solution can be applied to the same unit in the local area where it was developed.

4) Dolomite vs. Limestone. The greater density of dolomite (2.85 vs. 2.71) in some cases allows a distinction to be made by the density log. However, porous dolomites have a lower bulk density than the rock material itself, making distinction difficult. The best solution is calibration of logs against cores and cuttings.

One general problem of interpretation of lithologies occurs where two or more rock types are interbedded on a small scale. Where the beds are less than about 2 m in thickness, log measurements are influenced by each of the rock types, and an intermediate response results. In this case, logs cannot be used effectively, and cores are necessary to identify lithology.

In many cases, empirical calibration of logs against cores or cuttings depends not on any intrinsic property of the rock, but on the observation that in some areas each rock type present has a range of porosity and permeability values which do not overlap with others. This causes different responses on logs which then can be interpreted by means of the empirical calibration. This approach is commonly very effective, but constant re-calibration should be done to check the results.

Recently, the concept of electrofacies has been introduced. An electrofacies is defined as the set of log responses which characterizes a sediment and permits it to be distinguished from others (Serra and Abbott, 1982). Sets of log responses can be separated into discrete classes by n-dimensional cluster analysis (n depends on the number of logs used). Each class is termed an electrofacies. Where facies defined by direct examination have lithologic differences (i.e., shaly facies vs. carbonate facies) electrofacies may correlate well with observed facies assuming observed facies do not vary in porosity, mineralogy, or fluids. Facies can also be defined on criteria which do not reflect changes in mineralogy, porosity, or fluid content (i.e., trough crossbedded sandstone vs. planar crossbedded sandstone). In this case, log responses for the two facies may be identical, and electrofacies cannot be correlated directly to observed facies. The concept of electrofacies, therefore, is not directly analogous to the concept of facies. However, this kind of quantitative approach to subsurface sedimentology will become of great value in the future when it is developed more fully.

In conclusion, it must be emphasized that lithologic interpretation from logs depends on understanding the properties measured by the logs. In some cases, a unique solution cannot be found, and empirical calibration can be used effectively.

CORE DESCRIPTION

In general, core description is much like measuring an outcrop section, and all the usual methods and procedures should be followed. This section will deal with some problems specific to core studies.

The most obvious limitation of cores is their width. Not only are large features such as channels or bioherms undetectable in them, but also much smaller sedimentary structures such as hummocky cross-stratification are difficult to recognize. In some cases, trough and planar crossbeds (Fig. 8) cannot be distinguished, especially in unslabbed core. Another general problem with core is less than perfect recovery. Because of stresses on the rock during drilling and later handling, soft or very brittle lithologies may be poorly represented, or even totally absent from the core. Lines of weakness such as contacts commonly are broken for the same reason. Bedding surfaces are rarely exposed, with the result that sole markings are difficult to detect in core.

To minimize the possibilities of error, before a core is logged, the order of the boxes should be checked. Oil industry cores and boxes are numbered from the top downwards, and notations are usually recorded on the tops of core segments. Cores should be described with the geophysical logs present to check for completeness of core recovery, thicknesses, core-log correlations, and log response.

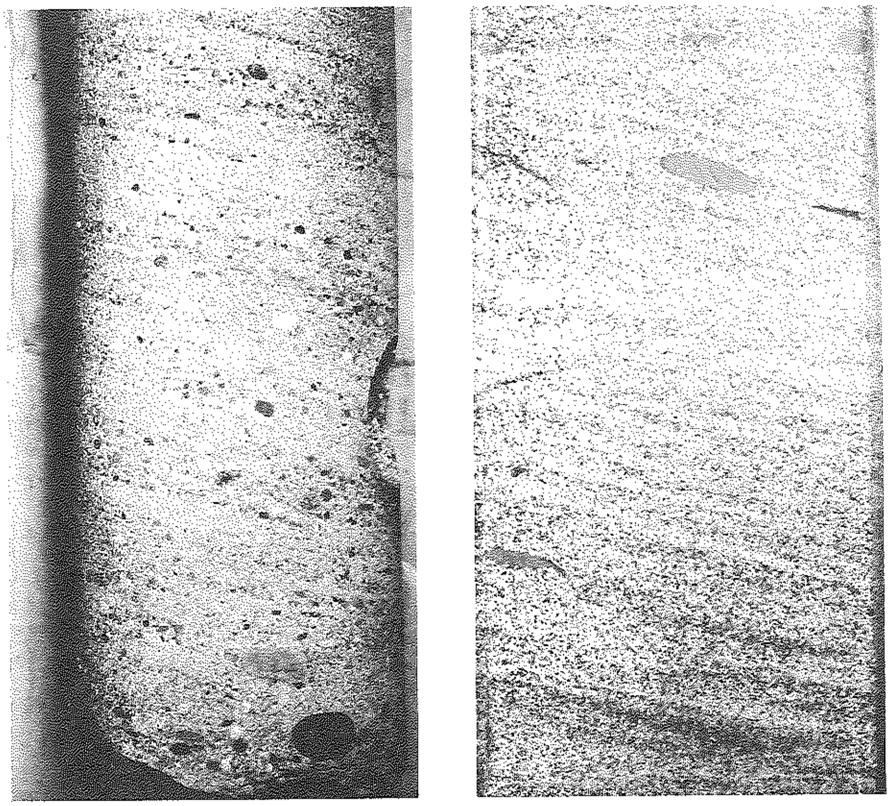


Figure 8
Two photographs of core segments showing slabbed and unslabbed core. The flat face on the slabbed core makes most observations easier, but the cut may not be in the most advantageous plane. Some unslabbed core (unlike this example) is scratched and shows sedimentary features very poorly. The hole in the side of the unslabbed core was drilled to obtain a sample for porosity and permeability measurements. Both cores are 9 cm in diameter, and are from fluvial deposits of the Spirit River Formation.

Cores are very unevenly distributed. Many rock units without economic interest are essentially uncored. Other units, particularly those forming hydrocarbon reservoirs have many thousand of metres of core distributed over wide areas, allowing for better three-dimensional control than virtually any outcrop. In Canada, Devonian stromatoporoid-dominated reefs, clastic shoreline and clastic shallow marine deposits are particularly well represented in cores.

RELATING CORES AND CUTTINGS TO LOGS

In many cases, recorded core depths do not correspond precisely to depths on the well logs. Where a core-gamma log (made by passing a detector down the core) is available, this can be compared to the gamma-ray log of the well to establish a correlation. When this kind of record cannot be obtained, a sedimentological log of the core relating grain size or "cleanness" of the rock can be used. This can be inspected and compared to patterns in any of the logs, but particularly the gamma-ray log from the well. In many cases, distinctive patterns, commonly fining- or coarsening-upward are present (Fig. 6) which allow the cored interval to be located precisely on the log. Distinctive lithologic units such as coals, bentonites, or any isolated bed different from other lithologies in the core can also provide a good correlation point to the log. When a core analysis (porosity and permeability measurements) is available, it can also be used to check core depths.

After a core-log correlation has been established, lithologic data from the core can be used to check or recalibrate the lithologic interpretations made from the logs. For example, sandstone-shale cutoffs (Fig. 6) can be adjusted to match the core data more closely.

Well cuttings are fragments of rock from 1 to 5 mm diameter ground out by the drill. Two main difficulties are associated with their study: (1) the time lag required for the cuttings to reach the surface, and (2) caving of rock from higher in the hole. The first problem can be overcome by carefully logging the proportions of lithologies present, working down the hole. The first occurrence of a new lithology, or increase in proportion of a lithology can be correlated to the logs. The problem of caving is alleviated because the cavings are larger and more angular in many cases. In some wells a steel liner termed casing is cemented to the wall of the hole when a certain depth is reached. Where casing was set (noted on logs) caving from higher up was prevented. By careful work, cuttings can provide valuable data on lithologies where no cores are present. However, cuttings should be used with caution because of the possibilities of error in the original collection of the sample.

CORRELATION OF LOGS

To conduct regional facies analysis, to map, and make cross-sections, logs must be correlated. Three major methods applicable to well logs will be discussed: correlation by (1) marker beds, (2) sequence analysis, and (3) slice techniques. Biostratigraphic and mineralogic correlation methods will not be discussed.

1) Marker Beds. Any bed or series of beds with a distinctive response on any log, and which can be recognized over the area of interest, can be used as a marker for correlation (basal marker in Fig. 9; see also K, L markers, Fig. 17, "Shelf and Shallow Marine Sands", this volume).

In cases where the section is simple and laterally unvarying, the major units themselves may be distinctive enough to use as markers. For example, a laterally extensive carbonate unit within a dominantly shaly section could be employed. In other cases, unusual lithologies must be sought. Bentonites, where present, are commonly used (top of Fig. 9). Other examples are shales rich in organic debris, such as the Fish Scales Horizon of the Alberta plains. This unit is present over thousands of square kilometres, and is recognizable by its characteristic very high gamma ray reading, slightly high resistivity response, and high density-porosity

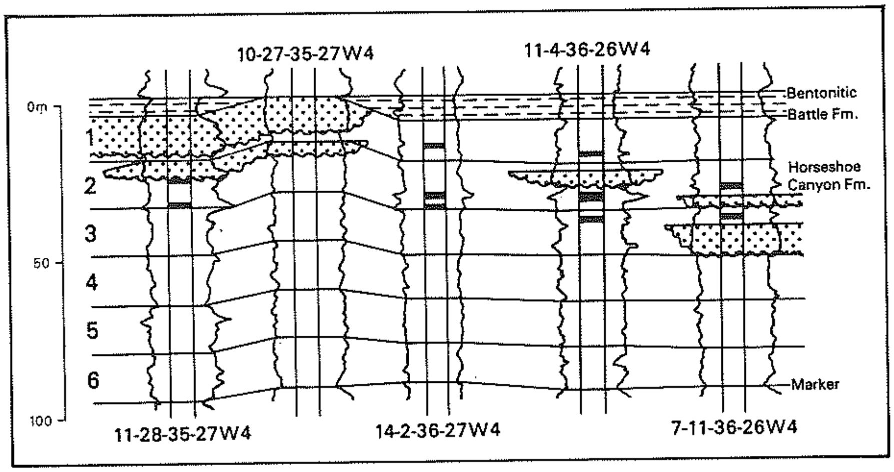


Figure 9
A cross-section (gamma-ray logs on left, resistivity logs on right) from the Upper Cretaceous Horseshoe Canyon Formation in central Alberta. The section between the bentonitic Battle Formation and the basal marker was subdivided into 6 equal slices. The slices were chosen to include but not subdivide the major channels (stippled) in this non-marine section, from Nurkowski and Rahmani (in press).

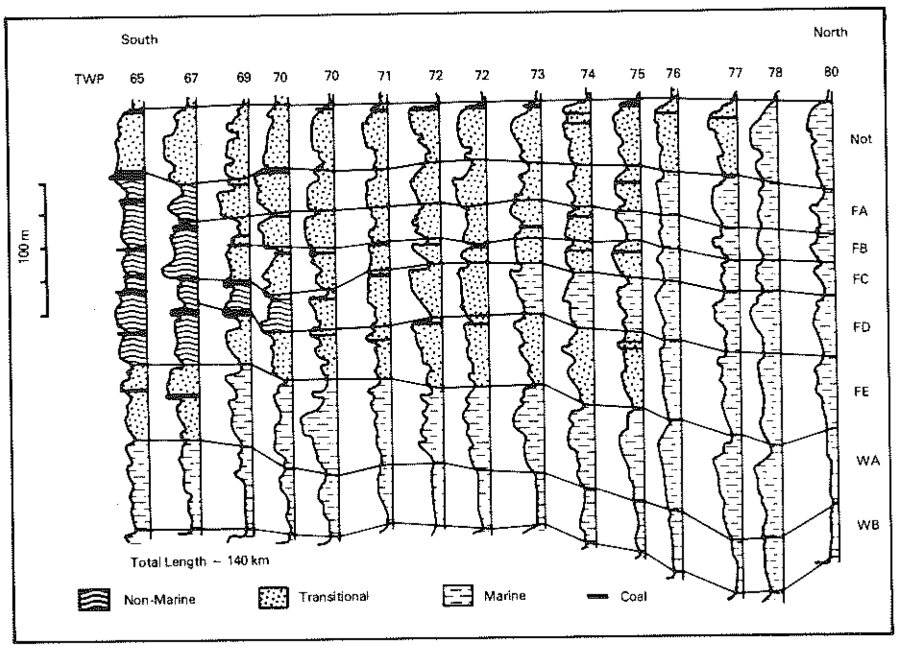


Figure 10
A north-south gamma-ray cross-section from the Lower Cretaceous Spirit River Formation near the Alberta-British Columbia border. Sequence analysis has allowed correlation of 8 genetic units in marine and transitional areas. Each sequence boundary represents a transgression which occurred over a short time interval compared to the regressive deposition of the sediment. The sequence boundaries, therefore, are taken to approximate time lines. The interpretation of depositional environments was made from cores, log curve shape analysis, palynology, and comparison to outcrop. From Cant (1983).

and neutron-porosity values. Other possible markers are tightly cemented zones, with high sonic velocities and density values, or shale beds with anomalously high radioactivity.

Many markers have the further advantage of approximating time lines. The Fish Scales Horizon has been dated paleontologically as occurring very close to the Upper-Lower Cretaceous boundary, and is taken to approximate this wherever it is found. Bentonite beds originate as ash falls, so are essentially isochronous.

Marker beds are most useful in sediment laid down in relatively low-energy environments such as lacustrine or some marine settings. In high energy fluvial and nearshore sediments, distinctive sediment types are likely to be dispersed by depositional processes.

2) Sequence Analysis. Sequence analysis involves the recognition and matching of distinctive log patterns such as the fining-upward or coarsening-upward sequences shown in Figure 6. In many cases, these sequences are prominent on logs and can be traced over wide areas. Sequences defined in this fashion may cut across lithologic and facies boundaries as shown in Figure 10. In this case several of the sequences (FA to WA) pass laterally from shoreline deposits capped by coal (south end) into marine coarsening-upward deposits (north end).

The major strength of this method of correlation is that well-chosen sequences are natural sedimentary units. Data collected from within a unit may be very meaningful because any patterns observed can be fitted into the overall depositional framework established by the sequence. Correlation of sequences is an example of "event" correlation. It has been suggested that time-significant correlations can be established by this method, and this has been partly verified paleontologically. Whether or not the correlations established by sequence analysis are precisely time-markers is difficult to judge, but these correlations appear to be closer to true time-lines than those defined by any other method.

The weakness of sequence analysis is that it cannot be applied in many sections. In non-marine sediments, the method commonly breaks down because of channelling and laterally-restricted sediment bodies.

3) Slice Techniques. Where no other method can be applied, an interval can be subdivided by establishing arbitrary slices, either of constant thicknesses, or of thicknesses proportional to the thickness of the entire interval. This method is not precise in that slices may cut through natural units, but it may be the only possible means to subdivide an interval. Slices should be chosen with some knowledge of the geology. For example, if most sand bodies are 30 m thick or more, to choose slices less than 30 m thick would complicate the results unnecessarily. Another way of establishing slices is to arbitrarily extend naturally-occurring sequences or marker bed correlations laterally into zones lacking them.

Slice techniques are most useful in non-marine sediments where other techniques do not work well because of channelling and differential compaction. In the Upper Cretaceous Horseshoe Canyon Formation, the distribution of sandstones and coals has been documented by Nurkowski and Rahmani (in press) by slicing an interval between a bentonitic marker and a persistent shaly marker (Fig. 9). In the Athabasca Oil sand deposit, Flach (in prep.) has also used a slice technique to subdivide the McMurray Formation. By noting the stratigraphic position below a marker horizon and thickness of each lithology, the data is in a form of maximum utility when computerized. The thicknesses of slices can be varied easily, and lithologic maps produced rapidly until patterns emerge.

A good example of subdivision of an interval using both marker beds and slice techniques has been published by Wermund and Jenkins (1970). They used marker-bed correlation for major subdivision of a thick pile of deltaic sediments, but subdivided between markers by creating slices of equal thickness. This allowed them to map lithologies in each slice to determine the effects of earlier deposits on the facies patterns developed in later slices.

SUBSURFACE FACIES ANALYSIS

Subsurface facies analysis depends heavily on the availability of cores. Without sufficient core material, interpretations must be generalized and imprecise. However, subsurface facies analysis is more than simply core examination. The interpretation made from cores can be extended farther than core coverage allows by use of log interpretation, and can be put into a larger context by cross-sections and maps prepared from log data.

Log Curve Shapes

A great deal has been written about the interpretation of log (gamma ray and SP) curve shapes in terms of depositional environment (e.g., Pirson, 1970; Selley, 1978). Much of the published literature is extremely simplistic, using a naive "pigeon-hole" approach to depositional environments; for example labelling every "bell-shaped" gamma-ray or SP curve as a meandering stream deposit (the left half of a "bell" can be seen in Figs. 6 and 11). The most typical patterns seen on these logs are shown in Figure 11 with some depositional settings indicated in which each curve could be generated. No pattern is unique to a particular depositional environment, so interpretation on the basis of curve shapes alone in the absence of other data is extremely dangerous. Calibration of log curve shape to depositional environments determined from cores can be very successful. Curve shapes on logs from wells with no core can then be interpreted. This is a very useful method of analysis which is widely used in many subsurface studies. The method is very powerful where an appropriate facies model is used. Laterally varying log patterns can be interpreted in terms of the lateral variation of different types of deposits in the facies model. It is a matter of judgement as to how far this calibration can be applied, both stratigraphically and geographically.

The log curve shapes of Figure 11 can clearly be thought of as *norms* (see "General Introduction", this volume) against which other log signatures can be compared. A log curve shape, by itself, however, has no predictive capability until it is linked by a genetic interpretation to a facies model. When the correct facies model is combined, the log curve shape becomes a powerful tool which can be used to *predict* the distribution of facies laterally (see Fig. 10). It also becomes a *guide for observations* both for cores and for well logs. For example, a bell-shaped log pattern implies a core in the same interval may show sedimentary structures typical of fluvial, tidal, or deep sea channels (Fig. 11). A few critical observations can discriminate among these possibilities. In the Spirit River Formation (case history discussed below), a funnel-shaped log pattern acted as a *guide for observation* of the log. Determinations of the presence or absence of coal at the top of the sequence is a critical observation for mapping shoreline regression and environmental interpretation. Log curve shapes, combined with knowledge of the general environmental setting, can be used cautiously as a *basis for interpretation*. For example, if we know a rock unit is in general a delta deposit, a cylindrical gamma-ray pattern might be reasonably interpreted as a fluvial or distributary channel, an irregular pattern lateral to that, an overbank or interdistributary floodplain or marsh, and a funnel shaped pattern basinward of these as delta-front deposits.

Problems In Interpretation

Funnel-shaped patterns (Fig. 11) can result from progradation of a crevasse splay into an interdistributary bay in a delta complex (see "Deltas", this volume) or from progradation of a submarine fan lobe (see "Turbidites and Associated Coarse Clastic Deposits", this volume). However a crevasse-splay sequence would be a maximum of a few tens of metres thick while the submarine fan lobe sequence could be many hundreds of metres thick. The scale of the sequence is therefore an important criterion in interpretation. General information on the scales of sequences in each environment can be found in the appropriate papers in this volume.

The mechanism of formation of the log pattern is also an important factor to be considered. Log patterns can be the result of three different processes. First, some log patterns represent a single depositional sequence; for example, a bell-shaped pattern resulting from lateral migration of a fluvial point bar, or a funnel-shaped pattern from a single shale-to-carbonate shoaling-upward cycle. Second, other log patterns result from amalgamation of several depositional units; for example, a cylindrical pattern formed by the stacking of many braided river channel sequences, or an irregular pattern of a coarse-grained submarine canyon fill where many individual channel-terrace units are superimposed. Third, some log patterns result from deposition in environments where individual sequences are not formed; for example, a cylindrical pattern from crossbedded aeolian sands or an irregular pattern from a deep-water carbonate slope and apron.

In the first two cases (single depositional sequences and amalgamated sequences), log patterns are very sensitive to the mechanism of stacking of sequences. For example, because of later channelling, fluvial point bar sands may be superimposed, forming a compound sequence which does not represent one depositional unit. Braided river channel fills may be separated by lacustrine muds. In either case, the resulting curve shape may differ from the idealized example in Figure 11.

Other Difficulties In Interpretation

Two other major problems exist with interpretation of log curve shapes. Amalgamation of units from different depositional environments and deviations from the idealized facies model may cause difficulties. Figure 12 shows a log cross-section in the Lower Cretaceous Mannville Group of Alberta. The thick sharp-based sandstone in well 10D-29 has an almost cylindrical log pattern; the entire thickness of sand was interpreted as a deep fluvial channel deposit by Putnam (1982). Core examination suggested that the sandstone is made up of three amalgamated bodies (stippled in Fig. 12), of which at least the lower one is marine (Wightman *et al.*, in prep.). The cross-section clearly shows that amalgamation of thinner units has created the thick

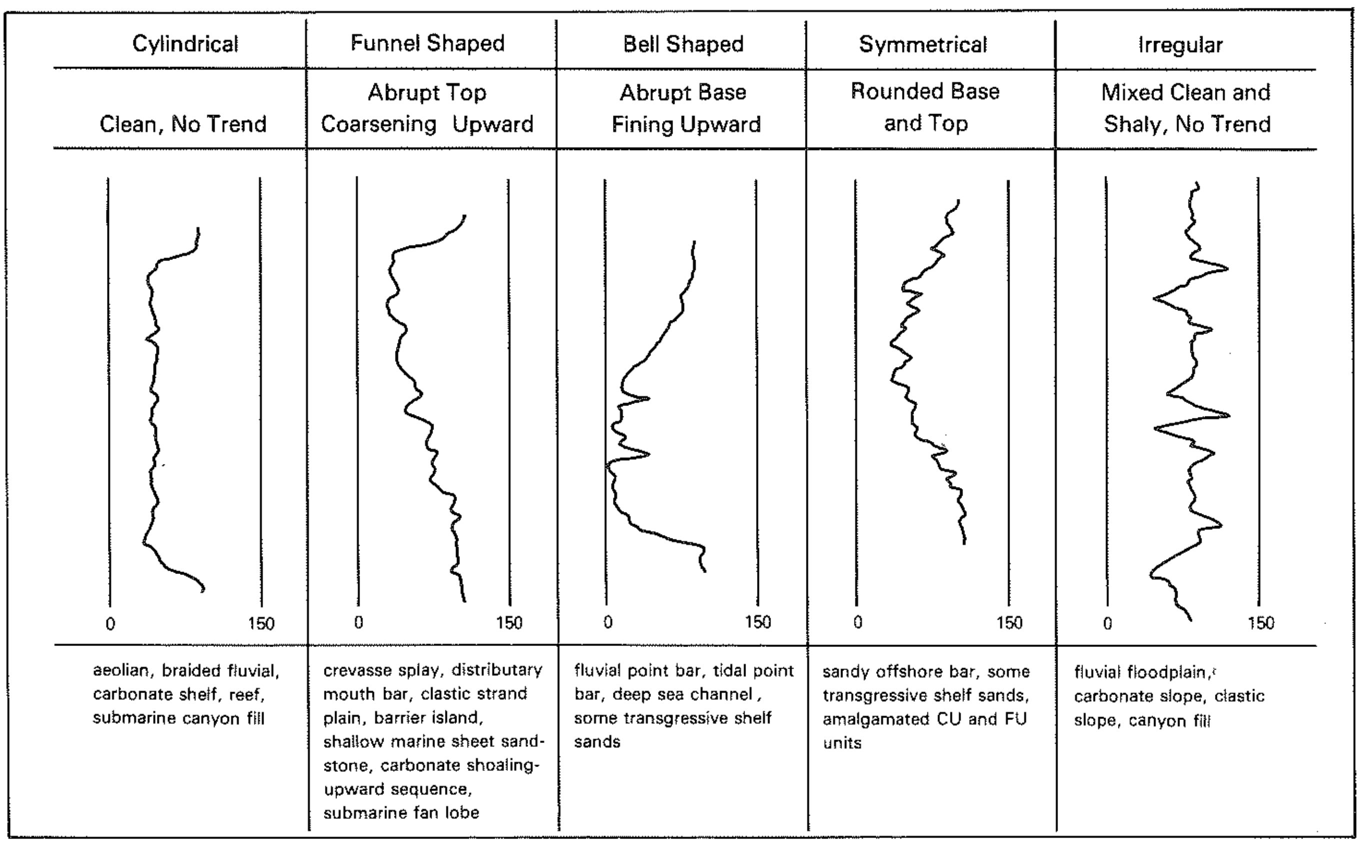
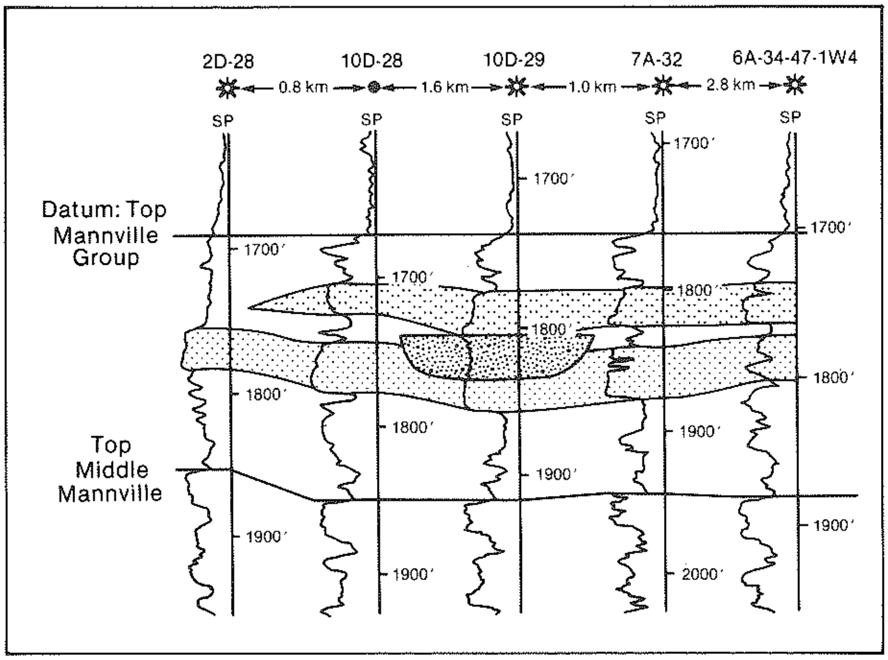


Figure 11

The most common idealized gamma-ray (SP) log curve shapes and at least some of the depositional settings in which they can originate. Several environments are listed under more than one curve, indicating they are somewhat variable. The limitations of this approach are discussed in the text.



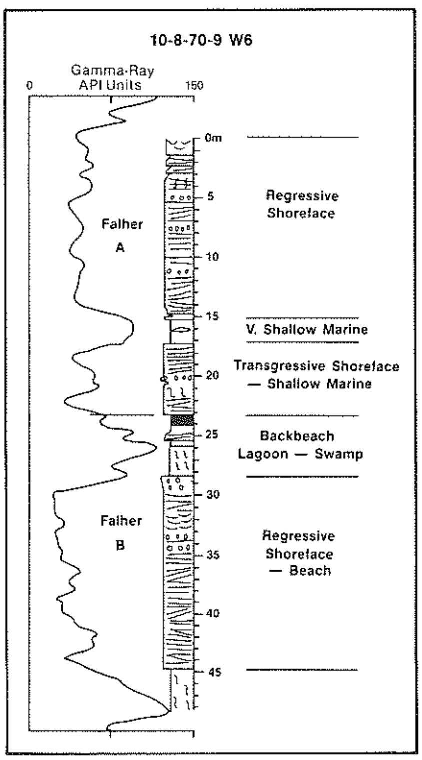


Figure 12

An SP-log cross-section in the Lower Cretaceous Mannville Group of Alberta. In the central well, the sandstone with the sharp base and almost cylindrical log pattern has been interpreted as a fluvial channel. Core logging suggested that the sandstone is actually made up of 3 amalgamated bodies (stippled) as shown on this cross-section. The shaly interval between the sands has been removed by a channel in the central well. From Wightman et al. *(in prep.).*

Figure 13

Gamma-ray log and core from the Spirit River Formation. The two thicker sandstones are both regressive shoreline deposits, but neither shows the funnel-shaped pattern of Figure 11. This is caused by deviations from the standard facies model - see "Barrier and Shoreline Sands" (this volume). The thinner sandstone in the FA sequence is transgressive in origin. In other wells nearby, the transgressive and upper regressive sandstones are amalgamated, further complicating interpretation.

sandstone which could not be correctly interpreted from logs alone.

Figure 13 shows a sandstone (FB) with an irregular to cylindrical gamma-ray log profile. From core logging, palynology, and the regional setting, this is known to be a littoral sandstone. The upper sequence of sedimentation (above the coal) consists of a basal transgressive sandstone and another regressive shoreline sandstone. The log patterns are irregular to roughly cylindrical in each case. Neither of the shoreline sand bodies has a log pattern which fits the idealized funnel-shaped pattern for a clastic shoreline deposit (Fig. 11). Deviations from the idealized facies model and the idealized log pattern make these sandstones difficult if not impossible to interpret without cores. This example is from the Spirit River Formation, a case history discussed later in the paper when the reasons for the deviations from the standard facies models will be considered.

Other Methods

This section will mention briefly other specialized methods of facies interpretation commonly used in the subsurface. Palynology and micropaleontology can be applied to cuttings. Mineralogic or lithologic criteria such as the presence of glauconite or coal also have this advantage. Ichnology is a very useful tool in many clastic units where microfossils and body fossils are lacking, but requires core (see "Trace Fossil Facies Models", this volume).

Dipmeter logs are not very common, but can provide useful data where available. They may show dips increasing or decreasing upward, patterns which can aid interpretation if other data are available. In the McMurray Formation of Alberta, epsilon crossbeds (see "Sandy Fluvial Systems", this volume) can be detected by dipmeters, and their directions mapped.

In general, it must be emphasized that all available lines of data should be integrated to form a complete interpretation. While core logging is undoubtedly the most powerful method of analysis, integration into a larger scale picture is necessary. This can be accomplished by use of correlation techniques discussed previously to enable construction of cross-sections and maps. No single technique is adequate to uniquely define and interpret sedimentary facies in the subsurface.

CASE HISTORY — THE SPIRIT RIVER FORMATION

This Lower Cretaceous (Albian) unit is part of a major clastic wedge within the foreland basin of the Cordillera. The earlier non-marine deposits of the Cadomin and Gething were inundated by the Boreal transgression from the Arctic (Fig. 14). In this seaway, northward progradation of shoreline and shallow marine deposits and southward transgressions during periods of low sediment input created the sequences of the Spirit River Formation. In the study area in west-central Alberta (Fig. 14), the unit was the subject of detailed facies analysis (Cant, 1983, 1984). Well control is adequate throughout the study area (Fig. 15), but cores are restricted to some stratigraphic levels within the formation and to the centre of the study area. Lithologic determination was made by core examination, then calibrating cores to gamma-sonic logs.

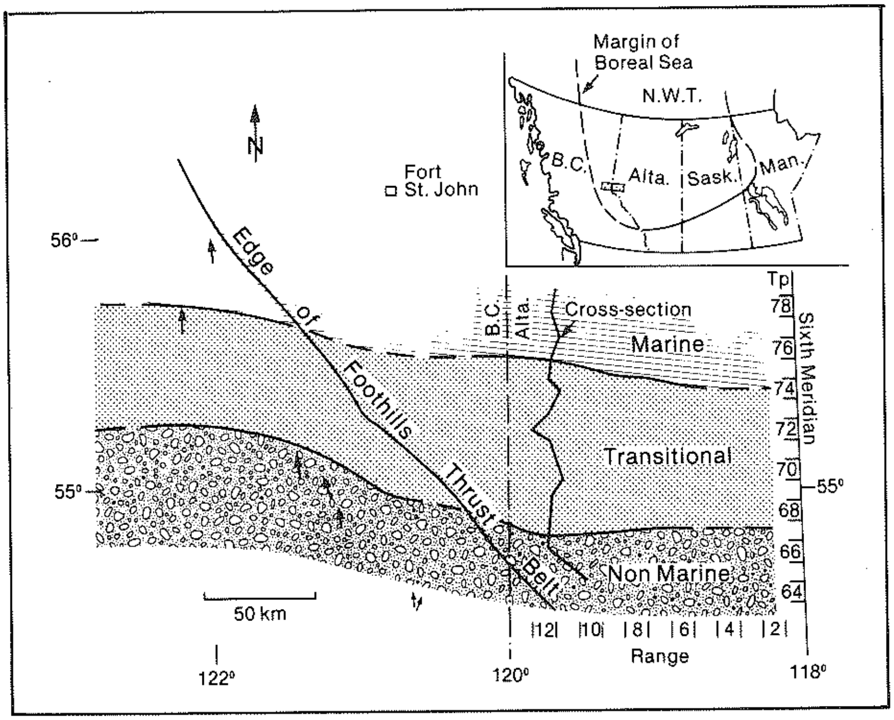


Figure 14
Location map of the study area in Alberta showing the foothills thrust belt to the west, the location of the cross-section in Figure 10, and the generalized environments of deposition of the FA to FE sequences. On the inset, the extent of the Boreal Sea is outlined.

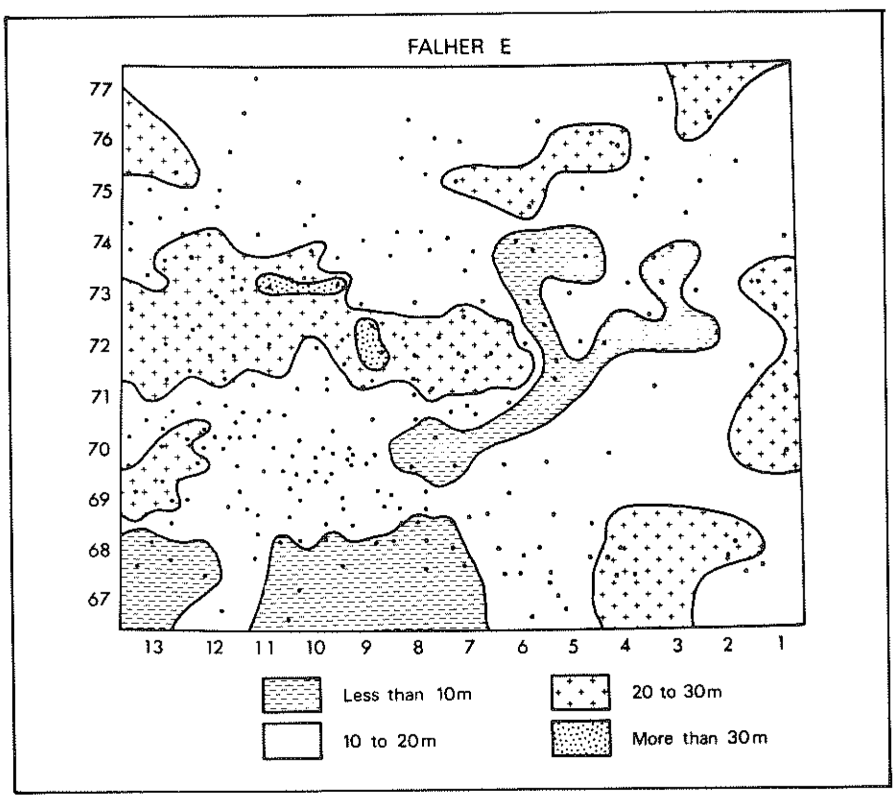


Figure 15
A map of the sandstone thickness in the FE sequence. The dots indicate the well control used in the mapping and facies analysis in this project.

The most important lithlogies present are sandstones and shales (separated by the gamma-ray log), coals and carbonaceous shales (identified by low sonic velocities), and conglomerates. Not all conglomerates are distinguishable from sandstones on logs. Very permeable matrix-free conglomerates show as zones of cleaner gamma-ray readings, and smaller diameter hole on the caliper log because of filter-cake buildup. Less permeable conglomerates with sandy matrix material are separable from sandstone only in core. Regional stratigraphic cross-sections were constructed (hung on the top of the unit to remove regional dip) on which sequences of sedimentation or cycles of sedimentation were identified. Correlation by sequence analysis of the dominantly coarsening-upward units allowed internal subdivision of the formation (Fig. 10). Several cycles (FA to FE) cannot be correlated into the southern part of the area where coals are abundant. Core logging reveals that the boundaries between sequences Not, FA, FB, FC, and FD in Townships 68, 69, 70, and 71 are surfaces of transgression, with basal marine sediments of each cycle overlying the upper non-marine deposits of the previous cycle (Fig. 13). Traced northward, the non-marine deposits (as interpreted from the presence of coals) disappear, and the cycles become more regular coarsening-upward, entirely marine units (Fig. 10).

Cores from the central part of the study area are interpreted as deposits of prograding shorelines or shoreface-beach deposits, capped by non-marine coastal plain muds and coals (Fig. 13). Locally conglomeratic channels and beaches are also present. Each cycle represents a regressive pulse of sedimentation, with totally non-marine deposits in the south, a transitional coastal zone with marine to non-marine sequences in the centre of the area, passing into fully marine deposits in the north (Fig. 10). The marine sand at the top of each cycle forms a seaward-thinning, shoreline-attached wedge extending a considerable distance into the seaway. In the lower cycles (WA, WB), the shorelines were so far to the south that non-marine deposits are virtually absent in the study area.

Because several transgressions terminated around Townships 68 and 69,

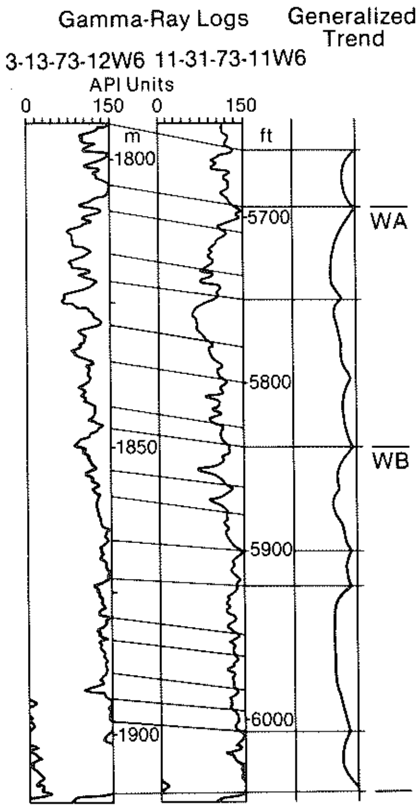


Figure 16
Two logs from the WA and WB sequences showing very detailed correlations between the two. The generalized trend curve is an "eyeball" estimate of the curve shape. Some correlation lines which have been found to extend great distances are extended through to this curve.

the resulting sequence boundaries cannot be extended farther south. The non-marine deposits were subdivided by arbitrarily slicing them with divisions extended southward from the sequence boundaries. The thickness of each slice depends on the thickness of the sequence which was being extended, but also the thickness was varied proportionally to the entire thickness of the entire non-marine zone.

By using a cutoff halfway between a sand line and a shale line (2/3 sandstone — see Fig. 6), the total amount of sandstone and conglomerate in each slice was isopached. The resulting maps (Fig. 15) show that thickenings in the coarser sediment bodies dominantly trend east-west, and occur in the transitional zone of each cycle (Cant, 1983).

Neither of the shoreline sandstones shown in Figure 13 has the standard funnel-shaped log signature shown in Figure 11. The reason for this becomes more clear in the context of the cycle. Near the limit of the transgression where this well is located, shoreline sands were laid down in very shallow water in high energy conditions. Marine shales are not present at the base of the sequence. Farther north, in deeper, quieter water, a more standard gradationally-based sand body was developed.

Other results of subsurface facies analysis include definition and correlation of minor (1 to 10 m) sequences (Fig. 16) within the marine parts of some cycles. The boundaries of these minor sequences slope down seaward and lap onto the basal surface of the cycle. These are interpreted as time lines, reflecting northward accretion of the sediments in each cycle (Cant, 1984). Subsurface methods in this case allowed clear definition of the detailed stratigraphy of the unit.

This case history serves to illustrate the procedures which yielded results in this clastic unit. These results probably could not have been obtained from outcrop study because of the scale of the units involved.

CONCLUSIONS

While subsurface tools, methods, and types of data differ from those of outcrop sedimentology, basic principles remain the same. Subsurface sedimentology can provide a larger-scale perspective of a rock unit or sequence by putting it into its areal context. It is particularly useful for investigating the geometries of facies and the relationship between facies. Log curve shapes mimic vertical trends in shaliness or grain size and therefore look like the familiar vertical sequences by which many facies models are summarized. It must be remembered that because: 1) there is not necessarily a unique relationship between log response and lithology, and 2) there is not necessarily a unique relationship between log responses and criteria used to define facies, log curve shapes or measurements do not necessarily directly reflect facies.

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