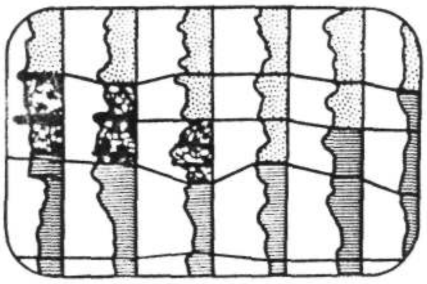

3. Subsurface Facies Analysis

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INTRODUCTION

This chapter will attempt to bridge the methodological and scale gap between sedimentology based largely on outcrops and modern environments, and techniques and results of large-scale, subsurface investigations. It is an introduction to 1) geophysical logs and correlation, 2) subsurface facies analysis, 3) seismic methods, and 4) larger-scale analysis of sedimentary facies successions and allostratigraphy.

Subsurface work lends itself to the study of facies relationships on a scale larger than can be accomplished on most outcrops. Consequently, many relatively new ideas concerning allostratigraphy, sequence stratigraphy, base-level changes, and global stratigraphic correlations have emerged !from subsurface geology, and are based on both geological and geophysical data.

DIFFERENCES FROM SURFACE WORK

Subsurface data provide a differently biased sample of a rock unit than outcrop data. Drill holes and cores are concentrated in localities and zones of economic interest whereas outcrops preferentially expose rocks which are harder and more resistant to weathering. Because drill holes and geophysical logs normally sample a continuous, uninterrupted section (whereas outcrops rarely do), subsurface correlation is based on more complete data. Seismic-reflection data may provide a coherent three-dimensional picture of a basin, along with information on the relationships between the sediments and structural features of a basin.

Subsurface data cannot provide as much local facies information. No matter how closely spaced wells may be, data from geophysical logs, 3 to 20 cm-diameter cores, and cross sections constructed from them, cannot match the level of local detail available from an outcrop. Seismic data give a view of a basin on a very much larger scale than outcrop studies. The differences in the appropriate scales of investigation for outcrop compared with subsurface studies are extremely significant, both scientifically and economically.

Subsurface methods

The following sections will briefly review the principles behind subsurface methods of investigation, including both geological methods (well logs and cores), and geophysical methods (seismic-reflection data). Other publications discuss these techniques in more detail, notably Krumbein and Sloss (1963), Allen

Table 1 *Log types, properties measured, and geological uses.*

Log	Property Measured	Units	Geological 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, cross plots 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, nonporous carbonates.
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (and direction)	Structural analysis, stratigraphic analysis

(1975), Payton (1977), Selley (1978), Anstey (1982), and Miall (1984). Some newly developed methods in subsurface sedimentology, such as the use of resistivity microscanners to detect sedimentary structures, and the analysis of high-resolution dipmeter data, are as yet not widely applied, but are discussed by Hurst *et al.* (1990). The two major types of data, subsurface geological and geophysical, will be treated separately, but where available, both can be integrated.

GEOLOGICAL USES OF WELL LOGS

Well logs are made by pulling an instrumented tool up the hole, and recording the data as a function of depth. They are used extensively in the petroleum industry for evaluation of the fluids in rocks, but this aspect will not be covered here. The interested reader is referred to the various logging company manuals, or to Asquith (1982). Geophysical logs are the fundamental source of data in many subsurface studies because virtually every oil and gas well is logged from near the top to the bottom. Almost all well logging is done by pulling the measurement tool up the hole on the end of a wire. Different types of logs and the properties they measure are shown in Table 1 and are discussed briefly below. On any well log, the absolute elevation of any bed or bed contact is obtained by subtracting its depth in the well from the surveyed elevation of the Kelly Bushing (KB) on the drilling platform; this elevation is given on the top (header) of the well log.

Spontaneous potential (SP) log

This log records the electric potential between an electrode pulled up the hole and a reference electrode at the surface. This potential exists because of electrochemical differences between the waters within the formation and the drilling mud, and because of ionic selection effects in shales (the surfaces of clay minerals selectively allow passage of cations compared to anions). The potential is measured in millivolts on a relative scale only (Fig. 1) because the absolute value depends on the properties of the drilling mud. In shaly sections, the maximum SP response to the right can be used to define a "shale line" (Fig. 1). Deflections of the log from the shale line indicate zones of permeable rock containing interstitial fluid with salinities different from the drilling mud.

Experience in many basins has shown that the SP log may be a good indicator of lithology in areas where sandstones are permeable and water saturated However, where low-permeability rocks occur, such as the tightly cemented sandstones of the western Alberta Basin or the bitumen-saturated Athabasca Oil Sands, the SP log cannot reliably distinguish lithologies If subsurface formations contain fresh rather than saline water (such as some Upper Cretaceous rocks of Alberta), SP deflection is suppressed or even reversed

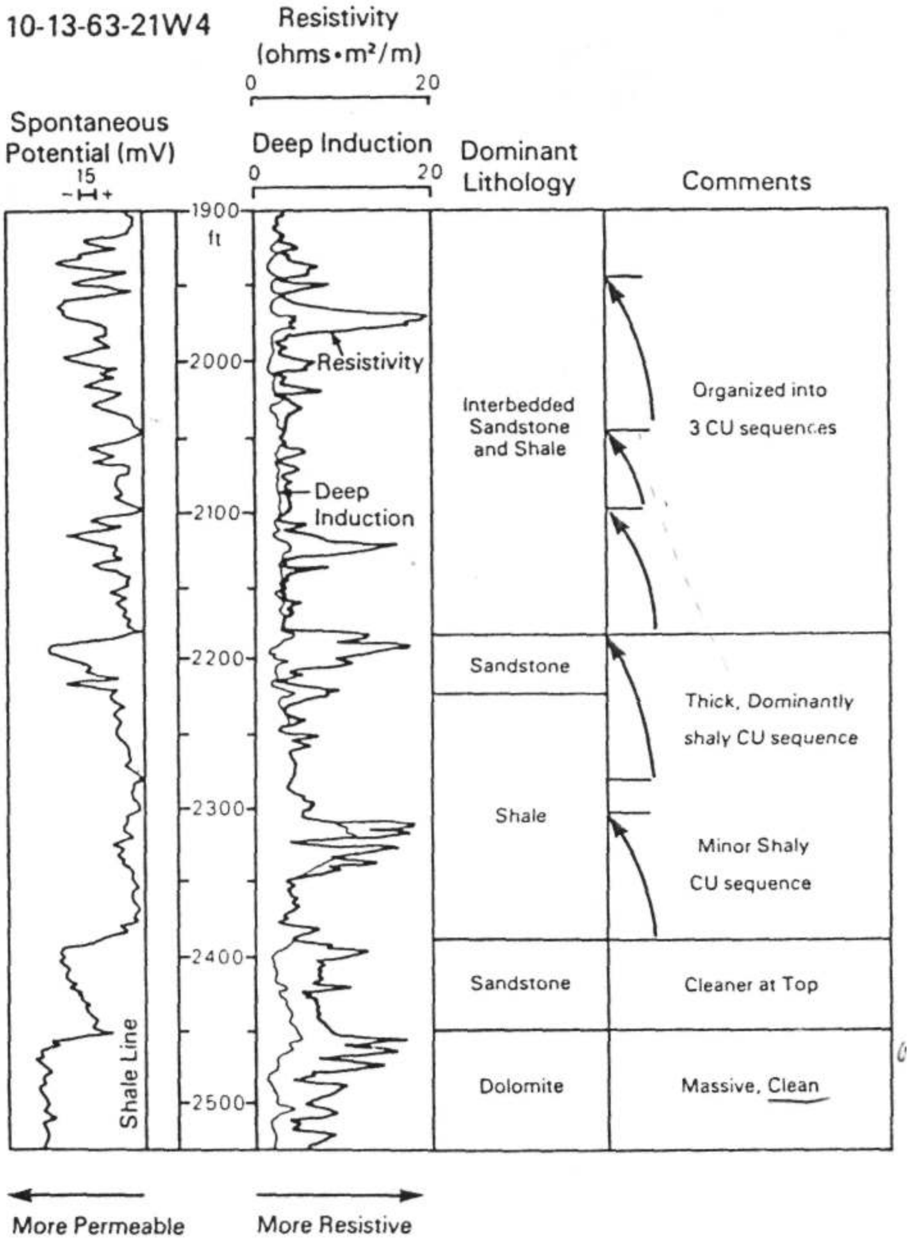

Figure 1 Example of SP and resistivity logs from the Alberta Basin. A shale line is shown on the SP — any deviation from this reflects porous rock. Two resistivity logs are shown — one of medium depth (resistivity) and another (deep induction) which reads farther into the rock beyond the influence of the drilling mud. The deep induction log shows lower resistivity in porous zones, probably indicating salt-water saturation. The carbonates are Devonian Winterburn dolomites overlain by Cretaceous Mannville Group sandstones and shales. The curved arrows indicate individual facies successions; these can be seen as progressive upward deflections in both the SP and resistivity logs.

from normal, depending on the salinity of the drilling mud. The best test of the reliability of the SP log in determining lithology is to calibrate the log against cores and cuttings~[cTJUinys are" 1 to 3 mm fragments of rock brought to the surface during normal drilling by the circulating mud) and hence gain experience in a particular area.

Resistivity log

This log records the resistance of interstitial fluids to the flow of an electric current, either transmitted directly to the rock through an electrode, or magnetically induced deeper into the formation from the hole (induction logs; Fig. 1). The term "deep" here refers to horizontal distance from the well bore. Resistivities at different depths into the rock are measured by varying the length of the tool and focusing the induced current. Several resistivity and induction curves are commonly shown on the same track (Fig. 1).

Resistivity logs are used for evaluation of fluids within formations. Thev 'can also be used for identification of coals (high resistance), thin lime- "sic gs in shales (high resistance), and jjentonites (low resistance), as shown in TaBte"-T. In older wells where few types of logs were run, the resistivity log may be useful for picking tops and bottoms of formalions, and tor^coTre^ lating between wells. Freshwater-saturated porous rocks have high resistivities, so the log can be used in these cases to^separate shales from porous sandstonesjirjd rnrhnnntnt

Gamma-ray log

This log (Fig. 2) measures the natural gamma-ray emission of the various layers penetrated in the well, a property related to their content of radiogenic isotopes of potassium, uranium and thorium. These elements (particularly potassium) are common in clay_ minerals and some evaporites. In terrigenous clastic successions the" log reflects the "cleanness" (lack of clays) or "phgjiness" fhigh radioactivities on the AP|_scale, Fig. 2) of the rock, averaged over an interval of about 2 m. Because of this property, gamma-ray log patterns mimic vertiral sandsCQOlgpJ nr carbonate-content trends of fades successions. It must be emr1'
the gamma-ray reading is •!<•
tion of grain size or carbo; <: -
only of the proportion *o* faiMOcViviC ements, which *may* be {-e'fej IrA^C. proportion of shale. For example, ciay-free sandstones or conglomerates with "any mix of sand and pebble clast sizes generally give similar responses, and lime mudstone gives the same response as grainstone. Distinguishing between clean (clay-free) lithologies such as sandstones, conglomerates, dolomites, and limestones is best done by calibration of one or more lqqsJo__ jc^s^icujtings,__

Once the main lithologies are known,

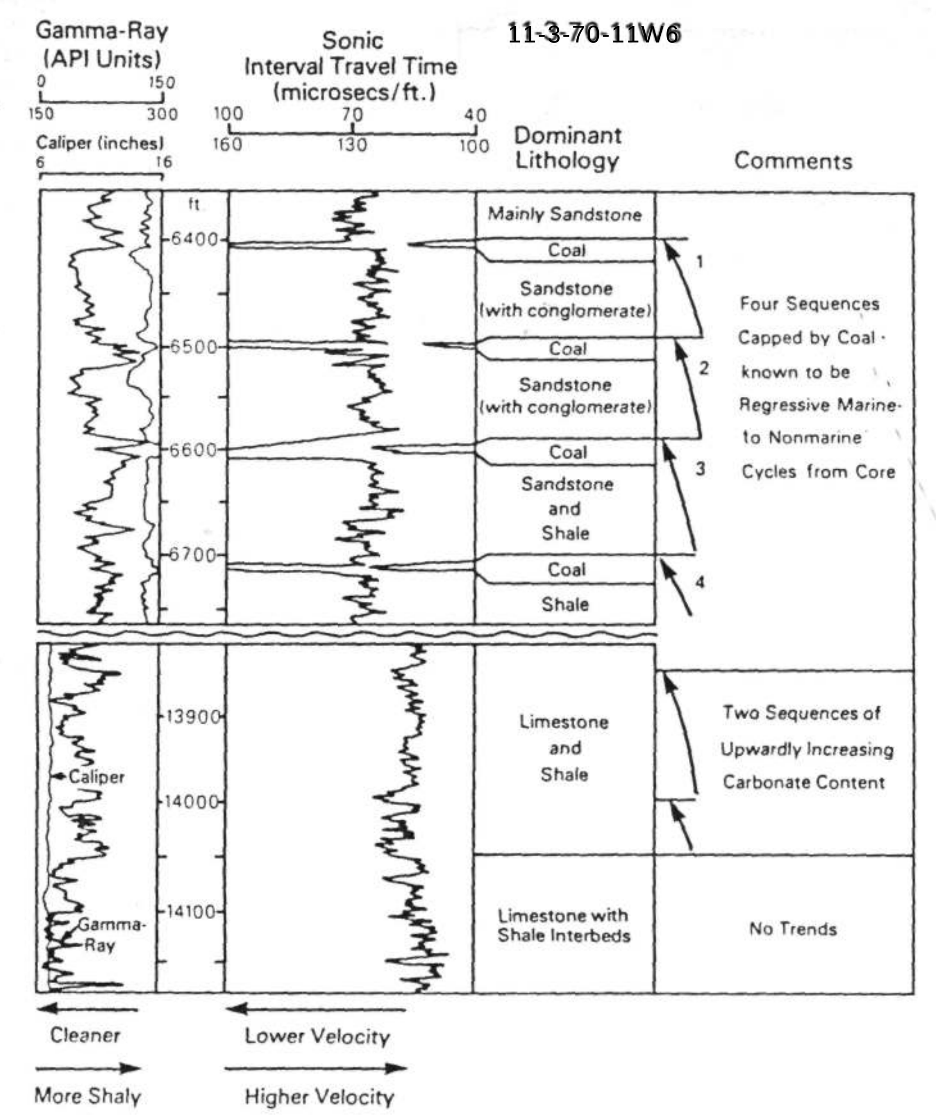

Figure 2 Gamma-ray, caliper, and sonic logs from the Alberta Basin. Because of space limitations, coaly shales (higher gamma-ray readings) are labelled coals. The lower section consists of the Ireton and Leduc Formations and the upper section shows regressive shoreline successions of the Upper Mannville Spirit River Formation.

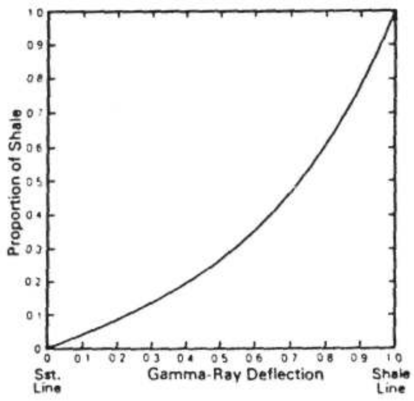

Figure 3 Relationship between gamma-ray deflection and proportion of shale. A cutoff half-way between maximum and minimum values corresponds to about 28 per cent shale, and is commonly used as a criterion for lithologic mapping.

the gamma-ray log can be calibrated to lithology by establishing minimum and maximum readings corresponding to pure carbonate or sandstone versus pure shale end members. The concentration of radioactive elements in shale increases with compactionn^ so the shale line should be readjtFsled.if a thick section is being studied. The tool response is nonlinear (Fig. 3), so a cutoff halfway between the shale line and sandstone (or other clean lithology) line has a value of roughly 30 per cent shale for purposes such as lithologic mapping.

There are three main interpretation problems with the gamma-ray log, 1) the log response may be affected by cliagenetic, radioactive clays in pores, 2) shales rich in illite (high K) are mi^re radioactive man tnose ncn in montmo^ rMlonites or^chloriTeg, ana 3) ajj<os"ic~sa^dstoTTes (high^-fjijdspars} are, more radioactive than those lacking feldspar. Calibration of the log against cores~or cuttings may be necessary to distinguish lithologies in some cases.

Sonic log

This log (Fig. 2) measures the velocity of sound waves in rock. This velocity depends on 1) lithology, 2) amount of interconnected porespaceJ_axid 3) typ"e~T5T~fUiidJflJhe pores. The log is useful for delineating beds of low-velo city material such as coal (Fig. 2) o poorly cemented sandstones, as well as high-velocity material such a*. f ightly cemented sandstones and carbonates or igneous basemenj. Sonic logs are also important in understanding and calibrating seismic lines, as explained below.

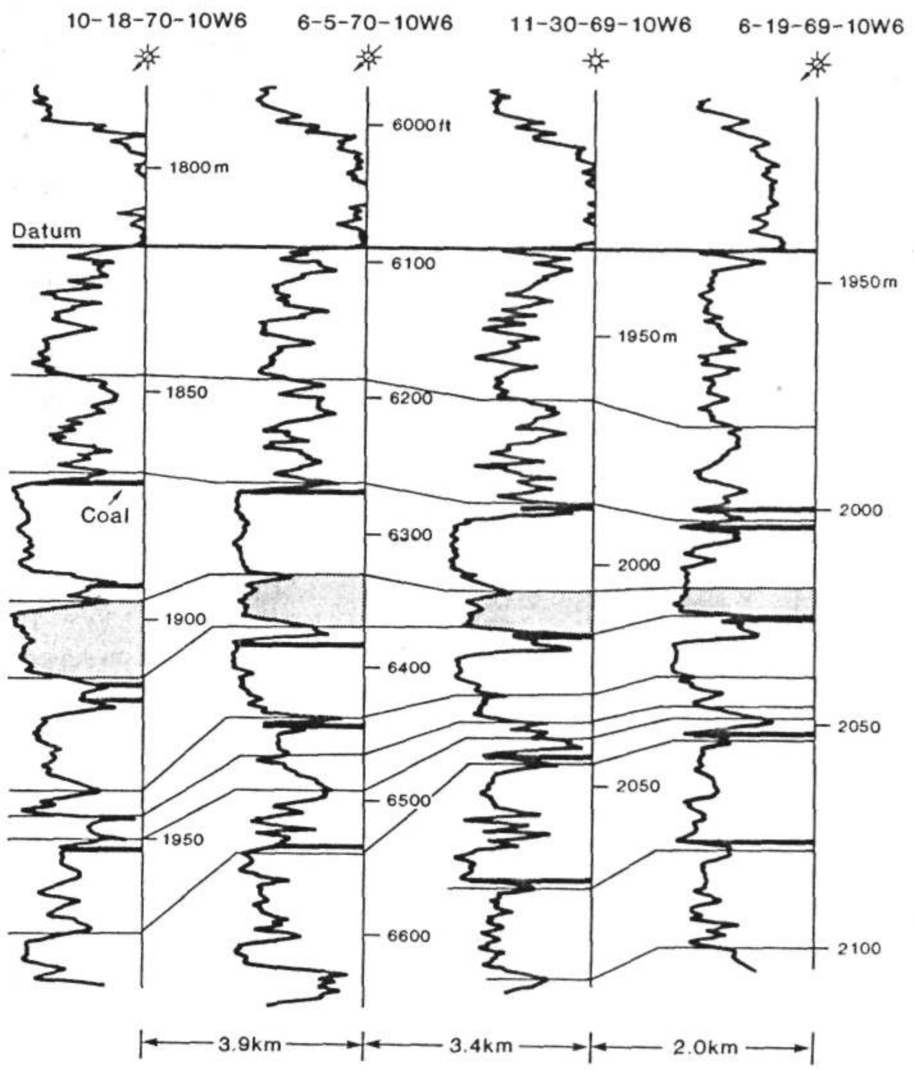

Figure 4 A gamma-ray cross section in the Upper Mannville Group of Alberta illustrating correlation by pattern matching. The correlations have been made using the following criteria, 1) facies successions do not show abrupt lateral changes in character, 2) facies successions do not show abrupt changes in thickness, 3) facies successions do not show seaward (right to left) coarsening, 4) correlated surfaces slo.-e seaward (to the left;. Coals (blank) were loentmea 0" sonir ions. ~-:etc logs are not spaced proportionally !c 'Mc distances between wells.

Porosity logs

Density and neutron logs can be d*> -played as estim4tes_oX_p_orosities. The density tool emits gamma radiai which is scattered back to the deteaur in amounts proportional to the electron density of the rock. The electron density, in most cases, is related to the density of the solid material, and the amount and density of pore fluids. Density porosity is calculated by assuming a density of the solid material (2650 kg/m^3 for sandstone and shale, 2710 kg/m^3 for limestone) and fluid (1146 kg/m^3 for salt water).

The neutron log measures the hydrogen concentration (in water or~ petroleum) in the rock. The tool emits neutrons of a known energy level, then measures the .energy of neutrons reflected from the rock. Because energy is transferred most easily to particles of <^sjmilar mass^the hydrogen concentration can be estimated. Neutron porosities are calculated by assuming that oil or water fills the pore spaces. Gas, or water bound intoclay, minprak ijivp anomalously low values.

Caliper log

This log records the diameter of the hole (Fig. 2), and gives an indication of its condition and hence the reliability of other logs. A very large hole indicates that dissolution, caving or falling in of the rock wall has occurred, which can lead to errors in log responses. This log is particularly useful in mixed evaporite successions where dissolution has preferentially leached out soluble evaporites. A hole smaller than the drill bit size may be present because the fluid fraction of the drilling mud invades permeable zones, leaving the solid fraction (mud or filter cake) on the inside of the hole. In one gas field in the Mannville Group of Alberta, very permeable, matrix-free conglomerate can be recognized on the caliper log where tne note bize is sfjiailei than the bit size.

Dipmeter log

This log is made by a resistivity tool with three or four electrodesmounle_d_ on separate arms with a common centre point. The orientation of the tool is also continuously recorded. Wh£re a dipping bed is enccajntered, the re3"fo the iitnofogic change takes place atUilferent elevations on eacfi^ aTmrfrTie direction and magnitude of Sip' can be calculated from this information.^

Tne dip_m_eter measures structural^ dig^ but can also detect various types of sedjmervtary dips such as arcompaction drape over ,a reej. a sloping ^jTQucrarspeTor even some cross-stratFligation. TrTmany cases/it is difficult to determine the nature of a dipping surface unless a core has been cut.

CORRELATION OF LOGS

Correct correlation of stratigraphic units is absolutely necessary to make reliable cross sections and maps, and to conduct regional facies analysis. Complex numerical procedures for matching and correlation of logs (such as a method adapted from gene-typing techniques; Griffiths and Bakke, 1990) may be the primary tools in the future. At present, most geologists match log patterns by eye (or by tracing and overlaying logs), allowing for variations in lithologies, thicknesses, and completeness of section. Three major correlation methods will be discussed, 1) marker beds, 2) pattern matching, and 3) slice techniques.

| Marker **beds** I

The log response ("kick") of a distinctive bed or series of beds can be used as a marker (e.g., Fig. 19 in Chapter 12) even if the lithology or origin of the bed is not known. Distinctive, laterally extensive groups of beds commonly result from transgressions or regressions or erosional episodes which redistribute proximal sediment far across the basin. Markers that can be mapped regionally may therefore be related to, or include, important allostratigraphic surfaces. For example, condensed sections (possibly expressing jna£imjjmJloj2dJiig_s^^ Chapter 1) are perhaps the most extensive marker beds, and are extremely useful because ihey are essentially time lipes. In the Alberta Basin the Fish Scale Horizonjis a shale rich in organic debris. It can be identified over most of the basin by its characteristic high-gamma ray, slightly high-resistivity, ancMiigh-porosity values. It is used in many studies 5t the units above and below it (particularly the Viking Formation), as a horizontal datum for cross sections. The top of the Middle Mannville Bluesky Sandstone is also a prominent marker in the Mannville Group. The Bluesky is a shoreline deposit abruptly overlain by marine shales; this contact is a bounding discontinuity used to define allostratigraphic units.

In other situations, markers are not related to allostratigraphic units. For example, volcanogenic bentonites are easily recognized on logs (Table 1), providing reliable markers as well as time lines.

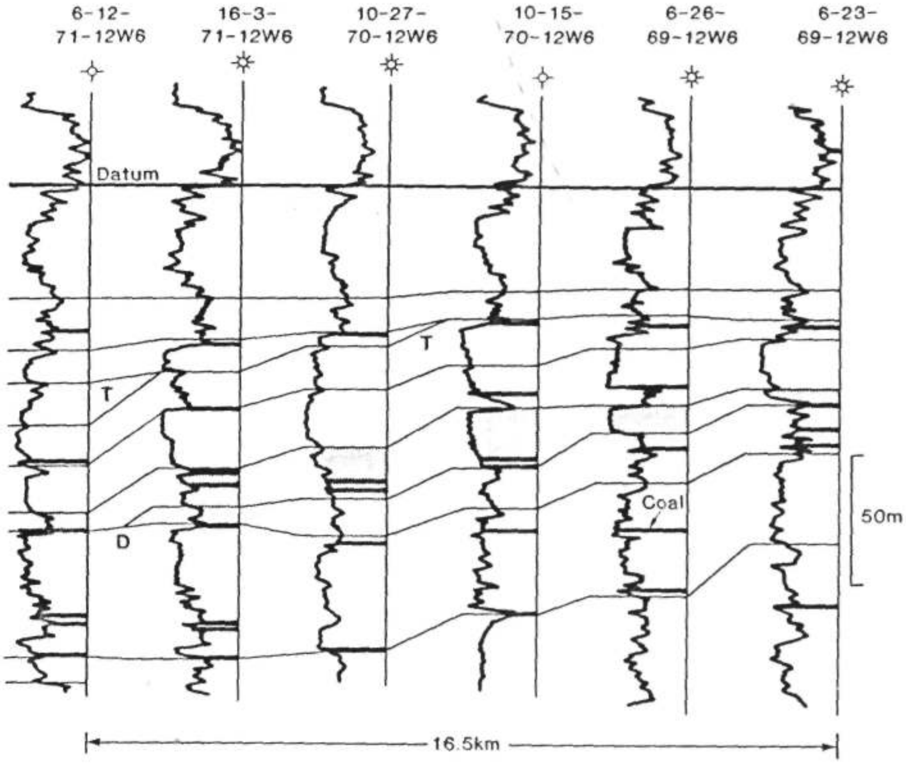

Figure 5 Gamma-ray cross section correlated by pattern matching which shows facies successions sloping seaward and downlapping against a lower surface. Correct pattern matching a|lowj>ja^ntifjcati^^ such as this. D indicates downlap and T indicates toplap. The logs are not spaced proportionally to distances between wells.

Pattern matching

This technique involves recognition andjriatching of distinctive log patterns^ J3l_any origin.JTie correlated patterns may represent vertical fgcies successions (Fig. 4), jguperimpospH fanips, Successions, or unconformity-bounded units (Fig. 19 in Chapter 12). The surfaces of the units chosen may be transgressive and separate individual facies successions (Fig. 4). Alternatively, surfaces of maximum transgressjaa_separatet ^mposrFe-transqressiv1r> fromrc^mpollle^gressive)units (to be discussed in more detail below). The bounding surfaces of the chosen units may also be unconformities, such as Cardium Formation surface E5 (Fig. 19 in Chapter 12).

By matching patterns, correlations are made on the basis of log shapes over intervals of metres or tens of metres, rather than on individual peaks, troughs, or markers within the succession. Pattern matching may allow_cjp£relation even *wb<*rf>* lateral variations in lithologies, facies, and thicknesses of units have occurred (Fig. 4). In diffi"cult ca'SesTTnatcningls facilitated by tracing one log and overlaying it on an adjacent log. The logs can be moved up and down until the best overall fit is obtained. Constantly changing positions of fit may indicate lateral facies PL thickness changes, and may mdF"cate synsedimentary tectonism. ..

Pattern matching is extremely useful because it can be used to correlate facies successions or allostratigraphic units as defined from cores or outcrop. It therefore facilitates investigation of regional facies relationships. Examples of this are shown in Figure 15 of Chapter 12, and Figure 16 of Chapter 9. Detailed pattern matching of individual facies successions may delineate surfaces of toplap, downlap or onlap (Fig. 5), and can therefore be used to define large-scale or composite allostratigraphic units. Pattern matching has worked extremej^well irTmanv studies oTshaitow-manne_sediments in the Cretaceous Western Interior Seaway of North America, largely because of the lateral uniformity of these rocks (at least compaTelTRrolrier facies).

Certain assumptions about the styles of lateral variation of facies must be made in pattern matching in order to decide between alternative possibilities. For example, the cross sections of Figures 4 and 5 show that in these shoreline-to-shallow-marine elastics, the correlated units satisfy a number of conditions: 1) individual facies successions do not show abrupt changes in thicknesses, log patterns, or inferred grain size patterns; 2) individual successions do not show seaward increases in the thicknesses of sandstones; 3) successions slope gradually seaward (unless synsedimentary or postsedimentary tectonism has occurred); and 4) abrupt lateral changes in facies successions imply that an unconformity exists. Readers may be able to make different correlations through the same wells, depending in part on the initial assumptions made.

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As a method of last resort, when no other method yields results, an interval can be subdivided by arbitrarily slicinglt either into units of constanjJhicknesR, or into units witFthickTiiiiesproportional to the entire interval (Fig. 6). Slicing an interval does not give true correlations; it is only a way of splitting a section which cannot be subdivided any other way. The implicit assumption is made that time lines through the interval are essentially horizontal. Where this assumption is invalid, slice techniques may yield results which aie grossly in error. It is a means of last resort, but is necessary in some situations which do not yield to the other methods discussed above.

The thicknesses of slices should be chosen to minimize complications. For example, if sandstones in JNs\ area average 30 m in thickness, the choice of slices less than 30 m may not yield interpretable results. In some cases, trial and error is necessary to find the optimum solution.

Slice techniques are most commonly agplied jn nonmarine deposits. Here, other techniques do not work well because of the lack of continuous beds and absence of laterally extensive facies successions. By noting the stratigraphic position and thickness of each lithologic unit with respect to a marker (commonly the top of the unit), the data is in a form of maximum utility when computerized. Thicknesses of slices can be changed easily until patterns emerge. Note that slice techniques may produce correlations which cut across depositional units or unconformities if they are applied to units with sloping depositional surfaces. Flach (1984) has used this technique to map sandstone-filled channels in the nonmarine to estuarine McMurray Formation of Alherta. He was ahlft_ta show the locationsofthe major oil sands reservoirs at different stratigraphic levels even though precise correlation cojjld not be achieved.

SUBSURFACE MAPS

Mapping in the subsurface differs little from surface work except for the huge volume of data which can be collected from a large number of wells. _C.orrt pjjterization of data bases and lane survey systems has progressed to the point where automatic map productior of some attributes is dorae routinely and quickly.

Subsurface geological maps are either compilations of data, or interp_re^___tive summaries, DatiTcompTTation maps of many different quantities have been made, but for stratigraphic and sedimentological purposes, there are three main types, 1) structure maps that. show the elevation of a surface (the example in Fig. 20 of Chapter 12 is similar to a structure map), 2) isopach maps that show the thickness oTVunTT (Fig. 21 in Chapter 9), and 3) lithological maps that show the composition of . a unit in one of several way_sJFig, 23 in CTiapter 9). Examples include maps of the thickness of carbonate rocks as a percentage of the total thickness, maps of net sandstone thickness, or maps of the ratio of clastic to carbonate thicknesses. Full descriptions of the different map types are given by Krumbein and Sloss (1963) and Mial! (1984). Interpretive summary maps and block diagrams of such aspects as facies distributions, paleogeographies, and sediment supply directions are also commonly made (Figs. 18, 21, 22 in Chapter 12; Figs. 11, 18 in Chapter 9). Note that all maps depend absolutely on correct correlation of units. If correlations are wrong, the resulting maps will be worthless.

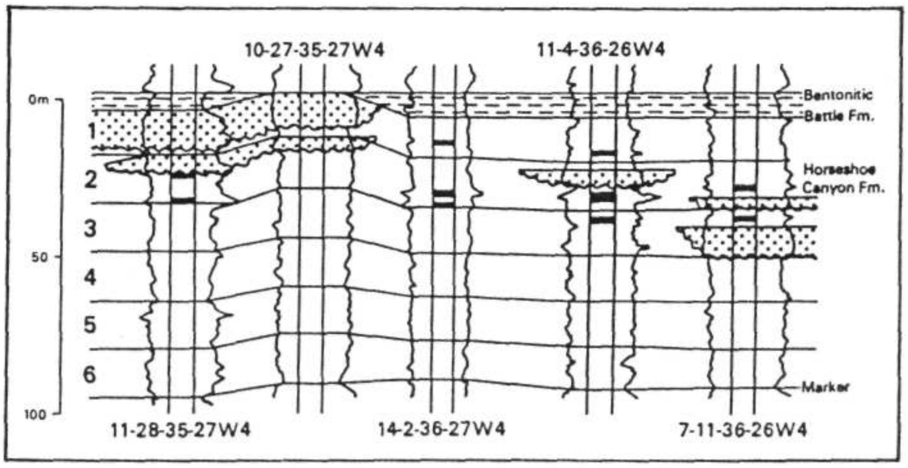

Figure fi rrncc Qsntion (gar.,ma-ray iuys on left. ʳ*»siRtiyity iog= on pigm) from the Upper Ciotaceous Horseshoe Canyon Formation, Alberta. The section between ihe E Formation and the basal marker was subdivided into six equal slices, chosen to include but not split the major channel sandstones. Simplified from Nurkowski and Rahmani (1984).

SUBSURFACE FACIES ANALYSIS

Without cores, the definition and interpretation of facies in the subsurface are generalized and imprecise. Making lithological logs of cores is similar to the measurement of outcrop sections, the most obvious differences being the scale of features which can be observed in a limited-diameter (commonly 9 cm) core, and the lack of oriented sedimentary structures for paleocurrent analysis, iahates^ and mudstones.however, are commonly more easily studied in cores than in outcrops (the trace fauna is particularly well displayed in cores, Chapter 4). Cores should always be examined with the logs present to check for completeness of recovery, core-log correlation, and log responses. Well-log cross sections (Fig. 15 in Chapter 12; Fig. 19 in Chapter 9) and appropriate kinds of maps can extend the interpretations made from cores, and set them into a larger-scale stratigraphic and paleogeographic context.

Log curve shapes

The shapes of well-log curves have long been interpreted in terms of depositional facies because of their resemblance to grain size successions (e.g., Selley, 1978). Where SP-Resistivity or Gamma-Sonic pairs of logs are used, the patterns are mirrored, resulting in (among others) Jjelk. sjiapedand funnel-shaped profiles (notelheHfunnel in the¯lower TialTof well 7-10-62-7W5 in Figure 15 of Chapter 12). Much published work uses a simplistic "pigeon-hole" approach to interpretation. An example is the classification of bell-shaped gamma-ray profiles as fining-upwaid. meandering-stream facies successions. Problems with this approach will be discussed below.

The most typical vertical patterns seen on gamma-ray, SP and resistivity logs are shown in Figure 7. *It is emphasized in this diagram that no pattern is unique to, or diagnostic of, any particular depositional environment. It follows that interpretation based on log curve shape alone is extremely imprecise.* In those specific studies where log patterns have been calibrated to well-understood depositional facies successions in cores and/ or outcrops, the log-pattern method can be applied successfully to the interpretation of correlative uncored facies successions.

The scale of facies successions is also a very important criterion constraining the interpretation of curve shapes. For example, funnel-shaped patterns (Fig. 7) may range from a few metres to several hundred metres in thickness. These are appropriate scales (respectively) for a crevasse. (§Pla$ building into an TnterdisTnbutaiy; _B|^j[Fig. 5 in Chapter 9), andjLEiQ-grading deltaic succession (Figs. 7, 16 In Chapte7~9~V

Difficulties in interpretation of log patterns may result from deviations of individual facies successions from the general model in Figure 7, possibly in

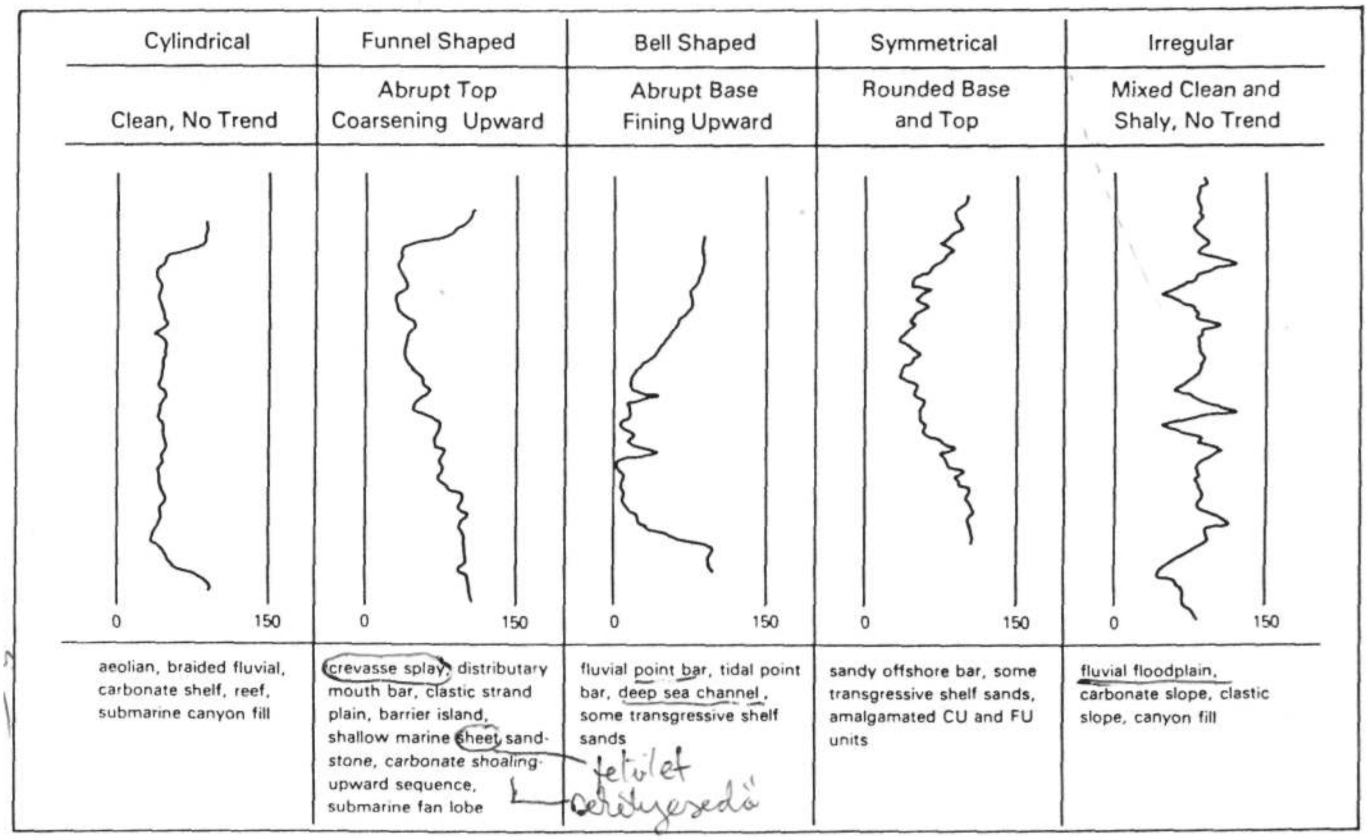

Figure 7 The most common idealized log curve shapes which may be interpreted by correlation with many different core examples (see other chapters). Where resistivity or sonic logs are shown opposite gamma-ray logs, the patterns are mirrored, resulting in the *bell* and *funnel* labels. The limitations of this approach to facies analysis, in the absence of other data, is emphasized in the text, and by the multiple possible environmental interpretations indicated below each curve. Log curve shapes, in the absence of other data, are not diagnostic of particular environments.

some cases because of base-level changes. Other difficulties result from the amalgamation of units. For example, the standard clastic prograding shoreline succession (left side of Fig. 14 in Chapter 12) generates a continuously upward-broadening funnel-shaped gamma-ray pattern (Fig. 7). *Sharp-based* sandy shoreline facies successions (right half of Fig. 14 in Chapter 12, also Fig. 15 in Chapter 12) may result from small drops in relative sea level followed by progradation (forced regression, Chapter 12), or erosional transgression followed by shallow water regressive deposition (Chapter 12). In both of these cases, the typical funnel-shaped log pattern is replaced by a cylindrical or blocky profile (Fig. 15 in Chapter 12), probably not correctly interpretable from log pattern alone.

Amalgamation of facies successions can also alter the standard log profiles of Figure 7. Superimposed channel deposits of meandering rivers can generate a stacked sandstone body characterized by a cylindrical log profile. Similarly, a transgressive sandstone capped by a regressive shoreline sandstone may be characterized by a cylindrical profile and conceal a transgressive unconformity or ravinement (Chapter 12). In the Middle Mannville Bluesky Formation, shoreline sandstones are in some places superimposed directly on nonmarine sandstones in the overall transgressive succession. These form sharp-based, cylindrical log patterns. These examples illustrate that simplistic labelling of log curve shapes in terms of depositional environments, without core or outcrop information, should be avoided.

RECOGNITION OF BOUNDING DISCONTINUITIES

Allostratigraphic units are defined by their bounding discontinuities (Chapter 1). Because subsurface data can be used to document lateral relationships on a large scale, recognition of these discontinuities (maximum flooding surfaces, surfaces of marine transgression and regressive surfaces of erosion) has become extremely important in subsurface investigations. Delineation of these discontinuities allows stratigraphic subdivision of rocks into large-scale genetic packages, with possible implications for large-scale facies relationships.

Condensed sections

These stratigraphic intervals represent periods of vrrv low sedimentation rates in marine depositional environments as a result of major transgressions (Fig. 27 in Chapter 13). They commonly characterize maximum flooding surfaces, and can also be present at marine flooding surfaces (Chapter 1). Condensed sections in clastic rocks are commonly formed as a result of cut-off of clastic supply. In carbonate successions, the sediment-producing environments are drowned. Condensed sections may show up lithologically in carbonate (and some clastic) successions as hardgroundt. with early diagenetic carbonate ana phosphatic cementation (see Chapter 4). In other clastic successions, they occur as intervals of oolite and lime mud sedimentation. In basinal shales

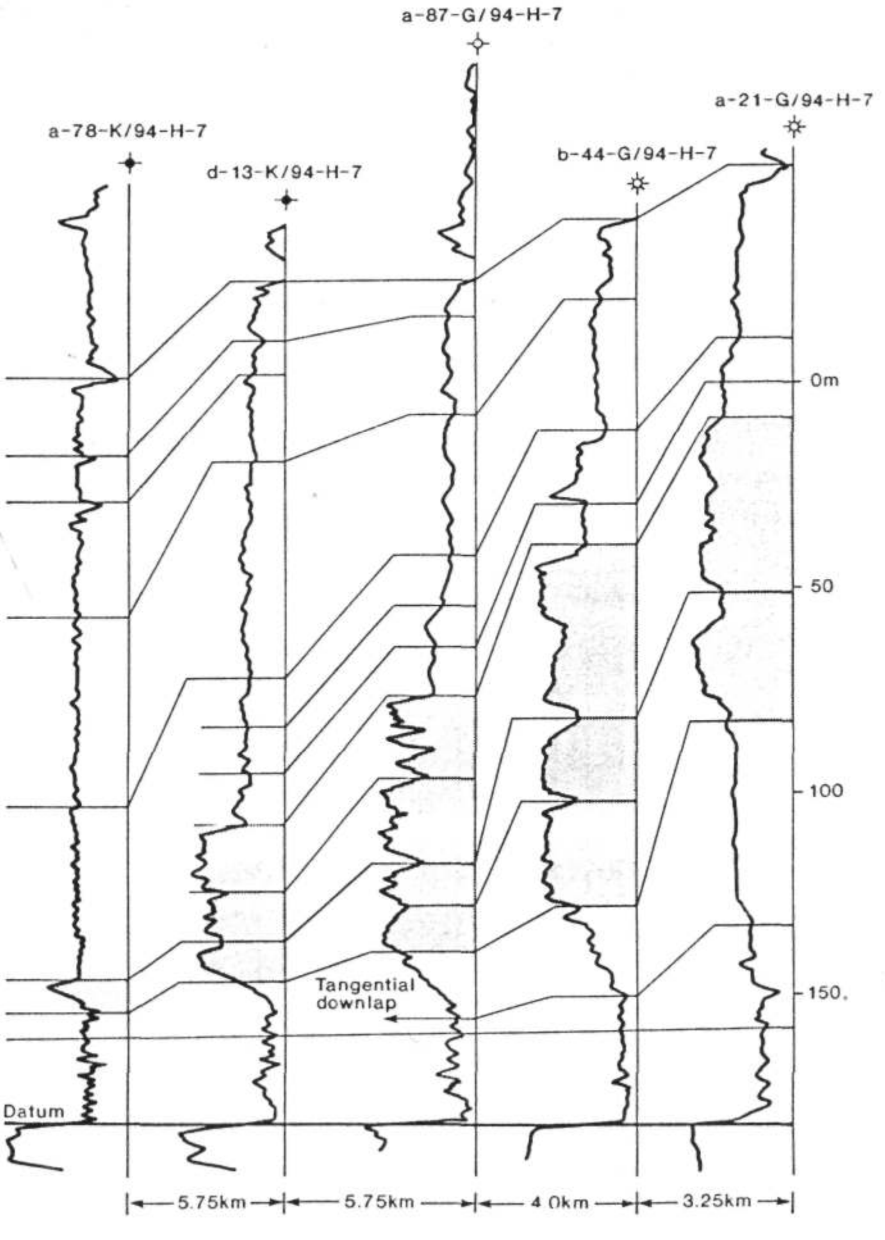

Figure 8 Gamma-ray cross section from the Upper Mannville Group in British Columbia, correlated by pattern matching. The correlation lines slope seaward (to the left), outlining clinoform surfaces which tangentially downlap onto transgressive shallow-marine shales. The section is hunn r.n mo mn nf tho Middie Maor.ville Elussky Formption (Datum). V>? maximum Hooding surface is the top of the transgressive ^haie (about 2a m above DHI. The sandstones (shaded) were deposited on the original clinoform slope. The logs are not spaced proportionally to distances between wells.

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the condensed horizons may be organic-rich radioactive shales, or pelagic deposits such as chalks or chalky shales. Because of these lithologic contrasts with adjacent rocks, as well as their wide lateral extent in many basins, condensed sections may be recognized on logs as marker beds with characteristically different well-log responses. A good example is the Fish Scale Horizon, which is commonly used as a horizontal datum for regional cross sections in the Cretaceous of the Alberta Basin.

Many condensed sections are overlain by downlapping depositional surfaces or clinoforms which may be recognized on seismic lines (see Seismic Stratigraphy section below), well-log cross sections (Fig. 8), and a few large outcrops. Clinoforms are developed in response to transgressive deepening followed by the re-establishment of laterally prograding sedimentary layers. In Figure 8, regressive shelf-to-shoreline clastic facies successions slope seaward creating a clinoform, and terminate against, or downlap onto the transgressive shales and sandstones below. The condensed section (and in this case, the maximum flooding surface) lies directly below the surface of downlap. In some nonmarine units, surfaces similar to condensed sections may be characterized by thin brackish to marine shales and limestones deposited in lagoons and estuaries as a result of transgression.

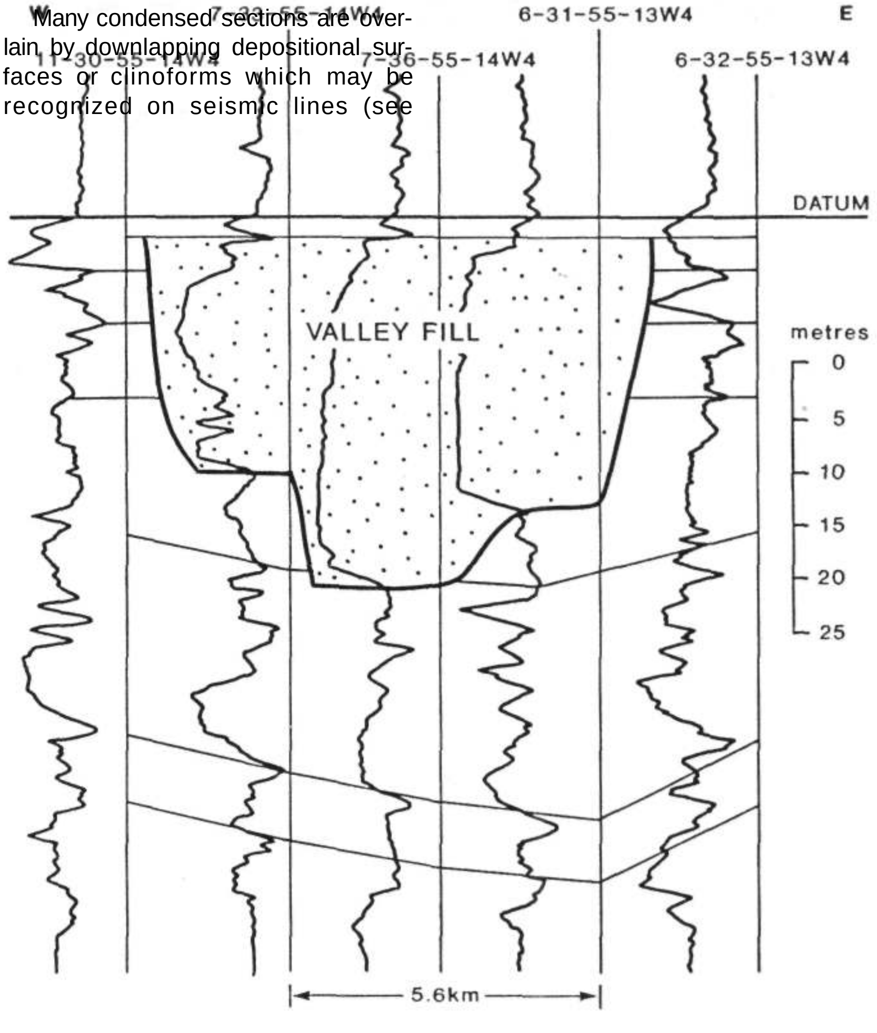


Figure 9 Gamma-ray cross section from the Upper Mannville of eastern Alberta. The regionally correlative log patterns in these fluvio-deltaic deposits (shown at each end) are replaced locally by the valley-fill sandstone. Mapping has shown these anomalous gamma-ray log patterns occur in a linear trend. Detailed pattern matching across the sandstones implies later incision of valleys into the top of the unit, rather than a contemporaneous channel.

Unconformities

Surfaces of erosion or bypass are generally identified where underlying markers or facies successions are truncated (Fig. 19 in Chapter 12), or overlying ones show onlapping relationships. Well-log cross sections of marine rocks commonly allow definition of very low-angle, regional unconformities which may be undetectable on the scale of most outcrops. The Cardium erosion surface designated E5 is a good example (Chapter 12). In shoreline to nonmarine depos:',' gional truncations are much more *ou;* cult to detect because of the ab?t-'" ' of extensive marker beds or easily co related facies successions. As shown in Figure 5, detailed correlations of shoreline facies successions may show surfaces of onlap and downlap, hence defining minor bounding discontinuities.

In other examples, unconformities may be inferred in shoreline and nonmarine sections where locally distinctive stratigraphic units or successions recognizable locally are cut out and replaced by anomalous units. An example is shown in the cross section (Fig. 9) from the Lower Cretaceous Mannville group of eastern Alberta. Here, the gamma-ray logs in wells 11-30-55-14W4 and 6-32-55-13W4 can be correlated in detail by matching coarsening-upward and fining-upward patterns in these shoreline and nonmarine sediments (interpretations from numerous cores). Sonic and resistivity logs (not shown) were also used to make the best possible pattern matches. The thick sandstones just below the datum in wells 7-33, 7-36 and 6-31 are anomalous deposits which locally replace the interbedded sandstones and shales. Numerous cores and some outcrops show that these thick sandstones are fluvial to estuarine in origin. Mapping has shown that they are linear bodies extending for tens of kilometres along the basin, but generally less than 5 to 8 km wide. Reasonable correlations can be made between the sediments on either side of the channel (Fig. 9, wells 11-30 and 6-32), probably indicating that layers were once continuous, but have subse-

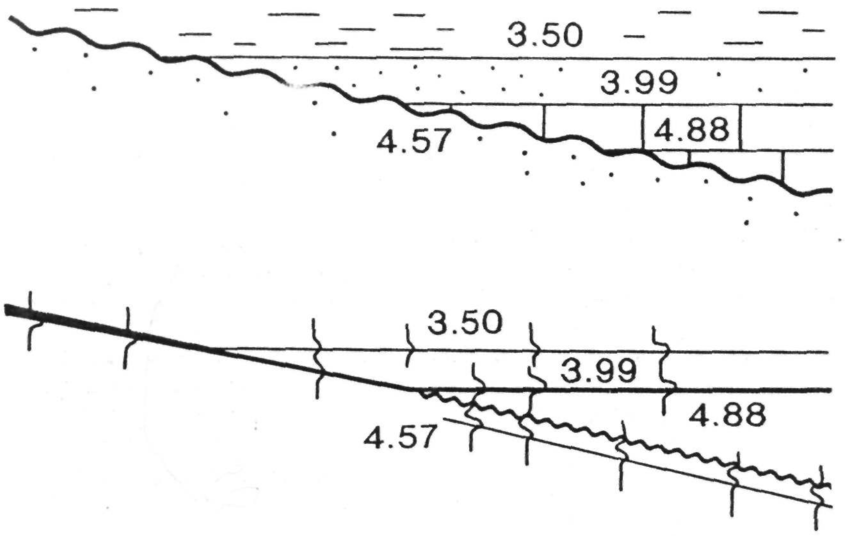


Figure 10 The seismic image of an unconformity (or any other surface) depends on the acoustic impedance across it. The upper diagram shows rock units with their sonic velocities (km/sec). The lower diagram shows reflections, with amplitudes indicated by the thicknesses. The polarity of the reflection (i.e., whether a peak or a trough is generated first) depends on the impedance change, whether positive or negative. Where the polarity is reversed, the unconformity is indicated by a wavy line. The shaded peak of the reflection actually occurs one-half wavelength below the unconformity here.

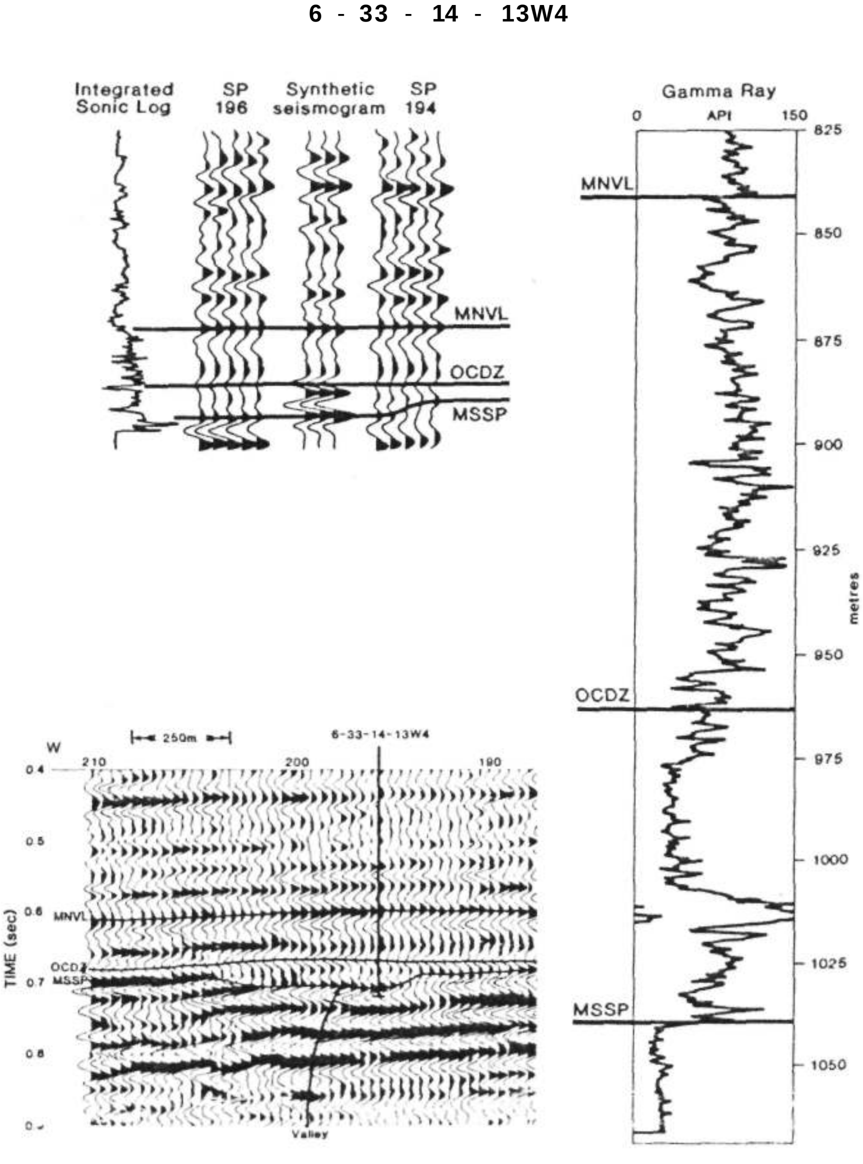


Figure 11 Well 6-33-14-13W4, in southern Alberta, showing (right) a gamma ray log, (top left) a display of sonic log data from the well, seismic data from shot points 194 and 196, with the synthetic seismogram between them, and (bottom left) a seismic line through the well. The tops of the Mannville Group (MNVL), Middle Mannville Ostracod Zone (OCDZ), and Mississippian (MSSP) are marked on each. The shot points (SP) are indicated above the seismic line. The peak (to the right) of each reflection is infilled. Note the lack of vertical resolution of the seismic data compared to the well log. However, the seismic line shows the context of the lower Mannville sandstone in a valley cut on the sub-Cretaceous unconformity. Note the truncations of reflections at the sub-Cretaceous unconformity. Modified from a well-integrated subsurface geology and seismic study by Hopkins *elal.* (1987).

quently been incised by valleys. A series of correlative incision events at the same stratigraphic level marks an **unconformity which is** undetectable where the channels are absent. These anomalous sandstone units were **therefore deposited within** valleys cut **as part of an unconformity that developed on fluvial and thin** deltaic **sequences. The most generally** accepted **interpretation of the** series of events in **this part of the Mannville Group (Fig. 9) is: 1) deposition of the** interbedded **fluvial and deltaic sands and** shales, 2) **drop of relative sea level,** allowing the **incision of 30 m-deep** fluvial valleys **through the coastal** plain, 3) rise **of relative sea level (transgression) and salt water invasion of the** valleys, **forming linear estuaries, and** 4) **complete filling of the valley** by transgressive sediments grading from fluvial to **estuarine deposits.**

This interpretation illustrates the integration of facies analysis performed on cores with allostratigraphic analysis essentially done on well-log cross sections. By itself, core logging could not have shown the relationships between the estuarine deposits and the older deltaic sediments. Equally, allostratigraphic analysis of cross sections would not have yielded much information about the nature of the sediments and their relationships to sea level.

SEISMIC REFLECTIONS

Seismic surveys are conducted to investigate subsurface geology by sending compressional sound waves into the earth and detecting the reflected or refracted energy returning to the surface. Shallow (up to several hundreds of metres penetration) single-channel systems (one receiver) or medium depth (up to 10 km penetration) multi-channel systems (many receivers, with digital data added mathematically) record entirely reflected energy. **By moving the point of** origin of the sound **waves (the shot** point) and the detectors, **a** continuous section of any desired **length may be** obtained. Seismic sections are normally shot in straight lines.

A seismic reflection **is generated** where a descending **sound wave** encounters an interface **which reflects** part of the energy **back to the** detectors. The reflectivity **of a surface has** been **found to depend on the contrast in the density and sound transmission** velocity of the **materials above and** below it. The **product of these quantities** is the *acoustic **impedance*** **of the** medium, and the **strength or amplitude** of a reflection from **a surface depends** on the acoustic **impedance contrast or** ratio, across it. Reflections are generated from stratigraphic **surfaces such** as bed contacts or unconformities only where a contrast in acoustic imped-

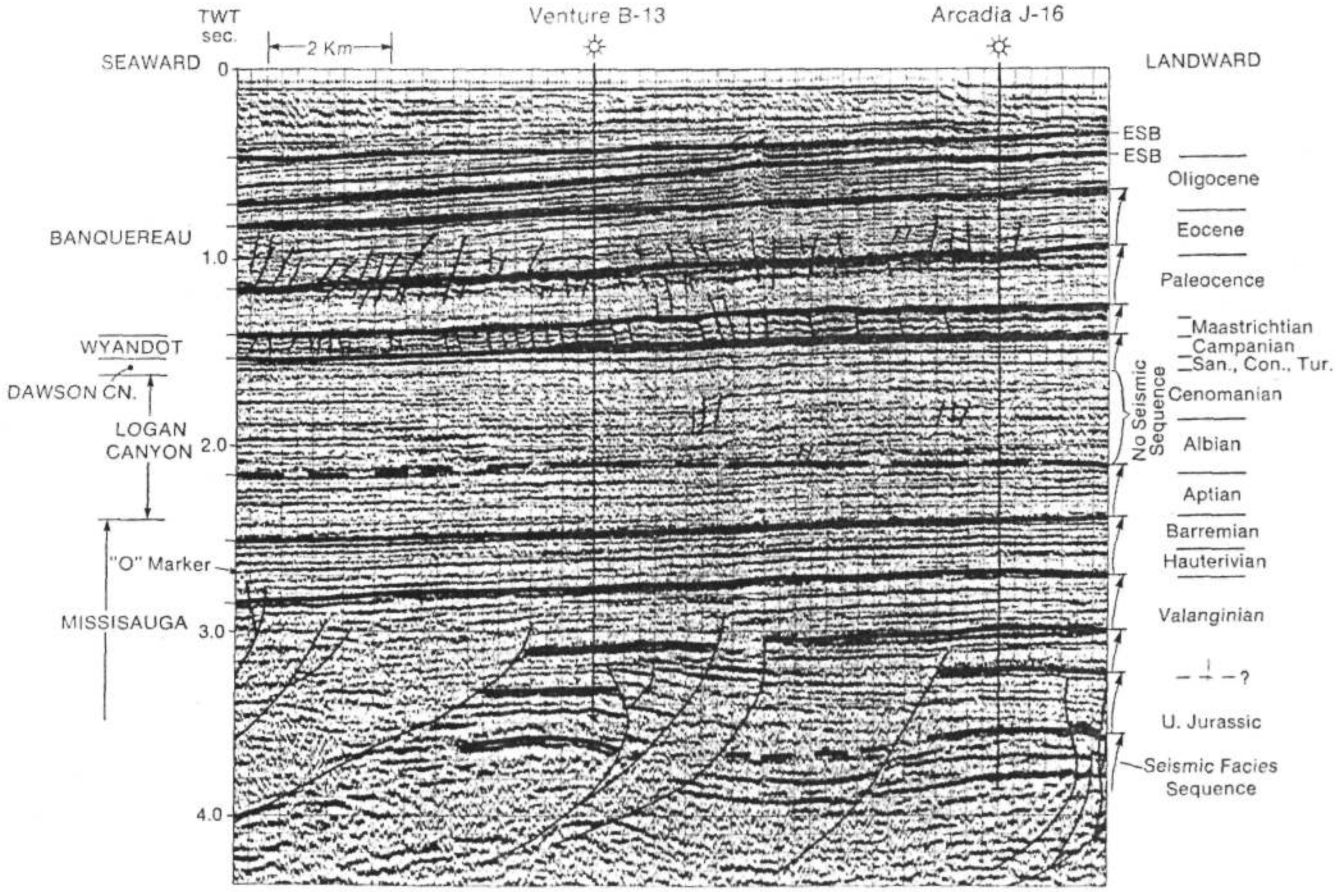


Figure 12 Seismic section from the Venture area, Scotian Shell of eastern Canada. The horizontal scale is distance, but the vertical scale is two-way travel time (up to 4 seconds), and is nonlinear with respect to depth in metres (the Venture B-13 well is 5219 m deep). The age data and formation picks are from the two wells shown, tied in by synthetic seismograms. In this area, growth faults affect the Upper Jurassic to Lower Cretaceous section, but younger rocks are almost undisturbed. Curved arrows indicate units of upward-increasing reflection frequencies, amplitudes, and continuities. ESB indicates an erosional sequence boundary.

ance occurs across them. For example, an unconformity is not cL imaged if sandstones of simila locity and density are superimp above and below it. However, latt where the sandstone lies be; shale with lower velocity, a reflects , generated (Fig. 10).

A seismic section comprises a series of shot points displayed horizontally, and a series of reflections shown at different vertical distances. In Figure 11 (lower left), the shot points are 25 m apart, and each shot point has a seismic trace displayed beneath it. By convention, the right half of each trace is filled in (blackened), for illustrative purposes. Where the trace deflects markedly left or right, a reflection from an interface is indicated. Reflections are characterized by their amplitude and frequency, and by the degree of continuity of peaks and troughs from shot point to shot point. A seismic section appears very much like a geological cross section (Fig. 12), with a series of surfaces of contrasting acoustic impedance displayed horizontally, appearing like sedimentary bedding. However, a seismic section is not a geological cross section. Individual sedimentary units are not imaged, regardless . sir lithology, if there is no impedan contrast at their surfaces. Also, ! ertical dimension of a seismic se^, n is not depth, but the two-way travel time (down and back) of the sonic wave (Figs. 11, 12). Because velocities generally increase with greater depths, the display is nonlinear with respect to depth. Depth conversion can be done roughly by using interval velocities, calculated during data processing, and commc -n at the tops of many sections ,ure 11, the 200 m-thick Mannvii • oup is represented by about truee peaks and troughs. Therefore the stratigraphic thickness represented by the average reflection (peak to peak) is about 67 m. It is therefore emphasized that one reflection does not represent a single bed, but a stratigraphic interval several tens to hundreds of metres in thickness.

In many cases, depths are obtained by using *synthetic seismograms.* Synthetics are created by assuming or

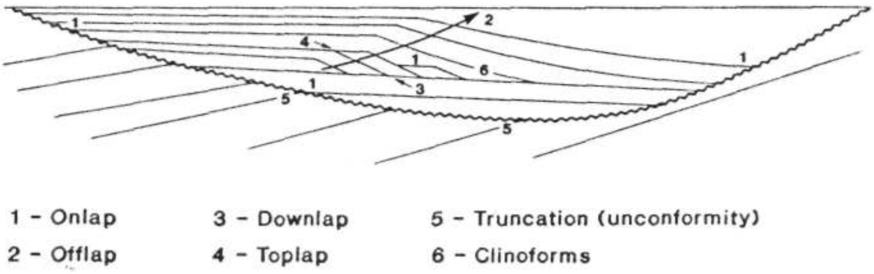
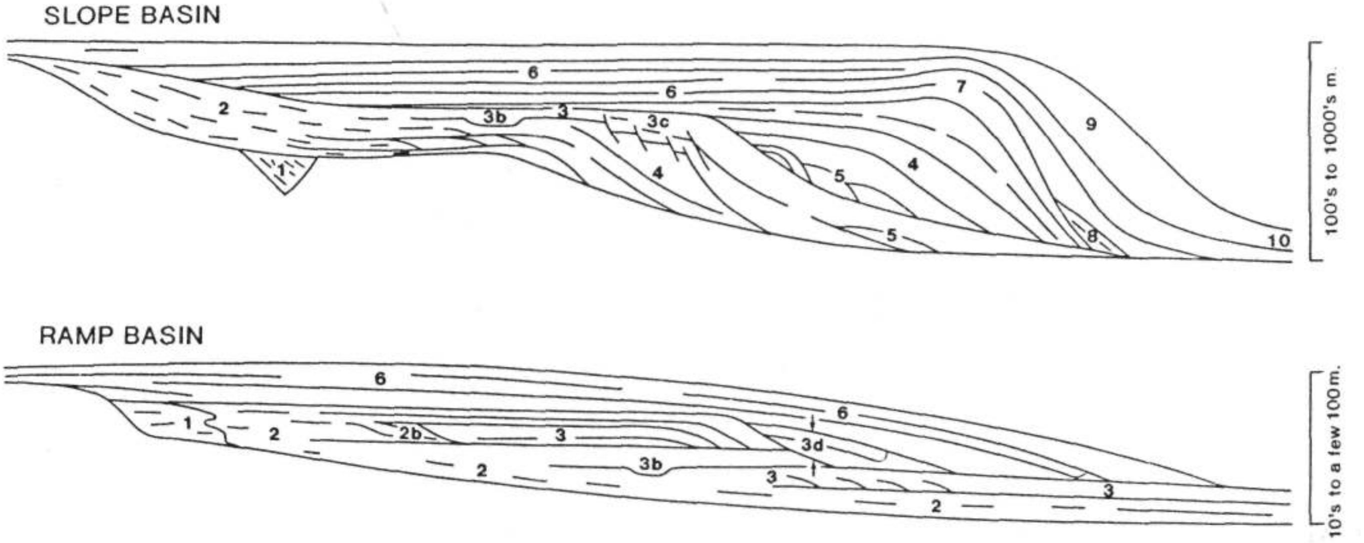


Figure 13 Stratigraphic patterns commonly seen on seismic lines, at many differer; scales. When combined with biostratigraphic dating, these patterns are the basis for int- pretation of the stratigraphic history of a basin. Similar patterns but generally of a smal< scale, may be identified on correctly correlated well-log cross sections.



1 - Alluvial conglomerate and sandstones.lacustrine shales
2 - Non-marine clastic and coal
2b - Deltaic facies
3 - Shoreline to regressive shallow marine facies successions
3b - As above.but with incised non-marine fill
3c - As above,but growth faulted
3d - Shoreline deposits-isolated by base-level drop
4 - Slope shales and interbedded sandstones
5 - Deep marine clastic fans
6 - Lagoonal-Shelf carbonates;shale interbeds
7 - Reef
8 -. Deep marine carbonate apron
9 - Carbonate slope.micrites and megabreccias
10 - Deep marine pelagic sediments

Figure 14 Composite diagrams of Ir.teral faeces rslationships shuv,!, or, seismic oaia in a s'ope basin (one with deep water such ~s < passive continental margin), and a ramp basin (one on the craton lacking very deep water). The depositional facies can be generally identified by the overall lateral relationships, and by the large-scale features such as the slope, the mounds, and the reefs that can be imaged.

measuring a characteristic seismic wavelet for an area, then mathematically combining it with depth, velocity, and density data from sonic logs used to calculate acoustic impedance contrasts. This procedure models or calculates from the sonic log data what the seismic response of the rock units should be. Visual comparison of amplitude and frequency patterns on the synthetic seismogram can be made with the real seismic record to estimate depths (from log depths) to reflections (Figs. 11, 13). Details of synthetic seismogram construction are given in a very understandable and readable form by Anstey (1982). A synthetic seismogram is a very powerful tool for calibrating the seismic response to the stratigraphy of an area, because it shows which lithologic interval is responsible for an individual reflection.

Single-channel seismic data (typical of marine geological investigations ot the upper few hundred metres) are recorded directly onto paper by analog processes. Multi-channel seismic data (collected by the petroleum industry for exploration and development) are recorded digitally to allow subsequent numerical processing by large computers. Seismic processing consists of a complex series of numerical operations performed on the raw data. It is designed to enhance the reliability (reduce multiple internal reflections and spurious reflections), sensitivity (increase signal to noise ratio) and positioning (correct locations of reflections from dipping beds) of the data. It also allows the data to be displayed in an interpretable fashion.

Reflection amplitude, as mentioned above, is a function of acoustic impedance contrast. It is well enough preserved during modern processing that the relative strengths of reflections can be observed. Reflectiorvfrequency (time interval between peaks) depends on the spacing of reflectors as well as processing. Reflection continuity depends on the lateral extent of the reflector. Within a data set of relatively uniform conditions of acquisition, processing, and display, variations in these characteristics may be interpretable in terms of rock properties and sedimentary facies (see Seismic Facies section below).

A typical seismic line through the Venture gas field, Scotian Shelf, is shown in Figure 12. Individual shot points and traces cannot be seen on this scale, but the more or less horizontal dark lines in Figure 12 are reflections like those in the lower left of Figure 11. The seismic line has been annotated with formation names on the left end, and ages on the right.

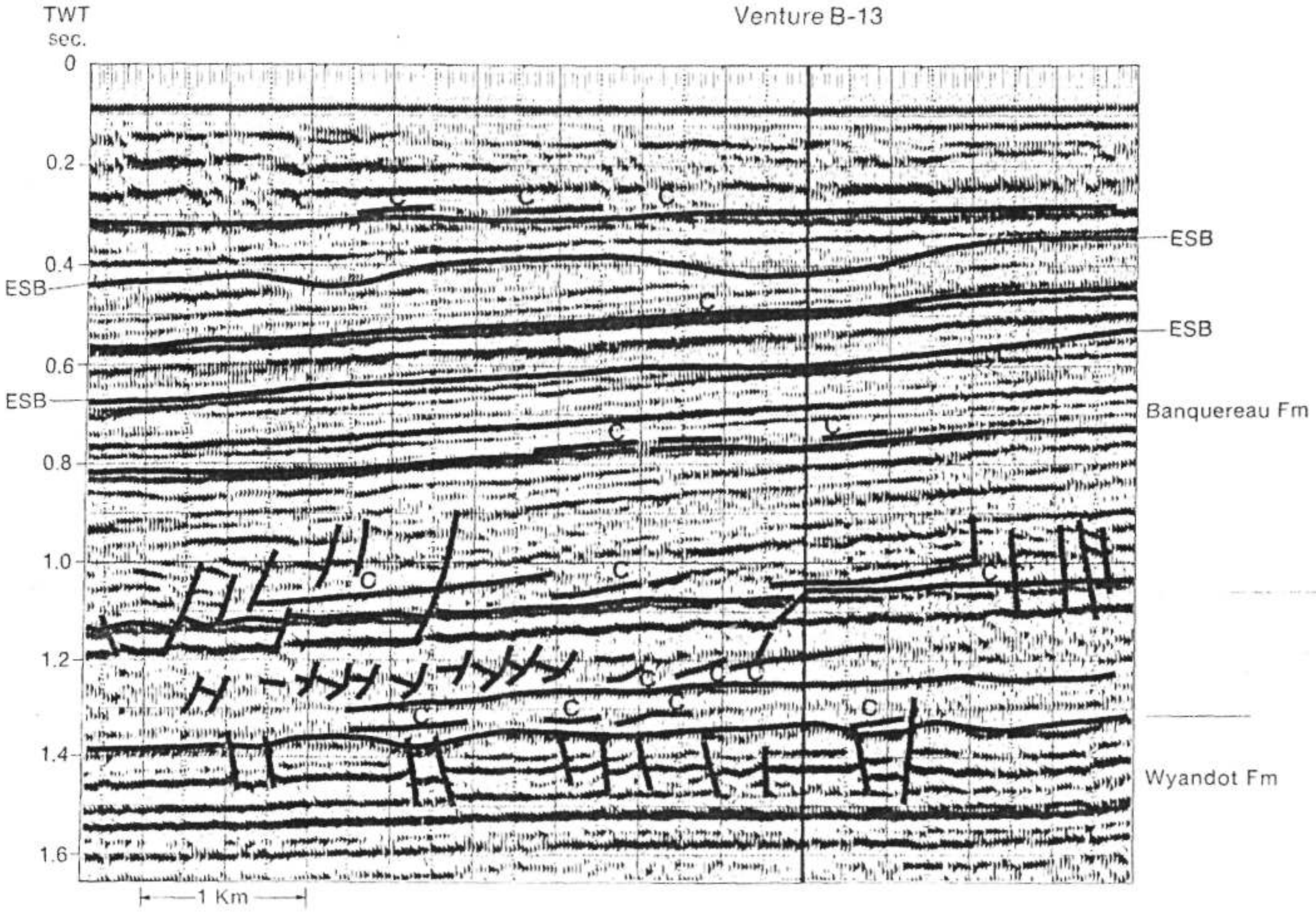


Figure 15 Upper Cretaceous and Tertiary section from the Venture area, Scotian Shelf. Erosional sequence boundaries (ESB) on seismic lines are indicated by truncation or onlap ot reflectors. Clinoforms are indicated by "C". Many rotational normal faults disrupt the clinoform sets at the base of the Banquereau Formation. The^ipJj^irnplitudejeflBctions in the Wyandot Formation originate from chalk beds which are essentially analogous to a co^densed_section, deposited at the peak of the transgiession when clastic input was low.

These data are derived from the two wells, as tied in with synthetic seismograms. In this case, seismic facies sequences were defined on variations in amplitudes, frequencies, and continuities of reflections. The growth faults in the Jurassic section and the minor fractures in the Lower Tertiary were delineated by correlating breaks in reflections. Detailed parts of this line will be discussed later in the chapter.

SEISMIC STRATIGRAPHY

Seismic stratigraphy involves the application of seismic data to the study of regional and global sedimentary sequences and their bounding unconformities. It grew out of investigations performed by the Exxon Production Research Company, summarized initially in Payton (1977). This publication explains many of the fundamentals of large-scale stratigraphic analysis (both seismic and otherwise) and must be understood by anyone attempting this kind of work. The interpretations of relative sea level changes *purely* in terms of eustacy (Vail *et a*/., 1977) have recently been modified by some workers, but the basic principles of seismic stratigraphy are demonstrated in this publication (Payton, 1977).

Figures 11 and 12 emphasize a fundamental condition of seismic stratigraphy, namely that the scale and resolution of multichannel seismic data are very different from outcrop or well-log cross sections. Particularly at great depths where velocities are high, seismic data are generally incapable of resolving stratigraphic features less than 50 to 100 m in thickness. These differences in scale of resolution are emphasized in the example from the Mannville Group of Alberta (Fig. 11), where a gamma-ray log, a synthetic of the well, and a seismic line, show the differences in degree of vertical resolution. Recent detailed work using well-log cross sections (Figures 5 and 9) has revealed several unconformities within the Upper Mannville alone, but these all occur within one *seismic* sequence (definition in Chapter 1). Many recurring stratal patterns are seen on seismic lines that are useful for stratigraphic subdivision and analysis of base-level changes. Figure 13 shows many of the more important configurations and this terminology applied to them. These configurations have been interpreted to result from eustatic variation of sea level, although other mechanisms are now considered possible (Chapter 1). However their origins are interpreted, these configurations are fundamentally important, large-scale features seen on seismic lines and some well-log cross sections.

Seismic reflections are in mos cases generated where sharp lithe logic contrasts occur between succe: sive stratigraphic units. Lateral grad,' tions of lithology or facies cannot t imaged. Sharp stratigraphic contr;.

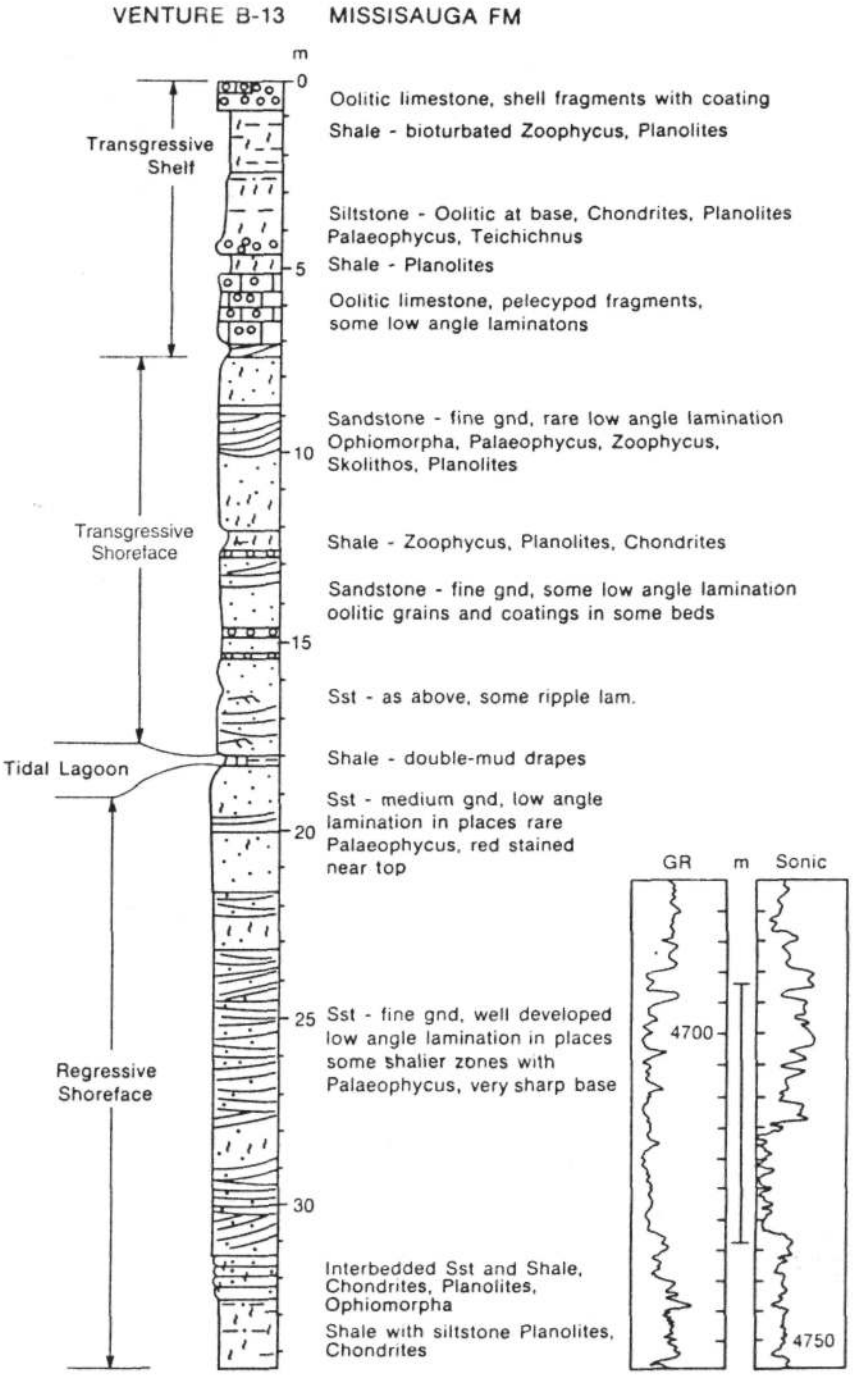


Figure 16 A core log from the Upper Jurassic-Lower Cretaceous Missisauga Formation Scotian Shelf, showing a regressive shoreface sandstone, followed by a transgressive sand stone. The flooding surface occurs at the top of the oolitic carbonates (just above top o *mrp* These transgressive carbonates generate high-amplitude, laterally continuous reflet tions on seismic iines. The patterns of upwaidly increasing reflection amplitude frpquerv and continuity are shown in Figures 12 (curved arrows) and 17.

complex stacking of thalweg sandstones and overbank mudstones in large submarine fan valleys (Fig. 29 in Chapter 13). Similar seismic fades occur in nonmarine fluvialjjeposits. with numerous variable-amplitude, discontJiUJjaiiS-^^BectiQns related to the presence of high-reflectivity coals and discontinuous shales in overbank areas, cut out by sandstone-filled channels. This seismic character differs TrorrTthe much more continuous, more constant amplitude reflections generated from shoreline and shallow-marine elastics (Fig. 12), and from continuous basin floor turbidites (Fig. 31E in Chapter 13). HigjTly_con^ tinuous, high-amplitude reflections fTorn interbedded shelf shales and" limesTones a£e_easily separable In many examples from chaotic, almost .^^TlectiQn-free>TeeTseismic facies. Some generalizations aboDTSTastic seismic facies have been discussed by Sangree and Widmier (1977) and Roksandic (1978), and carbonate seismic facies by Bubb and Hatlelid (1977) and Sarg (1988).

Where uniform seismic data collection, processing, and display have occurred, simple qualitative calibration of reflection characteristics to core and well-log data from a specific area can also be made. This calibration procedure is analogous to the calibration and interpretation of SP or gamma-ray log patterns but is probably even more risky because of the lack of resolution of individual successions on the seismic scale.

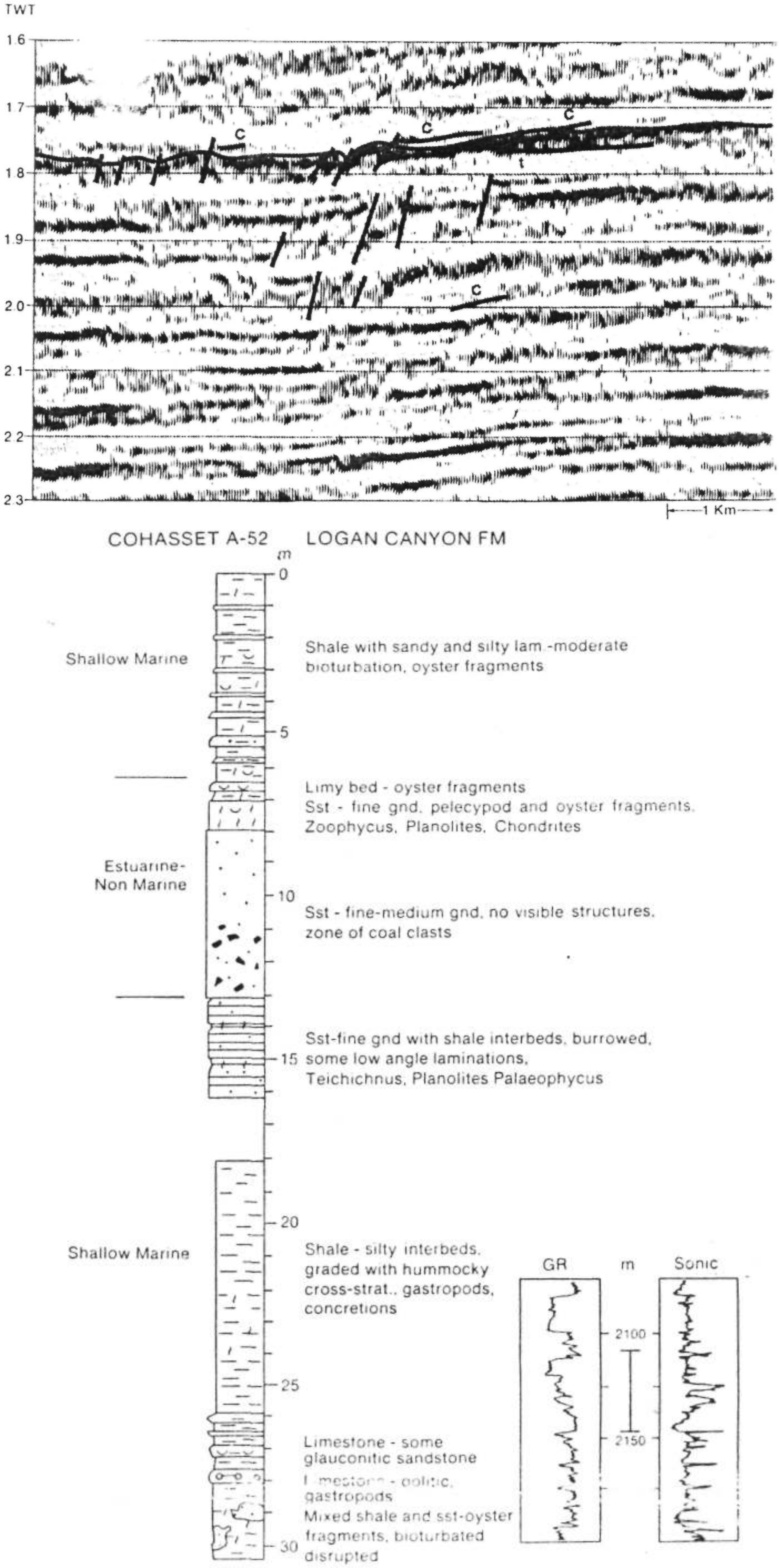


Figure 18 A seismic line with core and well-log control from the Upper Cretaceous Logan Canyon Formation, Scotian Shelf. The core suggests interbedded open marine (from micropaleontology) and estuarine deposits, with erosion and generation of intraclasts and coal clasts. The alternation of open marine and estuarine deposits is interpreted to result from short-period base-level drops which cut erosion surfaces on the shelf (see Chapter 11). The seismic line shows a complete lack of seismic-reflection patterns (compare to Figures 12 and 17). The core is equivalent to the section imaged between 1.9 and 2.0 seconds.

Calibration of well logs, cores and seismic responses: Scotian Shelf

This calibration has been carried out on two intervals of shallow-marine sediments on the Scotian Shelf of eastern Canada. The Upper Jurassic to Lower Cretaceous Missisauga Formation (Fig. 16) consists mainly of stacked coarsening-upward shallow marine to shoreline clastic facies successions, with apparent transgressive shelf deposits as shown by many cores and logs (Fig. 17) from Venture gas field, The transgressive units commonly are capped"b~y oofltlc caroonattTbeds on the flooding surTacesTfiaTgenerate" strong seismic refiectionsTThese surfaces are in many examples overlain by small clinoform sets (C in Fig. 17) of the basal, slightly deeper-water shelf deposits above. The patterns of upward-increasing reflection amplitudes, continuities, and frequencies can be used to interpret the same style of sedimentation in uncored areas.

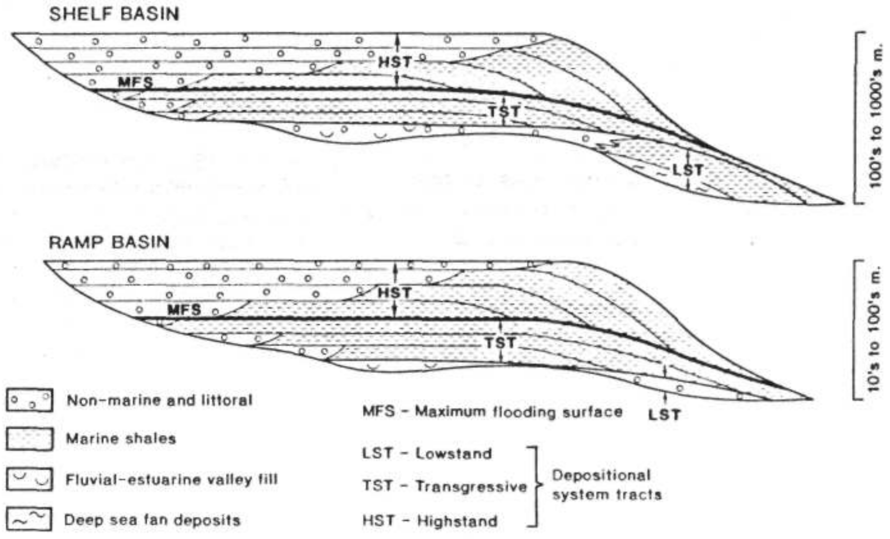


Figure 19 Generalized diagram of systems tracts in unconformity-bounded sequences in shelf and ramp basins. MFS is the maximum flooding surface.

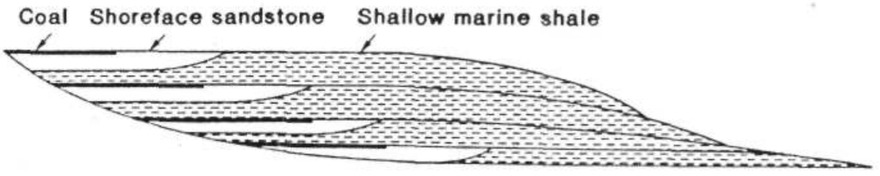


Figure 20 Diagram illustrating four progradational facies successions stacked in an overall retrogradational or transgressive pattern. The stacking pattern is important in determining the systems tract.

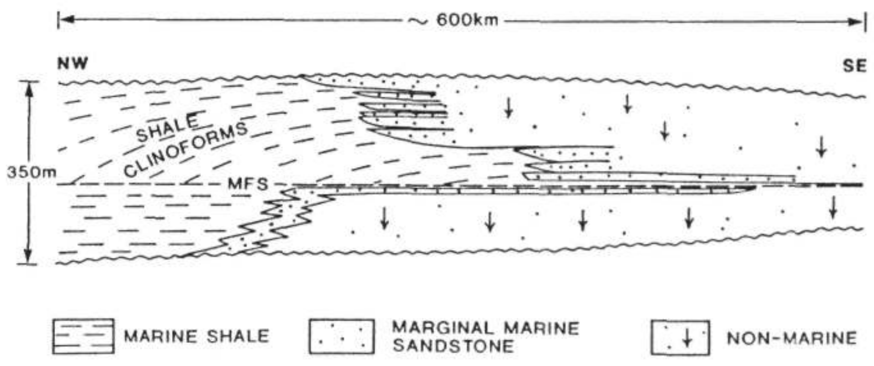


Figure 21 Stratigraphy of the Mannville Group of the Alberta Basin from a proximal area (SE) to a distal one (NW). The lower part of the succession (up to the MFS, maximum flooding surface) consists of a transgressive systems tract, and the upper part is a highstand systems tract. The shale clinoforms are shown in Figure 8. Depositional environments from outcrop and subsurface work are shown.

The shaly Albian to Cenomanian Logan Canyon Formation shows completely different shallow-marine facies in cores (Figs. 12, 18). The sharp-based sandstones do not appear to be parts of regressive coarsening-upward successions; they are more randomly interbedded. On the basis of their sedimentary and biogenic structures in cores, they can be interpreted as estuarine or even nonmarine deposits intercalated within the marine shales. Although well control is not adequate to map incised valleys, it is believed that the basal surfaces of the sandstones represent erosional events resulting from short-term base-level drops.

The seismic response of this shallow-marine facies (Fig. 18) is completely different from that of the Missisauga interval (Fig. 12) discussed above. Amplitudes and times of arrival (depths) of individual reflections vary laterally in an irregular fashion across the interval. No vertical patterns of reflection amplitudes or frequencies can be documented. Some sloping reflections with apparent onlaps exist (Fig. 18) which could be interpreted as delineating erosion surfaces, but resolution of these is poor. Small (less than 50 m high), laterally restricted clinoforms and minor growth faults also occur in places (Fig. 18). The overall aspect of the seismic response of this interval is an absence of patterns of any seismic attributes, either vertically or horizontally. The discontinuous reflections have variable amplitudes which are not organized into any larger-scale patterns; this is due to lateral variation in the amount of sandstone, minor growth faults, and absence of major transgressive or condensed horizons. This seismic facies should be contrasted with the packages of upwardly increasing reflection amplitudes, frequencies and continuities shown in Figure 17.

LARGE-SCALE FACIES RELATIONSHIPS

Subsurface work has contributed a great deal in recent years to knowledge of large-scale facies relationships. It has particularly helped in understanding the way in which facies successions relate to one another and to the different types of L ding surfaces. This section presents, in the most abbreviated form possible, a few of the most general conclusions achieved by subsurface study of these large-scale relationships.

Large-scale facies associations can be grouped into depositional systems tracts, depending on relationships to allostratigraphic bounding discontinuities, positions in the basin with respect to other systems tracts, and whether they have overall progradational or retrogradational patterns (Fig. 19). Depositional systems tracts are associated with specific bounding discontinuities. For example, a transgressive systems tract is capped by a maximum flooding surface or condensed section (Fig. 19), whereas a highstand systems tract is capped by an unconformity (Fig. 19). The facies associations or systems tracts are normally composed of several vertical facies successions (Fig. 20). Individual successions do not necessarily show the same trend. The associations of bounding discontinuities systems tracts have been reviewed by Posamentier and Vail (1988). These authors interpret the organization of depositional systems and erosional discontinuities almost entirely in terms of eustatic sea level variation. However, other interpretations can be made in terms of tectonic subsidence and variations in the rate of sedimentation. An example of this is shown in Figure 21, from the Lower Cretaceous Mannville Group of Alberta. The Lower to Middle Mannville (below MFS **in** Fig. 21) comprises a lowstand to transgressive systems tract made up of individual progradational facies successions. The thin shale directly above the Bluesky Sandstone contains the maximum flooding surface, as shown by regional cross sections. The Upper Mannville is **a** strongly progradational highstand depositional systems tract. The stratigraphy of this clastic wedge has been interpreted as the result of variations in tectonic subsidence and sediment supply rates from the Cordillera to '"« fo^{roi}»nH basin, rather than eustailc variations in sea level. The Mannville systems tracts occur in the same arrangement as she. in Figure 19, but the interpretat ay differ from that of Posan, and Vail (1988).

Large ,ale subsurface analysis in terms of systems tracts has *i.* ed to a greater understanding of relate ^hips between siliciclastic and carbonate sediments in many areas. Figure 22 shows a cross section of one side of a basin rimmed by carbonate banks and reefs. The basin centre facies was deposited beyond the bank edge, and consists dominantly of sandstones and shales. The relationships between these systems tracts imply that elastics were supplied from the land and transported across the carbonate shelf, probably in incised valleys during periods of relative sea level fall. At the slope break, they were deposited as deltas, shorelines, or deep sea fans, depending on the local basin depth compared to sea level. During subsequent transgressions, some shelves were covered by thin siliciclastics but others completely lack this facies. Rapid production of carbonate sediments during the relative rising sea level phase allowed aggradation and progradation of the carbonate complex (Chapter 18). This kind of alternating highstand-lowstand deposition of carbonates and elastics has been termed reciprocal sedimentation. Most well-established examples have been imaged on seismic lines, but well-log cross sections and rare outcrops also show these relationships.

CONCLUSIONS

Large-scale subsurface facies analysi' combined with allostratigraphy and/ sequence stratigraphy, is now one of tl most dynamic fields of research in sec mentary geology. Comparison of th volume with previous editions of *Fact Models* shows the increase in unde standing of sedimentary systems ar the extent of the contribution of subsu face work. While many ideas about inc vidual facies have not changed marked; in the last ten years, ideas of facies relr tionships and the nature and signif cance of the bounding surfaces betwee them have been revolutionized.

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An exceptionally entertaining book e plaining the basics of the seismic metho Nonmathematical, for nonspecialists.

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An excellent introduction to well-log an, lysis, directed at the interpretation of tlun in rocks by use of mathematical equatioi and calibrations. Very clearly presented -

Payton, C.E., 1977, Seismic stratigraphy applications to hydrocarbon explorative American Association of Petroleui Geologists, Memoir 26, 516 p.

A basic, necessary reference, no\ somewhat dated by advances in th: field.

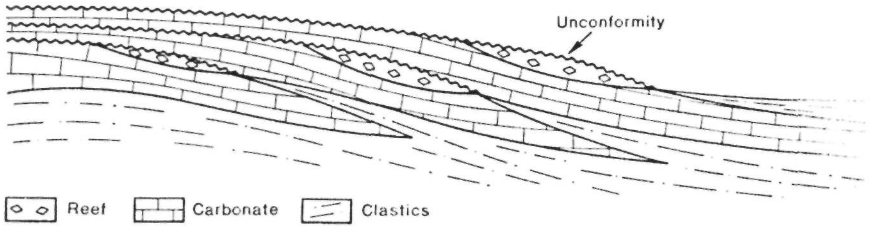

Figure 22 Cross section illustrating a succession that results from "reciprocal" sedimentation. Note that carbonate platforms and bank edges intertongue basinward with elastics, commonly sandstones proximally and shales distally. This configuration of lithofacies is interpreted to result from a carbonate shelf prograding and aggrading under conditions of rising relative sea level. During a base-level drop, the elastics are transported througf breaks and channels in the carbonate margin, and deposited either as turbidites and othei deep sea deposits, or in other situations as coarse-grained deltas. Because of the low rela tive sea level, carbonate deposition is minimal at that time. Thus relative sea level fluctua tic" r$^{o<}$=u!ts ;n deposition o! i lighsicrd carbonates aiiernating with iow.,innu riacti^e m Il-.I seliing. The cross station is a composite from the Permian Guadeloupe P.cct Complc- west Texas, and seismic lines across the northwest Australian shelf.

Van Wagoner, J.C., Mitchum, R.M. Jr., Posamentier, H.W. and Vail, P.R., 1987, Key definitions of sequence stratigraphy, *in* Bally, A.W., ed., Atlas of seismic stratigraphy. American Association of Petroleum Geologists, Studies in Geology 27, p. 11-14.

Many basic definitions presented graphically in a large format. All the genetic associations of sequence stratigraphy are shown, with the assumption that eustatic sea level variation is the controlling parameter of stratigraphic units.

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