Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis

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Abstract A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities. This concept of a “sequence” is modified from Sloss. A depositional sequence is determined by a single objective criterion, the physical relations of the strata themselves. The combination of objective determination of sequence boundaries and the systematic patterns of deposition of the genetically related strata within sequences makes the sequence concept a fundamental and extremely practical basis for the interpretation of stratigraphy and depositional facies. Because distribution and facies of many sequences are controlled by global changes of sea level, sequences also provide an ideal basis for establishing comprehensive stratigraphic frameworks on regional or global scales.

A depositional sequence is chronostatigraphically significant because it was deposited during a given interval of geologic time limited by ages of the sequence boundaries where the boundaries are conformities; however the age range of the strata within the sequence may differ from place to place where the boundaries are unconformities. The hiatus along the unconformable part of a sequence boundary generally is variable in duration. The hiatus along the conformable part is not measurable, and the surface is practically synchronous. Stratigraphic units within a sequence are essentially synchronous in terms of geologic time.

Depositional sequences may range in thickness from hundreds of meters to a few centimeters. Sequences of different magnitudes may be recognized on seismic sections, well-log sections, and surface outcrops.

To define and correlate a depositional sequence accurately, the sequence boundaries must be defined and traced precisely. Usually the boundaries are defined at unconformities and traced to their correlative conformities. Discordance of strata is the main criterion used in the determination of sequence boundaries, and the type of discordant relation is the best indicator of whether an unconformity results from erosion or nondeposition. Onlap, downlap, and toplap indicate nondepositional hiatuses; truncation indicates an erosional hiatus unless the truncation is a result of structural disruption.

Examples of depositional sequences are presented on well-log and seismic sections. Both examples depend primarily on correlation of physical stratigraphic surfaces for identification of the unconformities bounding the sequences, and on biostratigraphic zonation for determination of the geologic ages of the sequences.

INTRODUCTION

This paper defines the depositional sequence, describes its chronostratigraphic significance and scale, discusses the significance of unconformities and their correlative conformities as sequence boundaries, discusses the relation of strata to sequence boundaries, and gives examples of deposi-

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FIG. 1—Basic concepts of depositional sequence. A depositional sequence is a stratigraphic unit composed of relatively conformable successions of genetically related strata and bounded at its top and base by unconformities or their correlative conformities.

A. Generalized stratigraphic section of a sequence. Boundaries defined by surfaces A and B which pass laterally from unconformities to correlative conformities. Individual units of strata 1 through 25 are traced by following stratification surfaces, and assumed conformable where successive strata are present. Where units of strata are missing, hiatuses are evident.

B. Generalized chronostratigraphic section of a sequence. Stratigraphic relations shown in A are replotted here in chronostratigraphic section (geologic time is the ordinate). Geologic-time ranges of all individual units of strata given as equal. Geologic-time range of sequence between surfaces A and B varies from place to place, but variation is confined within synchronous limits. These limits determined by those parts of sequence boundaries which are conformities. Here, limits occur at beginning of unit 11 and end of unit 19. A sechron is defined as maximum geologic-time range of a sequence.)
Sequence as a Unit for Analysis

The hiatus represented by the unconformable part of a sequence boundary generally is variable. It may range from about a million years to hundreds of millions of years; however, the unconformity is chronostratigraphically significant because, in general, rocks above an unconformity are everywhere younger than those below it. The conformable part of a sequence boundary is practically synchronous because the hiatus is not measurable; the time span generally is less than a million years. The physical surfaces that separate groups of strata or individual beds and laminae within a sequence are essentially synchronous (Part 5, Vail et al, this volume). Some may form in instants of geologic time as discussed by Campbell (1967).

Boundaries of lithostratigraphic units such as formations and lithofacies units may be parallel to stratal surfaces, or in the case of diachronous lithostratigraphic boundaries, may cross stratal surfaces (see Campbell 1967, 1971, and 1973; Part 5, Vail et al, this volume). Because these gradational formations and lithofacies boundaries are diachronous, they practically are useless in seismic chronostratigraphic analyses, although they may be significant in seismic facies analyses.

Hedberg (1976, p. 92) recognized that unconformity-bound units (synthsms) have great significance in chronostratigraphy because unconformities frequently serve as guides to the approximate placement of chronostratigraphic boundaries. However, he indicated that such units cannot be chronostratigraphic units because they are not bounded by synchronous (isochronous) surfaces. In contrast to those of a synthem, the boundaries of a depositional sequence are conformable and, therefore, synchronous in many places. A depositional sequence has chronostratigraphic significance because all the rocks of the sequence were deposited during the interval of geologic time defined by the ages of the sequence boundaries where they are conformities.

A depositional sequence may have more significance in geologic history than a unit bounded only by synchronous surfaces that are chosen arbitrarily. A sequence represents a genetic unit that was deposited during a single episodic event, whereas the arbitrarily chosen unit may span two or more incomplete portions of genetic depositional units, and therefore not accurately portray the depositional history.

A sechon (from sequence and chron time) is defined as the total interval of geologic time during which a sequence is deposited. As shown on Figure 1, a sechon is determined as the time interval between the upper and lower sequence...
boundaries where they are conformities. Because the conformities at the base and the top of a depositional sequence may lie in different areas, it may not be possible to date the entire sechon at a single locality. Where the lower and/or upper boundaries of a depositional sequence are unconformities, partial sechons would be determined that may differ in duration from place to place. Further aspects of the chronostratigraphic significance of depositional sequences are discussed in the sections on sequence boundaries and the relations of the strata to the boundaries.

**MAGNITUDE OF DEPOSITIONAL SEQUENCES**

A depositional sequence generally is tens to hundreds of meters thick, although the range may be from thousands of meters down to a few millimeters. In general, the smaller scale sequences can be correlated only very short distances. Also, there are practical limits imposed by the resolution limits of the correlation tool (seismic sections, well-log correlations, or outcrops).

Depositional sequences can be identified on seismic sections (seismic sequences can be correlated only to the nearest reflection cycle). At the present resolution of good data, a seismic reflection represents a unit of strata with a minimum thickness of several tens of meters. If such strata are continuous, sequences can be traced by seismic-cycle correlation for tens or hundreds of kilometers in a dip direction across a basin, and even farther in a strike direction. Seismic reflections tend to parallel stratification surfaces, rather than the gross boundaries of lithologic units that may cut across stratification surfaces (Part 5, Vail et al, this volume). Thus a seismic reflection correlation approaches a chronostratigraphic correlation, and the result provides a level of geologic synchrony that is commensurate with the scale of strata represented. However, a reflection may terminate on a seismic section owing to a thinning of the unit of strata represented, and this unit may continue below the resolution of the seismic tool. Where most pre-Quaternary seismic sequences, have been dated by biostratigraphy from well samples, they generally compare in duration to standard chronostratigraphic units of about stage or series rank, and cover a geologic-time span on the order of 1 to 10 million years (Part 4, Vail et al, this volume).

Depositional sequences determined by correlation with closely spaced well logs may be smaller in scale than sequences on seismic sections. Not only are the larger scale (seismic) sequences recognized, but sequences of intermediate size may also be detected within them. With fine electric or radioactivity tools, stratigraphic units may be differentiated on logs down to a thickness of a meter or even less. Because stratification surfaces generate both seismic reflections and well-log responses, both these tools may be used to make accurate chronostratigraphic correlations. However, log-marker correlation can be made to a more precise level of geologic synchrony because unconformities involving smaller units of strata can be recognized. Generally, the smaller sequences detected by log correlation are at a lower order of magnitude than many standard chronostratigraphic units. The major disadvantage of well-log correlation is the lack of continuous correlation between wells, although closely spaced well control can be nearly as effective as seismic correlation.

The most detailed chronostratigraphic correlation can be reached with stratum correlation in cores or good exposures of surface outcrops, where individual beds or even laminae can be traced (Campbell, 1967). Control usually limits drastically the areal extent over which stratigraphic relations can be made. However, within the smallest stratigraphic units recognized with log-marker units, one may see terminations of bedding against log-marker unit boundaries and terminations of laminae against bedding surfaces. Thus, at least two additional levels of more precise geologic synchrony are indicated by these smaller unconformities (or diastems).

**BOUNDARIES OF DEPOSITIONAL SEQUENCES**

To define and correlate a depositional sequence accurately, the sequence boundaries must be defined and traced. Usually, the boundaries are defined at unconformities based on discordant relations of strata to unconformities. Also, the geologic ages of the rocks above and below the unconformity are determined to provide a measure of the hiatus at a given location. As a particular sequence boundary is traced laterally, the strata may become concordant, but enough of a hiatus may still be evident to continue the designation of an unconformity (a paraconformity). Finally, the boundary may be traced between concordant strata to a place where there is no evidence of a hiatus, and the unconformity has been traced into its correlative conformity (Fig. 1).

**Unconformities and Conformities**

An *unconformity* is a surface of erosion or non-deposition that separates younger strata from older rocks and represents a significant hiatus (at least a correlative part of a geochronologic unit is not represented by strata). A *conformity* is a surface that separates younger strata from older rocks, but along which there is no physical evi-
dence of erosion or nondeposition, and no significant hiatus is indicated.

Dunbar and Rodgers (1957, Fig. 57) illustrated the conventional classification of unconformities and defined the familiar terms nonconformity, angular unconformity, disconformity, and paraconformity. That classification places more emphasis on the angularity or parallelism of the strata above and the strata below the unconformity than on the relation of strata to the unconformity itself. Although this criterion gives some indication of the degree of folding that took place prior to the deposition of the strata above, it is of little value in chronostratigraphy, so we rarely use the conventional classification of unconformities.

**Hiatuses**

A hiatus is the total interval of geologic time that is not represented by strata at a specific position along a stratigraphic surface. If the hiatus encompasses a significant interval of geologic time, the stratigraphic surface is an unconformity (Fig. 1).

To place a sequence within the standard chronostratigraphic framework, some measurement of the hiatuses along the unconformable sequence boundaries must be made. Also, the conformities that mark the maximum geologic-time range (sechon) of a sequence are determined only where the hiatuses along the sequence boundaries are shown to have decreased to an insignificant interval of geologic time.

Ideally, the hiatus is measured quantitatively by some radiometric method. In practice, the hiatus commonly is measured in qualitative units (such as periods, epochs, or faunal zones) by biostratigraphy, paleomagnetic reversal correlations, or some other method. These units are then correlated to a radiometric scale to make a best estimate of the age in millions of years.

The concept of the magnitude of a hiatus along a sequence boundary is analogous to the concept of the magnitude of a sequence. The order of magnitudes depends on the degree of resolution of the tool used. Whereas a seismic sequence commonly encompasses a geologic-time span of a few million years, its absence suggests a hiatus of that magnitude. A well-log sequence that is smaller than a seismic sequence may be used to detect a hiatus ranging in magnitude from a million years to hundreds of thousands of years. Although a very small-scale sequence of bedsets or laminasets can be used to determine a hiatus of very short duration, it commonly falls below the practical limit of what may be considered a significant hiatus, and so it would not be used to define an unconformity.

Hiatuses may be attributable either to erosion or to nondeposition of strata, or to both. As shown on Figure 1 the distinction is based on whether the strata in a depositional sequence terminate against a boundary as a result of erosional truncation or by lapout.

**RELATIONS OF STRATA TO SEQUENCE BOUNDARIES**

Figure 2 illustrates concordant and discordant relations of strata to boundaries of depositional sequences. These relations are based on the parallelism, or the lack of it, between the strata and the boundary surface itself. If the strata both above and below a surface are concordant (that is, essentially parallel to it), then there is no physical evidence of an unconformity along that part of the surface. On the other hand, if either the strata above or the strata below a surface are discordant (if they terminate against it), then there is physical evidence of an unconformity (or structural disruption).

Concordant relations may be seen at the upper or lower boundary of a depositional sequence. The concordance may be recognized as parallelism of a stratum to an initially horizontal, inclined, or uneven surface. At the base of a sequence, the concordance may be expressed as parallel draping over a bottom irregularity (Fig. 2).

Discordance is the main physical criterion used in the determination of sequence boundaries. The type of discordant relation is the best indicator of whether an unconformity results from erosion or nondeposition. The direction of progressive termination from older to younger strata above the unconformity is the direction of increasing nondepositional hiatus along the unconformity.

The type of discordance is based on the manner in which strata terminate against the unconformable boundary of a depositional sequence (or a structural boundary). **Lapout** is the lateral termination of a stratum at its original depositional limit. **Truncation** is the lateral termination of a stratum as a result of being cut off from its original depositional limit. More specific types of discordance and their significance in stratigraphic analysis are given below. They are determined with greater confidence where several strata within the sequence show a systematic pattern of discordance along a given surface.

**Baselap: Onlap, Downlap**

Baselap is lapout at the lower boundary of a depositional sequence. Two important types are recognized. **Onlap** is baselap in which an initially horizontal stratum laps out against an initially in-
clined surface, or in which an initially inclined stratum laps out updip against a surface of greater initial inclination. Downlap is baselap in which an initially inclined stratum terminates downdip against an initially horizontal or inclined surface.

Onlap or downlap usually can be readily identified. However, later structural movement may necessitate the reconstruction of depositional surfaces. In areas of great structural complication, the discrimination between onlap and downlap may be practically impossible, and the worker may be able to determine only that the strata are in a baselap relation.

The diagrammatic illustrations in Figure 2 are two-dimensional representations, and the assumption generally may be made that the sections are in the dip direction, and that strike sections at right angles would show essentially horizontal traces of strata. However, a two-dimensional section may show an apparent onlap and a section at right angles to it could show true downlap. If two sections intersecting at right angles both show apparent onlap, then true onlap is the likely relation.

The regional positions of proximal onlap (onlap in the direction of the source of sediment supply) and distal onlap (onlap in a direction away from source of sediment supply) commonly mark the lateral beginning and the lateral ending of deposition of a given stratum (or unit; Fig. 1). In narrow or regionally confined depositional sites, distal onlap (onlap in a direction away from the source of sediment supply) is commonly encountered, for example against the opposite side of a basin. In some depositional sites, the pattern of distal onlap may be controlled more by local bottom irregularities than by the proximal or distal relations to sediment supply.

Onlap and downlap are indicators of nondepositional hiatuses (Fig. 1) rather than erosional hiatuses. Successive terminations of strata at their depositional limits along the initial depositional surface produce an increasing nondepositional hiatus in the direction of onlap or downlap.

Toplap

Toplap is laid out at the upper boundary of a depositional sequence. Initially inclined strata,

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**FIG. 2.—Relations of strata to boundaries of depositional sequences:**

A. Relations of strata to upper boundary of a sequence. A1. Erosional truncation: strata at top of given sequence terminate against upper boundary mainly as result of erosion (e.g., tilted strata terminating against overlying horizontal erosion surface, or horizontal strata terminating against later channel surface). A2. Toplap: initially inclined strata at top of given sequence terminate against upper boundary mainly as result of nondeposition (e.g., foreset strata terminating against overlying horizontal surface at base-level equilibrium where no erosion or deposition took place). A3. Top-concordance: relation in which strata at top of given sequence do not terminate against upper boundary.

B. Relations of strata to lower boundary of a sequence. B1. Onlap: at base of sequence initially horizontal strata terminate progressively against initially inclined surface, or initially inclined strata terminate updip progressively against surface of greater initial inclination. B2. Downlap: at base of sequence initially inclined strata terminate downdip progressively against initially horizontal or inclined surface (e.g., initially inclined strata terminating against underlying initially horizontal surface). B3. Base-concordance: strata at base of sequence do not terminate against lower boundary.
such as foreset beds and clinoforms, may show this relation. The lateral terminations updip may taper and approach the upper boundary asymptotically. On seismic sections, the resolution may be such that reflections appear to terminate abruptly against the upper surface at a high angle.

Toplap is evidence of a nondepositional hiatus. It results from a depositional base level (such as sea level) being too low to permit the strata to extend farther updip. During the development of toplap, sedimentary bypassing and possibly minor erosion occurs above base level while prograding strata are deposited below base level. Although toplap commonly is associated with shallow marine deposits, such as deltaic complexes, it may also occur in deep-marine deposits (such as fans) where depositional base level is controlled by turbidity currents and other deep-water processes.

Truncation: Erosional and Structural

Erosional truncation is the lateral termination of a stratum by erosion. It occurs at the upper boundary of a depositional sequence; and it may extend over a wide area or be confined to a channel. Strata tilted by structural movement commonly have their updip limits truncated by subaerial or submarine erosion, and the reconstruction to the original depositional limits of onlap or toplap may be a difficult choice. In some cases, the distinction of toplap and erosional truncation may be difficult, but in the latter relation the strata tend to maintain parallelism as they terminate abruptly against the upper boundary rather than taper to it. Such truncation is evidence of an erosional hiatus.

Structural truncation is the lateral termination of a stratum by structural disruption. Such truncation is most easily recognized where it cuts across the strata within a sequence or a group of sequences. The disruption may be produced by faulting, gravity sliding, salt flowage, or igneous intrusion. The distinction between erosional and structural truncation may be difficult, but it should be made before further stratigraphic analyses are attempted. Although structural truncation may produce a discordant relation of strata to a sequence boundary, such disruption has minor, if any, regional chronostratigraphic significance with respect to unconformities or hiatuses.

EXAMPLES OF DEPOSITIONAL SEQUENCES

Figures 3 and 4 are examples of depositional sequences on well-log and seismic sections, respectively. These examples depend primarily on physical stratigraphy for identification of the unconformities at the sequence boundaries, and on biostratigraphic zonation for determination of the geologic ages of the sequences.

Well-Log Section

Figure 3 is a subsurface cross section from the Western Canada basin of northeastern British Columbia prepared by G. T. MacCallum and provided by Imperial Oil, Limited. The stratigraphic relations are determined by detailed logmarker correlation, including the discordances which are used to determine sequence boundaries. The following features are associated with each sequence: (1) sequence J with erosional truncation at its top; (2) sequence SR-1 with onlap at its base and concordant strata at its top; (3) sequences SR-2, 3, and 4 with downlapping strata at their bases and subtle toplap above; (4) sequence SR-5 with discordant strata at its base and top; and (5) sequence SR-6 similar to SR-4.

Each sequence has an internal stratification pattern that is genetically significant. For example, the marine Jurassic sequence (J) is made up of even, parallel strata. The Lower Cretaceous Gething Formation (G) is a nonmarine sequence of discontinuous sandstones and shales which are difficult to correlate on the electric logs. The thin basal sequence of the Spirit River Formation (SR-1) is a littoral deposit of sandstone and shale which tends to fill in the lows of the unconformity on top of the Gething (G). In contrast, the overlying sequences of the Spirit River (SR-2 to 6) consist of sandstones and shales which exhibit marked progradation into deep water. Note how the undaform sandstones at the tops of these sequences exhibit toplap.

Seismic Section

Figure 4 is a seismic section from offshore northwestern Africa. It trends parallel with depositional dip and encompasses units ranging in age from Triassic to Quaternary as projected from surface geology and well control. The physical stratigraphic relations have been worked out by means of detailed correlation of seismic reflections. The same principles of interpretation used with the well-log example apply equally well to this seismic example. However, on the seismic data, larger-scale features are recognized more easily, and continuity of reflection cycles provides a degree of correlation reliability not easily obtained with logs, especially where wells are far apart. Moreover, the fact that much of the physical stratigraphy can be interpreted before drilling emphasizes the advantage of the seismic approach.

In this particular example, the seismic section has been given the following stratigraphic interpretation. The oldest unit correlated is the Trias-
FIG. 3—Subsurface section from western Canada showing sequences defined by well-log marker correlation (prepared by G. T. MacCallum, and provided by Imperial Oil, Ltd.) Marker correlation of closely spaced well logs displays depositional patterns of Lower Cretaceous strata in northwestern British Columbia. Erosion truncation of Jurassic beds (surface J), onlap of lowermost Spirit River onto Gething (surface G), and progressive downlap and minor onlap of prograding upper Spirit River beds are used to determine several sequence boundaries.
FIG. 4—Seismic section from offshore northwest Africa showing sequences defined by seismic reflections. Systematic reflection termination patterns used to determine downlap, onlap, truncation, and toplap of strata at sequence boundaries. Geologic ages of sequences determined from wells on section and in surrounding area. Age notations explained in text.
sicc (TR) shown on the eastern half of the section. (Paleozoic and Precambrian rocks occur in the region but are not differentiated here). Five sequences have been designated within the Jurassic (see Part 8, Vail et al, this volume). The Lower Jurassic (J1) strata onlap the somewhat irregular unconformity at the base of this sequence. Low-angle downlap characterizes the bases of the Middle Jurassic (J2) sequences. The upper reflections of the lower Middle Jurassic (J2.1) are in a classic undaiform-clinoform-fondoform relation (Rich, 1951). The lower Upper Jurassic (J3.1) and the Upper Jurassic—Berriasian (J3.2) sequences are similar to the Middle Jurassic, but their deposition culminates in an impressive carbonate shelf margin with a well-developed reef.

The Valanginian sequence (K1.1) is areally restricted to the basin in front of the shelf and consists of deep-marine clastic deposits with high initial dips at both the onlap and downlap terminations.

A great thickness of Lower Cretaceous shales and deltaic sandstones loaded the platform built during Jurassic time and produced a major system of down-to-basin faults and mobile shale structures. Three sequences recognized by downlap and onlap within the Lower Cretaceous are: Hauterivian to lower Aptian (K1.2), middle to upper Aptian (K1.3), and Albian to lower Cenomanian (K1.4). A thin unit of marine shelf deposits is designated as Upper Cretaceous (K2).

The boundary between the Cretaceous and Tertiary is marked by a sloping surface with submarine erosional truncation. A thin unit of early Tertiary age (Paleocene to lower Oligocene [T1, 2]) lags out basinward. The middle Tertiary sequences (middle to upper Oligocene [TO2, 3]; lower Miocene [TM1]) of deep-marine shales onlap steeply updip to terminate shelfward against lower Tertiary rocks. Upper Tertiary (middle Miocene [TM2], upper Miocene [TM3], and Pliocene [TPL1, 2]) and Quaternary shales (Q) form a complex set of prograding and onlapping sequences. Probably most of the Albian to pre-middle Oligocene sequences extended originally over the eastern part of the section, but during Oligo-Miocene time they were uplifted and eroded from this shelf area.

Much information can be determined from analysis of sequences on seismic sections, even without well control. However, stratigraphic analyses are best documented where sufficient well control is available to date the sequences and determine their depositional facies.

REFERENCES CITED