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CHRONOSTRATIGRAPHIC ANALYSIS AND THE TIME SURFACE

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RESUMEN

La estratigrafía clásica comprende subdivisiones lógicas de los estratos basados en la litología, fósiles y discordancias. Las implicaciones filosóficas participan en el resurgimiento de la historia geológica de una cuenca sedimentaria, cuando se hacen esfuerzos para subdividir los estratos en cualquier localidad, basándose estrictamente en el tiempo. Debido a que la subdivisión es prerrequisito de la correlación y la correlación infiere equivalencias de tiempo de las unidades, los esfuerzos del estratígrafo deben de comprender el reconocimiento de criterios, el establecimiento de parámetros y la correlación y características de amplias áreas isocrónicas, para entender la historia tectónica de una cuenca sedimentaria. El reconocimiento de los eventos cronostratigráficos anotados en los registros litológicos de las secciones aflorantes, las descripciones litológicas y detalladas de las muestras de los pozos, así como la utilización de registros geofísicos detallados de los pozos, sugieren que todas las secciones estratigráficas tienen, inherentes a ellas, indicadores que son esencialmente isocrónicos y para fines prácticos son altamente confiables para la correlación en la misma cuenca y la delineación de las zonas de porosidad que controlan la migración y acumulación de petróleo.

ABSTRACT

Classical stratigraphy involves logical subdivision of strata based on lithology, fossils, and unconformities. Strong philosophic implications enter into the resurrection of the geologic history of a sedimentary basin when efforts are made to subdivide strata at any point based strictly on time. Because subdivision is prerequisite to correlation, and correlation infers time equivalence of stratal units, the efforts of the stratigrapher must involve the recognition of criteria, establishment of parameters, and correlation of characteristics over wide areas, hopefully, isochronic, in order to understand the tectonic history of a basin of sediment deposition. The recognition of chronostratigraphic events recorded on lithologic logs of outcrops, sections, and by detailed lithologic descriptions of well samples, as well as utilization of detailed geophysical logs of wells, suggests that all stratigraphic sections have, inherent to them, markers which are essentially isochronous, and, for all practical purpose, are highly reliable for intra-basin correlation and the delineation of porosity zones that control the migration and accumulation of petroleum.

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INTRODUCTION

Subsurface stratigraphers, utilizing geophysical and sample logs, have long recognized the existence and value of markers in stratigraphic sections. These markers facilitate the subdivision of strata into correlative units controlled by many geologic events involved in the filling of a sedimentary basin. Refined geophysical logging techniques developed since 1940, coupled with adequate drilling density, have given us the stratigraphic tool of thin, easily recognizable, regional lithologic markers which are correlative, separating sedimentary increments that contain important facies gradations. Two problems, other than the relative capabilities of the stratigraphic investigator, have always been uppermost: (1) Are the markers truly isochonous, or nearly enough so that their utilization is valid? (2) What are the origins of markers? Although stratigraphers have long argued the validity of markers as indicators of synchroneity, few have attempted to determine the origin of these markers. Both of these problems have led this investigator to consider the practical and philosophical implications of marker-controlled stratigraphy.

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THE MARKER

TERMINOLOGY.—Harrington (1965), in a classical paper entitled "Space, Things, Time, and Events — An Essay on Stratigraphy", has noted that sedimentation is characterized by geologic situations involving instantaneous events and flow events. In order to facilitate discourse in utilitarian terms applicable to stratal logs, whatever the type, the following terminology is suggested:

Event	*Log Term*	*Characteristic*
Instantaneous	Punctuation	Thin sediment increments with low facies gradients, radically different from character spans above and below.
Flow	Character span	A sediment increment with log character correlation over wide area despite facies gradation of high gradient.
Vacuity	Punctuation	Absence of sediment but presence of recognizable log punctuation in base, on top, or both, of adjacent sediment increments.

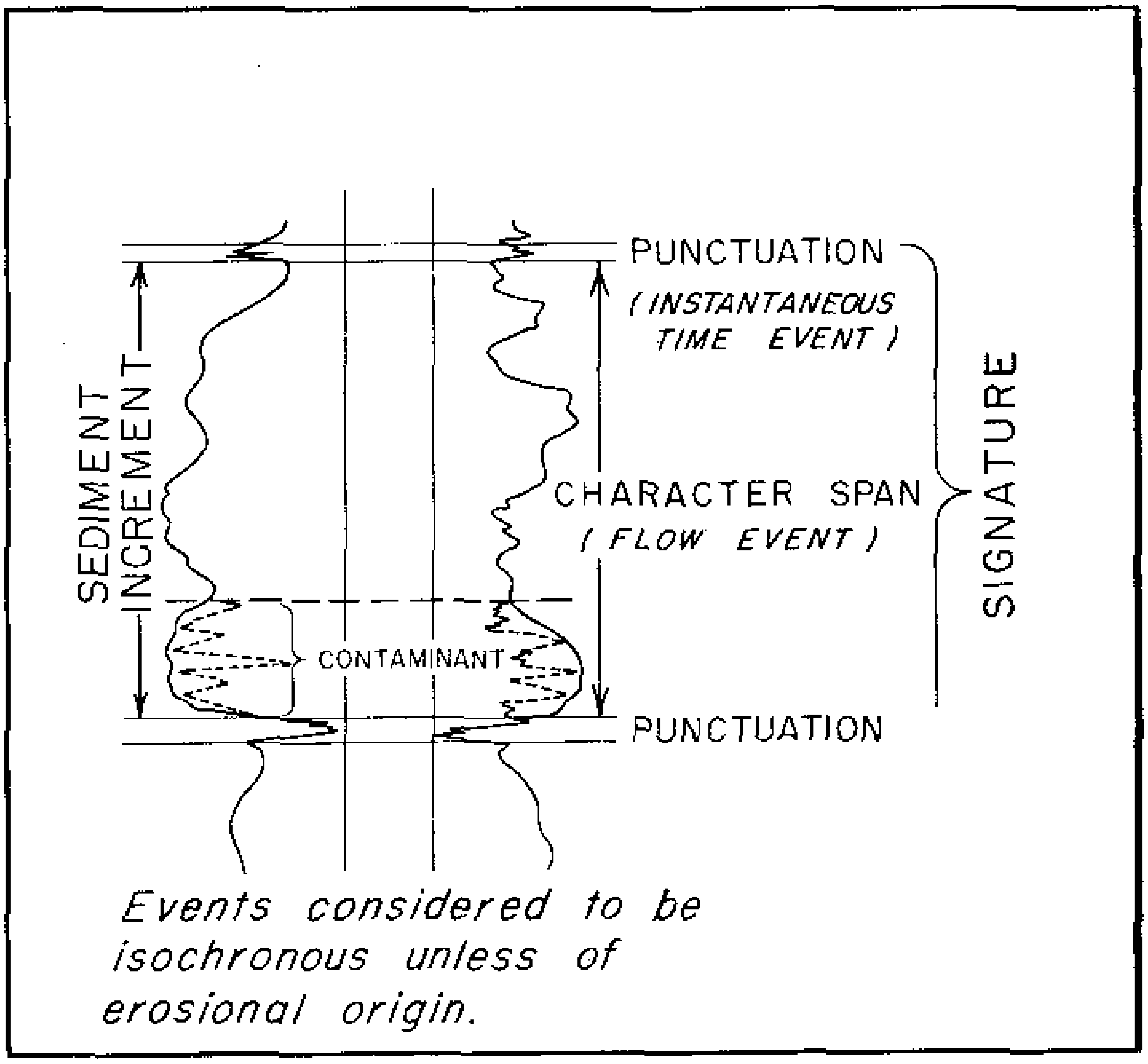

FIG. 1.—Log terminology. A schematic representation of geophysical log subdivision of a stratal section showing a suggested new terminology for stratigraphic analysis. The signature comprises punctuations (markers) as instantaneous geologic events separated by the character span representing the mappable, correlative sediment increment. Lithologic contaminants may alter the character span but the lower punctuation allows recognition of the altered section as a part of the correlative sediment increment.

The punctuation and character span together may be called the "signature" of an increment of sediment preservation — a physical fact recognizable on a log.

ORIGIN.—By definition, an "instantaneous punctuation" is one in which a very thin but recognizable sediment increment is present. Despite its origin, and to be consistent, it is included at the top of the flow event which created the character span on the log. A punctuation may be formed during the short time interval that creates a vacuity. Or it may be caused by post-depositional upward or downward streaming of chemically charged fluids from labile clays, silts, or calcareous micrites into a more porous sediment increment causing a chemical change recognizable on a detailed lithologic log as a thin zone of cement aggradation or degradation, or particle degradation in that sediment increment. Another type of punctuation is created by virtually contemporaneous contact chemical reactions on the sediment-water interface due to sub-sea halmyrolic (weathering) alteration, replacement, or syngenetic emplacement of constituents sufficiently different to be recordable on lithologic and geophysical logs. Another type of punctuation may be created by subaerial weathering on an exposed sediment increment. By environmental definition, the halmyrolic and subaerial weathering events which caused these punctuations are at the top of the affected sediment increment. The origins of punctuations recorded as virtually instantaneous geologic events by upward streaming fluids during compaction, and those due to downward streaming fluids, can not be determined on geophysical logs alone. Such results of contact phenomena require very careful sedimentologic analyses and petrogenetic reconstruction utilizing thin sections, microprobe analysis of cements, as

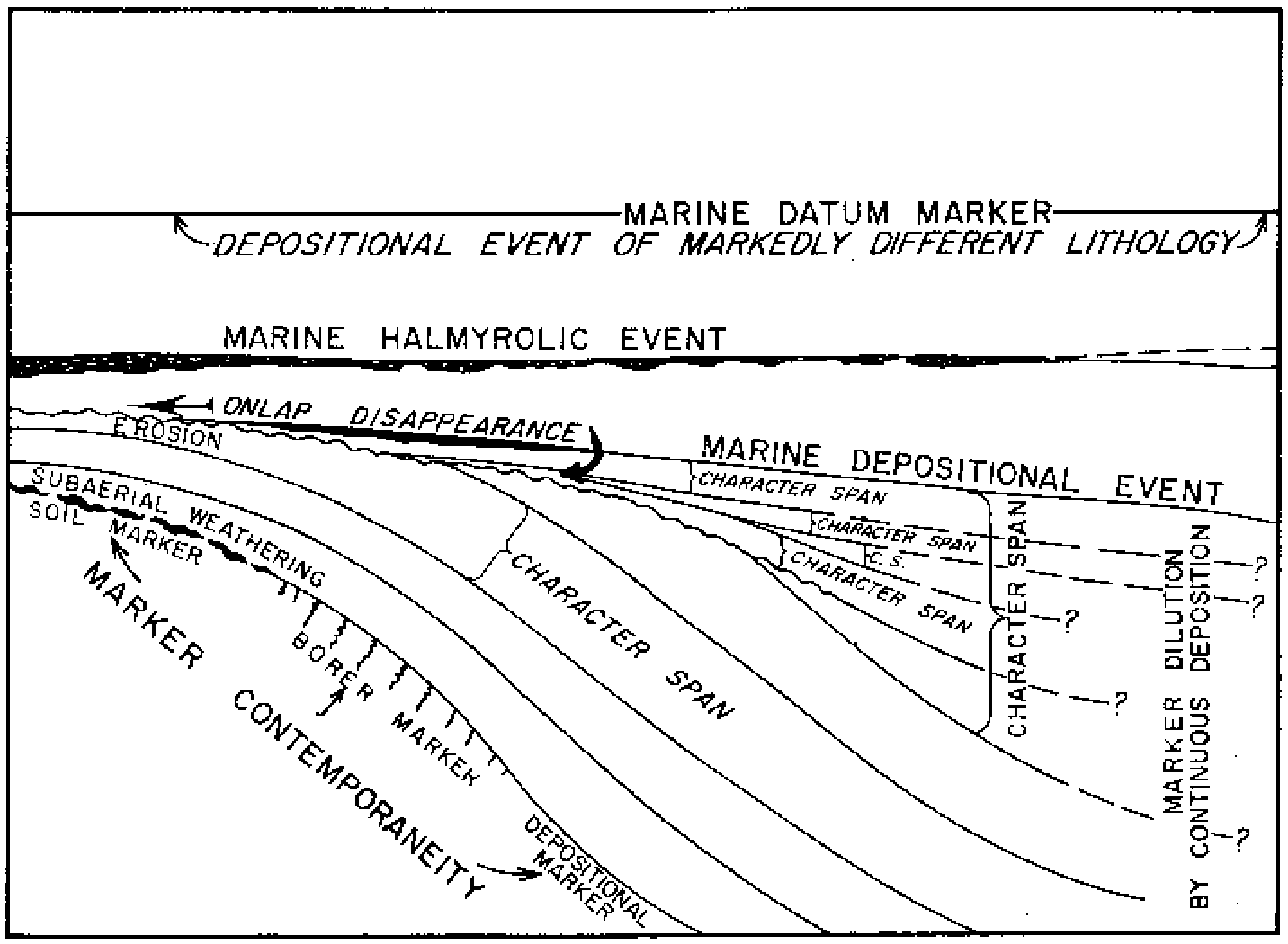

FIG. 2.—Event continuity and discontinuity. A summation of several major types of geologic events which create isochronous markers separating sediment increments. Erosional events are time transgressive (migratory discontinuities) and may represent time gaps which are elsewhere equivalent to several markers. Marker contemporaneity and marker dilution are detectable by detailed sedimentologic analysis of well cuttings and cores. Event discontinuity has many possible origins, and such marker losses represent areas critical in the search for petroleum.

well as scanning electron microscope analysis of allogenic particles which have been corroded by the streaming fluids.

In all cases involving vacuity during which contact chemical reactions occur at the top of a sediment increment, the chemical reaction must occur downward more rapidly than the upper lentils of an increment are removed by submarine or subaerial erosion; otherwise, the punctuation which creates the log marker is lost.

Other types of practically instantaneous events which create recognizable punctuations include borer-infected surfaces in or near the tops of sediment increments which show prolonged contact with sea water, deep soil zones formed across many lithologic units but relatively undisturbed by gently transgressive seas, thin algal mattes, and encrusting animal biostromes cataclysmically killed by floods of suspensoid allogenic sediments.

THE SEDIMENT INCREMENT

INTRA-INCREMENT TIME.— The sediment increment we see as a stratum having a distinctive character span on a log is in fact an increment of *sediment preservation* (John Harris, personal communication, March, 1967). The difference between time span of sediment deposition and time span represented by the sediment preserved may be in the ratio of 2 to 1, 5 to 1, 10 to 1, or in some cases 100 to 1. That is, strata present may represent only a relatively short part of total time for an increment present between recognizable punctuations, *but not necessarily so!* Such intra-incremental time gaps leave no record for the sensing span of geophysical logging instruments to record, and these microhalts may or may not be represented by bedding planes. The macro-halts in sedimentation which do leave evidence in the form of punctuations may also represent important vacuities during which chemical reactions can occur on the upper parts of preserved sediment increments. The most easily recognized punctuation is one represented by basin-wide rapid deposition of thin lithic units of totally different lithology from the subjacent and superjacent sediment increment. The sediment increments themselves must thus represent at least a second order of time greater than that necessary to deposit the punctuation sediment which represents the time surface.

Therefore, regardless of the number of unrecognizable micro-halts present in a sediment increment, the gross thickness and facies character of the preserved increment, independent of total time, will record remarkably well those localized areas of penecontemporaneous tectonic deformation involved in basin subsidence, as those areas receive and preserve sediments. Thickness differential is only one major criterion of tectonic instability; the other involves those facies controlled by the local tectonic movements and the hydrographic regime. What finally is preserved as a sediment increment is thus to a large extent dependent on sediments available, organic growth outside the range of clastic sediment incursion, efficiency of the scattering agents, and sedimentational space available during the complex interplays of competitive sedimentation controlled in large part by penecontemporaneous deformation within the basin of deposition.

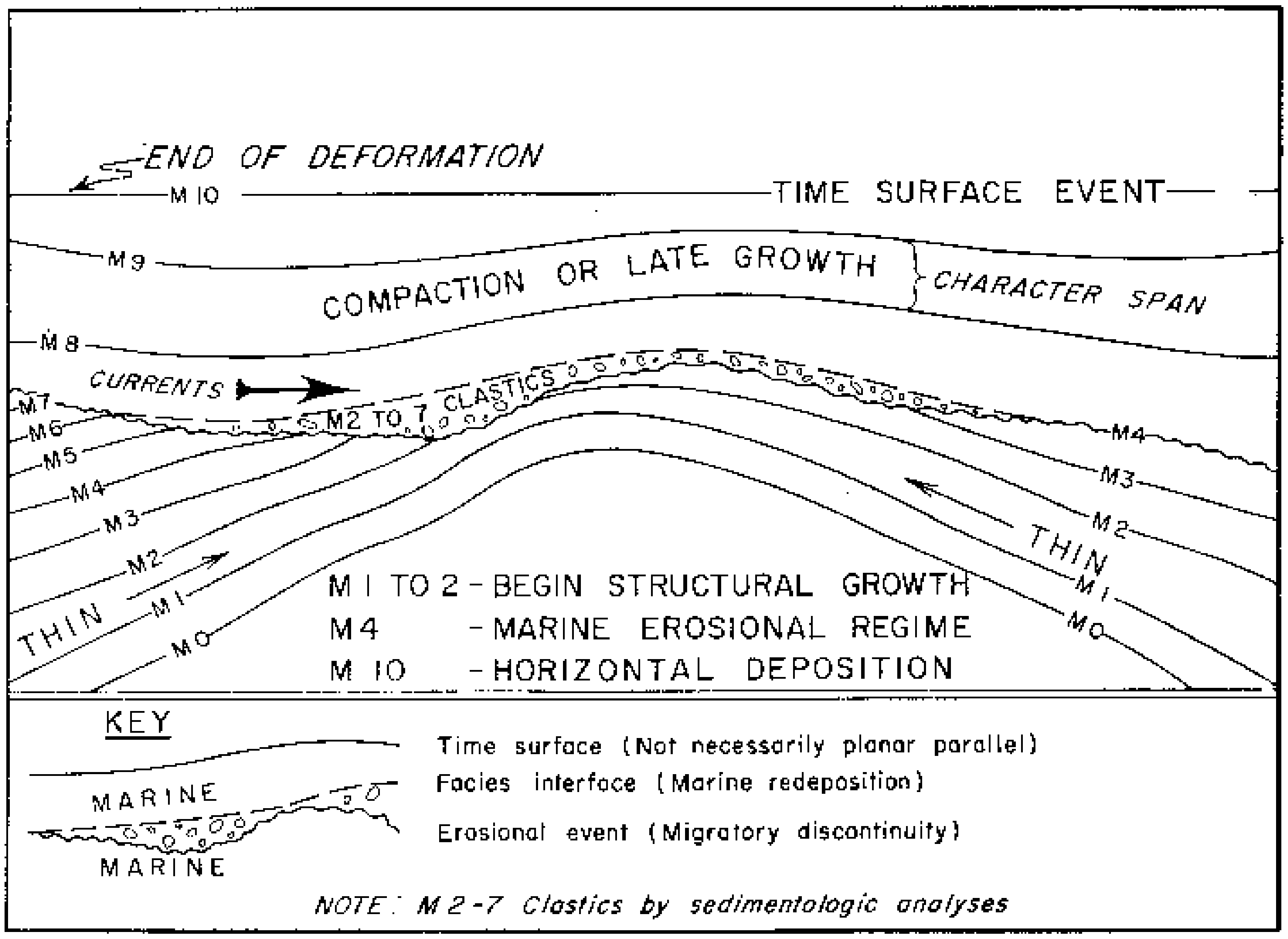

FIG. 3.—Event utilization - structural growth. A schematic representation of a projectable condition within a formation, which might be unrecognized if only the top (M-10) and the bottom (M-0) of a formation are mapped. Such localized tectonic deformation creates penecontemporaneous variations during sedimentation, an important factor in environmental reconstruction and in the search for petroleum.

THICKNESS OF INCREMENT.—At any given point in sedimentary basin, whether on the shelf (undaform), the shelf slope (clinoform), or nearer the more continuously subsident basinal axes (fondoform) (Rich, 1951, p. 20), both regional and local variations in thickness of the sediment increment will exist. In reiteration, seven major factors appear to control thickness variations:

1. Sediment availability
2. Relative depositional "velocity"
3. Sedimentational space available (subsidences versus structural growth or relative "lag" in subsidence)
4. Efficiency of the scattering agent and the accelerations of energy dissipation or enhancement in waves, currents, and density flows
5. Compaction differential of differing lithologic components
6. Time length of still-stand with consequent removal of upper sediments

by submarine erosion or solution, whether by currents or in the shallow zone of effective wave erosion near shorelines

7. Subaerial erosion after uplift, to place the sediment-sea water interface in contact with the atmosphere.

These variables inter-react with such complexity that even the most refined sedimentologic and stratigraphic analyses over wide areas may not allow separation of all of the controls which created the tickness variations. However, as the density of drilling increases, separation of regional subsidence controls from local structural growth can be made. With the aid of detailed facies maps of time-marker controlled sediment increments, those regional porosity trends related to clinoflexes and high undaform shoreline trends can be delineated for each increment. Inasmuch as the sinuous lineal clinoflex formed during the deposition of any sediment increment is generally the area of maximum interfingering of source-environment sediments and the distal

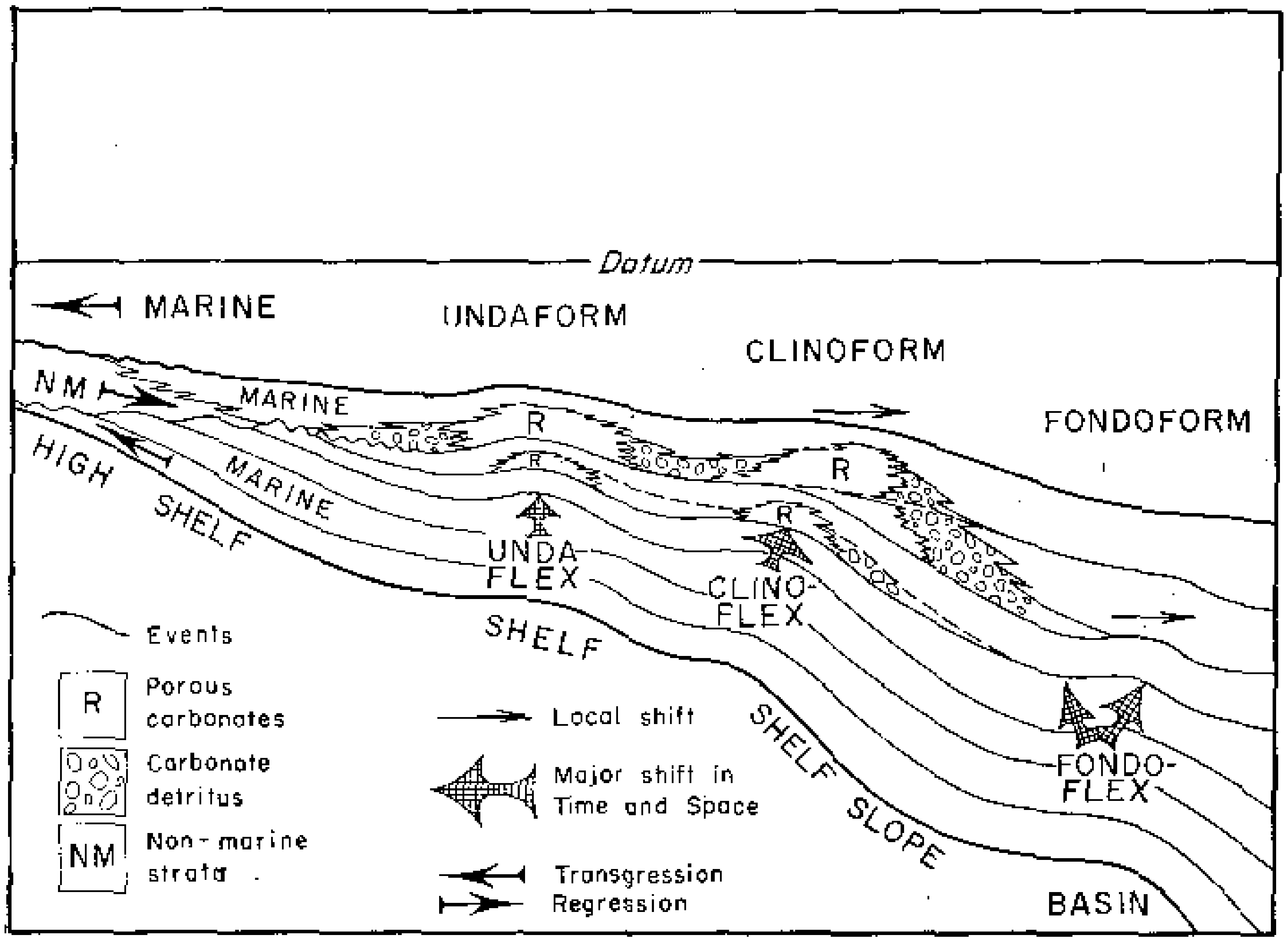

FIG 4.—Shelf-basin configuration, Marker-controlled analyses of stratal sections facilitate reconstruction of the sedimentational and tectonic history of a basin of deposition. Differential subsidence creates undaform (shelf), clinoform (shelf slope), and fondoform (basin) environments, which have marked regional effects on sediment type, distribution, and thickness. Local departures from these regional characteristics are created by tectonic flexing in all three environments which, combined with variations in the hydrographic regime, result in interfingering of the resultant source and *reservoir lithologies*.

edges of allogenic reservoir sediments or the growth of barrier reefs, any cross-trend organic or structure growth area will be the site of second-phase accumulation of petroleum. Therefore, sediment variation coupled with thickness variation in the clinoflex trend or in the undaform environment is the critical locale for petroleum exploration by detailed subsurface analysis.

SEDIMENT DECREMENT

Sediment decrement, whether by non-deposition due to sediment by-passing or erosion or superjacent parts of already deposited sediment increments, creates a vacuity. The word "gap" simply denotes the stratigrapher's recognition that strata are absent which should be at any one point of investigation but are not, without a judgment as to why the sediments are not there. "Palimpsest" denotes a gap in which sediments were deposited but were stripped off because of 1) increased wave and current energy prior to superjacent deposition which may or may not be related to marine regression and consequent shallowing of water, or 2) structural growth penecontemporaneous with sedimentation. Note that No. 1 requires no marine regression or shallowing of water but only a change to a higher energy regime by changes in the hydrographic environment rather than changes in the slope, shape, and condition of the substrate. No. 2 is detectable provided sedimentary materials in the subjacent sediment increment are notably recognizable as different from those in the superjacent sediment increment, but are found in the base or scattered through parts of the superjacent increment as exotic components. Therefore, facies maps of these lesser components in the superjacent increment provide clues as to the locations of early structural growth. Combined with thickness maps of both the sediment increments above and below the reservoir increments, projections to trends and areas of thinning and greater facies gradients become valuable adjuncts to the location of stratigraphic traps.

The causes of submarine structural growth which lifts, relatively, the sediment-water interface to create recognizable inter-incremental vacuity are numerous. These appear to be 1) subsidence flexing, 2) sag and spur formation along the clinoflex trend and sediment-controlling along the lower undaform (shelf) and the upper fondoform (lower shelf slope), 3) lineal relative uplift along down-to-the-basin normal faults related to renewed flexing essentially parallel to the clinoflex of each sediment increment, 4) torsional stress release and shelf-edge uplift along linear wrench or transcurrent faults originally flexed during subsidence, and then normal-faulted when the rupture point of flexing is passed as the basin subsides, 5) early salt welting, succeeded by salt doming generally along trends related to deeper normal faulting along the clinoflex.

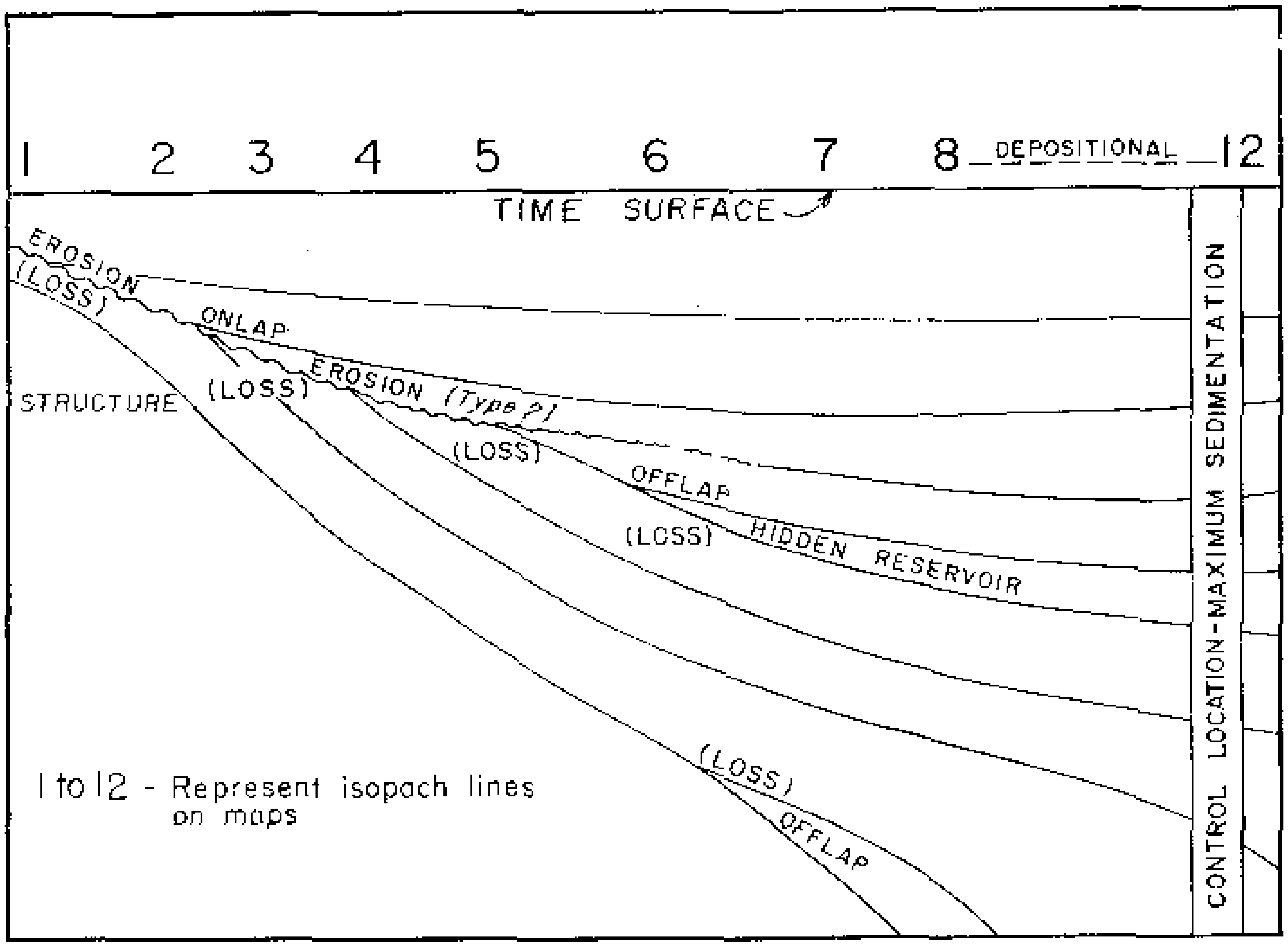

FIG. 5.—Vacuity quantification. Any attempt to quantify vacuity, whatever the origin, fails in analysis by simple gross-unit isopach mapping. Maps showing lines joining points of equal numbers of time slices, however, show market variations which, combined with sedimentologic analysis of the lithologic characteristics of the markers, suggest the causes and types of loss of sediment increments whose individual reservoir characteristics may contain petroleum. Note the following tabulation of dimensionless numbers:

Thickness	*Number of Sediment Increments*
1	2
2	3*
3	5*
4	6
5	6*
6	8*
7	9
8	9
12	9

**Analyze in detail for specific location of stratigraphic trap.*

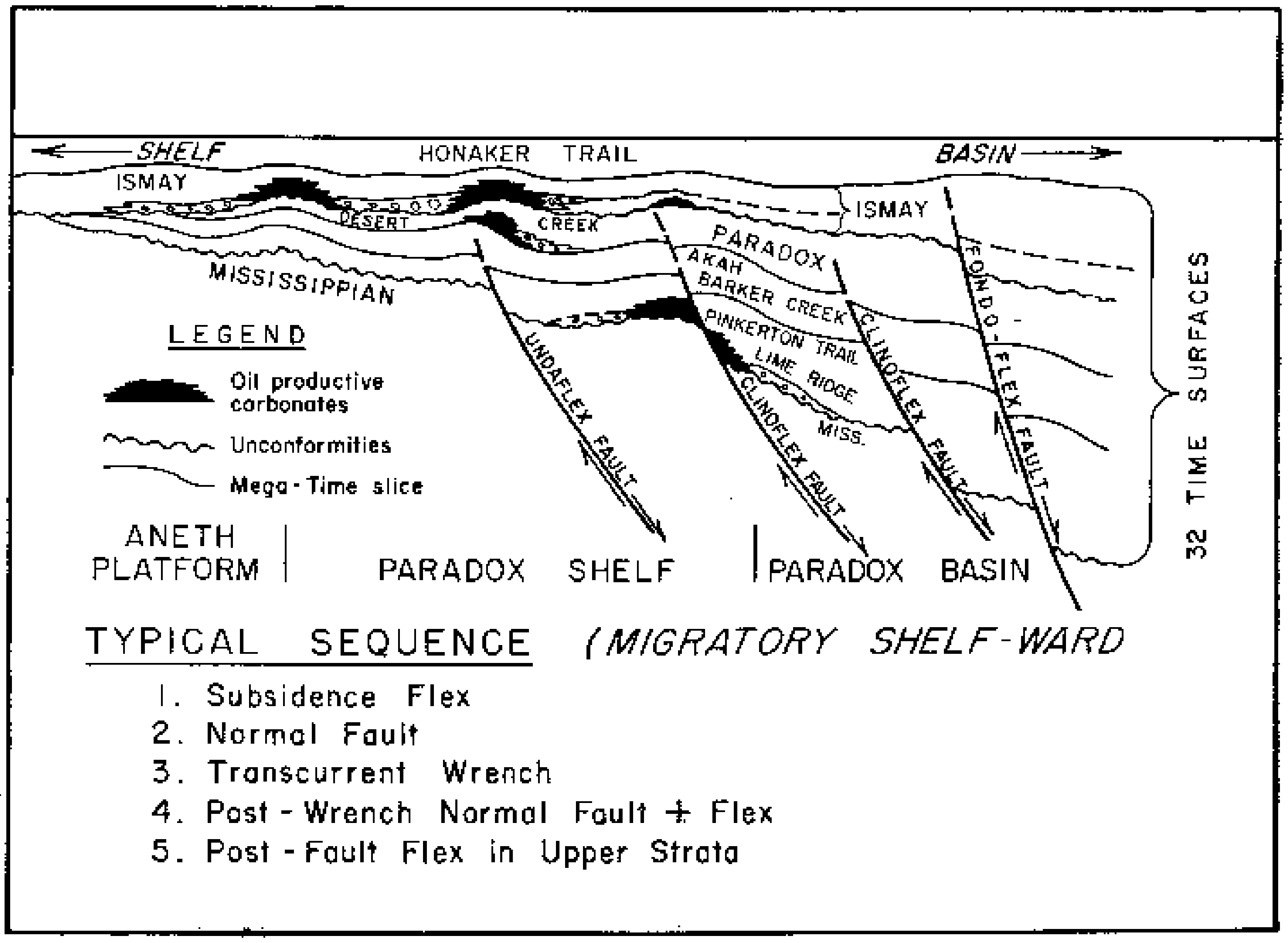

FIG. 6.—The Paradox case (schematic). Tectonic migration during basination and the causes of subsidence during and subsequent to the deposition of each sediment increment can be detailed when an optimum density of drilled wells is attained in any basin. Actual penetration of fault planes by wells results in loss of markers on geophysical logs, and, combined with such loss, it is notable at the optimum drilling density, that each sediment increment is markedly thicker basinward from sharp clinoflex for that increment. The flex develops into a normal fault with later wrenches (strike-slip movement) displacing formerly contiguous facies. This lateral displacement is also recognizable as an anomalous arrangement of isopachs in trends parallel to the various northwest-trending flexes. This diagram, in a very generalized way, shows that tectonism is penecontemporaneous to sedimentary sequences in the Paradox Basin in southeastern Utah. This subdivision of the 500 to 5000 foot thick middle Pennsylvanian section into 32 time slices separated by easily recognized markers (punctuations) has resulted in an integrated picture of the origin of the Paradox Basin and the control on major gas and oil accumulations such as that found in the giant Aneth complex of fields.

LOSS OF MARKERS

The value of markers is greatest when they are 1) easily recognizable, 2) basinwide in distribution, 3) numerous but not too numerous in relation to increment thickness, and 4) depositional in origin. All subsurface stratigraphers have noted the disappearance of markers geographically. Such disappearance becomes a valuable tool in appraising sediment variations in the sediment increments preserved, in recognition of locales of tectonic disruption, and in environmental reconstruction. Following are several of the many conditions wherein marker disappearance occurs: 1) marker convergence to form "doublets" shoreward owing to non-deposition of an intervening sediment increment, 2) similar convergence basinward beyond the lineal aprons of sediment deposition essentially parallel to the clinoflex but beyond the zones of allogenic sediment incursion, 3) inter-incremental chemical destruction or *alteration of normally easily recognized marker*, 4) *submarine structural* growth and sub-sea erosion on flexes, local spur-folds normal to the clinoflex, and along active faults which cut the sediment-water interface, 5) subaerial destruction by erosion as the sea regresses from the area, 6) cut out by normal faulting where the drill penetrated the fault plane, 7) basinward dilution creating a thick sediment increment correlative with a thin marker bed, 8) non-deposition of the marker for unknown reasons.

Fortunately, depositional markers may be contiguous shoreward with contemporaneous marine borer markers and basinward with chemical alteration markers developed on previously deposited sediments.

Stated in another context, a marker may disappear geographically by a *combination of non-deposition and erosion in a shoreward direction, or over* a shoal area of the same age as the subjacent marker strata, or by intrabasin flex rise related to basin subsidence and relative uplift shoreward. At the same time, basinward, younger markers and sediment increments may have formed with debris from the eroded areas mixed with normal basinal components by off-shore current transport or by the action of turbidity currents. During any of these conditions, when sediment is not available and strong subsea erosion is not taking place, chemical reaction on and just below the sediment-water interface may create a contiguous and correlative marker prior to deposition of the next sediment increment.

CONCLUSIONS

Regional lithologic markers believed to be of very short time span appear to be practical time surfaces or correlative "punctuations" *in stratal sections.* Highly refined sonic and gamma ray-neutron logging techniques combined with sufficient drilling density yield reliable stratigraphic subdivisions necessary to appraise in detail the tectonic evolution of a sedimentary basin. Between these specific, widely correlative time surfaces which logically may be assumed to be "instantaneous events", lie volumes of strata comprising mappable units representing "flow events" whose lithologic gradations represent *not only longer intervals of time* but also the diluted results of environmental impress important to the geographic and stratigraphic delineation of porous strata vital to the search for petroleum.

Correlative stratal units, despite facies gradation, are probably practical "time slices" and can be rigidly controlled by marker as to initiation, conclusion, and time span represented, and provide the bases for detailed facies maps. Thickness variations of such time-controlled units represent measures of competitive sedimentation by the complex interplay of those total environmental factors which involve the allogenic and syngenetic sediments in most stratal prisms of a marine basin.

The markers (instant events) themselves represent: 1) widespread, essentially contemporaneous deposition of thin lithologic components either at the base or the top of time-correlative units (flow events), 2) virtually contemporaneous contact phenomena created by halmyrolic chemical reactions, replacement, or emplacement at the sediment-water interface during times of non-deposition, usually of considerably lesser time span than that necessary to deposit the sediment increment representing the flow event.

The unit thickness of sediment deposited at any one locale is dependent upon rates of sediment supply (availability), strength and duration of the effective scattering or distributive agents (fluxes) in the depositional medium; regional variations in the chemical impress of the depositing medium (rate), and amplitude of local and regional structural growth and subsidence (amount). Although marked lithologic gradation of a sediment increment is normal, the geophysical log character of these bounding "markers", "punctuations", "time surfaces", or "time interfaces" is remarkably consistent throughout almost entire basins of deposition. If unit sequences are similar or consistently gradational to yield facies separated by the markers, we may consider the successive environments to have been similar or gradational and the time interval represented by any marker-defined unit to be essentially time equivalent not only as to duration but also as to simultaneity. These markers "cut" through facies geographically and in many instances signal the termination of vertical facies continuity and thus represent massive change in any one or all of the important environmental controls which created the sedimentary unit.

These time surfaces represent short-interval lithologic inflictions which may be related to 1) rapid transgression or regression of marine waters, 2) gradient of the paleoslope, 3) climatic variations affecting the depositional medium, 4) rapid changes in depth of water and distance from shore, 5) changes in wide influx of suspensoids of chemical and physical character markedly different from the sediments in the body of the time-marker bounded unit. It is recognized, however, that erosional markers representing sediment decrements related to transgressing or regressing seas are migratory discontinuities, and thus are not regionally chronostratigraphic (isochronous).

The astute stratigraphic analyst is able to construct detailed isopach and lithofacies maps of short time-interval flow-event units. Such analyses yield a consistent sequential picture of basin genesis and permit the construction of detailed environmental maps. Via these "time-slice" maps, areas of intrabasin structural growth so important to first-phase oil migration can be isolated and delineated. In addition, time-length vacuity may become susceptible of quantitative analysis.

In the final analysis, the working stratigrapher is justified in the assumption that markers are essentially isochronous, that loss of markers represents a special event which denotes a post-depositional condition important in the search for petroleum, and that detailed identification of marker components must be done in order to determine the significance of these almost-ubiquitous punctuations of the stratal column in sedimentary basins.

If our concepts of uniformitarian geology are even approximately correct, such "geochron" maps, based on marker control, systemize haphazard lithologic patterns into geographic time units whose interval characteristics enable us to determine rates of sedimentation, rates of facies gradation, reconstruction of paleoslope gradients, lateral variation in intensities of environmental impress, origins of sediments, depth of water, distance to shore, and a host of other sedimentational variables not otherwise easily susceptible of quantification.

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