Sedimentary Geology, 50 (1987) 95–118
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

CURRENT ASPECTS OF BASIN ANALYSIS

GEORGE deV. KLEIN

Department of Geology, University of Illinois at Urbana-Champaign, 245 Natural History Building, 1301 West Green Street, Urbana, IL 61801-2999 (U.S.A.)

(Received October 8, 1986)

ABSTRACT

Klein, G. deV., 1987. Current aspects of basin analysis. Sediment. Geol., 50: 95–118.

Current research in basin analysis focuses on interdisciplinary integration of geodynamics, mathematical and physical modelling, and sedimentary geology. These efforts are organized into a research framework emphasizing basin formation, nature of the basin fill, maturation (diagenesis) of the basin fill, and timing of events.

Research in geodynamics permits development of a proposed classification of sedimentary basins in which basin types are discriminated according to nature of the plate margin, basin position on or within a tectonic plate, nature of the crust, and geodynamic models or known process of formation. A summary of current research developments on sedimentary basin-fills focuses on the interdisciplinary solutions developed to understanding carbonate distribution through time, origin of black shales, sea-level history, and global sedimentary cycles. Maturation of basin fills requires an understanding of both thermodynamic aspects of mineral phase changes, and changing character of the chemistry of flow of water through porous sediments during basin evolution. Summary case histories from the Illinois Basin and the Appalachian Basin illustrate these approaches.

INTRODUCTION

Over the past 25 years, the field of basin analysis has matured to where it integrates interdisciplinary approaches across the entire spectrum of the earth sciences to solve specific problems. Current research focus is directed more to correlating the geodynamics of basin evolution processes with sedimentary, tectonic, igneous, geochemical, hydrogeological and global events. This approach addresses research in basin analysis which focuses on formation of the basin, nature of the sediments filling the basin, maturation of the sediment fills during and after deposition, and timing of specific events controlled by geodynamically driven processes. This paper aims to provide an overview of current approaches and concepts within this framework, as well as emphasizing certain special topics germane to such research activity.

0037-0738/87/$03.50

BASIN FORMATION

Understanding the formation of sedimentary basins concentrates currently on developing physical models to account for the observed record of tectonic and sedimentation events. Pioneer studies by Sleep (1971) on the Atlantic continental margin were most germane because he established that continental crust in passive margins undergoes subsidence by mechanical loading and thermal cooling similar to oceanic crust. The most major advance underpinning present research is the crustal extension model proposed by McKenzie (1978). In his model, McKenzie (1978) proposed that when lithosphere is stretched, it becomes thinned and asthenosphere rises closer to the surface. The thinned zone is subjected to one-dimensional conductive heat generated from the asthenosphere upwards to the surface of the crust. Crustal thinning is amplified by additional heating from the asthenosphere combined with additional stretching. This thinned zone becomes the site of basin formation by an initial mechanical rifting event followed by simple thermal decay as outlined by Parsons and Sclater (1977) who demonstrated that such heat loss follows the square root of time. A stretching factor, β, can be evaluated and determined from several families of curves of heat loss with time. Lithospheric thinning is the inverse of β, or $1/\beta$.

According to McKenzie (1978), the record of such subsidence is preserved by the thickness of sediments that fill the basin. Subsidence history can be modelled from both preserved basin stratigraphy and its preserved sediment accumulation rate. The resulting tectonic subsidence curve is, in effect, a derivative of the preserved sediment accumulation rate and the curve shape records a history of changing subsidence mechanisms from initial rifting to subsequent thermal cooling. Correction for compaction must be considered also (Sclater and Christie, 1980; Bond and Kominz, 1984).

McKenzie's (1978) model became the basis for analyses of basin evolution, of which the study by Sclater and Christie (1980) from the Viking Graben of the North Sea is perhaps one of the best examples. Their study demonstrated that evolution of the Viking Graben followed a stretching history in which rifting of continental crust was followed by a history of thermal decay. A seismic section processed by Solli and described by Ziegler (1978) confirmed that the lithosphere thins below the Viking Graben.

Later work expanded the scope of the McKenzie (1978) stretching model. Royden et al. (1980) modelled the influence of intruded sheeted dikes as the heat source for thermal decay. Hellinger and Sclater (1983), Watts et al. (1982), and Sawyer et al. (in press) considered the role of two-dimensional heat transfer involving both a vertical and lateral component. They demonstrated in a rift-valley system that increased temperatures caused by rising asthenosphere in response to stretching would cause a buoying of the crust. As rifting ensued, a shift in heat sources laterally away from the rift center to the rift flanks maintained relief of the rift-flank blocks while the basin subsided by thermal decay. These uplifted rift flanks acted as a sediment source to fill the basin. Deposition of sediment in the basin itself favored both additional loading and enhanced lateral heat transfer to the flanks to maintain the rift-valley geomorphic profile, flank uplift and continued sediment yield into the basin.

A series of studies by Watts and Ryan (1976), Steckler and Watts (1982), and Watts et al. (1982) demonstrated that many of the tectonic subsidence curves generated by the application of uniform heat conduction (McKenzie, 1978) or two-dimensional heat flow (Hellinger and Sclater, 1983) are explained also by crustal flexural processes where the vertical load of accumulated sediment is distributed laterally over a broader zone than the dimensions of the sedimentary basin. Both elastic and viscoelastic processes were considered in their studies of the Atlantic margin of the eastern U.S.A. Major differences in elastic and viscoelastic flexure can account for the geometry of the stratigraphic units in sedimentary basins and the preservation or absence of onlap stratigraphies. Theoretical stratigraphic calculations showed that through time, the rate of accumulation (as expressed by thickness) decreased as flexural rigidity inhibited subsidence, particularly in models involving viscoelastic crust. Thus the profile for basins developed on viscoelastic crust is a synclinorium. In basins showing elastic crustal behavior, onlap sedimentation away from the basin center beyond the basin margin maintained a relatively uniform volumetric sediment accumulation rate.

Basin classification

As a consequence of plate tectonics, the approach to classification of basins has changed. Pre-plate tectonic classifications were epitomized by Kay (1948) who used geosynclinal theory to explain differences in known associations of stratigraphy, sedimentary facies and tectonics. With the advent of plate tectonics, geosynclinal theory is no longer an acceptable basis for recognizing different basin types. Modern basin classifications have been proposed by Dickinson (1974), Klemme (1975), Bally and Snelson (1980), Kingston et al. (1983) and Miall (1984).

Criteria for distinguishing various sedimentary basins in these classifications lack consistency. Dickinson (1974) recognized three criteria for distinguishing sedimentary basins; type of crust, degree of proximity to a plate margin, and type of plate juncture or boundary. In terms of crustal types, besides continental and oceanic crust, Dickinson (1974) recognized four types of transitional crusts depending on the nature of their materials and overlying sediment characteristics. The degree of proximity to a plate margin is significant because the setting of the basin will be influenced by the tectonic effects related to plate interaction which are affected by distance from the margin. The type of junctures or boundaries Dickinson (1974) recognized are the divergent, convergent and transform boundaries. Dickinson's classification is summarized in Table 1.

TABLE 1

Basin types according to Dickinson (1974)

Oceanic basins (includes crest, rise and deep ocean basins)
Rifted continental margins
Pre-rift arch
Rift valley
Proto-oceanic gulf
Narrow oceanic gulf
Narrow ocean
Open ocean
Aulacogen
Arc-trench system
Trench
Subduction zone
Fore-arc basin (arc-trench gap)
Intra-arc basin
Back-arc basin (or inter-arc basin)
Retro-arc basin
Suture zone
Foreland basin
Intracontinental basin

Klemme's (1975) classification is restricted to those basins containing giant petroleum fields, although he expected it to be applicable to basins lacking sizable petroleum reserves. He started with the premise that Precambrian shields on continents are surrounded by sialic crust of the craton. An intermediate crustal zone lies between cratonic sialic crust and oceanic crust and shows variable crustal thickness of the continental slope, shelf, and coastal plain, some of which extend into mountains bordering coastal zones. Recent work by Sims and Peterman (1986) and Bickford et al. (1986) demonstrated that the Precambrian shields of North America represent a collage of tectonic plates and thus Klemme's (1975) assumption is suspect. Because of the focus on oil occurrence, Klemme's basinal types are confined to those on cratonic and intermediate crust.

Klemme (1975) emphasized the importance of position of a sedimentary basin on a continent, somewhat akin to Dickinson's (1974) distance of a basin from a plate boundary. His cratonic basins are distinguished into two types in terms of their location within the interior of a craton or the margin of a craton. Rifted basins on the edge of a craton represent a third class. On intermediate crustal zones, extracontinental basins and pull-apart basins are common. Where the intermediate crust parallels subduction zones and occurs between continental crust and oceanic basins, two separate types of intermontane second-cycle basins are recognized.

TABLE 2

Proto-type basins according to Klemme (1975)

Cratonic interior basin
Cratonic multicycle basin
Cratonic rift basin
Extracontinental margin basin
Closed basin
Foredeep basin
Open basin
Pull-apart basin
Intermontane basin
Transverse strike basin
Delta basin
Successor basin

Finally, deltas represent an eighth class of sedimentary basin, although most workers would view deltas as a depositional system that occur in any basinal setting (Klein, 1985a). Eight prototype basins are recognized (Table 2) but Klemme (1975) recognized also that changing tectonic histories provide a succession of basinal types or successor basins. In short, Klemme's (1975) classification considered two criteria, type of crust and position with respect to a plate boundary.

A detailed basin classification (Table 3) was proposed by Bally and Snelson (1980) and Bally (1980). Their criteria include the nature and composition of the lithosphere including its rigidity, the position of the basin with respect to formation of compressional megasutures (old or present subduction zones), basins occurring in the surface zones of large megasutures (episutural basins), and style of subduction where A-type subduction involving the collision of oceanic and continental lithosphere, are contrasted with B-type subduction which involves the collision of two plates of oceanic lithosphere. Classes are differentiated in terms of location of basins with respect to megasutural boundaries and whether that boundary involves either A-type or B-type subduction. Three broad classes are recognized including basins on rigid lithosphere but independent of formation of megasutures, perisutural basins on rigid lithosphere associated with flanking compressional megasutures, and episutural basins contained within the megasuture.

This classification by Bally and Snelson (1980) possesses a great deal of merit, but it is the view of this author that some of the basinal types are too local (Pannonian Basins), or new work has demonstrated that the basinal origin differs from what they proposed. Chen and Nabelek (1985) reported that the so-called Chinese Basins are pull-apart basins rather than requiring recognition as a distinct class of perhaps local or regional importance, for instance.

TABLE 3

Basin classification according to Bally and Snelson (1980)

1. Basins located on the rigid lithosphere, not associated with formation of megasutures
   11. Related to formation of oceanic crust
       111. Rifts
       112. Oceanic transform fault associated basins
       113. Oceanic abyssal plains
       114. Atlantic-type passive margins (shelf, slope and rise) which straddle continental and oceanic crust
            1141. Overlying earlier rift systems
            1142. Overlying earlier transform systems
            1143. Overlying earlier back-arc basins of (321) and (322) type
   12. Located on pre-Mesozoic continental lithosphere
       121 Cratonic basins
            1211. Located on earlier rifted grabens
            1212. Located on former back-arc basins of (321) type
2. Perisutural basins on rigid lithosphere associated with formation of compressional megasuture
   21. Deep-sea trench or moat on oceanic crust adjacent to B-subduction margin
   22. Foredeep and underlying platform sediments, or moat on continental crust adjacent to A-subduction margin
       221. Ramp with buried grabens, but with little or no blockfaulting
       222. Dominated by block faulting
   23. Chinese-type basins associated with distal blockfaulting related to compressional or megasuture and without associated A-subduction margin
3. Episutural basins located and mostly contained in compressional megasuture
   31. Associated with B-subduction zone
       311. Fore-arc basins
       312. Circum Pacific back-arc basins
            3121. Back-arc basins floored by oceanic crust and associated with B-subduction (marginal sea sensu stricto)
            3122. Back-arc basins floored by continental or intermediate crust, associated with B-subduction
   32. Back-arc basins, associated with continental collision and on concave side of A-subduction arc
       321. On continental crust or *Pannonian-type* basins
       322. On transitional and oceanic crust or *W. Mediterranean-type* basins
   33. Basins related to episutural megashear systems
       331. Great basin-type basins
       332. California-type basins

Kingston et al. (1983) proposed a geometric classification so as to avoid connotations of past classifications (Table 4). They used three different criteria: basin-forming tectonics; nature of depositional sequences within the basin; and basin-modifying tectonics. Detailed examination of their classification shows the crustal type, position within a plate, past plate-tectonic history (if decipherable) and nature of the plate boundary are crucial to their subdivisions also. Its chief weakness is its

TABLE 4

Basin types according to Kingston et al. (1983)

Interior sag basin
Interior fracture basin
Marginal sag basin
Wrench basin
Trench associated basin
Oceanic trench basin
Oceanic fracture basin
Oceanic sag basin
Polyhistory basin

reliance on depositional sequences, which are basically depth-dependent across a variety of tectonic domains (Klein, 1985b). Moreover in their classification, a single depositional cycle represents a completed single basinal class. In actual fact, many basins show multiple and repeated cycles of depositional sequences during a single long-term subsidence event. Thus, most cratonic basins such as the Illinois Basin or the Michigan Basin (Sloss, 1963; Heidlauf et al., 1986; amongst many others) record a history of sea-level fluctuations bracketing several sedimentary sequences while the basin subsided continuously in response to thermal cooling.

A slightly different approach to basin classification was developed by Miall (1984) in which many of Dickinson's (1974) and Bally and Snelson's (1980) basin types were reorganized in terms of the Wilson cycle of opening and closing oceans (Table 5). This emphasized the significance of plate-margin behavior as the principle criterion of classification. Its principle utility seems to be that it works well, perhaps, in the Atlantic margins of Europe, North and South America, Africa and even the Precambrian (Sims and Peterman, 1986), but it may not apply to other areas of differing tectonic evolution. It may be difficult, for instance, to apply the Wilson cycle to either the geological evolution of California or Japan.

Proposed revised basin classification

This brief review of existing basin classifications shows that differences exist in terms of principle criteria, goals, process and nomenclature. This author incorporates both past criteria for basin classification and introduces a new criterion as a basis for proposing a new classification. This new classification builds in part on the concept of prototype basins developed by Klemme (1975), crustal type, margin type, and basin location with respect to the margin (as per Bally and Snelson, 1980) and some of Dickinson's (1974) basin nomenclature. It must be stressed, therefore, that in both principle and nomenclature, some overlap between the proposed classification and prior classifications exists. The key differences between the proposed

TABLE 5

Basin classification according to Miall (1984)

Divergent margin basins
Rift basins
rifted arch basins
rim basins
Ocean margin basins
Red Sea type basins
Atlantic type basins
Aulacogens
Convergent margin basins
Trenches and subduction complex basins
Fore-arc basins
Inter-arc and back-arc basins
Retro-arc (foreland) basins
Transform and transcurrent fault basins
Basin setting:
plate boundary transform fault basin
divergent margin transform fault basin
convergent margin transcurrent fault basin
suture zone transcurrent fault basin
Basin type:
basins in braided fault systems
fault termination basins
pull-apart basins in en-echelon fault systems
Basins developed during continental collision and suturing
Foreland basins
Peripheral (foredeep) basins
Infra-suture embayment basins
Associated transcurrent fault basins
Cratonic basins

classification and the earlier ones is incorporation of geodynamic modelling and tectonic subsidence analysis regarding basin evolution. The proposed classification is summarized in Table 6.

Criteria

The principle criteria that are used to categorize basin types (Table 6) are: (1) nature of the margin (active, passive, transform, collision, plate interiors); (2) position on or within a tectonic plate (interior, edge, off-edge, suture zone); (3) nature of the crust (continental, oceanic, transitional); and (4) geodynamic processes of basin formation (rifting, stretching, flexure, compression, extension, translation). The first three criteria are the same as suggested in the classifications of Dickinson (1974),

TABLE 6

Basin classification proposed in this paper

Continental margin	Basin type	Basin position on or within plate	Crustal type [a]	Geodynamic model of formation
Plate interior	interior cratonic basin	interior	C	rifting, stretching and thermal subsidence
	cratonic margin basin	edge	C	rifting, stretching and thermal subsidence
Passive margin	rift basin	interior and edge	C, T	rifting and stretching
	aulacogen	edge to interior	T, C	rifting and stretching
	flexure basin	edge	C	loading, flexure: elastic and viscoelastic
Active margin	trench basin	edge	O	convergence; compression
	trench slope basin	edge	O or older sediment	compression-extension, folding
	fore-arc basin	off edge	O or older sediment	compression
	intra-arc basin	arc	C-magmatic	extension-rifting
	back-arc (interarc) basin	interior	O	rifting, stretching
	retro-arc basin	interior	C	compression
Transform margin	pull-apart basin	transform edge	C/T or O	rifting, translation, thermal subsidence
	transform basin	transform edge	C/T or O	rifting, translation, thermal subsidence
Collision margin	foreland basin	interior	Annealed C&O or C&C	compressional folding, flexure
	superposed (or collage) basin	suture	C/T or O	compression
(Margin independent)	polyhistory basin	interior or edge	C/T or O	multiple
	successor basin	interior or edge	C/T or O	multiple
	resurgent basin	interior or edge	C/T or O	multiple

[a] C = continental; T = transitional; O = oceanic.

Klemme (1975) and Bally and Snelson (1980). A major departure is the combining of Dickinson's (1974) four intermediate classes of crust into a single transitional class. The geodynamic criteria are both those of tectonic forces recognized from geological and geophysical mapping, and mathematical and physical modelling (McKenzie, 1978; Watts et al., 1982; Hellinger and Sclater, 1983). Incorporation of these geodynamic factors permits clearer distinctions between certain classes of basins that appeared to share certain features in common, but differed from each other in terms of structural boundary conditions. The proposed classification thus incorporates both descriptive and genetic parameters.

Commentary on basin types

The characteristics of the proposed basin types are reviewed briefly below. Examples are discussed in a forthcoming paper.

Cratonic basins as used here are as defined by Klemme (1975). The distinction in the proposed classification is between those cratonic basins that occur within the interior of a continental plate, such as the Illinois Basin, and those that occur on the edge of a continental plate but inboard from a tectonic hingeline separating the continental interior from a passive margin.

Rift Basins and Aulocogens are defined as per Dickinson (1974) and Klemme (1975). The term Flexure Basin is introduced to incorporate basins known to form by either viscoelastic and elastic flexural processes in passive margins. These have been discussed adequately by Watts and Ryan (1976) and Watts et al. (1982).

Basins of active continental margins including Trench Basin, Forearc Basin, Intra-arc Basin, Backarc Basin, Interarc Basin, and Retroarc Basin are as defined by Dickinson (1974). The term Trench Slope Basin is used here to define a graben type of basin caused by extension on the trench slope as summarized by Hilde (1983). The associated extensional processes are discussed also by Auboin et al. (1984).

Foreland Basins are as defined by Dickinson (1974), Pull-apart Basins as defined by Klemme (1975) and Transform Basins as defined by Miall (1984). The Superposed (or Collage) Basin is a new term proposed for basins that develop in the suture zones of plate collisions such as described by Kleinspehn (1985) from the collage tectonic zone of British Columbia. This new basin type is distinct, but details of its geodynamic origin are preliminary. Two types of polyhistory basins are recognized. Successor Basins are as defined by Klemme (1975) to recognize a succession of changing basin-types along zones of tectonic weakness. Resurgent Basins (new term) are polyhistory basins where the original basin-style is repeated and maintained along older tectonic boundaries and trends.

THE BASIN FILL

Interpretation of basin sediment-fills has evolved with increasing sophistication of stratigraphy and sedimentology over the past quarter century. The current approach is integrative and interdisciplinary and is categorized as a sedimentary geological approach. Sedimentary geology incorporates the interpretive basis of sedimentology, (sedimentary *processes*), stratigraphy (spatial and temporal relations of sedimentary rock bodies), facies and depositional systems (organized response of sedimentary products and processes into sequences and rock bodies of a contemporaneous or time-transgressive nature), paleoceanography, paleogeography and paleoclimatology, sea-level analysis (local, global, eustatic) and sedimentary petrology mineralogy of sedimentary rocks to determine source areas to constrain paleocurrent analysis of basins; diagenesis). Biostratigraphy is relevant for establishing a temporal framework for correlating time-equivalent facies and systems and to constrain timing of specific events. Isotope geochronology (Williams, 1984) constrains both event stratigraphy and the history of changing chemical processes and their associated petrologic responses. Sedimentary geology includes paleoecology to calibrate sedimentary process-response interactions so as to constrain facies and depositional systems as well as paleoceanographic circulation patterns. Current summaries of most of these topics can be found in Klein (1985a), Davis (1983) Matthews (1984a), Brenchley and Williams (1984), Schopf (1980), and Ziegler et al. (1979, 1982), amongst others.

Topical research in sedimentary geology where major advances were made during the past decade include black shales, sea-level history and sedimentary sequences, global cycling and paleogeography and paleoclimatology. Plate reconstructions are sufficiently advanced now (Ziegler et al., 1979, 1982) that certain puzzling geological relations can be explained in terms of known processes of sedimentation, or by combining such data into sophisticated modelling by machine computation. For instance, latitudinal control of light refraction patterns in present day oceans shows a direct control on carbonate sedimentation (Ziegler et al., 1984). Areas of light refraction on the globe tend to favor formation of carbonate sediments, whereas areas of light reflection were found to be carbonate deficient. This pattern is controlled strictly by incidence of solar radiation on the earth's surface which has not changed over time. Ziegler et al. (1984) demonstrated cogently that the same latitudinal control for light refraction persisted throughout geological history in limiting carbonate rock distribution. Moreover, because solar light incidence is fixed with respect to the earth, paleogeographic mapping of carbonate facies (Ziegler et al. 1984) provided an independent check on the latitudinal controls on plate reconstruction itself.

Modern investigation into the origin of black shales illustrates the interdisciplinary nature of sedimentary geology. Most earlier hypotheses about black shales lacked credibility simply because no physical or chemical process accounted for their occurrence. A combined chemical, petrologic and paleoceanographic approach appears to have solved the problem. The best explanation for the origin of black shales (Schlanger and Jenkyns, 1976; Byers, 1977; Arthur and Schlanger, 1979) appears to be that conditions favoring their preservation are identical to present-day anaerobic zones. These zones are associated closely with depths of the sea bed on which the oxygen-minimum zones impinge. Under present-day conditions, however, these zones are minimal in vertical extent in the oceanic column, and their areal impingement on the sea bed is relatively small. Changing conditions in global oceanic circulation in response to atmospheric changes would cause an expansion of the oxygen-minimum zone both vertically and areally over the ocean floor. Several studies (Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Ettensohn and Elam, 1985) showed that during past times, such as during the Albian and also the Devonian, the oxygen-minimum zone expanded both over shelf environments and into deeper water environments, and thus black shale deposition was far more widespread than today. These findings are supported by studies of carbon-isotope composition of coeval sediments which showed a larger heavy carbon-isotope content in associated rock types. These data show that oceanic circulation is driven in a rhythmic fashion involving complex global, climatic, tectonic and volcanic processes (Fischer and Arthur, 1977; Fischer, 1984; Worsley et al., 1984).

One associated factor that influences these events is fluctuations in global and local sea level. Changes in sea-level fluctuations were deduced by stratigraphers from their recognition of both facies changes and transgressive and regressive events. Moreover, Sloss (1963) recognized that within cratonic stratigraphic successions, most are subdivided by large interregional unconformities, defining specific cratonic sequences, which recorded major transgressive and regressive events on a continent-wide basis. These sequences are recognized on four continental plates (Sloss, 1972, 1979) and are bounded by interregional unconformities of identical age.

Vail et al. (1977, 1984) recognized from analysis of seismic sections from several of the world's continental margins, that during Mesozoic and Cenozoic time, major sea-level changes were synchronous over a wide area and show three orders of magnitude of vertical change on a cyclic basis. These changes were documented primarily from a limited number of passive continental margins, or from active margins which lacked major uplift in response to plate collision. They interpreted these changes to occur on a global eustatic basis. First-order changes in sea level as defined by Vail et al. (1977), involve two major rise and falls in sea level during Phenerozoic time, and appeared to correlate to changes in oceanic spreading rate (Pittman, 1978). During times of rapid spreading, oceanic crust was buoyed upward by excess heat over a wider terrain flanking oceanic ridges and caused a shallowing of the ocean floor and displaced oceanic water to higher sea levels on land (Pittman, 1978). The second- and third-order sea-level cycles of Vail et al. (1977) appeared to be related more to global climatic events, including major episodes of glaciation extending as far back as 100 Ma (Matthews, 1984a,b), documented particularly well during the Oligocene (Miller et al., 1985), in addition to well-known Pleistocene glacio-eustatic sea-level fluctuations. Second- and third-order sea-level fluctuations appear to be controlled by changing ice volume as expressed by changes in oxygen-isotope signature of benthonic marine foraminifera (see Williams, 1984 for a review). These first- and second-order sea-level changes reported by Vail et al. (1977, 1984) from seismic analysis are interpreted to be interbasin-wide, and eustatic in nature.

However, other considerations must be addressed. First, the role of local tectonics needs to be evaluated (Parkinson and Summerhayes, 1985) because tectonic effects in local basins can mask global sea-level fluctuations. Parkinson and Summerhayes (1985) provided several examples of sedimentary basins and margins where the sea-level changes reported by Vail et al. (1977, 1984) are absent and could be explained away on tectonic grounds. Rapid rate of uplift associated with collision margins may also mask fluctuations in sea level (Klein, 1985b,c). Additionally, the factual data from which Vail et al. (1977, 1984) interpreted their reconstructions is proprietary. Third, passive margins such as of the Atlantic appear to be characterized by a flexural history (Steckler and Watts, 1982) and as shown by Watts et al. (1982), many of the known changes in sea-level rise reported by Vail et al. (1977) are coeval with so-called rift episodes of continental break-up associated with continental separation. Moreover, the onlap signature in a seismic section is relied upon by Vail et al. (1977) to recognize and calculate a relative rise in sea level, yet as Watts et al. (1982) demonstrated, a similar signature can represent a response of basin formation by flexure on an elastic crust. Finally, as Cloetingh (1986) and Cloetingh et al. (1985) showed, sea-level fluctuations of 120 m can be explained by changes of intraplate stress-fields associated with changing plate movements. Thus sea-level change of major magnitudes mirrors changes in stress fields within crustal plates through time (Cloetingh, 1986). Consequently, the conclusion is inescapable that although global sea-level changes are recognized, the cause of these global fluctuations are variable and future research in basin analysis will permit the isolation of the many causes that are recognized in specific cases.

Temporal change of certain facies and associated geochemical and paleontological diversity trends show that many recur in a cyclic mode. In a seminal paper, Fischer and Arthur (1977) reported that over the past 222 m.y., the patterns of faunal diversity, black shale occurrences, red clay occurrences, carbon-isotope signature, oxygen-isotope fluctuations, distribution of major marine unconformities, and fluctuations of the Calcite Compensation Depth (CCD) show a periodicity of approximately 32 m.y., with minor fluctuations of these same parameters of approximately 16 m.y. These are named oligotaxic and polytaxic events, with oligotaxic processes in the cycle being more uniformitarian, whereas polytaxic events share characteristics that appear to be non-uniformitarian (Leggett, 1984). During oligotaxic times (uniformitarian), sea level tends to be down relatively, climates are cooler, species diversity is limited, carbon-isotopic signatures are skewed to lighter carbon content, the elevation of the CCD is deeper, red clays accumulate, oceanic circulation is thermohaline, vigorous and more stratified, and deep-sea unconformities are more widespread. During polytaxic times (non-uniformitarian), species diversity expands, climates are more equitable, the carbon-isotope signature is skewed towards heavier carbon isotopes, oceanic circulation is more sluggish, sea level is high, the oxygen-minimum zone expands, black shales accumulate, the oxygen-isotope signature is skewed towards warmer paleotemperatures, and unconformities are fewer. These alternations were attributed to changing climates caused by changing rates of volcanic activity at oceanic ridge crests. Moreover, with sea level being higher, climates become moderated and circulation slows as rainfall increases. Later work by Fischer (1984) showed that two supercycles are superimposed on this 32 m.y. cyclicity with a 200 m.y. periodicity paralleling the first-order sea-level changes of Vail et al. (1977) and of Pittman (1978). These he labelled icehouse (uniformitarian) and greenhouse (non-uniformitarian) phases. This larger-order cyclicity is also a reflection of longer-term climatic change in response to global volcanism as shown by the age distribution of preserved continental areas of granite intrusions. Fischer (1984) suggested that the control of volcanism is governed by changing lengths of mid-ocean ridges and its control on the number of tectonic plates. Thus during times of development of supercontinents, ridge activity is minimal and fewer exist; thus volcanicity is reduced and global icehouse conditions prevail. As these supercontinents break up, the number of plates increases as does ridge length, favoring greenhouse conditions. Worsely et al. (1984) and Nance et al. (1986) demonstrated also that such alternations of supercontinent accretion and breakup characterized the last 2 GA of earth history. When supercontinents exist, thermal heat loss is focussed underneath continents, rather than being vented by ridge volcanism. These effects cause major changes in sea level, atmospheric properties, sediment facies distribution, climate and evolutionary history (Worsley et al., 1984; Nance et al., 1986) and drive the supercycles.

Clearly, such diverse processes of differing scales affect the end product of preserved sediment accumulations in sedimentary basins. Superimposed on subsidence events are cyclic changes in sea level, oceanic circulation, climate and life history which require careful identification when considering timing of events and preferred facies distributions in response to tectonic subsidence history.

MATURATION OF SEDIMENT

During and after sediment filling of sedimentary basins, other physical, chemical and hydrologic processes are superimposed in response to changing fluid regimen, thermal regimen and burial regimen. These processes cause major diagenetic changes in both mineral components and organic components in sedimentary fill.

The burial factor in diagenesis considers the effect of sediment load coupled with the geothermal gradient because with increasing depth and pressure, temperature will increase also and effect changes in mineral phases. For instance, Perry and Hower (1970, 1972) demonstrated that in the Gulf Coastal Plain of the U.S.A. burial depth causes not just compactional reduction in porosity and permeability, but also fabric change in clay minerals and an increase in both illite crystallinity and illite content with the addition of potassium ions from degradation of smectite.

The role of fluid circulation in diagenetic reactions is of significance also. Bethke

(1985, 1986) demonstrated using numerical modelling methods, that in the Illinois Basin, gravity flow of water through porous sediments enhanced by compaction-driving, moved ground water from the southern edge of the basin to its depocenter. As it flows to the deeper portions of the basin, water temperature increases in response to thermal changes. This water transports up-dip from the basin center towards the basin flanks in the north. These hot waters within the depocenter reacted with surrounding sediments, leached associated metals and transported them to a zone of cooler temperatures where the metals precipitated in concentrations of economic importance. This flow history appears to account for the lead and zinc occurrences of northwest Illinois and southeastern Wisconsin and the origin of so-called Mississippi Valley-type base metal deposits.

Fluid convection within porous sediment will impose certain diagenetic reactions. Abbott et al. (1981, 1983) demonstrated that in the Mariana Basin and the Indian Ocean, fluids within sediment experience a thermally-driven convective flow when deposited on basaltic basements characterized by high heat-flow. This thermally-driven fluid circulation advects ocean waters in the downwelling phase and hot waters emanating from the basaltic basement in the upwelling phase. These advective effects cause major departures from a simple thermal gradient in interstitial fluid temperature within sediments. Recently, Lee and Klein (1986) explained a series of complex diagenetic reactions in sandstones from the back-arc basins of the western Pacific Ocean by this process, accounting for precipitation of relatively high temperature zeolite cements from advective upwelling convective thermal circulation, and later calcite pore-fill cements from a lower temperature downwelling phase. These reactions are preserved only if the sediments underwent a slow or moderate burial rate during the active rifting phase of basin formation. In back-arc basins, diagenetic reactions of sandstones appear to be controlled primarily by timing of sandstone deposition during basin rifting coupled with slow and moderate burial rates and thermally driven convective fluid circulation, in addition to original sandstone composition. Clearly, here is a case where basin geodynamics and timing of depositional events in terms of rifting processes controls the diagenetic reactions closely.

Progressive burial of sediments in deep basins are subjected to the development of secondary porosity also (Schmidt and McDonald, 1979). The cause of these reactions is not known fully, although Lee and Klein (1986) reported development of secondary porosity by leaching under thermally driven fluid circulation in back-arc basins.

Of interest to petroleum geologists is the maturation of organic material incorporated into sediments. A large literature on this topic has evolved and is summarized ably by Waples (1985). The gist of these studies is that with progressive burial and heating, organic matter undergoes diagenetic alteration as the original structure and chemistry of the organic remains are altered into a fluid or gaseous phase and migrate into potential petroleum and gas reservoirs. However, in order to preserve petroleum, a liquid window defined by narrow temperature ranges is required, if the upper temperature of this window is exceeded, organic phases are preserved as natural gases. Several projections of organic maturation and diagenesis can be made from basin studies utilizing burial depth, geothermal gradient, heat-flow data, and departures from geothermal gradient to predict the probability of observing petroleum and natural gas in a basin and calculating potential reserves. This time–temperature–depth approach is commonplace in sedimentary basin analysis. Examples of it include published papers by Royden et al. (1980) and Sclater and Christie (1980) amongst others.

TIMING OF EVENTS

Analysis of timing of events in sedimentary basins represents the integrative mode of basin analysis where an attempt is made to determine which geological events and interpreted processes occurred at specific times and how, in fact, they are linked in a causal way. It must be emphasized again as elsewhere (Klein and Lee, 1984; Klein, 1985b) that just because certain events occur coincidently doesn't mean that a correlation of process exists within a sedimentary basin. The integrative effort to correlate events permits evaluation of processes and responses within basins and isolation of associated variables.

This type of integration is summarized traditionally in a correlation diagram where specific information is plotted against the geological time scale. Crucial to a basin analysis, then, is the accuracy of dating methods used to establish timing of specific events or processes. This problem needs no further discussion here. However, it is not unusual within a basin analysis that the resolution of timing of events will be variable and thus constrain some interpretations. Two examples are considered briefly.

Figure 1 is a correlation diagram taken from Heidlauf et al. (1986) who completed an analysis of the subsidence history, sedimentary history and regional tectonic events of Illinois Basin. Subsidence history in Fig. 1 is represented by the sediment accumulation rate because the tectonic subsidence curve is the derivative of sediment accumulation rate. In the Illinois Basin, the shape, trend and scale of both tectonic subsidence curves derived from three wells and sediment accumulation-rate curves are identical (Heidlauf et al., 1986). Distant tectonic events such as repeated uplift of the Appalachians caused major influx of mud which accumulated in the Illinois Basin as the Maquoketa Shale and Knobs Group, respectively, during Ordovician, late Devonian and early Mississippian time. The tectonic subsidence curves show that the Illinois Basin went through several stages of evolution including an initial mechanically-dominated rift phase, followed by a thermal subsidence phase akin to a passive margin. The Illinois Basin as known today is actually a post-early carboniferous (Mississippian) feature in response to uplift of the Pascola Arch (see Bethke, 1985; Heidlauf et al., 1986). That uplift may well

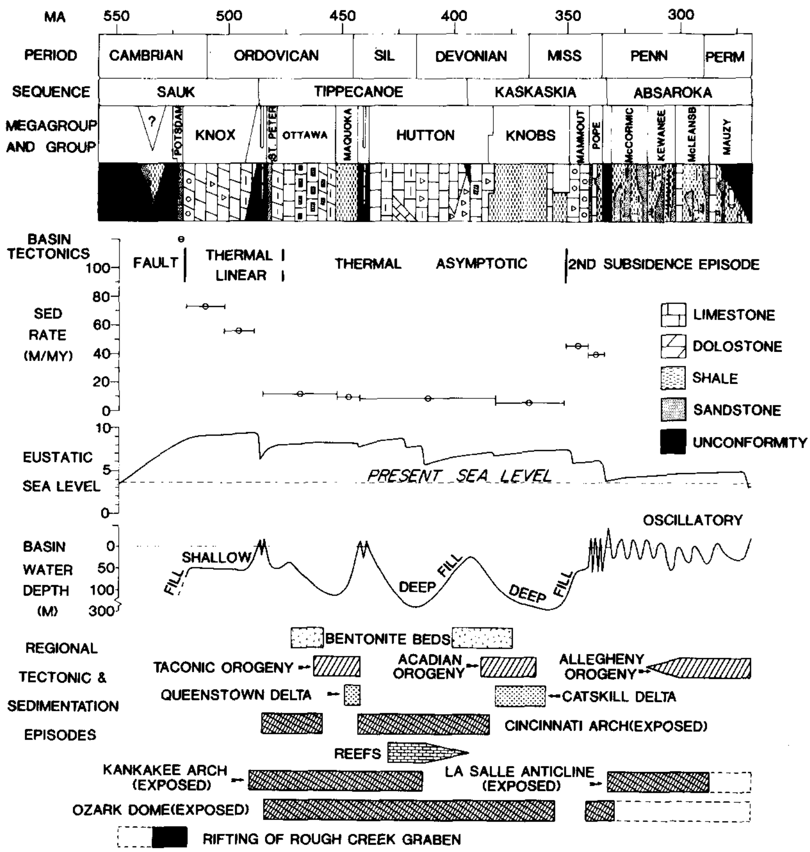

Fig. 1. Correlation diagram of the Illinois Basin showing time scale, stratigraphy, cratonic sequences (as per Sloss, 1963), sediment accumulation rates (equivalent to general tectonic subsidence curve), sea-level history, changes in depositional depth, and regional tectonic events (redrawn from Heidlauf et al., 1986).

account for a sudden increase in subsidence during Carboniferous time (Fig. 1). In summary, the Illinois Basin evolved through several complex stages of formation including initial rifting, thermal decay similar to passive margins with some viscoelastic processes (Heidlauf et al., 1986), followed by a repeated event of basin formation which is observed today as a cratonic basin. Thus, the basin followed a complex history involving several basinal phases.

The sediment fills of the Illinois Basin represent a history of initial rift sediments consisting of clastic sediments which appear to be both non-marine and coastal plain facies. The Lower Paleozoic sediments which accumulated during the thermal subsidence phase represent a complex array of coastal plain, barrier islands, eolian dunes, carbonate and clastic intertidal flats, storm deposits, and complex carbonate ramp-shelf deposits. These were subjected to periodic major changes in sea level which caused interregional unconformities that were used by Sloss (1963) to define cratonic sequences. Positive departures from subsidence history are recorded by Heidlauf et al. (1986) at times of sea-level reduction and later rise, and clearly indicate transgressive overlap, increases in sediment accumulation rate and preservation in response to sea-level rise, and filling of the basin to where sediment accumulation was again in balance with basin subsidence.

Of interest is dolomitization during a time of maximum thermal subsidence in the Illinois Basin, but whether a causal connection involving thermally driven fluid circulation exists, such as described by Abbott et al. (1981, 1983), remains an open problem. Possibly, some of this dolomitization could be correlated to a major release of water and associated fluids with Appalachian tectonics as suggested by Oliver (1986).

A second example of such an integration of timing of events comes from the Appalachian Basin (Willard and Klein, in prep.) of the eastern U.S.A. The Appalachian Basin of the Central Appalachians of Pennsylvania, West Virginia and Virginia represents a polyhistory basin that has undergone complex evolution. Figure 2 shows a correlation diagram of the principal orogenic events plotted against sediment accumulation rates, sea-level change, lithology, and recognizable sedimentary sequences as defined by Colton (1970). As with the Illinois Basin example, trends of the sediment accumulation rate parallel tectonic subsidence curves calculated from eight wells (Willard and Klein, in prep.) The present-day Appalachian Basin owes its origin strictly to two collisional tectonic events which caused it to form as a foreland basin. Initially, the Appalachians comprised part of a major supercontinent (Bond et al., 1984) which broke up during latest Precambrian time. This breakup involved an initial rift phase followed by a thermal subsidence phase during Cambro-Ordovician time (Bond and Kominz, 1984; Bond et al., 1984) when eastern North America subsided as a passive margin. The site of the present Appalachian Basin was inboard from collision tectonics associated with the closing of the Iapetus Ocean and the basin formed as a foreland basin. Repeated collision tectonics during the Devonian–Mississippian (Acadian Orogeny) and the Pennsylvanian and Permian (Allegheny Orogeny) amplified the foreland basin structure. The lithosphere responded to flexural and compressional stress and clearly downbulging of the basin favored both rapid subsidence rates and concomitant rapid sediment accumulation rates. Flexural relaxation slowed subsidence and sediment accumulation rates are preserved as predicted from a viscoelastic model (Watts et al., 1982). These subsidence events are mechanical in nature and the role of thermal subsidence is diminished in significance in this foreland basin just as in other foreland basins (Jordan, 1981).

Sediment deposition followed this pattern (Willard and Klein, in prep.). During initial rifting, non-marine clastics accumulated, whereas during the passive-margin phase of thermal linear subsidence, coastal barriers, tidal flats, and tidal sand bodies as well as shelf carbonates and dolomites accumulated. With the uplift associated with the Taconic collision event, Upper Ordovician clastic sequences, consisting

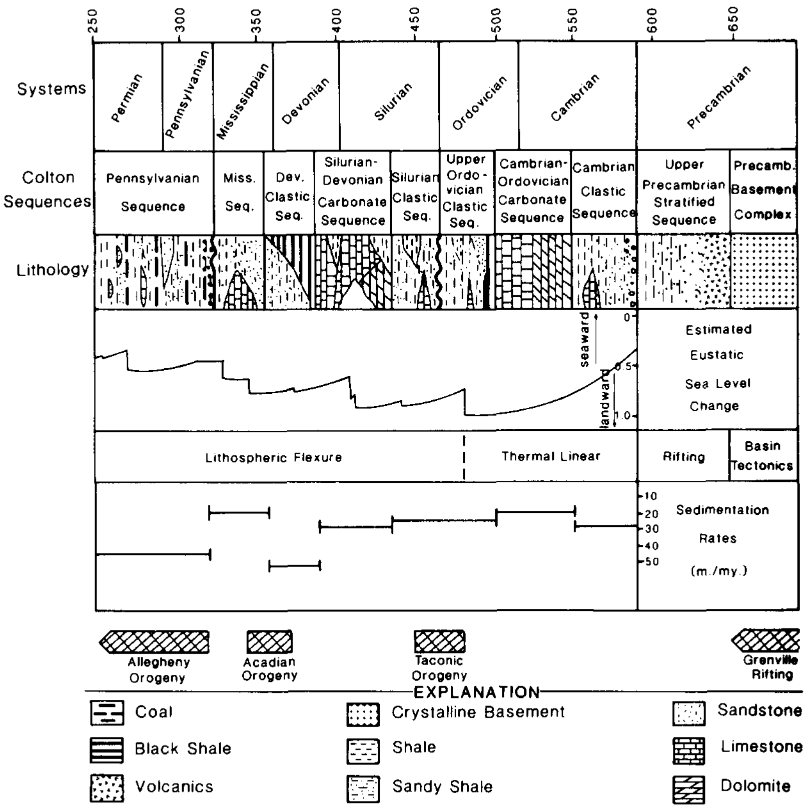

Fig. 2. Correlation diagram of the Appalachian Basin, central Appalachians, showing time scale, sedimentary sequences after Colton (1970), basin evolution (based on tectonic subsidence curves from eight wells), sediment accumulation rates (average from eight wells), sea-level history, and orogenic events (after Willard and Klein, in prep.).

mostly of deltas, accumulated, followed by additional coastal and shelf clastics and shelf carbonate deposition. Collision tectonics of the Acadian orogeny caused deposition primarily of thick clastic wedges in the form of deltas. These deltas tongued laterally into black shales of relatively deeper water origin, and of the lower delta front and prodelta zones of the Catskill Delta in response to increased elevation of the oxygen-minimum zone (Ettensohn, 1985a,b). These deltaic systems gave way to a limited transition of shelf clastics and carbonates, which were limited in time because of uplift of the Hercynian–Alleghenian orogenic belt favoring deposition of thick clastic wedges comprising mostly coal measures and associated inner deltaic sequences. Again, the sedimentation patterns tend to follow the changing patterns of basin evolution. It is noteworthy, however, that the sequences defined by Colton (1970), which followed basin subsidence history so closely, are independent of larger-order global sea-level changes of Vail et al. (1977). The

Paleozoic sea-level changes of Vail et al. (1977) are based on Sloss' (1963) cratonic sequences, and it is to be expected therefore that local variation and local tectonic styles and associated change in stress fields would mask such global effects (Watts et al., 1982; Parkinson and Summerhayes, 1985; Cloetingh, 1986; Miall, 1986), particularly in collision orogens (Klein, 1985c) as it does in this case.

Again, analysis of timing of events associated with the subsidence history of the Illinois Basin and the Appalachian Basin demonstrate that certain processes and events are interrelated, whereas others remain problematic, despite their coincidence. It demonstrated also that extrapolation of cratonic-defined sea-level fluctuations into an active-margin collision zone does not necessarily lead to a global correlation.

SUMMARY AND CONCLUSIONS

This brief overview of the current aspects and status of basin analysis shows that an interdisciplinary approach tends to solve the major problems confronted in sedimentary basins. This interdisciplinary approach focuses on the formation of basins, the nature of their sedimentary fills, maturation of the sediment fills, and timing of events. Certain events clearly show a correlation between process of formation and sedimentary responses. The utilization of geophysical mechanical analysis of basin formation has provided considerable understanding in isolating processes of subsidence in complex basins, has demonstrated the polyhistory of many basins and in turn provided a genetic resolution to classifying most sedimentary basins. A variety of problems still remain outstanding, including the nature and cause of sea-level fluctuations and in particular, why certain basins show a record of sea-level changes that fits a suggested global pattern and others do not. Future research in basin analysis will continue in the interdisciplinary mode discussed in this overview and it is expected that the process cause-and-effect connection between certain sedimentary events and basin evolution that appear as unexplained coincidences today, will be resolved in terms of newer discoveries concerning basin formation.

ACKNOWLEDGEMENTS

My research on basin analysis and sedimentary geology which is incorporated in this paper was supported at various times by the Geological Society of America, Sigma Xi, the National Science Foundation (Grant OCE-81-09447), the American Philosophical Society, and the Research Board and The Center for Advanced Study, both of the University of Illinois at Urbana-Champaign.

REFERENCES

Abbott, D.H., Menke, W., Hobart, M.A. and Anderson, R.N., 1981. Evidence for excess pore pressures in southwest Indian Ocean sediments. J. Geophys. Res., 86: 1813–1827.

Abbott, D.H., Menke, W. and Morin, R., 1983. Constraints upon water advection in sediments of the Mariana Trough, J. Geophys. Res., 88: 1075–1093.

Arthur, M.A. and Schlanger, S.O., 1979. Cretaceous "oceanic anoxic events" as causal factors in development of reef-reservoired giant oil fields. Bull., Am. Assoc. Pet. Geol., 63: 870–885.

Auboin, J., Bourgois, J. and Azema, J., 1984. A new type of active margin: convergent-extensional margin as exemplified by the Middle America Trench of Guatemala. Earth Planet. Sci. Lett., 67: 211–218.

Bally, A.W., 1980. Basins and subsidence—a summary. In: A.W. Bally, P.L. Bender, T.R. McGetchin and R.I. Walcott (Editors), Dynamics of Plate Interiors. Am. Geophys. Union, Geodynamics Ser., 1: 1–16.

Bally, A.W. and Snelson, S., 1980. Realms of subsidence. In: A.D. Miall (Editor), Facts and Principles of World Petroleum Occurrence. Can. Soc. Pet. Geol. Mem., 6: 9–94.

Bethke, C.M., 1985. A numerical model of compaction-drive groundwater flow and heat transfer and its application to the paleohydrology of intracratonic sedimentary basins. J. Geophys. Res., 90: 6817–6828.

Bethke, C.M., 1986. Hydrologic constraints on genesis of the Upper Mississippi Valley mineral district from Illinois Basin brines. Econ. Geol., 81: 233–249.

Bickford, M.E., Van Schmus, R.A. and Zietz, I., 1986. Proterozoic history of the midcontinent region of North America. Geology, 14: 492–496.

Bond, G.C. and Kominz, M.A., 1984. Construction of tectonic subsidence curves for the early Paleozoic Miogeocline, southern Canadian Rocky Mountains: implications for subsidence mechanisms, age of breakup and crustal thinning. Geol. Soc. Am. Bull., 95: 155–173.

Bond, G.C., Nickeson, P.A. and Kominz, M.A., 1984. Breakup of a supercontinent between 625 Ma and 555 Ma; new evidence and implications for continental histories. Earth Planet. Sci. Lett., 70: 325–345.

Brenchley, P.J. and Williams, B.P.J. (Editors), 1984. Sedimentology: Recent Developments and Applied Aspects. Blackwell, Oxford, 342 pp.

Byers, C.W., 1977. Biofacies patterns in euxinic basins: a general model. In: H.E. Cook and P. Enos (Editors), Deep-water Carbonate Environments. Soc. Econ. Paleontol. Mineral., Spec. Publ., 25: 5–18.

Chen, W.P. and Nabelek, J.L., 1985. Strike-slip earthquakes and the development of the North China Basin. Eos, Trans. Am. Geophys. Union, 66: p. 1067 (abstract).

Cloetingh, S., 1986. Intraplate stresses: a new tectonic mechanism for fluctuations of relative sea level. Geology, 14: 617–620.

Cloetingh, S., McQueen, H. and Lambeck, K., 1985. On a tectonic mechanism for regional sea level variations. Earth Planet. Sci. Lett., 75: 157–166.

Colton, G.W., 1970. The Appalachian Basin—its depositional sequences and their geological relationships. In: G.W. Fisher, F.J. Pettijohn, J.C. Reed Jr. and K.N. Weaver (Editors), Studies of Appalachian Geology: Southern and Central. Wiley, New York, N.Y., pp. 5–47.

Davis Jr., R.A. 1983. Depositional Systems. Prentice-Hall, Englewood Cliffs, N.J., 669 pp.

Dickinson, W.R., 1974. Plate tectonics and sedimentation: In: W.R. Dickinson (Editor), Tectonics and Sedimentation. Soc. Econ. Paleontol. Mineral., Spec. Publ., 22: 1–27.

Ettensohn, F.R., 1985a. Controls on development of Catskill Delta complex basin-facies: In: D.L. Woodrow (Editor), The Catskill Delta. Geol. Soc. Am., Spec. Pap., 201: 65–77.

Ettensohn, F.R., 1985b. The Catskill Delta complex and the Acadian Orogeny: a model. In: D.L. Woodrow (Editor), The Catskill Delta. Geol. Soc. Am., Spec. Pap., 201: 39–49.

Ettensohn, R.F. and Elam, T.D., 1985. Defining the nature and location of a Late Devonian–Early Mississippian pycnocline in eastern Kentucky. Geol. Soc. Am. Bull., 96: 1313–1321.

Fischer, A.G., 1984. The two phanerozoic supercycles. In: W.A. Berggren and J.A. van Couvering (Editors), Catastrophes and Earth History. Princeton Univ. Press., Princeton, N.J., pp. 129–150.

Fischer, A.G. and Arthur, M.A., 1977. Secular variations in the pelagic realm. In: H.E. Cook and P. Enos (Editors), Deep-water Carbonate Environments. Soc. Econ. Paleontol. Mineral., Spec. Publ., 25: 19–50.

Heidlauf, D.T. Hsui, A.T. and Klein, G. deV., 1986. Tectonic subsidence analysis of the Illinois Basin. J. Geol., 94: 779–794.

Hellinger, S.J. and Sclater, J.G., 1983. Some comments on two-layer extensional models for the evolution of sedimentary basins. J. Geophys. Res., 88: 8251–8269.

Hilde, T.W.C., 1983. Sediment subduction versus accretion around the Pacific. Tectonophysics, 99: 381–397.

Jordan, T.E., 1981. Thrust loads and foreland basin evolution. Cretaceous, western United States. Bull., Am. Assoc. Pet. Geol., 65: 83–91.

Kay, G.M., 1948. North American geosynclines. Geol. Soc. Am., Mem., 48: 143 pp.

Kingston, D.R., Dishroon, C.P. and Williams, P.A., 1983. Global basin classification system. Bull., Am. Assoc. Pet. Geol. 67: 2175–2193.

Klein, G. deV., 1985a. Sandstone depositional models for exploration for fossil fuels. IHRDC Press, Boston, Mass., 3rd ed, 209 pp.

Klein, G. deV., 1985b. The control of depositional depth, tectonic uplift and volcanism on the sedimentation processes in the back-arc basins of the western Pacific. J. Geol., 93: 1–25.

Klein, G. deV., 1985c. The frequency and periodicity of preserved turbidites in submarine fans as a quantitative record of tectonic uplift in collision zones. Tectonophysics, 119: 181–193.

Klein, G. deV. and Lee, Y.I., 1984. A preliminary assessment of geodynamic controls on depositional systems and sandstone diagenesis in back-arc basins, western Pacific Ocean. Tectonophysics, 102: 119–152.

Kleinspehn, K.L., 1985. Cretaceous sedimentation and tectonics, Tyaughton-Methow Basin, southwestern British Columbia. Can. J. Earth Sci., 22: 154–174.

Klemme, H.D., 1975. Giant oil fields related to their geologic setting: a possible guide to exploration. Bull. Can. Pet. Geol., 23: 30–66.

Lee, Y.I. and Klein, G. deV., 1986. Diagenesis of sandstones in the back-arc basins of the western Pacific Ocean. Sedimentology, 33: 651–675.

Leggett, J.K., 1984. Deep-sea pelagic sediments and paleo-oceanography: a review of recent progress. In: P.J. Brenchley and B.P.J. Williams (Editors), Sedimentology: Recent Developments and Applied Aspects. Blackwell, Oxford, pp. 95–121.

Matthews, R.K., 1984a. Dynamic Stratigraphy. Prentice-Hall, Englewood Cliffs, N.J., 489 pp.

Matthews, R.K., 1984b. Oxygen-isotope record of ice-volume history: 100 million years of glacio-eustatic sea level fluctuations. In: J.S. Schlee (Editor), Interregional Unconformities and Hydrocarbon Accumulation. Mem., Am. Assoc. Pet. Geol., 36: 97–107.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett., 40: 25–32.

Miall, A.D., 1984. Principles of Sedimentary Basin Analysis. Springer, New York, N.Y., 490 pp.

Miall, A.D., 1986. Eustatic sea level changes interpreted from seismic stratigraphy: a critique of the methodology with particular reference to the North Sea Jurassic record. Bull. Am. Assoc. Pet. Geol., 70: 131–137.

Miller, K.G., Mountain, G.S. and Tucholke, B.E., 1985. Oligocene-glacio-eustasy and erosion on the margins of the North Atlantic. Geology, 13: 10–13.

Nance, R.D., Worsley, T.R. and Moody, J.B., 1986. Post-Archean biogeochemical cycles and long-term periodicity in tectonics processes. Geology, 14: 514–518.

Oliver, J., 1986. Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. Geology, 14: 99–102.

Parkinson, N. and Summerhayes, C., 1985. Synchronous global sequence boundaries. Bull. Am. Assoc. Pet. Geol., 69: 685–687.

Parsons, B. and Sclater, J.G., 1977. An analysis of the variation of ocean-floor heat-flow and bathymetry with age. J. Geophys. Res., 82: 803–827.

Perry Jr., E.A. and Hower, J., 1970. Burial diagenesis in Gulf Coast pelitic sediments. Clays Clay Miner., 18: 165–177.

Perry Jr., E.A. and Hower, J., 1972. Late-stage dehydration in deeply buried pelitic sediments. Bull. Am. Assoc. Pet. Geol., 56: 2013–2021.

Pittman III., W.C., 1978. Relationship between eustacy and stratigraphic sequences of passive margins. Geol. Soc. Am. Bull., 89: 1389–1403.

Royden, L., Sclater, J.G. and Von Herzen, R.P., 1980. Continental margin subsidence and heat flow: Important parameters in formation of petroleum hydrocarbons. Bull. Am. Assoc. Pet. Geol., 64: 173–187.

Sawyer, D.S., Hsui, A.T. and Toksoz, M.M., 1987. Subsidence and thermal history of the Los Angeles Basin as resulting from Middle Oligocene extension. Tectonophysics (in press).

Schlanger, S.O. and Jenkyns, H.C., 1976. Cretaceous oceanic anoxic events: causes and consequences. Geol. Mijnbouw, 55: 179–184.

Schmidt, V. and McDonald, D.A., 1979. The role of secondary porosity in the course of sandstone diagenesis. In: P.A. Scholle and P.R. Schluger (Editors), Aspects of Diagenesis. Soc. Econ. Paleontol. Mineral., Spec. Publ., 26: 175–208.

Schopf, T.J.M., 1980. Paleoceanography. Harvard Univ. Press, Cambridge, 341 pp.

Sclater, J.G. and Christie, P.A.F., 1980. Continental stretching: an explanation of the post-Mid Cretaceous subsidence of the central North Sea Basin. J. Geophys. Res., 85: 3711–3739.

Sims, P.K. and Peterman, Z.E., 1986. Early Proterozoic Central Plains orogen: a major buried structure in the north-central United States. Geology, 14: 488–491.

Sleep, N.H., 1971. Thermal effects on the formation of Atlantic continental margins by continental breakup. Geophys. J.R. Astron. Soc., 24: 325–350.

Sloss, L.L., 1963. Sequences in the cratonic interior of North America. Geol. Soc. Am. Bull., 74: 93–114.

Sloss, L.L., 1972. Synchrony of Phanerozoic sedimentary-tectonic events in the North American Craton and the Russian Platform. XXIV Int. Geol. Congr., 6: 24–32.

Sloss, L.L., 1979. Global sea level change: a view from the craton. In: J.S. Watkins and C.L. Drake (Editors), Geological and Geophysical Investigations of Continental Margins. Mem., Am. Assoc. Pet. Geol., 29: 461–467.

Steckler, M.S. and Watts, A.B., 1982. Subsidence history and tectonic evolution of Atlantic-type continental margins: In: R.A. Scruton (Editor), Dynamics of Passive Margins. Am. Geophys. Union, Geodynamics Ser., 6: 184–196.

Vail, P.R., Mitchum. R.M. and Thompson III, S., 1977. Seismic stratigraphy and global changes of sea level. Part IV: Global cycles of relative changes of sea level. In: C.E. Payton (Editor), Seismic Stratigraphy—Applications to Hydrocarbon Exploration. Mem., Am. Assoc. Pet. Geol., 26: 83–98.

Vail, P.R., Hardenbol, J. and Todd, R.G., 1984. Jurassic unconformities, chronostratigraphy and sea level changes from seismic stratigraphy and biostratigraphy. In: J.S. Schlee (Editor), Interregional Unconformities and Hydrocarbon Accumulation. Mem., Am. Assoc. Pet. Geol., 36: 129–144.

Waples, D.W., 1985. Geochemistry in petroleum exploration. IHRDC Press, Boston, Mass., 232 pp.

Watts, A.B. and Ryan, W.B.F., 1976. Flexure of the lithosphere and continental margin basins. Tectonophysics, 36: 25–44.

Watts, A.B., Karner, G.D. and Steckler, M.S., 1982. Lithospheric flexure and the evolution of sedimentary basins. Philos. Trans. R. Soc. London, Ser. A, 305: 249–281.

Williams, D.F., 1984. Correlation of Pleistocene marine sediments of the Gulf of Mexico and other basins using oxygen isotope stratigraphy. In: N. Healy-Williams (Editor), Principles of Pleistocene Stratigraphy Applied to the Gulf of Mexico. IHRDC Press, Boston, Mass., pp. 65–118.

Worsley, T.R., Nance, R.D. and Moody, J.B., 1984. Global tectonics and eustasy for the past 2 billion years. Mar. Geol., 58: 373–400.

Ziegler, A.M., Scotese, C.R., McKerrow, W., Johnson, M.E. and Bambach, R.K., 1979. Paleozoic paleogeography. Annu. Rev. Earth Planet. Sci., 7: 473–502.

Ziegler, A.M., Scotese, C.R. and Barrett, S.F., 1982. Mesozoic and Cenozoic paleogeographic maps. In: P. Brosche and J. Sundermann (Editors), Tidal Friction and the Earth's Rotation. Springer, New York, N.Y., pp. 240–252.

Ziegler, A.M., Hulver, M.L., Lottes, A.L. and Schmachtenberg, W.F., 1984. Uniformitarianism and paleoclimates: inferences from the distribution of carbonate rocks. In: P. Brenchley (Editor), Fossils and Climate. Wiley, New York, N.Y., pp. 3–25.

Ziegler, P.A., 1978. Northwestern Europe Tectonics and basin development. Geol. Mijnbouw, 57: 589–626.