Part 1 Perspective and General Information

INTRODUCTION

Why a South African Sequence Stratigraphy Atlas?

Development and application of seismic stratigraphy in exploration have been underway worldwide for more than two decades. The application of modern sequence stratigraphy, however, is only beginning. Recent proliferation of continuing education courses on the subject clearly indicates the growing level of international interest in understanding and evaluating these new ideas and methods. Standing-room-only crowds attending sequence stratigraphy presentations at recent international and regional geologic and geophysical annual meetings show how popular the subject has become during the past several years. Since 1990, most companies have been sponsoring in-house courses and workshops. Most professional meetings have scheduled one or more courses on some aspect of sequence stratigraphy. Within many companies, individual explorationists have begun to study and attempt to apply recently published concepts and procedures. Management in other companies is mandating that these new tools be applied in all future prospecting and field development.

Geoscientists at Soekor (Pty) Ltd. conceived this atlas in response to the recent growing interest in the subject and because of the limited number of published case histories that document the application of sequence stratigraphy. Sequence stratigraphy provides some very powerful chronostratigraphic and play prediction tools for exploration, as well as an unusual stratigraphic perspective required for subsequent field development and reservoir characterization. A need exists for real world examples that provide sufficient basic data to enable geoscientists to evaluate the practical application and contribution of sequence stratigraphy to an active exploration and drilling program. This atlas is thus designed to document examples of how these new sequence concepts and methods have contributed to the petroleum exploration of offshore South Africa.

The South African offshore basins outlined in Figure 1 provide examples of sequence stratigraphy application in two types of postrift basins filled with rocks of Cretaceous age (Figure 2). The Pletmos and Bredasdorp basins are located in the Indian Ocean along the northern side of the major Agulhas-Falkland Fracture Zone, along which dextral strike-slip motion occurred early in their divergent margin histories, as shown on plate tectonic maps in Figures 3 and 4. The South Atlantic Orange Basin, in contrast, is located along the trailing, divergent, southwestern margin of the African plate. How can these studies help petroleum geologists who are exploring elsewhere in the world and in other types of basins? Are the same basic concepts and methods applicable in basins that had different tectonics, paleoclimates, and sediment supplies?

Many geologists are now successfully applying sequence stratigraphy to analyze sedimentary basins with diverse tectonic styles. The first step in using these ideas universally, however, is to gain experience analyzing basins with less complex tectonic histories. Intracratonic and various divergent margin basins with minimal structural overprints are generally better for training than, for example, rift basins, foreland basins, and forearc basins. In tectonically less complex basins, it is easier to apply key criteria to recognize depositional sequences, component depositional systems tracts, and erosional or nondepositional surfaces. In turn, it is easier to observe the relationship between eustasy and subsidence in producing cycles of relative change in sea level, which controlled accommodation space. Also, the interplay of accommodation space and sediment supply, which determines sequence geometry and types of depositional systems, can be easily demonstrated within a divergent margin basin.

Once these fundamental concepts are understood and the skills and experience acquired, they may be used to interpret the chronostratigraphy and sequence stratigraphy and to identify potential hydrocarbon plays within any type of basin in the world. The basic data and sequence interpretations of the South African basins constitute case histories that document basic concepts and procedures that are relevant, applicable, and transferable worldwide to basins of all ages and types.

Exploration in Offshore South Africa

Oil and gas exploration in offshore South Africa (Figure 1) began more than 20 years ago when Soekor and several other companies began prospecting for structural traps and synrift sandstone reservoirs of Late Jurassic and Early Cretaceous age. Although there were some encouraging oil and gas shows and mature source beds in the younger Cretaceous postrift sequences, early exploration was focused on synrift potential. Targets were principally shale-draped, rift horst blocks with sealing faults. Gas and condensate were encountered in synrift sandstones of shallow marine origin. Hydrocarbons in the synrift reservoirs are inferred to have migrated across the rift-drift unconformity from deeply buried postrift shales.

The first commercial discovery, a synrift structural play, was in 1980 in the Bredasdorp Basin (Figure 1). Soon, there were other synrift gas and condensate discoveries in Lower Cretaceous sandstones that were structurally trapped in a trend along the northern flank of the basin. This rift play provides the gas and condensate that is currently piped onshore to the Mossgas synfuel plant at Mossel Bay (Figure 1), the first commercial refinery using South African liquid petroleum.

During the mid-1980s, limited success in exploring for synrift targets caused Soekor to refocus its exploration activity on Cretaceous sandstone reservoirs within the younger postrift divergent margin succession (Figure 2) in the Bredasdorp Basin. By that time, a number of rift structures had been tested and one field discovery had been made in the South African rift basins. Although oil and gas shows and source beds had been encountered in the postrift succession during earlier rift prospecting, the less structured Cretaceous divergent margin strata essentially constituted an unexplored frontier. Because the postrift succession exhibited limited structural closures, exploration interest focused on stratigraphic or subtle combination traps. The potential for such subtle traps is greatest in deep water basinal facies, where shale seals, sandstone pinchouts, and source beds were predicted and later identified. Consequently, attention was directed toward the occurrence and recognition of deep marine gravity flow sandstones.

During late 1986, the first oil (and gas) discovery in South Africa was made in the postrift rocks of the central Bredasdorp Basin (Figure 1). Targets were Barremian sandstones within deep marine fans (Figure 2), which are mounded seismic facies within the relatively unstructured divergent margin succession. This discovery immediately pointed to the need for a basinwide chronostratigraphic framework of the postrift rocks within which the distribution of other basin floor fans might be predicted and correlated. Such a framework was needed to unify the results (such as wireline logs, microfossils, and geochemistry) derived from the proposed drilling program so that all viable hydrocarbon plays could be identified in the Cretaceous divergent margin sequences.

Soekor explorationists concluded that the most expeditious way to prospect within the postrift rocks for these kinds of reservoirs, traps, and source rocks was to integrate seismic and sequence stratigraphy into their exploration program. During the next 3 years, sequence stratigraphy studies of three South African basins were undertaken by Soekor geoscientists, in cooperation with The University of Texas at Austin. These studies were completed for the Bredasdorp Basin in 1987, the Pletmos Basin in 1988, and the Orange Basin in 1989. Results of these investigations were applied immediately to Soekor's ongoing prospecting and drilling program. As wells were drilled in each basin, resulting sedimentary, microfossil, petrographic, and source rock data were integrated within the sequence stratigraphic framework.

Results of the application of sequence stratigraphy in offshore South African basins from 1988 to 1994 are discussed for each of the three basins covered in this Atlas. Several papers already published by Soekor's explorationists (Brink et al., 1993; Muntingh and Brown, 1993; Winters and Kuhlmann, 1994) were generated during the preparation of the Atlas. Soekor's explorationists have concluded that the results of the intensive drilling program for 57 primary sequence stratigraphic targets in the Bredasdorp Basin fully document the successful application of sequence stratigraphy in their exploration for subtle deep water reservoirs and stratigraphic traps. To date, only eight sequence stratigraphic targets have been drilled in Pletmos Basin, all without commercial discoveries. The application of sequence stratigraphy in the exploration of the Orange Basin since a sequence stratigraphic framework was completed has involved two unsuccessful secondary sequence targets drilled as part of two structural prospects.

In late 1994, Soekor offered international companies the opportunity to explore in the Pletmos and Orange basins. This Atlas provides a ready source of regional information and interpretations for those explorationists interested in an overview of the hydrocarbon potential of the South African offshore basins.

Studies in Geology 41: Sequence Stratigraphy in Offshore South African Divergent Basins (1995)

Exploring within a Sequence Stratigraphic Framework

The decision made by Soekor in 1987 to apply sequence stratigraphy to their exploration of offshore South Africa was based on the conclusion that prospect generation, evaluation, and correlation of drilling results could best be carried out within a basinwide chronostratigraphic and lithogenetic framework. This framework, consisting of seismically resolvable unconformities, marine condensed sections, and other important stratigraphic surfaces, could then be calibrated with existing microfossil chronology. A chronostratigraphic and sequence stratigraphic framework was also considered to be the best approach for delineating and mapping deep water depositional systems and locating sediment dispersion points along respective shelf edges.

The company further reasoned that the sequence framework would permit maximum unification and basinwide correlation of downhole information. Exploration borehole data sets could then be directly integrated into the basinwide sequence stratigraphic framework to verify or qualify the maps of lowstand depositional systems. In this manner, it would be possible to refine the geologic interpretations and maps in order to generate further prospects.

Within each postrift Cretaceous depositional sequence, maps of lowstand systems tracts and component depositional systems were used to delineate potential hydrocarbon plays. Basin floor submarine fans and channel fills resting on type 1 unconformities and sealed by deep marine shales have proved to constitute the principal oil- and gas-bearing reservoirs discovered in offshore South Africa. The source beds are mostly deep basin, marine condensed shales. Subtle structural closures appear to have contributed to the entrapment of oil in some submarine fans, but stratigraphic trapping remains the dominant entrapment mechanism.

As the drilling program continued, favorable sandstone quality and petroleum shows were found to occur repeatedly on type 1 unconformities at the base of several specific lowstand systems tracts, particularly on second-order unconformities. These preferred systems tracts had been correlated and mapped regionally during sequence analysis. They became primary targets for more detailed analysis, prospect generation, and drilling. Wherever the original sequence studies had predicted that appropriate paleogeography and lowstand depositional systems might exist, new plays and prospects were generated. This procedure quickly led to the identification and exploitation of the more promising sequences and lowstand tracts. It also permitted maximum use of drilling results in the ongoing generation of future prospects.

Organization and Content of the Atlas

This Atlas is divided into four parts. Part I is an introduction presenting general background information, plate tectonic settings, basic sequence stratigraphy concepts and methods, and the general chronostratigraphy and sequence stratigraphy of offshore South Africa. The remaining parts provide analysis and interpretation of the seismic and sequence stratigraphy and their roles in the exploration of the Pletmos, Bredasdorp, and Orange basins. Part II is on the Pletmos Basin and emphasizes fourth-order sequences. In Part III on the Bredasdorp Basin, the focus is on basin floor fans and their petroleum potential. Part IV on the Orange Basin examines low-frequency supersequences and supersequence sets and shelfal incised valley erosion. Provided for each basin are basic seismic and well data (wireline logs, microfossils, geochemistry, and lithology); maps, charts, and cross sections generated from the basic data; resulting geologic and geophysical models; and an interpretation of the geologic history and potential hydrocarbon plays in the basin.

Each part of the Atlas text has been designed to stand alone for the reader who is interested in an overview of offshore South Africa (Part I) or in information on a particular basin (Parts II–IV). In Parts II–IV, there may appear to be some duplication of critical observations, but these were restated only when necessary to demonstrate and document conclusions about other key issues. We believe that restatement of the observations when necessary to support an important interpretation makes the Atlas a better resource.

The Atlas was designed to present extensively captioned seismic profiles, wireline logs, maps, charts, and models to permit readers to use it at several levels, depending on interest and experience. The Atlas was conceived to be a self-directed, super-poster presentation. First, a careful perusal of illustrations and extended captions should be sufficient for the casual reader to obtain a general, balanced perspective of the authors' conclusions. Second, reading the text and carefully examining the illustrations should permit the diligent reader to follow and critique the authors' reasoning and basis for conclusions. Finally, a careful cross check of the cross-tied seismic and well data, the interpretive products, and the text should allow the experienced interpreter to reach some degree of independent confirmation or rejection of the authors' interpretations and conclusions.

The 165 figures have been sequenced to give the Atlas maximum visual continuity. Figures are discussed essentially in numerical order, but some comprehensive illustrations contain information related to principles addressed in later sections of the text. Consequently, we have referenced any figures (even out of sequence) that provide additional

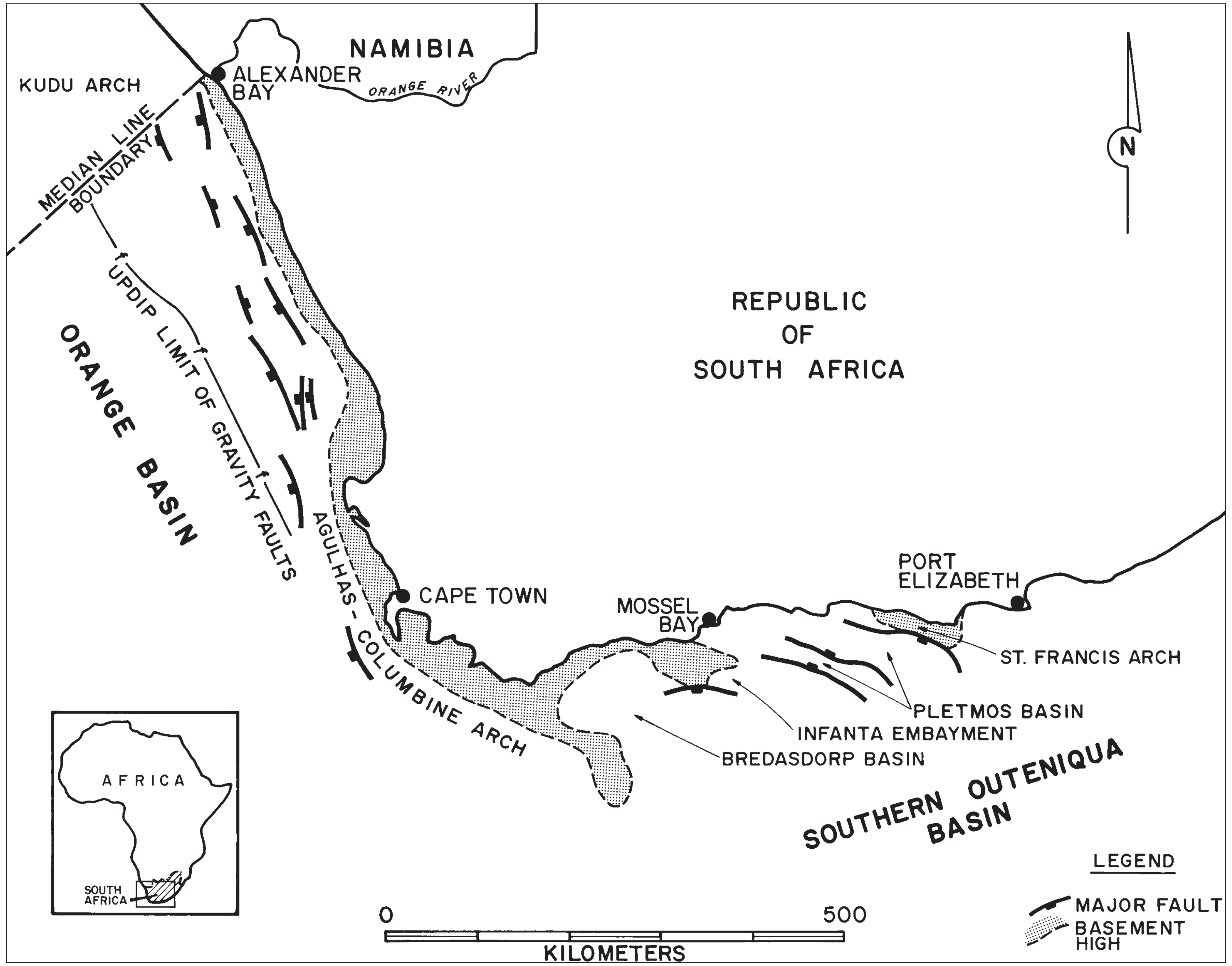

Figure 1. Locations of Pletmos, Bredasdorp, and Orange basins, offshore South Africa. Outeniqua Basin includes offshore rift and postrift basins north of the Agulhas-Falkland Fracture Zone (Figure 3). The northern part of synrift Outeniqua Basin evolved into four postrift basins bounded by faulted arches (west to east): Bredasdorp, Pletmos, Gamtoos (not shown), and Algoa (not shown). Southern Outeniqua Basin refers to the undivided deeper offshore part of synrift and postrift Outeniqua Basin. West coast Orange Basin includes small synrift and large postrift basins, which display major gravity faults along the shelf-slope break. Atlas interpretations cover 173,000 km2 and are based on 109 boreholes, 22,600 km of two-dimensional seismic profiles, and 416 km2 of recon three-dimensional seismic profiles.

examples. Some figure references, therefore, may appear out of order and ahead of the discussion of their primary contribution. Also, figures have been cross referenced in captions to provide additional information on related key topics.

The opportunity provided by AAPG and Soekor to use an atlas format permitted the presentation of an unusual amount of documentation for each basin. The basic data and the derived interpretive geologic documents are the distillation of a massive effort by many geoscientists. It is our hope that the Atlas supplies sufficient types of data and interpretations to permit its use as a training document and as a source of information on the application of sequence stratigraphy in a real-world exploration program.

REGIONAL TECTONIC AND DEPOSITIONAL SETTING OF OFFSHORE SOUTH AFRICAN BASINS

The offshore basins along the southern and southwestern margins of the African plate (Figure 1) were produced by Middle Jurassic–Early Cretaceous rifting and subsequent Cretaceous drift and divergent margin tectonic phases (Figure 2). The rift and drift basins, which formed along the southwestern African (Atlantic) plate margin, were complementary to southeastern South American basins (Figure 3) and compose the Orange Basin of this Atlas.

The rift and divergent margin (drift) basins located beneath the Indian Ocean along the southern margin of the African plate collectively compose the Outeniqua Basin and are complementary to the Falkland region of offshore South America (Figure 3). The Bredasdorp and Pletmos drift basins lie within the northern part of the large Outeniqua Basin. Two other drift basins, the Gamtoos and Algoa, lie east of the St. Francis Arch (Figure 1; basins not shown). The deeply buried southern Outeniqua Basin, which lies in deep water south of the present continental shelf, was filled principally during Tertiary time.

Southern Offshore Basins

Rifting between the African and Antarctic plates (Figure 4) was initiated west of Madagascar when southeastern Gondwana began to break up between ~143–142 Ma (M22) and 133 Ma according to the interpretation of the magnetic anomalies (M16, Dingle et al., 1983). The African and South American break-up initially developed in response to dextral shear stress exerted along the Agulhas-Falkland Fracture Zone when the Falkland Plateau began to separate from the Mozambique Ridge (Figures 3, 4). Break-up between the incipient African and South American plates began during the Middle–Late Jurassic with the formation of horsts and grabens composing the early Outeniqua Basin (Figure 1). The rift faults of the Outeniqua Basin typically originated along the axes of older compressional structures of the Permo-Triassic Cape foldbelt. The rift basins, which are separated by narrower horst blocks and arches, became the sites of several Late Jurassic–Early Cretaceous cycles of shallow marine synrift sedimentation. Brief episodes of transpressional stress were locally superimposed on the extensional stress field to produce complex compressional basement structures.

Southwestern Gondwana began to diverge at ~127 Ma into the African and South American plates along the Agulhas-Falkland Fracture Zone (Figure 3), according to Larsen and Ladd (1973), but Martin et al. (1982) question whether M10 or M12 is the oldest recognizable magnetic anomaly. (Minor variations in absolute ages quoted may exist because of the difficulty of equating the ages from different sources.) The termination of rifting in South Africa during the early Valanginian (Figure 2) was accompanied by regional uplift and extensive erosion of a drift onset unconformity (126 Ma), especially along the northern margin of the Agulhas rift terrane. At this time, the integration of various Agulhas rift basins resulted in the initial formation of the postrift Pletmos and Bredasdorp basins (Figure 1). Early Valanginian (126 Ma) onset of drift tectonics along the southern African plate probably occurred several million years later than separation of the Antarctic from the African plate to the east (Dingle et al., 1983), which initiated the development of the proto-Indian Ocean (Figures 3, 4).

Most normal faulting terminated during the westward (right lateral) movement of the Falkland Plateau along the southern margin of the African plate from early Valanginian to early Aptian time (126–112 Ma) (Figure 2). Along a few faults, however, slow movement continued during a 5–8-m.y. rift-drift transition, and principal deposition was restricted to these fault-bound, basinal areas exhibiting greater subsidence rates. Local strike-slip motion, minor reverse faulting, and some rotation of basement anticlines affected pre-Barremian rocks, reflecting intermittent episodes of transpressional stress that followed drift onset.

At the end of the Hauterivian (~117.5 Ma), strong uplift and intense erosion occurred along the margins of the divergent basins, initiating a second tectonic episode during separation of the African and South American plates (Figure 2). Following this episode, initially high subsidence rates again diminished for about 4 m.y. during the Barremian–early Aptian (116–112 Ma), perhaps in response to a final phase of transpressional stress along the Agulhas-Falkland Fracture Zone, which temporarily reduced the thermal decay (cooling) subsidence of the early drift basins. Low subsidence rates during the Barremian–early Aptian were at least partially responsible for the appearance of seismically resolvable fourth-order sequences in the Pletmos Basin.

Movement of the Falkland Plateau westward past the Pletmos and Bredasdorp basins culminated during the early Aptian (~112 Ma) (Figure 2) as a result of a third episode of postrift basement uplifts and intense erosion. When the Falkland Plateau finally cleared the southwestern tip of the Agulhas Arch, final separation of the Falkland Plateau and southern Africa resulted in permanent connection of the Indian and South Atlantic oceans. Thermally driven subsidence rates began to accelerate, ending the transform phase of divergent (drift) motion and introducing purely divergent margin tectonic subsidence cycles, each of which was terminated by uplift and erosion of a second-order unconformity. Subsidence and sediment supply rates diminished near the end of the Cretaceous. Cenozoic history in the region was limited principally to marine shelf depositional and erosional cycles.

Southwestern Offshore Basins

The southwestern part of Gondwana began to break up during the Late Jurassic–Early Cretaceous when tensional stresses associated with the separation of the Falkland Plateau and the Mozambique Ridge began to generate extensional synrift basins along the axis of the future proto-Atlantic basin (Figure 3). These basins are typically half-grabens bounded by north-south striking normal faults that extended northward through southwestern Gondwana, dividing the incipient South American and African plates. The synrift basins, which were filled predominantly with Cretaceous strata derived from adjacent uplifted prerift basement rocks, were sites of initial deposition in the region subsequently occupied by the postrift Orange Basin (Figures 1, 4).

One or more cycles of continental and lacustrine synrift sedimentation terminated during the late Hauterivian (~117.5 Ma) with drift onset along the southwestern margin of South Africa (Figure 2). The onset of drift and the associated generation of oceanic crust progressively shifted northward. Lower Aptian separation (~112 Ma) between the Falkland Plateau and the African Agulhas terrane coincided with uplifts and erosion along the margins of the Orange Basin. Progressive northward separation of the South American and African plates along the Mid-Atlantic Ridge coincided with continued dextral motion along the Agulhas-Falkland Fracture Zone from ~117.5 Ma until about middle Cretaceous time (~100 Ma), when the spreading centers shifted and terminated movement along the fracture zone.

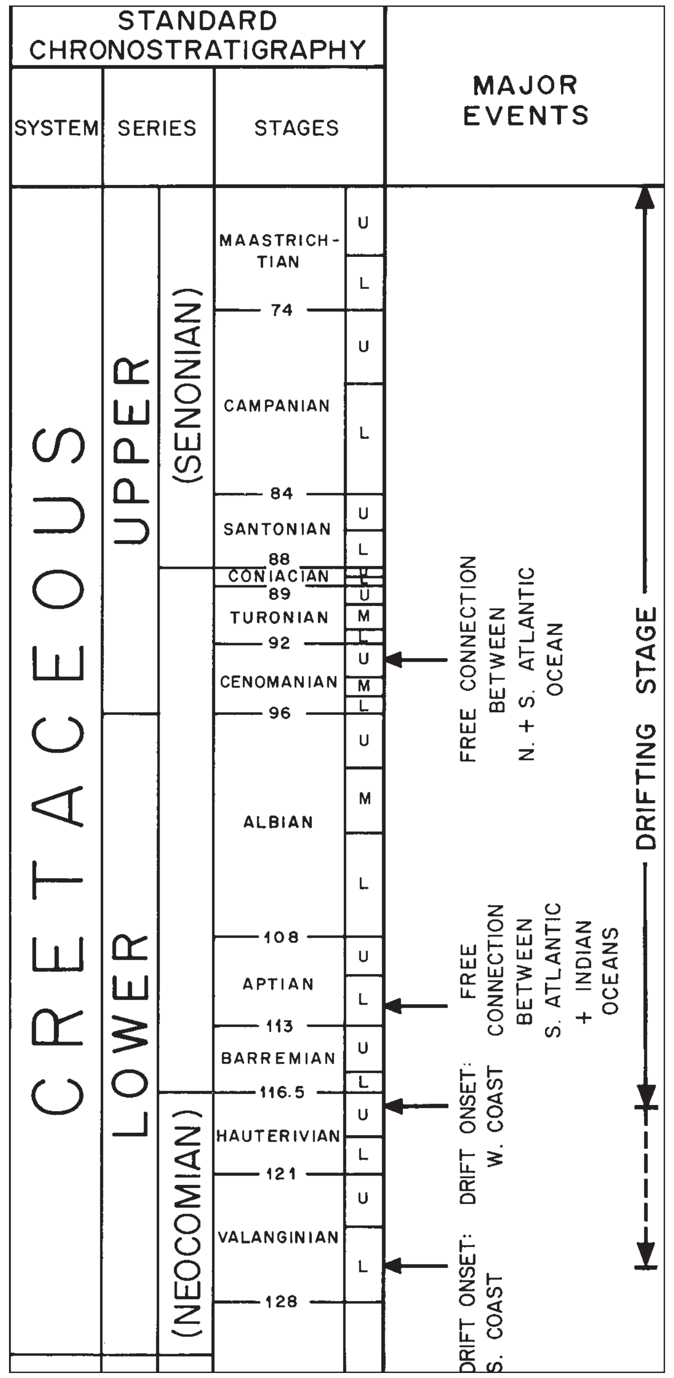

Figure 2. International standard chronostratigraphy, Cretaceous System, showing timing of drift-onset in South African basins. Stage boundaries by Haq et al. (1987, 1988) agree with microfossil interpretations by Soekor Ltd. Timing of oceanic connections is based on degree of mixing of South African assemblages with other faunal realms.

Late Hauterivian (~117.5 Ma) separation of the southwestern margin of the African plate from the South American plate initiated drift deposition in the Orange Basin. Drifting initiated thermal subsidence along the southwestern African plate margin and marine encroachment by the narrow proto-South Atlantic Ocean until it was connected with the North Atlantic Ocean in the late Cenomanian–early Turonian (~93–91.5 Ma) (Figures 2, 4B). From drift onset (~117.5 Ma) to about middle Cenomanian time, slow subsidence rates generally resulted in progradation to construct the sedimentary wedge along the drifting plate margin. Locally within the Orange Basin, reactivation of rift faults affected depositional patterns.

Divergent margin deposition dominated the trailing southwestern margin of the African plate, except in proximity to the long-lived Orange River delta complex, where major listric faulting occurred. Faulting was generated by episodic gravity failure of highly aggradational deltaic and slope systems that were deposited within the Orange Basin depocenter (Figure 1) when rates of increased accommodation space and sediment supply were generally balanced (~93–80 Ma). Complex arcuate listric and antithetic faults were initiated along steep, depositionally controlled shelf edges peripheral to the distal Orange deltaic system.

In about middle Campanian time (~80 Ma), subsidence rates diminished and renewed progradation of a Late Cretaceous sedimentary wedge extended depositional shelf edges farther into the South Atlantic Basin. Rates of Cenozoic deposition and subsidence slowed, but depocenters continued to shift basinward.

SEQUENCE STRATIGRAPHY CONCEPTS AND PRINCIPLES

Background and General Approach

Depositional systems analysis and seismic stratigraphic analysis are now generally well understood concepts and procedures. *Depositional systems analysis* evolved during the 1960s from lithogenetic facies analysis, based mainly on models derived from studies of Holocene depositional environments and processes carried out intensively by petroleum research laboratories (Fisher and McGowen, 1967; Fisher and Brown, 1972; LeBlanc, 1972, 1975). *Seismic stratigraphic analysis* evolved a short time later, also from studies that began in the 1960s by petroleum companies (Vail et al., 1977; Brown and Fisher, 1977, 1980).

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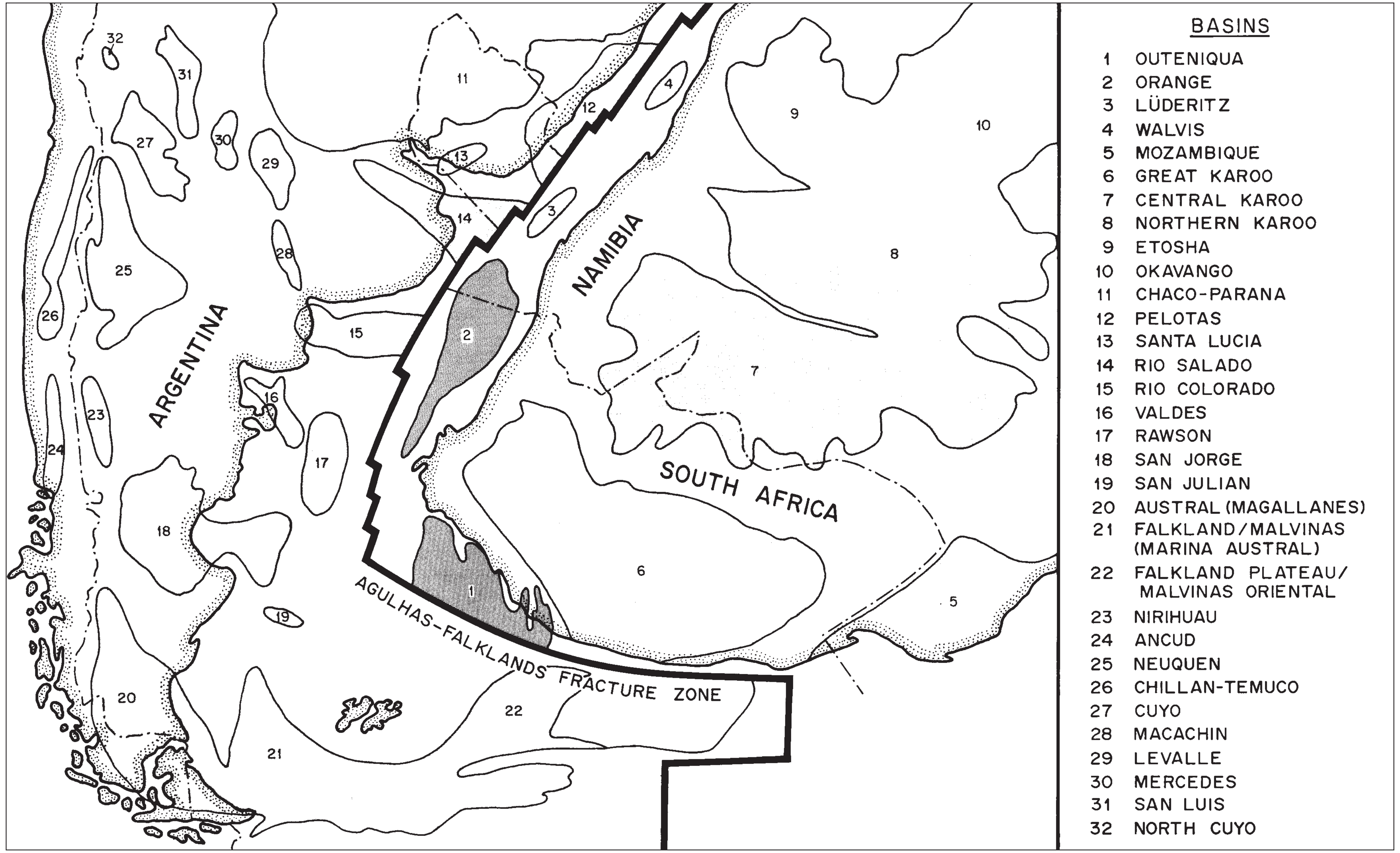

Figure 3. Location of Outeniqua and Orange basins relative to other Gondwana basins soon after drift onset. Early Cretaceous right-lateral movement along Agulhas-Falkland Fracture Zone at ~126 Ma initiated separation of South America and African plates (Dingle and Scrutton, 1974), which generally agrees with magnetic anomalies M10 or M12 (Larson and Ladd, 1973; Martin et al., 1982). The Falkland Plateau moved past the Outeniqua Basin, creating transtensional stress in Bredasdorp, Pletmos, and other southern basins that evolved from rifted subbasins of Outeniqua Basin. The approximate prerift location of the Falkland (Malvinas) Islands is stippled. Postrift Orange Basin experienced drift onset at ~117.5 Ma by movement away from the Mid-Atlantic Ridge. Based on De Wit et al. (1988) and Martin and Hartnady (1986).

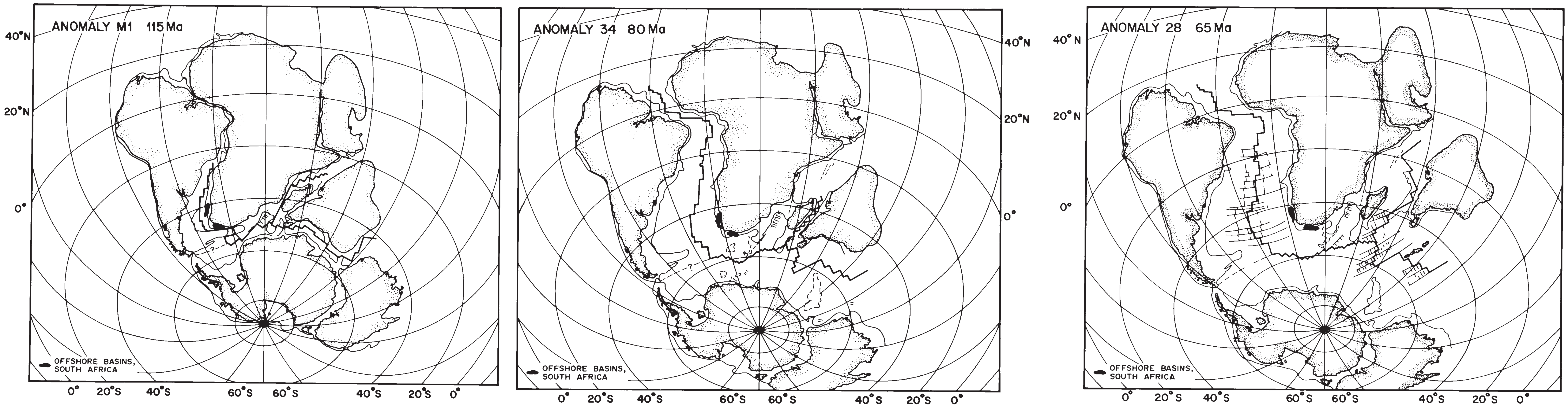

Figure 4. Plate tectonic settings, South African offshore Cretaceous basins, after Gondwana breakup at (left) 115 Ma (Barremian), (center) 80 Ma (Campanian), and (right) 65 Ma (Danian). The Falkland Plateau moved relatively westward along the southern margin of the African plate (Pletmos and Bredasdorp basins) until complete separation by ~100 Ma (Dingle and Scrutton, 1974; Martin et al., 1982). Second-order 14At1 (103 Ma) may be related to this structural event. After separation of the Malvinas Oriental from the Pletmos and Bredasdorp basins, thermal decay subsidence dominated tectonics. Drift onset in Orange Basin began at ~117.5 Ma with spreading along the Mid-Atlantic Ridge. Drift history was dominated by thermal decay subsidence and deposition of a thick postrift Cretaceous succession supplied by the ancestral Orange River system. Modified after De Wit et al. (1988) and Martin and Hartnady (1986).

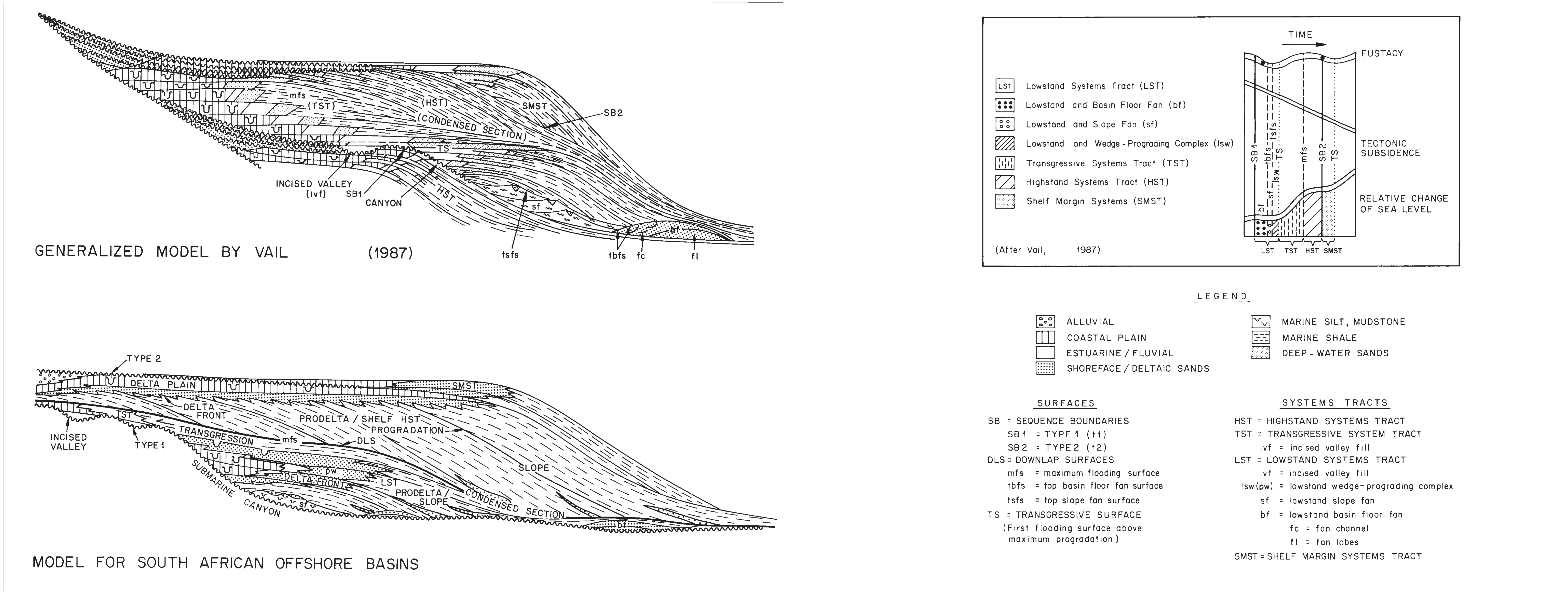

Figure 5. Sequences and systems tracts illustrating cyclic concepts, terminology, and lithofacies. Divergent margin model displays distinctive parasequence sets (paraSeqSs) for each systems tract. This model is not a template but a conceptual representation of interrelated depositional processes, shelfal accommodation, lithofacies, erosion, sediment starvation, shoreline movements, and resulting erosional and depositional surfaces, all produced by a cycle (subsidence plus eustasy) of relative change in sea level and an independent sediment supply. The South African model is based on a synthesis of observations from Pletmos, Bredasdorp, and Orange basins. The main difference between the models is limited development of transgressive systems tracts, especially in Pletmos and Bredasdorp basins, because of generally lower shelfal accommodation and sediment supply rates. Modified after Vail (1987).

Sequence recognition and relative sea level interpretations were proposed in the mid-1970s (Vail et al., 1977), but it was not until the 1980s that a unified system of *sequence stratigraphic analysis* appeared, with major contributions from the following (in chronologic order): Vail and Todd (1981), Vail et al. (1984), Mitchum (1985), Haq et al. (1987), Vail (1987), Van Wagoner et al. (1987, 1988), Haq et al. (1988), Jervey (1988), Loutit et al. (1988), Posamentier et al. (1988), Posamentier and Vail (1988), Sarg (1988), Sangree et al. (1990), Van Wagoner et al. (1990), Mitchum and Van Wagoner (1990, 1991), and Vail et al. (1991). The current status of sequence stratigraphy has recently been summarized by Posamentier and Weimer (1993) and Weimer and Posamentier (1993a).

Concepts and procedures presented in these papers (Figures 5, 6) by current and former Exxon staff members have significantly impacted the prospecting approach of many petroleum explorationists, particularly those searching for deep water reservoirs and stratigraphic traps. At the same time, sequence stratigraphy has been making major contributions to development geology through its application to reservoir characterization. Analyzing parasequence stacking and correlating flooding surfaces within shallow marine facies composing highstand and transgressive tracts and lowstand prograding complexes has added a powerful tool for delineating reservoir heterogeneities within both siliciclastic and carbonate depositional systems. Assessing sequence-bounding subaerially exposed surfaces and submarine ravinement surfaces and their relationships to diagenesis provides new ideas for predicting reservoir quality. Defining the role of marine condensed sections in sealing and sourcing is also helping to better characterize reservoir potential. Within deep water lowstand facies, reservoir level characterization has gone beyond the level of exploration by allowing detailed characterization of slope and basin floor channels and unconfined sheet facies (Weimer et al., 1994).

The terminology used in this Atlas is mostly based on seismic facies and seismic sequence analysis, although the resolution of seismic profiles and wireline logs has permitted recognition of many of the more recently proposed reservoir architectural terms. Amalgamated basin floor channel fills, leveed channel fills, and nonamalgamated channel fills, for example, have been observed through the iteration of seismic and wireline or core data. The authors do not, however, intend to imply that the Atlas begins to address adequately the important problems of reservoir facies architecture. This more detailed phase of reservoir interpretation is now underway at Soekor as geoscientists develop the fields discovered using sequence stratigraphy primarily at regional exploration scales.

The ideas and approaches addressed in the Atlas have therefore involved the integration of earlier seismic stratigraphy and depositional system concepts within a chronostratigraphic framework composed of depositional sequences bounded by regional subaerial and submarine unconformities resulting from cyclic relative falls of sea level. Astute geologists will, however, recognize many development implications that are displayed by the data sets.

Depositional systems analysis involves the delineation, interpretation, mapping, and integration of component lithofacies commonly recognized in the subsurface by distinctive vertical successions of geophysical log patterns and, where resolvable, by seismic facies interpretations. Interpretation of seismic facies and geophysical log motifs depends on an understanding of depositional processes, environments, and the resulting spatial distribution of lithofacies within the spectrum of depositional systems. Bathymetric and paleoenvironmental interpretations from microfossils provide supporting documentation of facies interpretations.

Seismic stratigraphic procedures, which have been used internationally during the past 20 years, mainly involve the recognition of unconformities and various lapout surfaces that bounded relatively concordant (i.e., conformable) packages of rocks called depositional sequences (Figure 7). Concordant stratal surfaces (and resulting seismic reflections) are considered to be essentially isochronous paleodepositional surfaces (mostly minor flooding surfaces) that can be used to interpret depositional processes, facies, and hence, depositional systems. External geometry, reflection configurations, reflection continuity, and amplitude are critical seismic parameters for recognizing, mapping, and interpreting these seismic facies.

Sequence stratigraphic interpretation depends on delineation of unconformities and lapout surfaces that permit recognition of depositional sequences postulated to have been deposited during one cycle of relative change of sea level (Figure 8). The following sections summarize the key aspects of sequence analysis and define the principal terms used in the Atlas.

Sequence Concepts and Models

A comprehensive discussion of sequence stratigraphy is beyond the scope of this Atlas, but a summary of concepts, processes, and terminology may be useful for the reader with limited experience in the field. Depositional systems and sequence models on Figures 5 and 6 illustrate basic principles, but are not intended to be used as templates (Posamentier, 1991). These models are only guides to help understand (1) depositional processes, environments, and resulting facies; (2) their relationship to the factors controlling cycles of relative change of sea level; (3) potential spatial variations in stratal geometries of the result-

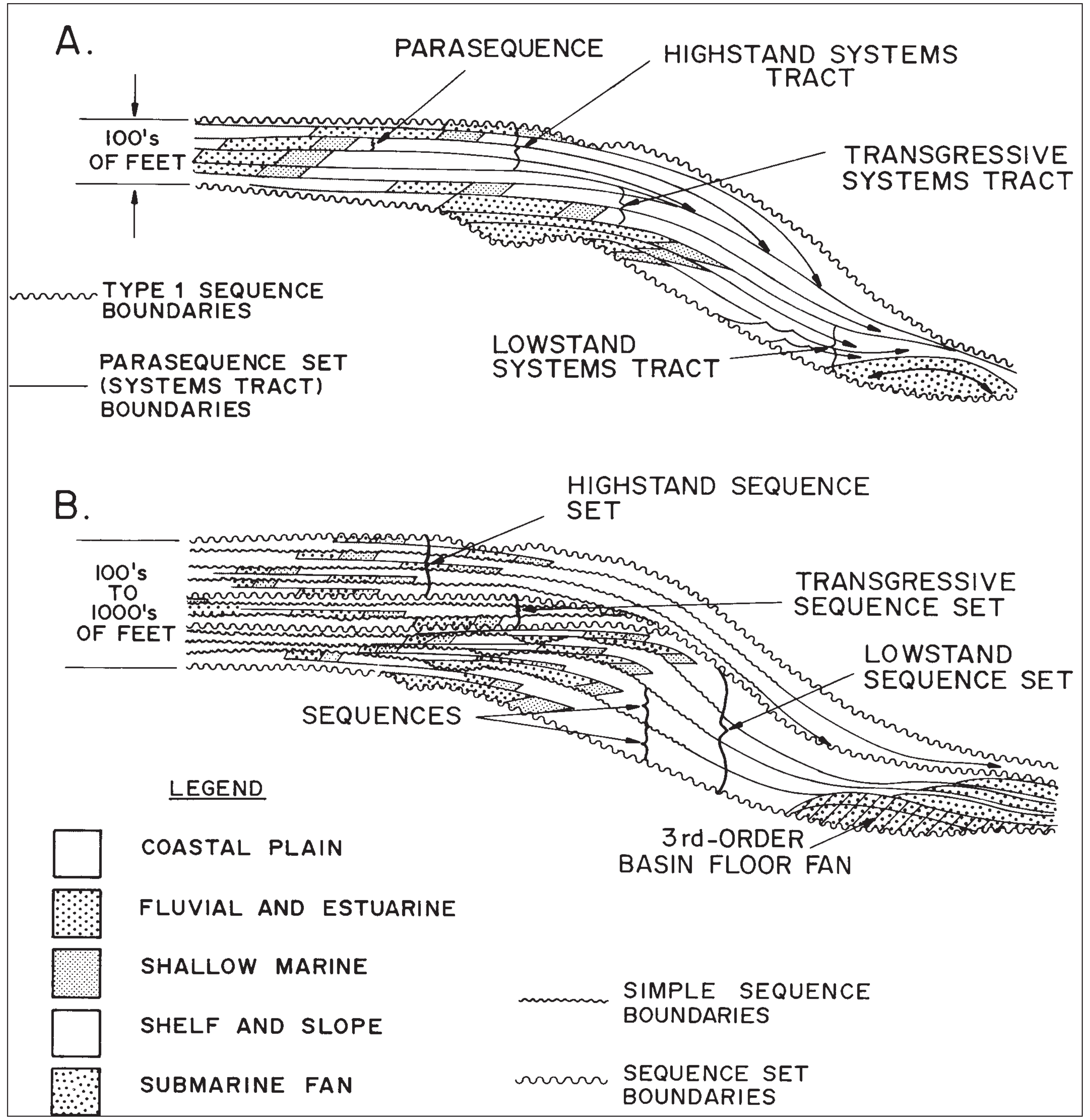

Figure 6. Models illustrating concepts of fundamental and composite sequences. (A) Fundamental sequences comprise systems tracts composed of higher order paraSeqSs. (B) Composite sequences comprise systems tracts composed of higher order sequence sets (SeqSs). Higher frequency eustatic cycles produce sequences (Seqs) rather than paraSeqs only when space-added accommodation rates are too low to cancel high-frequency eustatic sea level falls. High-frequency relative falls of sea level are therefore enhanced on falling limbs (type 1 erosion and deposition of Seqs) and suppressed on rising limbs (flooding and normally deposition of paraSeqs) of lower frequency eustatic cycles. Low subsidence (= low space-added accommodation rates) and high sediment supply rates favor deposition of fourth-order Seqs. After Mitchum and Van Wagoner (1990, 1991). Reprinted by permission of the Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation.

ing stratigraphic units; and (4) the nature and significance of bounding unconformities and nondepositional surfaces. References to principal sources of information are listed in the previous section and are cited throughout the Atlas.

Depositional Sequences

A *depositional sequence* (Figures 5–8) is “a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities and their correlative conformities” (Mitchum et al., 1977, p. 53). The sequence is inferred to have been deposited during one cycle of relative change of sea level. *Relative change of sea level* is the product of eustatic change of sea level and tectonic subsidence (or less commonly, uplift). *Eustatic* or *absolute sea level* cycles (Vail et al., 1977; Haq et al., 1987, 1988) may be of any duration or frequency (Figures 9, 10). Specific erosional episodes and depositional events characterize various relative positions of sea level. Bounding unconformities, which are independent of variations in sediment supply rates, result from subaerial and submarine erosion during a relative fall of sea level that occurs where and when the *equilibrium point* (rate of eustatic fall or rise = the rate of subsidence or uplift; Posamentier et al., 1988; Posamentier and Vail, 1988) moves basinward to or beyond depositional or shoreline break (Figure 8). The unconformities are identified from the truncation or onlap of strata displayed by outcrop or wireline log cross sections and seismic profiles (Figure 7). Microfossil interpretations may also provide important verification of unconformities.

Transgression and flooding of the basin margin occur during a relative rise in sea level (Figure 5), which occurs when or where the equilibrium point moves landward of the depositional or shoreline break. Maximum flooding is typically marked by an abrupt increase in the abundance and diversity of microfossils (Figure 11). Relative changes in sea level either add or diminish space available for deposition, which is called *accommodation space.* The interplay of rates of added or subtracted accommodation space with variable rates of sediment supply control water depths and shoreline positions. Increased accommodation space provides room for deposition, and diminished space constrains this room and may reach a negative value and initiate erosion.

Type 1 unconformities (Vail, 1987) are eroded when sea level relatively falls rapidly and the equilibrium point moves basinward of the coastal or shoreline depositional break (basinward of regressive shelf edge in most divergent margin basins) (Figures 5, 8). Type 1 surfaces exhibit intense subaerial and submarine erosion, valley and submarine canyon incision, significant basinward shift of facies, and subsequent deposition of a lowstand systems tract (Figures 5–8). Major downward shifts in coastal onlap are documented by basinward shifts of proximal facies deposited on distal facies. In updip areas, type 1 surfaces that were eroded into the previous highstand tract are further modified by ravinement erosion (transgressive surface) and subsequent onlap of transgressive systems tracts. Sequences with basal type 1 unconformities are called type 1 sequences, which are by far the most common in the postrift Cretaceous rocks of offshore South Africa.

Type 2 unconformities (Vail, 1987) form by a relatively slow fall of sea level, but the equilibrium point does not move basinward of the coastal or shoreline depositional break (Figures 5, 8). Type 2 surfaces exhibit subaerial exposure but no subaerial valley erosion, submarine canyon incision, or basin floor fan deposition. Type 2 relative falls of sea level produce a downward (basinward) shift from alluvial to coastal onlap, but no major basinward shift of proximal over distal facies occurs (Figure 5) (Posamentier et al., 1988; Posamentier and Vail, 1988). Sequences with basal type 2 surfaces are called type 2 sequences. In South African Cretaceous rocks, lateral changes from type 1 to type 2 surfaces have been observed to occur from the stable to less stable sides of faulted hinge lines because greater subsidence rates tend to favor the occurrence of lower rates and magnitudes of relative falls of sea level.

On seismic profiles, type 1 or 2 unconformities may generate a reflection if an acoustic impedance contrast occurs across the surface. Where a reflection is absent, the surface may be recognized by reflection terminations and onlap. Type 1 surfaces exhibit subaerial and submarine erosion, as well as coastal onlap, and are generally more easily identified than type 2 surfaces, which display only coastal onlap. On seismic profiles with a *negative standard* or *trough polarity* (an increase in acoustic impedance producing a trough on zero-phase data), unconformities commonly generate trough reflections, although variations in impedance across and along an unconformity can vary considerably. On seismic profiles with *positive standard* or *peak polarity* (an increase in acoustic impedance producing a peak on zero-phase data), unconformities normally generate peak reflections. According to the SEG standard, an increase in acoustic impedance is represented by a central peak on zero-phase data, that is, positive standard polarity. Although most of the seismic profiles in this Atlas are displayed in trough (negative standard) polarity, some peak polarity profiles are also included (Figure 12). Most of the seismic profiles here have been corrected to zero phase (basic seismic wavelet is zero phase). This was done by first determining the phase spectrum of the basic seismic wavelet on the migrated seismic traces at many well locations and then constructing phase correction filters to convert the wavelets to zero phase.

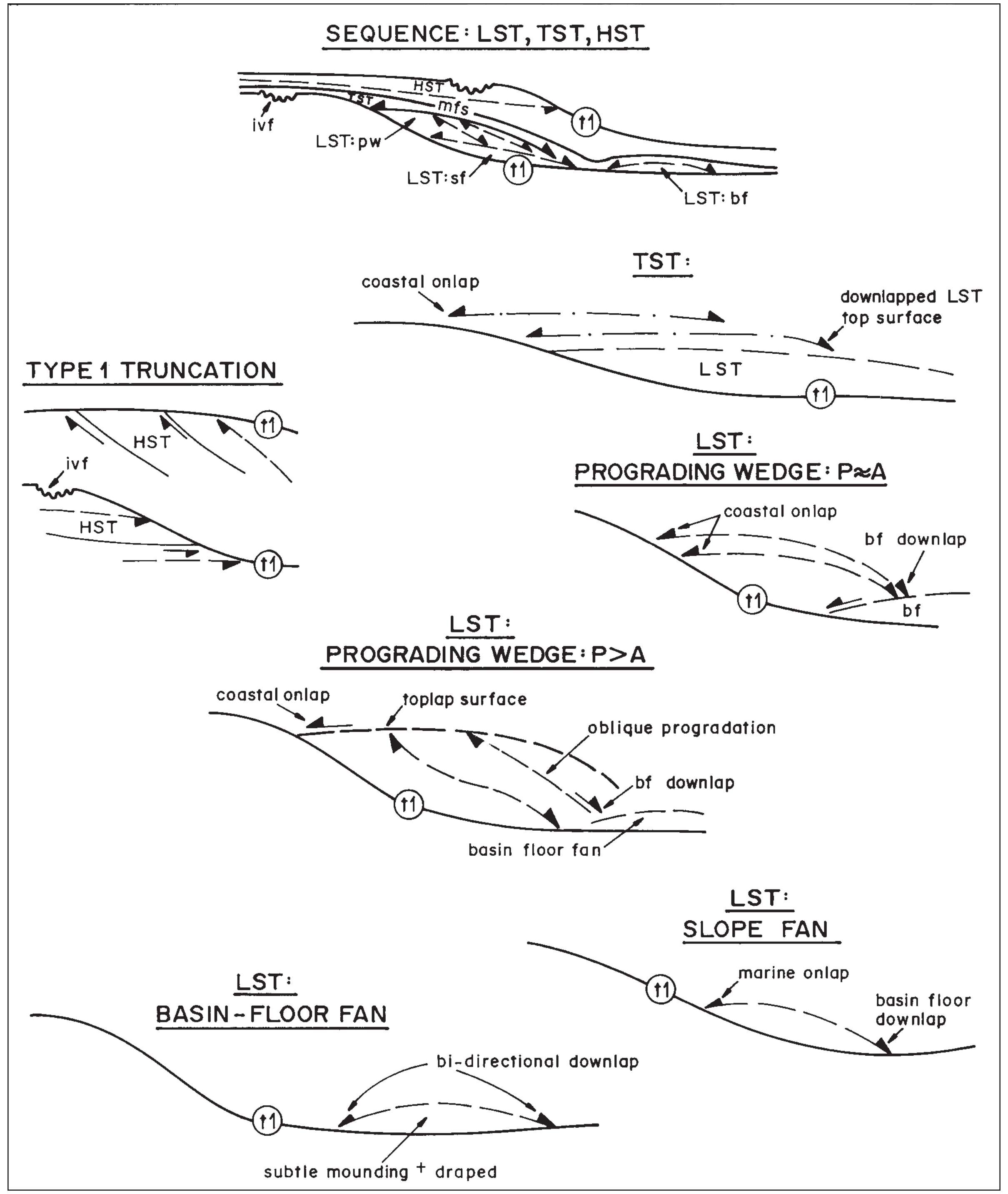

Figure 7. Seismic facies, reflection terminations, and stratal stacking patterns exhibited by depositional systems tracts, offshore South African basins. Most depositional Seqs are type 1. Lowstand systems tract prograding wedges (LST: pw's) may have stratal stacking patterns that are oblique (progradational), sigmoidal (progradational and aggradational), or both. LSTs occur at distal ends of incised valleys. Care is required to separate LST:pw from highstand systems tract (HST) systems. Terminology and symbols derived from Vail et al. (1977) and Wilgus et al. (1988). See Figure 12 and Table 1 for definition of symbols; P = progradation; A = aggradation.

Alternative Sequence Models

Some workers prefer to use transgressive or maximum flooding surfaces as sequence boundaries. Flooding surfaces, which may be regionally diachronous because of variations in sediment supply rates, are commonly well defined by high-amplitude reflections on seismic profiles and on wireline logs using gamma peaks, low density and sonic travel time values, and microfossil abundance and diversity. In basins with complex faulting and folding, marine condensed sections are especially helpful in correlation. These regional "marker beds" have been used for many decades by geologists (present authors included), and their historical use is not addressed here. Transgressive surfaces, however, are highly diachronous. Refer to Van Wagoner et al. (1990, p. 2–4) for a historical discussion of the concepts.

Galloway (1989a) popularized the application of transgressive-regressive sequences by bounding them with maximum flooding surfaces and calling them "genetic sequences," within which he did not necessarily recognize regional subaerial unconformities. Galloway referred to Frazier's (1974) "depositional episodes," which are the updip shelfal parts of high-frequency late Quaternary glacial cyclic sequences, as a model for genetic sequences. Galloway (1989b, 1990) inferred that sediment supply and subsidence control the genetic sequences (which he contrasted with the cyclic sea level model proposed by Vail, 1987) and recognized principally submarine unconformities produced by slumping during regression (progradation). His 1989 model therefore did not incorporate relative falls of sea level, but instead relied on variations in tectonic and sediment loading subsidence and sediment supply rates to control the deposition of genetic sequences.

The relatively long-term transgressive and regressive cycles (~5–10 m.y. in duration) that Galloway (1989b, 1990) defined are most likely the result of long-term variations in subsidence and sediment supply. They are analogous to the inferred tectono-eustatic supersequences and supersequence sets of Haq et al. (1987, 1988), Vail et al. (1991), and Muntingh and Brown (1993), which result from plate tectonic activity. These major T-R cycles have been recognized in most explored basins of the world for many years and are controlled by variations in accommodation and sediment supply rates under the ultimate influence of tectonics, both basinal and global. The shorter duration sequences (frequencies of less than ~3 m.y.) are probably driven principally by eustatic cycles of uncertain origin superimposed on tectonic and loading subsidence.

The occurrence of relative cycles of sea level at many frequencies has been documented. Subaerial and submarine unconformities eroded at relatively high frequencies (generally less than 2 m.y. and as short as ~10–100 k.y. duration) have been well documented by many workers (e.g., Weimer and Posamentier, 1993a; Loucks and Sarg, 1993). Consequently, the decision to use flooding surfaces versus subaerial or submarine unconformities (eroded during relative falls of sea level) for sequence boundaries depends on the worker's view of their respective usefulness. Certainly, the significance of all the sequence stratigraphic surfaces must be fully realized in any sequence analysis, as recently confirmed by Xue and Galloway (1995).

In the South African basins, unconformity-bounded sequences were applied for a number of utilitarian reasons. (1) All recognized basin floor fan targets were found to rest on type 1 surfaces. (2) Principal hiatuses in the basins were found to occur at second- and third-order type 1 or type 2 unconformities. (3) Second-order sequence boundaries coincide with deflections on the geohistory curves. (4) The subaerial parts of type 1 or type 2 hiatuses were times of significant hydrologic and vadose diagenetic alteration. (5) The type 1 hiatuses were times of extensive valley incision that connected downdip with lowstand offshelf submarine canyons and channels and with deltaic, slope, and basin floor depocenters. (6) The areal distribution of on-shelf lithofacies beneath the type 1 surfaces predicted the facies composition and areal distribution within subsequence downdip lowstand tracts. Finally, (7) it was believed that unconformities should exhibit highly variable relief and duration bounding rather than occurring within the fundamental, generally conformable stratigraphic units of the basins. As long as workers clearly understand the significance of each type of surface within a basin, the selection of a bounding surface for sequences is probably irrelevant. Recognition throughout the geologic record of relative falls of sea level at frequencies of less than 2–3 m.y., however, is not irrelevant, and the significance of repeated subaerial and submarine erosion must be addressed by every interpreter.

Parasequences

A *parasequence* is a relatively conformable, coarsening-upward (shoaling or progradational) succession of shallow water beds or bedsets bounded by marine flooding surfaces or their correlative surfaces (Van Wagoner, 1985). They constitute the fundamental building blocks of sequences and systems tracts (Figures 5, 6). Parasequences are deposited during *paracycles* of relative change in sea level, which comprise accelerated rises (typically resulting in flooding) and subsequent decelerated rises and stillstands (typically resulting in progradation or shoaling). Paracycles produce equivalent changes in rates of added accommodation space: increased rates (typically flooding) followed by decreasing rates (generally progradation).

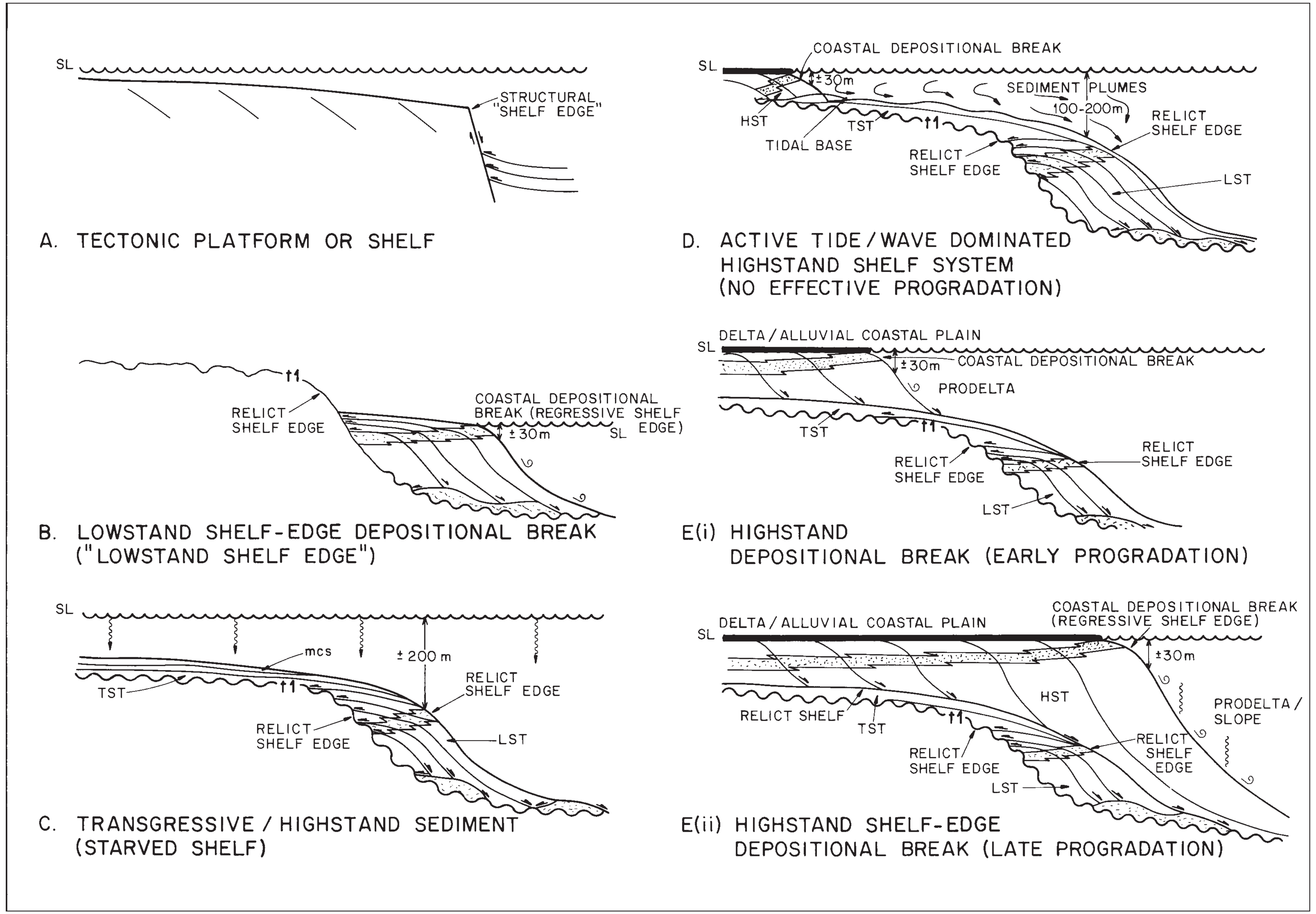

Figure 8. Terms applied to depositional (active) and nondepositional (relict or inactive) sites during a relative change in sea level cycle. (A) Structural shelf: stable platform that may have been site of shallow submarine or subaerial erosion or active depositional systems. Relict shelf edge: basinward edge of inactive (nondepositional) shelf, either (B) subaerially exposed during a relative fall of sea level or (C) site of sediment-starved marine condensed deposition during relative rise of sea level. (D) Siliciclastic shelf depositional system: a shelf unrelated to coastal progradation under influence of intense tidal or ocean-ic current activity. (D and Ei) Coastal (or shoreline) depositional break (Posamentier and Vail, 1988): boundary between subaerial and submarine environments. (B and Eii) Coastal (or shoreline) depositional break synonymous with regressive shelf edge where active shoreline marks boundary between subaerial and prograding slope environments. (In part after Vail, 1987.) The terms shelf break (Van Wagoner et al., 1988), shelf-slope break, shelf edge break , and offlap break are synonymous.

Paracycles can result from *autocyclic* events such as faulting, sediment compaction, or deltaic channel avulsion or from *allocyclic* causes such as the interplay of third- and fourth-order (composite) eustatic cycles with subsidence (Van Wagoner et al., 1990). Parasequences are best developed in shallow marine facies and are absent or difficult to recognize in deep water facies where minor rapid relative rises in sea level have little impact on sedimentation.

Parasequences, as well as high-frequency sequences, typically occur in sets characterized by various *stacking patterns* (Figures 5, 6) that are controlled by the interplay of independent rates of sediment supply and accommodation space (Van Wagoner et al., 1990). Sets can display the following stacking patterns: *progradational* (deposition > accommodation), *aggradational* (deposition = accommodation), or *retrogradational* (deposition < accommodation). These shallow marine parasequence or sequence sets comprise systems tracts. Lowstand and shelf margin tracts are characterized by progradational to aggradational sets, transgressive tracts by retrogradational sets, and highstand tracts by aggradational to progradational sets.

Systems Tracts

Internally, a sequence ideally comprises three depositional systems tracts (Figures 5, 6): lowstand or shelf margin, transgressive, and highstand tracts (Vail, 1987). A depositional systems tract is composed of one or more contemporaneous depositional systems (Brown and Fisher, 1977; Brown et al., 1990), and each tract is deposited during a specific part of one cycle of eustatic fall and rise of sea level (Vail, 1987). Systems tracts are composed of higher frequency parasequences or sequences (Figure 6). Sequences and component systems tracts are defined and recognized on the basis of stratal geometry and physical relationships based on stratal and facies criteria that are independent of frequency, thickness, areal distribution, or inferred depositional processes (Mitchum and Van Wagoner, 1990, 1991).

Lowstand depositional systems tracts (Vail, 1987; Posamentier and Vail, 1988) are deposited during relative fall and early rise of sea level (Figure 4). When falling eustatic sea level approaches and passes its maximum rate of fall (falling inflection point), the equilibrium point moves basinward of the depositional break. Updip of the equilibrium point, relative fall of sea level induces stream incision and submarine erosion to produce the type 1 surface at the base of the lowstand tract. Sediment, which is transported down the slope and into the basin, is deposited on the type 1 surface as basin floor channel fills, fans, or sheets. Near low relative stillstand and earliest rise, slope fans may develop if sufficient sediment is available to begin constructing an onlapping marine wedge. During early relative rise, a prograding wedge or complex of deltaic and coastal systems typically deposits progradational (oblique) parasequences. Progradation may gradually change upward into more aggradational (sigmoidal) parasequence sets if sediment supply can keep up with accelerating relative rise of sea level (and added accommodation space). During relative rise of sea level and aggradation, the proximal part of the wedge complex coastally onlaps the type 1 surface and eventually onlaps and back-fills the incised valleys. Lowstand deposition is terminated when relative rise of sea level cannot be accommodated and extensive flooding begins to generate the transgressive surface at the top of the lowstand tract.

Transgressive depositional systems tracts (Vail, 1987; Posamentier and Vail, 1988) are deposited when rising eustatic sea level approaches its maximum rate of rise (rising inflection point). Except for estuaries within incised valleys, the base of the transgressive tract (Figures 5–8) is the transgressive surface (TS), a diachronous ravinement surface eroded during the first flooding event to inundate the coastal plain. The surface in distal areas is eroded progressively into the preceding lowstand or shelf margin systems tracts and in proximal areas into the previous highstand systems tract. The tract is typified by deltaic and associated coastal parasequences having retrogradational stacking patterns.

The thickness of the transgressive tract depends on the balance between accommodation space and sediment supply. When in balance, relatively thick tracts may develop. In the South African basin (Figure 5), however, the transgressive systems tracts are typically thin, perhaps as a result of generally low rates of sediment supply and, more importantly, the impact of rapid eustatic rise and flooding of the broad and stable shelves. The top of the transgressive tract is actually within the marine condensed section. On seismic profiles, the distal downlap of back-stepping parasequence sets may generate the illusion of erosional truncation at the top of the transgressive tract, a configuration called *apparent truncation* (Figure 8C).

During a relative rise of sea level, sediment-starved and typically anoxic environments shift progressively from deep basinal areas onto the retreating transgressive systems, forming broad, low-energy shelves, sites of principally authigenic and biogenic processes. The lowermost part of the condensed section comprises distal plume-transported deposits of the transgressive tract. *Marine condensed deposition* (Figure 5, 8) shifts landward over the retrogradational transgressive tract as sediment starvation progressively shifts landward (Vail, 1987; Posamentier and Vail, 1988). A *maximum flooding surface,* which occurs somewhere within the marine condensed section, is reached when rising sea level has restricted shorelines to their ultimate landward position (Loutit et al., 1988). The age of maximum flooding may vary, especially near the margin of a basin, depending on the interplay of accommodation and sediment supply rates.

Relative rise of sea level eventually decelerates sufficiently to permit early prograding highstand deltaic and other associated strike-fed coastal systems to discharge distal suspension sediments onto the shelf, even before the arrival of downlapping parasequences. This discharged sediment plume slowly eliminates and progressively confines marine condensed deposition to more distal parts of the shelf and basin floors (that is, distal highstand facies actually form the uppermost part of the marine condensed section). As initial highstand systems prograde into the basin, their distal facies are deposited on the upper surface of the marine condensed section, marking the *downlap surface.* On seismic profiles with normal (negative standard or trough) polarity (Figure 12), a relatively thick marine condensed section is commonly represented by a high-amplitude, peak-trough-peak (doublet) reflection. An opposite reflection character appears on the peak polarity profiles.

Highstand depositional systems tracts are deposited when sufficient sediment supply exists to fill the accommodation space generated by the decelerating relative rise of sea level (Vail, 1987; Posamentier and Vail, 1988). The base of the highstand tract (Figures 5–8) is the downlap surface, and the top is either a type 1 or type 2 unconformity. This systems tract typically displays a gradual shift from sigmoidal aggradational to oblique progradational parasequence stacking patterns as rates of relative rise of sea level and accommodation space decrease. On seismic profiles, highstand progradational systems typically display toplap reflection terminations where clinothems terminate upward and landward against the base of the shallow water coastal facies.

Shelf margin systems tracts are deposited under a slowly accelerating relative rise of sea level. The rate of falling eustatic sea level never quite reaches the rate of subsidence at the depositional break. Because the equilibrium point never moves basinward of the depositional or shoreline break, no relative fall of sea level occurs basinward of that point (Vail, 1987; Posamentier and Vail, 1988). During early eustatic sea level rise when the equilibrium point moves landward in response to a relative rise in sea level, the shelf margin systems tract (Figure 5) is deposited on a basal type 2 surface. Early deposits of progradational parasequence sets typically grade upward into younger aggradational parasequence stacking patterns in response to accelerating relative rise of sea level. Well-developed coastal onlap occurs in response to an accelerated relative rise in sea level. Shelf margin deposition terminates with flooding and development of a transgressive surface. Shelf margin tracts are uncommon in the South African Cretaceous sequences, perhaps because slow subsidence rates more commonly permit falling sea level to shift below depositional breaks.

Hierarchies of Sequences and Parasequence or Sequence Sets

The sequences previously discussed and those most commonly recognized on seismic profiles and wireline logs contain depositional systems tracts comprising parasequence sets. Such sequences, which can be called *fundamental sequences* (Mitchum and Van Wagoner, 1991), are typically of third-order frequency (Figures 5, 6A). Sequences of third-order frequency, which comprise depositional systems tracts that are composed of fourth-order sequence sets rather than parasequence sets (Figure 6B), have been named *composite sequences* (Mitchum and Van Wagoner, 1991). Third-order composite sequences, like fourth-order sequences, represent deposition during one cycle of eustatic change in sea level. In offshore South African basins, the third-order sequences typically range from 1 to 3 m.y. and average ~1.3 m.y. in duration (Figures 9, 10). Third-order cycles reflect strong eustatic control generally superimposed on less dominant rates of tectonic subsidence or uplift.

Fourth-order sequences in South Africa range from ~0.1 to 0.5 m.y. in duration, and they comprise systems tracts composed of fifth-order parasequences (~10 k.y. in duration). Fourth-order sequences have been called *simple sequences* (Vail et al., 1991). The deposition of fourth-order and higher frequency parasequences probably reflects dominant eustatic control, whether climatic or of some other unknown process. The deposition of simple sequences rather than parasequences, however, apparently requires low subsidence and high sediment supply rates (Van Wagoner et al., 1990).

The fourth-order sequences composing the systems tracts within third-order composite sequences (Figure 6B) are not always resolvable on seismic profiles, but they can be recognized on wireline logs and in outcrop. Postrift Cretaceous rocks of South Africa (Figures 9, 10) exhibit several third-order (~1-m.y. duration) composite sequences composed of seismically resolvable fourth-order sequence sets that define lowstand and highstand systems tracts. Transgressive (retrogradational) sequence sets, however, are poorly developed (e.g., see Pletmos Basin).

Second-order sequences called *supersequences* (~10-m.y. duration) typically comprise three sets of third-order sequences and represent deposition during even lower frequency relative cycles. The low-frequency cycles may represent some kind of dominant composite global tectonic signal, such as subduction rates (Engebretson et al., 1992). The third-order sequence sets composing supersequences commonly display stacking patterns that define lowstand progradation to aggradation, transgressive retrogradation to aggradation, and highstand aggradation to progradation. In most basins, notably those in offshore South Africa, supersequences are bounded by tectonically enhanced

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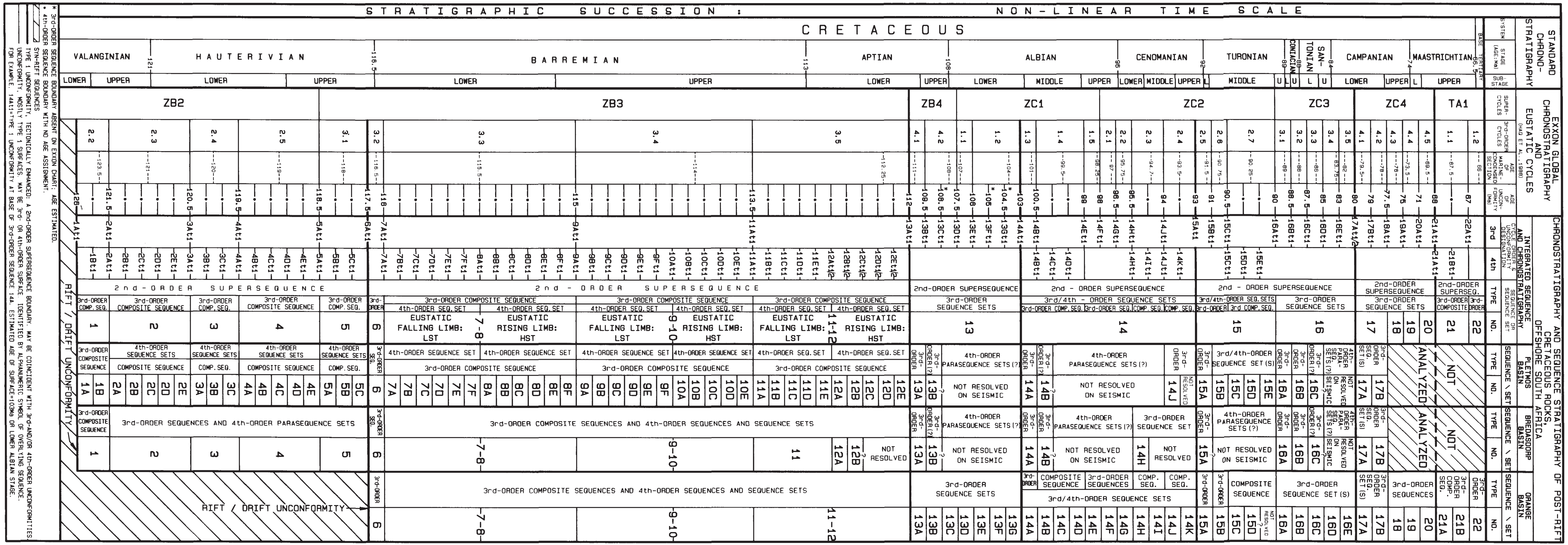

Figure 9. Nonlinear time chart showing Seq nomenclature and possible chronostratigraphic correlation of postrift Cretaceous unconformities in Pletmos, Bredasdorp, and Orange basins with Exxon's (Haq et al., 1988) global eustatic cycles. Preexisting Soekor stage and age interpretations were honored when assigning provisional absolute time values (Ma). Ages of second-order marine condensed sections 6A mcs (116.5 Ma), 13A mcs (112 Ma), 14A mcs (101 Ma), and 15A mcs (91.5 Ma) provided the most precise absolute dates for calibration. Correlation with Exxon's cycles was attempted only after each basin study was completed. "Integrated Sequence and Chronostratigraphy" column compares Soekor's predetermined microfossil age and stage assignments with Exxon cycles. Whether correct or coincidental (Miall, 1992), independently delineated South African Seqs correlate approximately one to one with Exxon's third-order cycles (realizing inherent microfossil resolution limits). Some South African second-order boundaries (heavy horizontal lines) correlate with Exxon second-order boundaries: 13At1 (112 Ma), 17At1/2 (80 Ma), and 21At1 (68 Ma). Two boundaries, 1At1 (126 Ma) and 6At1 (117.5 Ma), vary by one cycle (~1–2 m.y.); and two other boundaries, 15At1 (93 Ma) and 14At1 (103 Ma), vary by ~3 m.y. and 5 m.y., respectively. Additional fourth-order Seqs not included exist below seismic resolution. Composite third-order Seqs comprise fourth-order SeqSs. Most seismically resolved fourth-order Seqs are in Pletmos Basin. Parts of Exxon chart reprinted by permission of SEPM.

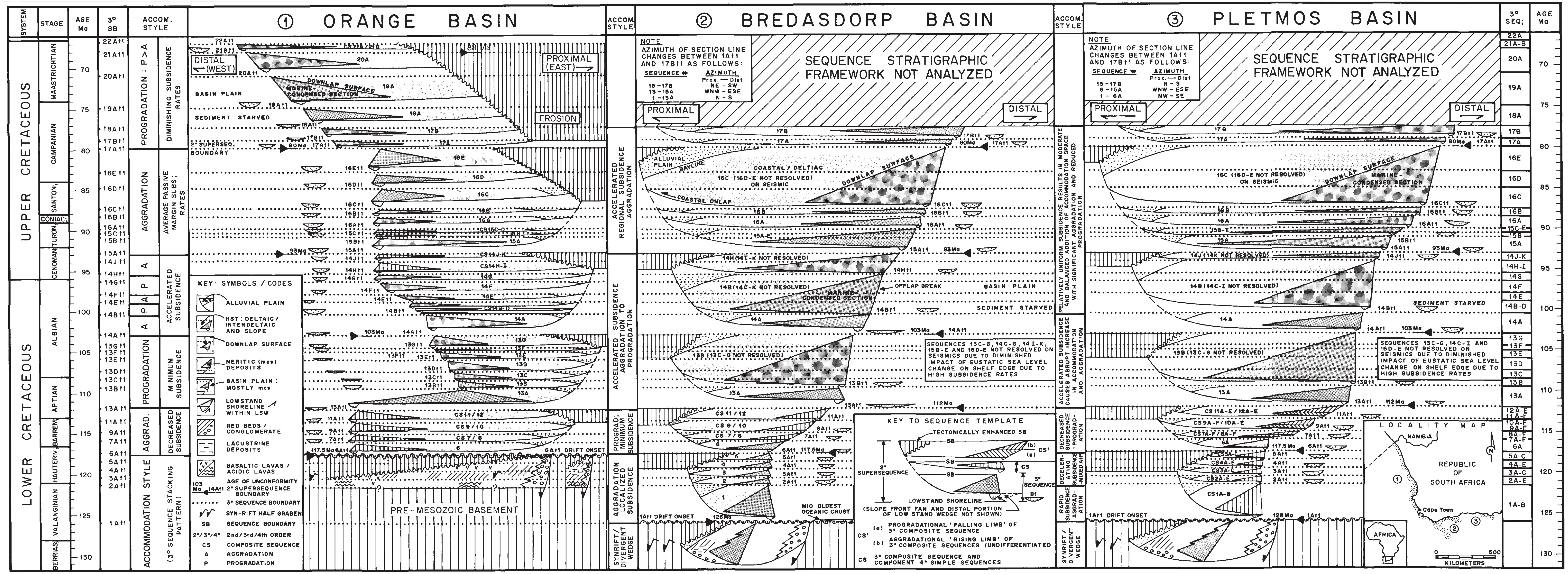

Figure 10. Time linear chart of Cretaceous chronostratigraphy, depositional Seqs, coastal onlap, and stacking patterns for second- and third-order Seqs, Orange, Bredasdorp, and Pletmos basins. Soekor's Seq boundaries and marine condensed sections (mcs's) were correlated with Exxon cycle chart (Haq et al. 1987, 1988). Absolute dates are provisional and based on inferred correlative cycles on Exxon's chart. Erosionally enhanced supersequence (SSeq) boundaries 1At1 (126 Ma), 6At1 (117.5 Ma), 13At1 (112 Ma), 14At1 (103 Ma), 15At1 (93 Ma), 17At1 (80 Ma), and 21At1 (68 Ma) (Orange Basin only) mark major tectonic events. Third-order SeqSs compose second-order SSeqs: 1-5 (126–117.5 Ma), aggradation; 6-12 (117.5–112 Ma), progradation; 13 (112–103 Ma), aggradation; 14 (103–93 Ma), aggradation to progradation; 15-16 (93–80 Ma), progradation to aggradation; and (Orange Basin only) 17-20 (80–68 Ma), progradation. See Figure 9 for further information. Key near bottom left shows specific lithostratigraphic and sequence stratigraphic symbols and patterns.

erosional unconformities (Figures 9, 10), probably produced by an interplay of accelerating rates of falling low-frequency eustatic sea level cycles and diminished rates of subsidence or even uplift during low-frequency South African basinal tectonic cycles.

Supersequences can be stacked into *supersequence sets*, which reflect even lower frequency (tectonically dominated extensional, thermal-cooling, or flexure-loading) cycles of relative change in sea level. Within the offshore South African postrift succession, supersequence sets of ~30-m.y. duration are typically composed of three supersequences, each of ~10-m.y. duration (e.g., see Orange Basin).

CHRONOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY OF SOUTH AFRICAN POSTRIFT CRETACEOUS ROCKS

General Interpretation Procedures

Five steps outline the general elements of the seismic and sequence interpretation that were applied to the Cretaceous rocks above the lower Valanginian drift onset unconformity (126 Ma) in the South African basins:

1. Unconformity identification and correlation
2. Depositional sequence analysis using seismic profiles and wireline logs
3. Seismic stratigraphy and seismic facies analysis and mapping
4. Interpretation of depositional systems tracts and component facies
5. Strategic petroleum play interpretation

Unconformity identification and correlation involved recognition and looping or tying of truncational and lapout unconformities and nondepositional surfaces on all profiles within the selected basinwide grid. Each unconformity was color coded to facilitate loop-tying seismic profiles and development of the superposition within the succession. This was the most time-intensive step of the project, requiring about one-half of the available time. Careful tracing and correlation of reflections (troughs or peaks) controlled the quality of all subsequent interpretations.

Depositional sequence analysis involved interpretation of seismic profiles and wireline logs to delineate depositional systems tracts, as well as individual depositional systems within lowstand tracts, which were hand colored on a selected set of regional seismic profiles. Synthetic logs and microfossil information for boreholes on or near the profiles were depth-time converted and used to estimate the age of reflections, paleobathymetry, and lithologic composition of the depositional systems.

The iteration between seismic profiles and wireline logs became increasingly important. Time-depth conversion of sequence stratigraphic surfaces and systems tracts from the seismic profiles to wireline logs permitted more detailed sequence stratigraphic interpretation. On high-resolution wireline logs, it was possible to place bounding surfaces much more precisely, to integrate microfossil interpretations, to use the log motifs to infer accommodation rates, and to recognize higher order sequences and parasequences that are unresolvable on seismic profiles. These wireline log parasequence motifs, high-gamma shale spikes, microfossil interpretations (abundance, diversity, environment, and paleobathymetry), and lithologic information, among other factors, were integrated in the context of depositional process and cyclic sea level to infer sequence scenarios. These hypotheses were then tested by correlation with other wells and by extrapolation throughout the seismic grid to areas with limited well control.

Seismic stratigraphy and seismic facies analyses and mapping characterized the stratigraphy of systems tracts observed on each profile in the grid. In this highly objective step, the most important seismic stratigraphic features and seismic facies within a systems tract were mapped on one or more overlays of its isochron map to permit the lithogenetic interpretation of systems tracts. Map symbols were used to define downlap and onlap directions, incised valleys, submarine canyons, basin floor channels, eroded shelf edges, critical pinchouts, and many other factors. Matrix charts were used for each sequence to record observations (lower surface, upper surface, geometry and fill configuration, seismic facies, wireline log character, and internal reflection characteristics), interpretations (depositional systems tracts and subelements, lithology, sedimentation rates, provisional age, cycle frequency, tectonics, and relative sea level variations), and hydrocarbon potential (reservoirs, source beds, seals, traps, and prospectivity evaluation). Combined interpretations of geometries and seismic facies of unconformity-bounded units, when calibrated and verified by available well logs, were then used to infer and map the depositional systems and their component facies.

Documentation of the sequence stratigraphic framework of the basins included the following: (1) isochron, seismic facies, and depositional systems maps; (2) color-coded seismic profiles; (3) sequence correlation tables; (4) provisional cycle charts; (5) matrix tables of sequence characteristics and interpretations; (6) sequence stratigraphically annotated wireline logs and synthetic seismograms; and (7) microfossil range charts and logs.

Final lithogenetic interpretation of depositional sequences and component systems tracts involved integration of seismic profiles, isochron maps, wireline logs, seismic facies, microfossil information, and inferred depositional systems. This most subjective step completed the construction of the sequence stratigraphy framework and also constituted a basinwide chronostratigraphic framework that had been calibrated by available paleontologic ages. Time-depth values of all unconformities and nondepositional surfaces were digitized to provide computer-generated time-depth (structural) maps of key surfaces and time-thickness (isochron) maps for systems tracts and individual lowstand depositional systems. This digital system permitted continued input of information from the drilling program to enable periodic remapping of all sequence stratigraphic surfaces and units. Maps of each sequence and its component systems tracts provided the basis for reconstructing the paleogeography during each sea level cycle, one of the fundamental requirements for developing hydrocarbon plays.

The final step in each basin study involved strategic petroleum play interpretation. Basic information for play development included isochron and time-depth structure maps, seismic facies maps, and inferred source rock distribution maps (based on analysis of drilling samples extrapolated using sequence stratigraphic information of condensed zones). These objective data were complemented by more subjective conclusions: sequence stratigraphy, depositional processes, depositional systems tracts, and source bed quality and maturation information. The potential hydrocarbon plays were then outlined by interpreting trap, seal, reservoir, source, and migration using appropriate depositional systems maps and source bed maps in the spirit of the recently proposed hydrocarbon systems approach (Magoon and Dow, 1994). Results were collectively summarized on proprietary play maps and matrix charts for each play type and stratigraphic position.

Drilling Results

Proprietary limitations preclude detailed presentation of specific drilling results from the hydrocarbon plays generated for the South African basins. Nevertheless, Soekor has released information on the exploration approach and finding rates for each basin to illustrate their success in predicting depositional systems, reservoirs, and petroleum (refer to Parts II–IV).

Limited structural closures for the postrift succession required a focus on the development of stratigraphic trap plays. Consequently, the lowstand systems tracts were assigned a high-priority potential for

(Text continues on p. 16.)

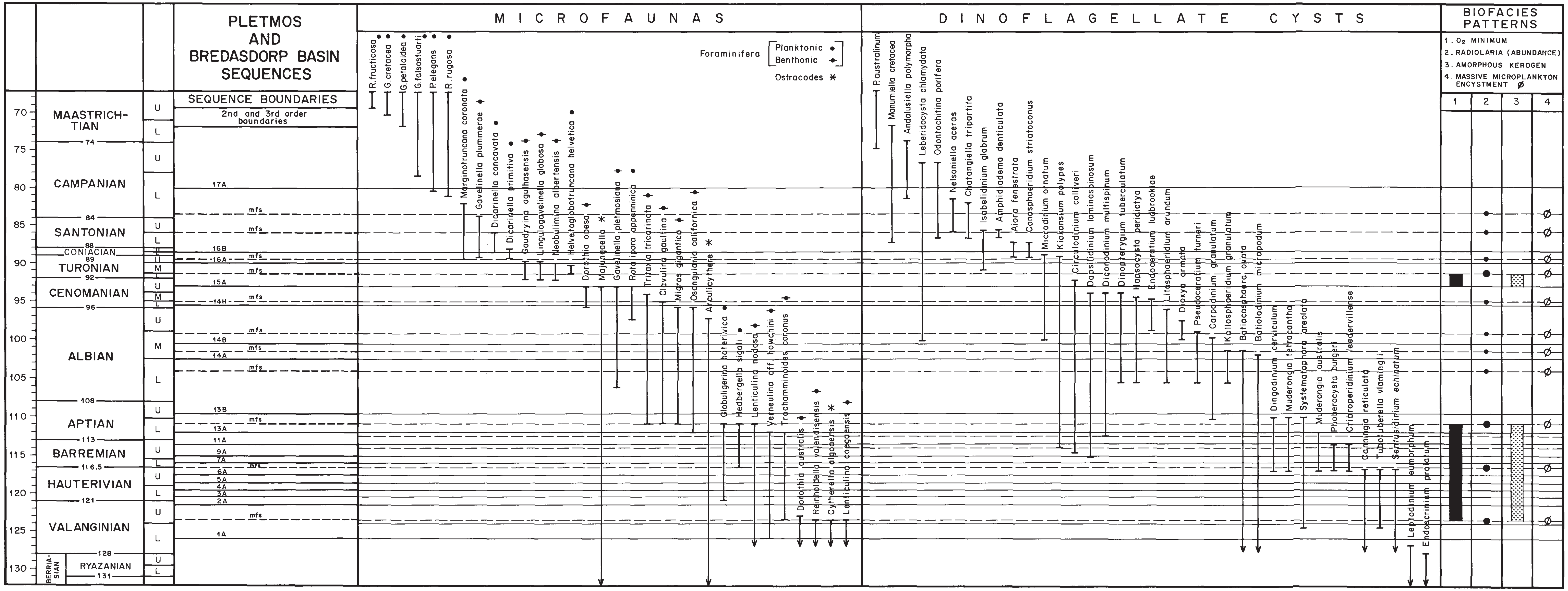

Figure 11. Ranges of key microfossils and their relationships to depositional Seq boundaries and mcs's in the postrift Cretaceous successions, Pletmos and Bredasdorp basins. Taxa are benthonic and planktonic foraminifers, ostracodes, and dinoflagellate cysts. Note that radiolarian abundance and massive microplankton encystment (high phytoplankton ratio = dinocysts : total palynomorphs) normally coincide with mcs's. Pre-middle Aptian oxygen minimums and amorphous lipid-rich kerogen reflect restricted oceanic circulation during early postrift isolation of southern basins, terminated at ~112 Ma when the Falkland Plateau moved west of the Agulhas Plateau (Figure 3), increasing circulation and decreasing anoxia. A late Cenomanian–early Turonian oxygen minimum and kerogen maximum coincided with Exxon's inferred conjunction at 91.5 Ma (15A mcs) of first-, second-, and third-order global eustatic highstand (Figure 70) and an oceanic anoxic event (Schlanger and Jenkyns, 1976; Schlanger et al., 1986).

LEGEND FOR INTERPRETED SEISMIC PROFILES AND BOREHOLE LOGS

BREDASDORP BASIN		DISPLAY MODE	INTENDED POLARITY
LINES	A-A' TO K-K'	WIGGLE TRACE VARIABLE AREA	TROUGH: NEGATIVE STANDARD
	O-O' AND P-P'	WIGGLE TRACE VARIABLE AREA	TROUGH: NEGATIVE STANDARD
LINES	L-L' AND M-M'	DUAL POLARITY	TROUGH: NEGATIVE STANDARD
LINES	Q-Q' TO U-U'	VARIABLE DENSITY	TROUGH: NEGATIVE STANDARD
LINES	V-V' TO W-W'	ACOUSTIC IMPEDANCE	

PLETMOS BASIN			
LINES	A-A' TO V-V'	WIGGLE TRACE VARIABLE AREA	PEAK: POSITIVE STANDARD

WEST COAST			
LINES	A-A', C-C', F-F', H-H'	WIGGLE TRACE VARIABLE AREA	PEAK: POSITIVE STANDARD
	G-G', I-I', J-J'	WIGGLE TRACE VARIABLE AREA	TROUGH: NEGATIVE STANDARD
	B-B', E-E'	DUAL POLARITY	PEAK: POSITIVE STANDARD
	D-D'	DUAL POLARITY	TROUGH: NEGATIVE STANDARD

Figure 12. Legend and explanation of general geophysical parameters, lithology, and conventional sequence stratigraphic symbols used in the Atlas text and illustrations. See Table 1 and Figures 9 and 10 for special unconventional symbols mostly related to South African alphanumeric sequence nomenclature system, frequencies, and sequences or parasequence sets and ages. Symbols such as Seq, SeqS, SSeqS, and paraSeqS are applied as either singular or plural (s). Some figures also include inset legends with specific symbols used in that figure. Symbols are based on Vail (1987) and Van Wagoner et al. (1987, 1988), among others.

SEQUENCES/SEQUENCE SETS

2nd, 3rd and 4th = order or frequency of sequence(s), sequence set(s)
Seq = depositional sequence(s)(any order/frequency)
CSeq = composite depositional sequence(s), 3rd-order
SSeq = 2nd-order supersequence
SeqS = sequence set(s), any order/frequency
1-22 = sequences or sequence-sets (any order/frequency)
A-E = sequence (oldest to youngest) within sequence or sequence set (any order/frequency)

SYSTEM TRACTS

LST	LOWSTAND SYSTEMS TRACT
HST	HIGHSTAND SYSTEMS TRACT
TST	TRANSGRESSIVE SYSTEMS TRACT
SMST	SHELF MARGIN SYSTEMS TRACT

SYSTEM TRACT ELEMENTS

pw	Prograding wedge
sf	Slope-front fan
bf	Basin-floor fan
bfi	Basin-floor infill
ivf	Incised valley fill
mfs	Maximum flood surface
mcs	Margin-condensed section
TS	Transgressive surface
t1	Type 1 unconformity (any order/frequency)
t2	Type 2 unconformity (any order/frequency)
(126)	126 Ma = 126 million years before present
TLS	Toplap surface (approx sea level)
DLS	Downlap surface
SL	Sea level
b14Abf(s)	base of 14A basin-floor fan (sandstone)
t14Abf(s)	top of 14A basin-floor fan (sandstone)
t14Asf(s)	top of 14A slope-front fan (sandstone)

* Symbols may be compounded; e.g., 13At1, 15Amfs, 3rd CSeq, 4th SeqS, 4th Seq, 6Abf

SYMBOLS

	Downlap
	Onlap
	Erosional truncation or toplap
	Fault
	Sandstone
	Conglomerate
	Shale
	Carbonate
	Intrusive
	Basement
	Fluvial
	Fluvial
Gr	Gamma ray log
Δt	Sonic log
	Upward coarsening
	Upward fining
	Uniform

stratigraphic trap plays for several reasons. (1) Prograding wedges composed of coastal sandstones (such as deltaic, barrier, and strand plain) were inferred to pinch out updip by coastal onlap onto type 1 unconformities eroded into distal highstand facies. (2) Channelized basin floor fans exhibit mounded compactional closure, 360° pinchout, and occasionally, subtle structural closure. (3) Basin floor reservoirs are typically enveloped by marine condensed sections and distal shales that commonly exhibit good to excellent source bed quality, depending on the degree of anoxia in the deep basin. (4) Lowstand reservoirs can be inferred to rest on impervious base seals because type 1 unconformities eroded into slope and basinal highstand shales. (5) Lowstand reservoirs may display an impervious top seal composed of marine transgressive shales, marine condensed sections, and base-lapping highstand shales. Finally, (6) lowstand tracts were subjected to higher thermal levels and burial pressure, contributing to maturity and migration potential.

Potential limiting factors within a lowstand tract included unfavorable reservoir volumes, diagenetic damage to porosity and permeability, textural and grain size constraints, inefficient seals, and poor migration pathways. The most important constraint, however, was found to be the common absence of structural closure for prograding coastal wedges, incised valley fill, and slope fan systems, which rarely displayed updip seal. These factors could be assessed only by intensive drilling. Also uncertain before drilling began was whether favorable reservoirs would be restricted to larger basin floor mounded anomalies and nonamalgamated basin floor channel fills or whether sheetlike turbidites might exist and be prospective. Some amalgamated, channelized basin floor fans were found to exist at the limits of seismic resolution within relatively thin but widespread lowstand basinal sheets, demonstrating the necessity of locating type 1 surfaces on seismic profiles in order to locate these extremely subtle stratigraphic traps.

Constructing the Sequence Framework

The chronostratigraphic frameworks established during the sequence stratigraphy analysis of postrift Cretaceous rocks of the Pletmos, Bredasdorp, and Orange basins cover ~175,000 km^2 and are discussed separately for each basin in Parts II–IV. Seismic profiles, wireline logs, and maps document the proposed sequence stratigraphy, lithostratigraphy, and chronostratigraphy. Variations in the chronostratigraphy of the South African basins are analyzed in terms of the unique tectonic and depositional histories of the individual basins. Two integrated summary charts (Figures 9, 10) plotted on nonlinear and linear time scales, respectively, display the proposed chronostratigraphy and sequence stratigraphy of postrift Cretaceous sequences in each basin, as well as an integrated summary of the three basins.

Several prominent and regionally extensive reflections were recognized and correlated during initial seismic studies of the postrift Cretaceous section in offshore South Africa. Most of the prominent reflections cannot be traced continuously from basin to basin along the southern and southwestern offshore regions of the continent. Within each basin, however, these generally concordant reflections display high amplitude, high continuity, and a doublet wave form. During early synrift exploration, wherever boreholes intersected these relatively thin intervals generating the prominent reflections, rich microfossil assemblages were encountered. These postrift, microfossil-rich horizons thus became identified with paleontologically defined ages (stage or zone), and the more prominent ones served as principal structural mapping horizons. Soekor micropaleontologists applied symbols to represent the most prominent key reflection horizons, which they informally called "paleo-horizons." Subsequent sequence stratigraphic studies have demonstrated that the prominent concordant regional reflections are the seismic response to thin, continuous, and generally shaly marine condensed sections (Figure 9).

When Soekor geoscientists later undertook detailed seismic stratigraphic studies of the postrift succession, they noted that as they traced the strong concordant marine condensed reflections (commonly peak-trough-peak) downdip to the vicinity of relict depositional shelf edges (Figure 8), lower amplitude and more discontinuous reflections could typically be resolved immediately below the prominent reflections. The truncational reflections were originally called "seis-horizons" by Soekor geophysicists who assigned to them the symbol of their respective superposed marine condensed section. They are most prominent near the basin margins along reactivated rift horst blocks and in the vicinity of respective relict shelf edges (Figure 8). These underlying reflections, which generally exhibit intense erosional truncation of subjacent reflections, were later confirmed to be type 1 unconformities. The downdip sedimentary wedges, which are bounded above by the marine condensed section reflections and below by the type 1 unconformity reflections, were found to thicken abruptly basinward of subjacent shelf edges. The lowstand wedges onlap below relict shelf edges (but rarely in incised valleys) and thin in deeper parts of basins where the marine condensed sections and the concordant type 1 surfaces converge.

Most postrift Cretaceous type 1 or type 2 unconformities that could be resolved on seismic profiles were correlated throughout each of the three South African offshore basins (Figures 9, 10). Only Maastrichtian rocks in the Pletmos Basin and upper Campanian and Maastrichtian rocks in the Bredasdorp Basin were omitted from analysis because of exploration priorities involving time and source bed constraints. The depositional sequences defined by these unconformities were further subdivided into component depositional systems tracts by identifying and correlating their bounding transgressive and downlap surfaces. Assessing the hydrocarbon potential of the lowstand systems tracts and their component depositional systems was the final and principal goal of the basin studies.

Dating Unconformities and Marine Condensed Sections

Ages of the third-order type 1 or 2 unconformities and marine condensed sections, which bound and subdivide South African sequences, respectively, are based on microfossil interpretations by Soekor paleontologists (Figure 11). The chronostratigraphic charts (Figures 9, 10) provide provisional correlations of South African postrift Cretaceous sequences with Exxon's Cretaceous chronostratigraphic and eustatic cycle chart (Haq et al., 1988). The Exxon chart is continually revised, and updated versions with additional sequences and revised ages will be published when possible (P. R. Vail, personal communication, 1992). Although current and future work may modify ages of global cycles, the Exxon chart provides the best global standard reference at this time.

The South African Cretaceous sequence stratigraphy, sequence symbols, inferred cycle orders and hierarchies, and provisional age assignments of unconformities and marine condensed sections (Figures 9, 10) are based on correlations of Soekor's microfossil stage and zone interpretations (Figure 11) with Exxon's second- and third-order unconformities and marine condensed sections. The South African chronostratigraphy and sequence stratigraphy of this Atlas will undoubtedly undergo improvements as further research is completed. Nevertheless, the current charts (Figures 9, 10) provide the basic framework for continued evaluation, as well as an integrated nomenclature and provisional ages for the South African sequences.

Postrift Cretaceous depositional sequences, which were identified and correlated using seismic profiles and wireline logs in the South African offshore basins, were provisionally dated using microfossil stage and zone interpretation charts (Figure 11) prepared from analysis of samples from wells drilled by Soekor during the past two decades. The most abundant microfaunas and microfloras were found within marine condensed sections or in adjacent underlying or overlying distal transgressive or highstand shales. Some localized abundance and diversity peaks were also recognized on top of some slope fans and basin floor fans. Consequently, those prominent marine condensed sections, which represent major flooding events, provide the most reliable age information for correlation with global standard Cretaceous chronostratigraphy. Unconformities, however, were dated less reliably and were commonly correlated by equating them with Exxon's unconformities below respective fossiliferous marine condensed sections.

Correlations within and among the South African basins using benthic and planktonic microfaunal and microfloral taxa are considered to be relatively precise, with full appreciation of the inherent precision limits of assigning ages using microfossils. Careful studies of the abundance and diversity of microfossils show that subtle cyclic bathymetric and environmental changes can be used to verify the position of unconformities and marine condensed sections. Range charts showing overlapping and terminating taxa (Figure 11) help to illustrate the relationships among principally benthonic, planktonic, and dinoflagellate microfossil ranges and sequence boundaries and marine condensed sections in the Cretaceous rocks of South Africa.

Two important limitations, however, may exist in attempting to correlate Soekor's assigned ages precisely with standard Cretaceous chronostratigraphic units. First, Cretaceous nannofossil ages were unavailable for the South African basins. Second, standard Cretaceous chronostratigraphy is influenced by northern hemisphere boreal faunal and floral assemblages. Because of probable global climatic variations, it appears that the generally recognized European–Tethyan and North Atlantic–Caribbean assemblages may be slightly diachronous with Cretaceous austral microplankton assemblages, such as those of South Africa and Australia. Further work is required before these problems can be answered. Until then, the current Soekor system (Figures 9, 10, 11) offers the most accurate means of correlation with global chronostratigraphic systems.

Several prominent oceanic anoxic events (OAEs) occurred during the Cretaceous in the proto-South Atlantic and Indian oceans, based on the interpretation of borehole (wireline logs, microfossils, and geochemistry) and seismic data from offshore South Africa (Soekor geoscientists, personal communication, 1990). At least two prominent marine condensed sections recognized in the offshore South African basins clearly appear to correlate with OAEs in the North Atlantic and Tethys seaways. Both lower Aptian (sequence 13A mcs [marine condensed section] = 111 Ma) and lower Turonian (sequence 15A mcs = 92.5 Ma) marine condensed sections appear to correlate (Figure 9) with similar events noted by Haq et al. (1987, 1988) and documented by Schlanger and Jenkyns (1976) and Schlanger et al. (1986), among others. Other South African marine condensed sections probably correlate with other OAEs, but more research is needed to date and correlate them unequivocally with proposed global eustatic cycles.

Nevertheless, without violating any of Soekor's prior microfossil stage and zone interpretations from offshore South Africa, it is now possible to propose provisional correlations (Figure 9) with Exxon's chronostratigraphic and eustatic cycle chart (Haq et al., 1987, 1988). This procedure first involved correlation of the most reliably dated South African marine condensed sections (Figure 11) with stage and zone equivalents on the Exxon cycle chart. This correlation relied on species-to-species correlations where possible and on stage, substage, and zone interpretations where necessary. Next, between these key horizons, all other prominent marine condensed sections and type 1 or 2 unconformities identified in the South African basins were also equated by stage and zone with available candidate condensed sections and unconformities shown on the Exxon chart. Despite comments such as those by Miall (1991, 1992) regarding well-understood inherent limitations in precise chronostratigraphic correlation (Weimer and Posamentier, 1993b), this process resulted in a remarkable match between the South African Cretaceous unconformities and flooding events and those displayed on Exxon's global chart.

Absolute ages applied to the South African sequence stratigraphic surfaces (Figures 9, 10) are those assigned to inferred equivalent third-order unconformities and marine condensed sections on the Exxon chart. The absolute precision of the ages assigned is not presumed. The ages do, however, convey the relative age relationships of unconformities and marine condensed sections within a chronostratigraphic sequence framework that is calibrated with the most precise age data currently available. The chronostratigraphic positions assigned to fourth-order sequences were also based on stage and zone correlations, but the fourth-order absolute ages were strictly based on interpolation among third-order absolute values proposed by the Exxon chart and are thus highly speculative.

Between the lower Valanginian drift onset unconformity along the southern margin of the South African plate (~126 Ma) and the uppermost unconformity of the standard Cretaceous System (67 Ma), Exxon's global cycle chart (Haq et al., 1987, 1988) contains 37 third-order unconformities and 36 sequences (Figure 9, Table 1). While honoring all of Soekor's previously determined microfossil ages, it is possible, by stage and zone interpretation (see Figure 11), to correlate each of Exxon's 36 sequences one-to-one with each of the 36 third-order sequences independently identified in the South African basins (Figure 9). Several Albian and Cenomanian sequences on the Exxon chart, although identified in the Orange Basin, were not recognized in the seismic data from the Pletmos and Bredasdorp basins, perhaps because of unusually high subsidence (see Figures 16, 79) along the southern plate margin during those time intervals, which may have precluded their recognition at a seismic scale.

The only apparent difference between the third-order sequence succession of the Exxon global chart and the South African integrated cycle chart on Figures 9 and 10 is the recognition in the Orange Basin of three additional ~1-m.y. sequences (at 108.5, 105, and 104.5 Ma) of late Aptian–early Albian age. The unconformity at 105 Ma is in the upper range of fourth-order frequencies (estimated at ~0.5-m.y. duration), and therefore may not represent a third-order cycle. These Orange Basin unconformities, which are not recorded on the Exxon global cycle chart, may have been suppressed in other parts of the world by higher subsidence rates.

Sequences and Stacking Patterns

The South African basins are characterized by complex sequence and parasequence stacking patterns at many orders or frequencies of cyclicity. Although the nomenclature is complicated, its use is necessary for describing and attempting to interpret the evolution of subtle but important stratigraphic relationships that help to reveal the history of the basin and for inferring favorable successions in which to develop hydrocarbon plays.

The order or frequency of each postrift Cretaceous sequence in the offshore South African basins was determined by its inferred duration (Figures 9, 10, Table 1). The sequences were then organized into a sequence stratigraphic hierarchy based principally on the various orders (frequencies), types (composite or fundamental), and stacking patterns (progradational, aggradational, or retrogradational) exhibited on seismic profiles and verified on wireline logs. The sequence hierarchy, mostly recognized on seismic profiles and verified by wireline log and microfossil interpretations, includes the following, from highest to lowest order: fifth- and fourth-order parasequence sets principally recognized on wireline logs and fourth-order simple sequences, fourth-order sequence sets, third-order fundamental sequences, third-order composite sequences, mixed fourth- and third-order sequence sets, third-order sequence sets, second-order supersequences, and second-order supersequence sets recognized on both seismic profiles and wireline logs.

Other fourth-order sequences not included in Figures 9 and 10 have been interpreted on wireline logs in the South African basins, but most of these simple sequences occur locally below seismic resolution. Nevertheless, reflections representing fourth-order unconformities and marine condensed sections do appear and disappear on some seismic profiles near the limits of seismic resolution, especially in the Orange Basin. The limited seismic resolution of these fourth-order sequences, along with the limited number of wireline logs and the low exploration potential of higher frequency sequences, precluded their detailed regional delineation. A detailed sequence analysis of all available wireline logs will be necessary if other higher frequency sequences are to be documented and correlated.

The sequences, sequence sets, frequencies, and ages of unconformities and marine condensed sections that had been developed for each basin were combined to produce an integrated hierarchical sequence and chronostratigraphic classification for the three offshore basins shown in Figures 9 and 10. A total of 87 third- and fourth-order principally type 1 unconformities were recognized on seismic profiles within the postrift Cretaceous rocks (Table 1). Twelve of these unconformities are coincident third- and fourth-order surfaces (at 121.5, 120.5, 119.5, 118.5, 116, 115, 113.5, 100.5, 95.5, 94, 90.5, and 68 Ma), and seven of the unconformities are coincident tectonically enhanced second- and third-order surfaces (at 126, 117.5, 112, 103, 93, 80, and 68 Ma). These unconformities identified in the South African basins divide the postrift Cretaceous strata into a total of 37 third-order composite and fundamental sequences and 63 simple fourth-order sequences, which have been placed into 6 second-order supersequences on the basis of the tectonically enhanced (second-order) unconformities. (Note that two or

Table 1—Types of Sequences and Sequence Sets and Estimated Ages of Postrift Cretaceous Rocks (lower Valanginian–upper Maastrichtian), Pletmos, Bredasdorp, and Orange Basins, Offshore South Africa

Fourth-Order (Simple) Sequences (Composed of Fifth-Order Parasequences)[a]		Third-Order (Fundamental) Sequences (Composed of Fourth-Order Parasequences)	Third-Order Composite Sequences and Component Fourth-Order Sequence Sets
1A, B[b] (126–121.5 Ma)	9D (114.67–114.54 Ma)	6A (117.5–116 Ma)	1A–B[b] (126–121.5 Ma)
2A (121.5–121.3 Ma)	9E (114.54–114.41 Ma)	13A (112–109.5 Ma)	2A–E (121.5–120.5 Ma)
2B (121.3–121.1 Ma)	9F (114.41–114.28 Ma)	13B (109.5–108.5 Ma)	3A–C (120.5–119.5 Ma)
2C (121.1–120.9 Ma)	10A (114.28–114.15 Ma)	13C (108–107.5 Ma)	4A–E (119.5–118.5 Ma)
2D (120.9–120.7 Ma)	10B (114.15–114.02 Ma)	13D (107.5–106 Ma)	5A–C (118.5–117.5 Ma)
2E (120.7–120.5 Ma)	10C (114.02–113.89 Ma)	13E (106–105 Ma)	7–8 (116–115 Ma)
3A (120.5–120.15 Ma)	10D (113.89–113.76 Ma)	13F (105–104.5 Ma)	9–10 (115–113.5 Ma)
3B (120.15–119.85 Ma)	10E (113.76–113.63 Ma)	13G (104.5–103 Ma)	11–12 (113.5–112 Ma)
4A (119.5–119.3 Ma)	10F (113.63–113.5 Ma)	14A (103–100.5 Ma)	14B–D (100.5–99 Ma)
4B (119.3–119.1 Ma)	11A (113.5–113.35 Ma)	14E (99–98 Ma)	14H–I (95.5–94 Ma)
4C (119.1–118.9 Ma)	11B (113.35–113.2 Ma)	14F (98–96.5 Ma)	14J–K (94–93 Ma)
4D (118.9–118.7 Ma)	11C (113.2–113.05 Ma)	14G (96.5–95.5 Ma)	15C–E (90.5–90 Ma)
4E (118.7–118.5 Ma)	11D (113.05–112.9 Ma)	15A (93–91 Ma)	21A–B (68–67 Ma)
5A (118.5–117.15 Ma)	11E (112.9–112.75 Ma)	15B (91–90.5 Ma)	
5B (117.15–117.85 Ma)	12A (112.75–112.6 Ma)	16A (90–88.5 Ma)	**Second-Order Supersequences and Component Third-Order Sequence Sets**
5C (117.85–117.5 Ma)	12B (112.6–112.45 Ma)	16B (88.5–87.5 Ma)	1-5 (126–117.5 Ma)
7A (116–115.9 Ma)	12C (112.45–112.3 Ma)	16C (87.5–85 Ma)	6-12 (117.5–112 Ma)
7B (115.9–115.82 Ma)	12D (112.3–112.15 Ma)	16D (85–83 Ma)	13 (112–103 Ma)
7C (115.82–115.74 Ma)	12E (112.15–112 Ma)	16E (83–80 Ma)	14 (103–93 Ma)
7D (115.74–115.66 Ma)	14B (100.5–100 Ma)	17A (80–79 Ma)	15-16 (93–80 Ma)
7E (115.66–115.58 Ma)	14C (100–99.5 Ma)	17B (79–77.5 Ma)	17-20 (80–68 Ma)
7F (115.58–115.5 Ma)	14D (99.5–99 Ma)	18A (77.5–75 Ma)	
8A (115.5–115.4 Ma)	14H (95.5–94.75 Ma)	19A (75–71 Ma)	**Supersequence Set and Component Second-Order Supersequences**
8B (115.4–115.32 Ma)	14I (94.76–94 Ma)	20A (71–68 Ma)	13, 14, 15-16 (112–80 Ma)
8C (115.32–115.34 Ma)	14J (94–93.5 Ma)	22A (67 Ma)	
8D (115.34–115.16 Ma)	14K (93.5–93 Ma)		
8E (115.16–115.08 Ma)	15C (90.5–90.35 Ma)		
8F (115.08–115 Ma)	15D (90.35–90.15 Ma)		
9A (115–114.93 Ma)	15E (90.15–90 Ma)		
9B (114.93–114.80 Ma)	21A (68–67.5 Ma)		
9C (114.8–114.67 Ma)	21B (67.5–67 Ma)		

[a]Ages of fourth-order sequences were assigned by interpolation between third-order ages and thus are highly speculative.
[b]May include unresolved third- and fourth-order sequences.

more simple fourth-order sequences compose the third-order composite sequences.)

Twenty-four of the third-order sequences are fundamental sequences (Mitchum and van Wagoner, 1991) composed of fourth-order parasequence sets (Figures 9, 10, Table 1). Fundamental sequences range from 1 to 4 m.y. in duration, but average 1.3 m.y. One South African sequence (at 105–104.5 Ma), which was interpreted to be third-order, exhibits a duration that places it in the upper fourth-order frequency range. Four fundamental sequences (at 117.5–116, 77.5–75, 75–71, and 71–68 Ma) display relatively unique geometries on seismic profiles and were thus independently assigned a single numerical designation (6, 18, 19, and 20, respectively).

Thirteen of the third-order sequences are composite sequences (Mitchum and Van Wagoner, 1991), which are composed of two or more fourth-order sequences (called simple sequences by Vail et al., 1991), and range from 1 to 4 m.y. in duration with an average of 1.38 m.y. (Figures 9, 10, Table 1). Some of the composite sequences clearly display systems tracts that are composed of well-developed fourth-order sequence sets. For example, in the Pletmos Basin, three third-order composite sequences (at 116–112 Ma) (Figure 9) are each composed of pairs of fourth-order progradational and aggradational sequence sets, which are inferred to represent deposition on falling and rising limbs of the third-order composite cycles. These high-frequency (simple) cycles range from 83 to 150 k.y. in duration (averaging ~120 k.y.), suggesting that they are related to Milankovitch cycles. Other composite sequences (at 126–121.5, 121.5–120.5, 120.5–119.5, 119.5–118.5, 118.5–117.5, 100.5–99, 95.5–94, 94–93, 90.5–90, and 68–67 Ma), which contain fourth-order sequences typically ranging in duration from 100 to 200 k.y., exhibit less clearly defined fourth-order stacking patterns. Hence, component third-order systems tracts may not be well developed.

The most prominent of the erosional type 1 surfaces in the South African basins mark the boundaries of the tectonically enhanced second-order supersequences (Figures 9, 10, Table 1), which range from 5.5 to 13 m.y. in duration, with an average of 9.5 m.y. The supersequences are defined by characteristic stacking patterns comprised of component fundamental and composite third-order (and component fourth-order) sequence sets. Beginning with the highly erosional and angular drift onset unconformity of early Valanginian age (at 126 Ma in the Pletmos and Bredasdorp basins), seven postrift supersequence boundaries (listed earlier) define six supersequences at 126–117.5, 117.5–112, 112–103, 103–93, 93–80, and 80–68 Ma. Of the six supersequences, two (at 126–117.5 and 117.5–112 Ma) are composed principally of third-order composite sequence sets. Two others (at 112–103 and 80–68 Ma) are composed of fundamental third-order sequence sets, and the final two (at 103–93 and 93–80 Ma) are composed of mixed third-order (fundamental and composite) sequence sets.

One fully developed supersequence set (112–80 Ma) exists within the basins, best displayed in the Orange and Bredasdorp basins. Above and below this complete supersequence set are supersequences composing parts of other incomplete sets: supersequences 1-5 (at 126–117.5 Ma) and 6-12 (at 117.5–112 Ma) are the upper two supersequences of an older set extending downward into synrift strata, and supersequence 17-20 (at 80–68 Ma) is the lowest supersequence within a younger set extending upward into the Tertiary. Second-order unconformity 21At1 (at 68 Ma), for example, is the base of a supersequence with an upper boundary near the middle Paleocene.

Classification and Nomenclature

A simple and totally unambiguous classification and nomenclature system for sequence stratigraphy ideally will have to wait until all analyses are completed and no more modifications or conceptual advances can be made. Unfortunately, this ideal can not be attained for the South African sequence because its classification system is an evolving one that has changed with exploration and is still changing as development takes place.

Consequently, an alphanumeric nomenclature system originated early in the project and evolved during the subsequent 5 years of hands-on interpretation of thousands of kilometers of seismic profiles from offshore South Africa. This system developed as an operational system long before most sequences were assigned ages and before the significance of many sequence sets was appreciated. Therefore, the sequence classification is not purely hierarchical but instead represents an open-ended, working empirical system. As exploration and research have continued, sequences have been classified into various orders of frequencies and types of sequences and sequence sets, along with improved age designations.

The sequence and sequence set classification and alphanumeric nomenclature are frequency independent. Numerical symbols (1–22) (Figures 9, 10) were assigned in stratigraphic succession to prominent, unconformity-bound, seismically distinctive sequences or sequence sets. Other less distinctive sequences were assigned alphabetical symbols (A–E) in stratigraphic succession within respective numerically designated sequences and sequence sets.

All sequence boundaries are designated as either type 1 (t1) or type 2 (t2). Most sequences are designated by the symbol that was applied to its basal unconformity. For example, the basal unconformity of third-order fundamental sequence 13A is 13At1. Third-order composite sequences such as sequence 9\10 comprise less prominent fourth-order sequences such as 9A–F and 10A–E. Figures 9 and 10 summarize, date, and classify all sequences involved in this study.

Marine condensed sections (mcs), maximum flooding surfaces (mfs), and other stratigraphic surfaces (e.g., TS, DLS, and TLS; see Figure 12) within sequences are also designated by their sequence symbols, for example: 15A mcs (91.5 Ma). On all Atlas figures, each unconformity and some other sequence stratigraphic surfaces are labeled. The inferred age of each second-order or supersequence-bounding unconformity is designated on all figures. This nomenclature system has permitted the addition of newly discovered alphabetically designated sequences within the numerically designated frequency-independent sequences or sequence sets with minimum disruption to the classification scheme.

Sequence sets were delineated by characteristic stacking pattern geometries (progradational, aggradational, or retrogradational) recognized on seismic profiles and confirmed on wireline logs. The classification system includes fourth-, third-, and second-order sequence and sequence set frequencies (Figures 9, 10, Table 1). Other sequence classification and nomenclature schemes for the South African postrift Cretaceous strata were rejected for various reasons. These alternative systems included absolute age designation for each sequence, successive numbering of all sequences without regard to frequency, and designation of the sequences in numerical succession by Cretaceous stage names (e.g., "Albian 3"). These were all rejected either because of provisional age determinations or because of difficulty in adding new sequences to the system.

The Soekor classification provides an operational system that not only reflects the unique tectonic history of the South African basins but also provisionally links to the Exxon global eustatic cycles and to standard international Cretaceous chronostratigraphy. Future studies will certainly modify this linkage, but the observed sequences and sequence stacking geometries will continue to unify the postrift geologic record of South African basins and provide the basis for more definitive future classifications.

Seismic Processing and Sequence Symbols Used in Atlas Illustrations

Seismic profiles presented in this Atlas were specifically processed by Soekor to provide the most detailed information possible within the dimensions of the Atlas format. Most of the seismic profiles are presented at time scales of 2.5 in./sec (~6.3 cm/sec) and at horizontal scales of 1:100,000 (1 cm/km) or 1:50,000 (2 cm/km). Some special seismic displays are presented at larger scales to enhance specific sequence features. All profiles underwent migration processing.

The display mode of the regional seismic profiles is wiggle trace, variable area. Some dual polarity, variable density, and acoustic impedance (Figure 12) displays are presented for the Bredasdorp Basin. Profiles for the Pletmos Basin display intended negative standard (trough) polarity. For the Bredasdorp Basin, the profiles display intended positive standard (peak) polarity, while Orange Basin profiles use both of these polarity conventions.

Symbols used to label figures or to abbreviate text were selected to conform with general sequence stratigraphic use and convention (e.g., Vail, 1987); many of these symbols are shown in Figure 5. Symbols used to designate South African sequences and sequence sets are illustrated in Figures 9 and 10 and in Table 1. Symbols and patterns used in Atlas figures are defined in Figure 12.

The Atlas format was designed to convey a highly illustrated perspective of the results of an in-depth sequence stratigraphic analysis of the three offshore South African basins, each of which displays unique sequence characteristics because of basinal tectonic and sediment supply variations. Figures illustrating each of the three basins are generally arranged in the order of their discussion in the text, but more importantly, they are primarily organized to provide the best visual presentation by which the reader can peruse the Atlas using only the figures. The arrangement progresses from basic information, to observational maps and charts generated from the basic data, and finally to subjective illustrations that present cyclic depositional, erosional, and tectonic events inferred for the basins. Figure captions, which are extensive and cross referenced, are specifically designed to provide in-depth but accessible explanations.

Illustrations for each basin include the following: (1) general basin location and orientation, (2) evidence for recognition of the sequences and sequence sets recognized in the basin, (3) uninterpreted and (4) highly interpreted or descriptive seismic profiles, (5) specially imaged seismic profiles needed to illustrate important sequence and depositional systems characteristics, (6) interpreted wireline logs, (7) cross sections and maps generated from seismic and wireline log data, (8) schematic drawings to illustrate inferred models and depositional and erosional processes, (9) chronostratigraphic frameworks, and (10) the basis for ages assigned to unconformities and marine condensed sections.

Tables 2, 4, and 6 in Parts II, III, and IV, respectively, provide lists of geologic features interpreted on the seismic profiles, wireline logs, maps, and charts along with cross references to figures in each of the three parts. These table indexes permit rapid access to figures that show a variety of interpretations.