Chapter 6

Cycles with Million-Year Episodicities

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A wealth of stratigraphic data has accumulated for cycles having durations and episodicities of a few million years. They have been recorded in a wide variety of Phanerozoic basins in many different tectonic settings. They constitute the main basis of the Exxon global cycle charts, where they are termed "third-order cycles" (Haq et al., 1987, 1988a). A small selection of these is described in this chapter in order to illustrate stratigraphic patterns and their reflection of tectonic setting. Sequence concepts have also been applied to the study of the Precambrian record (e.g., Christie-Blick et al., 1988), but this work is not discussed here because at this time the record is fragmentary and regional correlations are very limited.

6.1 Continental Margins

It is now routine practice to subdivide stratigraphic successions into sequences, on various scales, based on the recognition and correlation of key surfaces and facies packages. Figures 6.1 and 6.2 consist of a set of diagrams constructed to illustrate the Upper Cretaceous stratigraphy of Oman. Three scales of "accommodation cycles" have been recognized in this data set. The thickest of the cycles spans much of the Cenomanian stage, and corresponds to a 10^6-year sequence. It can be divided into two higher-order sets of sequences, of the type discussed in Chap. 7.

6.1.1 Clastic Platforms and Margins

The Atlantic and Gulf Coast continental margins of the United States are classic examples of extensional continental margins (Fig. 6.3). Their stratigraphy and structure were influential in the development of plate-tectonic basin models for continental margins, and much research has been carried out there to investigate the tectonic history and petroleum potential of the major basins. Techniques for backstripping and for modeling of the geophysical controls of flexural and thermal subsidence were first developed using Atlantic-margin data (see Miall, 1999, Chap. 7 for summary). In more recent years, a major research project has been undertaken to thoroughly analyze the sequence stratigraphy of the Atlantic margin off the coast of New Jersey. This project, led by K. G. Miller of Rutgers University, is discussed below in greater detail, and in Sect. 14.6.1.

One of the suggestions made by the Vail-Haq-Hardenbol/Exxon school of seismic stratigraphy was that "Neogene stratigraphic successions from a number of continents are characterized by very similar stratal geometries" (Bartek et al., 1991, p. 6753;

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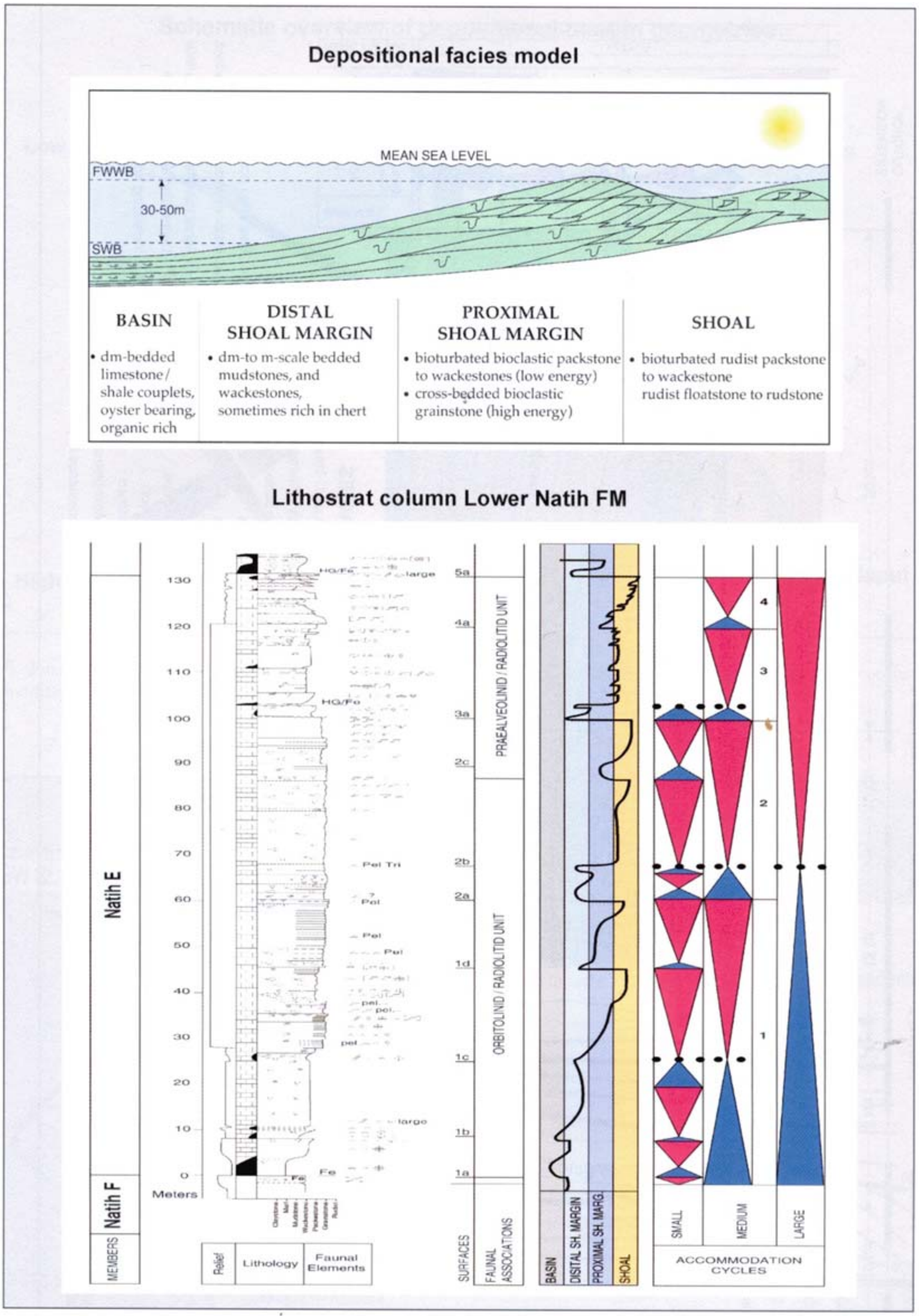

Fig. 6.1 The subdivision of a stratigraphic section into "accommodation cycles" at several different scales, showing a relative sea-level curve (at centre of *lower diagram*) and its relationship to coastal depositional systems (*top diagram*). From a study of Upper Cretaceous deposits in Oman (Veeken, 2007, Fig. 4.34)

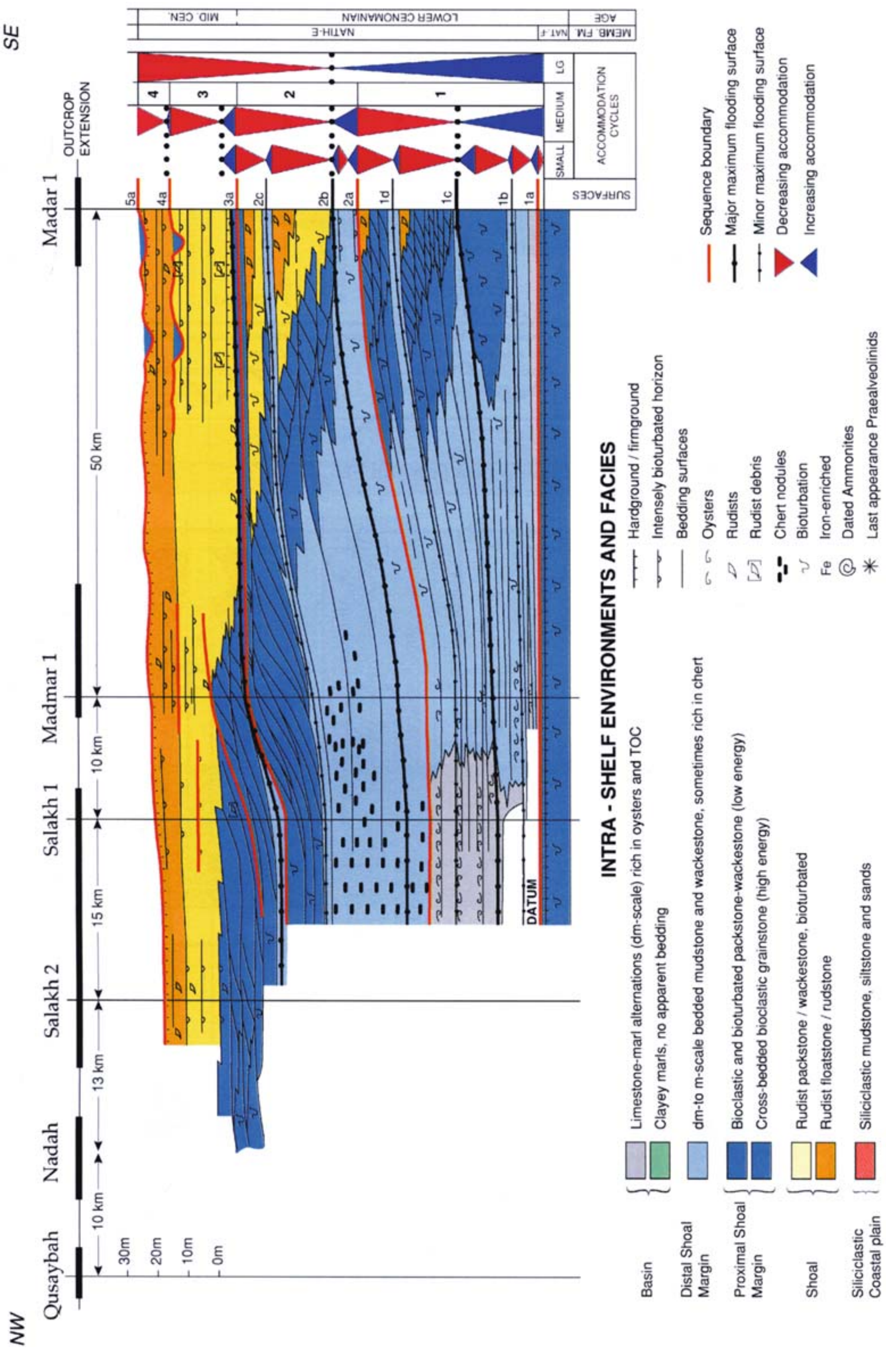

Fig. 6.2 High-resolution sequence stratigraphy of the same section in Fig. 6.1, showing the lateral and vertical relationships of the various facies assemblages. From a study of Upper Cretaceous deposits in Oman (Veeken, 2007, Fig. 4.35)

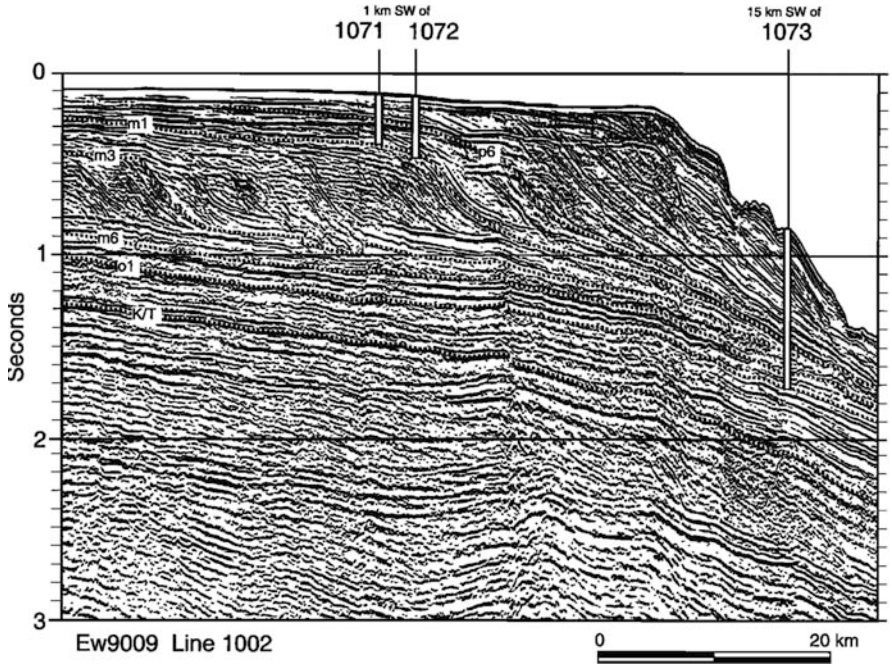

Fig. 6.3 Reflection-seismic line across the outer New Jersey continental shelf and slope, showing the Cretaceous-Tertiary boundary (K/T) and some of the Cenozoic sequence boundaries that can be differentiated along this section. These are part of a data set that defines a complete succession of 10^6-year sequences along this part of the North American margin (see Fig. 4.10) (Miller et al., 1998, Fig. 3)

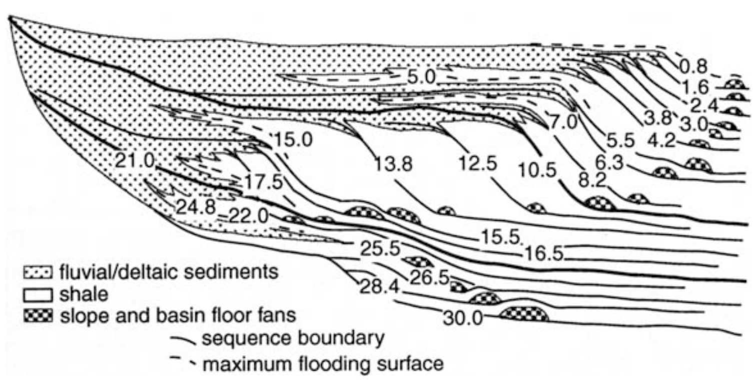

Fig. 6.4 Schematic cross-section of a generalized, hypothetical continental margin, based on assessment of a global record of seismic-reflection data by Bartek et al. (1991). This section purports to illustrate what the authors term "the global stratigraphic signature of the Upper Paleogene and Neogene. This version of the illustration is from McGowran (2005, Fig. 5.21)

see Fig. 6.4). It was thought that this indicated a global control of continental-margin stratigraphy by eustatic sea-level change. The signature included 12 recognizable "third-order" elements, beginning with these three: "(1) Lower Oligocene landward thickening, (2) upper Oligocene wedge, which laps out at or near the shelf margin and thickens basinward, (3) basal lower Miocene flooding," and so on (Bartek et al., 1991, p. 6753). As discussed in Chap. 14, subsequent detailed chronostratigraphic correlation of some individual continental margin sections does not lend support to this characterization of Neogene stratigraphy. While there is good agreement in sequence boundary ages between some individual successions, paradoxically, the Vail Neogene "signature" of Fig. 6.4 does not correlate with these events (Fig. 14.34). Nevertheless, cross sections such as Fig. 6.4, as constructed for individual basin-fill stratigraphies, are an invaluable guide to the long-range development of the basin fill. For example, this diagram suggests a long-term transgression from 30 to 21 Ma, during which the shelf margin underwent significant backstepping, and a long-term period of high sediment supply from 15 Ma to the present day, during which time the continental margin underwent both substantial progradation and aggradation.

The lack of "fit" of the sequence boundary ages of Fig. 6.4 with other, independently dated continental margin sections (Fig. 14.34) is probably a consequence of the method by which the ages of the events and the procedure by which correlation was carried out. As discussed at length elsewhere in this book (Sect. 1.2, Chap. 12), the Vail-Haq-Hardenbol/Exxon "School" of sequence stratigraphy adopted a "deductive" approach to the issue of sequence classification and correlation, and this has led to problems that limit the usefulness of the work.

Some of the details of the Atlantic-margin project of K. G. Miller are discussed here. This project has focused on the New Jersey margin, but also includes a detailed analysis of an outcrop section in Alabama, which provides some interesting comparisons. The St. Stephens Quarry in Alabama was one of the sites used in the early Exxon work as a reference section for Paleogene stratigraphy, in particular, for documentation of the Eocene-Oligocene boundary (Baum and Vail, 1988). As Miller et al. (2008a) noted, this is potentially an important section, because the Eocene-Oligocene boundary has long been thought to coincide with a major drop in sea level following a build-up in Antarctic ice volumes, and there has existed a need to document this transition in detail. Modern oxygen-isotope data spanning the Cenozoic (Miller et al., 2005a, b) do, in fact, show such a drop (Fig. 11.16). Given controversies surrounding the sequence stratigraphy and correlation of this section, Miller et al. (2008a) undertook a thorough re-evaluation of the succession, based on a continuous core obtained at the site.

Figure 6.5 illustrates the sequence stratigraphy and correlations of the Alabama section. The precise positioning of the sequence boundaries was accomplished using calcareous nannofossils and planktonic foraminifera, tied into the time scale of Berggren et al. (1995). The method of dating is described in Sect. 14.6.1. As discussed there, potential errors of ± 0.5 million years may be expected with this type of data set at this level in the geological column. Given that, a reasonably close comparison is apparent between the Alabama and New Jersey sections, in Fig. 6.5. A virtually continuous section in Alabama from 31.7 to 33.9 Ma contains two breaks that correlate with longer hiatuses in the New Jersey section, and the other unconformities in the Alabama section partially overlap those in New Jersey. The two areas are approximately 1,500 km apart and located in different, but tectonically related structural provinces. Does this indicate that the correlations pass the test for eustasy? It can be observed, here, that two sequence boundaries shown in Fig. 6.5, at 33.5 and 33.9 Ma, appear to coincide with sudden increases in $\delta^{18}O$, which would seem to confirm a relationship to ice build-up. We return to this question in Chap. 14.

The complete section on the New Jersey continental margin (coastal plain, shelf and slope) spans the Lower Cretaceous to present, and exhibits a set of 10^6-year sequences (Fig. 4.10). A portion of the section is shown in Fig. 6.6. The synthesis was constructed from seismic and borehole data, calibrated using a series of drill cores subjected to lithofacies and biofacies analysis, biostratigraphy and other methods of dating, including strontium and oxygen isotope data and magnetostratigraphy (see Sect. 14.6.1). As discussed above (see also discussion of Fig. 6.6 by Browning et al., 2008, p. 241), the Eocene-Oligocene interval illustrated in Fig. 6.6 spans a transition into cool, icehouse climates, with a substantial buildup of ice postulated to have occurred on Antarctica (see Chap. 11). Facies analysis of drill cores through this interval document a transition from a carbonate ramp accumulating carbonate-rich clays to a prograding siliciclastic margin, commencing in the middle Eocene. In Fig. 6.6 it can be seen that carbonate sediments occur only in the lowermost sequence (E8). The total time span represented by the preserved sequences illustrated in Fig. 6.6 represents only 32% of the total elapsed time encompassed by this diagram (middle Eocene to late Oligocene), as measured at the 10^6-year scale.

Figure 6.6 includes two versions of a calculated sea-level curve constructed using the backstripping methods summarized in Sect. 3.5. As noted by Kominz et al. (2008, p. 211), such curves can, initially, only be assumed to relate to local sea-level changes. Careful construction of local curves must precede any attempt to develop global curves, a topic discussed at

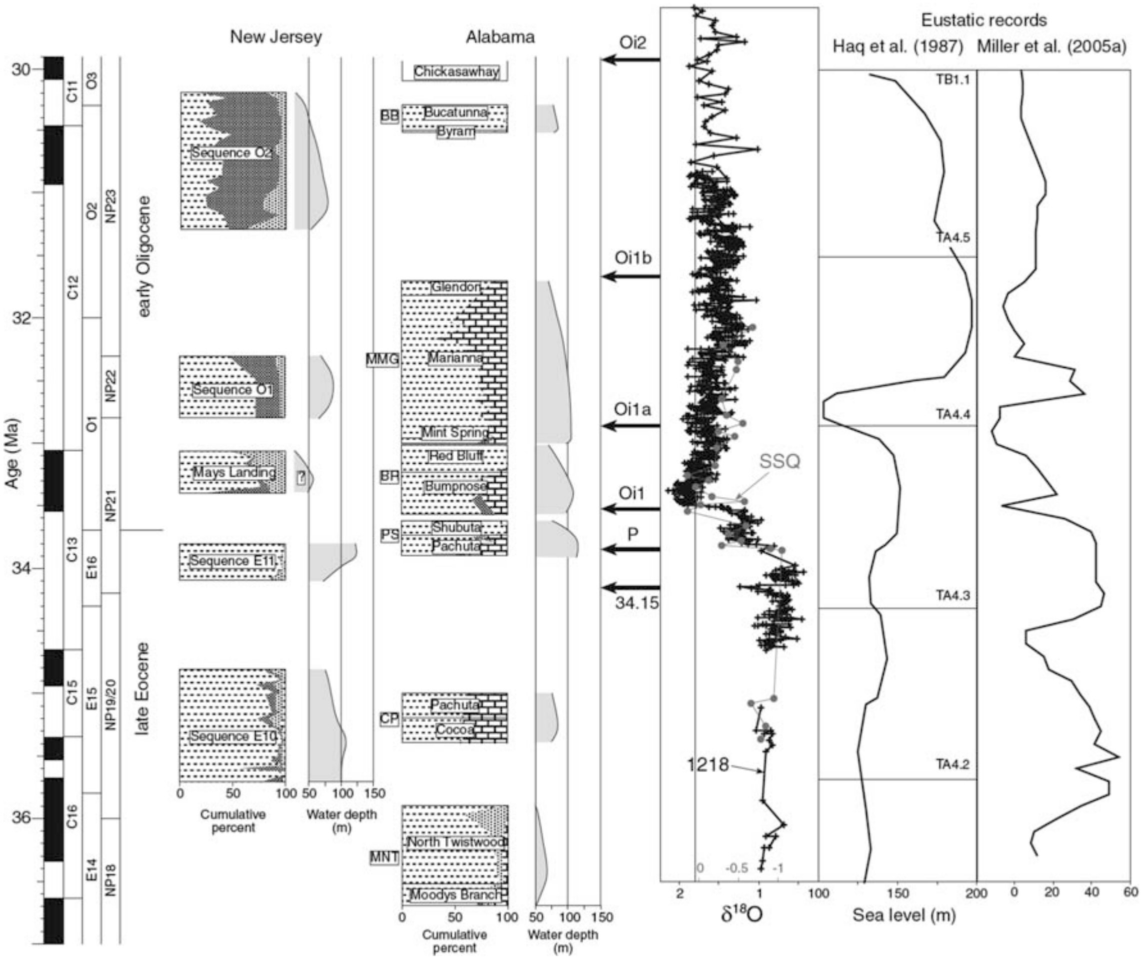

Fig. 6.5 The sequence record of an outcrop section in Alabama, compared with contemporaneous strata in New Jersey, and correlated against a standard oxygen isotope curve and published sea-level curves. The *rectangles* for each sequence indicate the assigned ages of both tops and bottoms. The internal ornamentation indicates lithofacies composition. Water depths, determined from biofacies data, are shown in the small graphs to the *right* of each *rectangle*. *Arrows* labeled Oi2, Oi1b, etc., refer to sequence boundaries in the New Jersey sections. This diagram is from the Alabama study (Miller et al., 2008a, Fig. 8); the New Jersey data are from Miller et al. (1998). The methods of chronostratigraphic correlation used in the construction of this diagram are discussed with reference to the New Jersey work of K. G. Miller and his colleagues in Chap. 14

length in Chap. 14. This is because basement elevation is controlled by local to regional tectonic effects (thermal and flexural subsidence, dynamic loading, etc.; see Chap. 10) and by sediment loading, as well as by the absolute elevation of the sea. Location-specific sea-level curves must also take into account changing water depths during sedimentation and post-depositional sediment compaction effects (Miall, 1999, Chap. 7; Allen and Allen, 2005). This is why detailed sedimentological studies (for this case study, reported by Browning et al., 2008) are essential.

6.1.2 Carbonate Cycles of Platforms and Craton Margins

Carbonate sediments are sensitive indicators of changing sea level for various reasons, including the following three: Firstly, the “carbonate factory” that develops within warm, shallow continental shelves that are free of clastic detritus can produce carbonate sediment at a rate that normally is rapid enough to keep up with the most rapid of sea-level changes. Secondly, within such shallow-water carbonates, depth changes are indicated

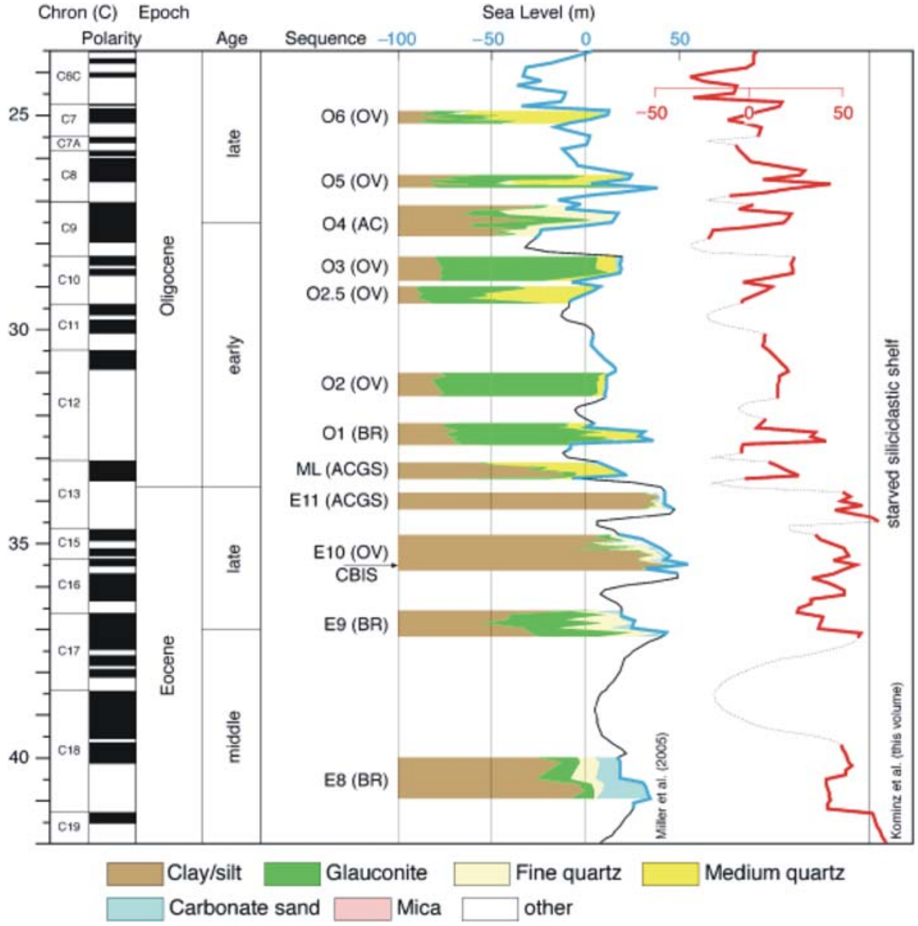

Fig. 6.6 Eocene-Oligocene sequence stratigraphy of New Jersey. The sequence terminology (E8, O1, etc.) is based on detailed studies of drill cores from the New Jersey coastal plain, the names of which are indicated by abbreviations (BR, OV, etc.). The sea level *curves* represent different version of backstripping reconstructions of the New Jersey data by Miller et al. (2005a) and Kominz et al. (2008). From Browning et al. (2008, Fig. 11)

by a variety of depth-sensitive facies characteristics. Thirdly, within carbonate platforms most carbonate sediments are deposited where they are produced. The complications of sediment redistribution by autogenic processes that characterize clastic sediments (e.g., the development of delta lobes) therefore are less extreme. For these reasons stratigraphic sequences are commonly well developed in carbonate rocks. Hierarchies of sequences may be present, reflecting the integration of several different generative mechanisms (Sarg, 1988; Goldhammer et al., 1990; Schlager, 1992a). It is important to note, however, that sequence boundaries can develop as a result of submarine erosion and environmental change, as well as in response to sea-level change (Sect. 2.3.3).

Prograding continental margins provide many examples of 10^6-year carbonate sequence stratigraphy, and these are well displayed in regional reflection-seismic records. Eberli and Ginsburg (1988, 1989) and Eberli et al. (1997) described an excellent example of this, revealing the dramatic lateral growth by progradation of the Bahama Platform. Other examples were given by Sarg (1988), Mitchum and Uliana (1988), Epting (1989) and Tcherepanov et al. (2008). Bosellini (1984) and Sarg (1988) provided outcrop examples. Many detailed case studies are contained in the book edited by Loucks and Sarg (1993).

Figure 6.7 illustrates the architecture and sequence stratigraphy of Miocene to Recent carbonate buildups in offshore Sarawak. The buildups are gradually

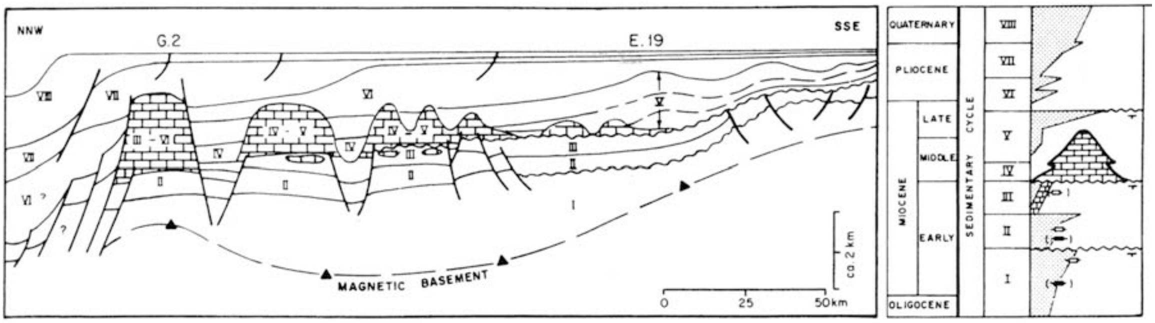

Fig. 6.7 Simplified stratigraphic cross-section showing relationship between carbonate buildups and depositional cycles, offshore Sarawak. The carbonate buildups of cycles III–VI are buried by deltaic clastics of cycles V–VIII. Seaward stepping of the carbonate buildups and deltaic progradation are continuing to the present day (Epting, 1989). AAPG © 1989. Reprinted by permission of the AAPG whose permission is required for further use

extending seaward, and are being buried by progradation of deltaic clastics. This is a very common pattern in continental-margin carbonate shelves (e.g., Devonian of the Alberta Basin, modern Gulf of Papua, as discussed and illustrated below). In the Sarawak and Gulf of Papua examples, the most recent reef buildups are not yet drowned by deltaic progradation and are still actively developing.

The Bahamas Bank is one of the more thoroughly studied carbonate margins. Some of the research carried out there by R. N. Ginsburg and G. Eberli is summarized in Figs. 6.8, 6.9, and 6.10. The Bahamas platform was built on fault blocks that formed initially during the mid-Jurassic, although the present topography of the bank, consisting of flat-topped carbonate platforms cut by deep oceanic channels, is thought to have originated in the Late Cretaceous. The platform has expanded laterally toward the Florida margin by spectacular lateral clinoform progradation (Figs. 6.8 and 6.9). Windward margins are steep and show chaotic seismic facies. Leeward margins evolved from steep, fault-bounded margins into bypass margins and into low-angle accretionary slopes during the Miocene (Fig. 6.9). The present configuration of the continental slopes around the platform and inter-island channels is partly the result of carbonate progradation and partly the result of increased submarine erosion, probably reflecting the gradual acceleration of thermohaline oceanic circulation as the climate became cooler with increasing latitudinal temperature gradients, during the Cenozoic.

Eberli and Ginsburg (1989) recognized multiple sequence boundaries in the Cretaceous-Cenozoic carbonate cover (Figs. 6.8 and 6.9), reflecting the interplay between vertical motions of the platform and eustatic sea-level changes. Architectural details of the sequences clearly record relative sea-level changes (Fig. 6.10). Two cored holes subsequently located

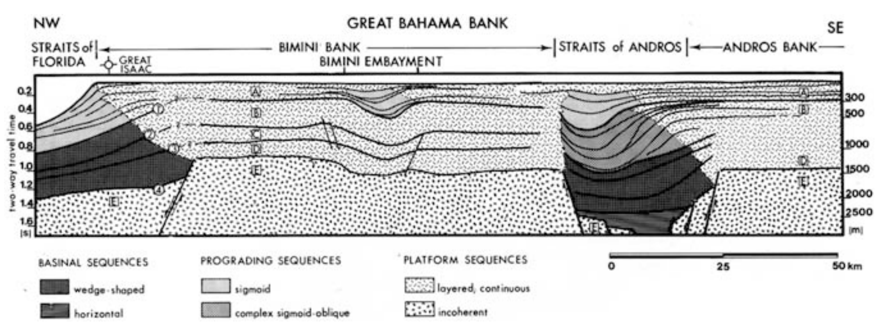

Fig. 6.8 Schematic cross-section across the northwest margin of Great Bahama Bank and margin of Andros Bank, based on seismic-reflection data. Patterns indicate variations in seismic facies. The margin facing the Straits of Florida and that on the SE side of the Straits of Andros are typical leeward platform margins. That on the NW side of the Straits of Andros is a windward margin. The evolution of the leeward margins is shown in greater detail in Fig. 6.7 (Eberli and Ginsburg, 1989)

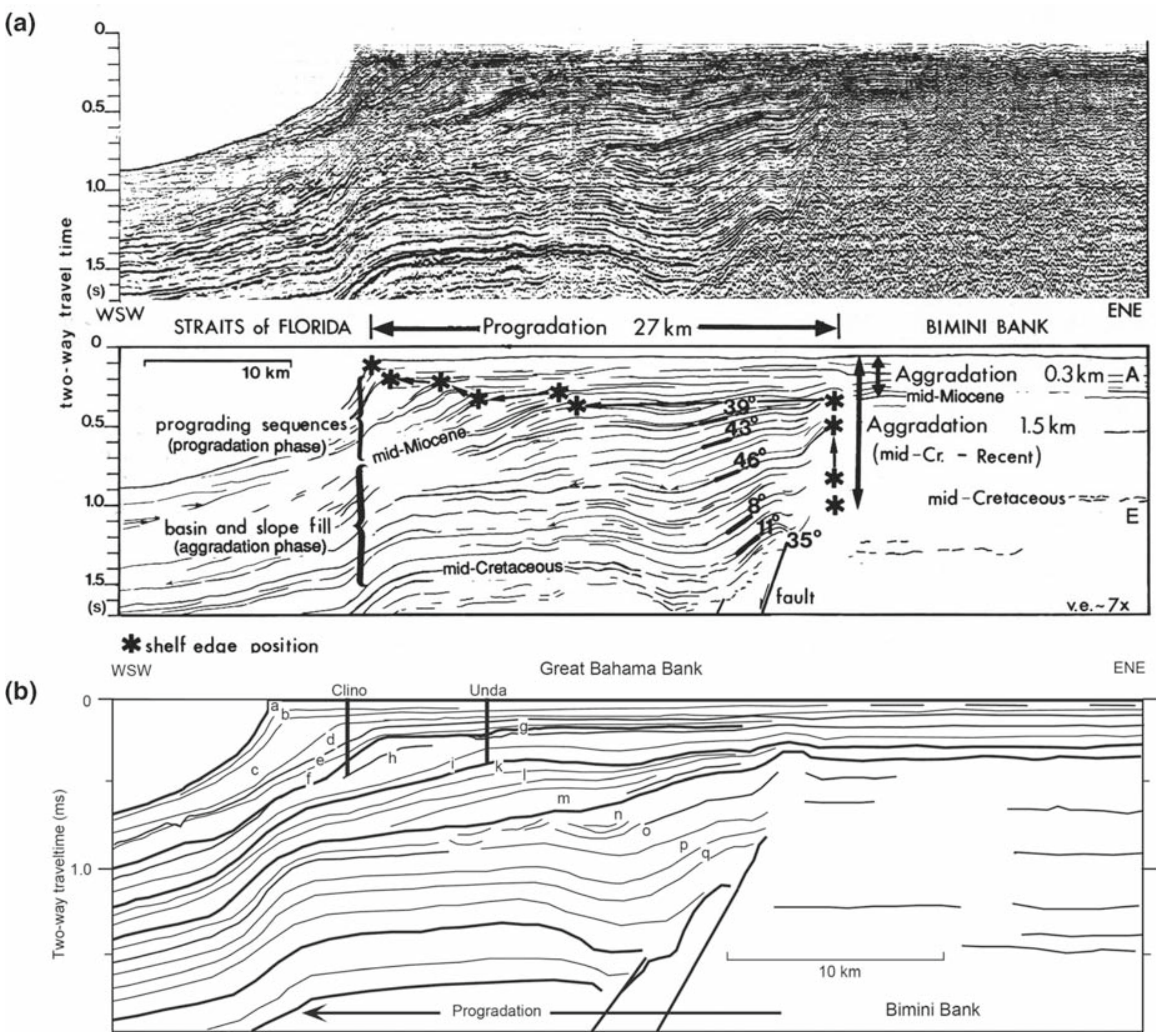

Fig. 6.9 West margin of Bimini Bank, showing details of margin evolution. (**a**) Seismic section and angles documenting the decrease in continental slope through time. *Asterisks* denote position of shelf edge (Eberli and Ginsburg, 1989). (**b**) Interpretation of the section based on the analysis of two core holes drilled along the line of section (Eberli et al., 1997). The ages of the sequences a–q are provided in Fig. 13.34

on and near the centre of the seismic line shown in Fig. 6.9b (within the topsets and foresets of the platform) drilled down to a Middle Miocene level at a maximum depth of 678 m, and revealed much about the stratigraphy, sedimentology, fluids and other features of the platform rocks (Eberli et al., 1997). Analyses indicate the importance of "highstand shedding" as the primary control on the depositional evolution of the Neogene western Great Bahama Bank:

> The principal source of sediment to the slope is the extensive offbank transport of suspended, fine-grained banktop 'background' sediment during periods of sea-level highstands when the entire platform was submerged providing the bulk, more than 80%, of the slope sediment. During sea-level falls, the supply of fine-grained sediment to the slope environment is reduced or completely stopped. These deposits of reworked margin-derived material form thin intercalations in the 'background' sediment. Factors controlling the thickness, composition, and diagenesis of the deposits, and the formation of discontinuity surfaces are (1) the morphology of the platform, hardgrounds may develop at the base (ramp morphology) or at the top of the lowstand deposits (flat-topped platform), (2) the frequency and amplitude of sea-level changes, and (3) the water depth and distance to the margin (Eberli et al., 1997, p. 35).

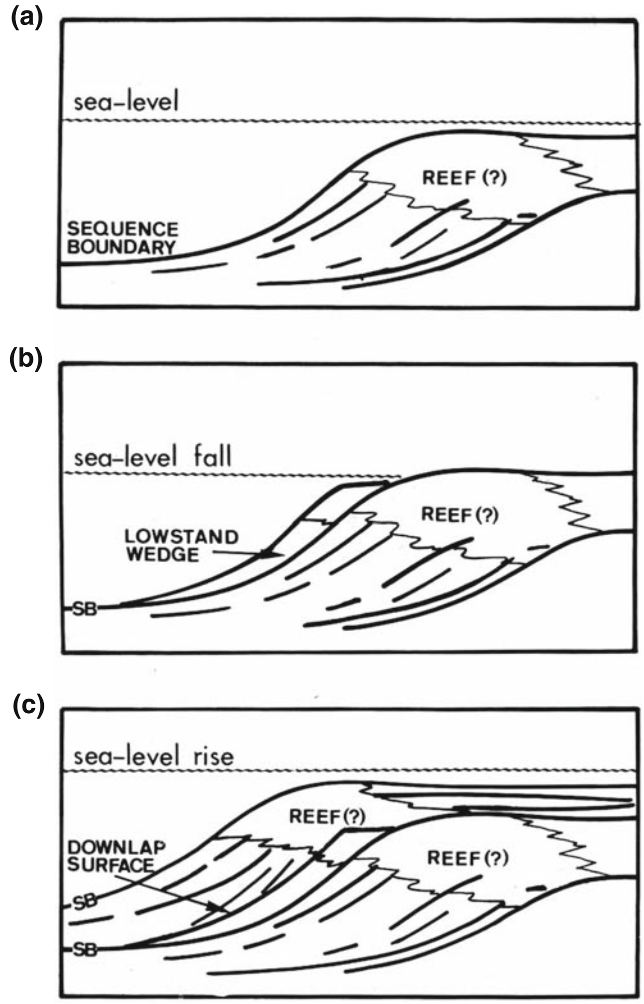

Fig. 6.10 Architectural details of carbonate sequence margins reveal changes in accommodation. Abundant sediment generation during a highstand in relative sea-level results in a trajectory of the facies belts sloping obliquely upward (diagrams **a**, **c**). An intervening episode of low relative sea level causes a downward shift in facies belts and reduction in sediment supply from a narrow coastal strip, resulting in a topset termination to the reef facies body that records the lowstand event (Eberli and. Ginsburg, 1989, Fig. 8)

A suite of ODP cores drilled mainly on the lower foresets and bottomsets along the seismic line of Fig. 6.8 provided additional details. They showed that much of the lower foreset deposits consists of carbonate turbidites, while the bottomset deposits include contourites (Betzler et al., 1999). Depositional slopes on the clinoforms reach a maximum of 47°, but this is exceptional. Most slopes are less than 4° (Betzler et al., 1999), a point that is obscured by the large vertical exaggerations characteristic of seismic displays.

These cores reveal three scales of sequence cyclicity, large scale cycles 60–170 m thick, a medium scale of cyclicity tens of metres thick, and a small-scale cyclicity on a metre scale (Eberli et al., 1997). Major sigmoid reflections within the progradational deposits define boundaries between individual sequences, formed at sea-level lowstands. They are estimated to represent cycles in the order of 1–2 million years duration (sequences a–q in Fig. 6.9b). Larger scale "megasequences" spanning 10–20 million years are identified by major bounding surfaces (letters in boxes in Fig. 6.8).The highest-frequency sequences represent sea-level cyclicity on a 20-ka time scale, according to Betzler et al. (1999). Three major progradational episodes, of late Miocene, late early Pliocene and latest Pliocene age, are considered to indicate sea-level lowstands (Eberli et al., 1997). The major lowstand unconformity dated as Late Pliocene-basal Pleistocene has been interpreted as correlating to the global lowstand that records the build-up of continental ice cover in the northern hemisphere.

6.1.3 Mixed Carbonate-Clastic Successions

A recent seismic survey of the Gulf of Papua provides some high-resolution detail of 10^6-year sequence episodicity in that basin (Tcherepanov et al., 2008). This basin was initiated by break-up of Gondwana (middle Triassic-middle Jurassic) and modified by spreading of the Coral Sea (Late Cretaceous-Paleocene). It became part of a peripheral foreland (proforeland) basin following the collision of Australia with the Banda arc in the Oligocene. A dominantly carbonate succession accumulated there from Eocene time until near the end of the Miocene, at which time it was uplifted and exposed. A subsequent rise in relative sea level resulted in flooding, backstepping and drowning of the carbonate platform, after which a major phase of clastic progradation commenced, sourced from the rising Papuan fold belt to the north. The relatively thin Eocene-Late Miocene carbonate succession and the overlying prograding clastic wedge are well displayed in reflection seismic data (Figs. 6.11 and 6.12). The extent and architecture of the carbonate succession do not appear to relate to the foreland basin setting, whereas the subsequent prograding clastic wedge is clearly a product of tectonic uplift of a clastic source to the north. The gradual burial of the reefs is well seen in Fig. 6.12, showing a very similar succession of events to that which occurred in offshore Sarawak (Fig. 6.7).

Stratigraphic data, including well-log correlation, strontium-isotope stratigraphy and biostratigraphy have been used to divide the carbonate succession into ten sequences, averaging about 2.7 million years in duration (Fig. 6.11). Well cuttings and cores indicate a range of sedimentary environments from shelf to upper bathyal. Isochron maps of these sequences (Fig. 6.13) permit a reconstruction of the evolving architecture of the carbonate-dominated succession, which, in turn, throws light on the relationship between the development of accommodation and the sediment supply. These trends are summarized in Fig. 6.14, as follows: 1. Late Oligocene-early Miocene aggradation, backstepping and partial drowning; 2. late early Miocene-early middle Miocene aggradation; 3. middle Miocene downward shift in facies belts; 4. late middle Miocene lateral progradation; 5. late Miocene-early Pliocene flooding and aggradation. There is some correspondence of these events with the "Global stratigraphic signature" of the Upper Paleogene and

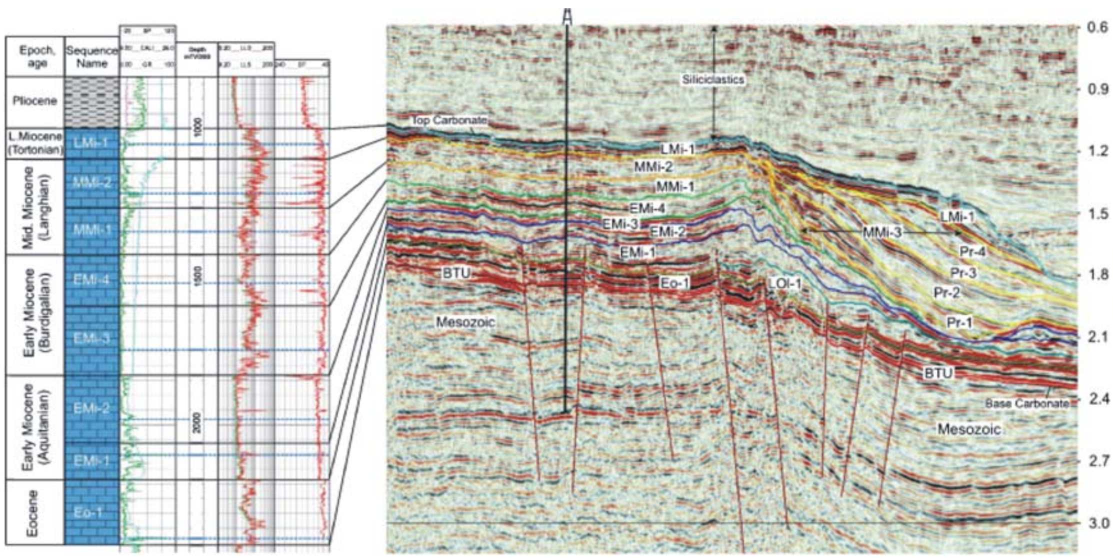

Fig. 6.11 Seismic profile across the continental shelf, Gulf of Papua, showing stratigraphic ties to an exploration well. Eight sequences of Eocene to late Miocene age have been defined based on this type of data (Tcherepanov et al., 2008, Fig. 4a)

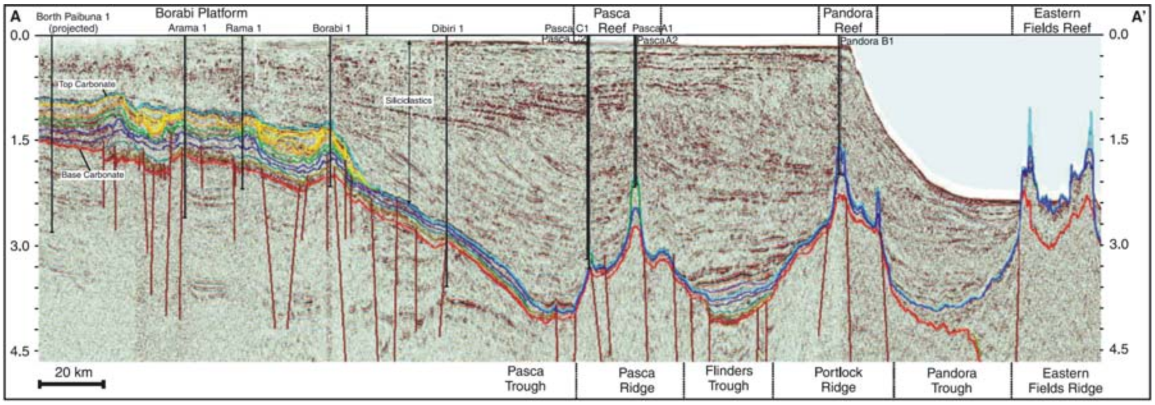

Fig. 6.12 An Eocene-middle Miocene carbonate succession (defined by "top carbonate" and "base carbonate" underlying the Gulf of Papua is overlain by clastics of Late Miocene to modern, in age. These have prograded from the continental margin, leaving only the Eastern Fields and a few other small reef bodies exposed. The reefs have been largely drowned by rising sea level, and only the tip of the Eastern Fields reef is still active (Tcherepanov et al., 2008, Fig. 5A)

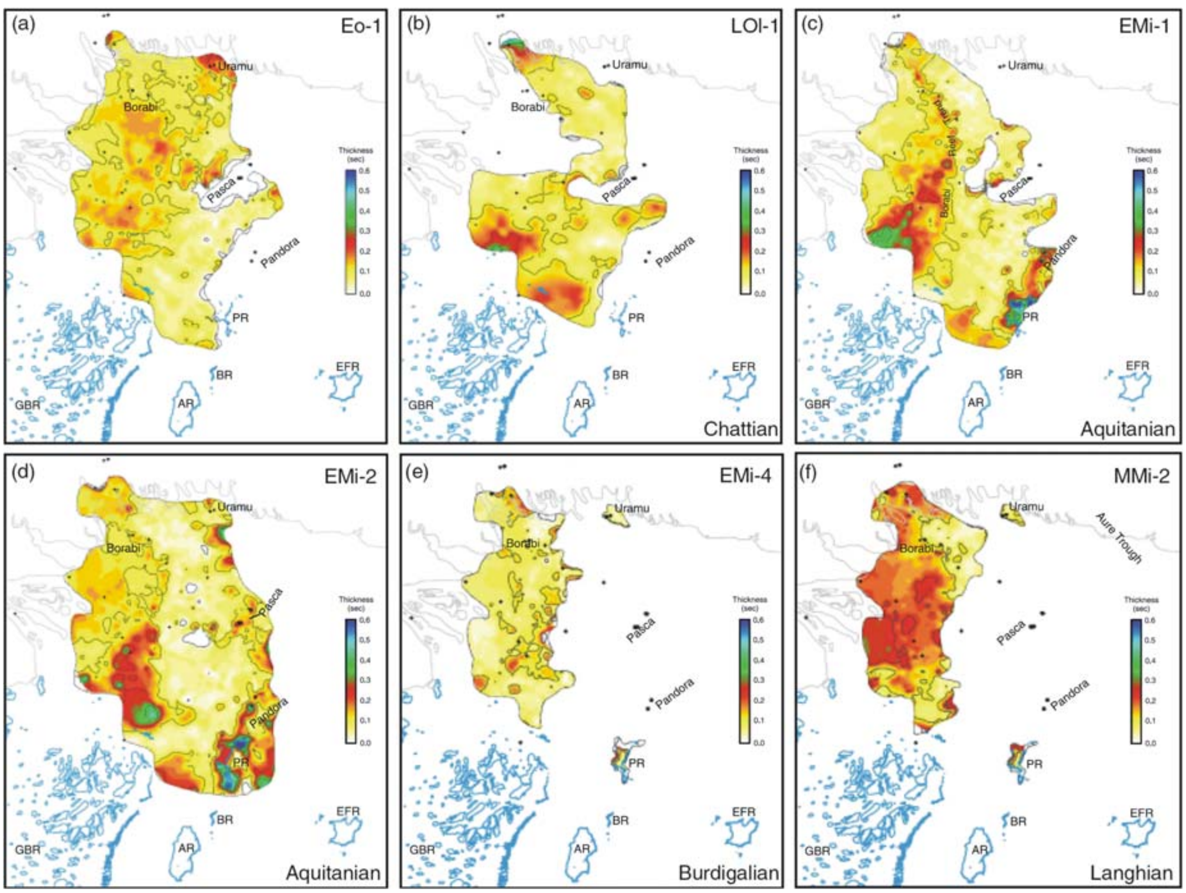

Fig. 6.13 Isochron maps of selected carbonate sequences, Gulf of Papua, showing their extent and distribution. Sequence nomenclature (*top right* corner of each map) is as shown in Fig. 6.11 (Tcherepanov et al., 2008, Fig. 7)

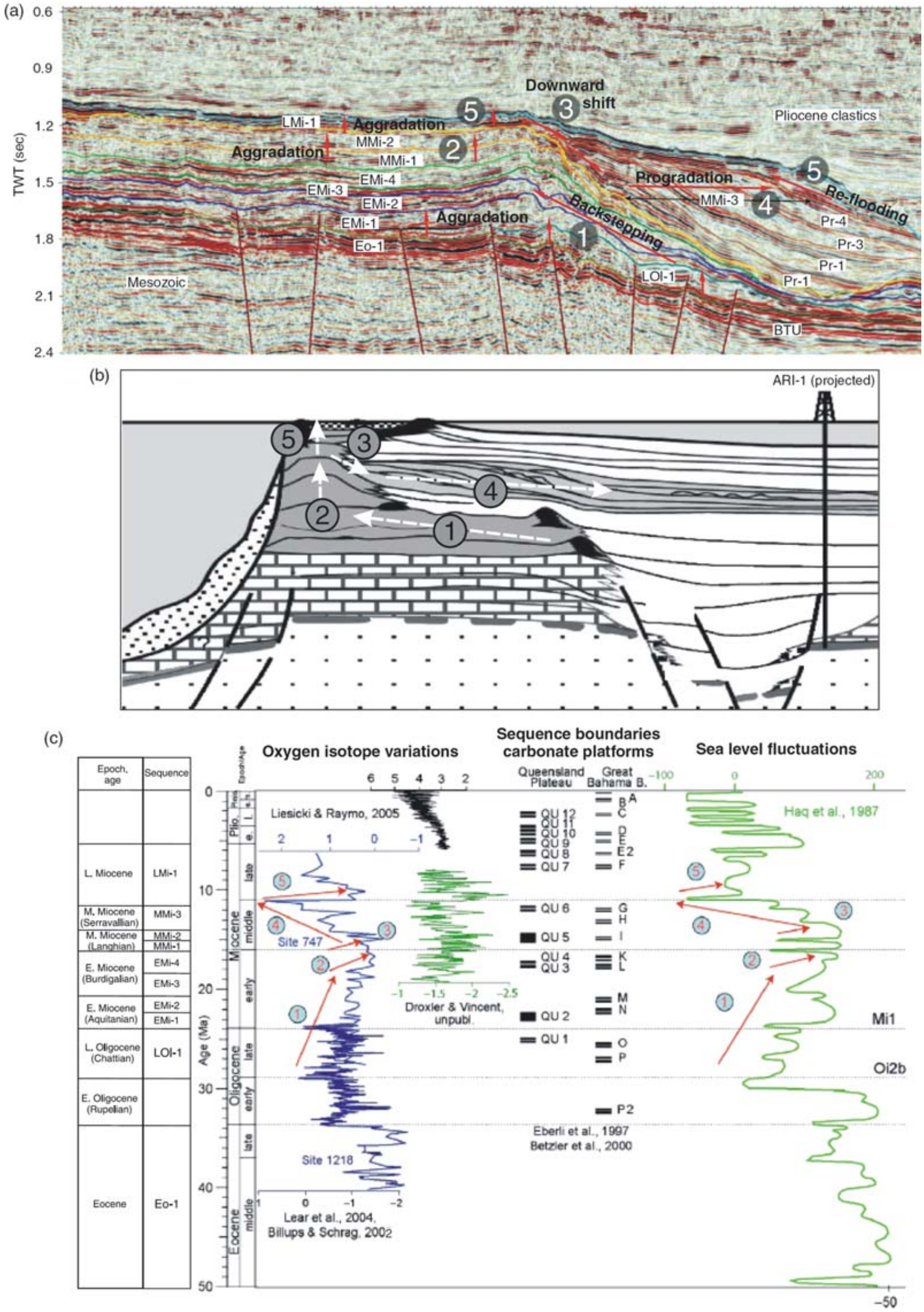

Fig. 6.14 (**a**) Typical seismic section, Gulf of Papua, showing the major architectural features of the stratigraphy. (**b**) As seismic synthesis diagram for the West Maldives (Beloposky and Droxller, 2004). Aggradation, progradation, backstepping, and other architectural features of the stratigraphy are clearly definable from the seismic data in these two locations, but they appear to define a series of changes in accommodation with longer-term episodicities than the events in Queensland and Great Bahama (from Betzler et al., 2000), with which these events are compared in diagram (**c**) This figure is from Tcherepanov et al. (2008, Fig. 10). The Queensland-Bahamas correlations are shown in Fig. 13.34 and are discussed in Sect. 13.6.3

Neogene, described by Bartek et al. (1991; illustrated here as Fig. 6.4), but as noted in Sect. 14.6.3, global correlation of this "signature" with other areas remains poor.

A well known and much studied example of reefal carbonates is the Upper Devonian succession of Alberta. These rocks span the late Givetian to Fammenian, a period spanning more than 25 million years. The Givetian to late Frasnian part of the succession discussed here has been described in detail in the Atlas of the Western Canada Sedimentary Basin (Oldale and Munday, 1994; Switzer et al., 1994). A more recent sequence-stratigraphic reinterpretation and synthesis has been published by Potma et al. (2001).

A schematic summary of the succession is shown in Fig. 6.15. The geology shown in this diagram provides an illustration of the problem with the traditional "order" sequence terminology. Oldale and Munday (1994, p. 155), in referring to the Beaverhill Lake Group, stated:

> Two second-order depositional phases are recognized within the strata ... a transgressive 'reefal' phase (a term introduced by Stoakes, 1988) and a regressive 'basin-fill' phase. Each phase exhibits a distinctive style of deposition and consists of genetically related depositional cycles (parasequences). The phases are bounded by an unconformity or a surface of nondeposition (disconformity) and can be equated to a depositional 'sequence' utilizing the sequence stratigraphic concept. Each cycle reflects a third-order depositional sequence.

They identified three reef cycles within the transgressive phase and "numerous" shale and argillaceous carbonate cycles comprising the regressive phase. However, Potma et al. (2001) referred to the entire succession from the base of the Gillwood Sand to the base of the Gramina Siltstone Formation as a "second-order sequence", and they subdivided the Beaverhill Lake Group into just three "third-order" sequences (Fig. 6.15). The average duration of the nine sequences identified by Potma et al. (2001) is about 3 million years, and so their characterization is consistent with Vail et al.'s (1977) original definition of third-order sequences, but as discussed in Sect. 4.2, the "order" classification has ceased to have any useful meaning.

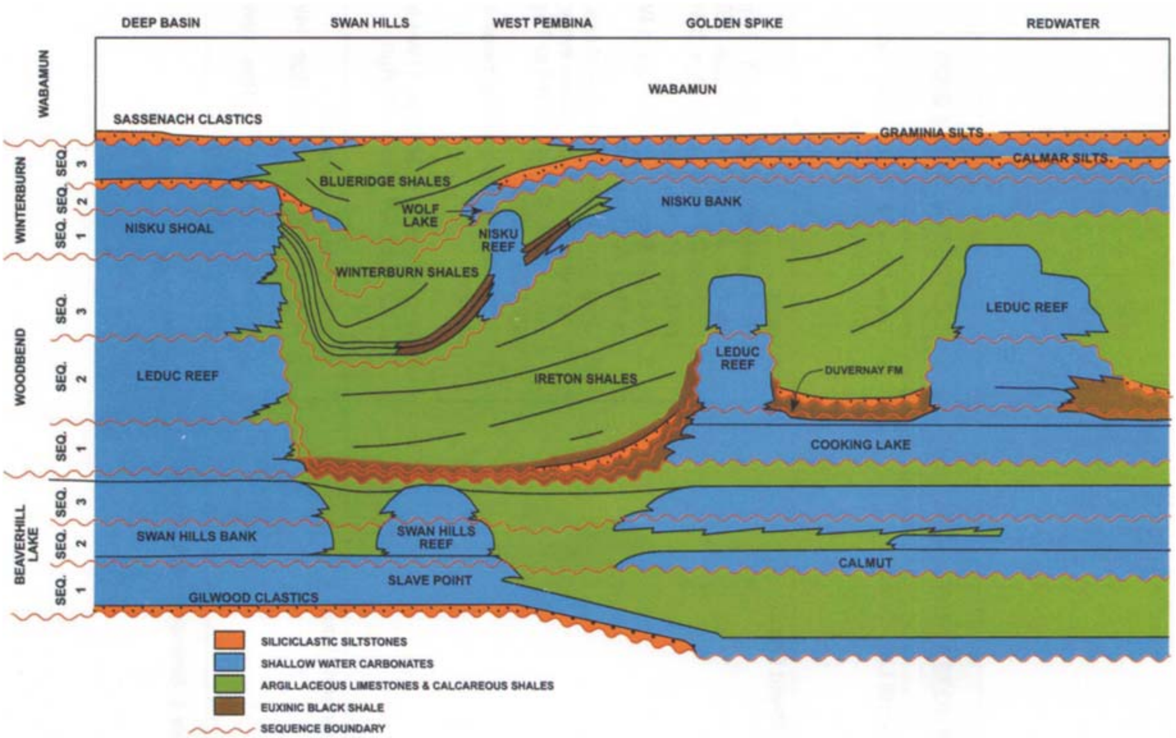

Fig. 6.15 Schematic sequence stratigraphic cross-section of the Late Givetian to Frasnian succession of central Alberta. Line of section is oriented southeast to northwest Potma et al., 2001, Fig. 2)

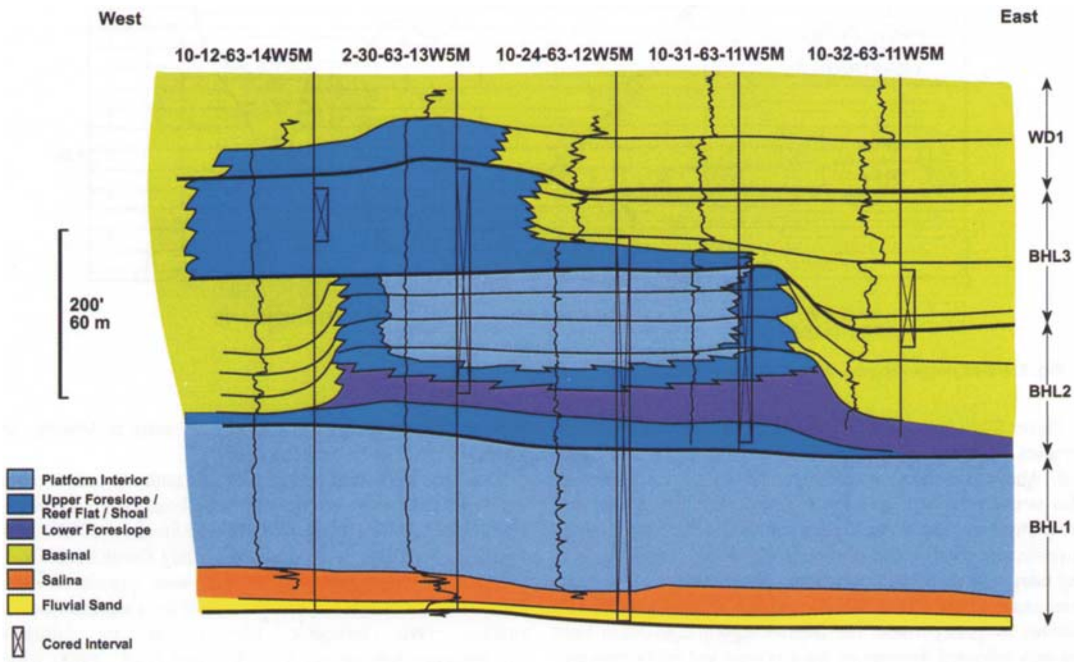

Fig. 6.16 Stratigraphy of the Judy Creek West Pool Alberta. Sequences (BHL1, etc.) are as shown in Fig. 6.15 (Potma et al., 2001, Fig. 8)

Sequence BLH1 commences with fluvial sandstone of the Gillwood Formation, interfingering with platform carbonate and evaporites to the east, and resting on a major regional unconformity (Figs. 6.15 and 6.16). The carbonates consist of *Amphipora* grainstones and boundstones. The BLH1-BLH2 boundary is interpreted as a regional unconformity, and is followed by the reef buildups of the Swan Hills Formation. These consist of atolls dominated by the stromatoporoid *Amphipora*, with well-defined foreslopes that can be mapped based on detailed wireline log correlation. Each of the reefs consist of stacked small-scale shallowing-upward cycles capped by a marine flooding surfaces. Potma et al. (2001, p. 47) termed these "parasequence sets" and indicated that they are "extensively correlatable." Each of the parasequence sets may be locally subdivided into metre-scale parasequences, particularly within the lagoonal facies. Sequence BLH3 indicates a westward backstepping of the reef facies into shallower water environments, closer to a regional upwarp, the West Alberta Ridge. This suggests a gradual, long-term deepening during deposition of the Beaverhill Lake Group.

The base of Woodbend sequence 1 is locally marked by the presence of charophyte oogonia, the reproductive part of fresh or brackish-water plants. This is interpreted to represent a fall of sea level of about 5 m. The main part of sequence WD1 consists of the widespread Cooking Lake Platform and the basal Leduc reef, between which the fine-grained clastics of the Ireton Formation prograded from clastic sources to the northeast. The platform has a near-vertical western margin, with a relief of about 100 m. The Leduc "pinnacle reefs" that subsequently developed at the edge of the platform built the platform margin relief to a maximum of more than 300 m, and wireline log correlations suggest that much of that relief was present during deposition, as a major topographic contrast between reef and basin.

Additional detail of WD2 is shown in Fig. 6.17. Outcrop data from the Rocky Mountains show that the sequence consists of seven shoaling-upward parasequence sets representing peritidal cycles.

Figure 6.18 is a model that has been developed to explain the development of the reef and related systems tracts in the Upper Devonian of Alberta. Throughgoing karst surfaces—difficult to pinpoint except where core is available and the geologist knows what to look for—indicate sea-level lowstands. These are commonly present within the reef deposits, and

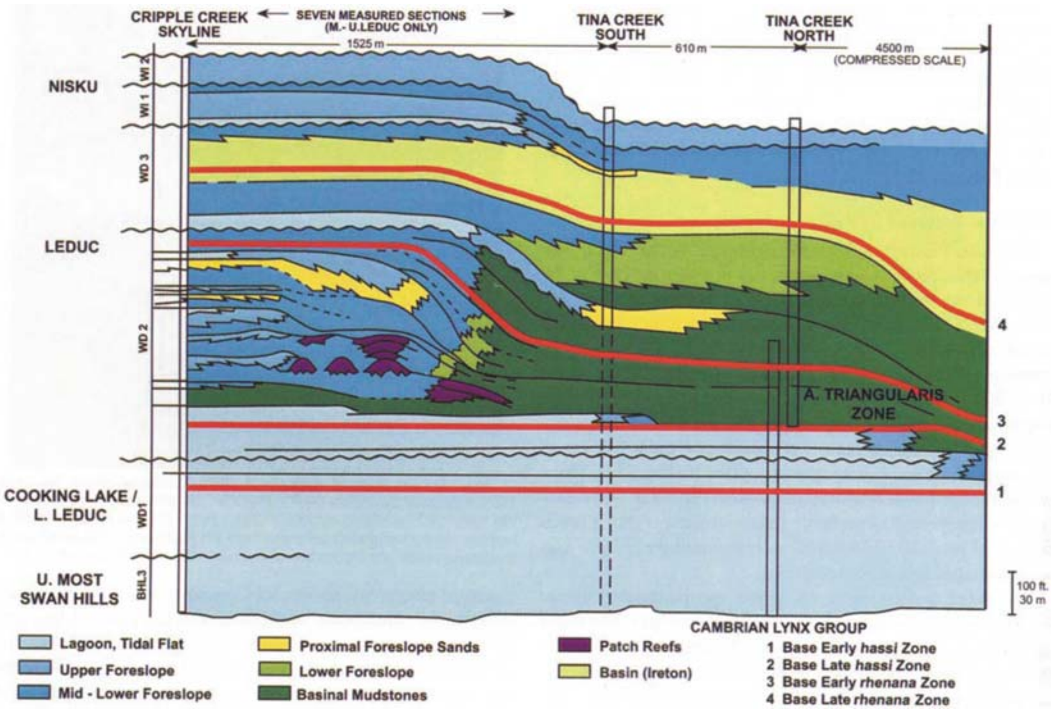

Fig. 6.17 Sequence stratigraphy of the Cripple Creek reef margin, Alberta, constructed from outcrop and subsurface data (Potma et al., 2001, Fig. 13)

are useful as indicators of sequence boundaries. Potma et al. (2001, pp. 81–82) explain reef development as follows:

> The pattern of sedimentation in the reef complexes is similar for each sequence. A drop in sea level initiates the base of the sequence. The reef complex is exposed and, due to the steep sides of the complex, there are few suitable sites for the reestablishment and growth of carbonate producing organisms downslope. Carbonate production on the atoll effectively ceases. Extensive tidal flats, some dissolution and occasional green shale beds, generally mark the surface. We interpret that the shales were sourced from the Canadian Shield to the northeast, and deposited by (fluvial) by-pass channels, through the exposed carbonate platform margins, into the basin. They form concentrations on the reef platforms due to the lack of dilution by carbonate production during depositional hiati. These shales, and cemented micritic tidal flats, typically form impediments to vertical fluid flow in the reefs. Minor dolomitization of the exposed reef complexes can also occur at this time.
>
> Coarse siliciclastic deposition into the basin is also greater during sea level lowstand, due to fluvial by-pass of the basin-fringing carbonate banks. The major sequence boundary at the base of the third Woodbend sequence has lowstand siliciclastics associated with it …. We correlate these quartz sands to time-equivalent exposure surfaces in the Redwater, Leduc and Golden Spike reef complexes.
>
> Above the sequence boundary, as relative sea level begins to rise in the transgressive portion of the sequence, the complex is again flooded, and carbonate production is re-established. Generally, this occurs somewhat landward of the pre-existing edge of the underlying reef complex. Initially, the sediments commonly consist of tidal flat deposits, but display more open marine character as relative sea level rise accelerates. The transgressive systems tract consists of a series of backstepping, well-circulated lagoon to shoal cycles. These units generally have good primary reservoir quality. The retrogradation creates an accretionary high, forming the locus of progradation during the early stages of the highstand systems tract.
>
> During highstand of sea level, aggradation, progradation or retrogradation of the reef can occur. The first cycle of the highstand is commonly characterized by strong progradation that begins at topographic highs on the underlying transgressive systems tract and then expands seaward toward the platform margin of the pre-existing sequence. The lower foreslope lithofacies at its base are thicker, and these downlap onto the maximum flooding surface of the transgressive systems tract. This part of the section may form a significant vertical permeability barrier at the edges of large reef complexes or over the entire base of base of smaller reefs …, and adds to the tight nature of the rocks adjacent to sequence boundaries.

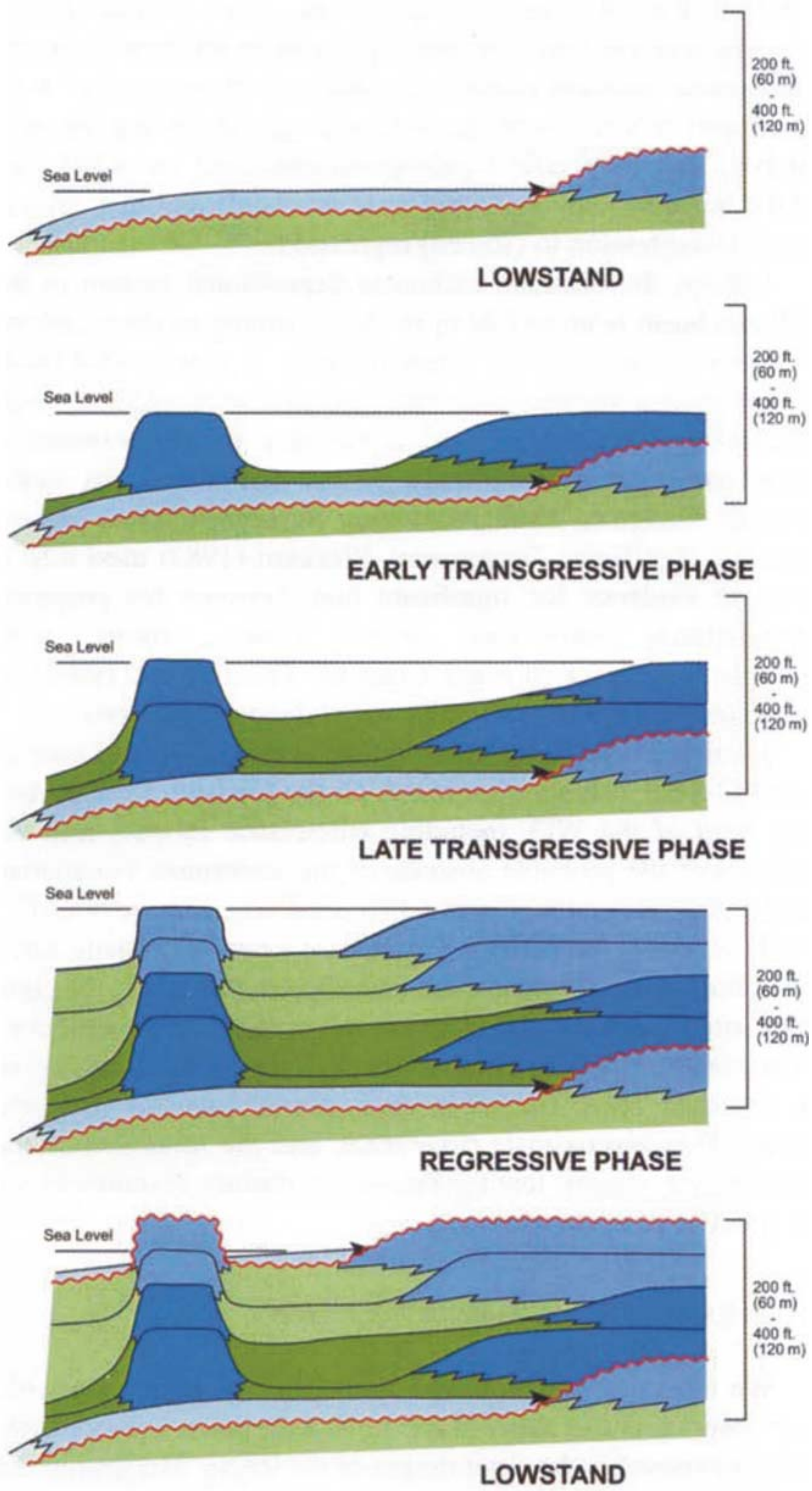

Fig. 6.18 Schematic evolution of reef systems tracts, Devonian, Alberta (Potma et al., 2001, Fig. 30)

6.2 Foreland Basins

6.2.1 Foreland Basin of the North American Western Interior

During the Cretaceous, the Western Interior of the United States and Canada formed a vast epicontinental seaway along a foreland basin extending from the Arctic Ocean to the Gulf Coast. The basin was asymmetric, with more rapid subsidence and sedimentation occurring along the western flank of the basin, adjacent to the fold-thrust belt of the Sevier orogen (Fig. 6.19; DeCelles, 2004; Miall et al., 2008). Up to 5 km of sediments accumulated during the Cretaceous. They constitute a classic "clastic wedge" (Fig. 6.20), as this term was defined by Sloss (1962). Weimer (1960) was the first to recognize that the Upper Cretaceous section constitutes a succession of large-scale transgressive-regressive cycles with 10^6-year episodicities. Figure 6.21 illustrates Weimer's (1986) most recent synthesis of the stratigraphy and age of Cretaceous cycles in the Western Interior Seaway, including some of the key stratigraphic names from the Rocky Mountain and other basins. Major interregional unconformities and their ages in Ma are indicated on this diagram. They do not correlate in any particularly obvious way with the sequence boundaries in the Exxon charts, unless allowance is made for errors of up to 1 or 2 million years, in which case they all correlate. The relationship between transgressive-regressive cycles and tectonism in the foreland basin was discussed by Fouch et al. (1983) and Kauffman (1984), and is considered at some length in Sect. 10.3.3.1.

Major regressive sandstone wedges within the succession include the Ferron, Emery, Blackhawk, Castlegate and Price River sandstones (Fig. 6.20). Details of the lowermost of these wedges are illustrated in Figs. 6.20 and 6.22, based on the work of Ryer (1984) and Shanley and McCabe (1991). In the latter, the sequences constitute alluvial-coastal plain facies successions ranging from 16 to 180 m in thickness. As shown in Fig. 6.23, some of these sandstone wedges are capable of even further subdivision. These high-order cycles are discussed in Chap. 7. Suffice it to note here that the foreland basin clastic wedge illustrated at the increasing scales of Figs. 6.20, 6.22 and 6.23 displays three scales of sequence cyclicity.

Another well studied cycle in the foreland-basin clastic wedge is that of the Gallup Sandstone and associated beds in San Juan Basin, New Mexico (Fig. 6.24; Molenaar, 1983). The Gallup Sandstone is of Coniacian-Turonian age, and represents approximately 1 million years of sedimentation. The sequence stratigraphy of these rocks has been described by

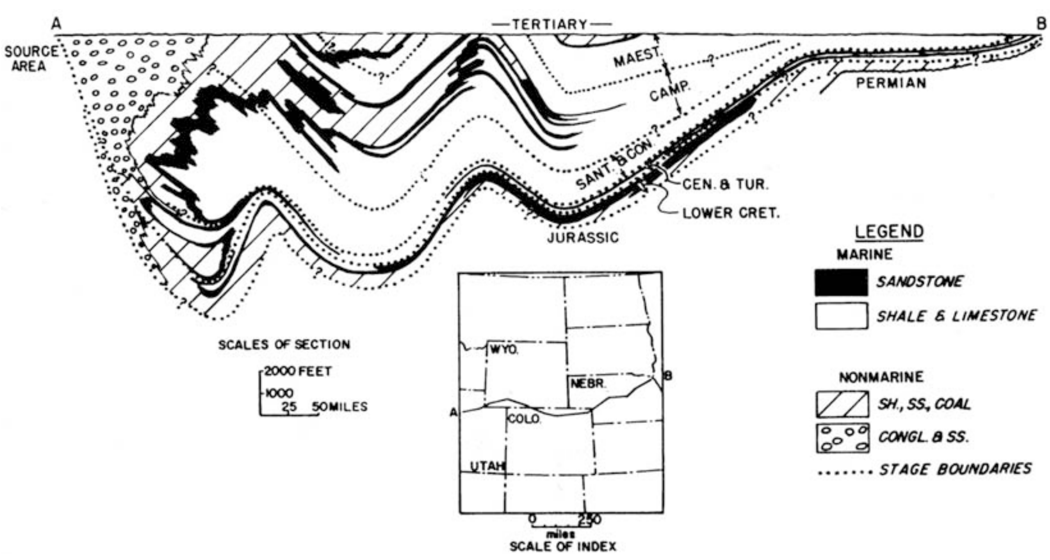

Fig. 6.19 Diagrammatic restored cross-section through the Upper Cretaceous rocks of the Western Interior Seaway, flattened on a datum at the base of the Tertiary (Weimer, 1970)

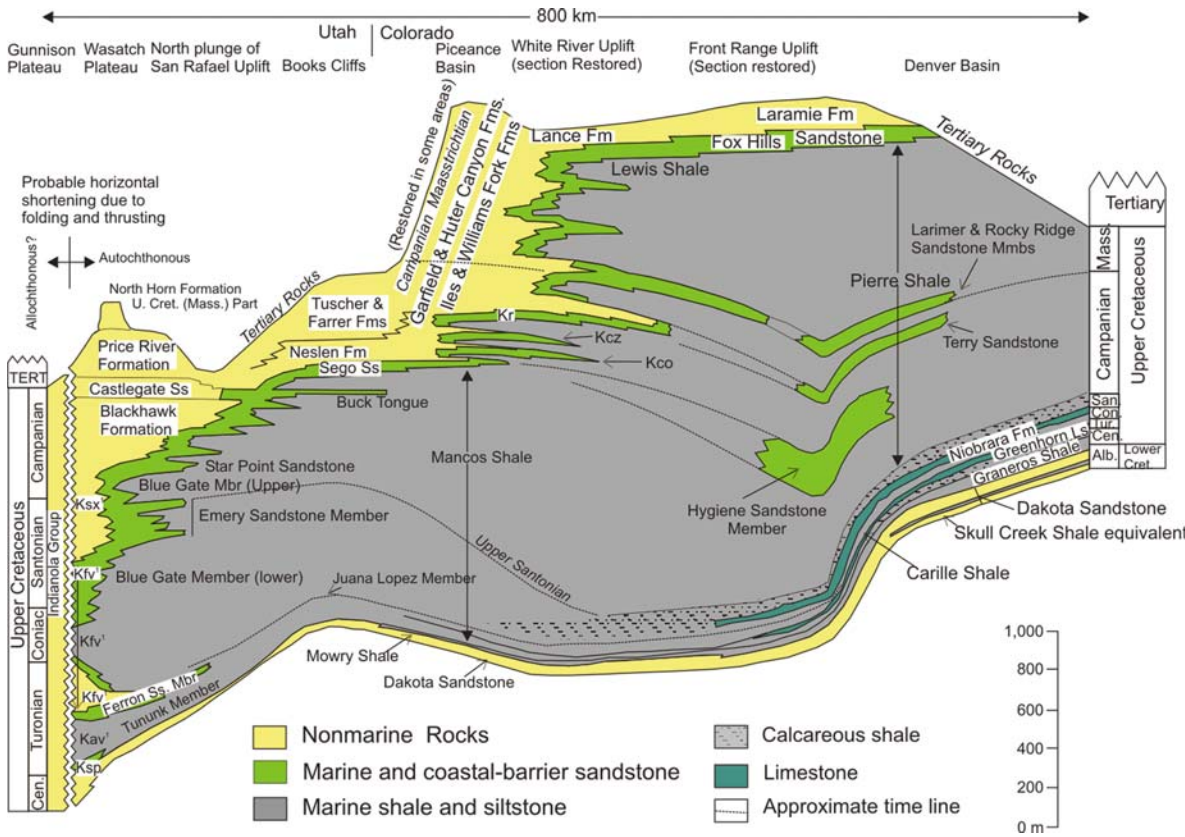

Fig. 6.20 Enlarged portion of Fig. 6.19, showing details of the stratigraphy of the Upper Cretaceous clastic wedge of Utah and Colorado (Molenaar and Rice, 1988)

Nummedal and Swift (1987), Nummedal et al. (1989), Nummedal (1990), and Nummedal and Molenaar (1995). The Gallup Sandstone can be subdivided into component higher-frequency cycles. It includes component members formed in a variety of shelf, coastal, and nonmarine environments.

A more recent study led by D. Nummedal focused on the identification and mapping of "megasequences" in Wyoming that are clearly of tectonic origin (Liu et al., 2005). These sequences are discussed briefly, here and tectonic mechanisms are considered in depth in Sect. 10.3.3.1. Mapping by R. L. Armstrong, P. G. DeCelles, and many others since the 1960s has unraveled a close relationship between episodes of thrust faulting and uplift along the Sevier fold-thrust belt and the development of coarse, source-proximal conglomerates derived directly from those uplifts. Eastward, the conglomerates pass into nonmarine and shallow-marine coastal plain deposits. Commonly the conglomerates are themselves cut and displaced by the faults, which is further evidence of the genetic relationship between tectonism and sedimentation. Figure 6.25 summarizes this relationship, as it has been documented in northeastern Utah and Southern Wyoming, and Fig. 6.26 is a synthesis of the stratigraphy of these sequences. Figure 6.27 is a chronostratigraphic chart which synthesizes the stratigraphy, facies and timing of these sequences in relationship to regional and global events.

The definition of the sequences shown in Figs. 6.26 and 6.27 did not automatically emerge from a synthesis of the regional stratigraphy, but required a search for and a recognition of the key indicators of changing regional accommodation that are now know to characterize sequence generation. This is a good illustration of the "genetic" nature of sequence stratigraphy—application of sequence concepts can greatly facilitate synthesis and interpretation, but only if there are existing concepts and models that are appropriate for the field case under study.

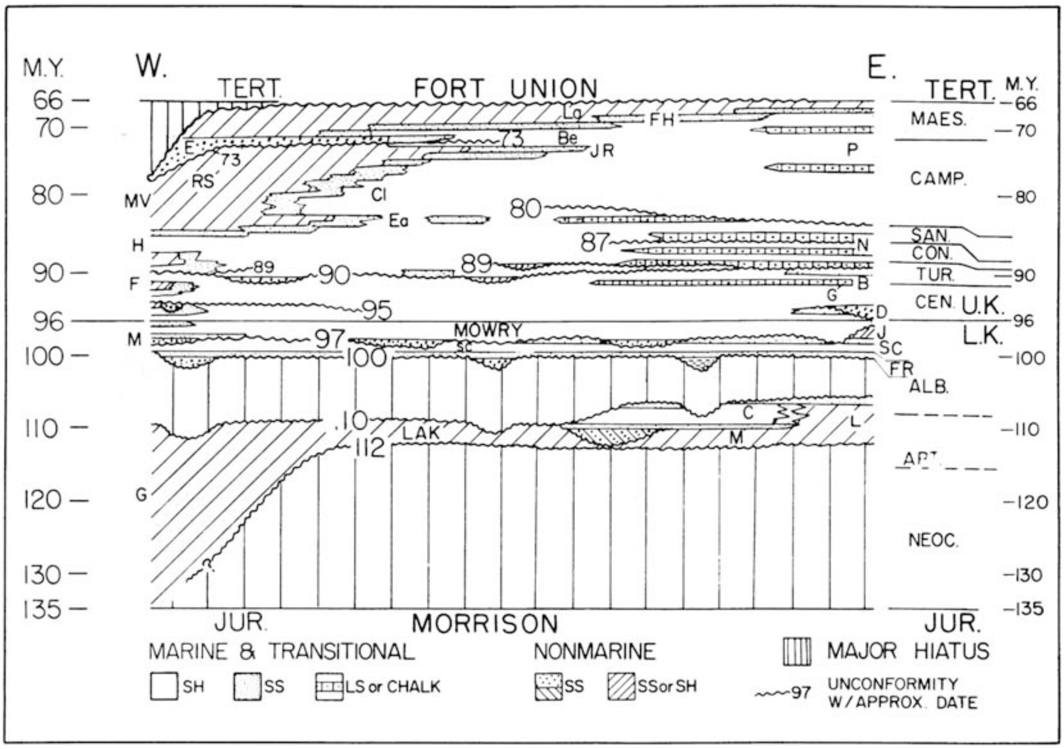

Fig. 6.21 Diagrammatic west–east cross-section through the Western Interior Seaway of the Rocky Mountains, from Wyoming-Montana in the west to eastern Colorado-Black Hills-eastern Alberta in the east, showing stratigraphic positions and approximate dates of major transgressive units and interregional unconformities. Formations or groups to the west are: G, Gannett; SC, Skull Creek; M, Mowry; F, Frontier, H, Hilliard, MV, Mesaverde; RS, Rock Springs; E, Ericson; Ea, Eagle; Cl, Claggett; JR, Judith River; Be, Bearpaw; FH, Fox Hills; La, Lance. To the east formations are L, Lytle; LAK, Lakota; FR, Fall River; SC, Skull Creek, J and D sands of Denver basin; G, Greenhorn; B, Benton; N, Niobrara; P, Pierre; M and C, McMurray and Clearwater of Canada (Weimer, 1986)

This illustrates both the strengths and the pitfalls of the method. In the case under study here, sequence mapping was facilitated by the appropriate choice of datum for the construction of the stratigraphic synthesis (Fig. 6.26). This is not a mundane methodological issue, but may become a key to the elucidation of stratigraphic relationships. The datum, in this case, was placed at the base of the Canyon Creek Member of the Ericson Formation, which clarifies the progradational nature of the units above, and introduces as little distortion as possible to the complex tectonostratigraphic relationships of the units below. The five sequences into which the succession has been divided were recognized in the basis of "an iterative process, in which regional unconformities and/or surfaces across which there was a demonstrable rapid change in subsidence regime were the chosen boundaries" (Liu et al., 2005, p. 493). Correlation of the units westward, through the facies change into the syntectonic conglomerates, was also an important criterion. Using accommodation cycles (such as those summarized in Chap. 2 of this book) as a model for interpretation, lithostratigraphic units that have long been known in this area could be assigned their appropriate position in the succession of systems tracts. Specific marine shales could then be identified as transgressive deposits or representing maximum flooding intervals, upward-coarsening transitions from coastal-plain sandstone to coarse conglomerate could be assigned to highstand systems tracts, and so on.

A sequence subdivision of the mid-Jurassic to Paleocene fill of the Alberta foreland basin is shown in Fig. 6.28. The thick, coarse, predominantly nonmarine clastic wedges, including the Kootenay,

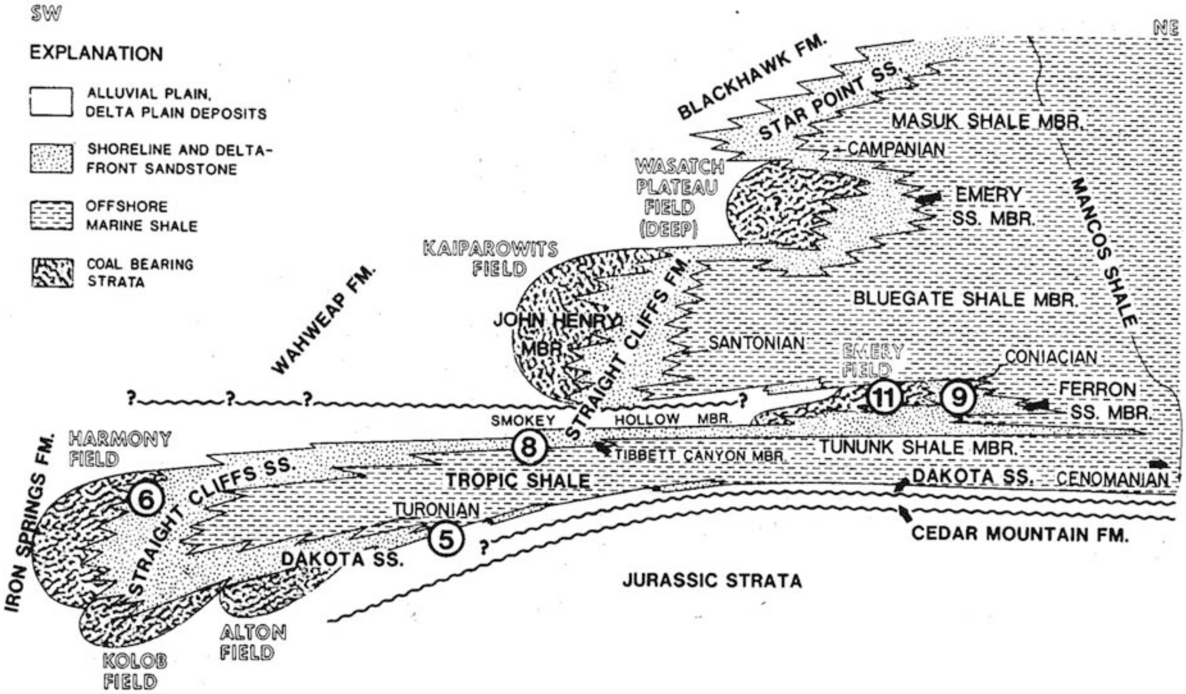

Fig. 6.22 Diagrammatic cross-section through the Ferron Sandstone and equivalent beds, southwestern Utah, showing the major (third-order) clastic cycles (Ryer, 1984)

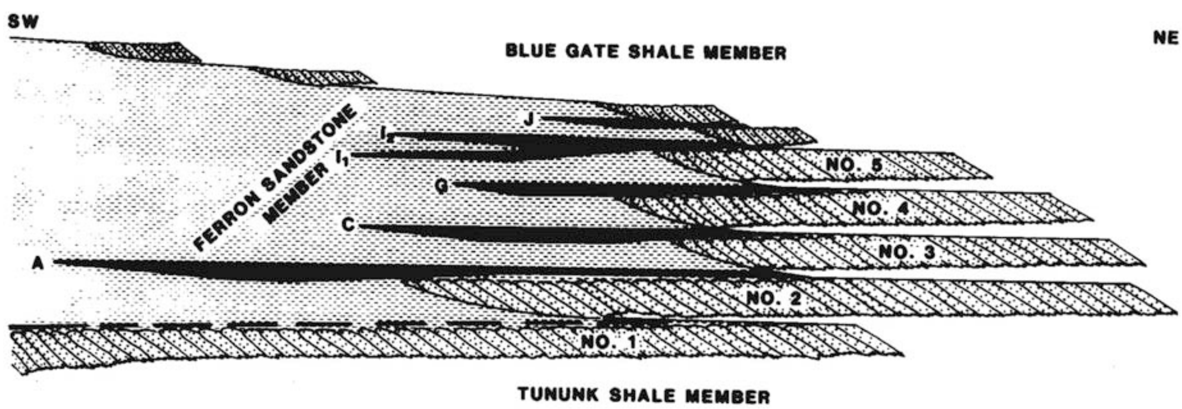

Fig. 6.23 Schematic cross-section of the Ferron Sandstone, central Utah. The stratigraphic position of these beds within the foreland-basin clastic wedge is shown in Fig. 6.22 (Ryer, 1984)

Mannville, Belly River-Edmonton and Paskapoo, each span several million years and would be classified as second- or third-order sequences using the Vail et al. (1977) classification. The relationship of these sequences to the orogenic development of the Cordillera is discussed in Chap. 10. The Mannville represents much of the Aptian and Albian stages, totaling 12–14 million years, which places it within the second-order classification of Vail et al. (1977). Note, however, that in Fig. 6.28 the Miannville is classified as one of several third-order sequences, and can be subdivided into a suite of constituent fourth-order sequences, additional details of which are shown in Fig. 6.29. Once again the "order" classification does not seem to provide much in the way of useful insights into the origins of these sequences, especially given

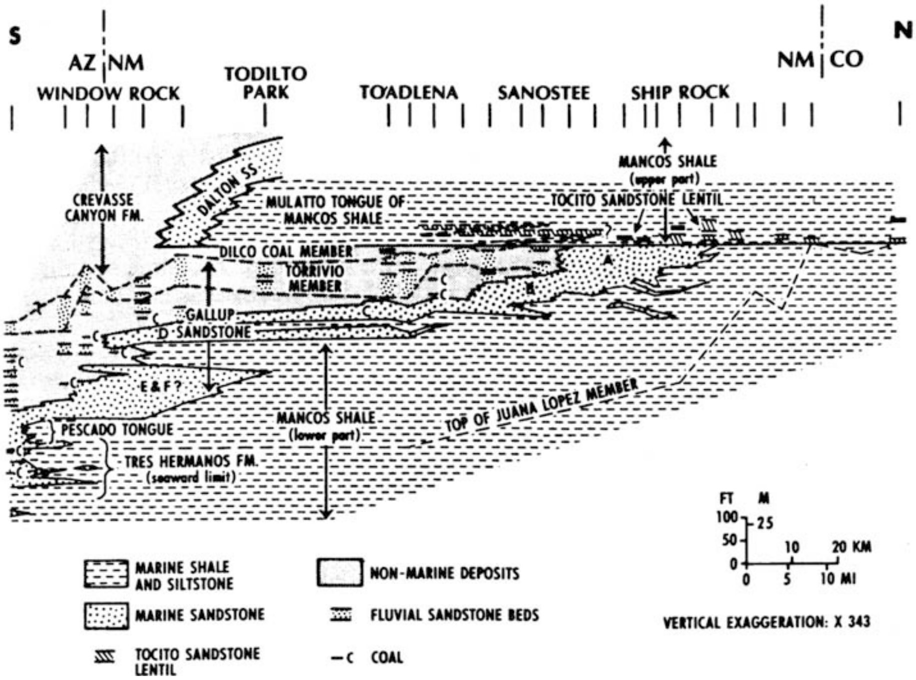

Fig. 6.24 Summary of the sequence stratigraphy of the Gallup Sandstone and associated strata, San Juan Basin, New Mexico (Nummedal, 1990)

that, as shown in Fig. 6.28, some of the unconformities between the sequences may represent longer time spans than the sequences, and therefore fall into a higher order in the classification!

The Mannville can be subdivided into a lower suite of nonmarine to estuarine units, commencing with the Cadomin Conglomerate (Fig. 6.29). This is a thin but very widespread unit, with equivalents such as the Burro Canyon, Cloverly and Lakota in the United States, indicating aggradation of a lowstand deposit following a long and widespread regional unconformity (Heller and Paola, 1989) This lower suite of units constitutes the lowstand to transgressive systems tracts of the overall Mannville sequence. The Falher and Notikewin formations constitute the highstand systems tract of the Mannville sequence. Nonmarine coastal-plain deposits of the Upper Mannville pass northwestward, in northwestern Alberta and northeastern British Columbia, into a coastal zone where marine-to-nonmarine facies transitions permit a subdivision into a suite of high-frequency sequences constituting the Falher Formation. Prograding shoreface sandstones and conglomerates are capped by flooding surfaces in a landward (SE) direction, and downlap northwestward onto the maximum flooding surface of the Mannville sequence. We discuss these high-frequency sequences in Chap. 7.

6.2.2 Other Foreland Basins

The Alpine foreland basins of western Europe have been intensively studied in recent years, aided by reflection-seismic data, magnetostratigraphic and refined biostratigraphic correlation, structural mapping and modern sedimentological methods (Mascle et al., 1998). A great deal has been learned from this work about the relationship between sedimentation and tectonics. We touch here briefly on one of these recent studies, that of the early-middle Eocene (Ypresian-Lutetian) succession in the Tremp-Ager sub-basin in the southern Pyrenees (Nijman, 1998). This is classified as a piggyback basin, but it correspond to the deepest and widest part of the Ebro foreland basin on the southern flank of the Pyrenean fold-thrust belt. The basin fill rests on, is cut by, and is overlain by thrust faults.

A paleogeographic block diagram of the basin is shown in Fig. 6.30. It shows that the basin filled longitudinally, from east to west, with sediment

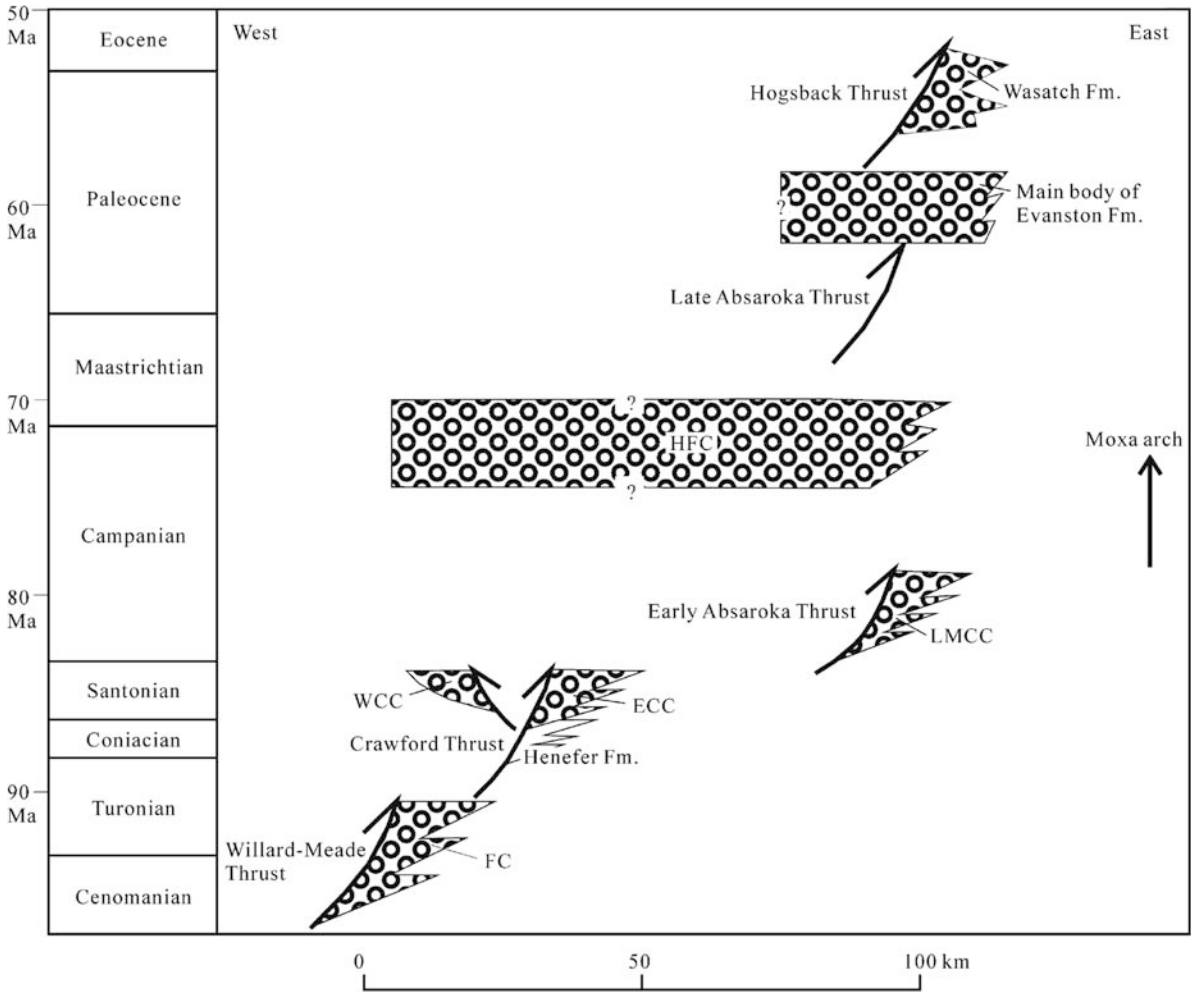

Fig. 6.25 The time-space relationship between thrust fault episodes and synorogenic conglomerate deposition in northeastern Utah and southern Wyoming. HFC, Hams Fork Conglomerate; LMCC, LittleMuddy Creek Conglomerate; WCC, Weber Canyon Conglomerate; ECC, Echo Canyon Conglomerate; FC, Frontier Conglomerate (Liu et al., 2005, Fig. 3)

derived in part from the northeast, and in part from the southeast. Deposition was in part contemporaneous with and in part modulated by tectonism, the nature of which is discussed further in Sect. 10.3.3.3. Environments varied down dip from alluvial fan to alluvial plain, to deltaic, to submarine fan in the west.

Cyclicity in the basin fill is present at three nested scales, two of which are shown in Fig. 6.31. Three "megasequences," UM-C, UM-D and UM-E, represent major cycles in the Upper Montanya Group and range up to 200 m in thickness. These may be divided into "sequences." Megasequence UM-D is divisible into six such sequences (Fig. 6.31). These range from 20 to 40 m in thickness and are compared by Nijman (1998, p. 141) to parasequences. He noted that the fluvial Castisent Sandstone, a lateral equivalent of the deltaic Middle Montanya (Fig. 6.32), contains a high-order cyclicity. The various subenvironments exhibited by these deposits are indicated by the colours in Fig. 6.31. This is also summarized in Fig. 6.32, which provides a chronostratigraphic classification of the sequences, based on marine micropaleontology. This shows that during the 11.5 million-year time span of the Ypresian-Lutetian, nine megasequences developed, indicating that they average 1.3 million years in duration. Nijman (1998) noted that

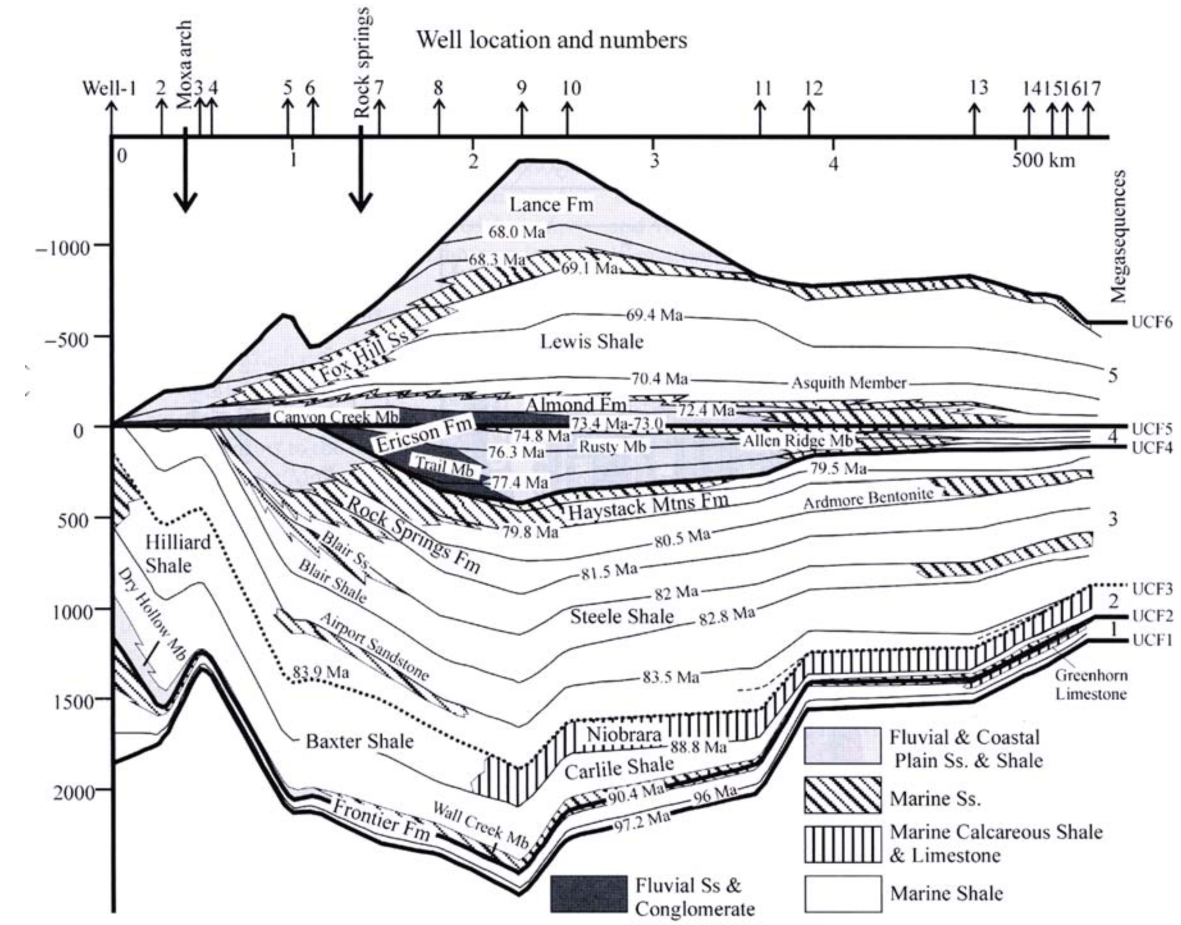

Fig. 6.26 The stratigraphy of Upper Cretaceous (mid-Cenomanian-Maastrichtian) "megasequences" in southern Wyoming. UCF=unconformity (Liu et al., 2005, Fig. 4)

there is no correspondence between thicknesses, age ranges and rates of sedimentation calculated for each of the megasequences, which suggests a non-regular generating mechanism. He also noted a general correspondence of some of the ages of the megasequence boundaries with sea-level events in the Haq et al. (1987) sea level curve (Fig. 6.32). It is a curious feature of some research literature, to which we return in Sect. 10.3.3.3, that basins which are clearly filled under the influence of active syndepositional tectonism, are nonetheless simultaneously interpreted with reference to the global cycle chart, as though sequence boundaries can be generated simultaneously by global sea-level change and regional tectonism.

Analysis of the Appalachian foreland basin (Ettensohn, 1994, 2008) has demonstrated the existence of stratigraphic packages very similar to those of the Alberta foreland basin and the Pyrenean basin. Figure 6.33 illustrates the "tectophases" of Devonian and early Mississippian age. These four phases span about 66 million years and therefore average 16.5 million years in duration. They contain within them constituent cycles that exhibit similar facies successions. Each cycle commences with a carbonate or calcareous sandstone unit resting on an unconformity. This passes up into a black shale which, in most cases, onlaps the carbonate to rest on a major pre-Devonian unconformity. The shale then passes up into a thick clastic succession of sandstones and shales that together constitute the well-known Catskill "delta." The five cycles that constitute the third tectophase in Fig. 6.33 span the mid-Givetian to late Famennian, and therefore average about 5.5 million years in duration.

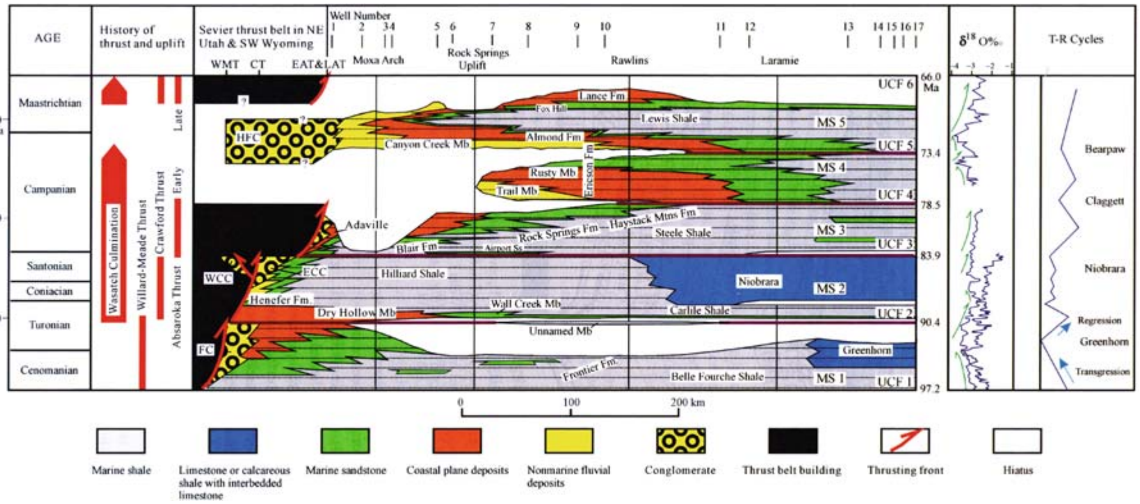

Fig. 6.27 Correlation chart for the Upper Cretaceous "megasequences" of southern Wyoming, showing facies variations, relationship to thrusting episodes and, at *right*, the oxygen isotope curve from Abreu et al. (1998) and the T-R cycles of Kauffman (1984). WMT, Willard-Meade thrust; CT, Crawford thrust; EAT, Early Absaroka thrust; LAT, Late Absaroka thrust. MS = megasequence, UCF = unconformity (Liu et al., 2005, Fig. 5)

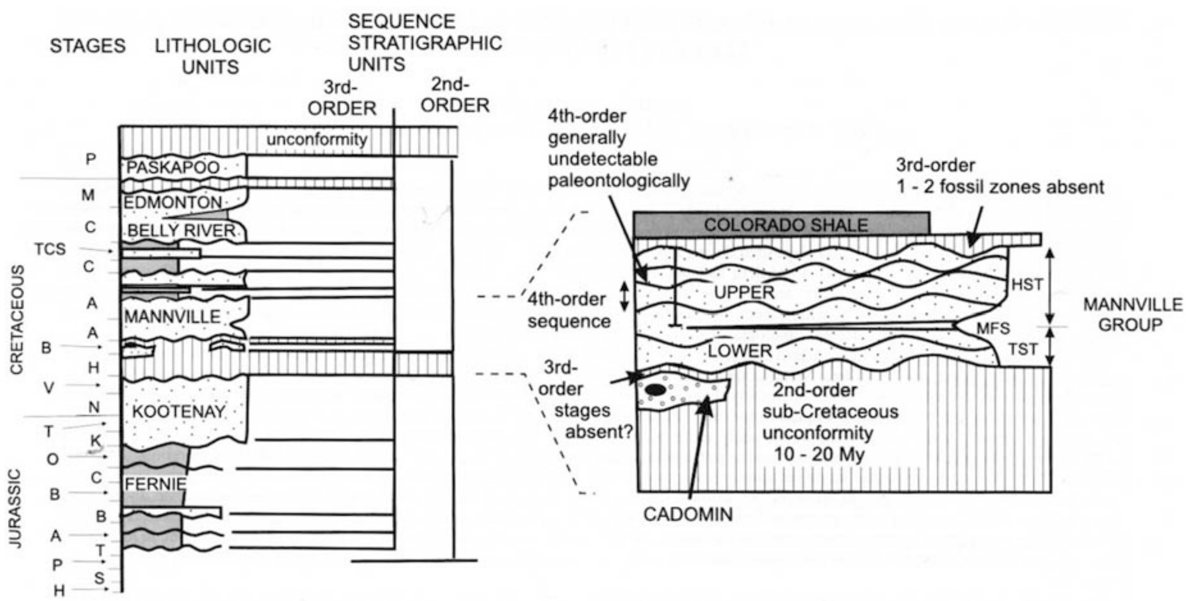

Fig. 6.28 A sequence subdivision and classification of the clastic wedges of the Alberta Basin (Cant, 1998, Fig. 1)

6.3 Arc-Related Basins

6.3.1 Forearc Basins

Forearc and backarc basins occur within convergent continental margins, so-called "active margins", a term which emphasizes the importance of tectonism in controlling stratigraphic architectures. Several recent studies of arc-related basins have examined the basin fills from the perspective of sequence stratigraphy, and in many cases major differences with the stratigraphic styles of extensional and rifted margins, and even with foreland basins, have become apparent. There is little

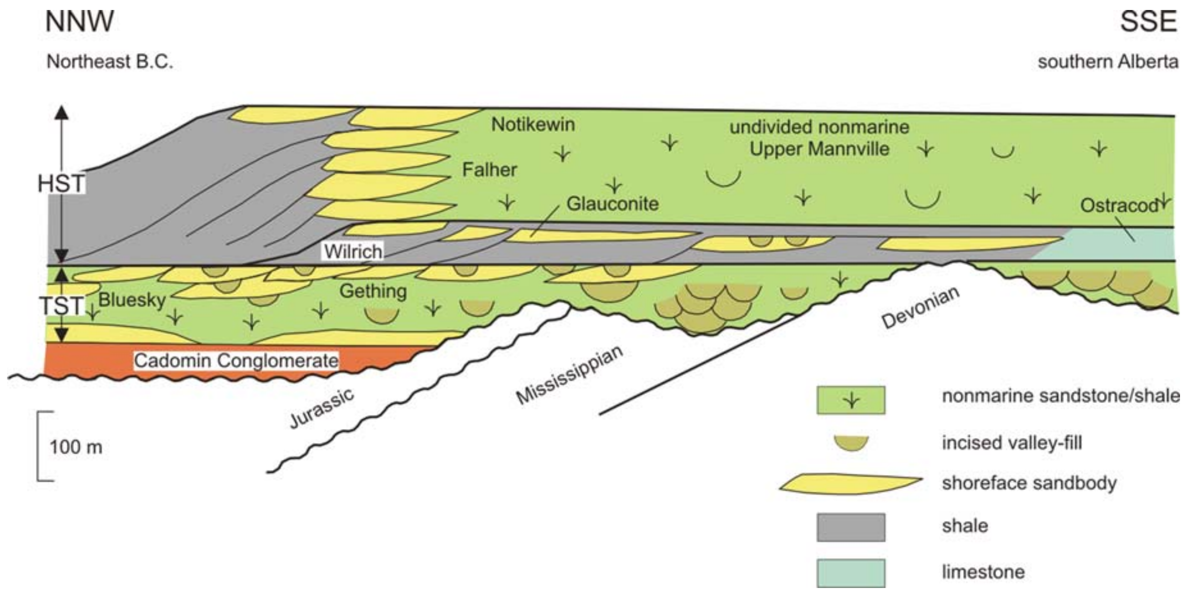

Fig. 6.29 Composite, simplified cross-section of the Mannville Group of Alberta, oriented along the axis of the basin, The group represents a single large-scale sequence, spanning 12–14 million years, which can be subdivided into a suite of higher-order sequences, each of which is marked by a regressive shoreline sandbody and an onlap surface (adapted from Cant, 1996)

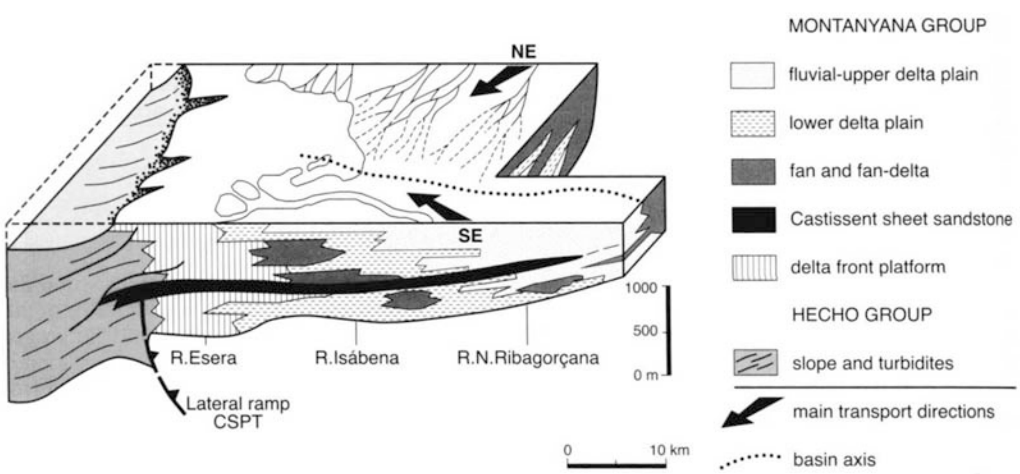

Fig. 6.30 Block diagram of the Tremp-Ager basin, northern Spain, during the Eocene. The front panel of the diagram is oriented west–east, showing that the axis of the basin runs approximately ESE-WNW, and is filled, in part, by progradation in that direction. The source of alluvial detritus from the north-east is from the Pyrenean uplift, that from the southeast, from the Iberian hinterland (Nijman, 1998, Fig. 5)

clear evidence for the existence of cycles caused by 10^6-year eustatic sea-level cycles. This contrasts with the record of $10^{4–5}$-year cyclicity, including that of glacioeustatic origin which is locally prominent in arc-related basins and has been mapped and documented in detail, for example, within the Japanese islands (Figs. 7.21 and 7.22), and North Island New Zealand (Fig. 4.11).

Several studies of arc-related basins have been carried out in Nicaragua and Costa Rica (Seyfried et al., 1991; Schmidt and Seyfried, 1991; Kolb and Schmidt, 1991; Winsemann and Seyfried, 1991). In general,

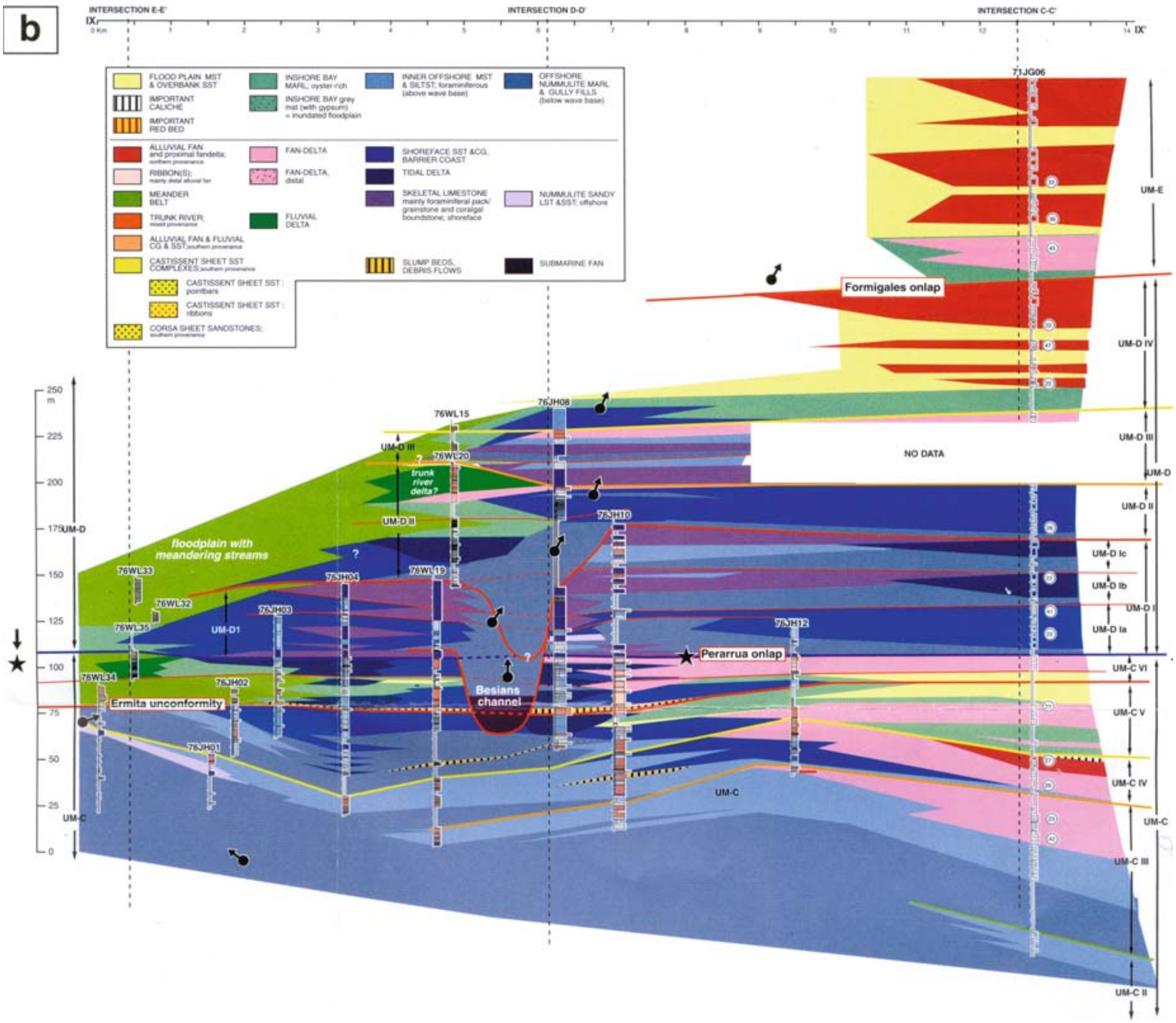

Fig. 6.31 South–north stratigraphic reconstruction across the Tremp-Ager basin, northern Spain, showing the various depositional environments, contact relationships and, at *right*, the subdivision of the succession into sequences and megasequences. The *arrows* attached to *small black circles* shown the gradual shift in the position of the basin axis, as a result of the changing balance in sediment supply from the north and the south (Nijman, 1998, Fig. 4b)

they demonstrate the importance of convergent tectonism as a dominant control in the development of stratigraphic architecture. An example of a sequence-stratigraphic framework of Miocene age in a fore-arc basin in Nicaragua was provided by Kolb and Schmidt (1991; Fig. 6.34). Fan deltas developed during episodes of sea-level fall, as pyroclastic and alluvial deposits spread across an exposed shelf. Coastlines retrogressed far inland during periods of sea-level rise. Correlations of these and other sections in Central America with the Exxon global cycle chart seem forced and unconvincing. Biostratigraphic evidence for the correlations is extremely limited. In most cases, it is evident that folding, faulting, tilting and tectonic uplift and subsidence are the major sedimentary controls (Seyfried et al., 1991; Schmidt and Seyfried, 1991). Seyfried et al. (1991) documented the presence of regional angular unconformities that can be mapped for distances of 900 km, as discussed in Sect. 5.3.2 (Fig. 5.22).

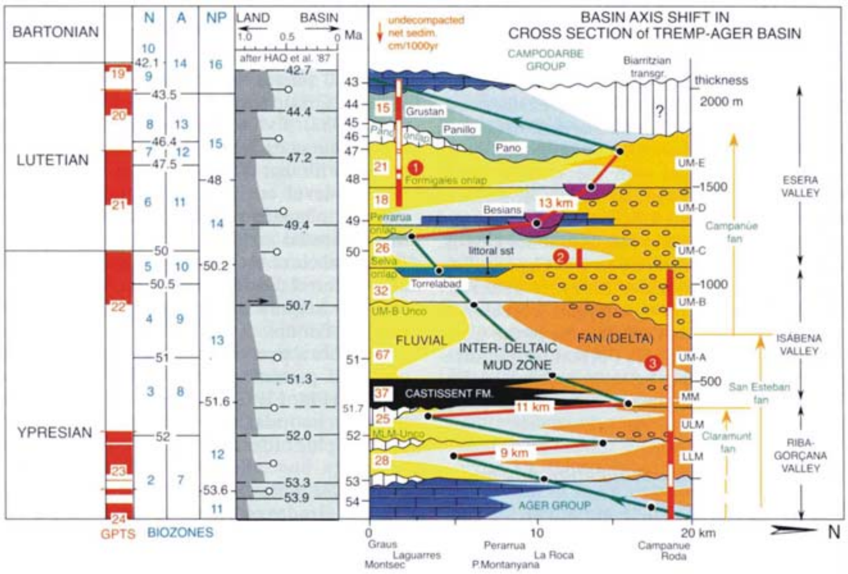

Fig. 6.32 Composite chronostratigraphic cross-section through the Montanyana Group in the Tremp-Ager basin, showing the biostratigraphic zonation and interpreted ages of the sequences. The development of this basin, including the shift in the basin axis (shown here) is discussed in Sect. 10.3.3.3. (Nijman, 1998, Fig. 13)

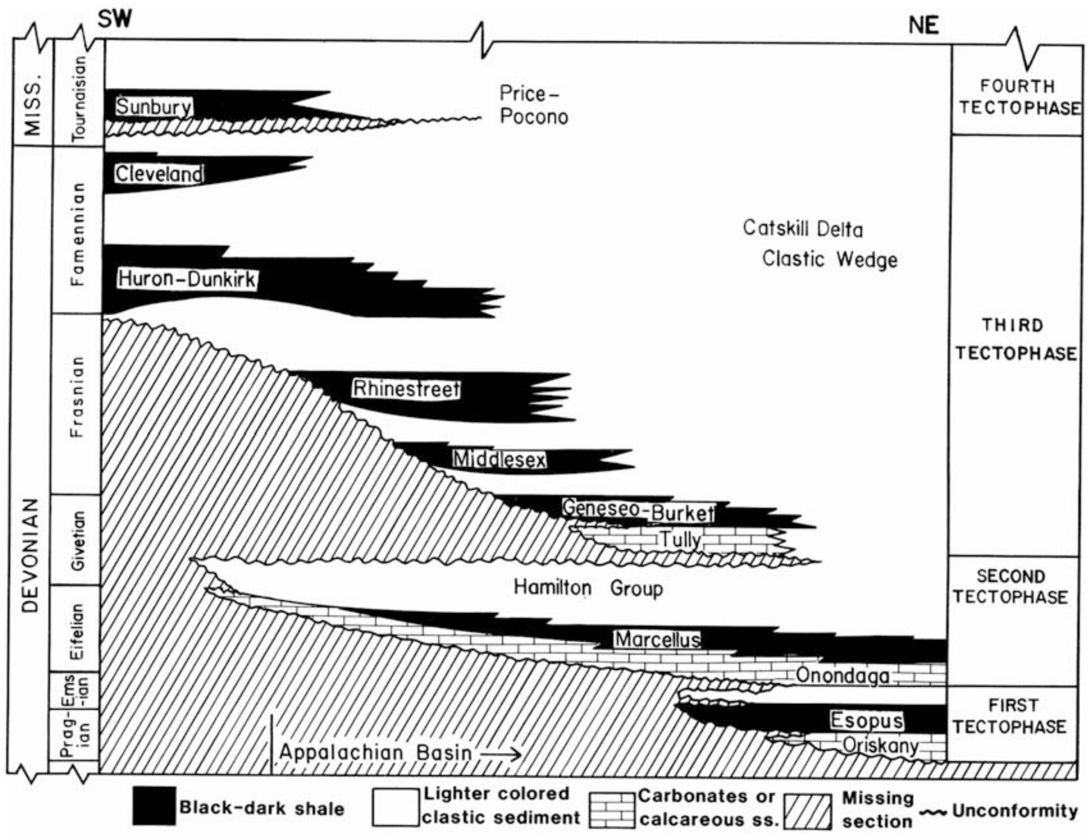

Fig. 6.33 Composite stratigraphic section from east-central New York to north-central Ohio, across part of the Appalachian foreland basin, showing how the Devonian stratigraphic succession may be subdivided into "tectophases" and cycles (Ettensohn, 1994, Fig. 13)

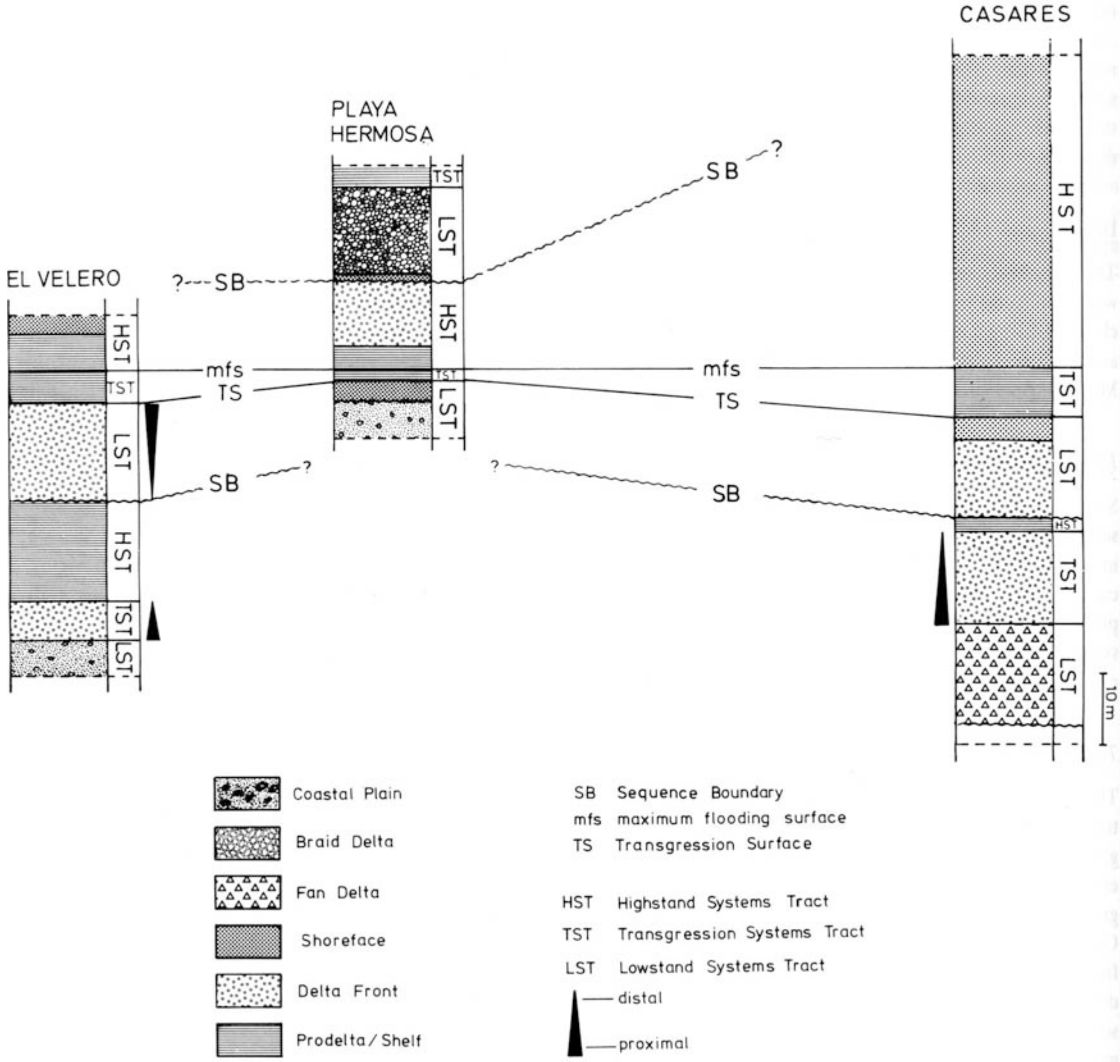

Fig. 6.34 Sequence framework, Miocene beds of southwestern Nicaragua (Kolb and Schmidt, 1991)

In some cases, volcanic control of the sediment supply is the critical factor. Thus Winsemann and Seyfreid (1991, pp. 286–287) stated

> The formation of depositional sequences in the deep-water sediments of southern Central America is strongly related to the morphotectonic evolution of the island-arc system. Each depositional sequence reflects the complex interaction between global sea-level fluctuations, sediment supply, and tectonic activity. Sediment supply and tectonic activity overprinted the eustatic effects and enhanced or lessened them. If large supplies of clastics or uplift overcame the eustatic effects, deep marine sands were also deposited during highstand of sea level, whereas under conditions of low sediment input, thin-bedded turbidites were deposited even during lowstands of sea level.

These tectonic and sediment-supply considerations are of paramount local importance, as discussed in Chap. 10.

A Jurassic-Cretaceous forearc basin succession in the Antarctic Peninsula is dominated by major facies changes at intervals of several millions of years, suggesting a control by "third-order" tectonism (Butterworth, 1991). One major, basin-wide stratigraphic event, an abrupt shallowing, followed by a transgression, gave rise to a unit named the Jupiter Glacier Member (JGM in Fig. 6.35), consisting of deepening-upward shelf deposits. Butterworth (1991) suggested correlation with a major eustatic low near the Berriasian-Valanginian boundary indicated on the

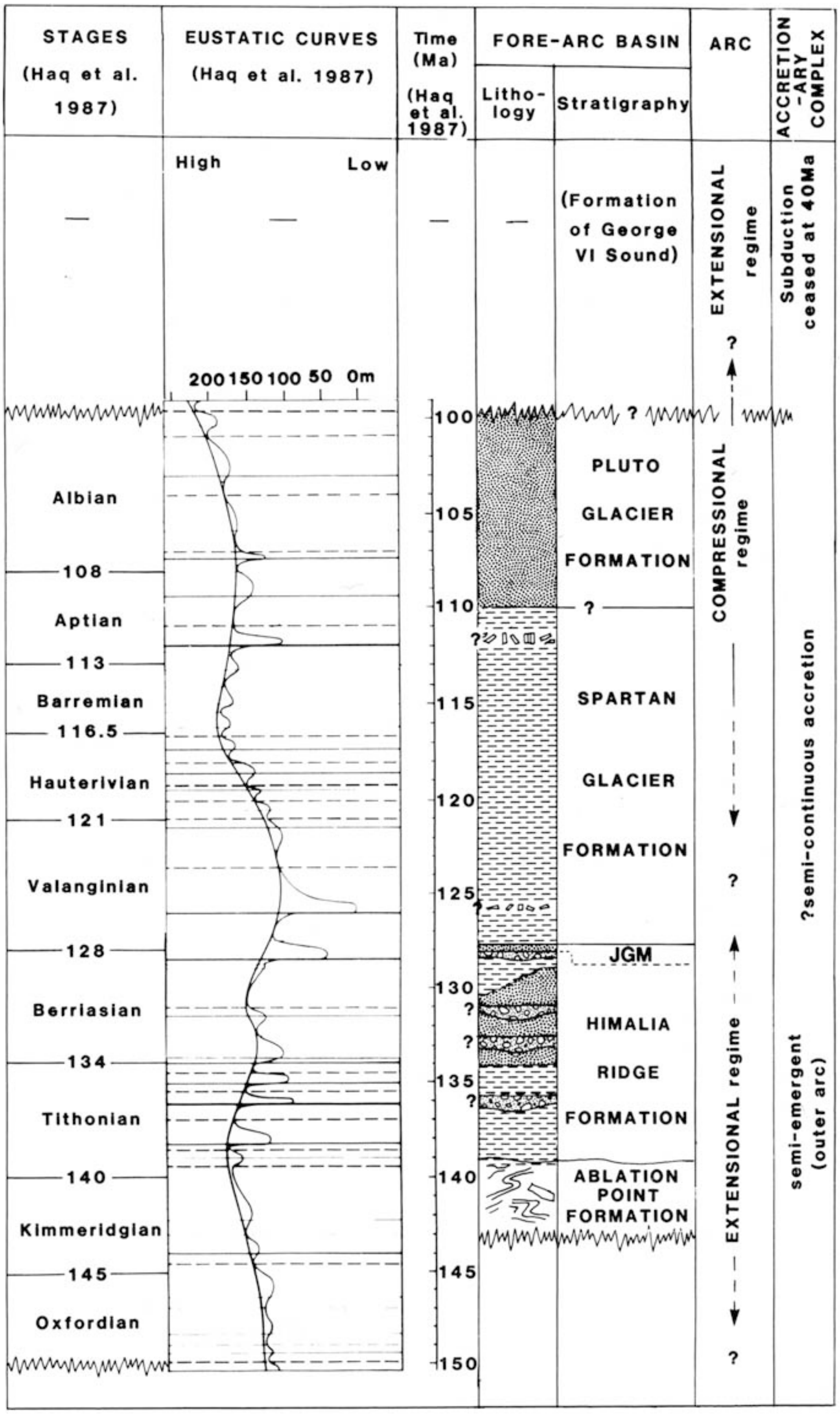

Fig. 6.35 Stratigraphy of the southern Antarctic Peninsula, compared to the Exxon global cycle chart (Haq et al., 1987, 1988a). One stratigraphic event, a shallowing that gave rise to the Jupiter Glacier Member (JGM), may correlate with the Berriasian-Valanginian eustatic low on the cycle chart (Butterworth, 1991)

Exxon chart (Fig. 6.35). However, this seems somewhat fortuitous. It is the only such correlation that can be proposed for this basin. Butterworth (1991) discussed the possibility of tectonic control of this particular event and suggested (p. 327): “It is unlikely that many eustatically-controlled sea-level fluctuations will be recognized from forearc basins, unless it is possible to demonstrate that there were prolonged periods of tectonic quiescence.”

A stratigraphic synthesis of the Cenozoic deposits of Cyprus by Robertson et al. (1991) also resulted in tentative (and rather tenuous) correlations of some stratigraphic events with the Exxon global cycle chart (Fig. 6.36). The evidence indicates that subduction and strike-slip deformation had a dominant effect on sedimentation patterns in this area. During the late Miocene (Messinian) plate-tectonic events led to the isolation and desiccation of the entire Mediterranean basin, an event that is clearly recorded in Cyprus (Fig. 6.36), at a time when global sea levels underwent several fluctuations, according to Haq et al. (1987, 1988a).

6.3.2 Backarc Basins

The tectonic evolution of backarc basins may be similar to that of extensional margins, especially along the interior, cratonic flanks of the basin. Legarreta and Uliana (1991) found that the Neuquén Basin, a backarc basin flanking the Andes in Argentina, underwent an “exponential thermo-mechanical subsidence” pattern, following an early Mesozoic thermal event. Sediment-supply conditions along the cratonic flank of a backarc basin are also likely to be comparable to those of extensional margins. For this reason these basins may show stratigraphic patterns comparable to those on Atlantic-type margins, including the presence of major carbonate suites (Sect. 6.1.2), relatively mature clastics, and a sequence architecture containing evidence of cyclicity with 10^6–10^7-year episodicities. Two studies of Andean basins confirm that this is the case. Legarreta and Uliana (1991) described a sequence stratigraphy that they correlated directly with the Exxon chart, while Hallam (1991), summarizing his own work plus that of various South American geologists, developed his own regional sea-level curve that contains transgressive-regressive cycles with 10^6–10^7-year frequencies.

6.4 Cyclothems and Mesothems

A unique type of high-frequency cyclicity characterizes the Carboniferous and Lower Permian strata of much of the American midcontinent, northwest Europe and the Russian platform (Ross and Ross, 1988; Heckel, 1990, 1994). As discussed in Chap. 11 there is general agreement that these cycles are glacioeustatic in origin. The Carboniferous-Early Permian corresponds to the time when major continental ice caps were forming and retreating throughout the great southern Gondwana supercontinent (Caputo and Crowell, 1985; Veevers and Powell, 1987; Eyles, 1993, 2008), while the areas where cyclothems and mesothems occur lay close to the late Paleozoic paleoequator. The term *cyclothem* was proposed by Wanless and Weller (1932) following their study of these cycles in the Upper Paleozoic rocks of the American midcontinent. They exhibit a periodicity in the 10^4–10^5-year time band. The term cyclothem, and the cycles to which it applies, are discussed in Chap. 11.

Ramsbottom (1979) noted that unusually extensive transgressive and regressive beds forming the sequence boundaries between some of the cyclothems enable groups of about four or five of them to be combined into larger cycles showing a 10^6-year periodicity, and he proposed the term *mesothem* for these. Moore (1936) and Wagner (1964) termed groups of cyclothems *megacyclothems*, but Heckel (1986) showed that these are higher-order cycles than the mesothems discussed here. Holdsworth and Collinson (1988) used the term *major cycle* for Ramsbottom’s mesothems. They compare in duration to the “third-order” cycles of Haq et al. (1987, 1988a). Ramsbottom (1979) identified nearly forty such cycles in the Carboniferous of northwest Europe, and showed that their average duration ranged from 1.1 million years in the Namurian to 3.6 million years in the Dinantian. A chronostratigraphic chart of these cycles as they occur in Britain is shown in Fig. 6.37, and a more detailed Wheeler diagram, showing the main lithostratigraphic components of the Namurian mesothems of part of northern England, is given in Fig. 6.38.

In the Namurian, each mesothem consists of a muddy sequence at the base containing several cyclothems, followed by one or more sandy cyclothems. The lower, muddy parts of the mesothems

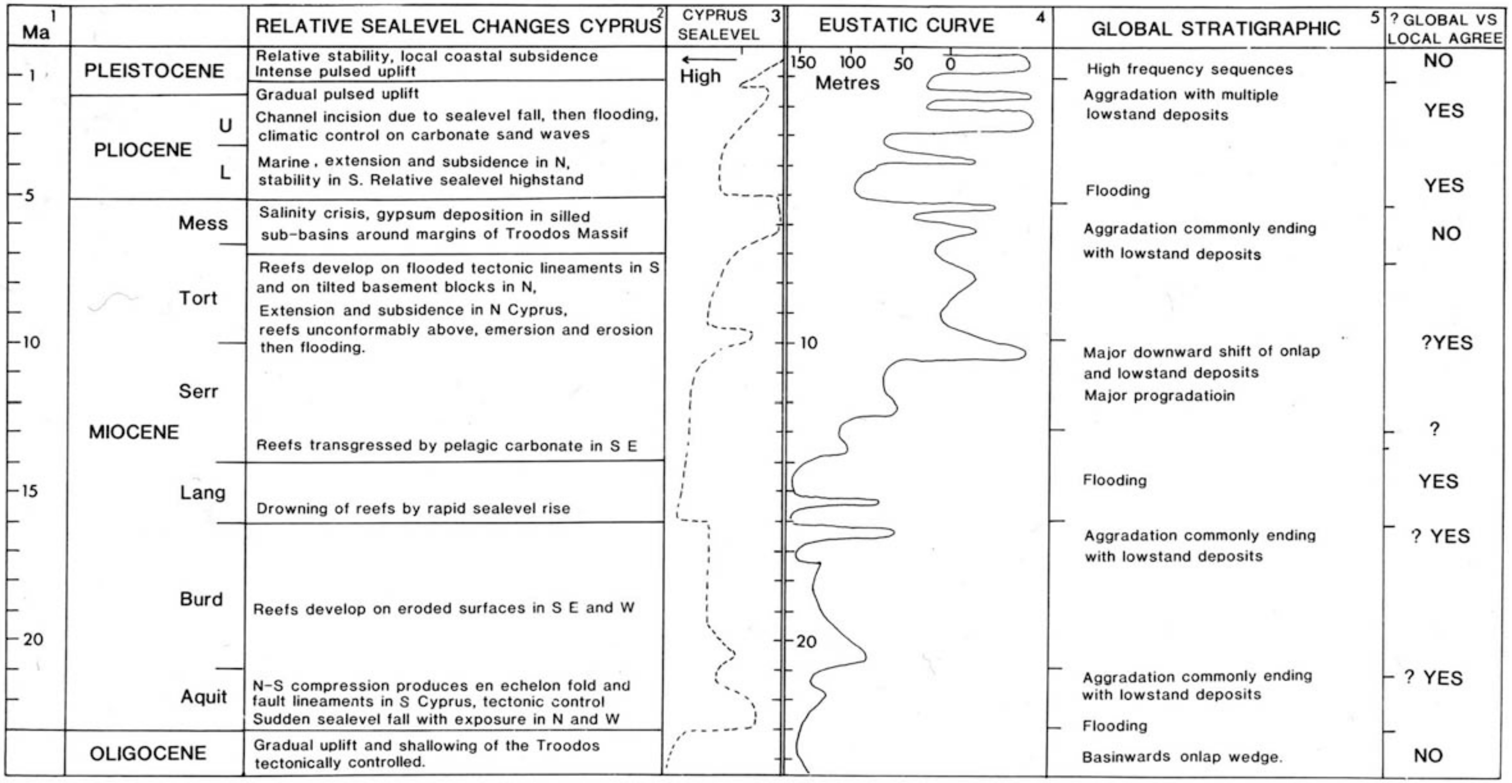

Fig. 6.36 Summary of stratigraphic events in Cyprus, with an interpreted sea-level curve. This is compared to the Exxon global cycle chart (Haq et al., 1987, 1988a). From Robertson et al. (1991)

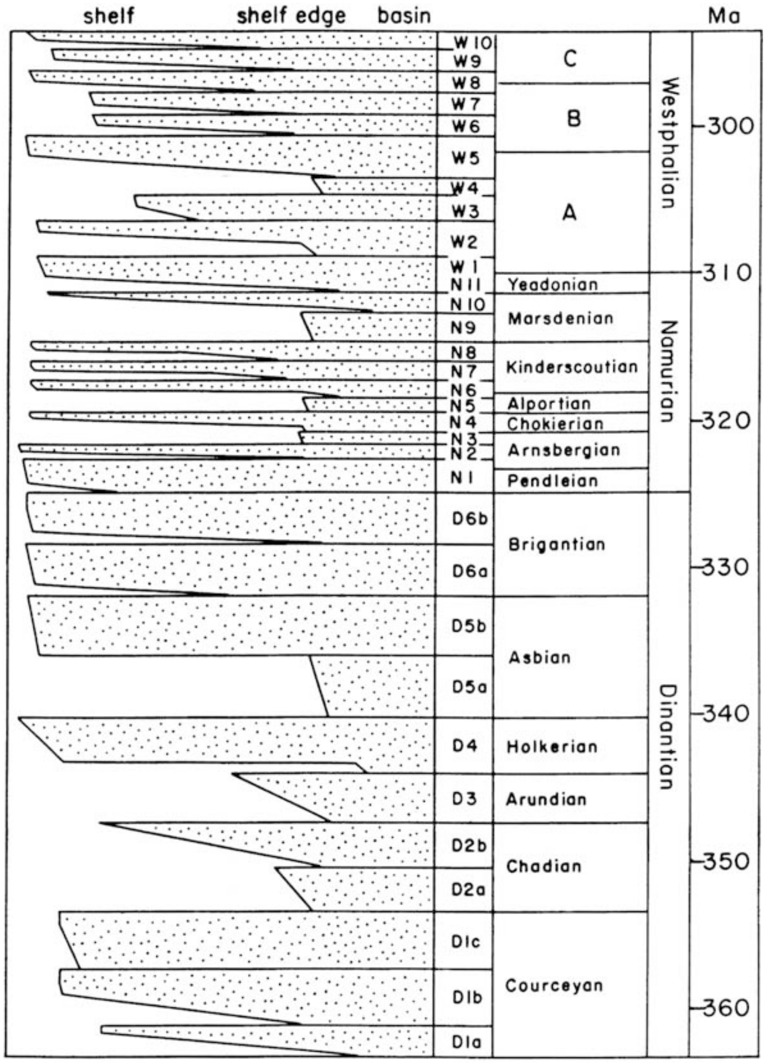

Fig. 6.37 Mesothems in the Carboniferous succession of northern England (Ramsbottom, 1979)

are broadly transgressive, although the transgressions were slow and pulsed. The original concept of Ramsbottom (1979) was that each cyclothemic transgression reaching further than its predecessor out from the basin on to the shelf., although there has been considerable discussion about the validity of this concept, based on detailed stratigraphic documentation (e.g., Holdsworth and Collinson, 1988). Basal beds in each cycle may contain evidence of high salinities, reflecting the isolation of individual small basins at times of low sea level. Marine beds containing distinctive goniatite faunas are supposedly more extensive at the transgressive base of mesothems than in the component cyclothems, indicating more pronounced (higher amplitude) eustatic rises corresponding to the mesothemic cyclicity. The regression at the end of each mesothem appears to have occurred rapidly. The sandy phase commonly commenced with turbidites and is followed by thick deltaic sandstones (commonly called Grits in the British Namurian; see Fig. 6.38). The cycles may be capped by coal. On the shelf each mesothem is bounded by a disconformity (Fig. 6.38), but sedimentation probably was continuous in the basins. Deltaic progradation was rapid, approaching the growth rate of the modern Mississippi delta.

Ramsbottom (1979) noted that the Namurian mesothems were of the shortest duration, and many do not extend up onto the shelf. This stage spans the Mississippian-Pennsylvanian boundary, which is designated as the boundary between the Kaskaskia and

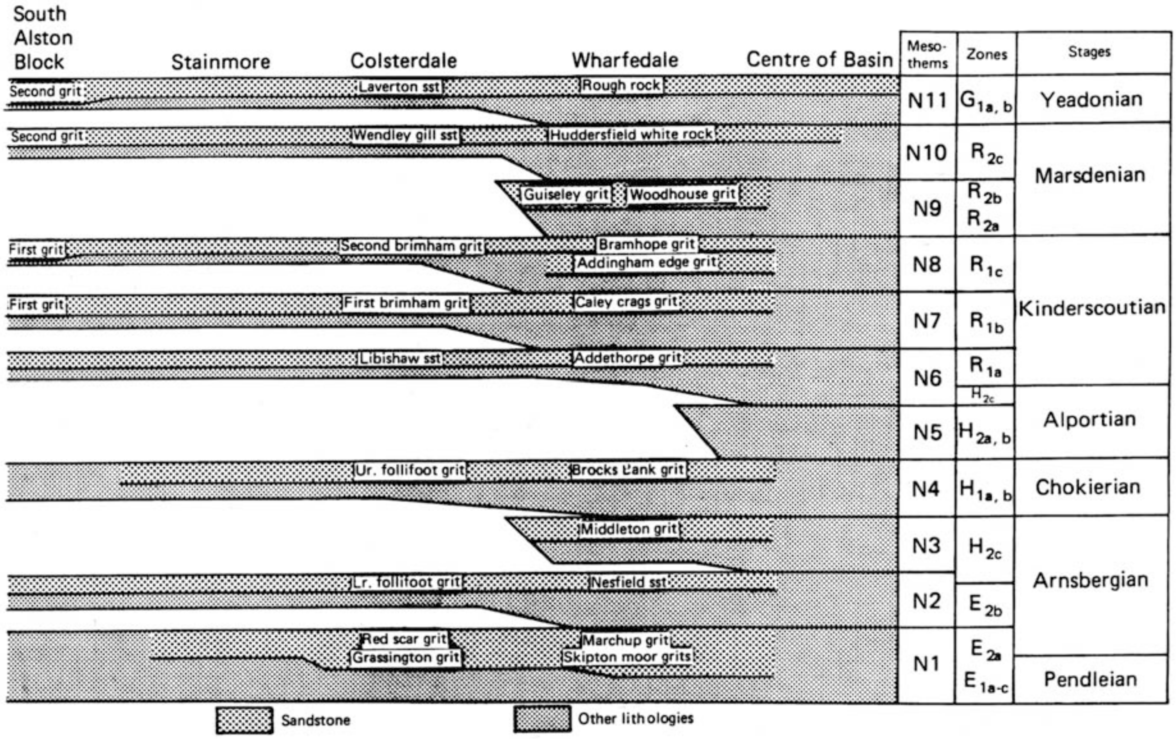

Fig. 6.38 Chronostratigraphic section of the Namurian rocks of part of northern England, showing the main lithostratigraphic units (Ramsbottom, 1979)

Absaroka sequences in North America, a time at which sea level was at a long-term eustatic lowstand (Sloss, 1963; Figs. 4.8, 5.5).

A subsurface analysis of the Middle Pennsylvanian cyclothem record in Kansas reveals an unmistakeable "mesothem" pattern, which Youle et al. (1994) attributed to 10^6-year eustatic cycles. They noted that higher-frequency cyclothems form a transgressive set in which deep-water deposits become more important upwards, and extend successively further onto the craton. The first few cycles overstep each other to onlap Mississippian basement. The highstand sequence set shows a distinctly progradational pattern, recording the long-term gradual drop in average sea level.

The Carboniferous succession in northern England, the type area for the mesothem model, contains evidence for considerable local tectonism, and for lithostratigraphic complexity resulting from local autogenic controls, such as delta-lobe switching. As a result, mesothemic cyclicity is not everywhere apparent, and Holdsworth and Collinson (1988) provided a critique of the mesothem model based on detailed local studies. In places the evidence does not support the simple mesothem model of Ramsbottom (1979) (see also Leeder, 1988). However, identification of a comparable form of cyclicity in the Late Paleozoic cyclothem succession of Kansas, as well as in other parts of Europe, as noted below, indicates that the mesothem concept should not be discarded. Groups of cycles are more likely to be mappable where tectonic influences are minor, as in Kansas.

Hampson et al. (1999) discussed the cyclothem model as applied to the Upper Carboniferous, coal-bearing succession of the Ruhr Basin, Germany. They refer to groupings of cyclothems that have been termed mesothems, but do not make it clear whether the mesothem concept can be applied to their rocks. By contrast, Cózar et al. (2006) made explicit reference to the mesothem concept, in their study of Lower Carboniferous (Visean) deposits in southwestern Spain. They used foraminiferal biostratigraphy to date sections through a mixed carbonate-siliciclastic succession, and suggested a

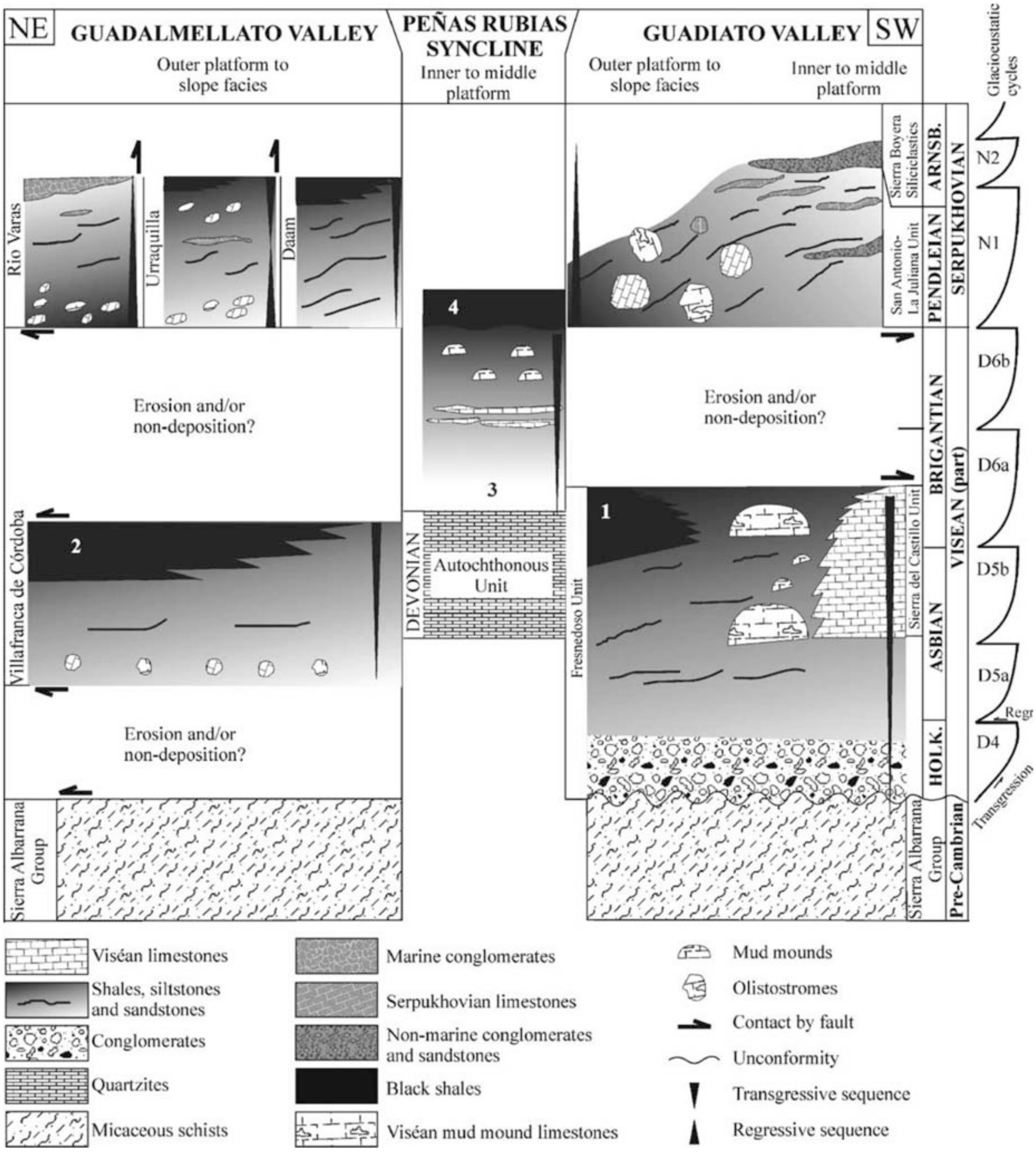

Fig. 6.39 Lithostratigraphic correlation of the upper Viséan to Serpukhovian rocks in the Guadalmellato and Guadiato valleys, Spain. 1–4: Brigantian age of these black shales. Glacioeustatic cycles (mesothems) defined by Ramsbottom (1979) for the Holkerian to Serpukhovian are shown in the *right hand column*. (Cózar et al., 2006, Fig. 4)

correlation with Ramsbottom's (1979) mesothem scheme (Fig. 6.39).

Ross and Ross (1988) carried out a worldwide comparison of these upper Paleozoic cyclic deposits, and proposed detailed correlations between cratonic sections in the United States, northwest Europe and the Russian platform. They recognized about 60 cycles in the Lower Carboniferous to Lower Permian stratigraphic record. They suggested that similar cyclic successions may occur in contemporaneous continental-margin sections, but that because most of these have been deformed by post-Paleozoic plate-tectonic events the record from these areas is less well known. In view of the scepticism surrounding the mesothem concept, and the difficulties in correlation based on limited chronostratigraphic data, such intercontinental correlation may be regarded as premature.

6.5 Conclusions

1. Stratigraphic sequences with 10^6-year episodicities are common in rifted and extensional continental-margin basins and on cratonic platforms. Their architecture comprises repeated transgressive-regressive packages of siliciclastic or carbonate deposits, of tabular form on continental shelves, or comprising prograding clinoform slope wedges. Mixed carbonate-siliciclastic sequences formed by reciprocal sedimentation are common. These sequences can readily be interpreted using standard systems-tract models.
2. Sequences of comparable duration are also common in foreland basins and can also be interpreted using the systems-tract approach. Siliciclastic deposits are dominant, particularly thick alluvial deposits in proximal settings. Transgressive carbonate successions may occur on the distal ramp and forebulge of foreland basins. Evidence for tectonic control is common.
3. In forearc basins, stratigraphic evolution is dominated by tectonic subsidence, faulting, and volcanism.
4. Where backarc basins border a continental margin, the tectonic and stratigraphic history are comparable to those of extensional continental margins, and commonly contain well-developed records of 10^6-year carbonate or clastic stratigraphic sequences.
5. A distinctive type of cyclicity occurs in upper Paleozoic rocks of the northern hemisphere. They are of glacioeustatic origin, resulting from the great glaciation of the Gondwana supercontinent. High-frequency cycles, called cyclothems, are the most prominent type of stratigraphic sequence (and are discussed in Chap. 7), but groupings of these into 10^6-year mesothems or major cycles can be recognized. Some detailed stratigraphic studies have thrown doubt on the mesothem concept as applied to the Upper Paleozoic record of northwest Europe, whereas some evidence for the concept has been obtained from the US midcontinent.