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Stratigraphic modelling of epicontinental basins: two applications

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ABSTRACT

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This paper highlights some recent results of computer simulations of sedimentary basin fills. Two types of applications of the simulation program are illustrated from epicontinental basins:

(1) Conceptual modelling. Computer simulations are ideal for establishing and quantitatively testing geological models. Here we investigate hierarchical levels of stratigraphic cyclicity, and record some criteria to distinguish cycles caused by eustatic variations and by fluctuations in clastic input or in intraplate stress. These possibilities may be differentiated by details in stratal patterns (time lines).

(2) Evaluation of "real" basin stratigraphy. This application is demonstrated with a calibration exercise from the Paris Basin. Data from only one well proved sufficient to simulate adequately the gross features of the basin-fill. With more well data being incorporated, more acurate simulations are obtained.

Stratigraphic modelling is useful as a learning tool and as a predictive tool, and is best used in conjunction with conventional basin-analysis techniques. Constraining the input parameters (e.g. by more empirical data) and the model sensitivity will remain a major task for future work.

Introduction

Basin analysis has become a rapidly expanding interdisciplinary research field and involves a large variety of fundamental issues concerning the geodynamics of basin formation, controls of basin-filling processes and thermal maturation of the sediment fills. In all these areas, "basin modelling", utilising computer simulation techniques, is increasingly integrated into conventional basin studies (e.g. Welte and Yalcin, 1987; Friedinger, 1988; Strobel et al., 1989; Nielsen and Balling, 1990; papers in Wilgus et al., 1989, and in Cross, 1990).

In this paper, we present some examples of the numerical simulation of basin architecture using a computer program designed to model the stratigraphic development of two-dimensional transects through sedimentary basins. The program has been developed over a number of years at the Shell Research Laboratories in Houston, U.S.A., and Rijswijk, The Netherlands (Lawrence et al., 1987, 1990; Aigner et al., 1989).

Epicontinental basins are particularly suitable for calibrating stratigraphie modelling studies, because they are characterised by continuous subsidence histories over long periods of time, they commonly show little structural complications, and they tend to have a relatively simple basin stratigraphy.

This paper will focus on the application of stratigraphie modelling techniques to epicontinental basins.

Stratigraphie modelling

Approach

Simulations are performed using a forward modelling computer program that consists of a

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framework of stratigraphical, sedimentological and geophysical principles. The program uses algorithms that describe the deposition and erosion of clastic and carbonate sediments, sediment compaction, and the isostatic response of the basement to surface loads and to horizontally directed tectonic forces (Lawrence et al., 1987, 1990). A major limitation of the program is that it is only two-dimensional.

Detailed descriptions of the concepts employed and their numerical representation in the program code are beyond the scope of this paper. Key input parameters for the model are: (1) tectonic subsidence history (from user-specified subsidence rates, lithosphere stretching models, or from well data); (2) sea-level history (either specified by the user or from a library of published sea-level curves); (3) clastic sediment input rate (specified by the user as the rate of sediment introduction, the rate of sediment dispersion, erosion, and slope stability); and (4) carbonate growth potential (following empirical relationships between average

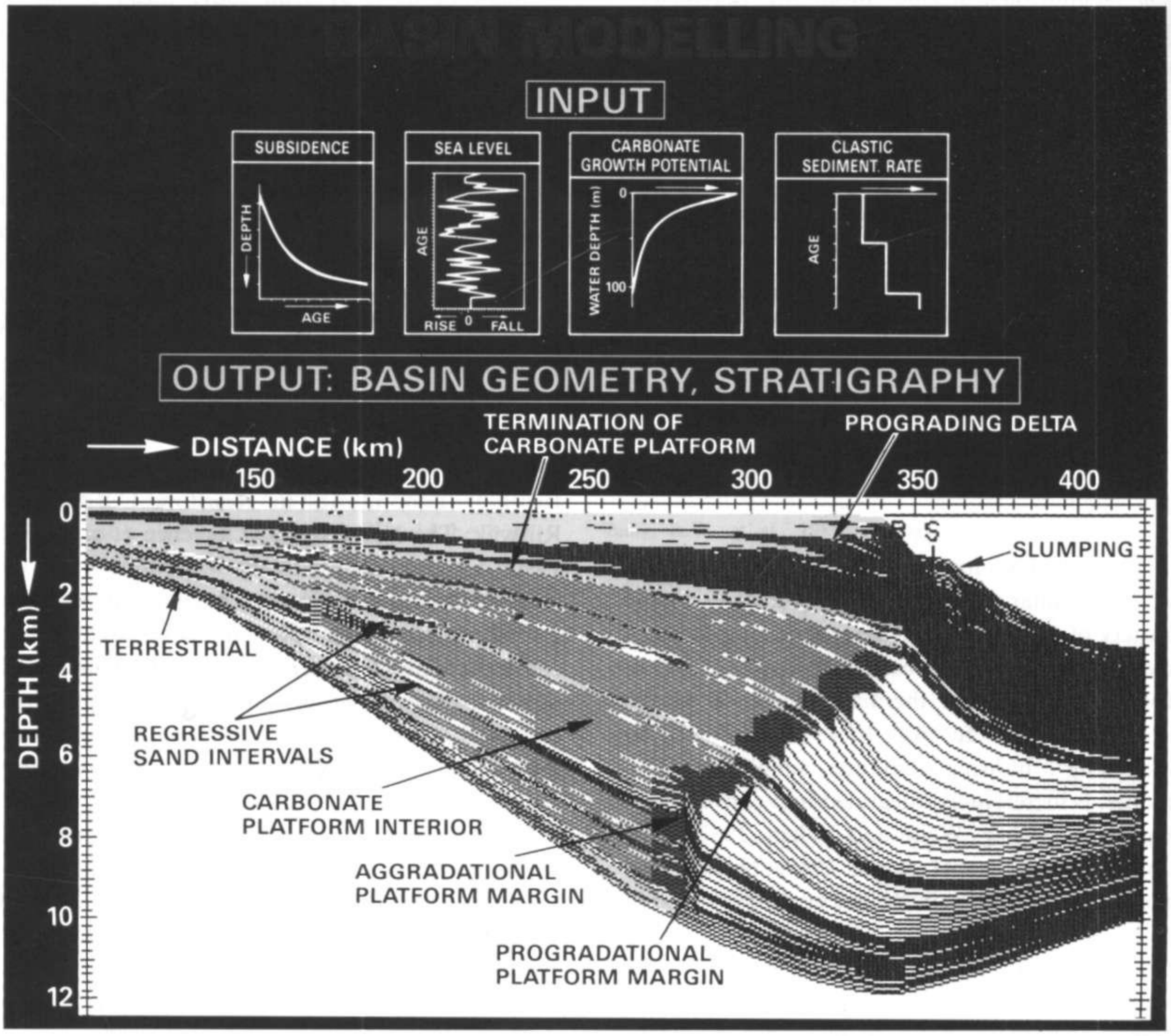


Fig. 1. An illustration of the computer program designed to simulate basin stratigraphy. Principal input parameters are the sea-level and subsidence history, clastic sedimentation rate and the carbonate growth potential (decreasing with increasing water depth). Typical model output is cross-sections displaying basin geometry, stratigraphy and facies (colours). Black lines are time-lines spaced at 1 Ma intervals.

carbonate production, water depth within the photic zone, clastic "pollution", and distance from open marine circulation).

A simulation is performed on a two-dimensional grid and in a sequence of small time steps from a prescribed set of initial conditions. Clastic, carbonate and mixed carbonate/clastic depositional systems can be handled. During program application, the user can vary the input parameters within the limits of known geological constraints, until the model is consistent with all available data and observations. Model results are displayed in two-dimensional cross-sections showing the basin and depositional sequence geometry through time, spatial and temporal distribution of unconformities, gross facies distribution, and details of stratigraphic relationships (Fig. 1).

Applications

(a) *Conceptual modelling*. Computer modelling is ideal for generating and quantitatively evaluating conceptual models. By isolating individual processes it is possible to improve our understanding of the basic factors that control the architecture of depositional systems. Here we investigate several hierarchical levels of stratigraphic cyclicity: the examples used come from the Permo-Triassic of Oman.

(b) *Basin evaluation*. In addition to conceptual applications, the modelling program can be used to simulate actual stratigraphic architecture. This can be done either on a basin-wide scale or on the scale of individual prospects. Program output includes sequence geometries, facies and lithology distribution, chronostratigraphic and burial history plots. This type of application of the program is demonstrated with simulations from the Paris Basin.

Conceptual stratigraphic modelling: an example from the Arabian Platform

For large parts of its history, the Arabian Platform was a stable cratonic ("epicontinental") area that was intermittently covered by epeiric seas from the Early Permian through the Mesozoic and Cenozoic (Hughes-Clarke, 1988; Fig. 2). The fill of the Rub'al Khali Basin shows a remarkable "layer-cake" stratigraphy with individual formations extending almost uniformly over huge areas (Fig. 3). Detailed log analysis reveals that the layer-cake stratigraphy is built by a hierarchical system of depositional cycles (Fig. 4).

"Supercycles"

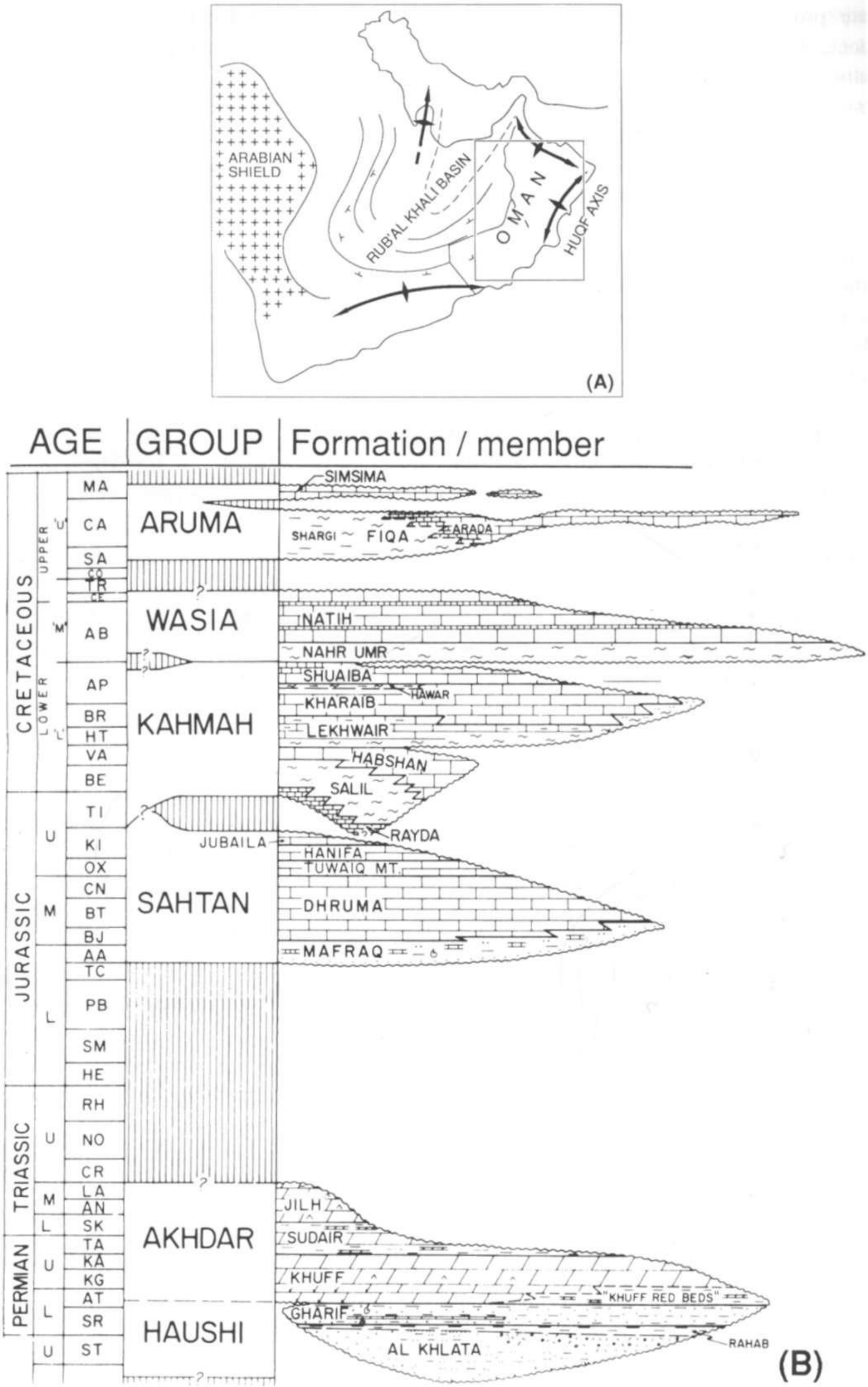
Figure 2C shows a cross-section from North to South Oman based on log correlation and documents the stratigraphy of the margin of the Rub'al Khali Basin. Major, unconformity-bounded depositional sequences correspond to the lithostratigraphic units of the Akhdar, Sahtan, Kahmah, Wasia and Aruma Groups. These units each represent a major transgressive/regressive cycle varying in duration from about 20 to 40 Ma and thus comparable to the "sequences" of Sloss (1963) or the "supercycles" of Vail et al. (1977). In sequence stratigraphic nomenclature, these cycles would rank as "second-order" sequences (e.g. Haq et al., 1987).

"Cycles"

The "supercycles" consist internally of a stack of smaller-scale depositional cycles. Many of these correspond to lithostratigraphic units of formation status within the Sahtan, Kahmah and Wasia Groups.

The symmetrical Akhdar Group supercycle is also built by a stack of "cycles", each cycle consisting of a lower branch of transgressive shallow-water carbonates and an upper, regressive branch with progressively more intervals of coastal plain clastics (Fig. 5A). The cycles are recognised on a basin-wide scale and are useful for both a practical and a genetic stratigraphic division of the Akhdar Group. These cycles range in thickness between 50 and 200 m and probably represent time-spans of about 2–10 Ma. They may be referred to as "third-order sequences".

In principle, the transgressive/regressive cyclicity could be caused by three different mechanisms: (1) eustatic sea-level fluctuations, (2) periodic fluctuations in clastic sediment supply, and (3) changes in relative sea-level caused by varia-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O M A N
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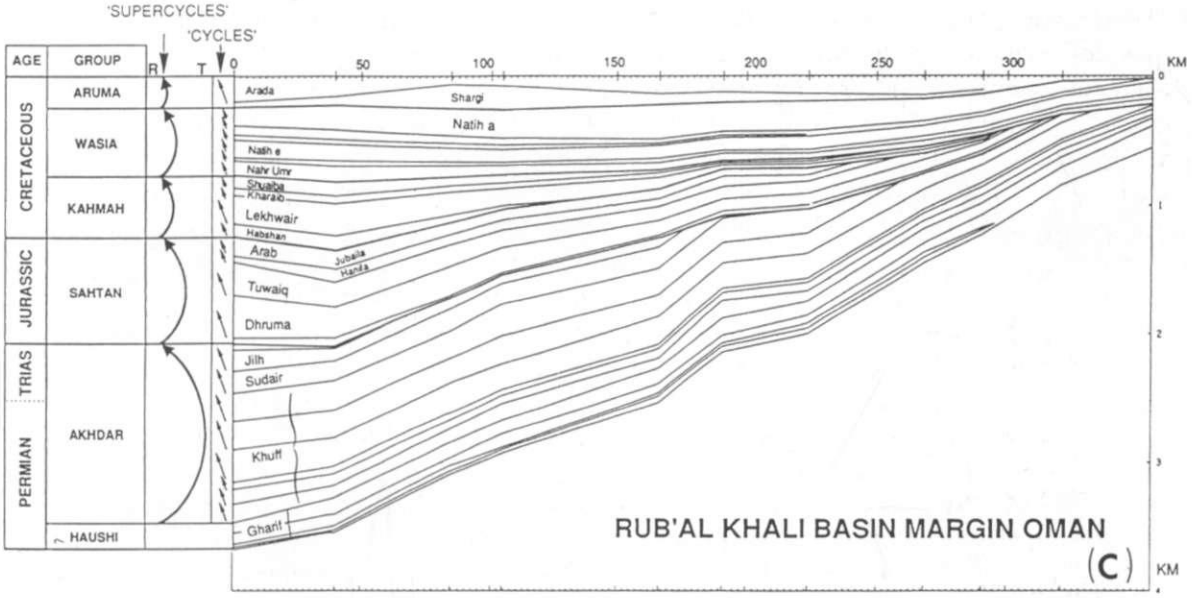


Fig. 2. A. Location of Rub'al Khali Basin on Arabian Platform; box shows study area. B. Stratigraphic chart of Permian to Cretaceous in Oman. From Hughes-Clarke (1988). C. Stratigraphic cross-section through margin of Rub'al Khali Basin from North to South Oman, based on well-log correlation. Note the layer-cake stratigraphy, built by a hierarchy of depositional cycles. (Note extreme vertical exaggeration.)

tions in intraplate stress (Cloething, 1986). Simple simulations were run to investigate these possibilities. Constant rates of tectonic subsidence and sinusoidal eustatic sea-level curves were used for the sake of simplicity only. The simulation of Fig. 5B indicates that the principal stratigraphic pat-

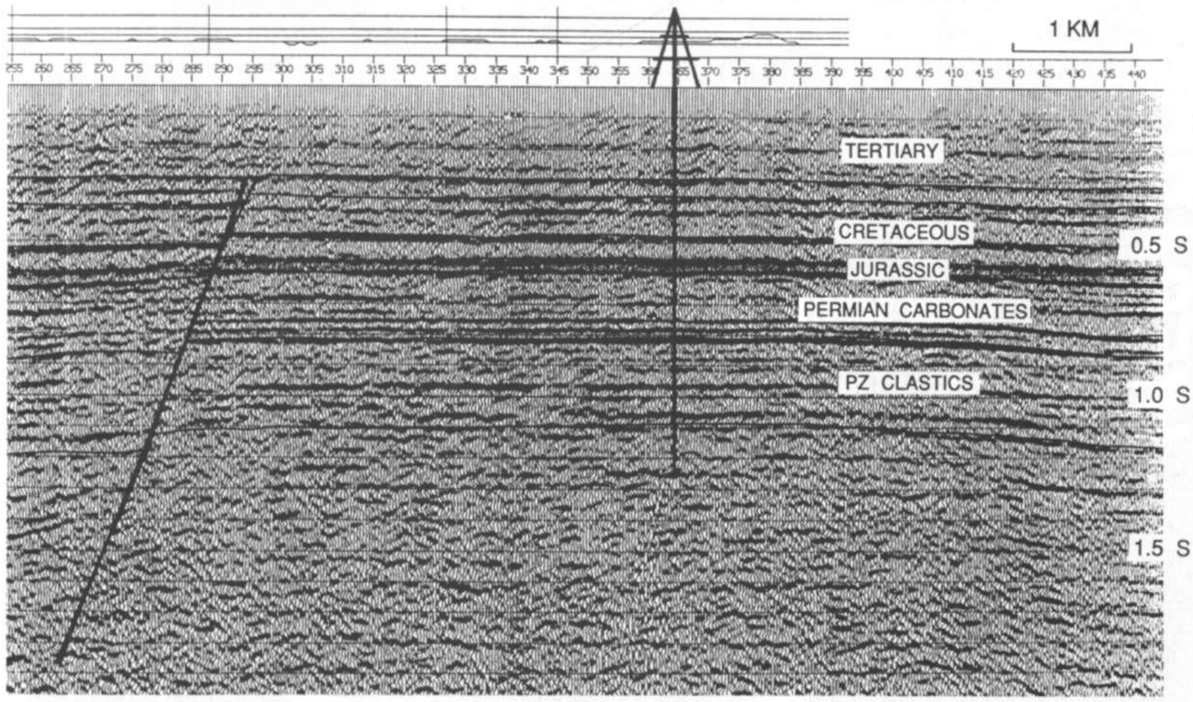


Fig. 3. Representative seismic line showing "layer-cake" stratigraphy in Rub'al Khali Basin.

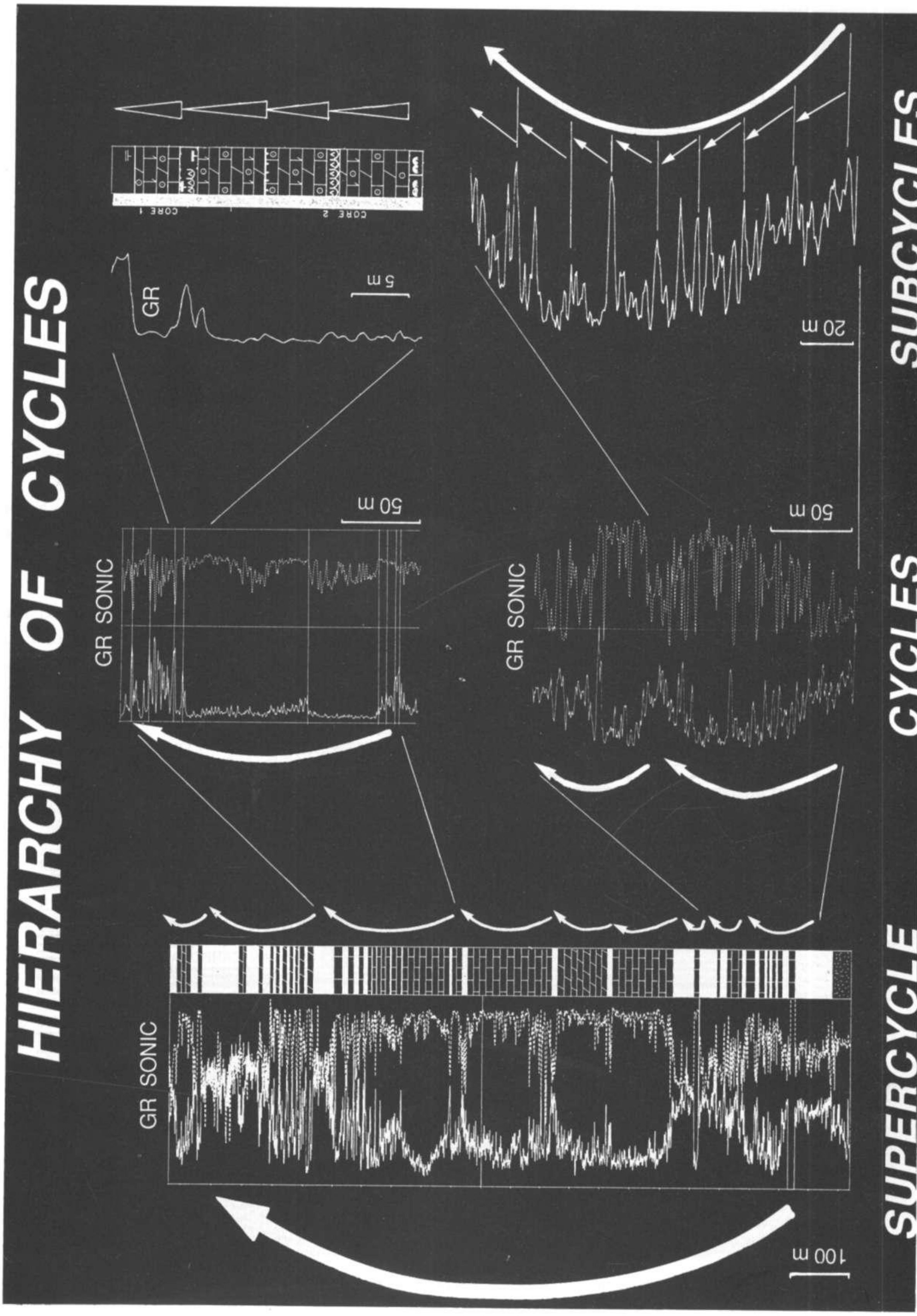


Fig. 4. Hierarchical levels of depositional cycles as recorded in well-logs from the Akhdar Group in Oman.

terns can be explained by eustatic sea-level fluctuations with a high-frequency signal being superimposed on a low-frequency signal, while the supply of clastics was left constant. The stacked cycles are produced by the high-frequency oscillations, which ride on the low-frequency curve that forms the "supercycle" of the Akhdar Group.

A similar stratigraphic pattern could be produced with a simulation that employed a constant tectonic subsidence, constant eustatic sea-level but periodic fluctuations in clastic sediment supply (Fig. 5D). Thus the gross stratigraphic patterns do not appear to allow a distinction between eustatic or sediment supply controls on the cyclicity. However, details of the stratal patterns can resolve the differences. In the case of fluctuations in space creation (eustasy), successive time-units vary regularly in thickness within each cycle, and cycles are

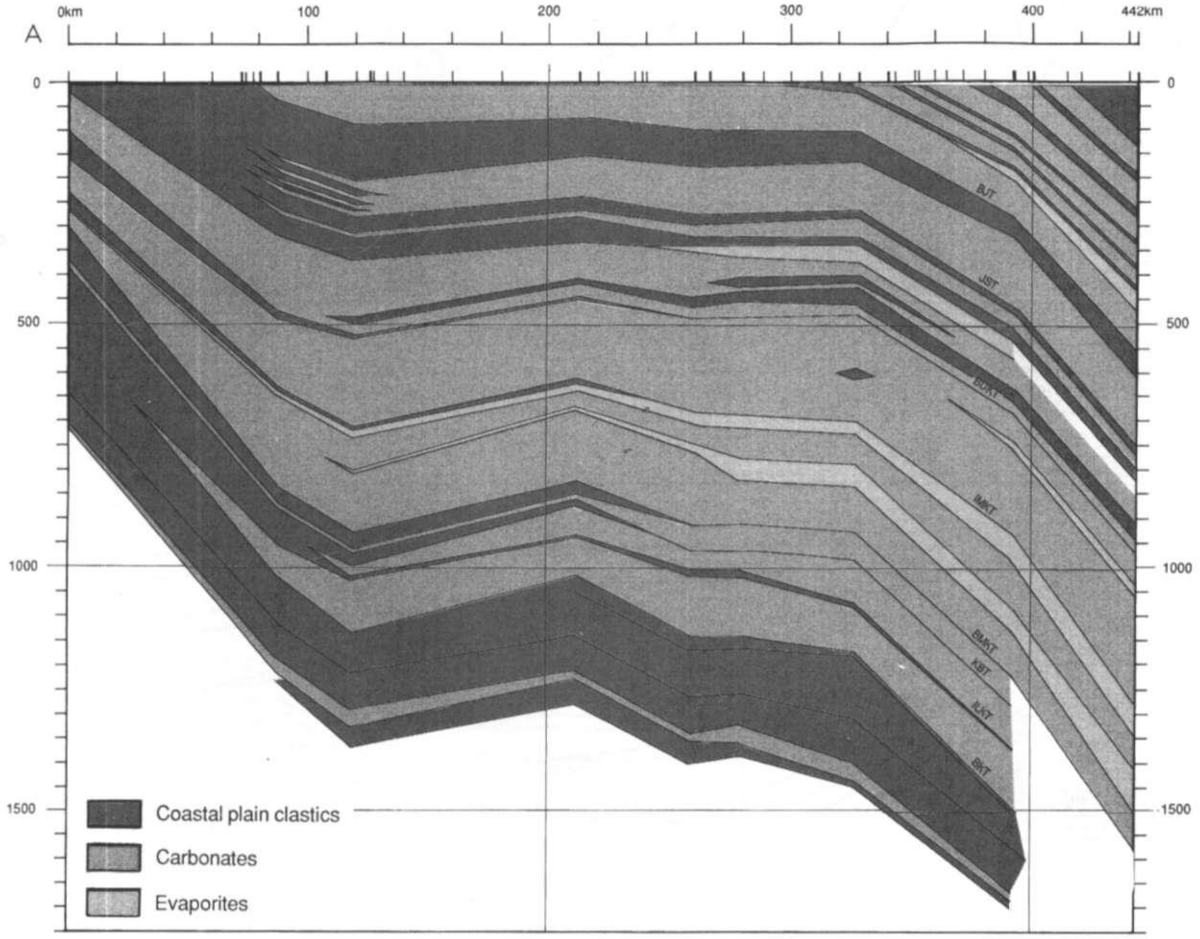
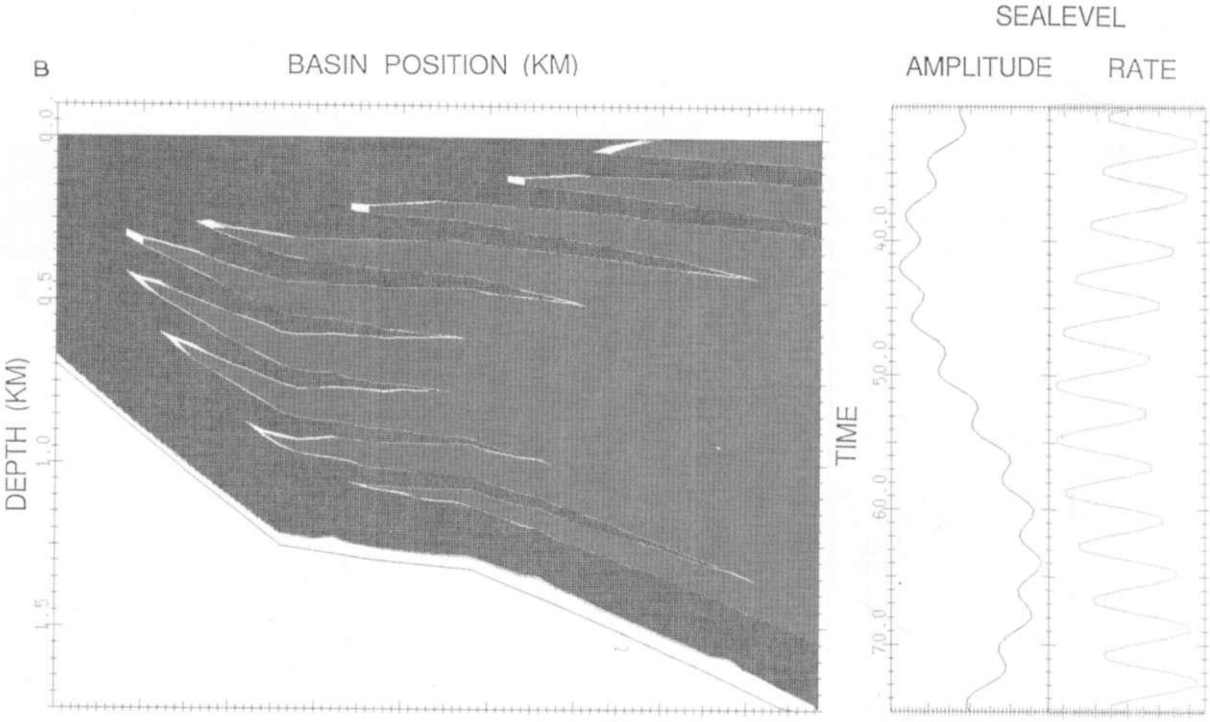


Fig. 5. A. Stratigraphic cross-section of Akhdar Group along the margin of the Rub'al Khali Basin in Oman based on log correlation. B. Simplified simulation of Akhdar Group cross-section with a sea-level input consisting of two sinusoidal curves. C. Same plot as B, but showing stratal patterns: time-lines spaced at 0.5 Ma intervals. Note thinning and thickening of time units and truncations (arrows) in up-dip portion of section. Heavy black line = shoreline. D. Simplified simulation of Akhdar Group with constant sea-level but fluctuating clastic sediment input. Note overall similarity to B. E. Same plot as D, but showing stratal patterns with time-lines spaced at 1 Ma intervals. Note that time units are uniform in thickness and no truncations occur. Heavy black line = shoreline. F. Simplified simulation of Akhdar Group with relative changes in sea-level caused by high-frequency variations in intraplate stress together with a low-frequency change in clastic sediment input. G. Same plot as F, but showing stratal patterns with time-lines spaced at 0.5 Ma intervals. Note vertical thinning and thickening trends and lateral onlap relationships against flexurally induced bulge (arrows). Heavy black line = shoreline.



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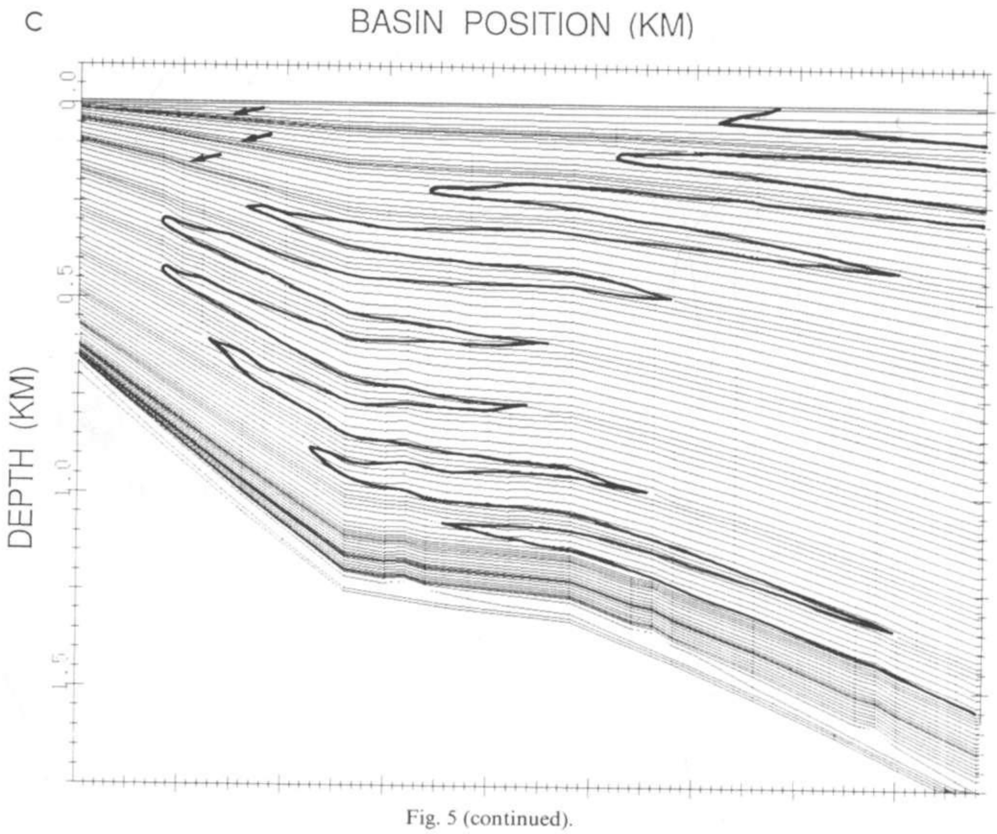

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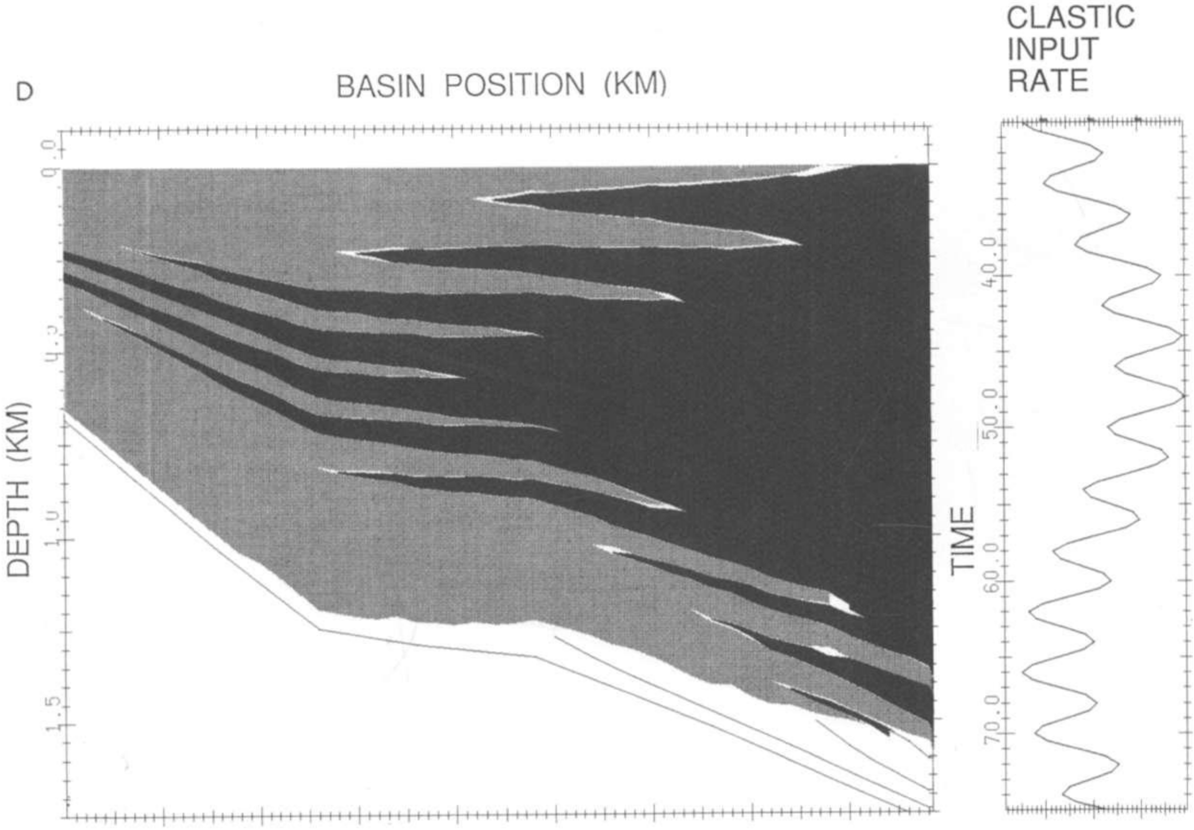

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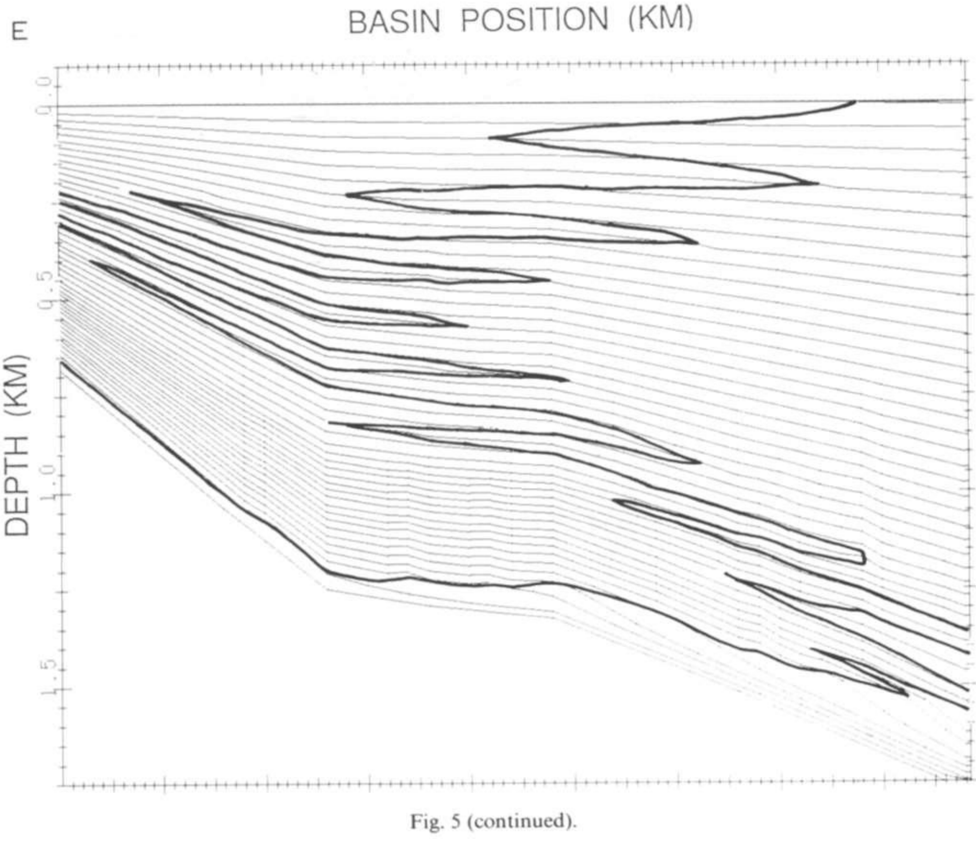

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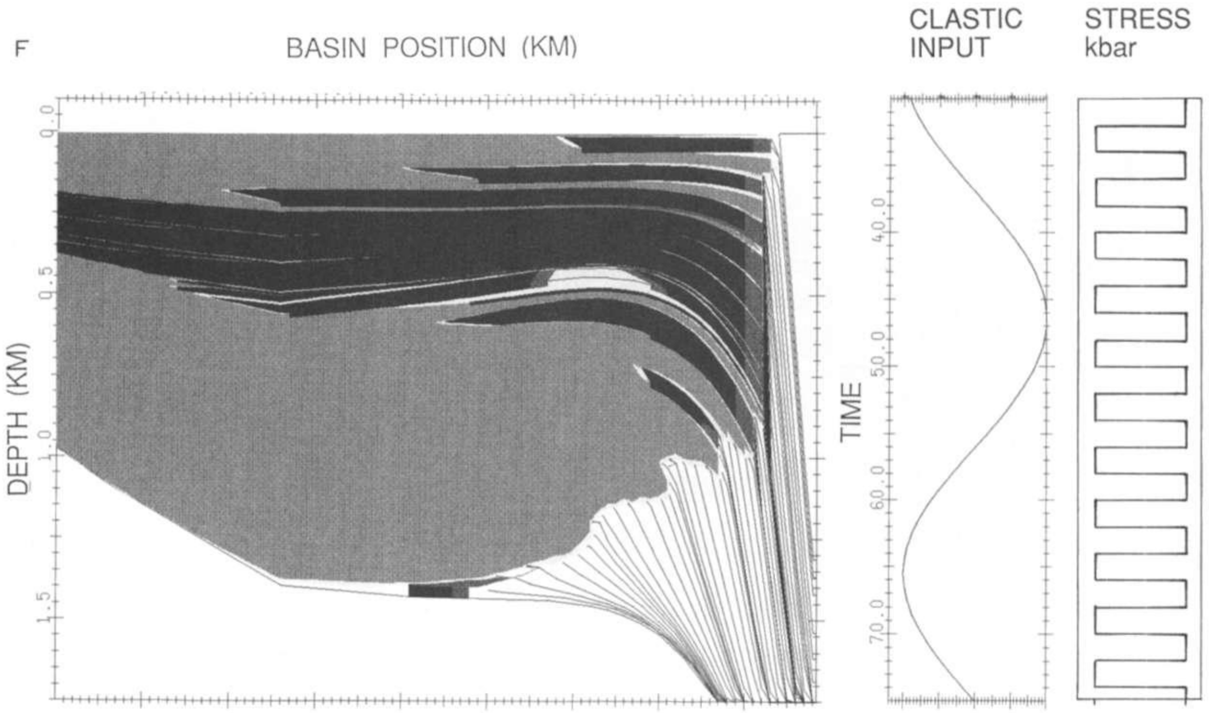

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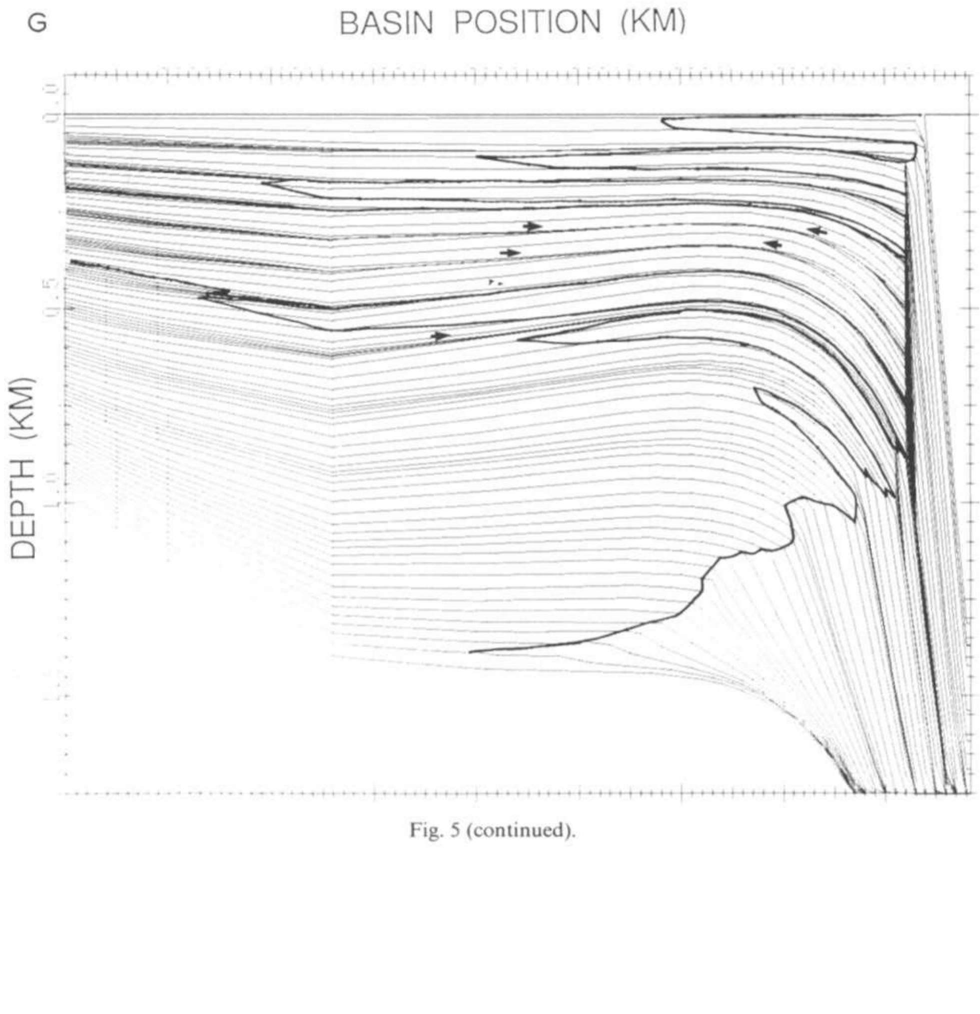


Fig. 5 (continued).

bounded by surfaces of erosional truncation (due to space-destruction, see Fig. 5C). In contrast, fluctuations in sediment supply produce time-units of uniform thickness without truncation surfaces (Fig. 5E).

Simulations employing changes in relative sealevel caused by variations in intraplate stress while leaving the other parameters constant (tectonic subsidence, clastic supply, carbonate growth potential) were not able to reproduce the observed stratigraphy. However, combinations of high-frequency intraplate stress variations with a low-frequency variation of clastic sediment input come closer to producing the principal stratigraphic patterns observed (Fig. 5F), but not as well as the previous simulations. A major difference is the development of a broad flexurally induced bulge in the central part of the simulated Arabian shelf. The stratal patterns in this case display vertical thickening and thinning trends along the basin margin (Fig. 5G) similar to the eustatic example (cf. Fig. 5C). However, time-lines show lateral thinning and onlap relationships against the flexural bulge that developed around the central shelf area. This lateral thinning is most pronounced during times of reduced clastic input (Fig. 5F).

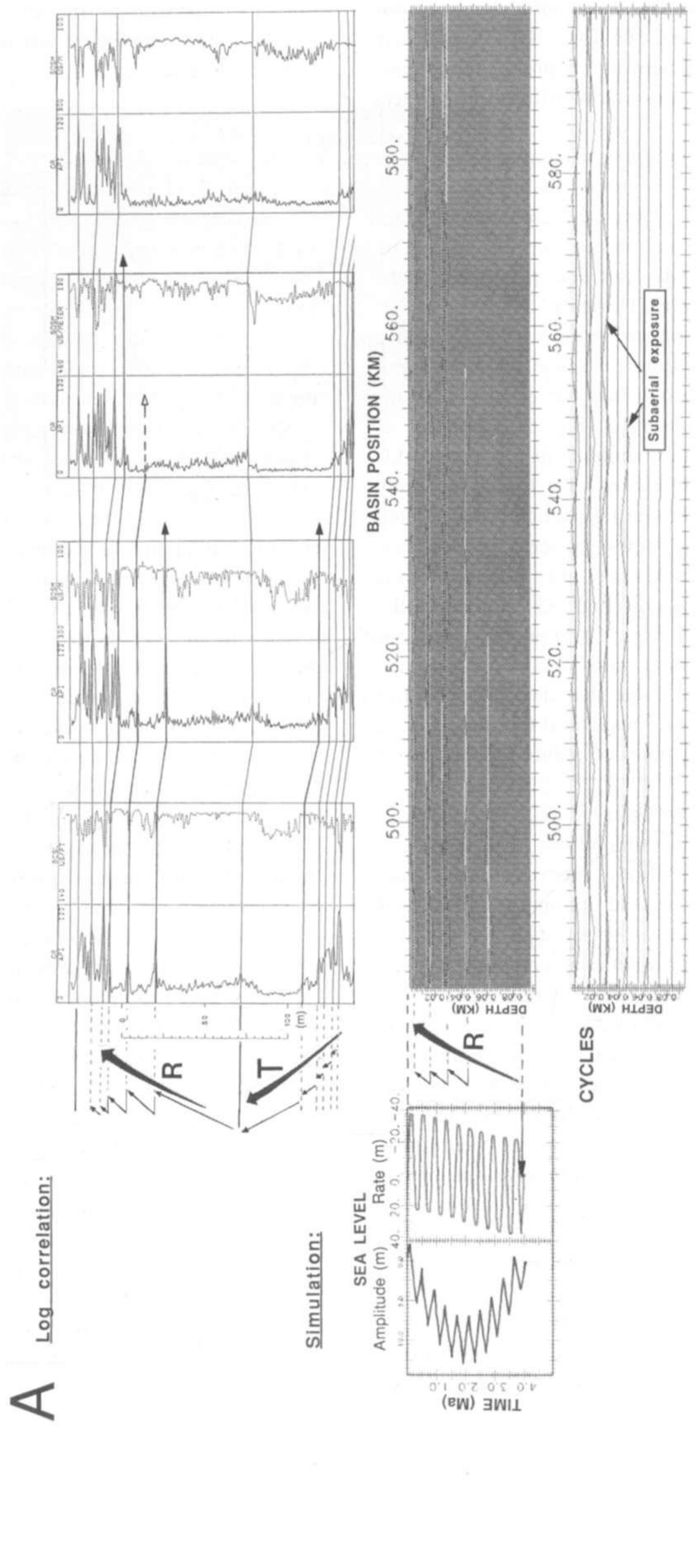
The principal stratigraphic patterns observed conform best to the simulations that employed periodic eustatic variations: subcycles display regular vertical thickening and thinning trends, bound by numerous subaerial exposure surfaces as predicted by the eustasy-dominated computer simulation. In the stratigraphic data, there is no evidence for lateral thinning and onlap of subcycles against a (flexural) bulge, as predicted by the simulations that employed relative changes in sea-level caused by intraplate stress variations. Moreover, the overall stratigraphic geometries are not as well reproduced as in the eustatic example. Stress values of 1–5 kbar usually assumed in literature (e.g. Cloething and Kooi, 1989) produced insufficient deflections to explain the present trans/regressive cycles with our simulation program. These values, however, depend on the rheological model employed for the lithosphere, which at present is controversial. Our present simulations were only able to approximate the observed stratigraphy roughly when employing stress variations in the order of 20 kbar.

"Subcycles"

"Cycles" are in turn composed of various orders of ever-smaller-scale "subcycles". In sequence stratigraphic terms, these subcycles represent fourth- and fifth-order sequences (e.g. Haq et al., 1987).

The subcycles vary regularly in thickness within the "Upper Khuff Cycle", with thin subcycles in the lowermost and uppermost part, and thick subcycles in the middle part (Fig. 6A). Core data clearly indicate numerous surfaces of subaerial exposure. Thus, on the basis of the above simulations, the details of the stratal patterns indicate a eustatic, rather than a sediment supply control of the cyclicity. Figure 6A also shows a simple simulation of the regressive arm of the Upper Khuff Cycle with an upwards increase in the number and duration of subaerial exposure intervals. Core studies revealed still smaller levels of decimetre- to metre-scale shallowing-upwards cycles in the Upper Khuff Cycle. The development of these minor cycles depends on their position within the transgressive/regressive "cycle". In the lower, transgressive branch of the cycle, the subtidal parts of the minor cycles are most prominently developed. By contrast, in the upper, regressive branch of the cycle, the supratidal parts of the minor cycles with subaerial exposure, anhydrite and clastics are progressively better developed. Thus the lithological expression of small cycles within larger cycles appears to vary regularly, and to some extent predictably. This pattern again indicates that variable rates of space creation (eustacy) rather than fluctuating clastic supply controlled the cyclicity.

Figure 6B shows that two "Lower Khuff cycles" consist of an almost symmetrical transgressive/regressive stacking of "subcycles". Their principal characteristics can again be simulated using constant rates of tectonic subsidence, clastic input and carbonate growth potential, and a sea-level curve composed of two superimposed sinusoidal signals.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Log correlation:
R
T
Simulation:
SEA LEVEL
Amplitude (m)
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Subaerial exposure

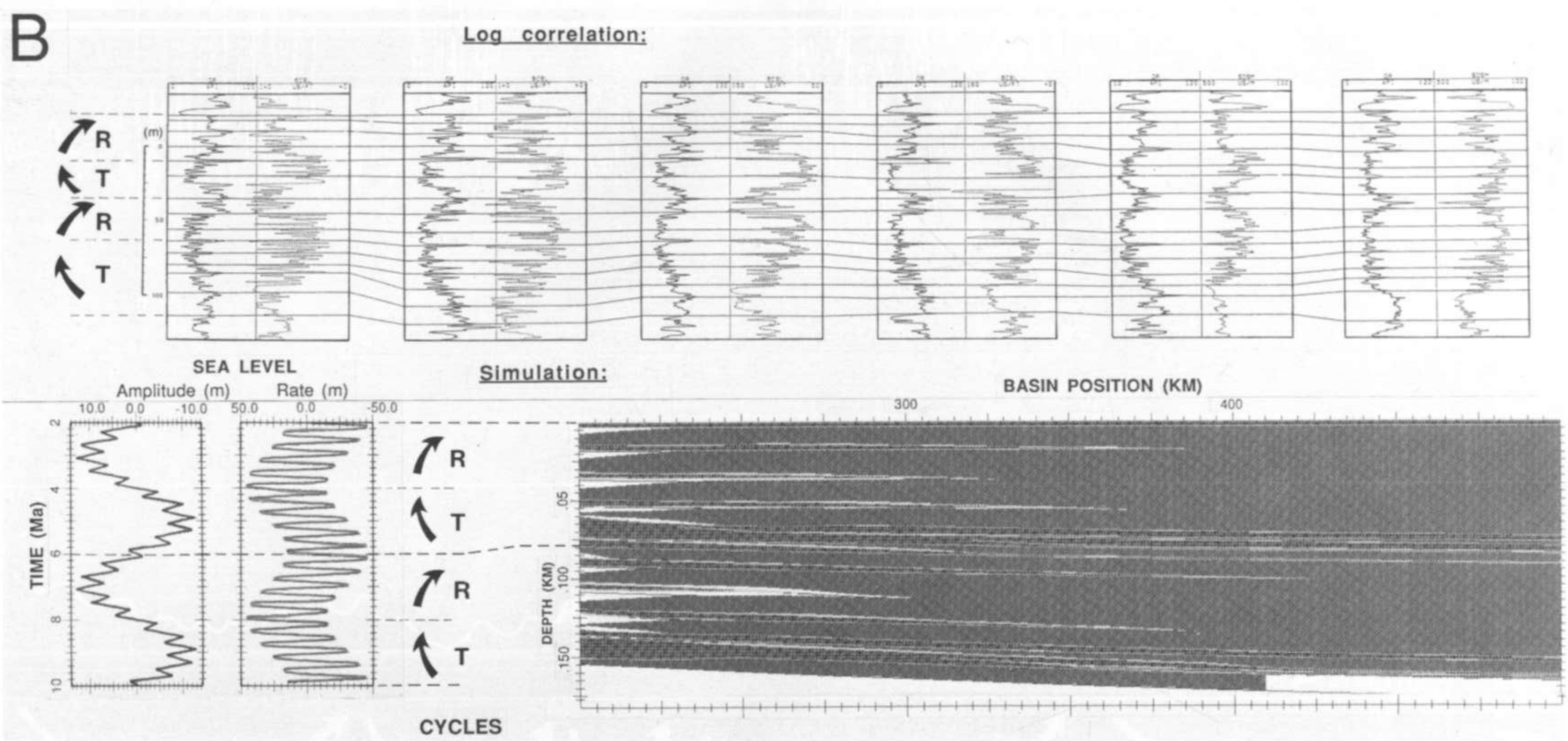

Fig. 6. A. Upper part: log correlation panel of "Upper Khuff Cycle". Note how this transgressive/regressive cycle (large arrows) is built by subcycles (small arrows) that vary regularly in thickness. Lower part: simple simulation of regressive arm of Upper Khuff Cycle using a sinusoidal sea-level signal and constant rates of clastic input and carbonate growth potential. B. Upper part: log correlation panel of part of Akhdar Group showing symmetrical "cycles", built by "subcycles". Lower part: simplified simulation with sea-level input consisting of two superimposed sinusoidal signals.

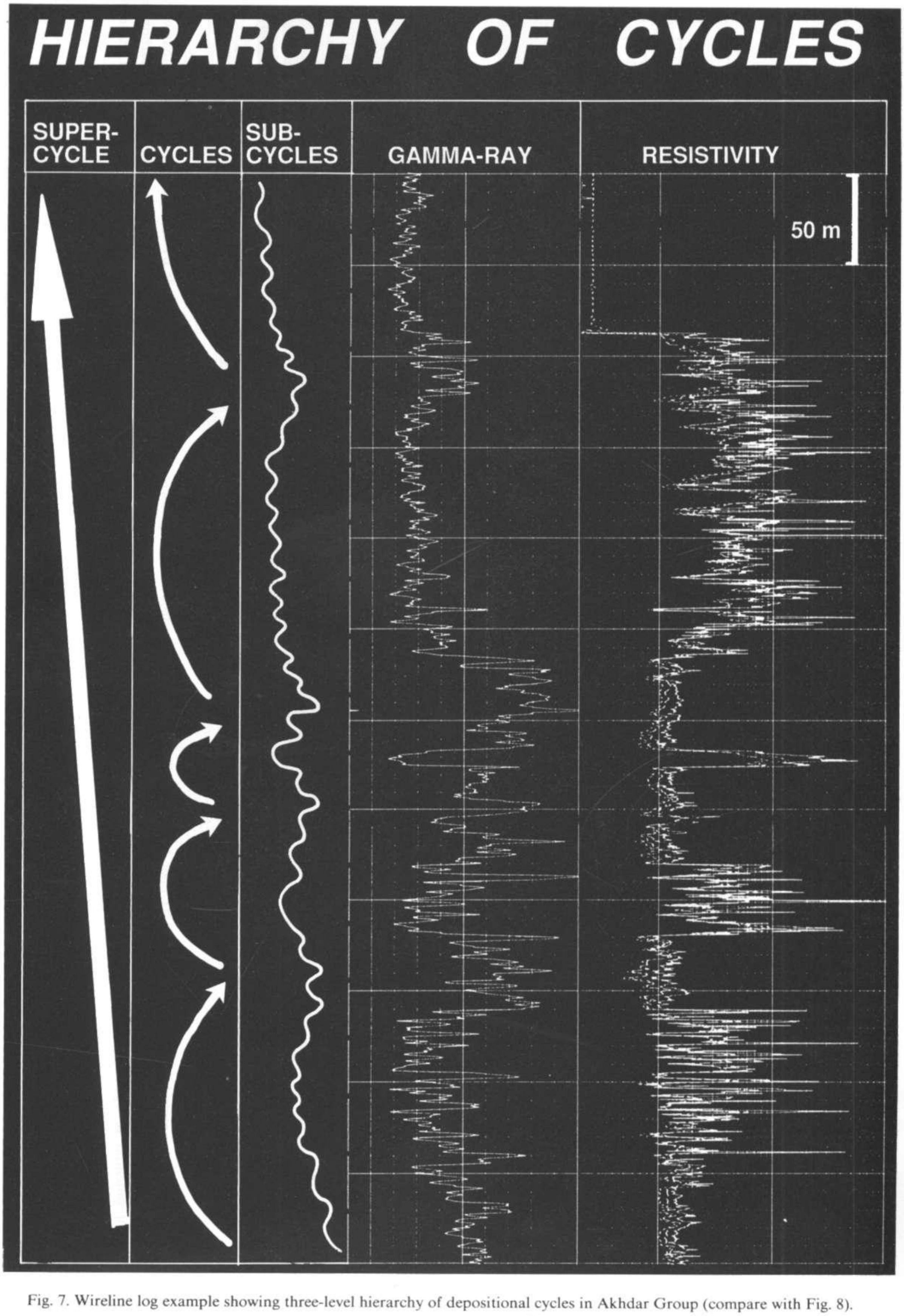

Fig. 7. Wireline log example showing three-level hierarchy of depositional cycles in Akhdar Group (compare with Fig. 8).

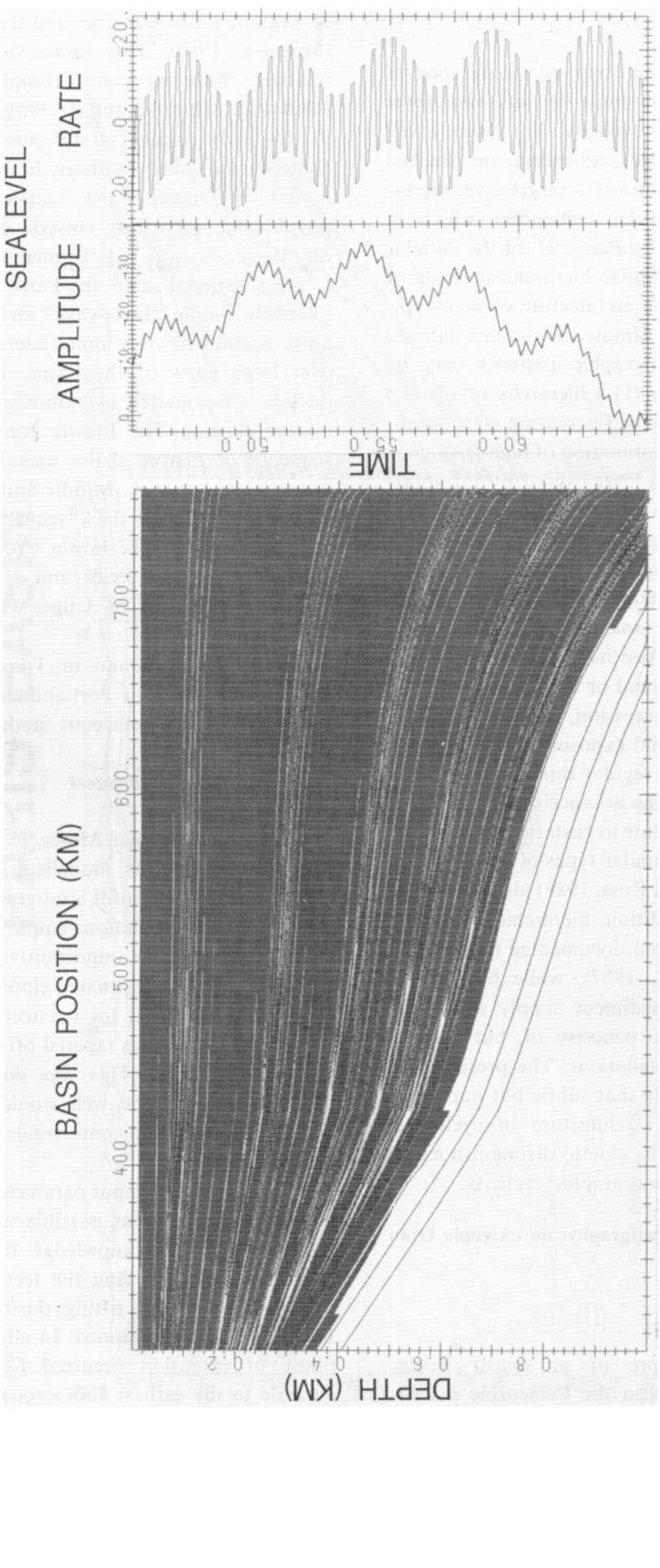

Fig. 8. Simplified simulation of part of Akhdar Group using three superimposed sinusoidal signals as sea-level input to reproduce roughly the observed three-level hierarchy of depositional cycles (compare with Fig. 7)

Discussion

In a general way, the observed stratigraphy of the Akhdar Group is built by at least three hierarchical levels of cyclicity: (1) "subcycles" (fourth- and fifth-order sequences) are stacked into (2) almost symmetrical transgressive/regression "cycles" (third-order sequences), which in turn comprise the (3) "supercycle" of the Akhdar Group (Figs. 7, 8). Similar hierarchical levels of cyclicity form the basic architecture of many epicontinental basin-fills. Simple simulations indicate that such cyclic stratigraphic patterns may be formed in principle by (1) a hierarchy of eustatic signals, (2) a hierarchy of fluctuating clastic sediment input, or (3) a combination of high-frequency relative changes in sea-level caused by intraplate stress variations with a long-term change in clastic input. These possibilities may be difficult to distinguish from the lithofacies distribution, but can be differentiated by details in stratal patterns. In addition, comparative analysis of age-equivalent basin-fills on various continental plates will separate global from regional or local signals. In the case of the Akhdar succession, details in individual cycles (e.g. subaerial exposure surfaces), their stacking patterns (e.g. regular thinning and thickening of cycles), and the absence of any evidence for a flexural bulge points to eustatic controls. The global occurrence of similar types of cycles within the Permian (Ross and Ross, 1988) also favour the eustatic model. In addition, hierarchical levels of eustatic changes are well documented (e.g. Vail et al., 1977; Haq et al., 1987), while hierarchical levels of fluctuating sediment supply are somewhat more difficult to conceive of, but may be possible by climate oscillations. The present simple simulations indicate that subtle but important details in the stratal architecture of cyclic sequences may provide the clue to distinguish major processes that cause stratigraphic cyclicity.

Evaluation of basin stratigraphy: an example from the Paris Basin

General

The Paris Basin represents an almost circular depocentre lying between the Palaeozoic massifs of Armorica, the Ardennes and the Massif Central (Mégnien, 1980). This saucer-shaped basin has relatively little structural complications and is filled with Mesozoic and Tertiary sediments (Fig. 9). Its early history is still poorly known, and controversial. Many authors, however, consider a period of Triassic/Early Liassic rifting, and a possible second rifting episode during the Middle/Upper Jurassic (e.g. Brunet, 1986).

On a regional scale, the Paris Basin exhibits a relatively simple "layer-cake" stratigraphy: many units extend with only minor lateral facies changes over large parts of the basin. The Triassic sequence is dominated by non-marine to marginal marine clastics. The Liassic consists of a thick sequence of marine shales including the prolific Toarcian source rock. Middle and Upper Jurassic sediments comprise thick sequences of shallow-water carbonates. The Lower Cretaceous includes non-marine clastic series and gives way to the widespread blanket of Upper Cretaceous chalk sedimentation.

Reservoirs are found in Triassic sands, Callovian (and minor in Portlandian) carbonates as well as in Lower Cretaceous sands.

Modelling: input parameters

Only the well-known Mesozoic–Cenozoic fill of the Paris Basin was modelled. Because of the almost symmetrical infill stratigraphy of the Paris Basin, our first simulations employed a number of simplifications. Most importantly, data from only one well (Fig. 10 A), situated close to the centre of the basin, were used for the tectonic subsidence input; subsidence was tapered off to zero towards the basin margins. This was done in order to evaluate whether one well would be enough to simulate a simple epicontinental basin infill in a reasonable way.

In setting up the input parameters for the simulation, as much use as possible was made of the regional geological knowledge that is generally available. For modelling the tectonic subsidence history, a phase of rifting during Triassic and Early Liassic was assumed. In addition, a second phase of extension occurred from the Middle Jurassic to the earliest Cretaceous, apparently re-

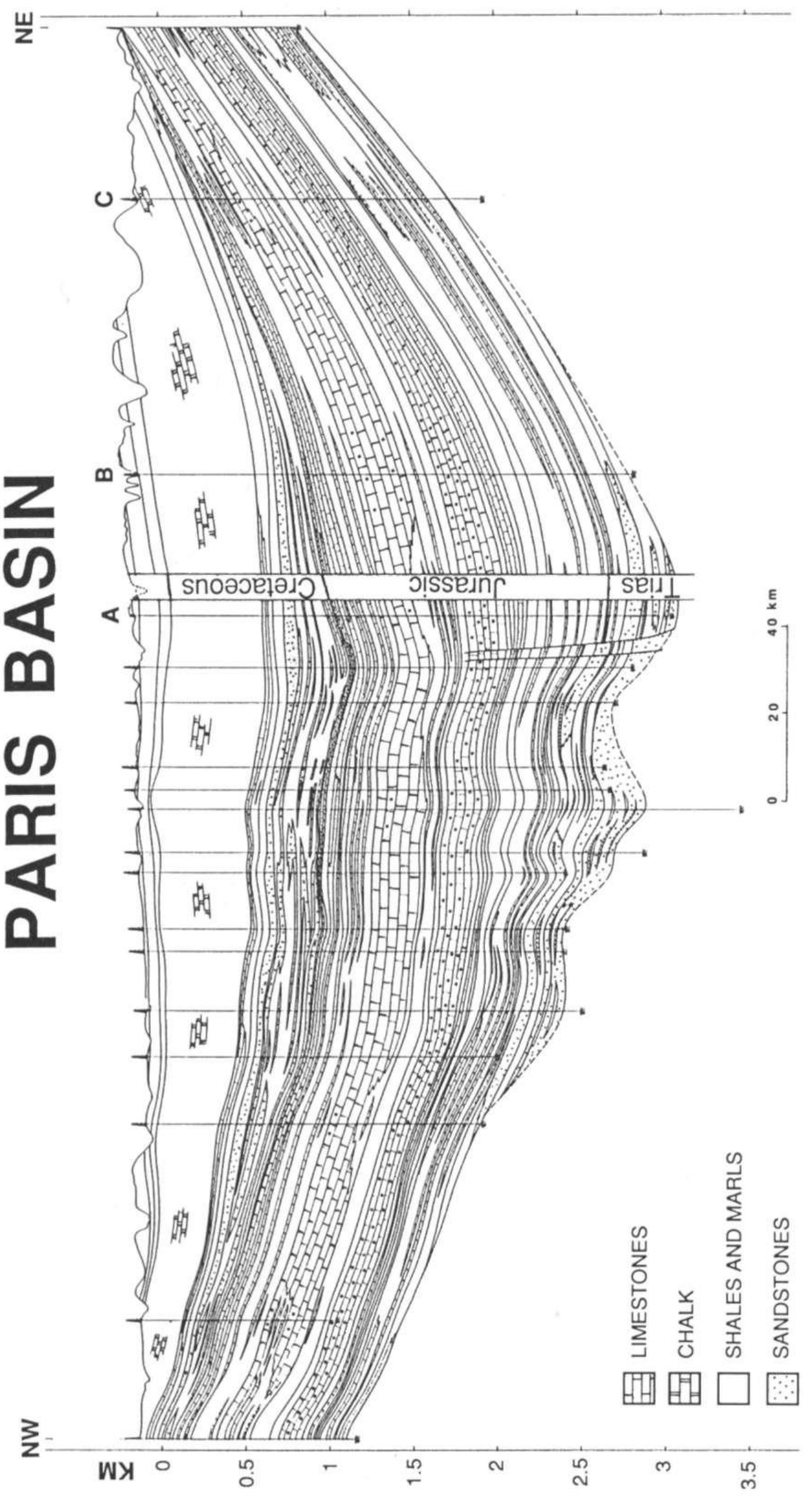

Fig. 9. Stratigraphic cross-section through the Paris Basin based on log data.

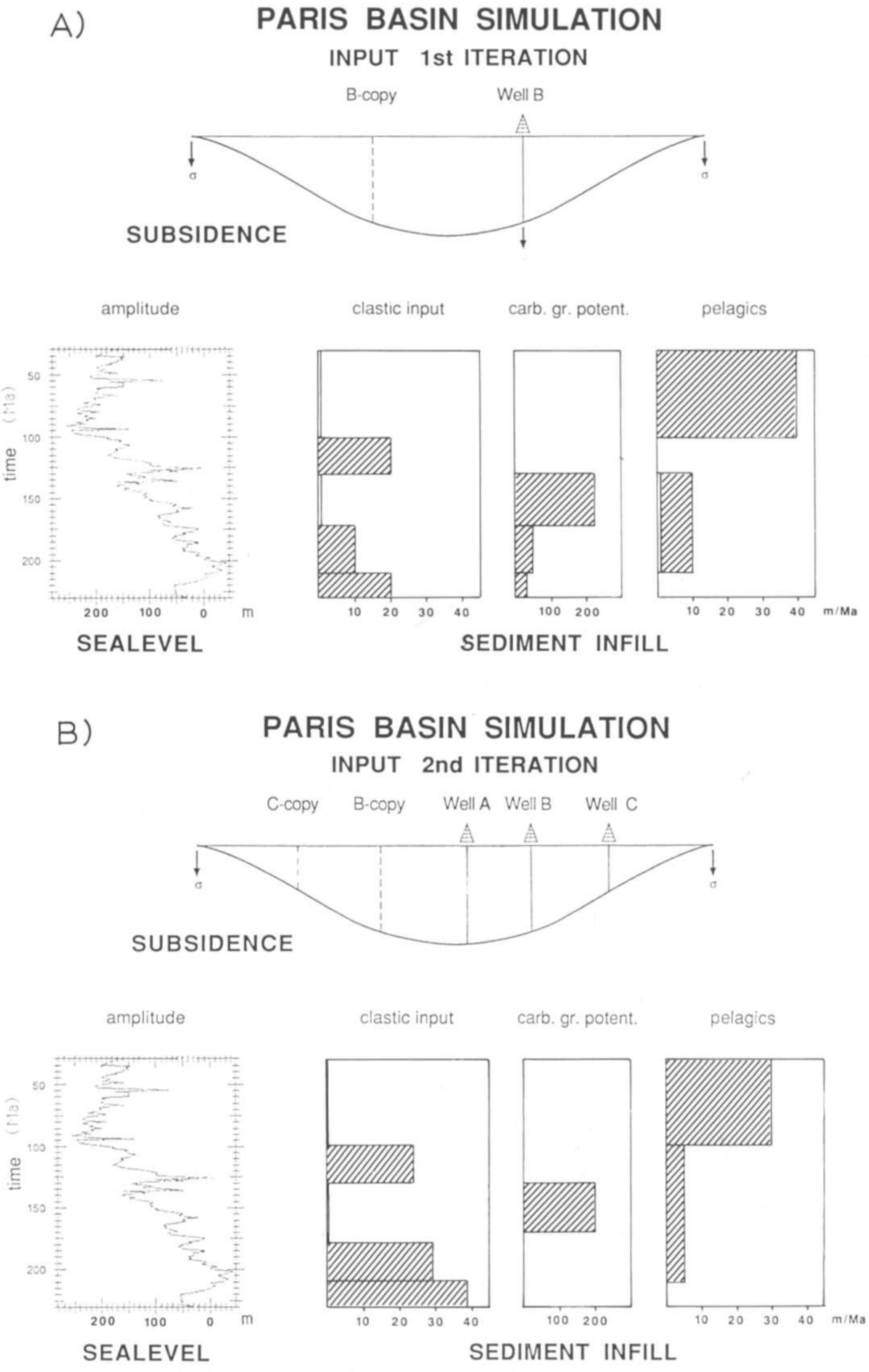

Fig. 10. Input parameters used in the simulations of the Paris Basin (see Figs. 11 and 13). A. First iteration. B. Second iteration.

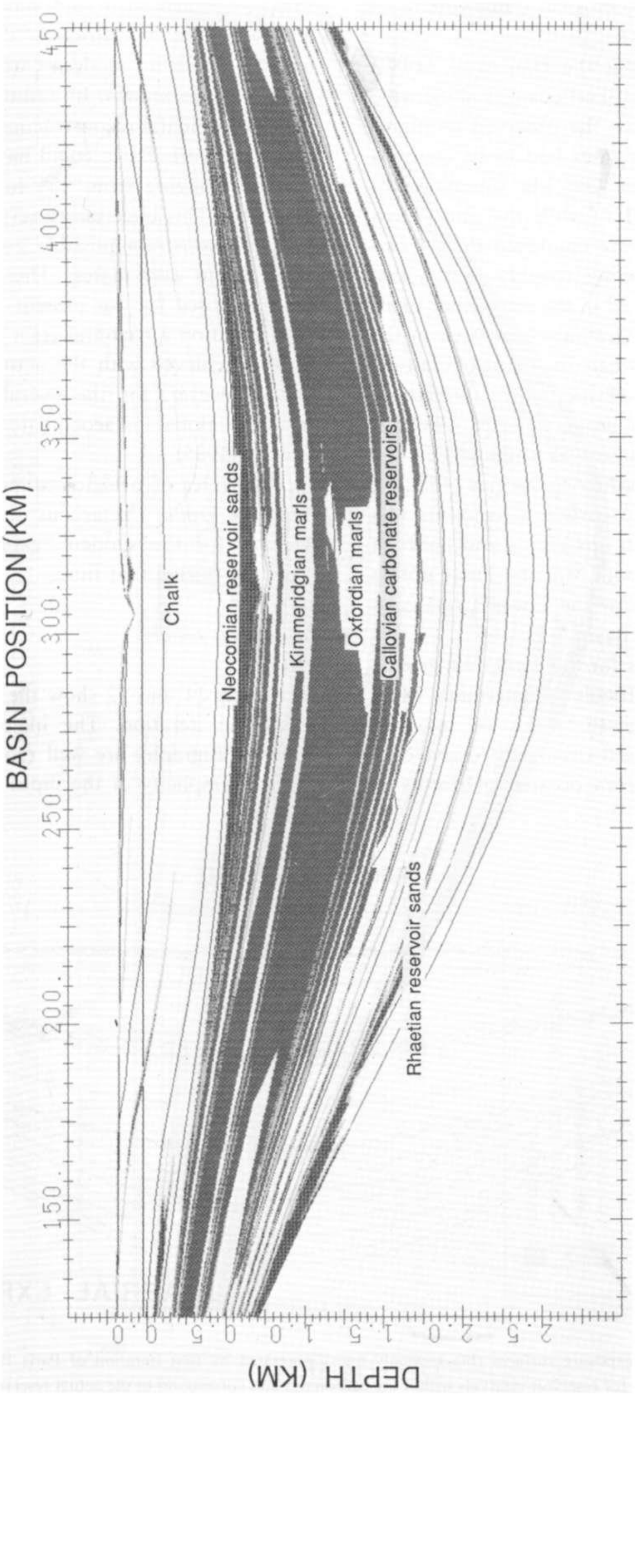

Fig. 11. Result of first iteration of simulating the Paris Basin (compare to Fig. 9). For input parameters see Fig. 10.

lated to rifting in the North Sea. This is in agreement with the regional geological framework (Ziegler, 1982; Brunet, 1986).

For the sea-level input the Haq et al. (1987) curve was employed. Sea-level changes alone were not sufficient to produce the observed stratigraphy, and sedimentation rates had to be changed several times during the 200 Ma simulation in order to obtain a good fit with the data. High rates of clastic input were employed during two time periods corresponding roughly to the two phases of rifting employed in the subsidence modelling. A first major clastic pulse was used in the Late Triassic (Keuper), when uparching of cratonic highs caused a strong clastic influx throughout many Middle European Basins (Ziegler, 1982). A second major clastic pulse was employed in the Early Cretaceous. According to Ziegler (1982), a rifting phase during the earliest Cretaceous was accompanied by regional upwarping and uplift of the Armorican and Brabant Massifs. These uplifts acted as major sources for the Lower Cretaceous clastics filling the Paris Basin.

The input parameters for the carbonate growth potential were more difficult to determine. Most measurements of growth rates of modern carbonates come from well-circulated passive continental margins and from oceanic platforms in tropical to subtropical settings (e.g. Schlager, 1981). The Paris Basin carbonates, however, clearly represent a more restricted "epicontinental" setting for which no modern carbonate growth rate analogues are known. In addition, since available palaeocontinental reconstructions differ from each other, the Paris Basin could have been situated in latitudes ranging from 20° to 40°N during the Mesozoic. This uncertainty severely limits any attempt to constrain possible growth rates for the Paris Basin carbonates. Therefore, the growth potential used for our present simulations had to be derived on a trial-and-error basis, until a good fit was achieved with the actual basin cross-section. However, for the overall trends, use was made of global palaeoclimate compilations (e.g. Hallam, 1985).

High rates of pelagic sedimentation were used from the Upper Cretaceous onwards, in order to account for the sudden "explosion" of nannoplankton during that time.

Modelling: results

Figures 11 and 12 show the results of the first modelling iteration. The major features of the basin stratigraphy are well reproduced, considering the simplicity of the input parameters. Nota-

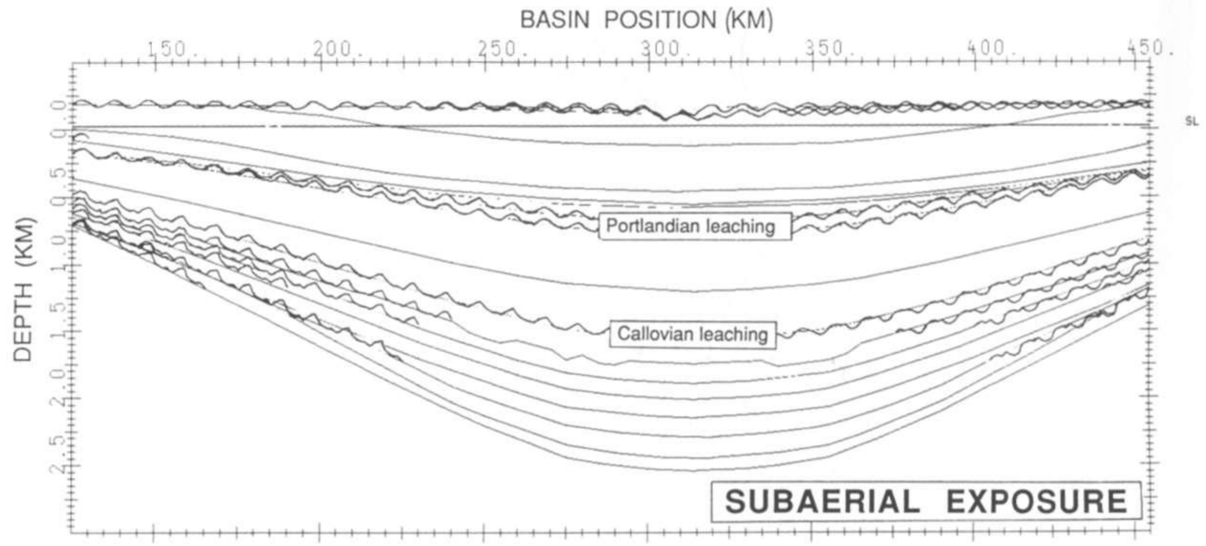

Fig. 12. Predicted subaerial exposure surfaces (black wiggly lines) generated by first iteration of Paris Basin simulation. These highlight the potential for reservoir intervals within the carbonates and correspond to the actual reservoir occurrences.

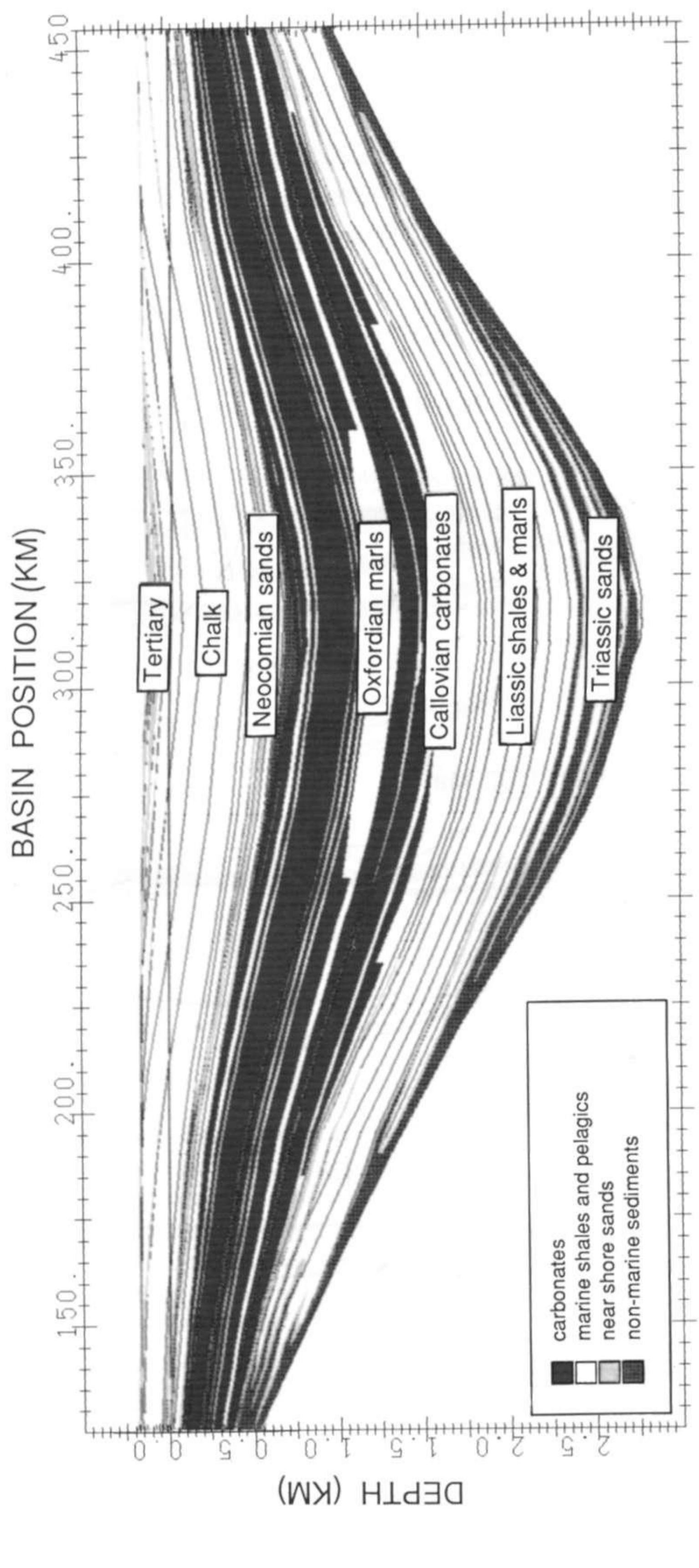

Fig. 13. Result of second iteration of simulating the Paris Basin (compare with Fig. 9). For input parameters see Fig. 10B.

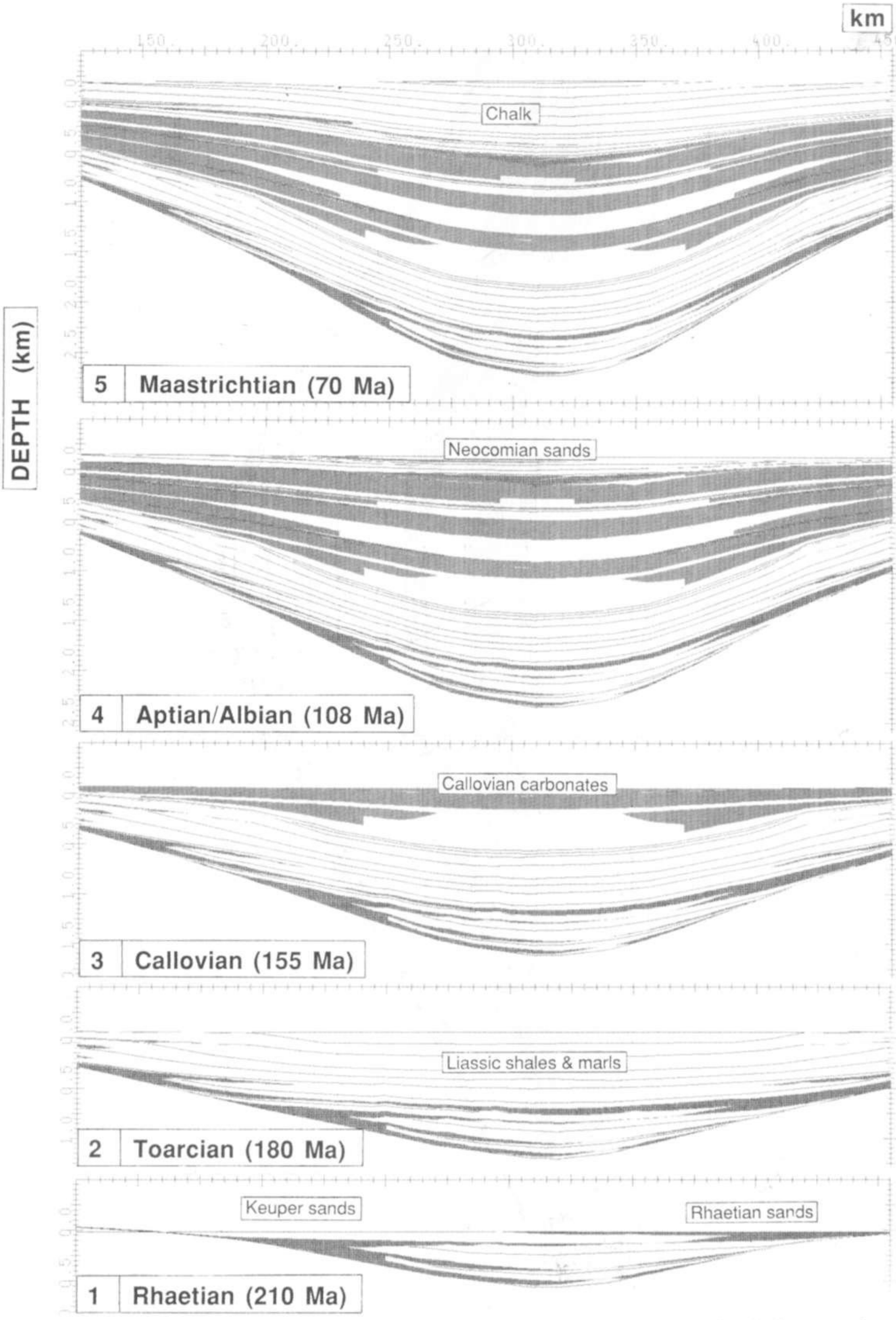

Fig. 14. Simulations showing the step-wise evolution and filling of the Paris Basin through time. Note that the Keuper sands are shed from the left, while the Rhaetian sands are derived from the right.

bly, the occurrence of two major carbonate reservoir packages caused by subaerial exposure was simulated correctly (Fig. 12). However, the distribution of the Triassic sands, and the overstep by the Jurassic sequence, are not satisfactorily modelled.

In order to adequately simulate the basin configuration, one input point for the tectonic subsidence is not sufficient. Thus, for a second modelling iteration, data from two more wells were used for the tectonic subsidence input (Fig. 10B). For this second simulation run, the same sea-level curve was used and the sediment infill was modified slightly with respect to the first modelling iteration.

Figure 13 shows the model results using these refined input parameters. Clearly this second iteration has more accurately reproduced the observed basin stratigraphy, especially in the Triassic package. Note that clastic input rates in this simulation are symmetrical from the left and from the right basin margins. However, from regional geological analysis it is clear that the Keuper sands were shed dominantly from the SW (left), the Rhaetian sands from the NE (right), and the Neocomian sands again from the SW (Mégnien, 1980). Consequently, in a third modelling iteration, the clastic input rates were varied along the southern and northern basin margins. The simulations of Fig. 14 incorporate these differences and show the step-wise evolution and filling of the Paris Basin through time.

Discussion

The above simulations demonstrate how an actual basin stratigraphy can be reproduced by stratigraphic computer modelling using relatively simple input parameters. Most surprisingly, data from only one well proved sufficient to simulate adequately the gross features of the basin fill. Obviously, the more well data and regional geological knowledge are incorporated, the more accurate are the simulations obtained. The present case represents a calibration study with the advantage of a relatively simple basin stratigraphy, a well-known regional geological picture and a sea-level curve that has been calibrated nearby (the Mesozoic part of the Haq et al., 1987 sea-level curve has been calibrated in European outcrop sections). However, the program was not yet able to simulate to our full satisfaction the particular type of epicontinental "restricted" carbonates of the Paris Basin. In order to reproduce the observed stratigraphy, abrupt changes in the input carbonate growth potential were necessary. Intuitively, such drastic changes in the input values do not appear to be realistic. This highlights the fact that our knowledge on temporal and spatial variations of carbonate growth potential is still very rudimentary.

Conclusions

The quality of stratigraphic simulation results depends on the degree of knowledge of the input parameters, such as the subsidence history, the timing and amplitude of eustatic sea-level changes, the history of sediment input rates through time, and on the capability of the program package to cope with the actual geological situation. Continuing improvements of the program algorithms and extensive testing in a variety of geological settings is therefore the subject of ongoing research.

In many simulation applications, some of the input parameters can be constrained by regional geological knowledge and already available data. In other applications there may be fewer constraining data, which makes predictions more difficult. Extensive data bases on carbonate growth potential, clastic input rates, sea-level changes etc. will thus have to be compiled. A better understanding of these key parameters on a local, regional or global scale will in the future enhance the predictive power of stratigraphic basin modelling.

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