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Rift Basin Sequence Stratigraphy: Some Examples from the Gulf Of Suez

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ABSTRACT

Unconformity-bounded sequences within the Miocene strata of the Suez Rift reflect a complex interplay between tectonism and sea level fluctuations. Analyses of Miocene outcrops along the Sinai margin of the Gulf of Suez provide new insights into the sequence stratigraphy of this basin. The Miocene strata can be subdivided into seven major sequences separated by biostratigraphically defined time breaks. These lacunae represent depositional sequence boundaries, transgressive surfaces and condensed sections. These basinwide time breaks were related to major tectonic events from rift initiation through rift climax, and post-rift stages. These events include regional sag and fault initiation, fault linkage, footwall uplift, shallowing of detachment depths and increased fault block rotations, regional isostatic uplift, and thermal subsidence. Superimposed on this complex structural evolution were Miocene sea level fluctuations of a magnitude of several tens of meters to a hundred meters. The Sinai outcrops expose the four oldest Miocene biostratigraphic sequences which correspond to two depositional sequences. The lower sequence consists of the Nukhul Formation which was deposited during a transgression (with the higher frequency events recorded as local erosional surfaces, flooding surfaces, and ravinements) and the Mheiherrat Formation which was deposited during a relative high stand. The upper sequence includes the Asl Formation which was deposited during a low stand and the Ras Budran Member of the Ayun Musa Formation which was deposited during the ensuing high stand.

INTRODUCTION

The Gulf of Suez (Figure 1) originated as a rift during the latest Oligocene-Early Miocene and continued through the Late Miocene (Tortonian) when active extension ceased (Patton et al., 1994). This area is attractive for the study of sequence stratigraphy in rifted basins since the early to mid-rift deposits are well exposed and biostratigraphic studies have resulted in a detailed chronostratigraphy (Krebs et al., 1995 and in press). Additionally, there is abundant well control with which to correlate across the rift. This paper describes some of the characteristics of the early to mid-synrift deposits exposed on the Sinai margin of the Suez Rift and attempts to integrate them within a sequence stratigraphic framework.

STRATIGRAPHY

The Miocene synrift interval is divided into seven well-defined biostratigraphic sequences, each of which is separated by a time break. These time gaps are regional and can be recognized in both wells and outcrop using graphic correlation techniques (see Mann and Lane, 1995, for background on composite standard and graphic correlation techniques). Locally, unconformities may merge and some sequences are absent. On composite standard graphs, breaks in time or lacunae, are represented by horizontal slopes. Consequently, in composite standard nomenclature, all breaks in time, including unconformities, condensed intervals, and ravinement surfaces (surfaces of marine transgression) are referred to as terraces.

In the Gulf of Suez, the pre-rift-Miocene unconformity is designated T_{00}. The first biostratigraphic sequence is designated S_{10} and is separated from S_{20} by T_{10} and so forth. Each of these lacunae also has a conventional name as do the formations comprising the biostratigraphic sequences, although they may change from place to place within the rift. The Lower to Middle Miocene outcrops along the Sinai margin of the Gulf of Suez encompass four biostratigraphic sequences (Figure 2) which are the subject of this paper.

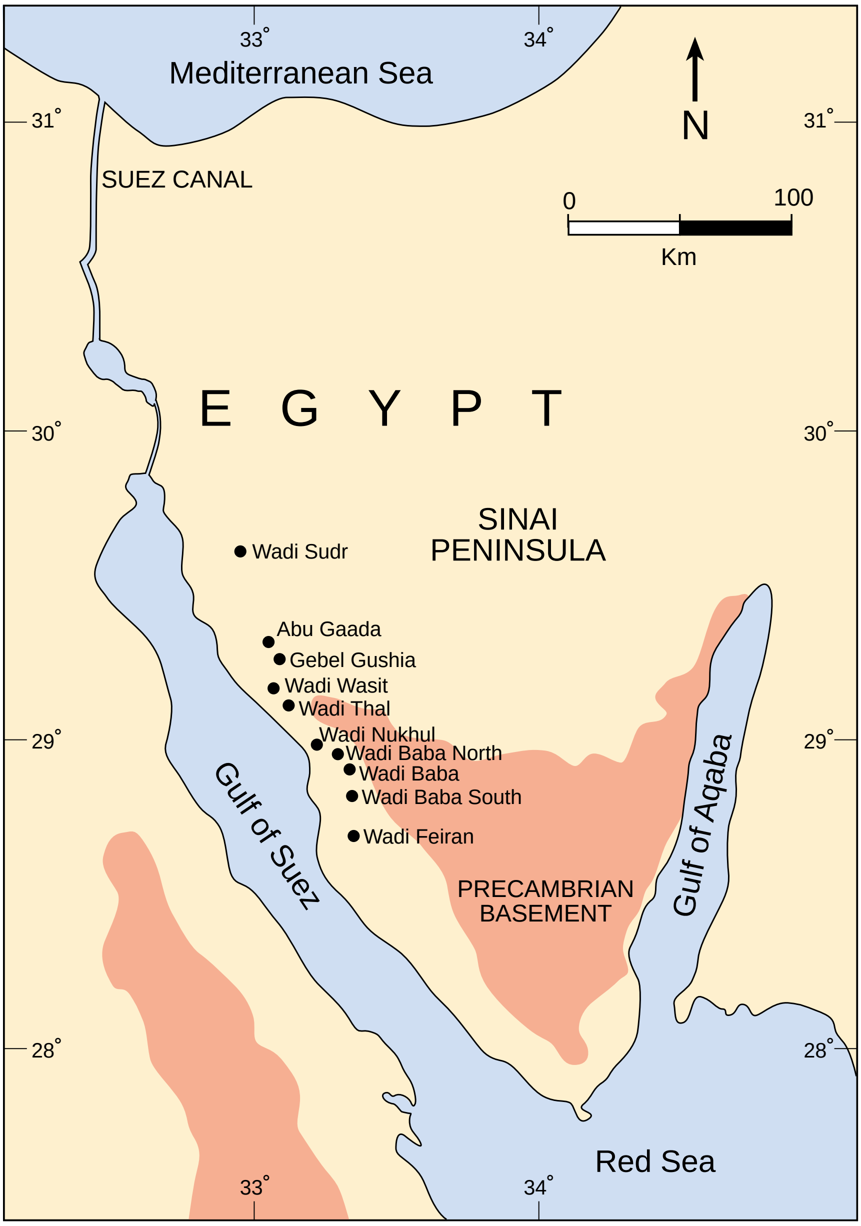

Figure 1: Locations of Miocene outcrops along the Sinai margin of the Gulf of Suez examined in this study.

The biostratigraphic sequences do not correspond to depositional sequences in the sense of Vail et al. (1977). However, the resultant sequence stratigraphy of the Early Miocene deposits in the Suez Rift reflect the complex interplay of rift tectonics and eustatic sea level changes that occurred at various scales of periodicity.

TECTONICS

Rifts evolve from continental extension to mid-ocean spreading ridges, although the cycle can end at any point along the continuum, frequently before sea-floor spreading. The rifting phase can be subdivided into three episodes (Figure 3; Prosser, 1993): (1) rift initiation (sag phase), (2) clysmic phase (rift climax), and (3) post-rift (thermal subsidence phase). All of these phases are recognized in the Suez Rift. The present day configuration of the Gulf of Suez area is the result of Miocene extensional tectonics and the basin is classified as a failed rift. The structure of the basin has been studied in great detail (e.g., Garfunkel and Bartov, 1977; Steckler and Watts, 1980; Steckler, 1985; Buck, 1986; Chenet et al., 1986; Omar, 1989) and the most detailed summation of the tectonic history of the Suez Rift was presented by Patton et al. (1994).

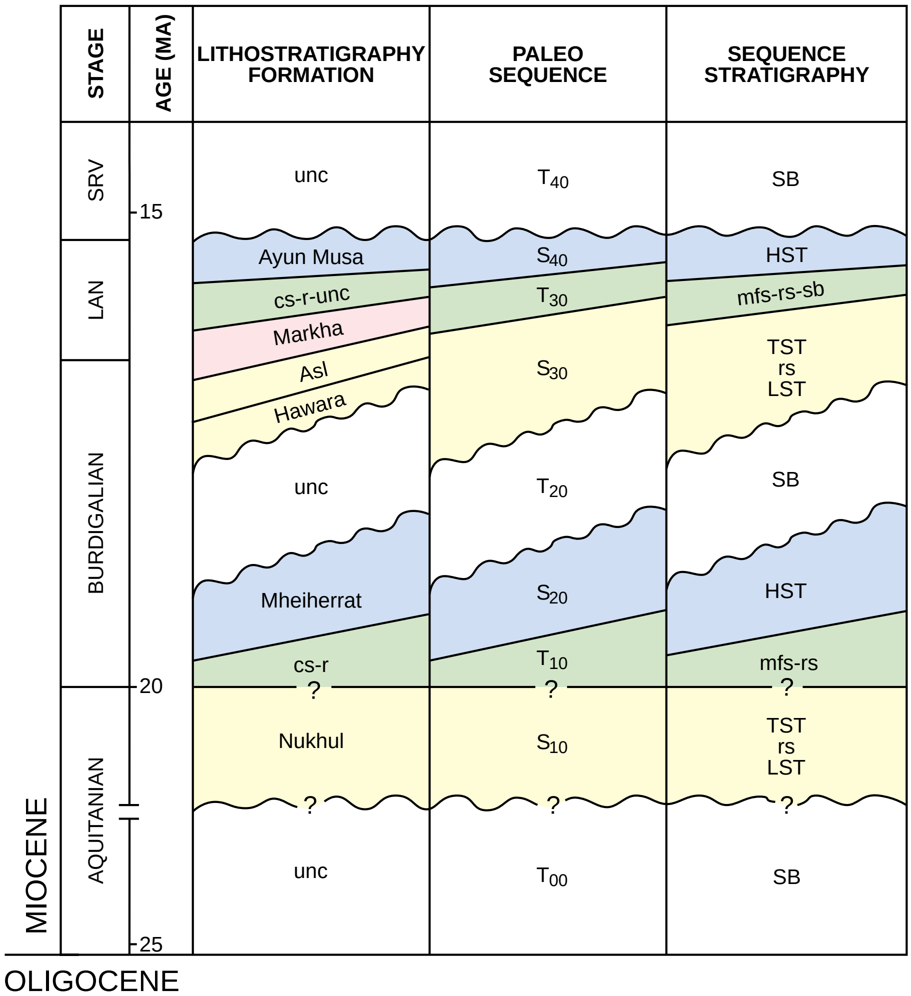

Figure 2: Stratigraphic column for the Lower and Lower Middle Miocene Gulf of Suez (after Krebs et al., in press). SB indicates sequence boundaries or major time gaps; yellow indicates: low stand systems tract (LST), ravinement surface (rs) and transgressive systems tract (TST); green: transgressive intervals including maximum flooding surfaces and ravinement surface (mfs-rs); blue: high stand systems tract (HST). Other abbreviations are: (cs) condensed section, (r) ravinement, (unc) unconformity, (sb) lower order sequence boundary, (LAN) Langhian, (SRV) Serravallian.

Rift Initiation (Sag Phase)

The Suez Rift began during the Aquitanian as a broad downwarping of the Eocene surface accompanied by normal faulting. As the land subsided, the Tethyan Sea slowly migrated across the area. Remnants of paleosols and weathering zones on the Eocene surface can be seen in the lower portion of the Gebel Gushia section, Wadi Thal, and Wadi Nukhul (Figure 1). Fluvial deposits in the Aquitanian Nukhul Formation occur in Wadi Thal and Wadi Nukhul. Elsewhere in the Sinai, the basal Nukhul Formation is characterized by shallow marine deposits that record the initial marine transgression.

Clysmic Phase (Rift Climax)

Initial isostatic uplift of the rift shoulders marked the commencement of the clysmic phase of rifting. At this time, the major rift-bounding faults were established and many other early forming faults became inactive or much less active with most of the strain now taken up by the bounding faults. Increased subsidence resulted in maximum flooding conditions at this time. Additionally, uplift and rotation of the rift shoulders rearranged the drainage systems that delivered sediment into the basin. Initially, fluvial flow was directed away from the rift resulting in sediment starvation in its deeper parts. As the drainage systems re-equilibrated, deltas formed on the rift margins and again brought coarse clastic sediments into the rift. Uplifted source terrains, high relief, and maximum subsidence rates together resulted in conditions that were favourable for gravity driven sedimentation and the deposition of basin-floor fans.

This phase of tectonic evolution of the Suez Rift is documented by the Mheiherrat Formation (S_{20}). Along the Sinai margin of the Suez Rift the best examples of S_{20} deposition can be seen at Gebel Gushia, Wadi Baba North, and Wadi Baba South.

Isostatic Adjustment

The culmination of the clysmic phase was characterized by maximum thinning of the crust and resultant isostatic uplift of the basin. It also was accompanied by a decrease in the depth of detachment; the zone of transition between brittle and ductile extension using the pure shear model of McKenzie (1978) and Kusznir et al. (1991). At this time, the depth of detachment decreased from approximately 20 to 30 kilometers (km) to 10 km, which resulted in increased rotation of fault blocks (Perry and Schamel, 1985; Moretti and Colletta, 1988). This event is represented by a regional lacuna that is recognized biostratigraphically and is designated as T_{20}. In outcrop this break in time is recognized at Gebel Gushia, Wadi Baba South, and Wadi Feiran.

At Gebel Gushia, T_{20} is represented by a submarine unconformity. At this location, normal faults are truncated by this unconformity and overlain by the Asl Formation (S_{30}). In Wadi Baba South the lacuna is not as apparent, but is marked by a change in sedimentation to shallower water deposition, an increase in sand, and a zone of sediment deformation at the point of the lacuna. At Wadi Feiran T_{20} is represented by a marine transgressive surface on top of the Eocene limestones which are intensively bored.

After the T_{20} event, new sedimentary patterns were established within and on the margins of the rift (see previous discussion for summary). The Hawara and Asl (S_{30}) deposits are exposed at Wadi Abu Gaada, Gebel Gushia, Wadi Baba South, and Wadi Feiran. A hiatal interval comprising high frequency sequence boundaries and condensed intervals is reflected as T_{30}, which is overlain by the Lagia and Ras Budran members of the Ayun Musa Formation. T_{40} is not exposed in outcrop but based upon subsurface interpretations it is believed to be a low stand erosional surface.

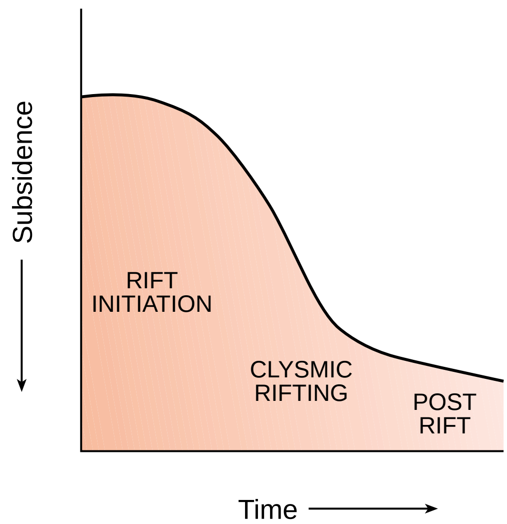

Figure 3: Diagram showing the changes in relative subsidence rates through time during the three major phases of rift development.

SEQUENCE STRATIGRAPHY

The stratal architecture of the Gulf of Suez can be discriminated on several different orders. Firstly, there are the sequences that can be defined paleontologically; however, since biostratigraphically detectable lacunae can be caused by several different events and conditions (Figure 4), the composite standard T-boundaries do not always correlate to true stratigraphic or depositional sequence boundaries. They can occur at regressive surfaces of erosion, where part of the sedimentary record is eroded due to sea level fall, at ravinements and related transgressive surfaces of erosion, and at condensed intervals, where sedimentation rates are so slow that several fossil zones are not preserved (Hallam, 1988). Depositional sequences are bounded by regional erosional unconformities generated by relative sea level fall. The bounding surfaces are regressive surfaces of subaerial or submarine erosion (Van Wagoner et al., 1988). Therefore, of the three categories of lacunae listed above, only one, the first, constitutes a depositional sequence boundary. The number of depositional sequences, related to long-term relative sea level changes in the Suez Rift should, therefore, be expected to be smaller than the number of biostratigraphically defined sequences.

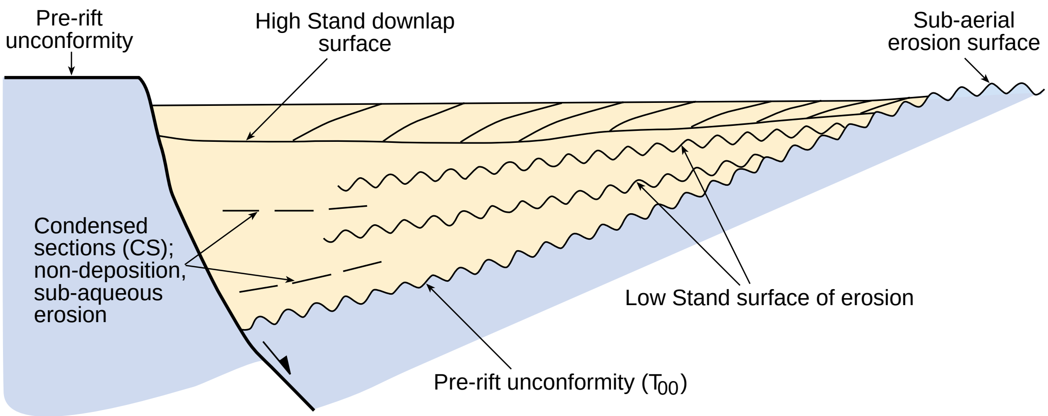

Figure 4: Diagrammatic representation of the various types of lacunae possible within an active rift.

Secondly, there are numerous small-scale, high order stratigraphic surfaces that can be put into a sequence framework that reflect autocyclic and eustatic sea level shifts. The major events controlling the sequence stratigraphy of the Suez Rift, however, are the tectonic processes responsible for extension, uplift, and subsidence. Consequently, through the entire Lower Miocene (Aquitanian and Burdigalian) there are only two depositional sequences: from T_{00} to T_{20} and T_{20} to T_{40} (see Figure 2).

Tectonostratigraphic Sequence 1 (T_{00}-T_{20})

Pre-Rift to Early Syn-Rift Sequence Boundary (T_{00})

A major regional unconformity separates the Miocene from the underlying Eocene marine carbonates in most places in the Sinai. The chalk and chert-rich Eocene carbonates were deposited in relatively deep open marine environments (several hundreds of meters). Therefore, this unconformity records a relative sea level drop of similar magnitude. This widespread erosional surface was the result of a broad regional uplift that affected northwest Arabia and the Sinai (Quennell, 1984), and the proposed major global eustatic sea level fall that occurred in the middle Oligocene (Haq et al., 1987). Additionally, there may have been a subtle doming of the region during the pre-rift phase, perhaps related to the active Red Sea rifting at that time (Quennell, 1984; Patton et al., 1994). The fact that nearly the entire Eocene carbonate package, which is only a few hundred meters thick, survived the Oligocene uplift and / or eustatic fall argues that the amount of erosion concomitant with the uplift was not very severe.

Low Stand Systems Tract

The rift initiation phase in the Suez area is represented by the Nukhul Formation. These rocks presently occupy a series of small low relief sub-basins on the hanging wall of larger, younger basins. An example of one of these small, kilometer-scale basins that exhibit marked changes in thickness of the Nukhul strata over a lateral distance of a few hundred meters is visible in outcrop at Wadi Wasit. Patton et al. (1994) argue, based upon isopach maps, that the basinal relief during Nukhul deposition was probably less than 200 meters (m). This is consistent with the depositional systems interpretation, which implies that the depositional surface was within a few meters above or below sea level during the rift initiation phase of the Suez Rift. Therefore, rates of deposition at this time kept pace with the rate of subsidence, suggesting relatively moderate subsidence rates. This is consistent with the characteristics of the rift initiation phase of other rifts (Prosser, 1993).

Transgressive Systems Tract

The vertical succession within the Nukhul Formation grades from non-burrowed, pebbly sandstones and mudstones at the base, to burrowed, finer-grained sandstones and mudstones near the top (Figure 5). The basal section is unfossiliferous, the middle contains large numbers of low-diversity coquinas, while the upper part contains a more diverse fauna of echinoids, bivalves, and gastropods. Crossbedding is ubiquitous throughout the Nukhul Formation, indicating traction-flow dominated depositional systems. We interpret the Nukhul as generally fluvial (sinuous) in its oldest portions, transitioning upward into a complex of estuarine and related coastal facies, which constitute the bulk of the formation. The uppermost Nukhul comprises open marine deposits.

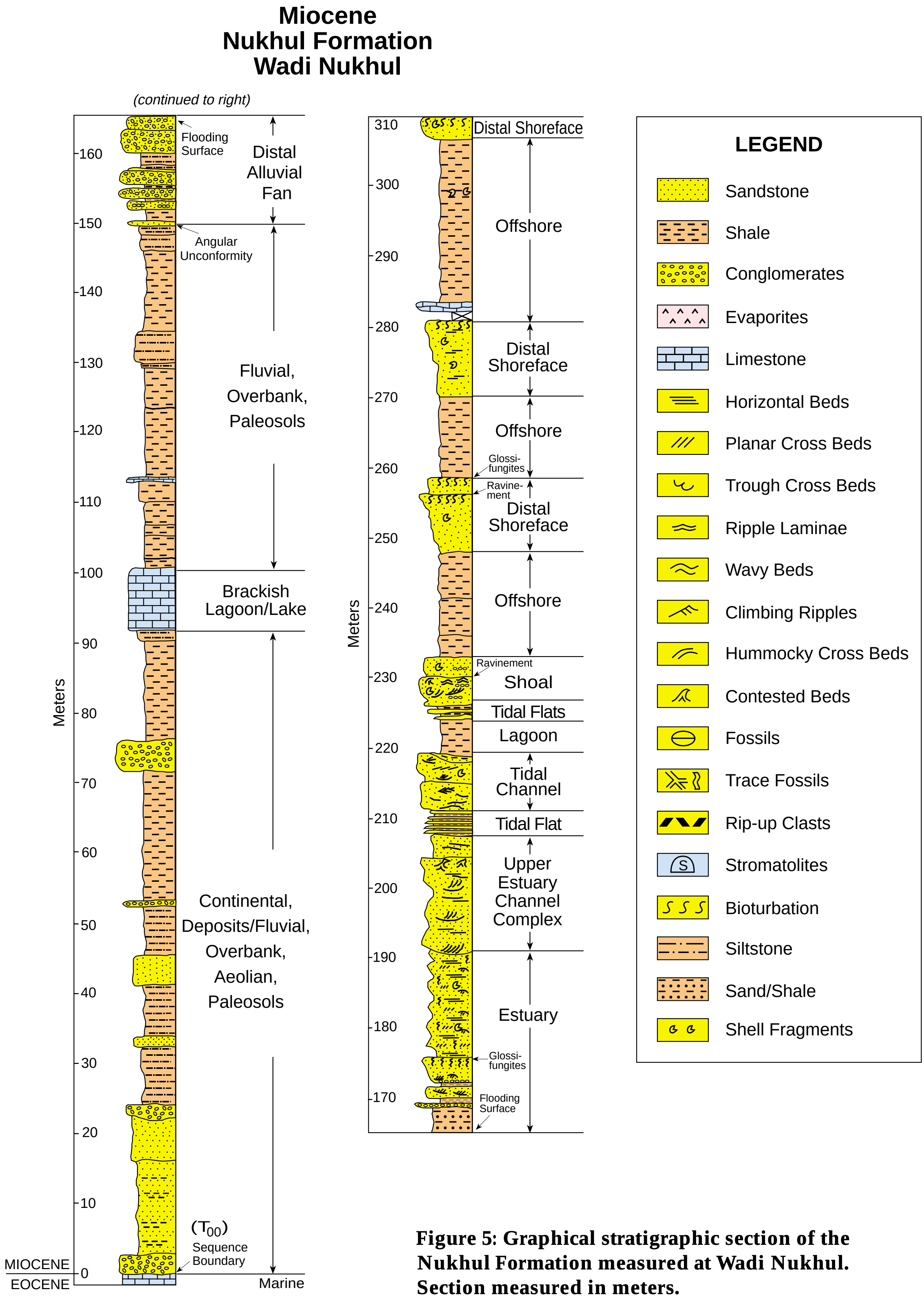

Figure 5: Graphical stratigraphic section of the Nukhul Formation measured at Wadi Nukhul. Section measured in meters.

The boundary between low stand and transgressive systems tracts is the surface that corresponds to a shift in the shoreline migration from progradation below to transgressive above. This transgression corresponds with the shift from fluvial to estuarine deposition systems within the Nukhul Formation. This surface (or surfaces) is clearly seen in outcrop at Wadi Nukhul, Wadi Thal, and Wadi Wasit.

The early synrift basins were infilled by the Nukhul sediments during a series of transgressions and regressions probably driven by high-frequency climatic cycles. Evidence for this is the existence of several erosional surfaces associated with the *Glossifungites* trace-fossil assemblage, which represents burrowing into firm substrates. A common way of producing these features is to have a relative sea level fall that essentially drains an estuary causing subaerial exposure. During the subsequent relative sea level rise, salt water organisms (mostly crustaceans) will “bore” into the flooded firm ground producing the unlined, cylindrical burrows that characterize the *Glossifungites* ichnofacies. The overall repetitive stacking of several tidal-channel complexes and flood tidal delta lobes, bay ravinements, and open marine ravinements, within the Nukhul Formation also argues for several episodes of relative sea level change during the Aquitanian.

High Stand Systems Tract

At about the Aquitanian-Burdigalian boundary, the Suez Rift entered the clysmic (climax phase of Prosser, 1993) phase of tectonism. Strain shifted from numerous small faults to fewer larger ones. Consequently, differential rates of subsidence increased: the new and larger half grabens subsided faster than the smaller ones and footwalls were uplifted faster and higher because of isostatic rebound due to unloading of the crust. One consequence of greater footwall uplift was the diversion of drainage away from the rift, thus reducing the rate of sediment supply. The combination of these factors shifted the balance between subsidence and sedimentation greatly in favor of the former, and the basins deepened dramatically. Benthic forams in the lower Mheiherrat Formation record deep water marine deposition.

Several Gulf of Suez studies have suggested that the water depths during the early Burdigalian may have been as deep as 1,000 m, implying that the differential relief in the clysmic rift was at least that great (Beleity, 1984; Evans, 1988). The generation of this much relief implies that the subsidence rates were much greater than during the Aquitanian. This interpretation is also supported by subsidence curves calculated by Moretti and Colletta (1987) and Steckler et al. (1988).

Maximum Flooding Surface

The “transgressive unconformity” or T_{10} lacunae is recognized biostratigraphically at about the Aquitanian-Burdigalian boundary. In outcrop, this surface (or surfaces) occurs near the Nukhul-Mheiherrat contact, and always above the thick estuarine deposits in the Nukhul Formation. In some localities, e.g. Wadi Thal, T_{10} (Figure 6) appears to be close to or at the ravinement surface, while at other spots like Wadi Nukhul and Wadi Baba North, it lies above the offshore (calcareous sandstone) facies of the Nukhul Formation. Therefore, this time break is interpreted as a maximum flooding surface. The stratigraphic thickness between the ravinement surface and the maximum flooding surface at the different localities simply records the offshore transgressive sedimentation at that site and probably reflects its relative structural position within the rift.

Tectonostratigraphic Sequence 2 (T_{20}-T_{40})

T_{20} Sequence Boundary

The T_{20} surface is referred to as the “mid-clysmic unconformity” and is manifested as a significant lacuna in the late Burdigalian. In outcrop along the Sinai margin the surface commonly (but not everywhere) forms a distinct, erosional break (Figure 7). Also, this lacuna does not correspond to a consistent lithostratigraphic boundary in the subsurface (Patton et al., 1994).

The tectonic origin of T_{20} remains controversial; however, it appears to have occurred at the time when the zone of detachment between the upper brittle plate and the lower ductile zone reached its shallowest level (Moretti and Colletta, 1988). At this time there is also evidence that the dip-oriented extension of the Suez Rift was transferred to the Aqaba wrench fault system (Steckler et al., 1988). Although extension continued, it progressed at a much slower rate. The reduction in the extension rate and increased rotation of the fault blocks due to the reduced depth to detachment resulted in deactivation of many of the

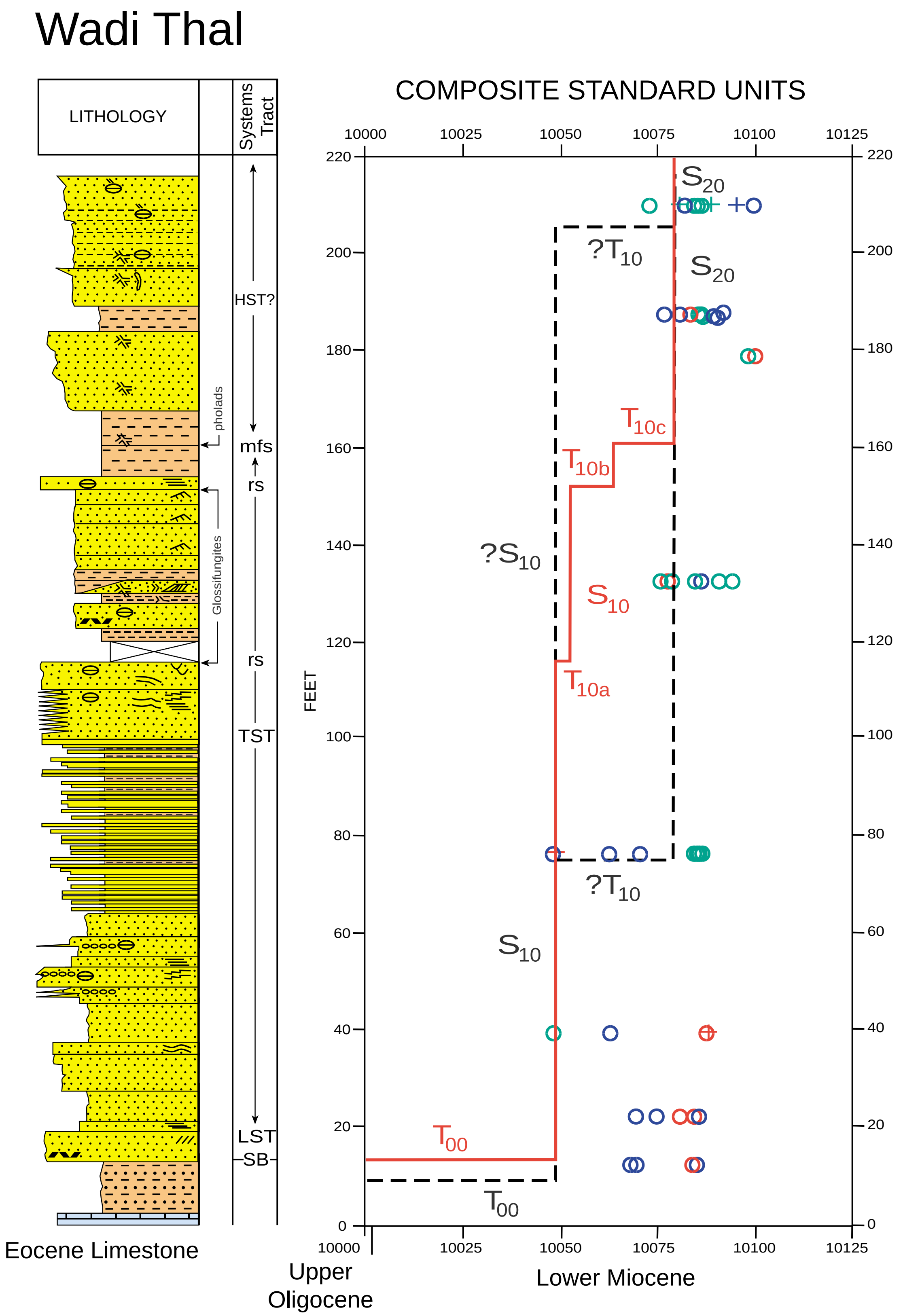

Figure 6: Measured stratigraphic section from Wadi Thal with the graphic correlation cross-plot (from Krebs et al., in press). The solid line is the paleontological line of correlation (LOC), and the dashed line is the inferred LOC. Abbreviations are as follows: (CSU) composite standard units; (SB) sequence boundary; (rs) ravinement surface; (mfs) maximum flooding surface; (LST) low stand systems tract; and (HST) high stand systems tract. Crosses and circles represent the youngest and oldest occurrences, respectively, of calcareous nanofossils (green), planktonic forams (red) and benthic forams (blue).

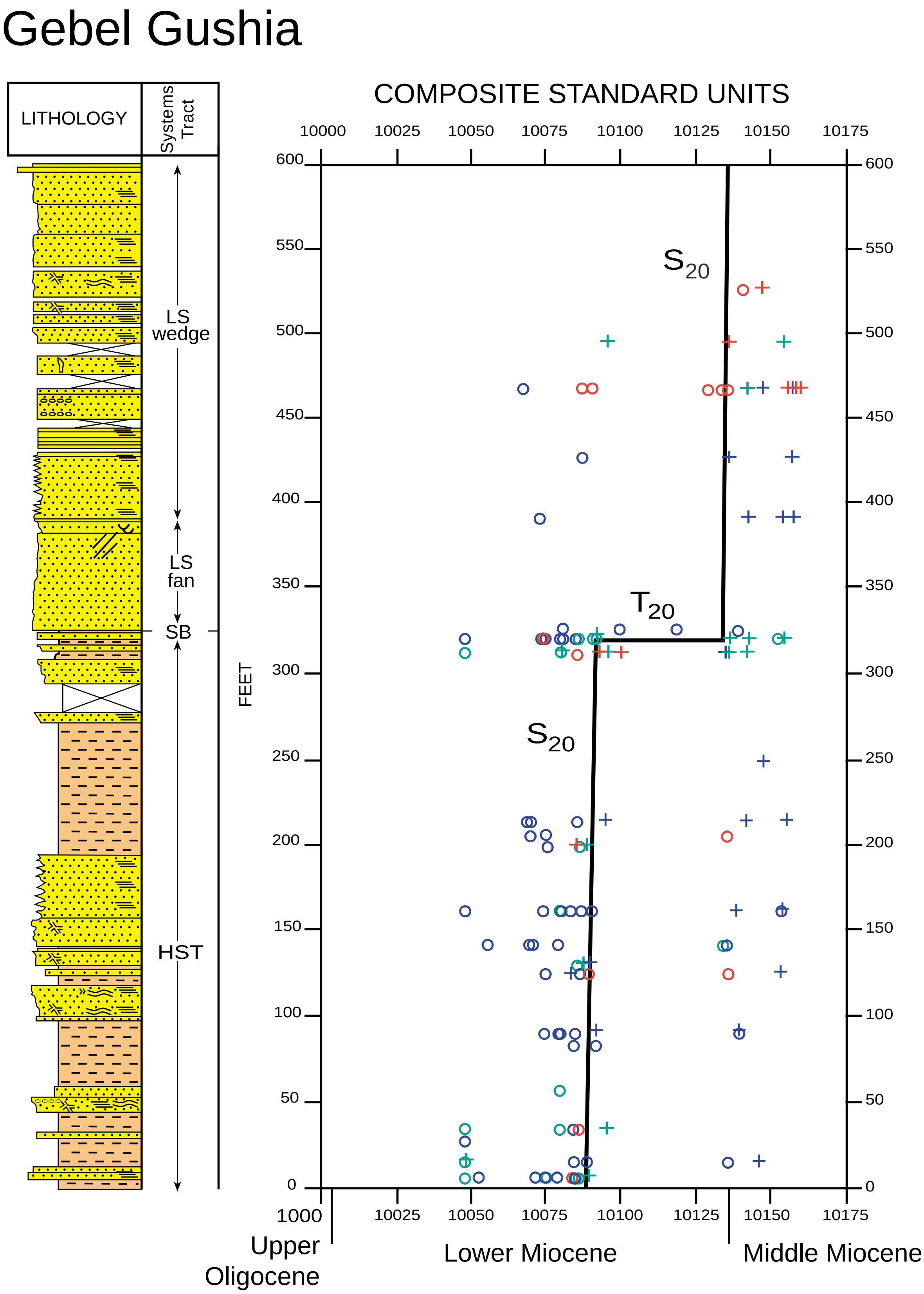

Figure 7: Measured stratigraphic section and graphic correlation of the Gebel Gushia section (from Krebs et al., in press). See Figure 6 for definitions of abbreviations.

extensional faults. This greatly reduced subsidence in the brittle, block faulted upper plate. Gartfunkel and Bartov (1977) documented that many faults terminate below the mid-clysmic unconformity. Such a fault termination below T_{20} is seen in outcrop at Gebel Gushia. The net result was isostatic rebound of the lower ductile plate and a regional uplift cutting a widespread unconformity across footwall highs.

Low Stand Systems Tract

The low stand systems tract of the second tectonostratigraphic sequence overlies the T_{20} unconformity. At this time erosion intensified on the uplifted footwall blocks as evidenced by an increase in the percentage of basement clasts in the sedimentary pile. Further evidence of regional uplift is that major conglomerate and sand bodies are shifted basinward relative to their locations in the underlying sequence.

At Gebel Gushia, the T_{20} lacuna is a submarine erosional or bypass surface with relatively deep water sandy basin-floor fan deposits below it. Above the surface there is a dramatic upward increase in clast size, the ratio of debris flow and high density turbidites relative to distal turbidites, and a pronounced development of large-scale accretion beds of a channelized submarine fan system (Figure 8). This represents an abrupt facies change from a distal to a proximal submarine fan system. We infer that this shift records a relative sea level fall, erosion at the base of a submarine channel system at the head of a fan, followed by a gradual infilling of the fan valley once sea level stabilized and began to slowly rise again.

An additional piece of evidence for low stand deposition during S_{30} is the widespread presence of Asl carbonates in the northeast platform area of the rift (Schutz, 1994). The rate of marine carbonate production decreases exponentially with depth (Schlager, 1992). Therefore, in modern rifts carbonate production is limited to bathymetric highs. The deposition of Asl carbonates across the northeast rift platform, therefore, suggests widespread low stand conditions such that this area was well within the photic zone and oxygenated layer.

The Hawara shale facies of S_{30} is also a low stand deposit. It is roughly age equivalent with and a facies of the Asl, but is generally overlain by the sandy facies of the latter because of the progradational geometry of both submarine fan and deltaic systems that formed these deposits. Because the shales were deposited in more distal systems, and therefore generally deeper into the basins, very few Hawara exposures were created during the subsequent shoulder uplift.

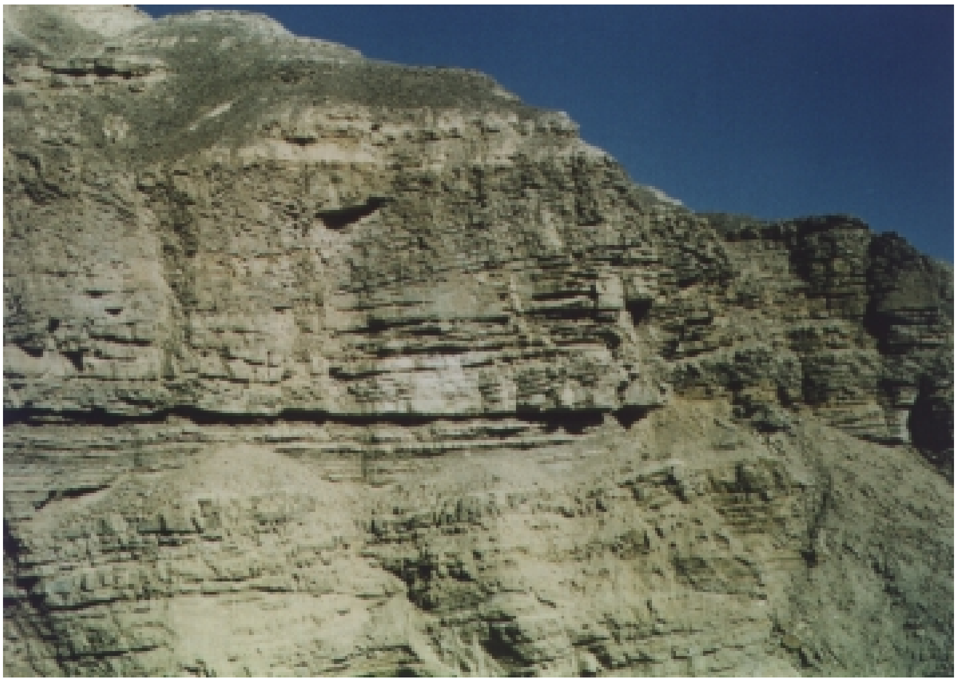

Figure 8: Photo of the T_{20} sequence boundary at Gebel Gushia. Turbidite sandstones of the Mheiherrat Formation, below the sequence boundary (arrow), were deposited as part of a submarine fan complex. Above T_{20} are large-scale cross-beds of the Asl Formation deposited in channelized fan complex.

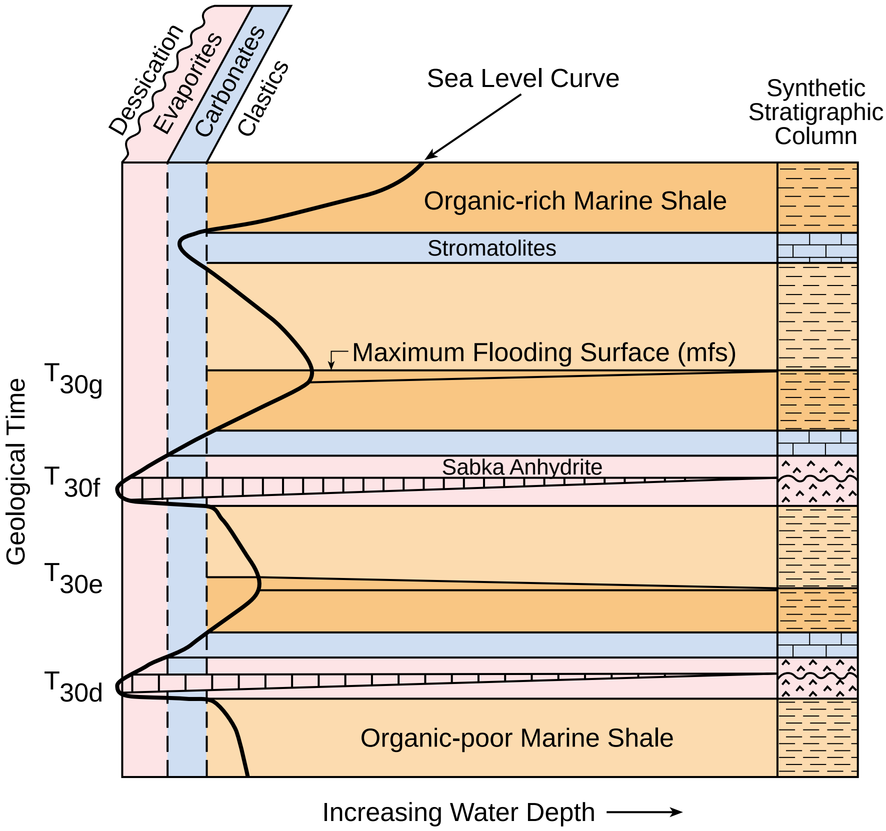

Figure 9: The diagram shows the interpreted depositional model for the stratigraphic sequence at Wadi Feiran. Lower order sequence boundaries (sb) and maximum flooding surfaces (mfs) are associated with small lacuna (T_{30d} to T_{30g}) related to short-term sea level fluctuations.

Transgressive Systems Tract

The transgressive systems tract above T_{20} is best exposed at Wadi Feiran. At this locality, T_{20} occurs topographically higher than it did at Gebel Gushia, and T_{20} was initially a subaerial surface that was subsequently flooded by a marine transgression. A very well developed suite of *Glossifungites* borings on this surface supports this interpretation. All of the Asl depositional environments at Wadi Feiran (estuarine, shoreface, and regressive delta front) represent a transgressive systems tract.

Most of the transgressive systems tract of the T_{20}-T_{40} sequence is represented by the Markha and Lagia members of the Ayun Musa Formation. The relatively abrupt surface on top of the uppermost delta-front sandstone bed at Wadi Feiran is interpreted as a ravinement surface, across which deposition shifted from the coastal plain to shallow offshore settings when deltaic sedimentation was abruptly shut off. This ravinement surface probably lies within the transgressive systems tract. The overlying succession of repeated evaporites, stromatolites, and shales records a long-term sea level rise with superimposed high-frequency sea level oscillations (Figure 9).

The presence of lacustrine shales in this sequence at Wadi Abu Gaada is also evidence for overall transgression during this time. Lakes frequently develop in low lying areas during long-term sea level rise in response to the associated rise in the ground water table.

High Stand Systems Tract

On graphic correlation plots the T_{30} lacuna is interpreted as a maximum flooding surface. T_{30} is not a distinct physical surface but a composite of high-order sequence boundaries and condensed intervals (Figure 10). This suggests that during this time sedimentation was relatively continuous in most of the sub-basins, albeit at very low rates.

At Wadi Feiran, the section above the uppermost maximum flooding surface (above the second evaporite) represents the high stand systems tract. In the Wadi Feiran area, this interval (Ras Budran) is a prograding clastic wedge with well-developed clinoforms downlapping onto the T_{30} interval (Figure 11). These clinoforms and sandbody geometries represent prograding deltas. Although not exposed in the sections we examined, the T_{40} sequence boundary is believed to overlay the Ras Budran deltaic wedges and the Upper Kareem Formation (S_{50}) represents the low stand phase of the next sequence.

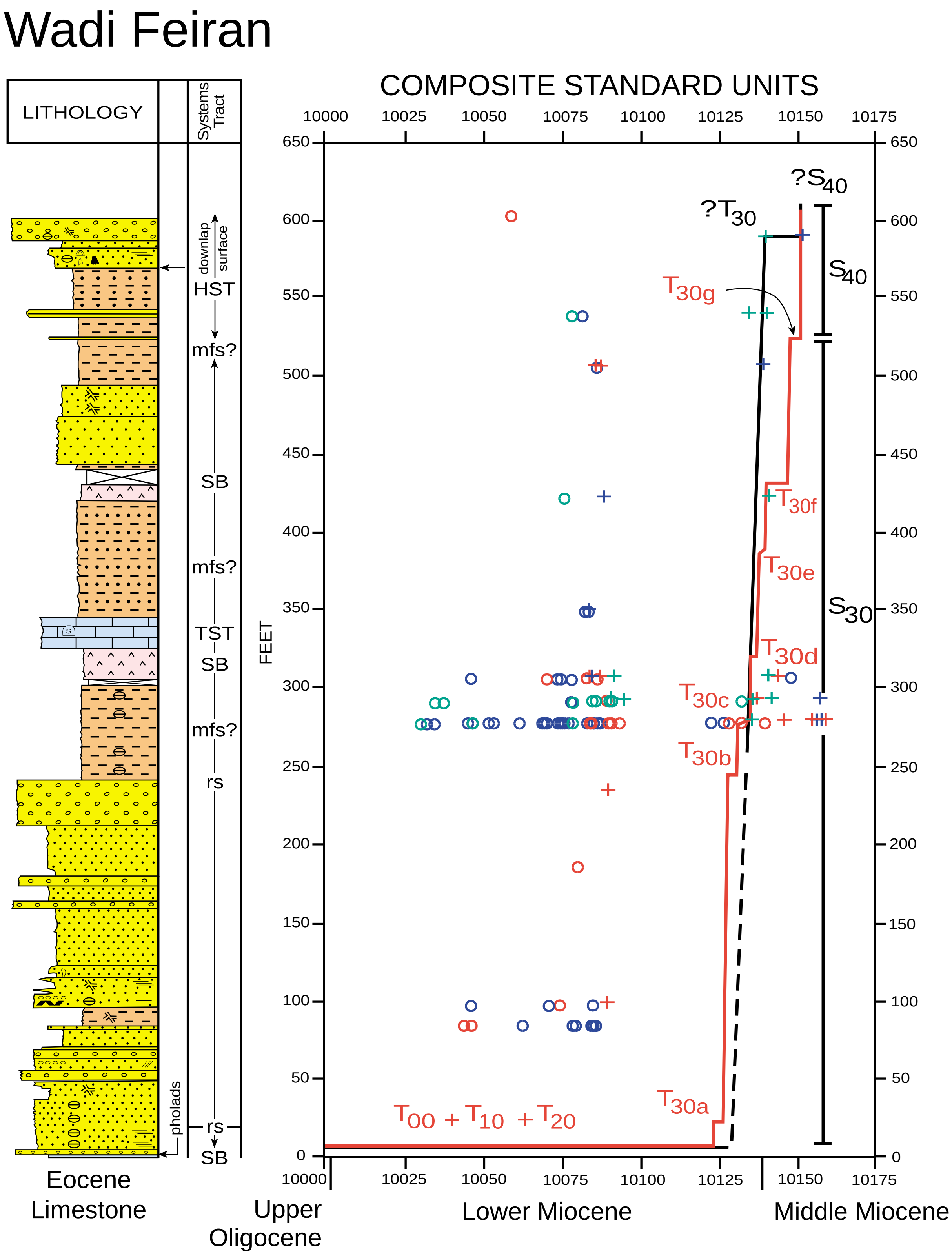

Figure 10: Graphic correlation and measured stratigraphic section from Wadi Feiran (from Krebs et al., in press). See Figure 6 for definitions of abbreviations.

Figure 11: Photograph of the large-scale prograding foreset beds of the Ras Budran Formation at the top of the Wadi Feiran section.

CONCLUSIONS

The detailed study of the Miocene strata exposed on the Sinai margin of the Suez Rift within a rigorous chronostratigraphic framework has resulted in a better understanding of the relative effects of tectonics and eustasy in controlling the stratal architecture of the synrift deposits, especially during the rift initiation and clysmic (climax) phases of rifting. Some of the major conclusions are as follows:

(1) Major rift tectonic events, including regional subsidence and initiation of extensional faulting, thermal uplift of rift shoulders and concomitant basinal subsidence, and isostatic re-equilibration were the major control on relative sea level and facies distributions during the rift initiation and major extensional period of rifting. However, higher order eustatic sea level fluctuations superimposed on the longer term tectonic events resulted in a complex ordering of depositional and erosional surfaces.

(2) Within the Miocene strata of the Suez Rift there are several sequences that can be defined paleontologically; however, since biostratigraphically detectable lacunae can be caused by several different mechanisms, the composite-standard defined time gaps do not always correlate to true stratigraphic sequence boundaries. They can occur at regressive surfaces of erosion, where part of the sedimentary record is eroded due to sea level fall, at ravinements and related transgressive surfaces of erosion, and at condensed intervals, where sedimentation rates are so slow that several fossil zones are not preserved. Therefore, of the three categories of lacunae listed above, only one, the first, constitutes a depositional sequence boundary. The number of depositional sequences, related to long-term relative sea level changes in the Suez Rift is, therefore, less than the number of biostratigraphically defined sequences.

(3) An understanding of the tectonostratigraphic framework and sequence stratigraphy of the Suez Rift allows us to develop better predictive models for the distribution of reservoir and seal facies. For example, in the deepest and oldest portions of the basin we can expect to find fluvial/continental facies of the Nukhul Formation. These were predominantly deposited by north flowing axial fluvial systems. This suggests that in the northern part of the gulf or beneath the Suez Canal region, there may be deltaic facies deposited at the point where the axial systems initially entered the Mediterranean Sea. Also, the most likely interval in which to expect basin-floor fans is in the S_{20} to early S_{30} bio-sequences since this was the time of maximum relief during the clysmic phase of rifting. Major deltaic facies should be

expected only in the intervals S_{40} and younger as this was the time that active extension waned and the basin topography infilled. S_{50} and younger represent the post-rift phase. During this time active extension was transferred to the Aqaba wrench trend and the Suez Rift was dominated by thermal and compactional subsidence. During this phase eustasy probably played a greater role in controlling stratal architecture than tectonics.

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