RESPONSE OF INTRASHELF BASINS TO EUSTASY, PLATE TECTONICS AND PALEOGEOGRAPHIC POSITION

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ABSTRACT

Carbonate depositional systems often respond almost instantaneously to fill the accommodation space caused by relative sea level change. Phanerozoic platform carbonates commonly contain thick successions of meter-scale aggradational cycles, filling accommodation space and maintaining very low-relief depositional topography landward of a well-defined platform margin. Widespread carbonate platform lithosomes of the geologic record are exemplified by sections of the Cambro-Ordovician of North America, the Khuff Fm. (Permo-Triassic) on the Arabian Plate and much of the Mesozoic of the Gulf Coast.

These periods of extensive platform carbonate accumulation were punctuated by episodes during which the platform margin retreats large distances onto the platform to form a new margin. Next, this new margin aggraded and prograded towards the original platform margin position while, seaward, local carbonate accumulated and caught up with sea level rise forming a barrier which isolated an Intrashelf Basin (ISB). For example, recent studies of carbonate depositional systems in the Arabian Gulf region have recognized at least four such periods of intrashelf basin formation during the Jurassic and Cretaceous: early Toarcian, Oxfordianto early Tithonian, late Aptian-early Albian, and late Turonian-early Cenomanian.

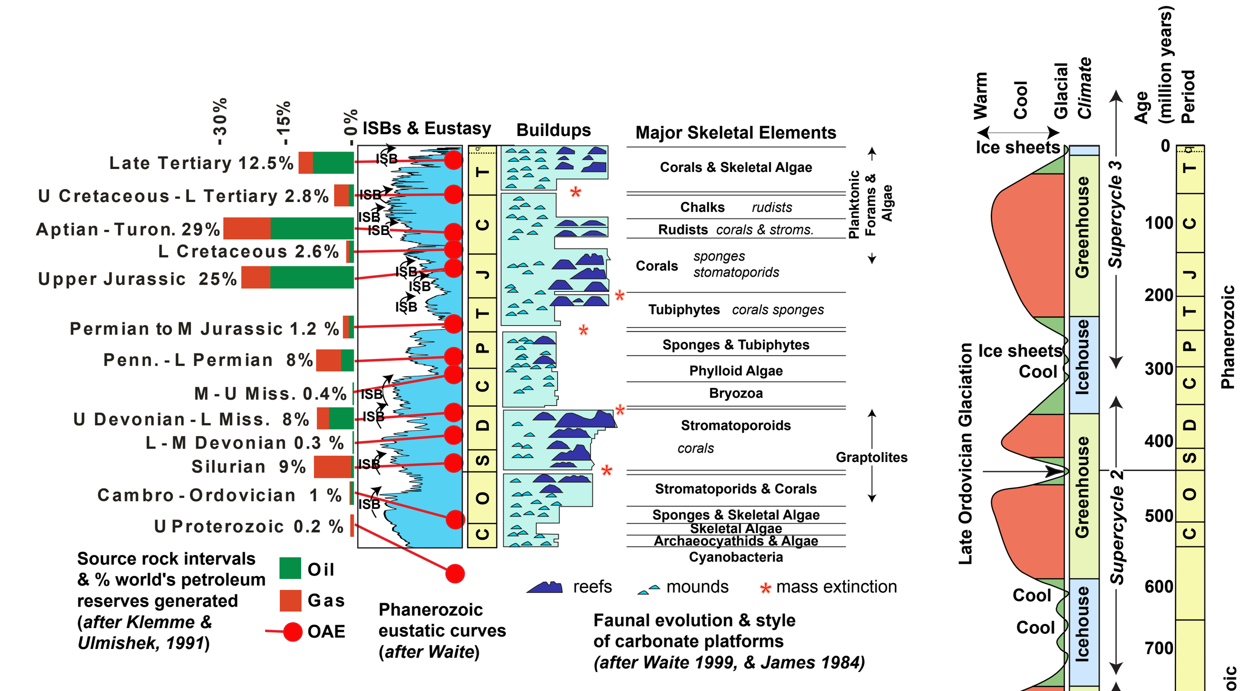
Similar episodes of widespread intrashelf basin formation can be recognized in the Paleozoic: Silurian (Michigan, Illinois, and Appalachian basins); Devonian (Williston-Western Canadian Sedimentary basin, and Canning basin – Western Australia); Early Carboniferous (numerous basins with Waulsortian buildups in North America and NW Europe), and Permo-Pennsylvanian (Permian and Midland basins, Paradox basin, and Sacramento Mts).

Most of these episodes of intrashelf basin formation were accompanied by basin starvation and deposition of organic-rich source rocks which subsequently matured and charged oil and gas reservoirs. In the Middle East, these source rocks include the basinal Toarcian Marrat, the Kimmeridgian Hanifa-Najmah-Naokelekan, the “tar” zone of the Bab Member of the Shuaiba Fm., and the Shilaif Fm. All of these except the Hanifa-Najmah-Naokelekan are also recognized as Oceanic Anoxic Events (OAEs).

Platform margin retreat can be correlated to changes in the width and length of the ridge system and/or rates of spreading and so a response to changes in the volume of the ocean basin. These reorganizations of the plate tectonic system coincide with larger-than-normal changes in sea level, causing the carbonate depositional systems to go from a “keep up” mode to “catch up” and then to “give up.” The area of significant carbonate deposition retreats to shallower portions of the platform, where aggradation gradually forms a new intrashelf platform margin which subsequently progrades and infills the intrashelf basin until the margin returns to its original position. These intrashelf basin histories can be subdivided into distinct stages and recreated in computer simulations that model rates of sediment accumulation, and relative sea level change.

Concomitantly, the high rates of fill of the carbonate depositional systems of the above listed intrashelf basins are controlled by favorable humotropic paleogeographic positions in the rain shadow leeward of giant continents. Understanding of the detailed linkage between carbonate accumulation, plate tectonic history, and paleo-climate enhances our ability to better correlate and predict the character of intrashelf basin sedimentary fill.

Interaction of Phanerozoic Platform Carbonates, Intrashelf Basins (ISBs), Eustasy, Climate, Oceanic Anoxic Events (OAEs) and Carbon Productivity



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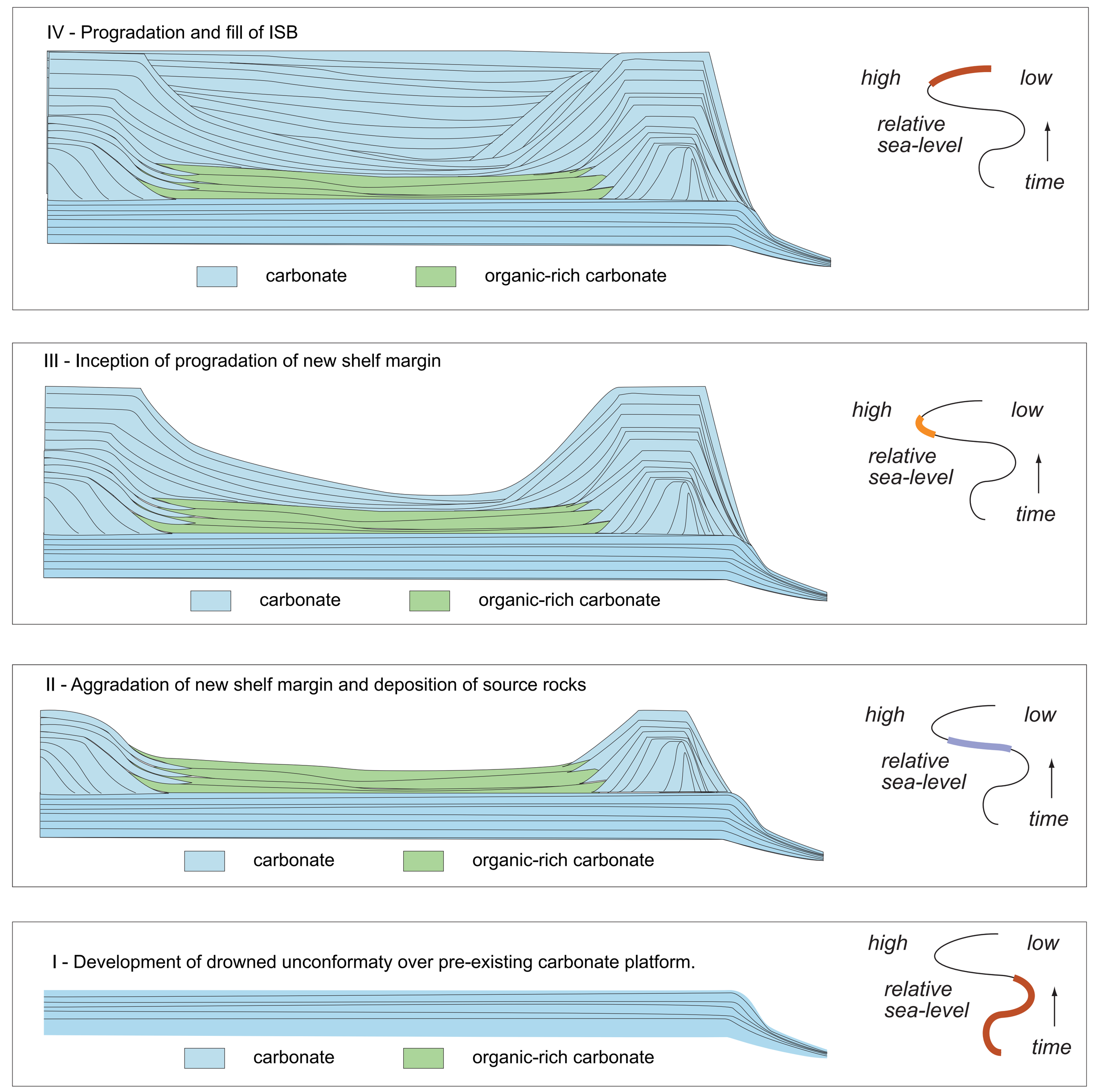
The geologic column captures Phanerozoic platform carbonate depositional system fill that reflects eustasy and instantaneous fill of accommodation. Concomitant intrashelf basin phases developed in Silurian ISBs with reefs in the Illinois, Michigan, and Illinois basins. In the middle and late Devonian, ISBs have stromatoporid reefs which developed in the western Canadian and Western Australian basins. In the latest Devonian, the Chattanooga-Woodford-Percha-Bakken-Exshaw source rock interval (OAE) preceded development of Tournaisian Waulsortian reefs as part of basin fill. This was also true of Western Europe, particularly the Carboniferous of Ireland and Great Britain. During the Permo-Triassic the Khuff Formation accumulated on the Arabian Plate on a broad platform, while in West Texas and New Mexico the Permian Basin developed. The Mesozoic of the Arabian Plate developed ISBs in the Jurassic and Cretaceous while the Gulf Coast of the USA saw a parallel development.

Gondwanaland’s breakup affected source rock potential. The Mesozoic section of the Middle East accumulated in tropical latitudes along the south-eastern margin of the Tethys Ocean exhibiting strong ties between plate setting and climate. This can be used to understand the occurrence of organic matter, evaporites and rain shadow zone. The proximity to the continental margin and the ISBs formed during and following continental break up and collision were associated with arid climates and accumulation of organic matter in the marine setting. The alternating beat of greenhouse and icehouse climatic events (illustrated above), in conjunction with the effects of transgressions and super-plumes, helped nutrients to flourish and to eventually be sequestered. The above diagram tracks the resultant significant source rocks through time, particularly on the Arabian plate, and explains why the ISBs were so rich in organic material which we propose were sequestered during rapid marine transgressions.

The eustatic changes in sea level that affected the Phanerozoic geological column were caused by both glacially induced eustasy and changes in ocean basin shape associated with combined changes in volume of global mid-oceanic ridge system and the orogenic compression of continental crust. The volume increase in mid-oceanic ridges during faster sea-floor spreading caused marine transgressions while slower rates caused regressions. We propose that the paradigm of Phelps et al. (2014) be extended beyond the Cretaceous to most Phanerozoic carbonate platform behavior. matching periods of intense submarine volcanism along mid-ocean ridges and large igneous provinces. We support the contention that when volcanism increased atmospheric carbon dioxide concentrations to at least four times the modern level, this initiated the global greenhouse climates recorded on the diagram. As with Phelps et al. (2014), where a glacio-eustatic signal is lacking (Huber et al., 2002; Miller et al., 2005; Forster et al., 2007) we associate mid-ocean ridge volcanism with first-order eustatic sea-level peaks and, like others (Hallam, 1971; Hays & Pitman, 1973; Kominz, 1984; Haq et al., 1987; Sahagian et al., 1996; Miller et al., 2004), we agree that submarine volcanism is the primary driver of both second order eustatic signal and third-order signals. In addition, we argue that occurrences of Phanerozoic OAEs generally coincided with emplacement of large igneous provinces (Sinton & Duncan, 1997; Weissert & Erba, 2004). We agree with Phelps et al. (2014) that oceanic anoxic events reduced rates of carbonate sediment production and caused deposition of shale intervals on many carbonate platforms (Follmi et al., 1994; Weissert et al., 1998).

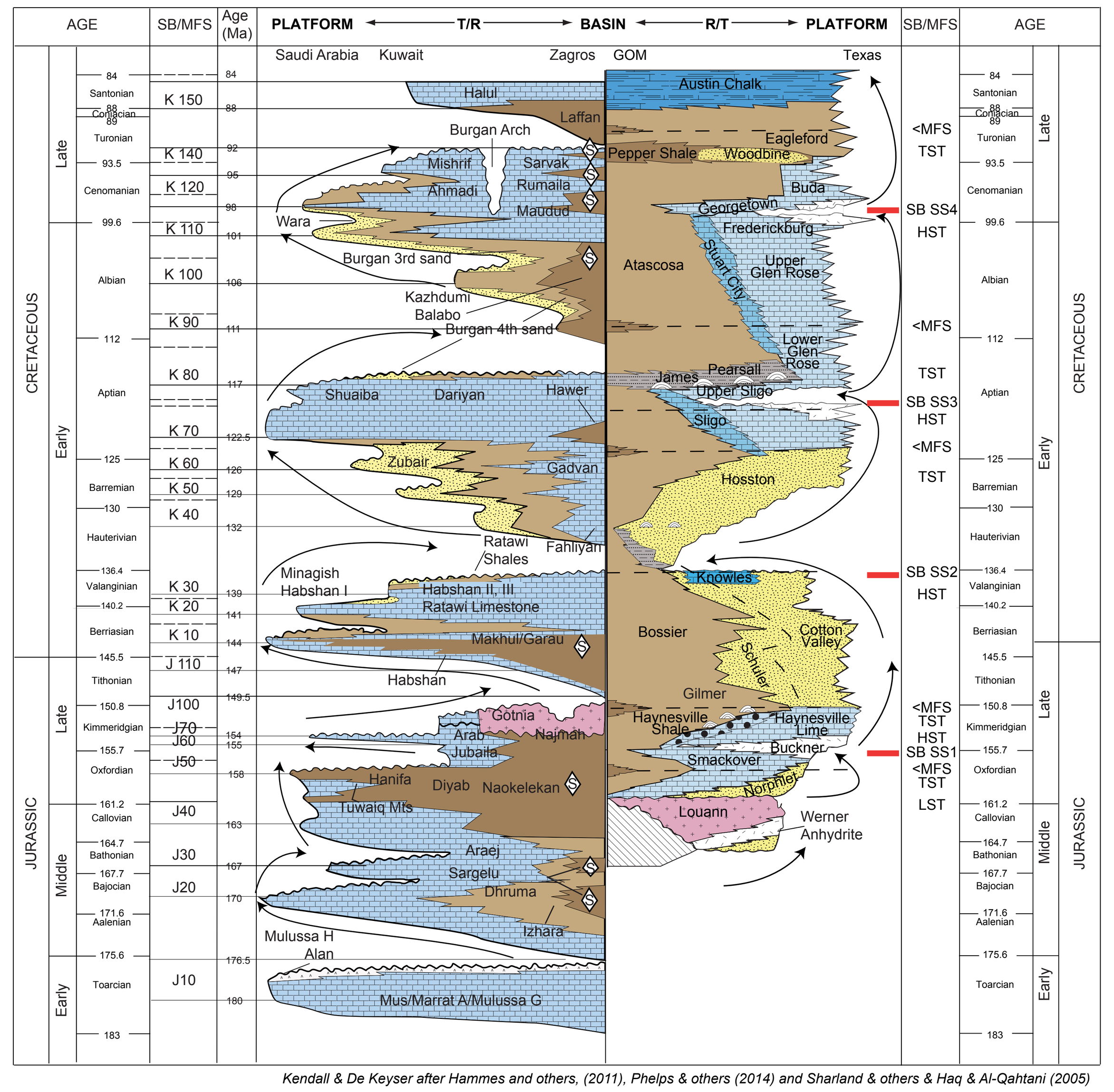
Relationship of Four Stages of ISB Development to Sea Level



The sedimentary section of the Arabian Plate Mesozoic accumulated during the AP 7 Megatectonic Cycle. Local ISBs formed while rifting occurred in the Mediterranean Sea, the Indian Ocean, and along the Tethyan margin. The Mesozoic sedimentary sections in the ISBs overlying the Arabian Plate are a mix of carbonates, evaporites, and organic-rich carbonates that collected behind barriers formed by tectonic movement on what was an original Hercynian horst and graben terrain adjacent to the southern shore of the Tethys Ocean. These barriers accumulated sediment over them and restricted access to the sea. An arid climatic setting is suggested by punctuation of the geologic record by the evaporites, carbonates, and associated source rocks. The ISBs contained isolated bodies of seawater with restricted entrances to the open Tethys Ocean. Regional drainage probably tended to flow into the basin interior and the air system was arid tropical. There was a wide envelope formed by the surrounding Gondwanaland’s subcontinents of Arabia and Africa.

The geometry and facies of the fill of the ISBs is interpreted to be a response to: (I) a rapid sea level rise, exceeding carbonate production, resulting in a retreat of the margin to the platform interior followed by, (II) aggradation of the new margin while condensed, organic-rich sediments accumulated in the starved basin center. The ISB margin then (III) prograded and (IV) infilled the basin, which was commonly less than 100 m deep.

Jurassic/Cretaceous Chronostratigraphy, T-R cycles and OAEs of Middle East and Gulf of Mexico

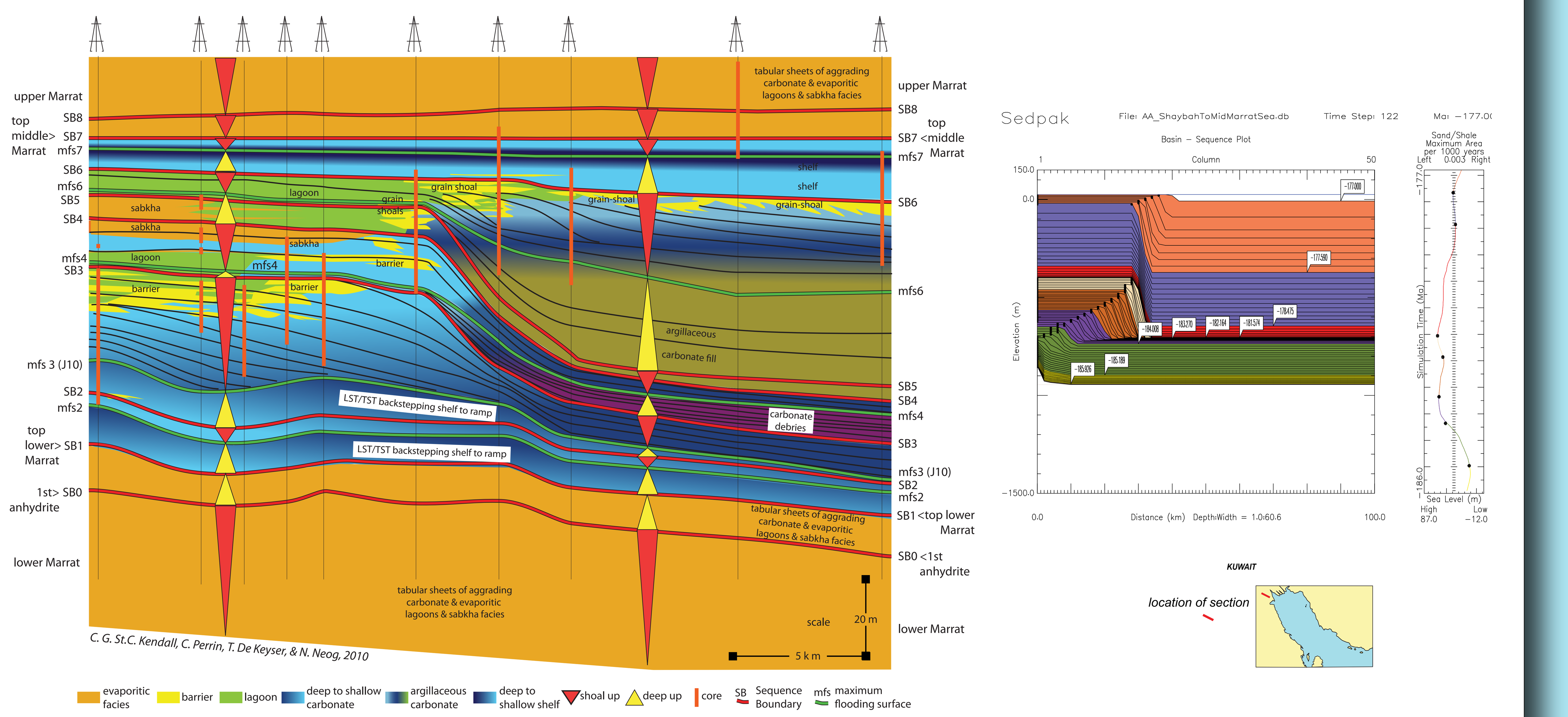


Kendall & De Keyser after Hammes and others, (2011), Phelps & others (2014) and Sharland & others & Haq & Al-Qahtani (2005)

Supersequences of worldwide carbonate provinces and published sea-level curves link numerous common global events, including eustatic, climatic, OAE's, and ISBs. Important differences occur too, often caused by differences in local tectonics and paleogeography. On this diagram, the geological time scale for GOM is partly derived from Hammes et al. (2011), and Phelps et al. (2014) while those of the Arabian plate are from van Buchem et al. (2010) and Sharland et al. (2001) and Haq and Al-Qahtani (2005), respectively.

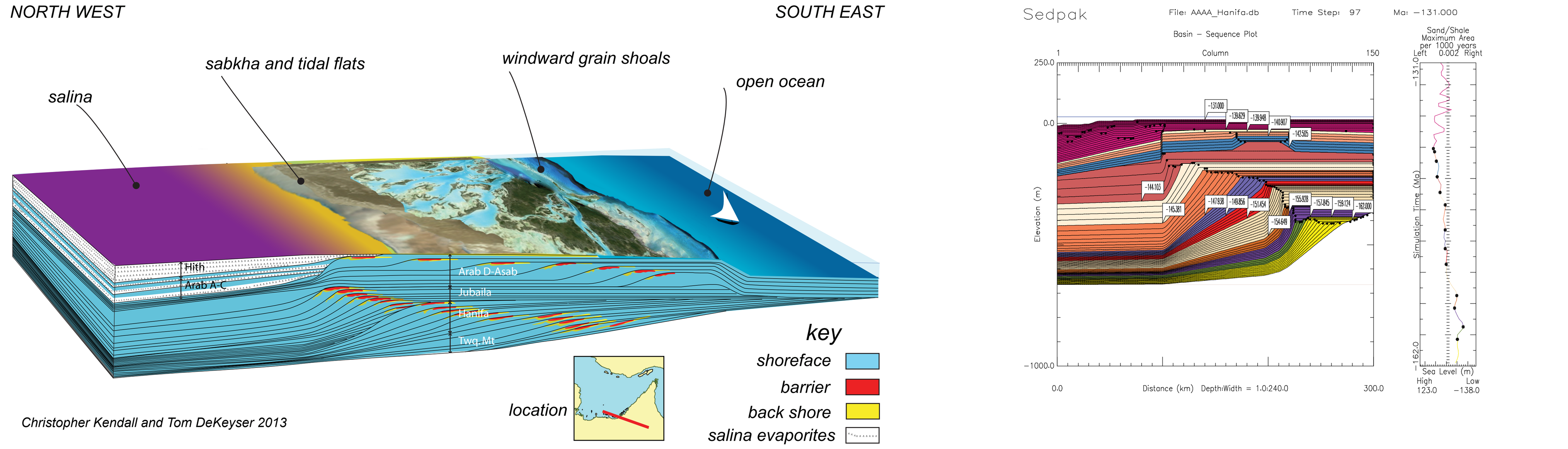
Jurassic Arabian Plate ISBs on left include the Marrat, Hanifa, Najmah, and Gotnia basins which were often filled by shallow marine arid-climate limestones and dolomites with common evaporites and interbedded minor transitional marine shales and basin-margin grain carbonates. Cretaceous ISBs include the Garau of Iraq, Kazhdumi of Iran and Bab of the UAE, and the Mishrif and Najaf ISBs of the UAE and Iraq, respectively. Fill is dominantly humotropic carbonates with dolomites and shales. Giant oil fields of both Jurassic and Cretaceous sections occur in grain carbonates while rudistid buildups are the reservoirs of the Cretaceous ISB margins. Source rocks, including the Hanifa Formation, the Najmah Shale, the Naokelekan in Iraq, and the Aptian "tar" zone of the Bab Member of the Shuaiba Formation. Collectively Jurassic and Cretaceous source rocks formed the prolific petroleum systems of the ISBs. To the right, the chronostratigraphic chart captures similar Mesozoic T–R Supersequences in the GOM to those of the Arabian carbonate platforms and ISBs and OAEs.

Simulation of NW - SE Sequence Stratigraphic Section of Middle Marrat Formation - Flattened on Top of middle Marrat



Simulated sedimentary fill of the Marrat ISB used the eustatic sea level curve proposed by Haq et al. (2012) for the lower Jurassic. There was a sea level high from 182 to 177 MYBP. Prior to the eustatic rise, contemporaneous platform carbonates filled the carbonate platform but post 182 MYBP carbonates formed clinoforms whose trajectory changed from horizontal to vertical while carbonates accumulated down slope from sea level to the deepest portions of the basin at around 150 meters. This sedimentary fill was a mix of carbonate and shale. Around 177 MYBP rates of eustatic sea level rise slowed while carbonate accumulation filled the basin and prograded out from the basin margin.

Simulation of Hanifa ISB Fill by Middle to Upper Jurassic Facies and Their Depositional Settings

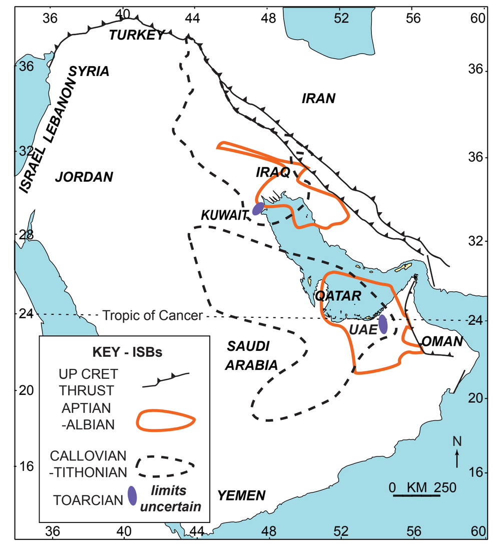


Christopher Kendall and Tom DeKeyser 2013

The sequence stratigraphic framework of this block diagram of the southeastern margin of the Hanifa Basin was developed by the authors from regional studies of subsurface data. The framework captures sedimentary layers bounded by surfaces of erosion and deposition. The geometries of the Jurassic fill of the Hanifa basin include the Lower Jurassic Marrat Formation and the updip grain carbonates of the Hanifa, Jubaila and Arab Formations.

Simulation of the Hanifa basin sedimentary fill involved modeling local accommodation by using the Haq et al. (2012) eustatic curve for the Middle and Upper Jurassic, conjunctly modulated by varying tectonic subsidence. Sea level progressively rose from 161 to 144 MYBP as the prograding Tuwaiq Moutain Group filled the basin. At 143.76 MYBP tectonic accommodation was reduced and sea level fell below the basin margin followed by a rise in relative sea level with the Jubaila Formation onlappping the margin. This was followed by a drop in sea level which exposed the shelf and eroded the platform, followed by a further eustatic rise when contemporaneous platform carbonates filled the carbonate platform crest with a horizontal trajectory. Carbonates accumulated to sea level and prograded both east and westward from the basin margin crest. To the west, the Hanifa basin then filled with a restricted carbonate-evaporite succession.

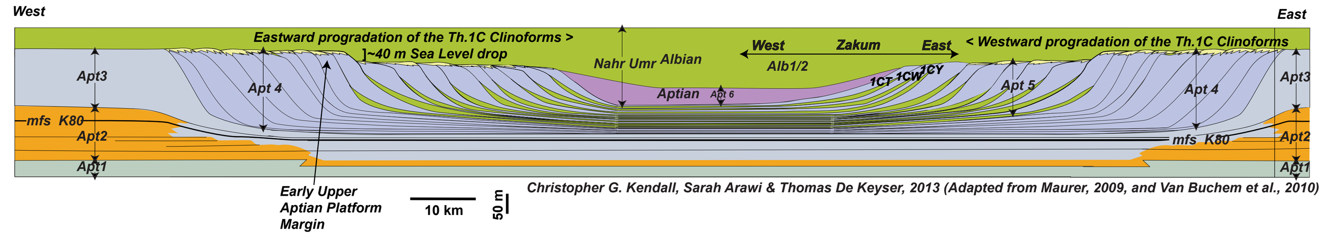
Location of Arabian ISBs



C.G. St.C. Kendall, P. Van Laer, V. Vahrenkamp & T. De Keyser, 2013

Simulation Results of the Fill of the Aptian/Albian ISBs

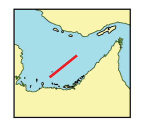
East West Cross Section of the Bab Basin for the Aptian to Early Albian

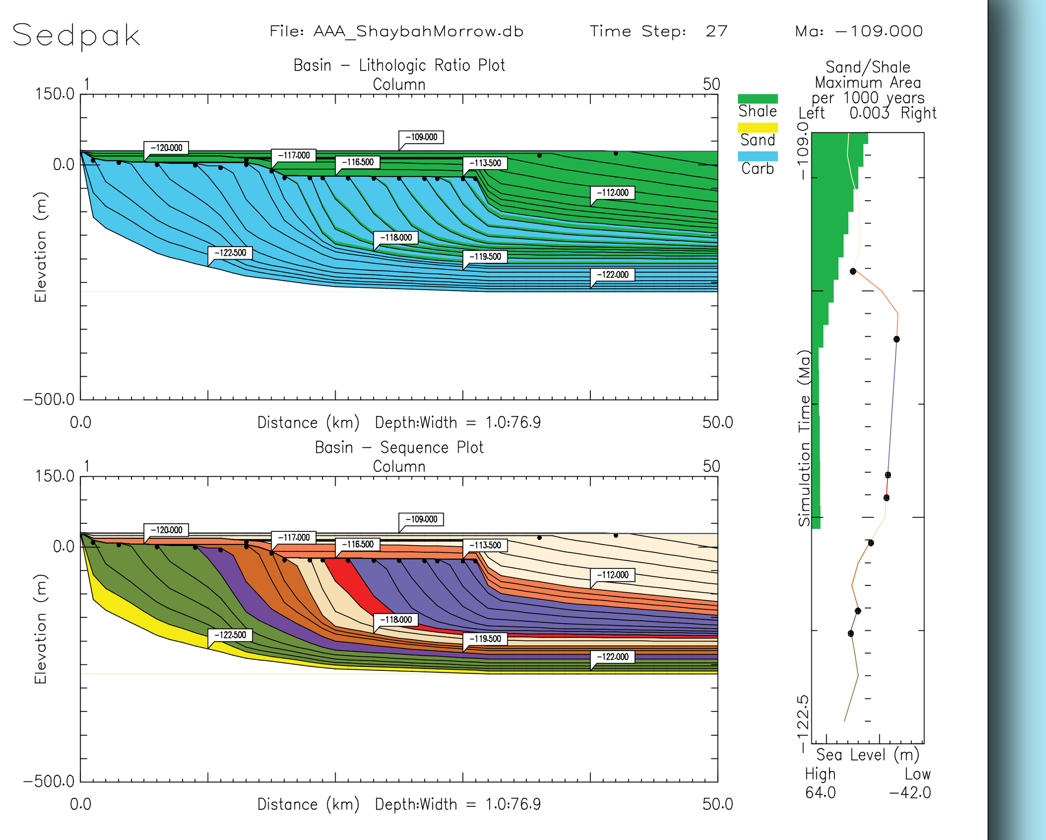


Christopher G. Kendall, Sarah Arawi & Thomas De Keyser, 2013 (Adapted from Maurer, 2009, and Van Buchem et al., 2010)

Simulation of the sedimentary fill of the Bab basin used the sea level curve proposed by Maurer et al. (2012), for the Aptian/Albian. These authors proposed a glacially induced sea level low from 117 to 113 MYBP. Prior to the eustatic fall contemporaneous rudist-rich carbonates formed clinoforms that accumulated down-slope, from sea level to the deepest portions of the basin at around 200 meters. This sedimentary fill was close to 100% carbonate but following the sea level low at 117 MYBP, alternations of shale and carbonate filled the basin margin. Around 113 MYBP in the mid-Albian, sea level rose eustatically while carbonate accumulation fell and the Nahr Umr Formation calcareous shale filled and onlapped the basin margin.

location





CONCLUSIONS

- Passive extensional margins favor thick successions of meter-scale aggradational cycles of platform carbonate.
- Increases in the length of the oceanic ridge system and in rates of spreading decreased the volume of the ocean basin, causing rapid, large rises of sea level and widespread transgressions.
- ISBs occur in these successions when rapid transgressions stress carbonate accumulation and platform margins retreat landward. The landward margins aggrade and prograde while, at the position of the original platform margin to seaward, a new margin forms and aggrades enclosing an ISB.
- ISB becomes the site of anoxia and OAEs result with the accumulation of organic rich sediments and their preservation. The organic-rich source rocks of ISBs later charge local oil and gas reservoirs.
- Four periods of ISB development occur in the Mesozoic of the Arabian Plate during the early Toarcian, Oxfordianto early Tithonian, late Aptian-early Albian, and late Turonian-early Cenomanian.
- ISBs also occur in the Paleozoic section including the Silurian (Michigan, Illinois, and Appalachian basins); Devonian (Williston-Western Canadian Sedimentary basin, and Canning basin – Western Australia); Early Carboniferous (numerous basins with Waulsortian buildups in North America and NW Europe), and Permo-Pennsylvanian (Permian and Midland basins, Paradox basin, and Sacramento Mts).