Sequence stratigraphy and seismic facies mapping of the syn-rift to post-rift transition in offshore Vietnam

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Abstract

The geological history of Southeast offshore Vietnam was closely related to the East Sea spreading process and could be divided into 3 main stages: pre-rift (Paleocene - Eocene), syn-rift (Oligocene and Middle Miocene) and post-rift (Upper Miocene to present). After the second rifting phase, this area was uplifted and eroded followed by a thermal subsidence which has created new accommodation space until present day.

This study focused on evaluating the sediment deposition based on sequence stratigraphic concepts for the transition time from syn-rift to post-rift phase. Seven sequences were defined based on characteristics of seismic facies and well log analysis. Sequence boundaries which are unconformity surfaces were interpreted by different evidence resulting from erosion activities. Within each sequence, seismic facies were characterized in accordance with the variation of lithology from wireline logs. The system tracts are able to be defined and then combined with the biostratigraphy data in order to predict the changes of depositional environment. From the Southwest to the Northeast of the study area, sediment supply decreases due to the farther distance from sediment source. The shelf break migration through time is from the west to the east of the study area. The depositional environment has shallowing upward trends from the lower to the upper part (from basin to outer-middle neritic) and deepening trend from the Southwest to the Northeast (from shelf to bathyal). Among them very good potential reservoirs were formed in syn-rift carbonates, basin floor fan/turbidite deposits in deep marine environment.

Keywords: sequence stratigraphy, seismic facies, syn-rift to post-rift transition, offshore Vietnam

1. Introduction

The study area is located in the Southeast offshore Vietnam. It is approximately 300km from the Vietnamese continent (fig. 1). The general structure of this area is a rift basin which underwent two extensional phases (Ngo Thuong San et al, 2007). Following the second rifting phase was a subsidence and sag phase. This significant difference in tectonic regime led to major changes in sediment deposition processes. Therefore, this study was carried out in order to use sequence stratigraphy concepts as well as seismic facies mapping to evaluate changes in depositional environment in this study area.

2. Methodology and database

Seismic data and well data were used to complete this study. Seismic data is a 3D seismic cube with an area of

1,300km^2. Seismic frequency varies from 20-40Hz. There is one well (well A) located in the Southwest (SW) of the study area. The well data include checkshot data, wireline logs (SP, Gamma ray, Density, Neutron, Resistivity and Sonic) and analysis results of two core samples and biostratigraphy.

In terms of methodology, this study based mainly on seismic interpretation which includes three main steps namely seismic facies mapping, horizon mapping and seismic attribute analysis. Lithology was interpreted based on wireline logs. In the final stage, all the interpretation results from seismic and well data were combined with biostratigraphic analysis to evaluate changes in depositional environment of the study area in a regional framework.

(From Google Map)

Figure 1. Location of the study area

3. Results

3.1. Well analysis

In the SW of study area, the well A is located in the outer neritic where water depth is 144m. This well was drilled to 3795m MD and goes through the whole studied section (fig. 2). The well data was tied with seismic from time depth curve of this well. The lithological characteristics were tied in more detail with the changes in seismic facies for each sequence. This was then used to interpret the changes in depositional environments. In general, below horizon H1, lithology shows coarser component than within sequence 1 which shows shale dominance (fig. 2). From sequence 2 up to middle of sequence 4, sediment is more sandstone interbedding with shale. The fining upward and coarsening upward changes within each sequence depending on the changes of depositional environment which will be discussed in more detail in the next part.

3.2. Seismic interpretation

The first step of seismic interpretation is seismic facies mapping. Based on changes in seismic characteristics of amplitude, continuity, frequency as well as internal and external geometries, different seismic facies were defined. In this study section, ten seismic facies units were defined and bounded by ten horizons namely from horizon H1 to H10 respectively (fig. 2) which separated 7 sequences. In addition, almost these horizons are sequence boundaries (horizons H2, H4, H5, H7, H8, H9 and H10) which are unconformity surfaces. These boundaries were interpreted based on erosional evidence of truncation and onlap (fig. 4.a) or toplap of the previous highstand system tract and downlap (fig. 4.b).

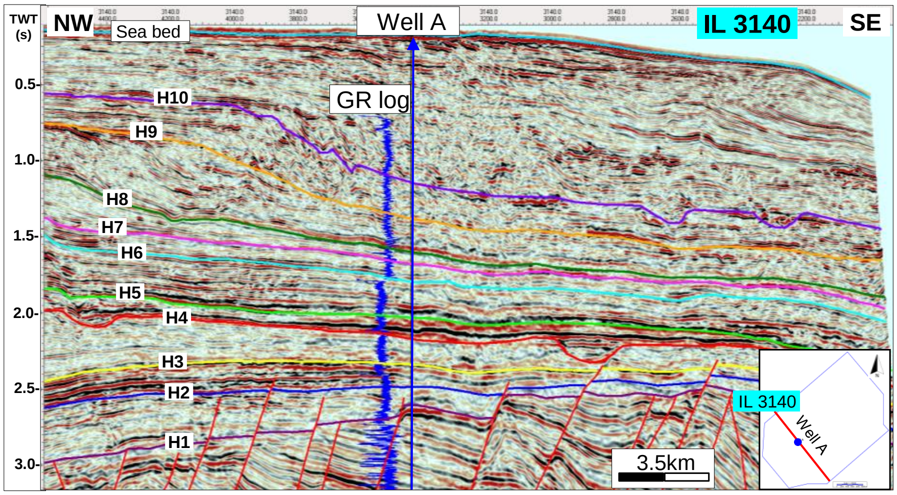

Figure 2. The seismic section shows ten seismic facies units separated by ten horizons namely from H1 to H10; and the gamma ray log of well A overlying

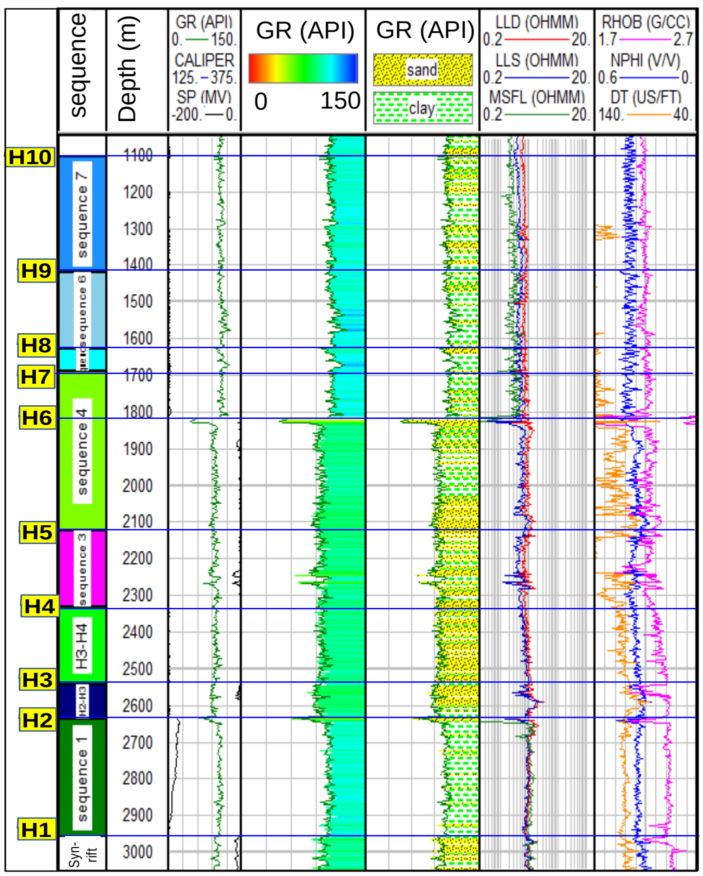

Figure 3. Wireline logs analysis of well A. All horizons and sequence interpreted from seismic data were tied with well log data

In the next step, checkshot data from well A was used to convert time to depth and construct depth structural maps for all horizons and then, thickness map for each sequence. In this paper, it was shown only two examples of depth structural maps of horizons H4 and H10 (fig. 5).

The seismic attribute analysis was carried out to enhance geological features. In this study, interval amplitude maps with Root Mean Square (RMS) and Incoherence attribute were run for window of 30ms and 20ms upper and below each sequence boundary, respectively. These attribute maps are very useful to identify channels and fan deposits. Each sequence will be discussed in detailed in the next part.

3.2.1. Syn-rift package

The first important thing of this study is to define syn-rift and post-rift sediment based on seismic data. The lowest part of the study section witnesses a significant change in seismic facies from very strong amplitude, continuous to discontinuous, parallel to sub-parallel to low amplitude, discontinuous and transparent of the upper part. Therefore, the horizon H1 was interpreted to separate these two different seismic packages. In addition, at the surface of horizon H1, erosional evidence of truncation and onlap of overlying sediment could be observed. Below horizon H1, fault planes were very clear and all of them are normal faults. The timeslice at 3.2s (below horizon H1) with Incoherence attribute shows that this normal fault system developed strongly in a Northeast-Southwest (NE-SW) direction. In contrast, upper horizon H1, almost these faults stopped (fig. 2). As a result, horizon H1 was interpreted as an unconformity separating syn-rift (lower part) and post-rift (upper part) sediments. Within the syn-rift package, there are very strong amplitude, parallel and continuous reflections which indicate for carbonate platform developing during rifting phase in the NE of the study area.

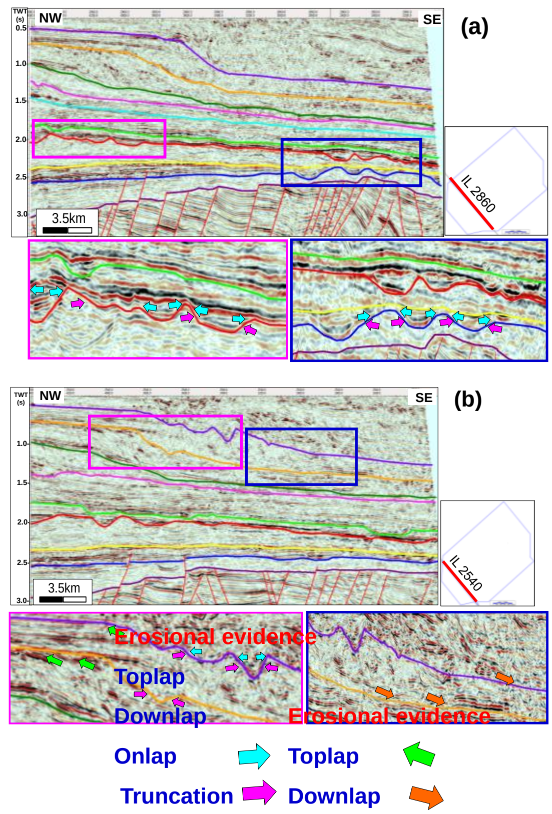

Figure 4.a. Sequence boundaries defined based on erosional evidence of onlap and truncation

4.b. Sequence boundaries defined based on toplap, downlap, onlap and truncation.

3.2.2. Sequence 1

Sequence 1 was bounded by horizons H1 and H2. This is the beginning of post-rift sediment. Seismic facies is very low amplitude, low frequency and discontinuous. Onlap terminations of seismic reflection onto the unconformity surface (horizon H1) are very clear. At well A, lithology interpreted based on wireline logs is shale dominant with a small amount of interbedded sandstone (fig. 3). The biostratigraphy data show the continuous presence of benthonic foraminifera in deep water which indicates the outer neritic to upper bathyal environment (VPI-Labs, 2012).

3.2.3. Sequence 2

Sequence 2 is bounded by the horizon H2 at the bottom and horizon H4 at the top. Within this sequence, seismic facies of lower part and upper part are different. Therefore, horizon H3 was interpreted to map the boundary between these two parts. The lower part from horizon H2 to horizon H3 shows very strong amplitude, continuous and low to medium frequency reflection (fig. 2). Lithology from wireline log at well A is dominant of sandstone with interbedded shale (fig. 3). In contrast, the upper part from horizon H3 to horizon H4, seismic reflection is low amplitude, discontinuous (fig.2).

Lithology shows fining trend with shale dominance (fig. 3). The assemblage from biostratigraphy data of this sequence is similar to that of sequence 1, therefore, depositional environment also is described as outer neritic to upper bathyal (VPI-Labs, 2012). Channel systems developed as two main directions: from SW- SE and NW to the North of the study area. The shape of channel systems are defined as higher amplitude area on RMS map. The incoherence attribute map represents channel systems as more coherent seismic reflections.

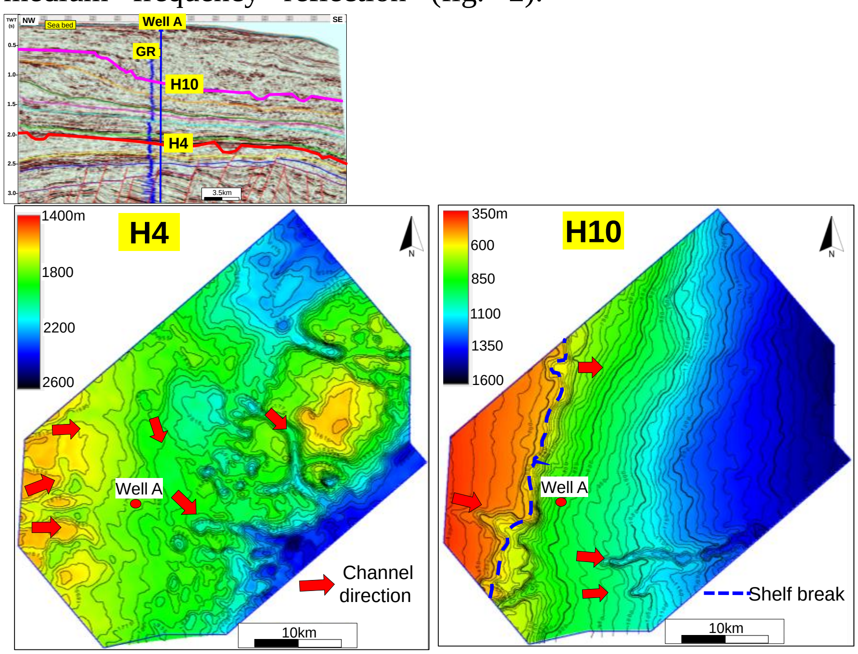

Figure 5. Depth structural maps of horizons H4 and H10

3.2.4. Sequence 3

Sequence 3 is bounded by horizons H4 and H5. Seismic facies is very strong amplitude, continuous, low to medium frequency (fig. 2).

Wireline logs at well A show that lithology is still shale dominant (fig. 3). However, there are two distinct sand layers at intervals of 2270m and 2248-2220m. These sand layers are consistent with a very strong amplitude on seismic.

In addition, some onlap termination of seismic reflection can be observed. Therefore, these intervals could be interpreted as turbidite sediment which may have a good reservoir potential. Attribute analysis helps to clearly define the channels and fan deposit whose shape are imaged as high amplitude and low values of incoherence (fig. 6).

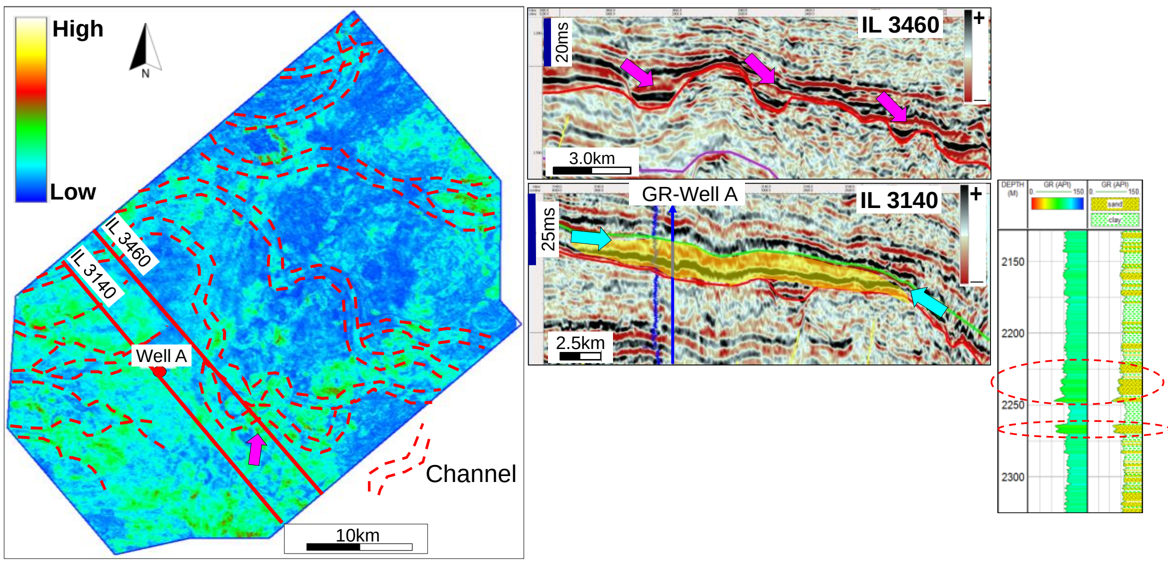

Figure 6. Channel s and fan deposits are imaged by high amplitude areas on RMS maps. Inline 3460 shows very strong amplitude reflections. On inline 3140, fan deposits/turbidites are very strong amplitude, continuous reflections; onlap termination of sediment can be observed both sides. On wireline log, they are distinct sand layers within a shale dominant interval.

3.2.5. Sequence 4

Sequence 4 is bounded by sequence boundaries H5 and H7. Characteristics of seismic facies changes from the bottom to the top (fig. 2). Horizon H6 was interpreted to separate two different parts of seismic facies. In the lower part (from horizon H5 to horizon H6), seismic facies is medium to strong amplitude, continuous to discontinuous, medium to high frequency. From horizon H6 to the top, seismic facies shows low amplitude to transparent, discontinuous, high to medium frequency.

At the location of well A, from sequence boundary H5 up to 2030m, lithology is sand dominant which is consistent with strong amplitude on seismic (fig. 3). It could be interpreted as lowstand sediment. Within 2030-1970m interval, lithology shows fining upward trend which could be a transgressive system tract followed by a coarsening upward up to 1820m. From 1820m to horizon H7 at the top where seismic facies changes to low amplitude, discontinuous reflection, wireline logs represent shale dominant lithology.

Channel systems developed from the SW and brought sediment to the NE. Shape of channels and fan could be predicted based on distribution of high amplitude and low incoherence areas.

3.2.6. Sequence 5

The sequence 5 is bounded by horizons H7 and H8.

Within this sequence, seismic facies are different between the lower part and the upper part. The lower part shows seismic facies of medium to high amplitude, continuous to discontinuous, medium frequency. The upper part has seismic facies of low amplitude, discontinuous, medium frequency (fig. 2).

Well A penetrates the thin part of sequence 5. Wireline logs of the well A in this interval show fining upward trend from sequence boundary H7 to about 1667m. Following the fining upward trend is a coarsening upward until the horizon H8 (fig. 3).

On amplitude map (RMS), channels are illustrated by higher amplitude areas. The incoherence attribute helps to recognize another channel system from SW to NE.

3.2.7. Sequence 6

The sequence 6 is bounded by horizons H8 and H9. This sequence developed with a clinoform shape from west to east. In the SW, seismic frequency is higher. Seismic facies in this area shows low amplitude, continuous to discontinuous. In the central and the Northern parts, frequency is very low (fig. 2).

The wireline logs of the well A within the sequence 6 show the main component of lithology is shale interbedded by sandstone. From 1580-1480m, parasequences were defined based on the alternative of coarsening upward trend. From 1480m up to the horizon H9 at the top, lithology component has more sandstone (fig. 3).

In this sequence, the shelf break was defined. Submarine canyons were created during erosion due to fall of relative sea level. On attribute maps, channel systems from submarine canyons are enhanced with high amplitude and high incoherence.

3.2.8. Sequence 7

The sequence 7 is bounded by the horizons H9 and H10. In the SW, the shelf part of clinofrom shows seismic facies of parallel, medium to strong amplitude, continuous and medium frequency reflection (fig. 2). However, toward the East and the North of the study area, frequency is very low which made it difficult to recognize seismic facies as well as termination of reflections.

The well log data within sequence 7 at well A shows shale dominant lithology (fig. 3). From sequence boundary H9 up to about 1300m, lithology is composed of shale interbedded with sandstone. Following this interval, sediment is very shaly which helps to define the maximum flooding surface. Up to horizon H10 at the top, sediment has coarsening upward trend.

The erosion activities created large submarine canyons and channel systems at the sequence boundaries H9 and H10.

4. Discussion

The rifting phase with strong extension led to the formation of grabens and normal fault systems in the NE – SW direction. During this period, the most important traps formed were structural traps which were sealed by faults. Another potential reservoir in this period was carbonate. According to the previous studies, these carbonates have good to very good reservoir potential with mainly interparticle and cavern pores having porosity from 10-35% (Nguyen Giao et al., 2007). At the end of the rifting phase, all the study area was uplifted and eroded. A regional unconformity was created as a result (horizon H1). This unconformity surface also formed seal surface. The depositional environment was shallow marine.

Following the rifting phase was a sag and subsidence phase. The tectonic regime was stable. Faults stopped developing almost at the regional unconformity, some faults continued to be weakly active and stopped at horizon H3 within sequence 2.

The early post rift sediment was divided into 7 sequences. The structural and attribute maps, seismic facies units, wireline log analysis and biostratigraphy analysis were combined to interpret the depositional environment through each sequence.

After the uplifting and erosion at the end of rifting phase, the relative sea level increased. The marine sediment (shale dominant) within sequence 1 was deposited onlap onto the previous unconformity. On seismic section, the onlap termination is observed clearly onto the unconformity horizon H1. Based on seismic facies, lithology from wireline logs as well as biostratigraphy analysis, the depositional environment was interpreted as outer to upper bathyal, toward the NE, environment was deep marine.

The decrease of relative sea level at the end of sequence 1 led to the development of channels during the lowstand system tract. Based on lithology characteristic interpreted from wireline logs and biostratigraphy data, the depositional environment of sequence 2 could be interpreted as outer neritic to deep marine. Therefore, channel systems could develop in the basin floor.

When the relative sea level decreased rapidly, erosion occurred very strongly. The sequence boundary H4 which covers the whole study area marks the beginning of the sequence 3. The channels developed during lowstand system tract from shelf to slope in the Southwest and created turbidite deposits at the base of slope. These turbidite deposits are expected to have very good reservoir potential. Overall, depositional environment changed from outer neritic – upper bathyal to middle – outer neritic upward, and became deeper into upper bathyal from the SW to NE.

Going up to sequence 4, channels still developed and sand fan deposits also are observed. Based on biostratigraphy analysis, these sand fans could be deposited at the slope. Therefore, in the SW, the depositional environment was slope to basin. In the west, carbonate build up developed indicating the shallow marine environment. Toward the NE, depositional environment was deep marine.

In sequence 5, the shelf is able to be interpreted in the SW more clearly. submarine canyons were created on the shelf and led to the development of channels to basin. Depositional environment changed from shelf in the SW to deep basin in the NE.

From sequence 6 and sequence 7, the progradation development is clearly recognized, therefore, shelf, slope and basin areas can also be illustrated from SW to NE. On the shelf, large submarine canyons were formed resulting from the erosion. Channels and channel levee complex are also observed at basin floor.

Going upward, channels still developed strongly at basin floor comparing to the previous time.

In summary, the lower part of the studied section (sequences 1, 2 and 3) are interpreted as far away from the sediment supply source. The sediments were deposited in the basin. Going upward, the shelf break migration is able to be seen from the west to the east. The depositional environment has shallowing upward trend from the lower to the upper part (from basin to outer-middle neritic). From the SW to the NE, it witnesses a deepening trend (from shelf to bathyal). The changes in depositional environment through every sequence in the study area are summarized by models in terms of regional environment on fig. 7.

5. Conclusion

This study gives an overview of the depositional processes from the late stage of rifting phase to post rifting phase in the SE offshore Vietnam. The study conclusions as follows:

1. Seven sequences were defined in the study area. These sequences were separated by sequence boundaries which are unconformity surfaces. These unconformities were determined by seismic termination reflections of onlap, truncation, toplap and downlap.

2. Seismic facies mapping helps to predict lithology properties and special objects such as sand body or carbonate where there is a lack of well data. Moreover, it is also very useful to map the distribution of depositional environment and potential reservoirs.

3. The tectonic regime has been the main factor controlling the development of sediment and sequences in this study area. During rifting phase, the extensional tectonics created normal faults and grabens that increased the accommodation space. Turning to post rifting phase, tectonic activities were stable and mainly sag phase and subsidence. Deposition can be evaluate for each sequences over time.

4. The depositional environment varied very complexly due to the changes in relative sea level through time. Going upward, the shelf break migration is from W-E. The depositional environment has a shallowing upward trend from the lower to the upper part (from basin to outer-middle neritic) and deeper trend from SW-NE (from shelf to bathyal).

5. When relative sea level fell, erosion occurred strongly on the shelf creating submarine canyons or channel systems. These channels brought the sediment from continent to make fan deposit at slope or basin floor deposit.

6. In the study area, the syn-rift carbonate, basin floor fan/turbidite deposits in deep marine environment of post-rift phase are potential reservoirs.

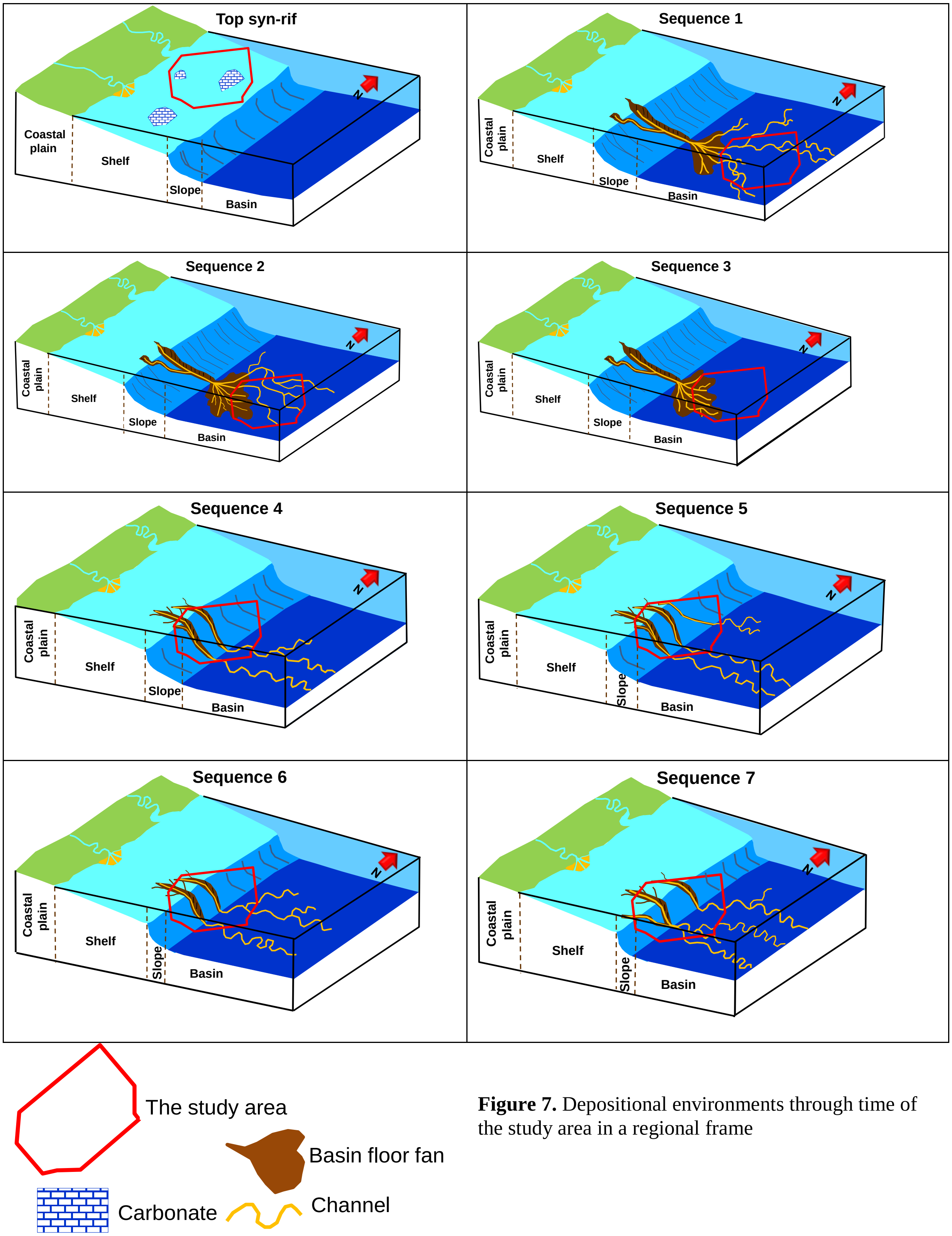

Figure 7. Depositional environments through time of the study area in a regional frame

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