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Method of sedimentary basin reconstruction and compilation of lithofacies - paleogeographic maps

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Summary. A secondary basin corresponds with a second order depositional cycle, is limited by two erosional surfaces which are also the boundaries of a seismic sequence. In other words, a secondary basin is a component of an overall sedimentary basin.

A secondary basin is formed at the same time with a tectonic phase where the three most important factors are faulting, subsidence and uplifting. Basin-forming faults are usually normal faults and are called "syn-depositional fault".

The reconstruction of a sedimentary basin is rather complicated, but it is very necessary for basin analysis, facial analysis and compilation of lithofacies-paleogeographic maps, as the dimensions and thickness of the present secondary basin are not the same as of the primitive basin. To get a true picture of the primitive basin one must carry out the following steps:

- Drawing the reconstructed geologic sections
- Reconstructing the sediment thickness

$$h_1 = h_2 . \sqrt[3]{K . \frac{P_1}{P_2}}$$

where h_1 is the primitive thickness

h_2 is the present thickness

K is the shrinkage coefficient (depending on the rock type)

P_1 is the primitive common porosity

P_2 is the present common porosity

- Reconstructing the integrated geologic-sedimentary sections:

+ Width of the basin

$$L_1 = C.[L_2 - \sum_{i=1}^{n} L_{1i} + \sum_{i=1}^{m} L_{2i} + \sum_{i=1}^{l} L_{3i}]$$

where C is a correction coefficient: C=1.25 (diagenetic stage), 1.55 (catagenetic stage) and 1.9 (metagenetic stage).

+ Thickness of the basin:

$H_1 = ch_2$

- Reconstructing the boundaries of the basin
- Reconstructing the isopach map
- Compiling the lithofacies-paleogeographic map.

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Introduction

So far sedimentologists usually draw lithofacies-paleogeographic maps with omission of a principled stage, i.e. the reconstruction secondary sedimentary basins [1-3]. So what is a secondary sedimentary basin and why must they be reconstructed before compiling a lithofacies-paleogeographic map?

The term *"secondary basin"* was proposed by the author while implementing the research project "Stratigraphic and lithofacies-paleogeographic studies of KZ sediments in Bach Ho and Rong oil fields, Cuu Long basin", in 2000 [4].

"Secondary basin is a daughter basin formed in a certain stage in the evolution history of the mother basin, controlled by a tectonic phase consisting of rifting, subsidence, syn-depositional faulting or folding compression and uplifting, forming an independent geostructure with clear lower and upper boundaries. Several secondary basins (daughter basins) make up a large basin (mother basin) characterizing a certain tectonic phase.

According to their size and classification criteria, secondary sedimentary basins usually correspond with a depositional cycle and in turn each depositional cycle corresponds with a seismic sequence limited by two erosional surfaces (depositional gaps). The boundary of depositional cycles coincides with a seismic reflection surface.

The matter to be discussed in this paper is why is it necessary to reconstruct the geologic-sedimentary sections and isopach maps when compiling lithofacies-paleogeographic maps?. The reason is very simple: all the present basin parameters are only *apparent* and even in the form of "remainders", "residuals", subjected to secondary alterations and volumetric shrinkage in all three dimensions of the sedimentary basin. Therefore, the task of the geologists - sedimentologists is to find a reasonable method to "reconstruct" the primitive natural geographic condition of the secondary basins in the evolution history of the common basin.

The method of reconstruction consists of 5 steps:

1/ Reconstruction of the geological section.

2/ Reconstruction of the thickness and volume of the secondary basin (daughter basin).

3/ Developing the formula for reconstruction of geologic-sedimentary section of a secondary basin.

4/ Reconstructing the primary basin (mother basin).

5/ Drawing the lithofacies-paleogeographic map.

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1. Reconstruction of geological section

1.1. Dealing with normal faults

Let Lt be the lateral displacement created by a normal fault. If in a section there are n normal faults, the width of the primitive basin L_{nt} must be equal the present width L_{ht} minus $\sum_{i=1}^{n} L_{1i}$, so we have the following general formula:

$$L_{nt} = L_{ht} - \sum_{i=1}^{n} L_{1i} \qquad (1)$$

where: Lnt is the width of the primitive basin; Lht is the width of the present basin.

1.2. Dealing with reverse faults

A reverse fault reduces the width of the basin (Fig. 2). If there are m reverse faults, the width of the primitive basin must be equal the width of the present basin plus $\sum_{i=1}^{m} L_{ni}$, where L_n is the lateral displacement of a reverse fault. We have the following formula:

$$L_{nt}=L_{ht} + \sum_{i=1}^{m} L_{ni} \quad (2)$$

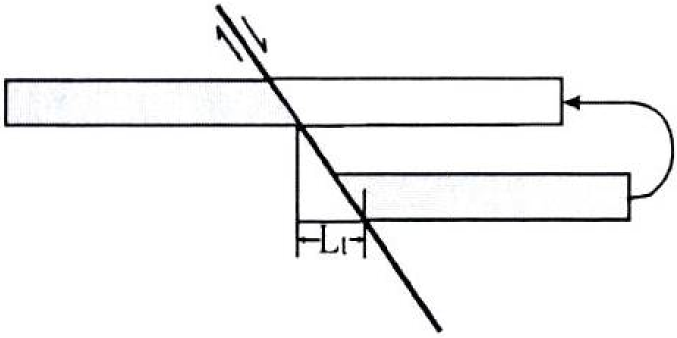


Fig. 1. Normal fault.

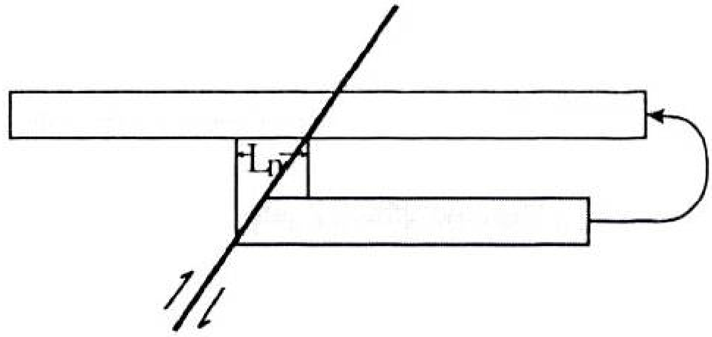


Fig. 2. Reverse fault.

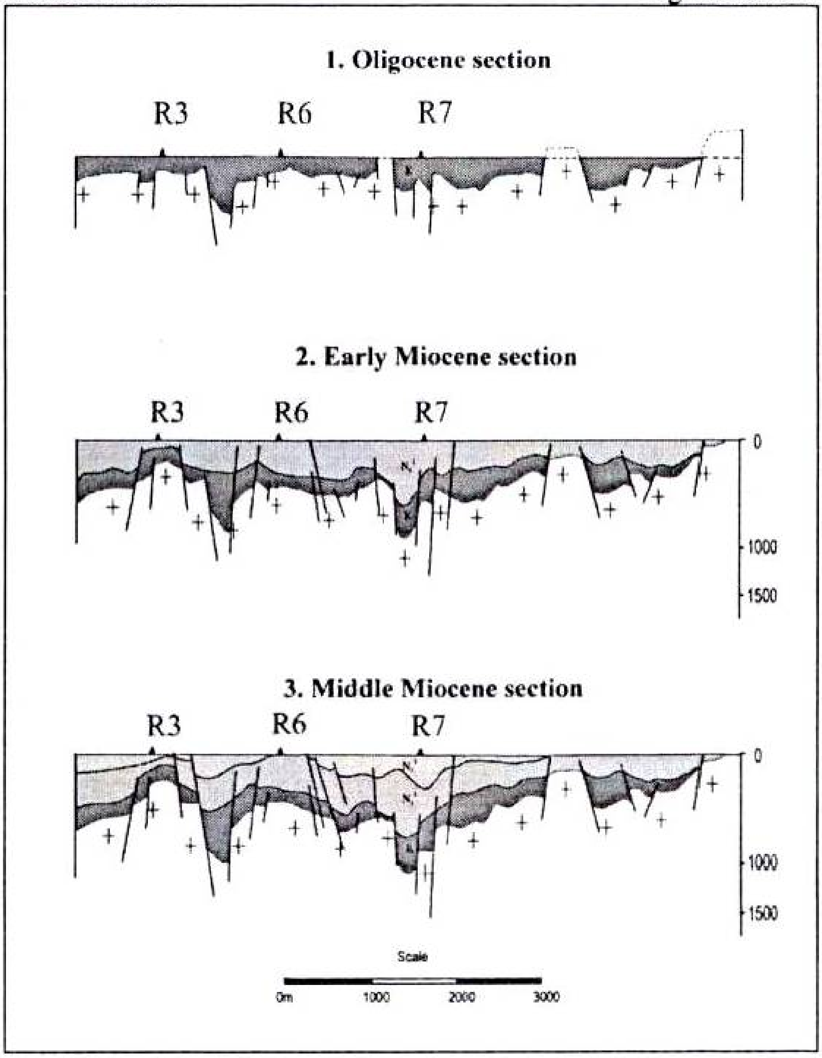


Fig. 3a. Reconstructed geologic-sedimentary sections of Rong oilfield - Cuu Long basin (Oligocene – Middle Miocene).

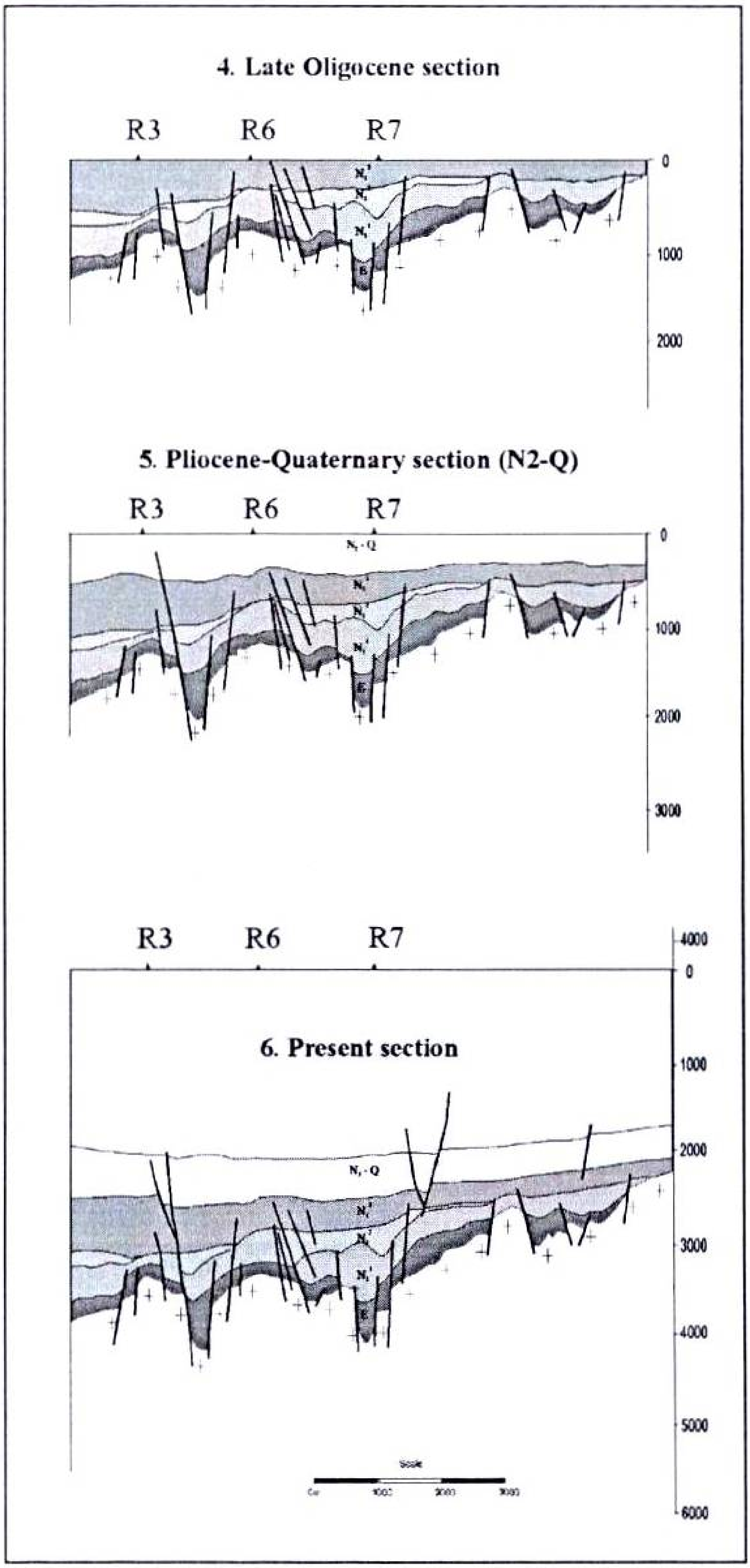


Fig. 3b. Reconstructed geologic-sedimentary sections of Rong oilfield - Cuu Long basin (Late Miocene – Present).

1.3. Dealing with folds

When the sediments are compressed, they are folded and this also reduces the width of the basin (Fig. 4). If there are f folds in the section being examined, the width of the primitive basin must be the width of the present basin plus $\sum_{i=1}^{f} L_{ui}$. Let Lu/2 be one half of the lateral displacement of a fold, the general adjustment formula is:

$$L_{nt}=L_{ht} + \sum_{i=1}^{f} L_{ui} \quad (3)$$

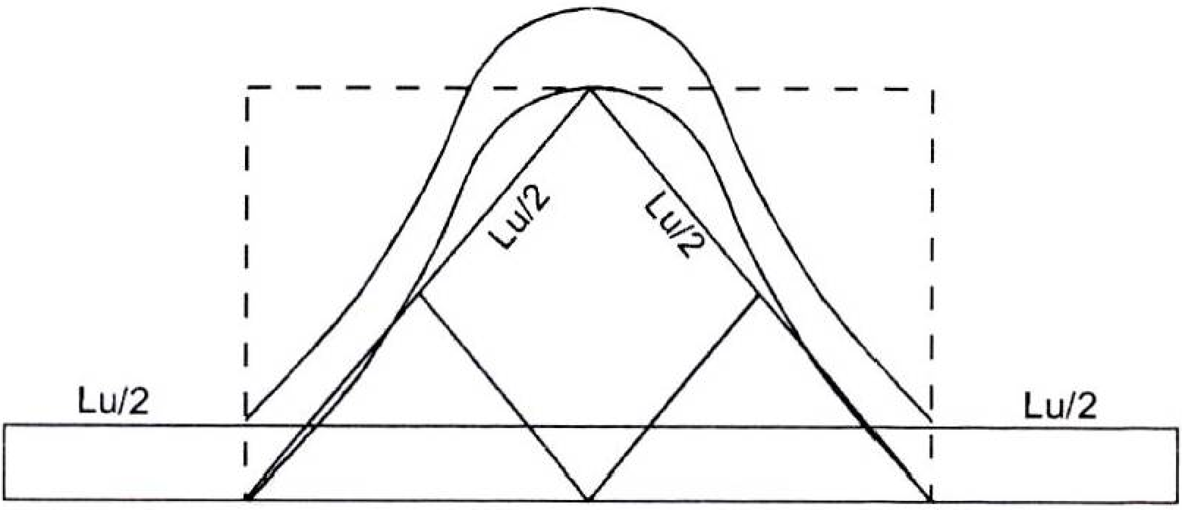


Fig. 4. Folding due to compression of the basin.

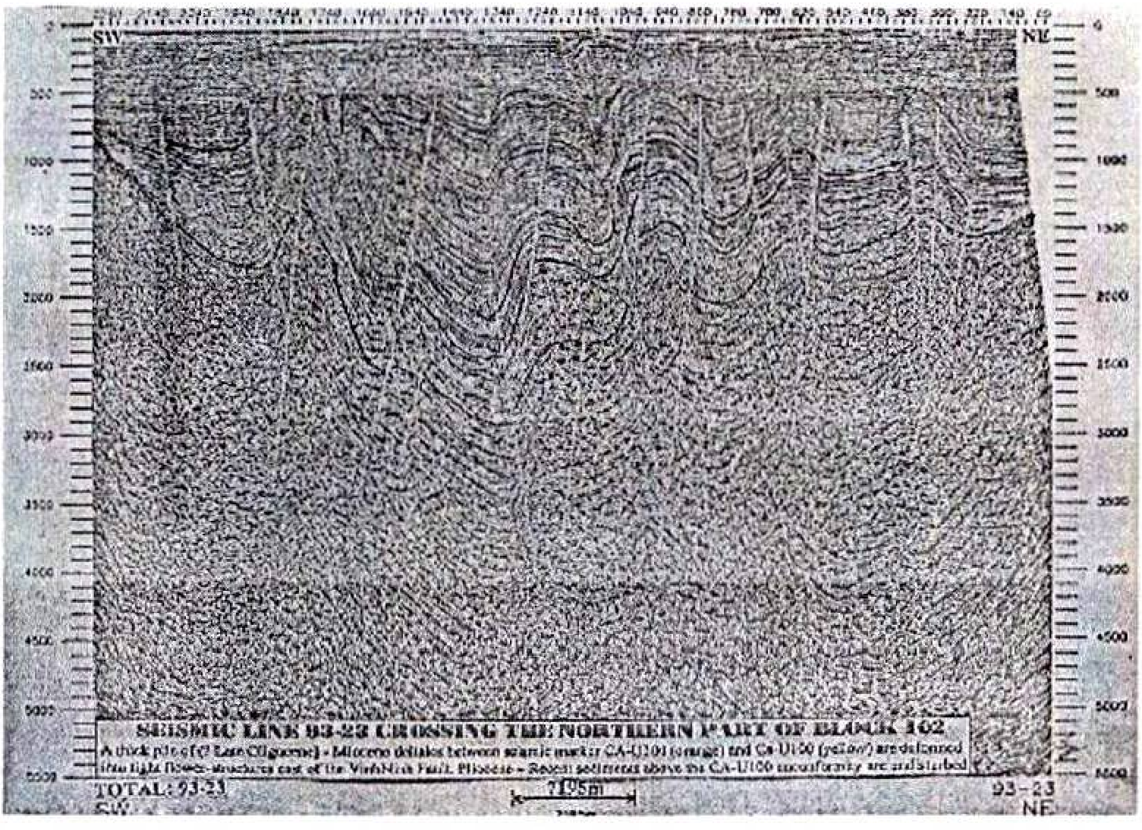


Fig. 5. Seismic section showing clearly the folds of the Upper Miocene sediments in the Red River sedimentary basin (Total, 1999).

Thus, finally if in one section there are all the above mentioned deformation factors, the width of the primitive basin is calculated as follows:

$$L_{nt}=L_{ht} - \sum_{i=1}^{n} L_{ti} + \sum_{i=1}^{m} L_{ni} + \sum_{i=1}^{f} L_{mi} \qquad (4)$$

where: Lnt is the width of the primitive basin; Lht is the width of the present basin [4].

1.4. Dealing with the deformations due to volcanic activities

Yong volcanic activities usually deform strongly secondary basins. Occasionally the penetration of a whole secondary basin by volcanoes causes confusion in determining the shape and thickness of the basin (Fig. 6). To reconstruct a section deformed by volcanic activities, first of all one must determine the age of the volcanic extrusion, then carry out facial analysis at the margins of the basin and the extrusive magmatic bodies.

The indications for identification of secondary penetrated by volcanoes include:

- The margins of the basin are composed of shallow marine clay

- The closer to the extrusive body, the thicker the sediments

- The boundary between the sediments and extrusive formations is a broken zone caused by the extrusion.

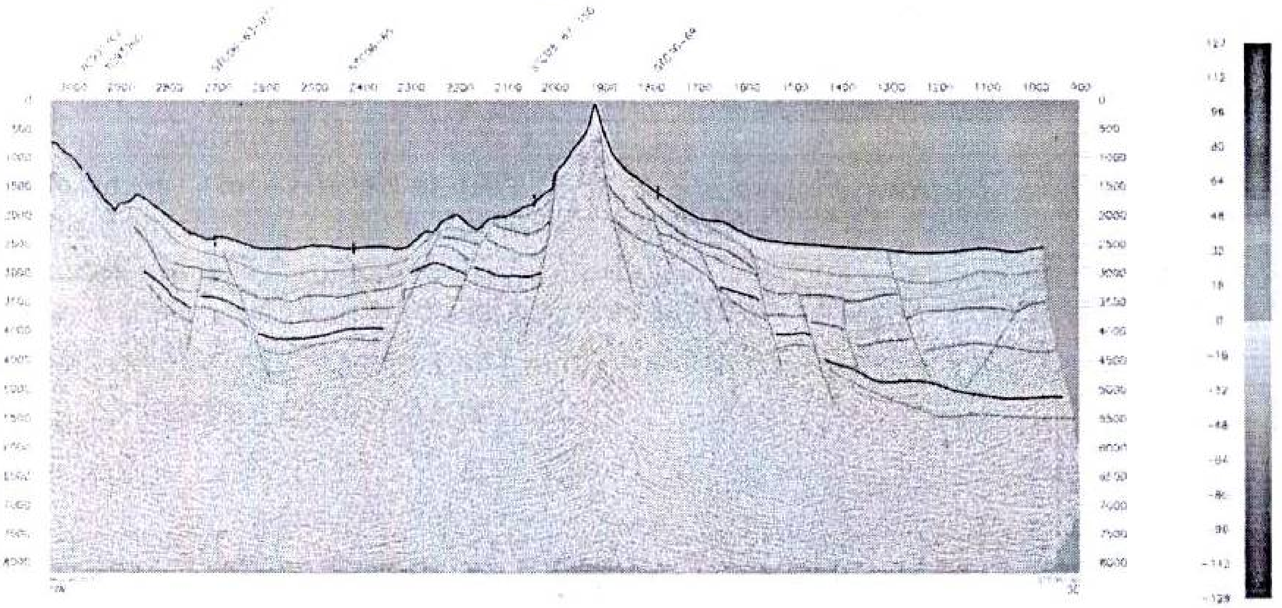


Fig. 6. Oligocene, Miocene, Pliocene – Quaternary secondary basins deformed by young volcanoes.

2. Reconstructing the thickness and volumes of secondary sedimentary basins

2.1. The thickness of a secondary basin is considered as the edge of a cube. When the sediment change, its volume decreases depending on the decrease of the common porosity of the sediment and the shrinkage coefficient (K). So the parameters present porosity (P2), primitive porosity (P1) and shrinkage coefficient (K) are used for calculating the thickness.

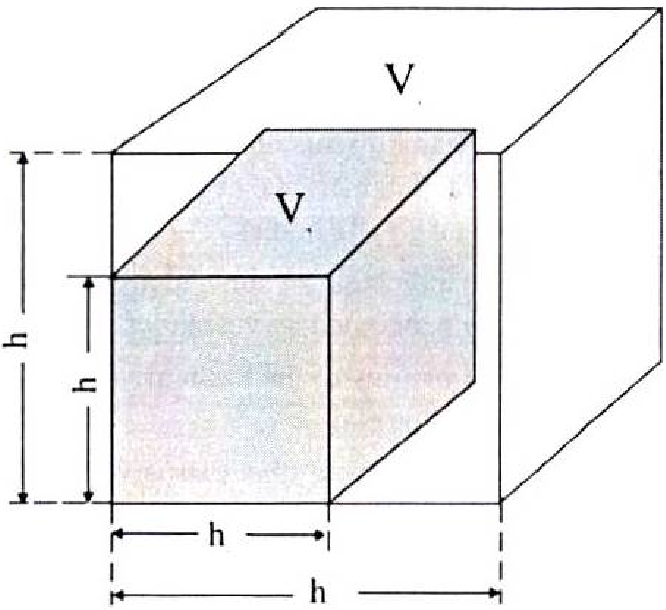


Fig. 7. The cubes representing the present and primitive sediments.

h2: Edge of the cube representing the present sediments.
h1: Edge of the cube representing the primitive sediments.

Let V_2 be the present unit volume, V_2 is calculated as follows:

$$V_2 = h_2^3 \tag{5}$$

$$V_1 = k.V_2.\frac{P_1}{P_2} \tag{6}$$

where k is correction coefficient (an empirical coefficient, depending on the shrinkage of each sediment type):

Gravel: k = 1

Sandstone: k = 1

Siltstone: k = 0.8

Claystone: k = 0.5

P_1 is primitive common porosity, P_2 is the present common porosity. Substituting (5) to (6) we have:

$$V_1 = h_2^3.\frac{P_1}{P_2} \tag{7}$$

Let h_1 be the edge of the primitive cube (the thickness of the primitive sediment), we have:

$$h_1 = \sqrt[3]{K.h_2^3.\frac{P_1}{P_2}} = h_2\sqrt[3]{K.\frac{P_1}{P_2}} \tag{8}$$

$$h_1 = h_2\sqrt[3]{K.\frac{P_1}{P_2}} \tag{9}$$

2.2. Correction of thickness according to porosity

The value of common porosity P_1 (unconsolidated sediments) and P_2 (cemented sediments) vary depending on the secondary alteration and type of sediments:

❖ **The porosities of unconsolidated sediments** (syn-genetic porosity) as determined for the Quaternary sediments of the Red river basin have average values P_1 as follows:

+ Cobble, gravel: P1 = 40% (0.4)

+ Sand: P1 = 50% (0.5)

+ Silt: P1 = 60% (0.6)

+ Clay: P1 = 70% (0.7).

+ Claystone: P_2 = 8% (0.08)

❖ **Porosity of cemented sediments:** Rocks have the following average porosities P_2 depending on the degree of secondary alteration of the rocks (diagenetic, catagenetic and metagenetic stages):

- Diagenetic stage:

+ Conglomerate: P_2 = 25% (0.25)

+ Sandstone: P_2 = 20% (0.20) (Fig. 7)

+ Siltstone: P_2 = 25% (0.25)

+ Claystone: P_2 = 15% (0.15)

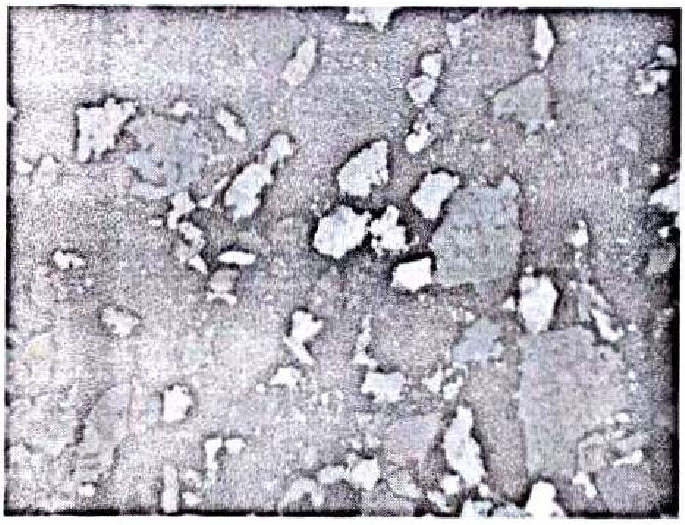


Fig. 8. Upper Cretaceous sandstone in Phu Quoc basin in the diagenetic stage (porosity 20%, I = 0,25), N^+, x90.

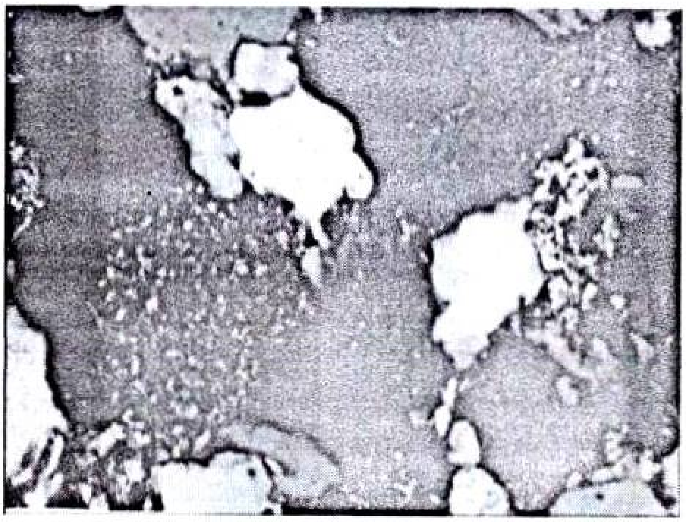


Fig. 9. Miocene arkosic sandstone in Cuu Long basin in the catagenetic stage (porosity 15%, I = 0,6), N^+, x90.

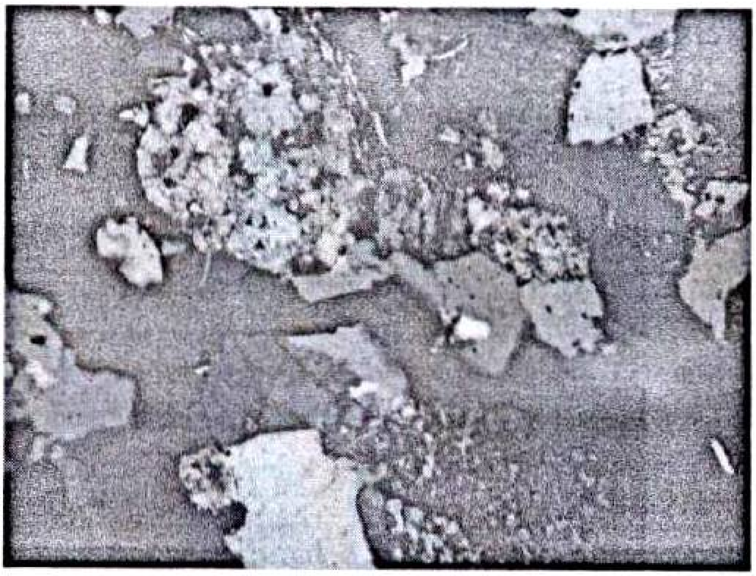


Fig. 10. Oligocene sandstone in the Red River basin in the early metagenetic stage (porosity 3%), N^+, x90.

- ***Catagenetic stage:***

+ Conglomerate: P_2 = 15% (0.15)

+ Sandstone: P_2 = 15% (0.15) (Fig. 8)

+ Siltstone: P_2 = 10% (0.1)

- ***Metagenetic stage***

+ Conglomerate: 5% (0.05)

+ Sandstone: 8% (0.08) (Fig. 9)

+ Siltstone: 7% (0.07)

+ Claystone: 5% (0.05)

Thus, formula (9) is applied for calculating the dimension of a sedimentary basin in three-dimensional space in three stages as follows:

- Diagenetic stage (10)

a. Conglomerate:

$$h_{1gr} = h_{2gr}\sqrt[3]{1.\frac{0.4}{0.25}} = 1.2h_{2gr}$$

b. Sandstone:

$$h1s = h2s\ \sqrt[3]{1.\frac{0.5}{0.2}} = 1.3h2s$$

c. Siltstone:

$$h1sil = h2sil\ \sqrt[3]{0.8.\frac{0.6}{0.3}} = 1.2\ h2sil$$

d. Claystone:

$$h1cl = h2cl\ \sqrt[3]{0.5.\frac{0.7}{0.15}} = 1.3\ h2cl$$

▪ Catagenetic stage (11)

a. Conglomerate:

$$h1gr = h2gr\ \sqrt[3]{1.\frac{0.4}{0.15}} = 1.4\ h2gr$$

b. Sandstone:

$$h1s = h2s\ \sqrt[3]{1.\frac{0.5}{0.25}} = 1.5\ h2s$$

c. Siltstone:

$$h1sil = h2sil\ \sqrt[3]{0.8.\frac{0.6}{0.10}} = 1.7\ h2sil$$

d. Claystone:

$$h1cl = h2cl\ \sqrt[3]{0.5.\frac{0.7}{0.08}} = 1.6\ h2cl$$

▪ Metagenetic stage (12)

a. Conglomerate:

$$h1gr = h2gr\ \sqrt[3]{1.\frac{0.4}{0.05}} = 2\ h2gr$$

b. Sandstone:

$$h1s = h2s\ \sqrt[3]{1.\frac{0.5}{0.08}} = 1.8\ h2s$$

c. Siltstone:

$$h1sil = h2sil\ \sqrt[3]{0.8.\frac{0.6}{0.07}} = 1.9\ h2sil$$

d. Claystone:

$$h1cl = h2cl\ \sqrt[3]{0.5.\frac{0.7}{0.05}} = 1.9\ h2cl$$

From here one can build a table of primitive sediment thickness of a secondary basin in each stage of secondary alteration and for each type of sediments.

Table 1. Thickness of sediments in an primitive secondary basin

Type of sediments	Thickness of primitive sediments (h_1)			Remarks
	Diagenetic stage	Catagenetic stage	Metagenetic stage	
	$I < 0.25$	$I = 0.25 - 0.65$	$I > 0.65$	
Conglomerate	1.2 h_{2gr}	1.4 h_{2gr}	2 h_{2gr}	
Sandstone	1.3 h_{2s}	1.5 h_{2s}	1.8 h_{2s}	
Siltstone	1.2 h_{2sil}	1.7 h_{2sil}	1.9 h_{2sil}	
Claystone	1.3 h_{2cl}	1.6 h_{2cl}	1.9 h_{2cl}	
Average	1.25 h_{2t}	1.55 h_{2h}	1.9 h_{2b}	
	$H_1 = 1.25\ h_{2t} + 1.55\ h_{2h} + 1.9\ h_{2b}$ (13)			

In this table 1.25; 1.55 and 1.9 are correction coefficient of sediments in different stages of alteration,

h_{2gr} – is the thickness of the present conglomerate layer

h_{2s} – is the thickness of the present sandstone layer

h_{2sil} – is the thickness of the present siltstone layer

h_{2cl} – is the thickness of the present claystone layer

H_1 – is the primitive sediment thickness of the whole secondary basin consisting of all types of sediments.

2.3. Developing the integrated formula for reconstructing the geologic-sedimentary section of a secondary basin

On the basis of formula (5) (reconstructing the geologic section) and (13) (reconstructing the dimension of a sedimentary basin) one can develop an integrated formula for reconstructing the primitive geologic-sedimentary section of a secondary basin as follows:

a. Reconstructing the width of a basin

- Diagenetic stage (Pliocene basin)

$$L_1=1.25.[L_2 - \sum_{i=1}^{n} L_{1i} + \sum_{i=1}^{m} L_{2i} + \sum_{i=1}^{f} L_{3i}] \quad (14)$$

- Catagenetic stage (Miocene basin)

$$L_1=1.55.[L_2 - \sum_{i=1}^{n} L_{1i} + \sum_{i=1}^{m} L_{2i} + \sum_{i=1}^{f} L_{3i}] \quad (15)$$

- Metagenetic stage (Eocene – Oligocene and Pre-Cenozoic basin)

$$L_1=1.9.[L_2 - \sum_{i=1}^{n} L_{1i} + \sum_{i=1}^{m} L_{2i} + \sum_{i=1}^{f} L_{3i}] \quad (16)$$

b. Reconstructing the thickness of sediments

+ If the basin has undergone only the diagenetic stage:

$$H1 = 1.25h_{2t} \quad (17)$$

+ If the basin has undergone the catagenetic stage:

$$H1 = 1.55h_{2h} \quad (18)$$

+ If the basin has completely undergone the metagenetic stage:

$$H1 = 1.9h_{2b} \quad (19)$$

2.4. Reconstructing the overall sedimentary basin

The reconstruction of an overall sedimentary basin includes:

- Reconstructing the basin boundaries (the boundary between the erosion and sediment deposition domains) (formulas (14), (15), (16)).

- Reconstructing the isopach maps of each secondary basin.

- Reconstructing the whole sedimentary basin by superimposing the primitive secondary basins to reproduce the evolutional picture.

2.5. Correcting the apparent dimensions of a secondary basin into the primitive dimensions based on the reconstructed sections with two conditions:

+ To determine the coordinates of each pair of present (X1Y1) and primitive (X2Y2) points

+ To fix the axial line of the secondary basins.

2.6. Reconstructing the isopach map

This is carried out in the following steps:

a. Determining the coordinates of intersection points between standard isopachs and reconstructed section lines

$(X_1Y_1, X_2Y_2...X_nY_n)$

$(X_1'Y_1', X_2'Y_2'...X_n'Y_n')$

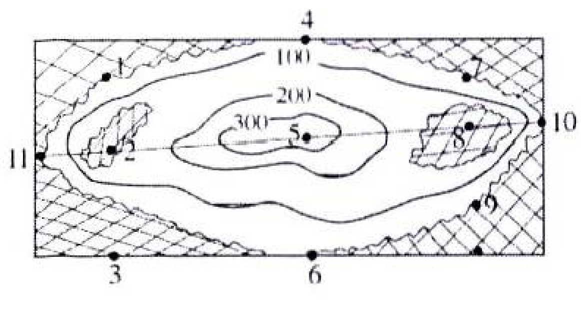


Fig. 11. Dimensions of the present secondary basin.

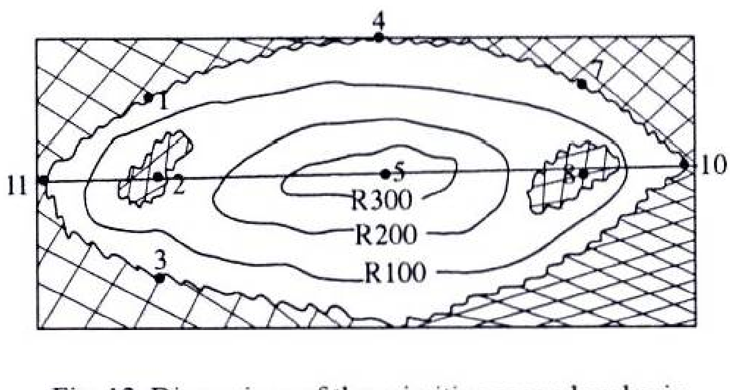


Fig. 12. Dimensions of the primitive secondary basin.

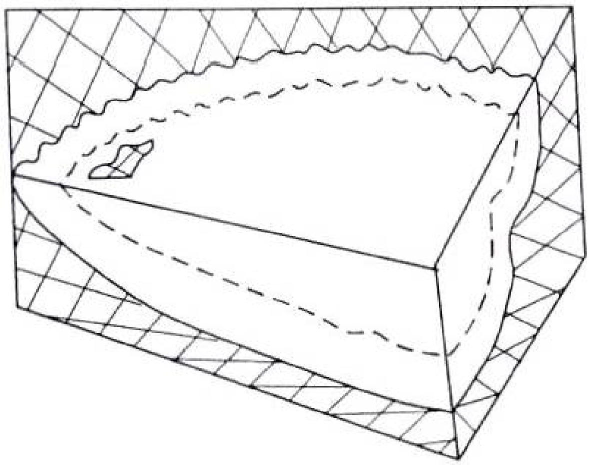


Fig. 13. Block diagram of the sedimentary basin before and after reconstruction.

2.7. Compiling lithofacies-paleogeographic map (see Fig. 14)

a. Determining seismic facies

b. Determining lithologic and fossil composition

c. Determining the facies based on the sediments and fossils

d. Determining facies based on well logging data

e. Drawing integrated lithofacies-paleogeographic sections based on the seismic, lithologic, fossil and well logging data.

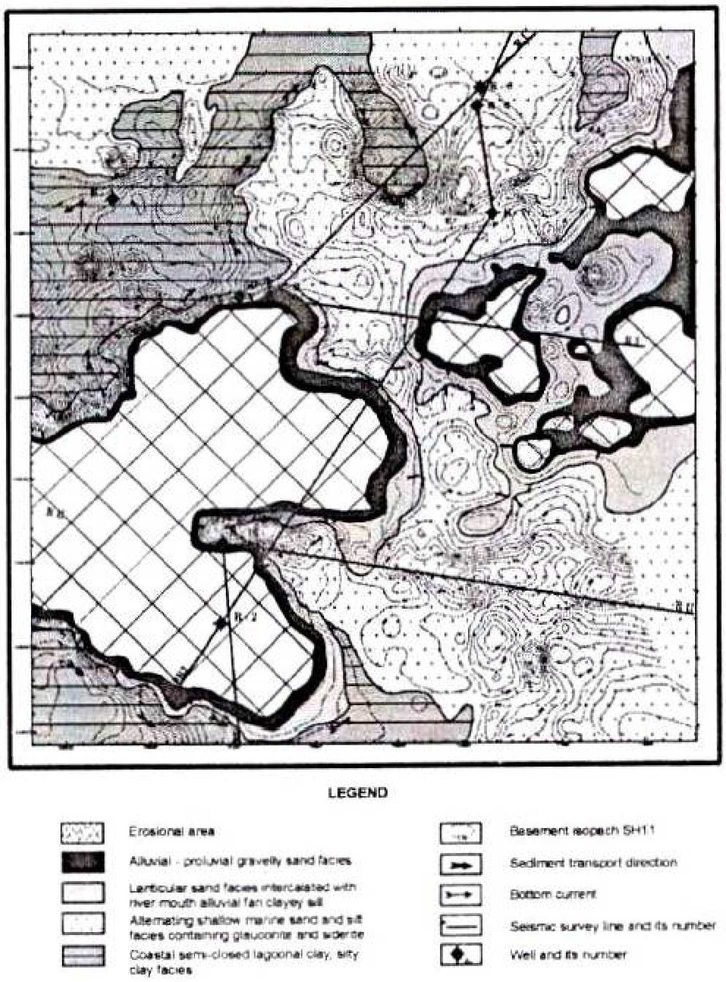
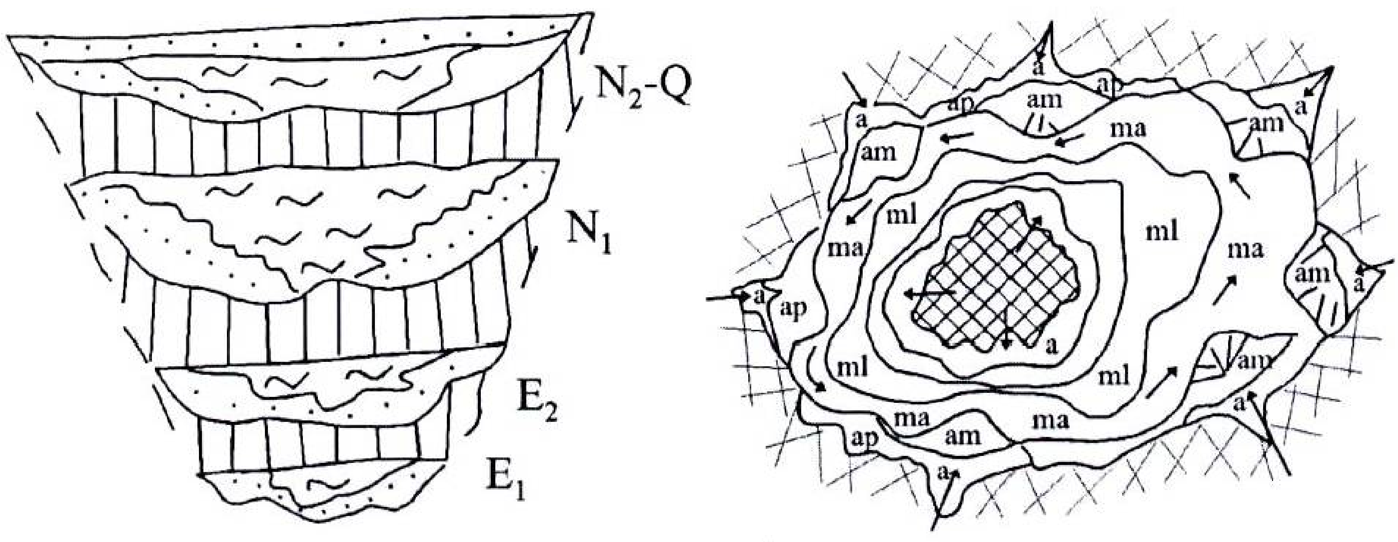


Fig. 14. Lithofacies-paleogeographic map of Early Oligocene period of Rong oil field, Cuu Long basin.

2.8. Drawing the lithofacies-paleogeographic map of a secondary basin with the following contents

- Boundary of erosional domain
- Distribution area of the erosional domain
- Distribution area of facies and facies groups demonstrating the facial paragenesis.
- Routes of sediment transport to the sea
- Old river channel
- Old coast line
- Long-shore currents
- Environmental physico-chemical indicators
- Temperature, salinity
- Organic matter
- Source rock facies
- Reservoir rock facies
- Seal rock facies



a b

Fig. 14. Diagrams of basin evolution (a) and horizontal facial paragenesis on a lithofacies- paleogeographic map.

The compilation of a lithofacies-paleogeographic map must be carried out step-by-step both according to the procedure and with extrapolation based on theory and experience and skill of each research expert. Therefore, the method of compiling this kind of map has been introduced in manuals, and some monographs in Vietnam and abroad.

Conclusion

1. Reconstruction of secondary basins is a basic principled task in compilation of lithofacies-paleogeographic maps. The simple reason is that, a the present three dimensional space of a sedimentary basin has been diminished, deformed by faults, folds, so it is necessary to reproduce the paleogeographic circumstances and the primitive sediment facies.

2. The procedure for reconstructing a secondary basin is developed based on the geophysical, geologic, depositional and physico-mechanical characteristics:

- Seismic facies
- Seismic reflection surfaces (erosional and depositional interruption surfaces)
- Normal, reverse faults, folds.
- Depositional cycles and sea level changes.

- Thickness of sediment layers and common porosity of rock types (conglomerate, sandstone, siltstone and claystone).

- Stages of secondary alteration.

3. Important reconstruction coefficients and formulas:

- Shrinkage coefficient (k): k = 1 (conglomerate, sandstone)

k = 0.8 (siltstone)

k = 0.5 (claystone)

- Porosity (P)

P_2 present porosity

P_1 primitive porosity

- Formula for reconstruction of sediment thickness, letting h_2 be the present thickness and h_1 be the primitive thickness:

$$h_1 = h_2 . \sqrt[3]{K.\frac{P_1}{P_2}}$$

4. Reconstructing the boundaries of the basin and the isopach map is an important step before drawing the lithofacies-paleogeographic map. This reconstructing procedure must be based on the algorithms for correction of basin boundary coordinates, isopach coordinates, thickness h_1.

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