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Modelling organic carbon distribution influenced by the presence of an oxygen minimum zone

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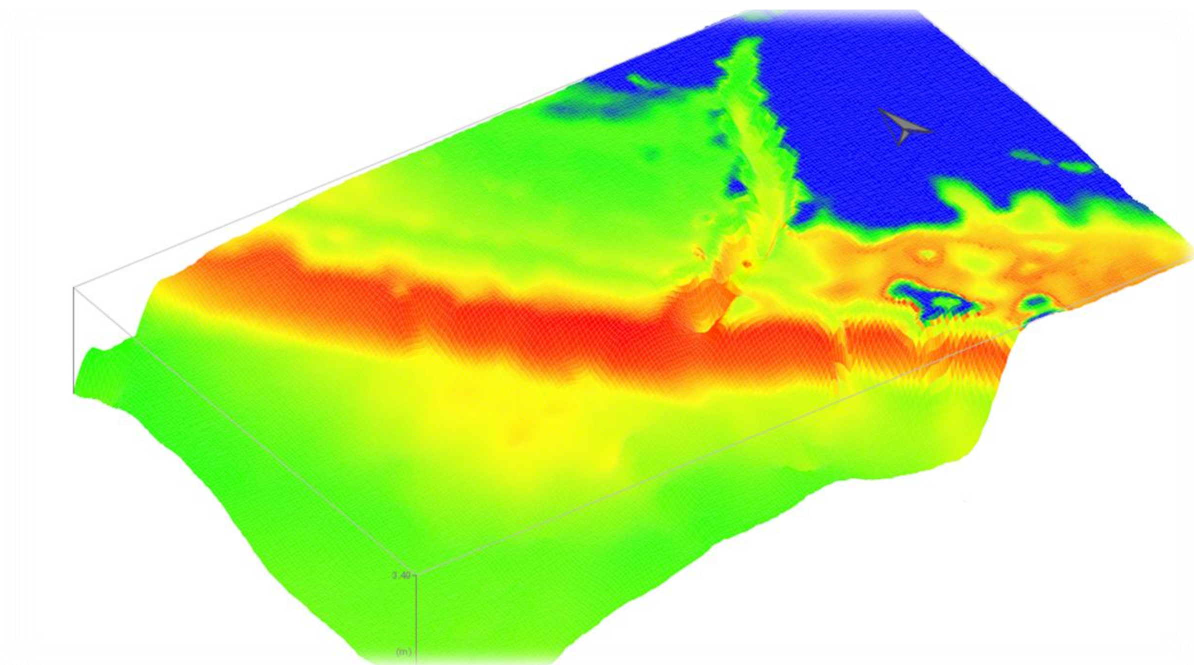

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Acknowledgements

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Abstract

The processes for the preservation of organic carbon in deposited sediment over geologic time have been a source of debate over the years. Several studies have been carried out on the topic; some studies indicate anoxia as the main factor controlling the preservation of organic carbon, while others suggest productivity. In order to study the influence of an oxygen minimum zone (an anoxic setting) on the preservation and distribution of organic matter in surface sediments, OF-Mod 1D and 3D were used to model the spatial distribution of organic carbon in surficial sediments across an oxygen minimum zone on the Pakistan margin north of the Indian Ocean. Measured data acquired from the area are used as input and also to calibrate the models. The spatial modelling of organic carbon across the Pakistan Margin using OF-Mod 3D showed that organic carbon was deposited within the OMZ as well as in areas outside the OMZ. There is an organic carbon maximum on the mid slope across the Pakistan margin, and areas around the Indus canyon in the south have relatively high organic carbon content compared to the northern areas. The margin is dominated by marine derived organic carbon with $\delta^{13}C$ values of -19 to -23 (‰) and terrigenous organic carbon content is low across the margin. Organic carbon quality is generally low across the margin due to degradation resulting in high amount of residual organic carbon as confirmed by low HI values of 180 to 275 (mg HC/g C). Preservation of marine derived organic carbon was found to be influenced by the OMZ and sedimentation rate on the slope while it is mainly influenced by sedimentation rate on the shelf. Higher source rock potentials are expected where the sedimentation rate is optimum in areas either within the OMZ or on the shelf outside the OMZ. Thus, within the Pakistan Margin the OMZ does not exclusively influence the preservation and spatial distribution of marine organic carbon, but it depends on the amount of organic carbon supplied to the system and an optimum sedimentation rate.

1 Introduction

The north eastern Arabian Sea is a unique environment characterized by strong seasonal variability of monsoonal upwelling and high primary productivity that favour an exceptionally broad mid-water oxygen-minimum zone (OMZ) (Cowie et al., 1999) (Figure 1). The distribution of organic rich sediments within this area, its paleoceanography and the presence of an oxygen minimum zone are still poorly understood. The Pakistan margin and western part of the Indian Ocean have been studied over the years and during the international Indian Ocean expedition IIOE. Von Stackelberg (1972) discovered the presence of laminated organic matter rich muds with sedimentation rates up to 1 mm/yr where the OMZ impinges on the sea floor (see also Paropkari et al., 1993). The oxygen minimum zone (OMZ) stretches across the Pakistan margin from east to west. It is present between 200m to 1200 m water depth and it impinges on the seafloor as shown in Figure 2 A, B. Figure 2C shows the oxygen depth profiles within the Pakistan margin and also part of the southern Indian Ocean. The concentration of dissolved oxygen in ocean bottom waters and pore waters has been considered to influence the preservation of organic matter. Anoxia has been widely accepted as the major contributor to the preservation of organic matter, while high concentration of oxygen may not favour organic matter preservation (e.g. Thiede and van Andel, 1977; Demaison and Moore, 1980; Paropkari et al., 1992, 1993; van der Weijden et al., 1999). In the Pakistan margin, high primary productivity, sedimentation rate coupled with the presence of an oxygen minimum zone has resulted in the preservation of organic rich laminated sediments which could represent present day analogues of organic rich source rocks.

The code OF-Mod 3D (Mann and Zweigel, 2008), a process based organic facies modeling tool has been employed to model the spatial distribution of the organic carbon within the Pakistan margin and to study the influence of anoxia on the preservation of organic carbon. OF-Mod 3D is convenient and easy to use in areas of limited data in the modeling of organic carbon distribution and predicting of source rock quality. It takes into account processes and conditions within the depositional environment, such as carbon flux, primary productivity and burial efficiency, to estimate the amount of organic carbon deposited and preserved within the area of interest (Mann and Zweigel, 2008). Data collected from literature and previous investigations (eg Schulz and von Rad 1997; Cowie et al., 1999) carried out on the Pakistan margin were used in generating input parameters, such as sedimentation rate, sediment dry bulk density, sand fraction and water depth data was used to calculate organic matter fractions using OF-Mod1D modeling software. Measured data from the area, such as Total organic carbon, Hydrogen index and carbon isotope measurements, were used to calibrate 1D modelling. The 1D result served as a guide in estimating the primary productivity, residual and terrestrial organic input for OF-Mod 3D modeling and also in adjusting the user defined end member values used in the 3D modelling.

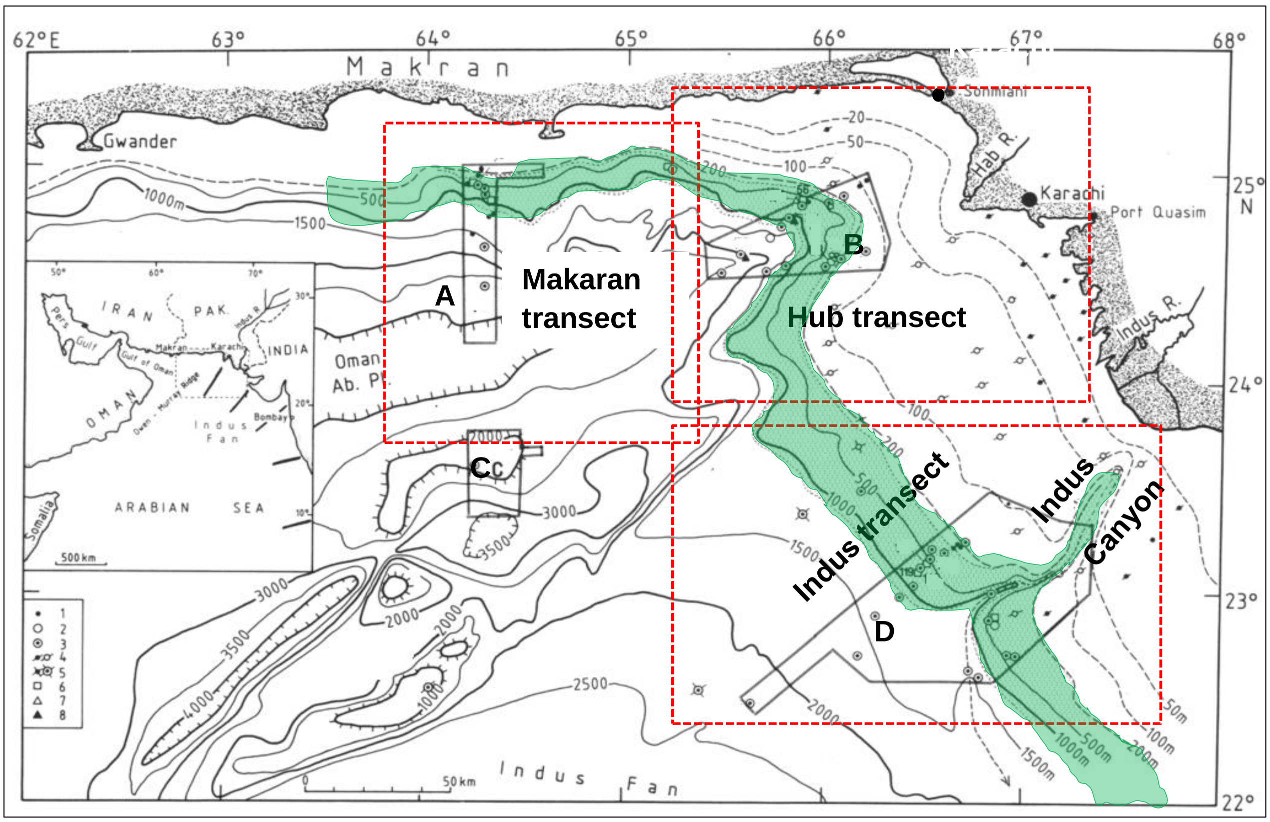


Figure 1 Location of the Pakistan margin and the areas of interest transect A, B and D acquired from Sonne 90 working areas A to D and area covered by OMZ in green and station locations. Cowie et al. (1999).

The map (Figure 1) shows the location of the Pakistan margin ,area covered by the oxygen minimum zone in green and also the areas of interest labeled A, B and D which were selected based on availability of data across the OMZ from previous studies carried out on the area (see Cowie et al. 1999). Area C was ignored because it is far from the OMZ and not needed for this study. Bathymetric data within the marked areas (areas within the boxes) where imported into Petrel 2012 in digital format to create present day bathymetric maps (Figure 3), which will serve as input data for OF-mod in modeling the sedimentary basin fill and 3D organic facies distribution.

1.1 Objectives

The project was carried out by achieving the following set of objectives, which are laydown steps needed to guide the work to accomplishing the main aim of the work.

1. Collect literature information about the area of interest needed for the studies.
    - well measurements (e.g. ODP data)
    - input values such as marine productivity, location and intensity of oxygen minimum
2. use OF-Mod 1D to determine input for OF-Mod 3D
    - Prepare maps for input into OF-Mod 3D and other basin modelling software.
    - model the organic carbon distribution in the area using OF-Mod 3D, calibrated by measured values obtained from the area.
3. investigate the influence of the oxygen minimum zone in the area
    - describe preservation factor
    - describe spatial and temporal distribution of relevant depositional influences

1.2 Aim of study

The deposition, distribution and burial of organic carbon in marine settings are strongly influenced by the concurrent deposition of inorganic mineral matter. Sedimentation rate (inorganic input), carbon flux and the level of anoxia all play an active role in the preservation of organic matter. Currently there is a debate about the dominant factor influencing the accumulation of organic matter within oxygen minimum zones. While some authors believe that the organic enrichment is due to upwelling-induced excessive biological productivity of overlying surface waters resulting in a high flux of biogenic material to the bottom (the production hypothesis; Parrish, 1982; Calvert, 1987; Pedersen and Calvert, 1990; Calvert and Pedersen, 1992), others believe that the formation of oxygen depleted conditions (anoxia), either in the oxygen minimum zone (OMZ) at intermediate oceanic depths, or in silled basins, is responsible for preservation and consequent enrichment of organic carbon in sediments (the preservation hypothesis Demaison and Moore, 1980; Bralower and Thierstein, 1987).

This project seeks to investigate the influence of an oxygen minimum zone on the distribution of organic carbon in surficial sediment and also investigate the influence of an OMZ and other factors on the preservation of marine organic carbon. In other to achieve this fit, OF-Mod was used to model the spatial distribution of organic carbon across the oxygen minimum zone within the Pakistan margin. The Pakistan margin is a good candidate for this study because of the presence of an oxygen minimum zone and also availability of data from previous studies on the area. OF-Mod is ideal for this study because in OF-Mod the influencing factors can be varied within a controlled setting to shed more light on the role played by anoxia and other factors within and outside the OMZ.

2 Geologic setting and depositional environment

2.1 Study area

The northern Arabian Sea is a unique environment characterized by strong seasonal variability of monsoonal upwelling and high primary productivity (Schulte et al 2000), coupled with the supply of oxygen-depleted intermediate-depth water masses from the south, which favour an exceptionally broad and stable mid-water oxygen-minimum zone (Schulte et al 2000). The OMZ (present at water depths of 200m-1100m) is characterized by low oxygen levels (down to 0.5 mg O_2/l), the presence of laminated organic rich surficial sediments and the absence of benthic organisms where the OMZ impinges on the sea bed (von Rad et al. 1995). High eolian and fluvial input from the surrounding continents, as well as monsoon-induced upwelling of nutrient-rich subsurface waters, make the Arabian Sea one of the most biologically productive oceanic areas in the world (Nair *et al.,* 1989).

The high productivity and subsequent bacterial decay of organic matter, as well as other oceanographic factors, lead to extremely low oxygen concentrations in the water column. In this area high surface ocean productivity and high season variability in sediment flux are closely related to monsoonal circulation changes and associated upwelling (Prel et al 1991, Haake et al 1993).

Lack of bioturbation due to severely reduced or stagnant bottom water ventilation is currently seen by some authors as the most important factor in the preservation of sediment lamina in marine sediments (Schulz et al 1996). Most organic rich laminated sediment occurs in areas of high oceanic productivity that leads to strong oxygen depletion in the water column and an enhanced seasonal flux of organic matter. Another factor responsible for sediment lamina formation is the enhanced deposition of terriginous material supplied by rivers and wind currents from the continent. Redistribution of fine grained material also plays an important role in the accumulation of laminated materials, originating from small scale, very low velocity turbidity currents on the sea floor, as well as gravity flows on the shelf slope. Such short term flows can be initiated by earthquakes, storms or water mass dynamic changes.

Von Stackelberg (1972) described a specific type of downslope resedimentation of fine grained sediment: this turbid layered transport may play an important role in the accumulation of organic matter and the formation of sediment lamina in the northeastern Arabian Sea, as well as in other continental slope environments (Gokçen 1987).

The samples collected from across the Pakistan continental margin during the Pak-German cruise with R/V Sonne 90 (Roeser et al., 2002) come from various depositional environments. The areas are shown in the map (Figure 1):

1. Area A: The Makran transect is on the active Makran continental margin where the Arabian plate is subducted below the Eurasian plate. This area is characterized by a narrow shelf and an extremely steep continental slope (Figure 2).
2. Area B: The Hub transect is characterized by a gentle slope and a broad shelf which forms a source area for most of the fine grained continental materials of the Indus River (Schulte et al 1999) (Figure 2)
3. Area D: The Indus transect consists of the deeply incised Indus canyon, a gentle continental slope and a broad shelf which is comparatively less affected by sediment redistribution. The Indus canyon and its seaward channel levee distributary systems are the major conduit for funneling riverine materials and all other detritus down slope.

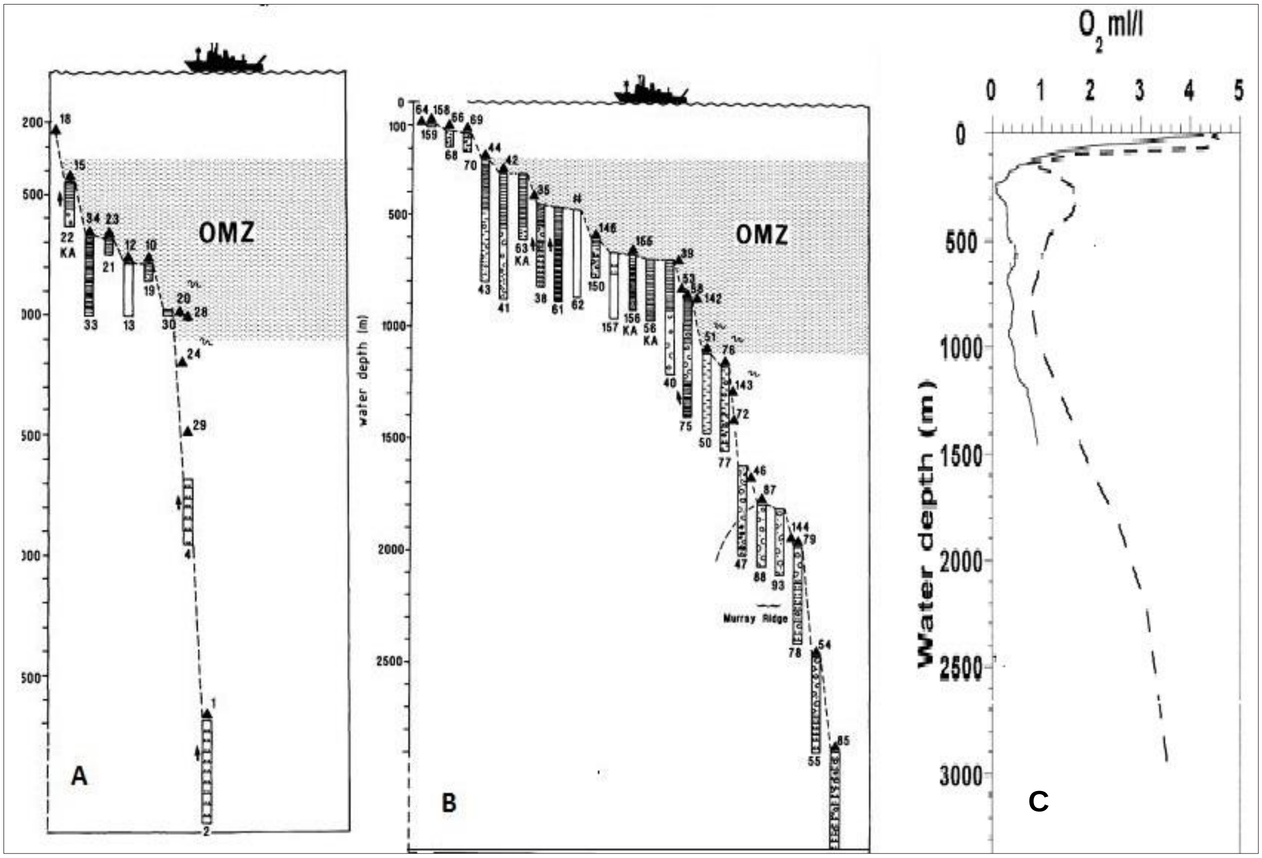


Figure 2 Lithofacies distribution in PAKOMIN cores across the continental slope off Pakistan. (a) Area A Makran transect; (b) Area B from Kemp et al (1996), (C) Oxygen depth profile of the northeast Arabian sea (solid Line) and southeast Arabian Sea (dotted line) from Schulte et al (1999)

2.2 Depositional environments

The depositional environments within the area of interest range from deltaic to shallow marine and from the continental shelf down the continental slope into the abyssal plain. The depth ranges from 0 to about 4000m below sea-level covering areas below and above the OMZ.

Figure 3 is a bathymetric map showing the specific areas of interest which were selected based on the availability of data within the area as well as the differences in depositional environment from very deep marine in the southern section of the map, to shallow continental shelf environment predominant in area B.

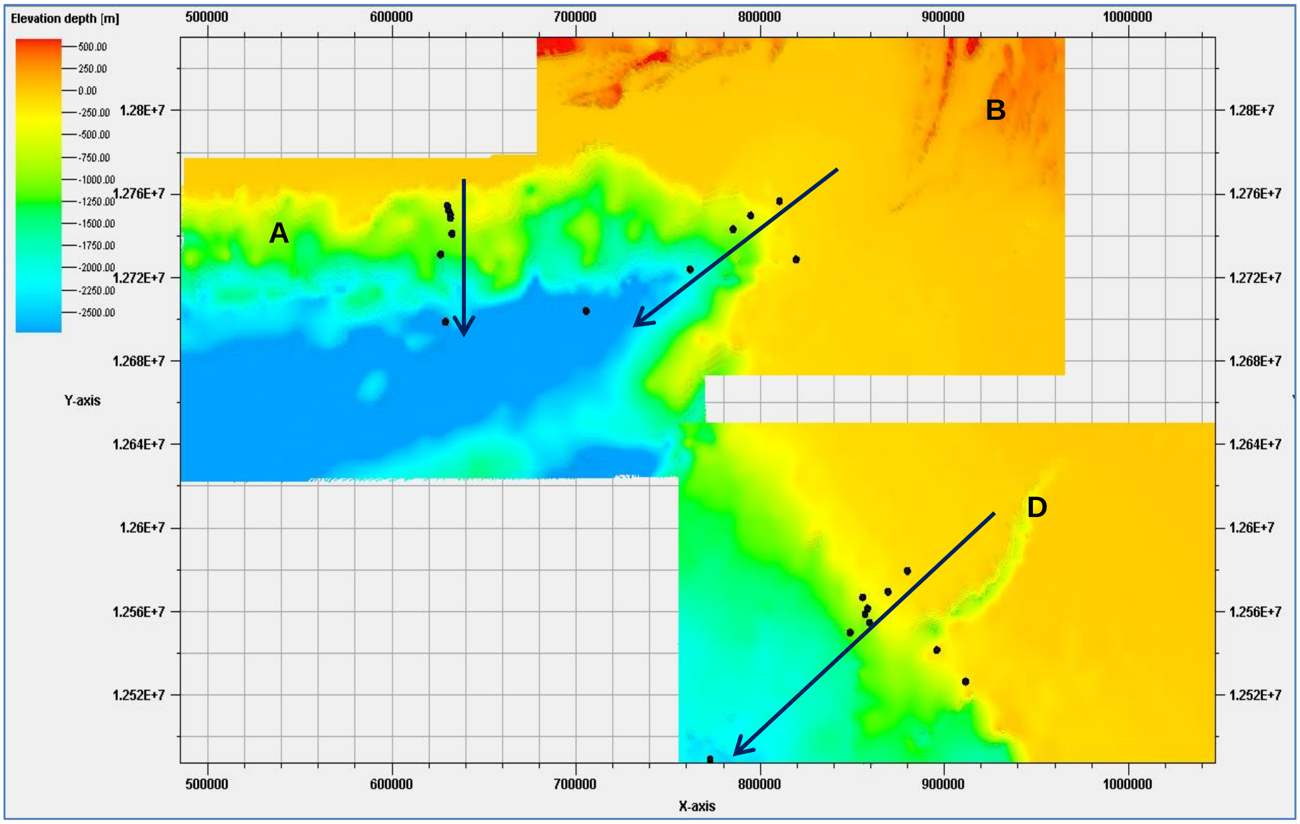


Figure 3 Bathymetric map of area of interest showing sample data points along transect A,B AND D. The map data were obtained from the British Oceanographic Data Center digital atlas. (http://www.gebco.net/).

3 The OF-Mod concept

The OF-mod organic facies modeling tool is based on several concepts which are dependent on processes and conditions involved in organic facies production and preservation in marine sedimentary environments. These are discussed in the following sections:

3.1 The organic matter origin (source type)

The three main organic matter types are the locally marine sourced (autochthonous) material and the terrestrial sourced material from the continent (allochthonous) (Figure 4) and also the degraded organic matter. The residual organic matter could be either marine derived or terrigenous depending on the level of degradation of the organic matter type. Residual organic carbons are in most cases related to terrigenous organic carbon because the terrigenous organic matter had undergone some level of degradation before entering the marine systems. Poor preservation in marine environment would also yield residual organic carbon which should be considered when modeling the organic carbon fractions. The marine organic carbon is associated with clay low energy deposition while terrigenous is associated with terrigenous rock fragments (high energy deposition) and residual could be found across both settings.

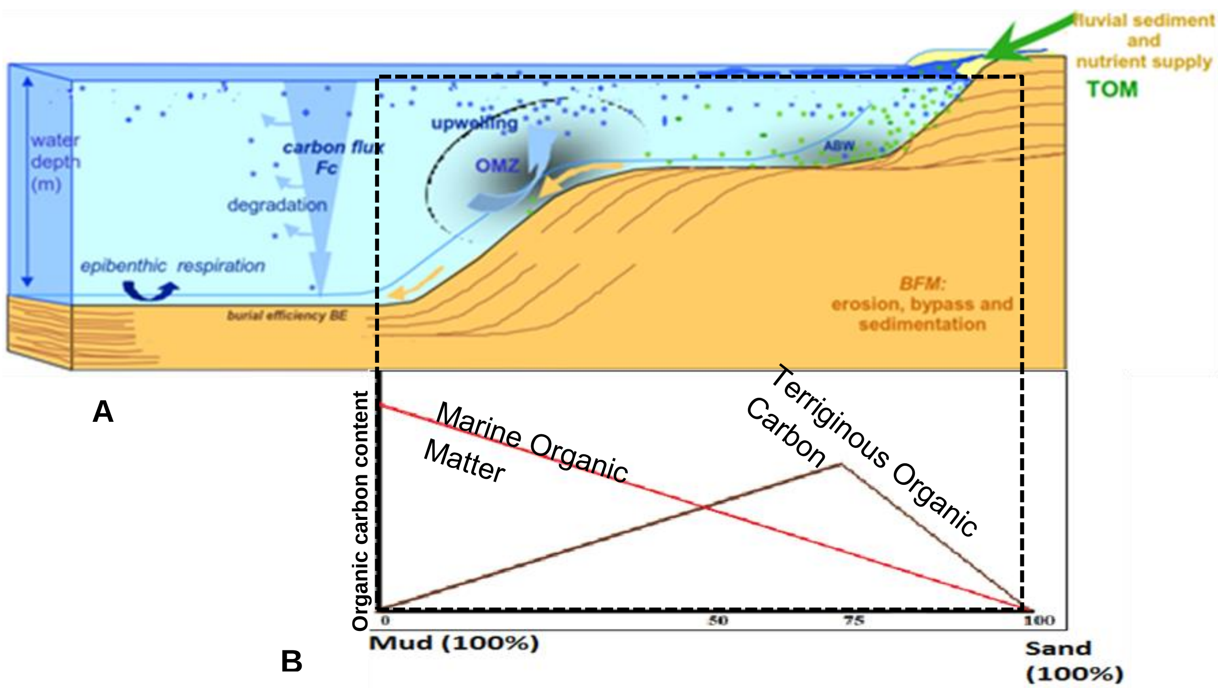


Figure 4 (A) Marine and terriginous organic carbon within various depositional setting (B) variations in sand and mud fraction across the environment. Red line marine organic carbon max in 100% mud and Terrestrial organic carbon max at 75% sand (Mann & Zweigel 2008)

3.2 Depositional conditions within sedimentary environment.

The prevailing environmental conditions and processes determine how much organic carbon gets preserved or undergoes further degradation. Different organic matter types are produced in different environmental conditions e.g. terrestrial organic matter is produced in oxygenated environments and has experienced some level of degradation prior to its introduction into the marine setting. Therefore it is important to differentiate the two organic matter fractions (terrestrial and marine). The terrestrial organic matter is considered to be more resistant to further degradation when in the marine environment (Mann & Zweigel, 2008). An exception which is not considered in OF-Mod modelling is the presence of turbidity currents which are able to transport coarse terrigenous material from source areas into distal deeper marine areas (Degens et al., 1986). The concept also assumes a decrease of terrestrial organic carbon (with regards to its association with the sand fraction) with reduction of depositional energy close to or far from the coastline. This is based on the concept that terrigenous organic carbon has similar characteristic trends with inorganic mineral grains with regards to grain reduction via wearing and sorting which is a function of the energy within the depositional environment (Littke et al., 1996). The relationship of source, composition and diagenesis of organic matter with respect to grain size and mineralogy was investigated by Bergamaschi et al. (1997) and Keil et al. (1998) and they showed that the particle size and mineralogy correlate with variations in composition and distribution of the organic matter.

- Fresh woody debris, as well as lignin-phenol enriched organic matter is concentrated in the sand-sized fraction.
- Pollen grains are associated with the silt-sized fraction and organic matter in the finer fractions becomes progressively more degraded.

Summing up, it is considered that the distribution and preservation of terrestrial organic carbon in the marine setting is a function of the transport distance from shore, depositional energy (water depth) and sorting similar to the inorganic sediment (Mann & Zweigel, 2008).

The marine fraction (autochthonous organic matter), which is produced within the water column or in the upper sediment layers would under some level of degradation, with increased resident travel time within oxygenated waters during settling. Thus, the faster the organic matter sinks to the bottom of the sea the less likely it is oxidized within the water colume. On the sea floor, its quick burial would ensure it is preserved hence sedimentation rate is important. Carbon flux is a measure of the quantity of sinking particulate organic materials through an aquatic system, usually in oceans. Measurements of carbon flux data from sediment traps have indicated that marine organic matter can be degraded in the uppermost part of the water column. Based on the above information, several authors have been able to estimate carbon flux by correlating primary produced organic matter (PP in $gCm^{-2}yr^{-l}$) to water depth (Figure 5). Primary production is the measure of the amount of organic matter produced from atmospheric or from aquatic carbon dioxide via photosynthesis by primary producers or autotrophs. In some cases where organic matter is adsorbed onto mineral grains (organic coating), as aggregates or incorporated in faecal pellets (solid excreta) this will result in faster sinking rates of the organic matter, short oxygen exposure time, rapid accumulation and burial. Keil et al., (1994), Mayer, (1994) and Hedges & Keil, (1995) are of the opinion that this is an important process in enhancing preservation of organic matter.

4 OF-Mod methodology

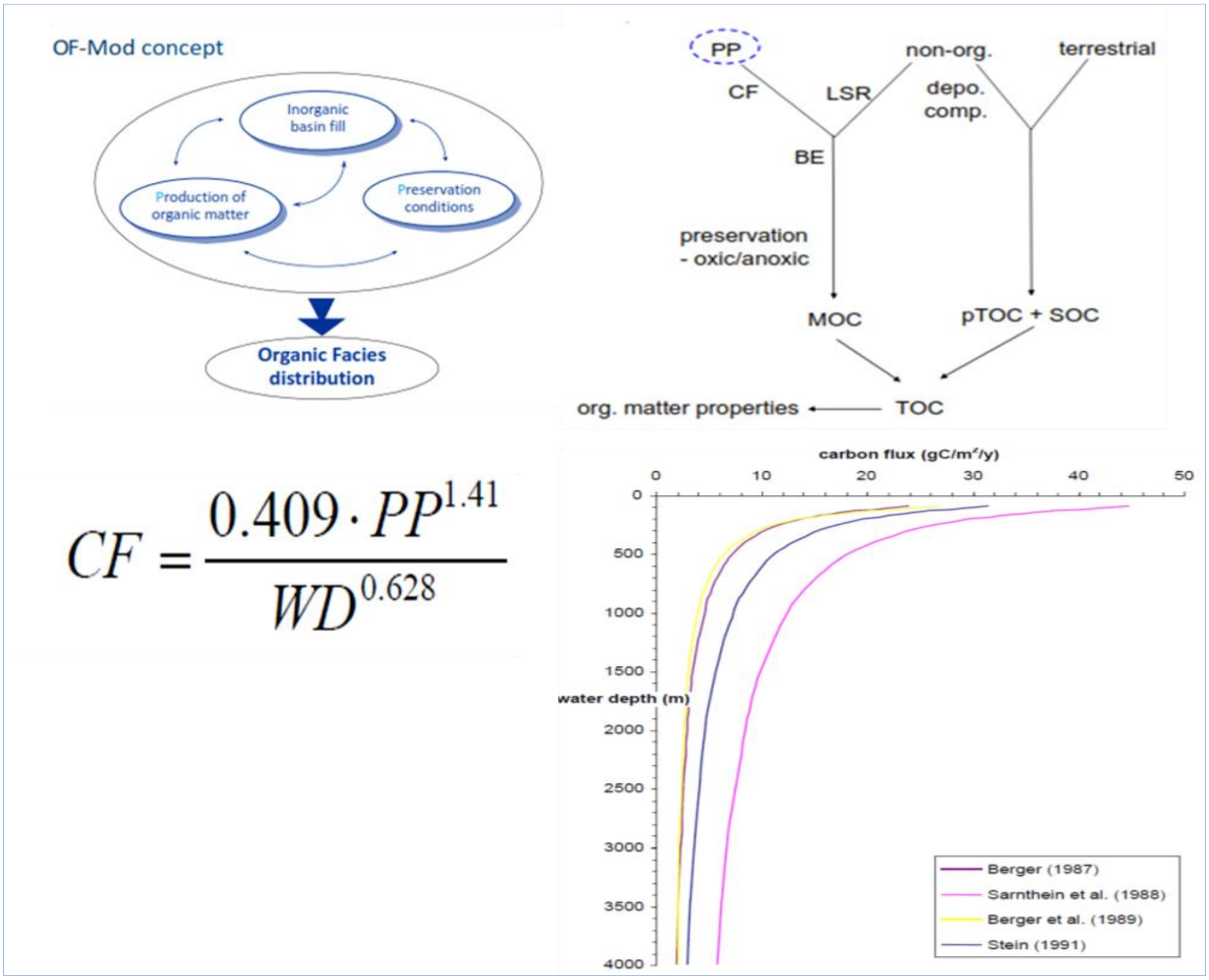


Figure 5 OF-Mod 3D organic facies modeling process (Mann & Zweigel, 2008)

Deposition and preservation of organic carbon are process based and in OF-Mod these processes are considered in modeling the organic facies and some of the key influencing factors includes the following:

I. **Carbon Flux (CF)**
II. **Dilution**
III. **Burial efficiency**

4.1 Carbon flux (CF)

The carbon flux is a function of the primary produced (PP) organic carbon and the water depth (Figure 5) as defined by Betzer et al (1994). This is the rate of flow of primary produced organic carbon down the water column as it settles to the ocean bottom. The carbon flux reduces with water increased water depth as more of the organic matter is consumed by oxidation and also by other fauna as it sinks down to the sea bed.

4.2 Dilution

The rate at which inorganic mineral grains (rock materials) are added to the deposit could result in dilution of the organic matter, when the rate of addition of inorganic fraction is far greater than that of the organic fractions. The sand fraction is dependent on the rate at which inorganic matter is added to the system thus the higher the sedimentation rate the higher the sand fraction. The sand fraction represents the inorganic fractions and the rate at which sediments are added into the system is the sedimentation rate SR [cm/ ka] and with increased SR the organic fraction reduces (Figure 6). High sedimentation rete would initially prevent deposited organic matter from oxidation (enhancing preservation) but more sedimentation would have no further influence on preservation but would trigger dilution. The dry bulk density (DBD [g/cm^3]) of the sediment is also important in calculating post depositional effects compaction which is an essential component of the accumulation rate. The compaction tells how much force as acted on the sediment in terms of sediment loading with this information the thickness of the sediment during deposition can be estimated to compute the sedimentation rate.

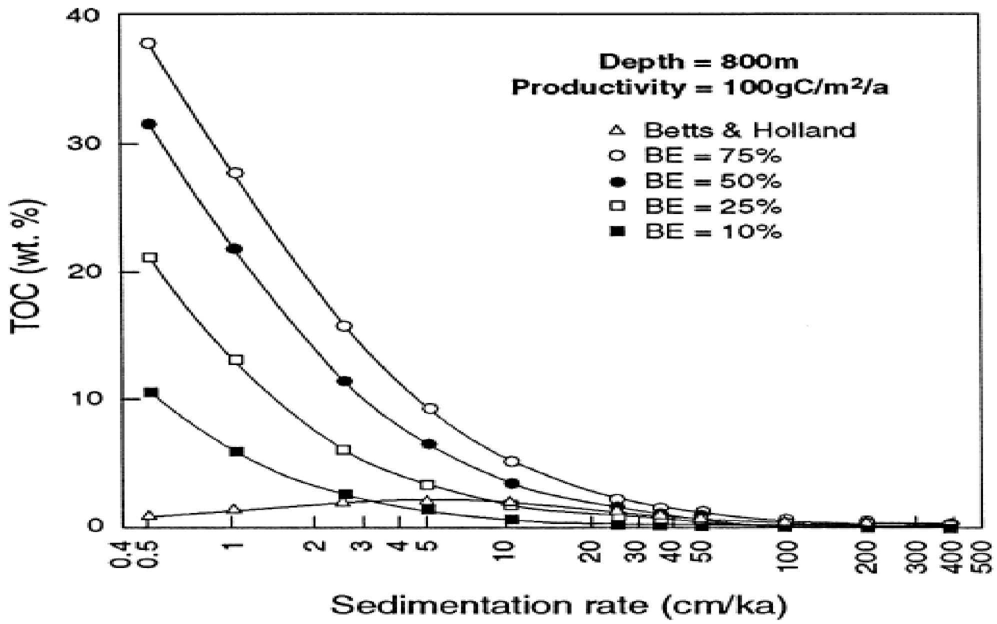


Figure 6 The relationship between TOC and sedimentation rate (SR) assuming 800 m water depth and a primary productivity fixed at 100 g C/m^2/a (a constant flux delivery) plus a range of carbon burial efficiencies from 10 to 75 (Tyson 2001)

$$\mathbf{Dilution} = \frac{\mathbf{100}}{\mathbf{DBD * SR}}$$ (Mann and Zweigel, 2008)

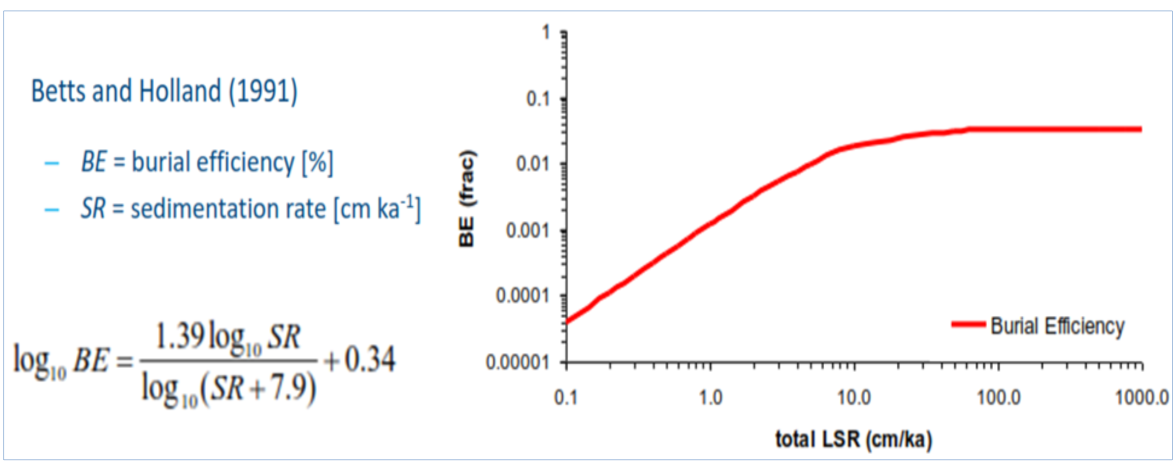


Figure 7 Relationship between sedimentation rate and burial efficiency (BE) (Mann & Zweigel, 2008)

4.3 Burial efficiency (BE)

This is the proportion of primary produced organic carbon that is sedimented and preserved once early diagenesis is essentially complete (Henrichs and Reeburgh, 1987). Burial efficiency is also influenced by the sedimentation rate and is given by the equation in Figure 7.

Figure 7 also shows the relationship between burial efficiency and sedimentation rate (SR): with increasing sedimentation rate, the burial efficiency initially increases as the mineral grains shields the organic matter from being oxidized or scavenged by bottom dwelling organisms. When the organic matter is sufficiently buried subsequent addition of sediment would have no effect on the burial efficiency hence the plot in Figure 7 levels out and the burial efficiency is constant with increased sedimentation.

4.4 Marine organic carbon (MOC)

The accumulation of the marine organic carbon is influenced by the carbon flux, inorganic dilution and the burial efficiency (in oxic conditions).

Marine organic carbon (MOC) in oxic conditions is given by:

CF *BE* Dilution = →

CF Dilution

$$MOC = \left(\frac{0.409PP^{1.41} * Z^{-0.063}}{10}\right) * \left(\frac{100}{DBD * LSR}\right)$$

BE

$$* \left(0.54 - 0.54 * \left(\frac{1}{0.037 * LSR^{1.5} + 1}\right)\right)$$

Oxic conditions

CF	= carbon flux to sea flux (sinking) **[gC m^{-2} a^{-1}]**
PP	= the primary productivity **[gC m^{-2} a^{-1}]**
WD	= water depth **[m]**
SR	= sedimentation rate **[cm/ka]**
BE	= Burial efficiency
MOC	= marine organic carbon

In anoxic conditions (ocean water column and bottom pore water) oxidation does not affect the marine organic matter and scavenging bottom dwellers are absent (they depend on oxygen for respiration), so sedimentation rate has little influence on the burial efficiency of the organic carbon. In OF-Mod a different formula is used in calculating the MOC because the BE approach cannot be applied. Instead the preservation factor (PF) approach or formula is applied because it is independent of burial efficiency. The PF (%) is the ratio the absolute amount of primary produced organic carbon deposited and preserved in the sediment. The preservation factor is independent of water depth (Bralower & Thierstein 1984) and is given by:

PF = $(MOC/100) * LSR * DBD/PP$

On rearrangement of the above equation the marine organic carbon in anoxic condition is given as:

$$\text{MOC} = \frac{(PP*PF*100)}{(\text{DBD}*\text{SR})}$$

Where

PP = the primary productivity **[gC m^{-2} a^{-1}]**
SR = sedimentation rate **[cm/ka]**
MOC = marine organic carbon
PF Preservation factor
DBD Dry bulk density

5 Methodology

The project was carried out in several steps which include:

- Data gathering and organization.
- OF-Mod input data preparation.
- Inorganic facies modeling: sedimentary facies and sand fraction.
- OF-Mod 1D organic facies modelling.
- Application of steps 1 to 4 to 3D organic facies modelling within the areas of interest.

5.1 Methodology step 1: Data gathering

This involves the collection of relevant data from the various sources related to the areas of interest and which were used as input into the OF-Mod modelling software and for model calibration. The data include bathymetric maps, measured sand fraction data, measured total organic carbon, hydrogen index, carbon isotope data ($\delta^{13}C$), facies maps, sedimentation rates and the geographical location on the map. Most of the data were acquired by searching through literature and previous work carried out on the area, especially data gathered during the Pak-German cruise with R/V Sonne 90. In this study some data gathered were from surficial sediments collected with a 50x50 cm Kasten box-core and range from coarse, shell-rich deposits on the shelf to fine, silty-clays below the shelf break (Cowie et al. 1999). Papers by von Rad et al. (1997), Schulte et al (2000), Mann and Zweigel (2008) also proved useful in the project. The geo-reference data library (www.pangea.de) was also a vital source of information and bathymetric maps were obtained from the British Oceanographic Data Centre (BODC) digital atlas in gridded format (http://www.gebco.net/).

5.2 Methodology step 2: Input data

The areas of interest were selected based on availability of data and variations in the depositional environment. The point grid data were imported from the BODC digital atlas into Petrel where surfaces were generated. Palaeo-water depth reconstructions were done using shallow cores which were available within the area of interest. The ages of the cores had been determined with depth, so a particular age (time) was selected and depth points corresponding to the age were calculated for each point where a core was available. A thickness map (Figure 8) was made using Petrel software and a palaeo-bathymetric surface was constructed by subtracting the thickness map from the present day bathymetric map. The water depth map was used as input in the OF-Mod modelling software to determine sedimentary facies distribution, water depth, and distance to shore. Grid size and grid resolution are defined and set for basin fill (inorganic facies) modelling (Figure 8).

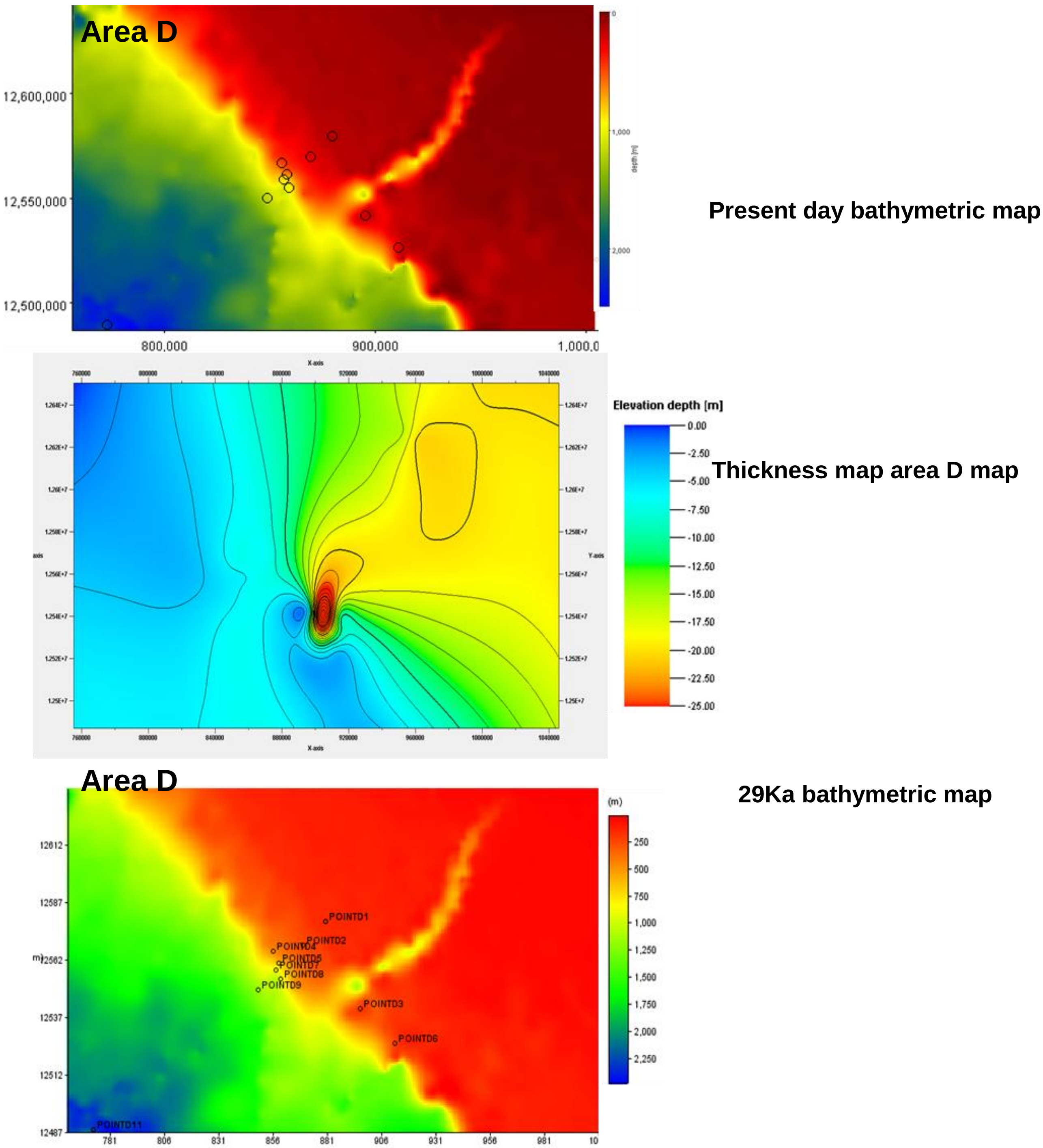


Figure 8 Present day , thickness and palaeo- Bathymetric maps

The present day map and palaeo-maps looks identical but they differ by the thickness of sediments deposited in the last 29 Ka. The thicknesses were based on cores collected during the Pak-German cruise with R/V Sonne SO-122 (Roeser et al., 2002).

The distance from point in the ocean to shore line is also important in defining the sedimentary facies distribution and the primary productivity trends during modeling in OF-Mod. The distance to shore map was determined in OF-Mod using the present day bathymetric map and the coastline was imported from Petrel after being implemented as a single polygon line defined along the shore (zero contour value) on the bathymetric map. (Figure 9, 10 &11)

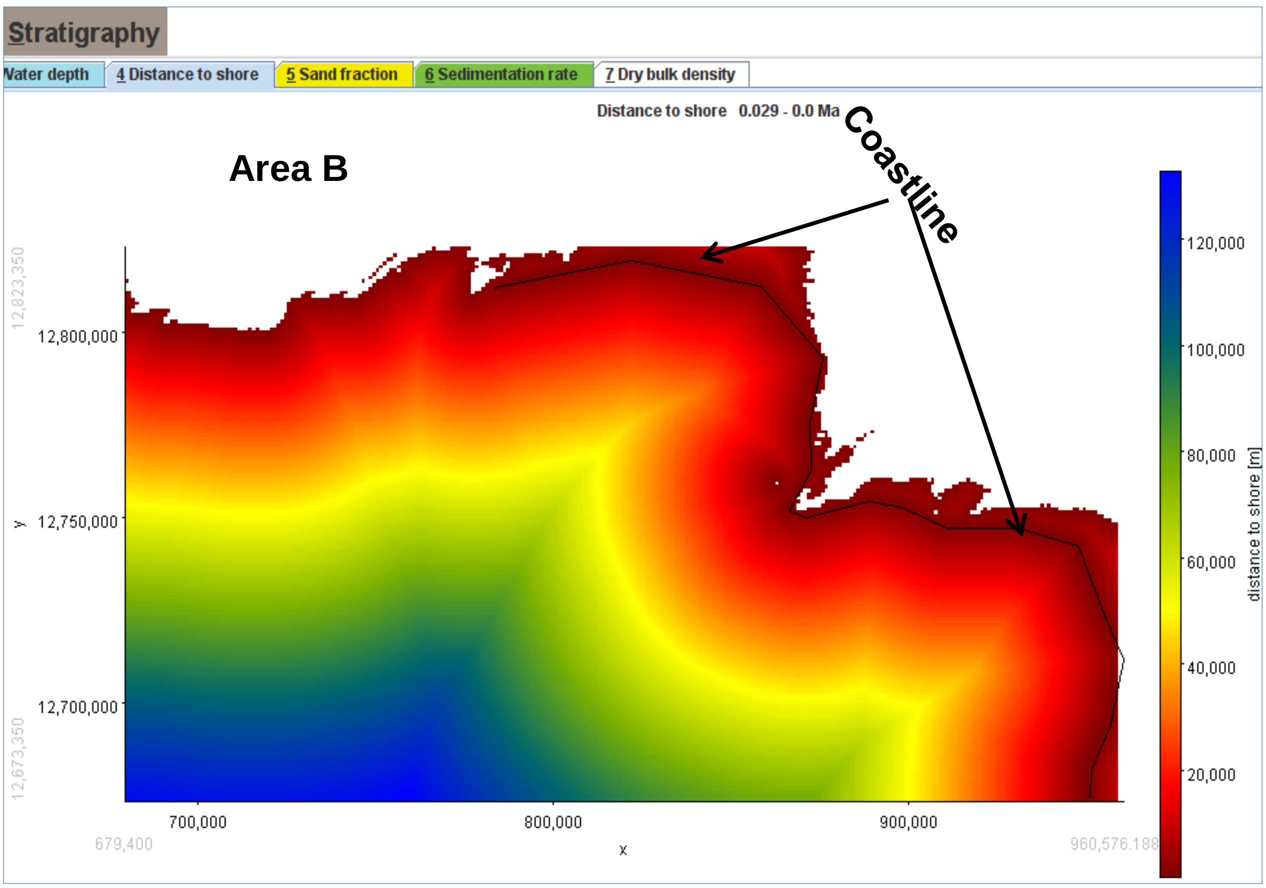


Figure 9 Area B distance to shore map showing the coastline clearly defined

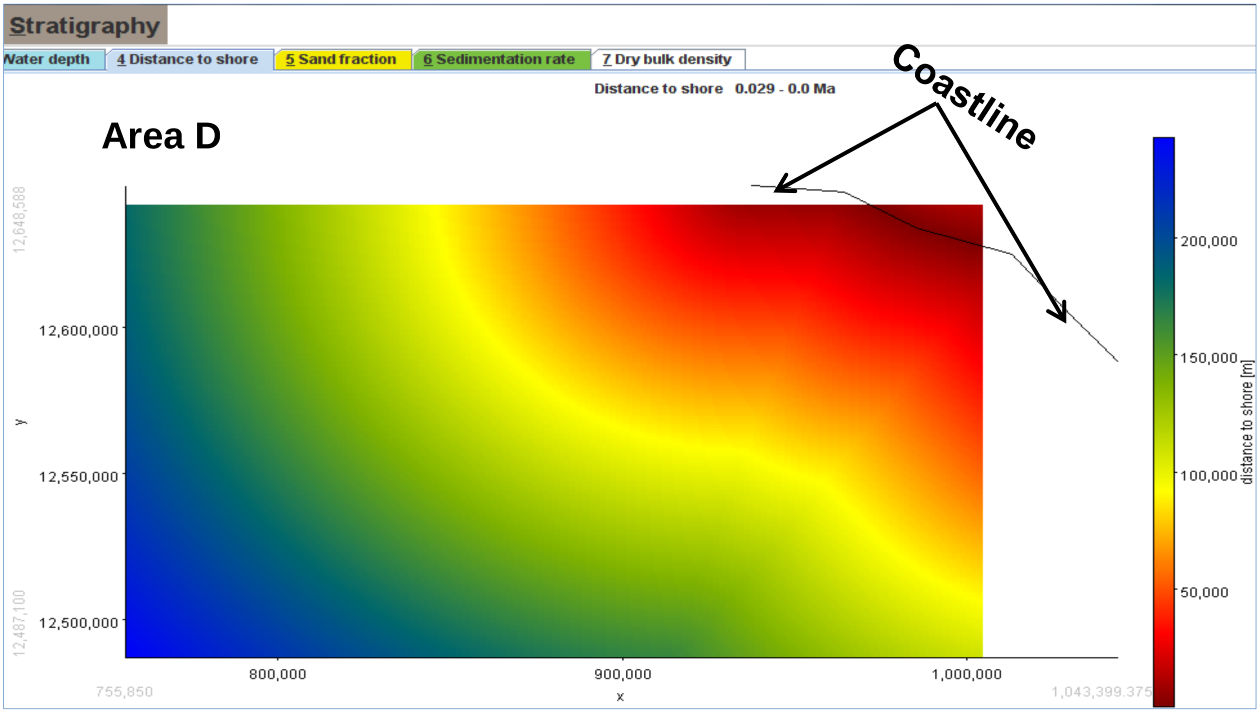


Figure 10 Area distance to shore map showing the coastline clearly defined (area D)

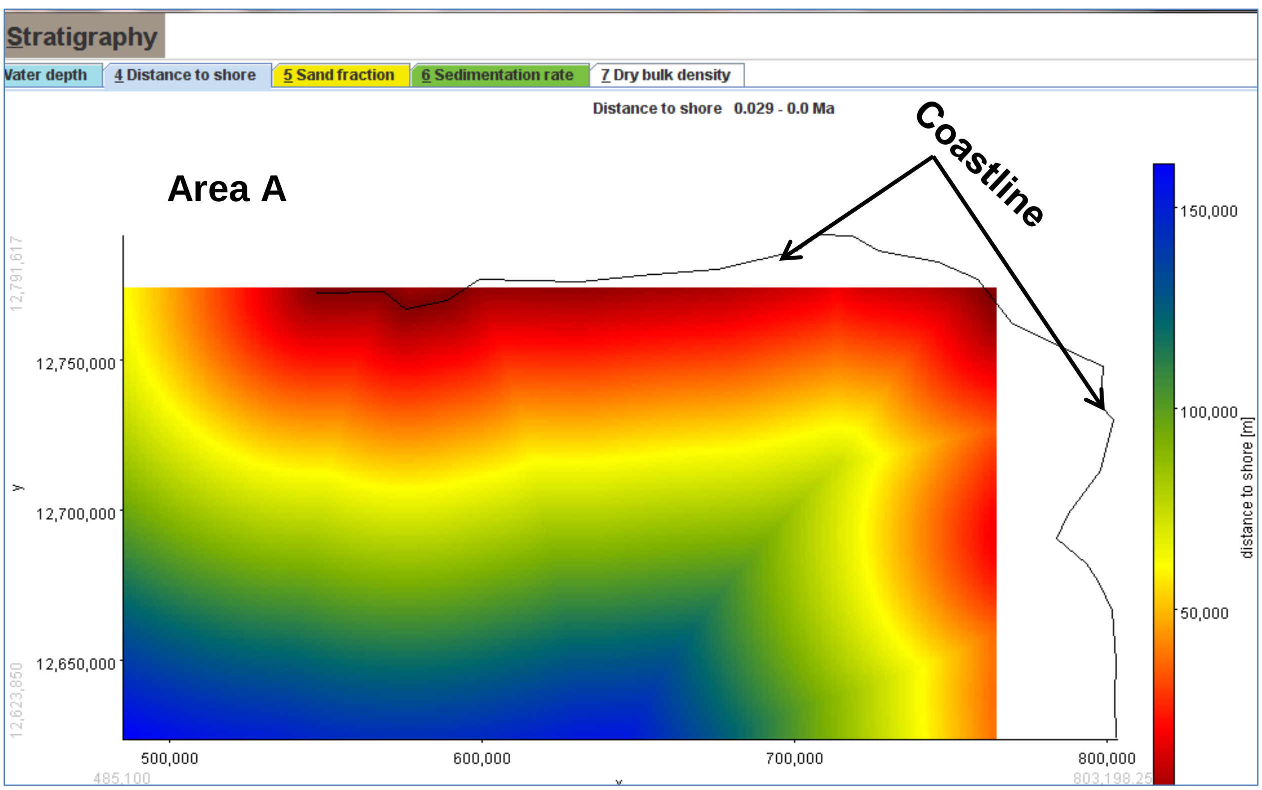


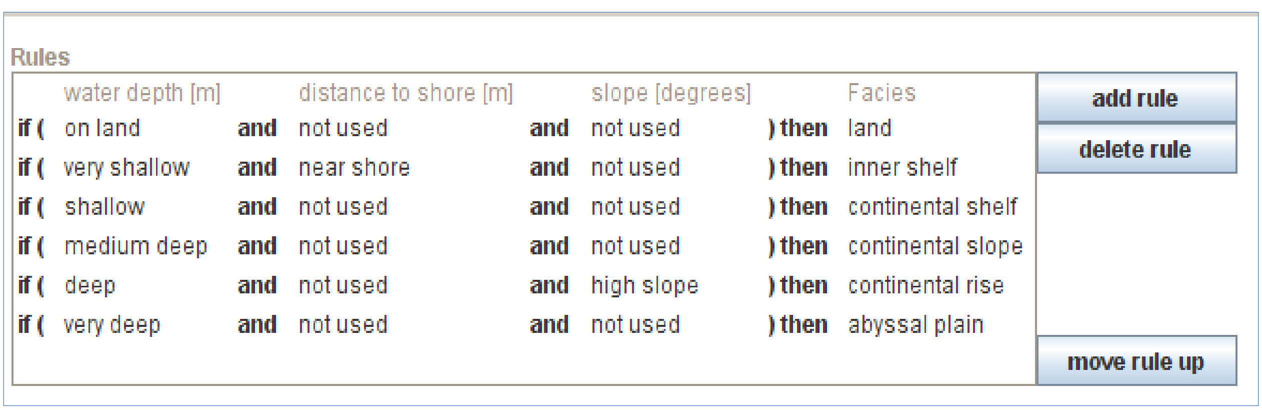
Figure 11 Area A distance to shore map showing the coastline clearly defined (area A)

5.3 Methodology step 3: Inorganic facies modelling

The sedimentary facies were modeled based on a set of fuzzy logic rules. Fuzzy logic was precisely described by Paola (2000) in his review paper (see also in M. Felix et al's presentation poster at AAPG Hedberg Conference 2012 in Nice, France). Fuzzy logic is an approach to computing based on "degrees of truth" rather than the usual "true or false" (1 or 0) of Boolean logic, on which the modern computer is based. Fuzzy logic includes 0 and 1 as end member cases of truth (or "the state of matters" or "fact"), but also includes various degrees of truth in-between the end members for example; the result of a comparison between two things could be not "true" or "false" but "20% true". This method was applied here because it is fast, accessible and easy to grasp for people with limited knowledge of numerical analysis. Another advantage of the use of this method is that limited information from study areas is readily incorporated into modelling; for example, depth map and distance to shore can be used to predict the sedimentary facies types present and also its distribution.

The application of fuzzy logic is explained here as used in OF-mod to model the spatial distribution of sedimentary facies. The rules as shown in Figure 13 , 14 & 16, and illustrate how distances from coastline and water depth are used to determine the facies types with respect to the depositional environment.

If water depth is shallow beyond the coastline, the truth value for land deposit occurring at this point is zero (0), while the truth value for inner shelf deposit is between 0 and 1 and for shelf deposit the truth value is one (1) at 100 m water depth upto a water depth of 200 m and reduces to zero at water depths of 400m and above (Figure 13).


Rules

	water depth [m]		distance to shore [m]		slope [degrees]		Facies
if (	on land	and	not used	and	not used	) then	land
if (	very shallow	and	near shore	and	not used	) then	inner shelf
if (	shallow	and	not used	and	not used	) then	continental shelf
if (	medium deep	and	not used	and	not used	) then	continental slope
if (	deep	and	not used	and	high slope	) then	continental rise
if (	very deep	and	not used	and	not used	) then	abyssal plain

Figure 12 Set of Fuzzy logic rules adopted in OF-Mod 3D

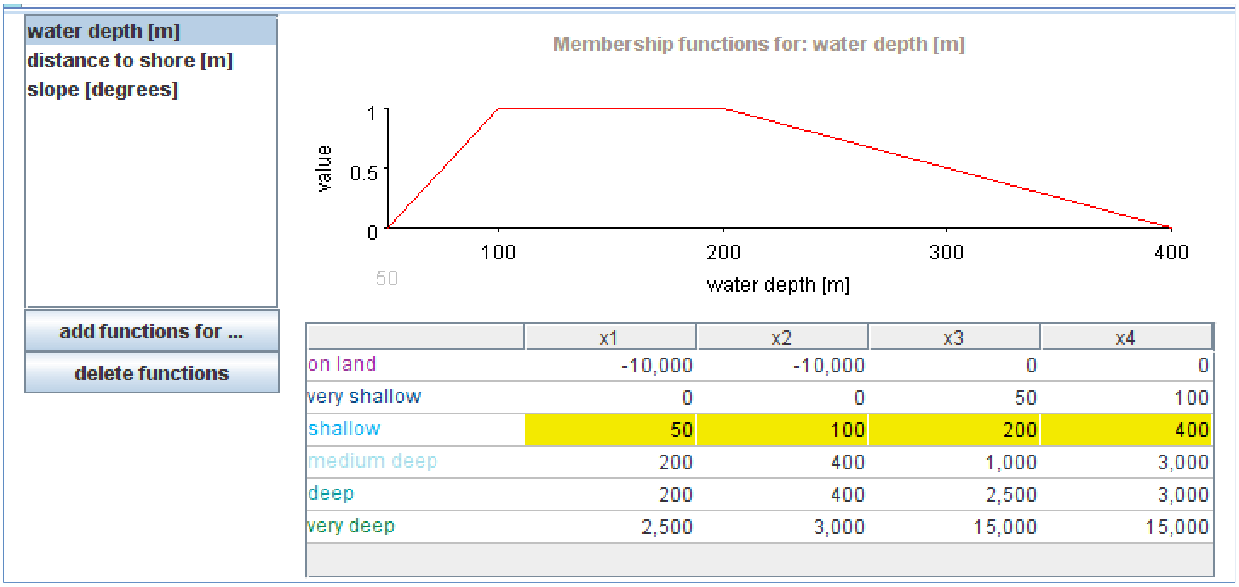


Figure 13 Water depth and sedimentary environments relationship (fuzzy logic)

With regards to distance to shore Figure 14, a similar fuzzy logic approach is applied. In order to define different sedimentary environments a combination of water depth and distance to shoreline truth logic is applied. This process enables the software to define the sedimentary environment in terms of water depth and distance from shore line. Defining the sedimentary environment is important because the inorganic mineral grains associated with this environment play some vital role in the preservation, degradation and/or dilution or organic matter.

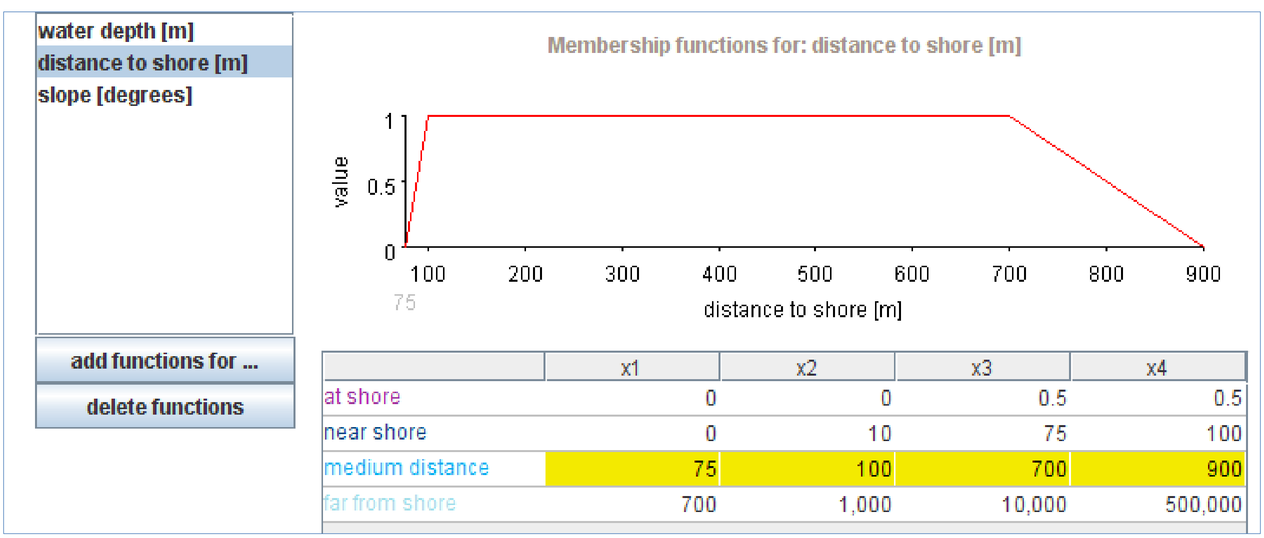


Figure 14 Distance to shore, sedimentary environment relationship (fuzzy logic)

Based on these rules, such as those stated in Figure 12 and implemented in the OF-Mod 3D stratigraphy builder, the spatial distribution of sand fraction, dry bulk density and sedimentary facies across the area of interest were modeled.

The sand fraction map clearly shows the spatial distribution of terriginous clastic sediments across the area of interest. The sand fraction reduces with increasing water depth and distance away from coastline.

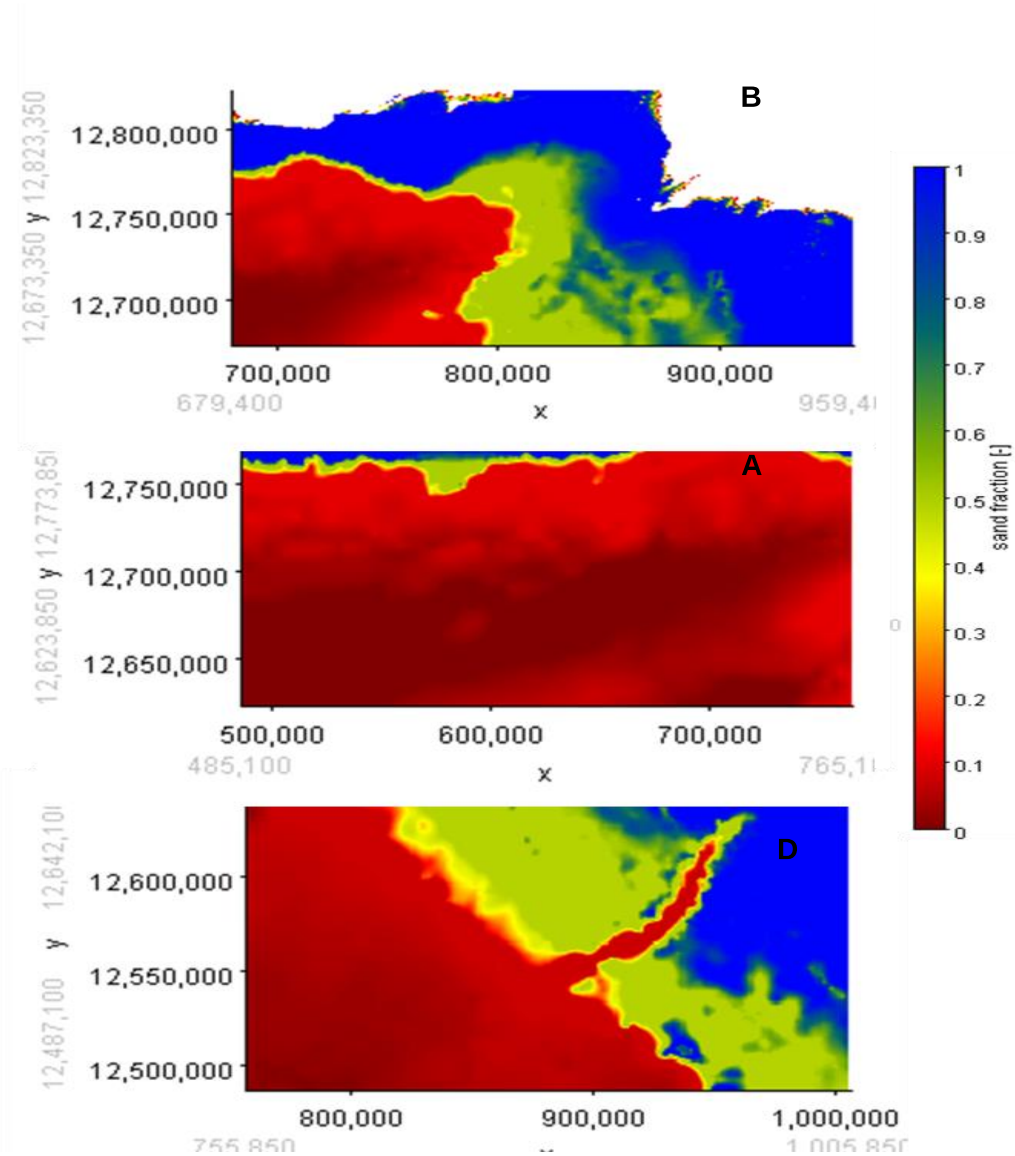


Figure 15 Modeled sand fraction distribution OF-mod 3D. Areas A, B & D

The spatial distribution of sedimentary facies was modeled across the three areas (Figure 16) and shows the extent of and changes in facies types from coastline through shallow marine to very deep marine.

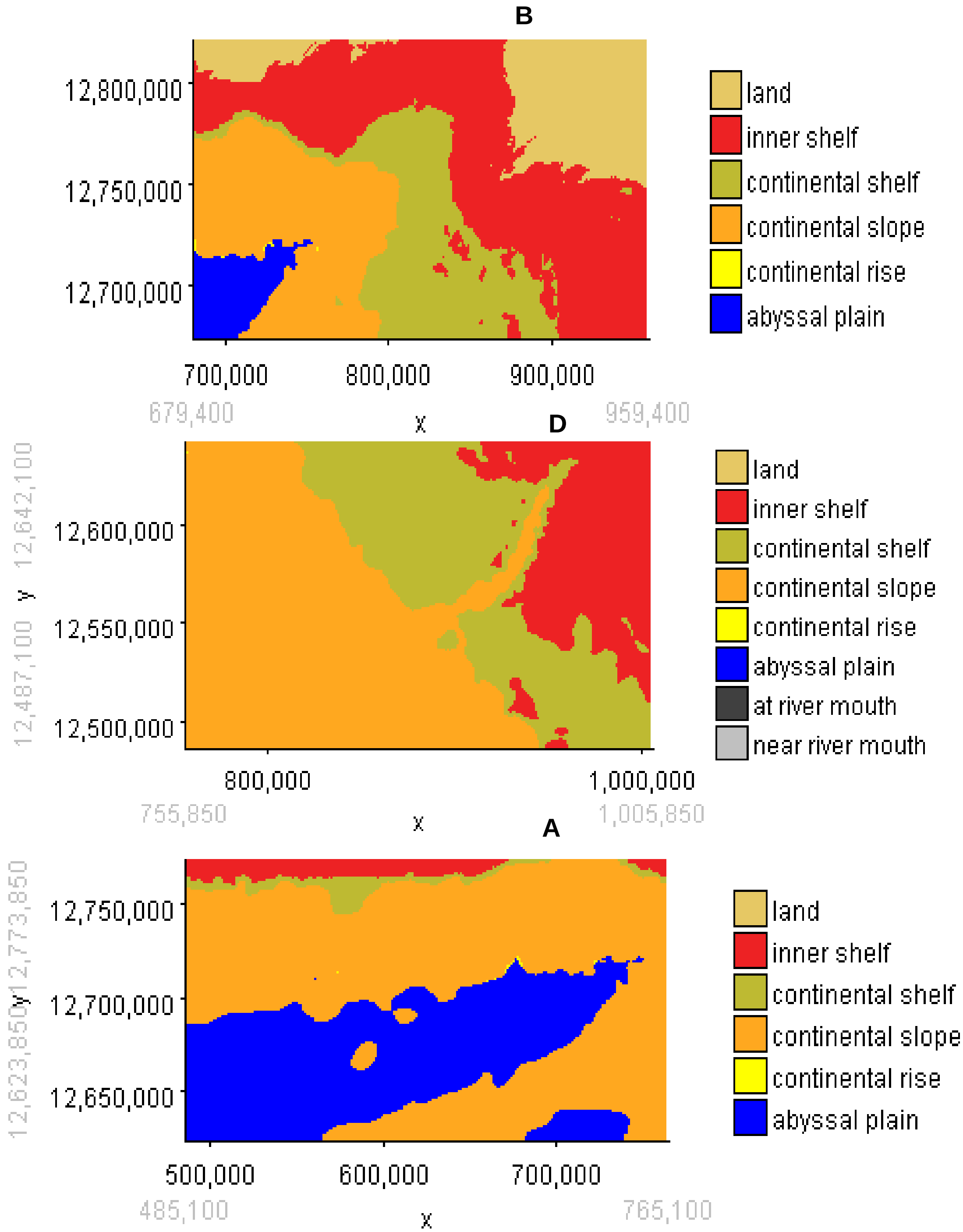


Figure 16 Modeled sedimentary facies distribution OF-Mod 3D. Areas A, B & D

Sediment dry-bulk density values are essential components of mass accumulation rate and it is a necessary component of any accumulation rate calculation. Mass accumulation rates incorporate the effects of depositional and post depositional processes and sediment composition. These processes also affect the organic component of the sedimentary deposit so an estimate of the bulk density is needed to calculate the organic fraction of the sedimentary deposit (Figure 18). The dry bulk density distribution across the area is modelled in OF-Mod and this is achieved by using the typical density values for sandstone (2.65), shale (2.76), and the sand fraction distribution across the area.

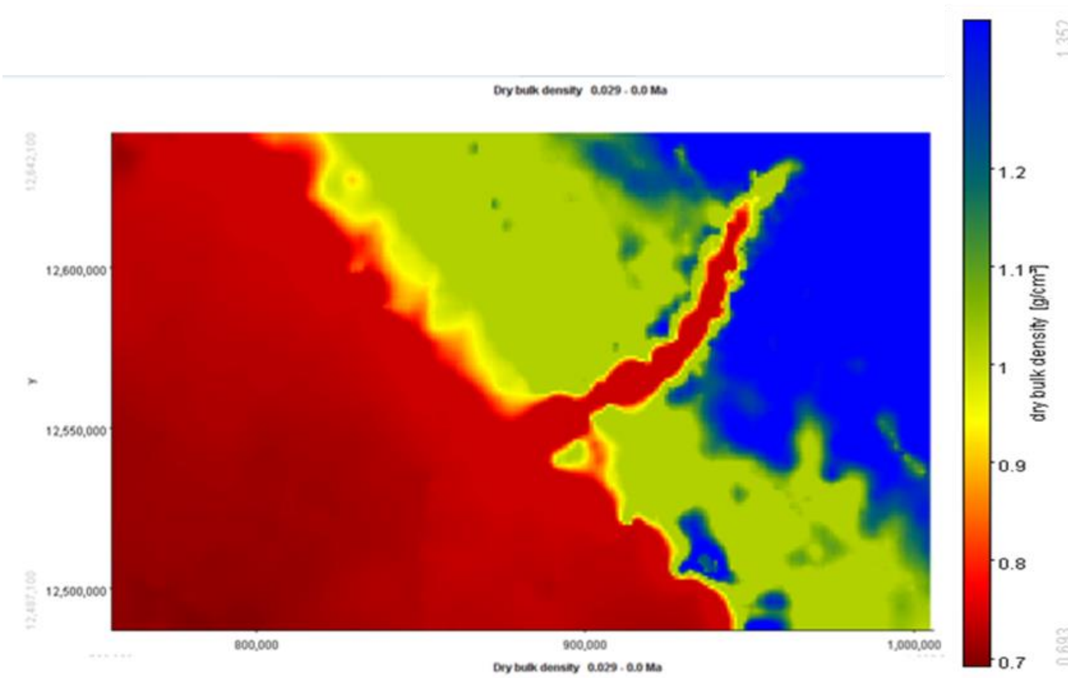


Figure 17 Model of spatial distribution of dry bulk density OF-Mod 3D for area A.

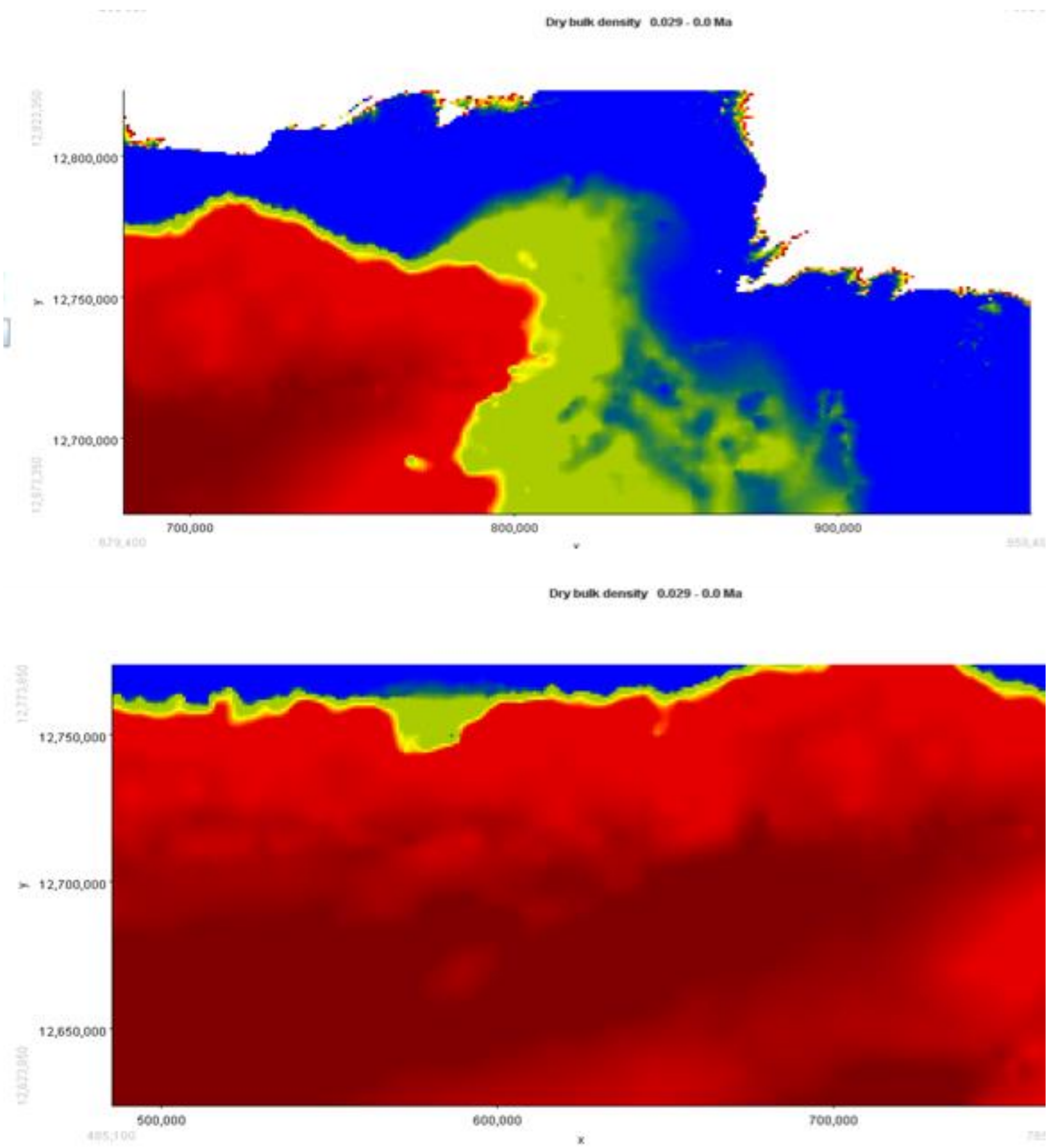


Figure 18 Model of spatial distribution of dry bulk density OF-Mod 3D for areas B and D.

To adjust the model and make it more realistic it is calibrated with measured data. Measured data, sand fraction values in this case, are imported into the model calibration panel. The panel displays the difference in measured sand fraction values (input values) and calculated sand fraction values (modeled values). If the absolute difference is high then fuzzy logic rules are adjusted until a match is achieved. In OF-Mod 3D this is implemented using the import well panel (Figure 19).

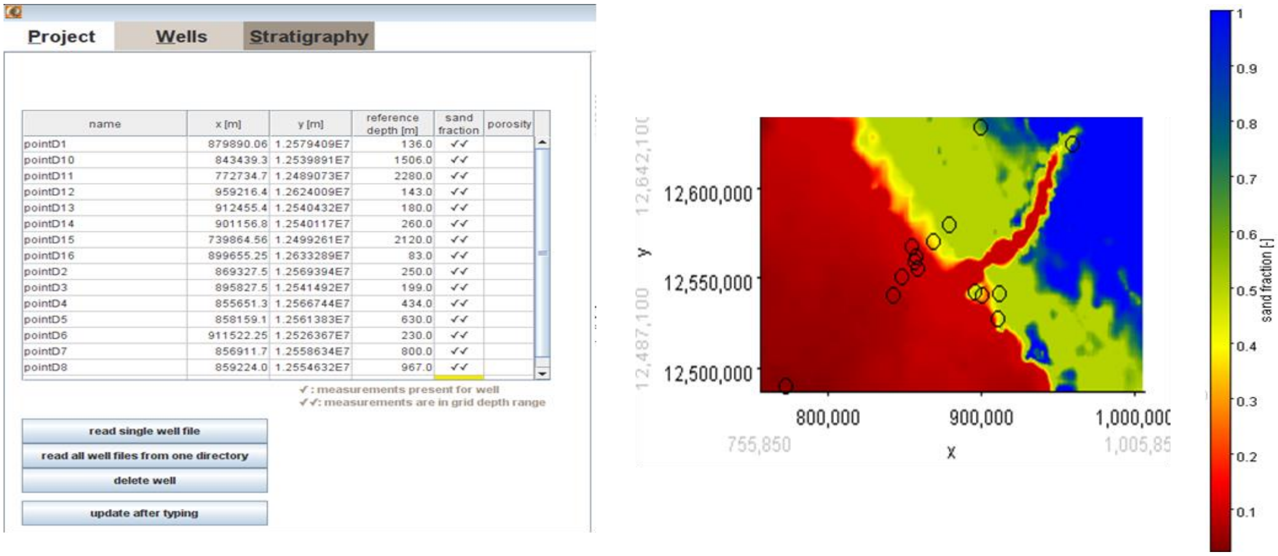


Figure 19 OF-mod 1D core data calibration panel (circles indicate locations of measured data points on map)

5.4 Methodology step 4: OF-Mod 1D organic facies modelling.

OF-Mod 1D was used to model the total organic carbon produced at a single position and to back calculate values for primary productivity, preservation factors and other prerequisite conditions needed to preserve the deposited organic carbon. The results of the 1D Model for several points in the area are used as input values for the 3D spatial distribution modelling, coupled with other data acquired in steps 1 to 3. Measured values are needed for calibrating the 1D model.

Data needed for the 1D modelling include:

- Measured TOC, hydrogen index (HI) values and carbon isotopes values ($\delta^{13}C$) needed as input to calculate the organic fractions (marine, residual and terrestrial).The data used were acquired from Cowie et al. (1999).

- Sedimentation rate, sand fraction dry bulk density and palaeo-water depth are needed to back calculate the primary productivity and preservation factor of the marine fraction. These data were acquired from previous studies on the area see Cowie et al. (1999) and the geo-reference data library (www.pangea.de)

In OF-mod 1D the organic fractions are calculated separately because the process of formation for each organic carbon fraction is different as explained in Chapter 2. Deposition of marine organic carbon is calculated using the three main processes controlling its accumulation and preservation. Under normal aerobic conditions: (I) primary productivity of marine organic matter and its flux through the water column; (II) dilution by inorganic mineral grain at the sea bottom; (ill) burial efficiency (see Mann & Zweigel, (2008) where this process was described in OF-Mod methodology). The terrestrial organic carbon (TOM) is not simulated in OF-Mod like the marine organic matter but it is added as input to the model for simulations. Modelling the deposition of terrestrial organic matter is quite complicated for realistic simulation because it requires information about changing climatic and atmospheric conditions and also the drainage area vegetation. So here the terrestrial organic fractions represent all organic matter which were not produced in situ in the marine environment but enters the marine system via rivers and runoff. It is assumed to be associated with the inorganic sediments, especially sands, and has undergone some level of degradation during transportation (Mann & Zweigel, 2008).

- The terrestrial organic fraction is divided into two sub fractions in OF-mod based on grain size, transport behavior and sorting. A discrete/ particulate fraction derived from higher plant materials mainly associated with coarse grained sand size particles.
- A soil or residual organic fraction associated with finer clay size particles (shale) which is degraded. Note residual organic fraction can also be marine partially marine due to degradation of marine fractions

In anoxic conditions for example within an oxygen minimum zone (OMZ) or anoxic bottom waters (ABW), redox reactions are reduced and preservation depends partially on burial efficiency and water depth with regards degradation within the water column. So the preservation factor (PF) approach is applied .It describes the relation between the primary produced organic carbon (PP) and the absolute amount of organic carbon preserved in the sediment (Bralower & Thierstein, 1984).

Using OF-mod 1D the input data is prepared and uploaded into OF-Mod 1D modelling environment and the outcome is shown in Figure 20. Note Figure 20, 23 and 24 shows the variation of input data with respect to position on the map and not depth. This method was used because the modeling was carried using data from various positions on a surface and does not vary with depth.

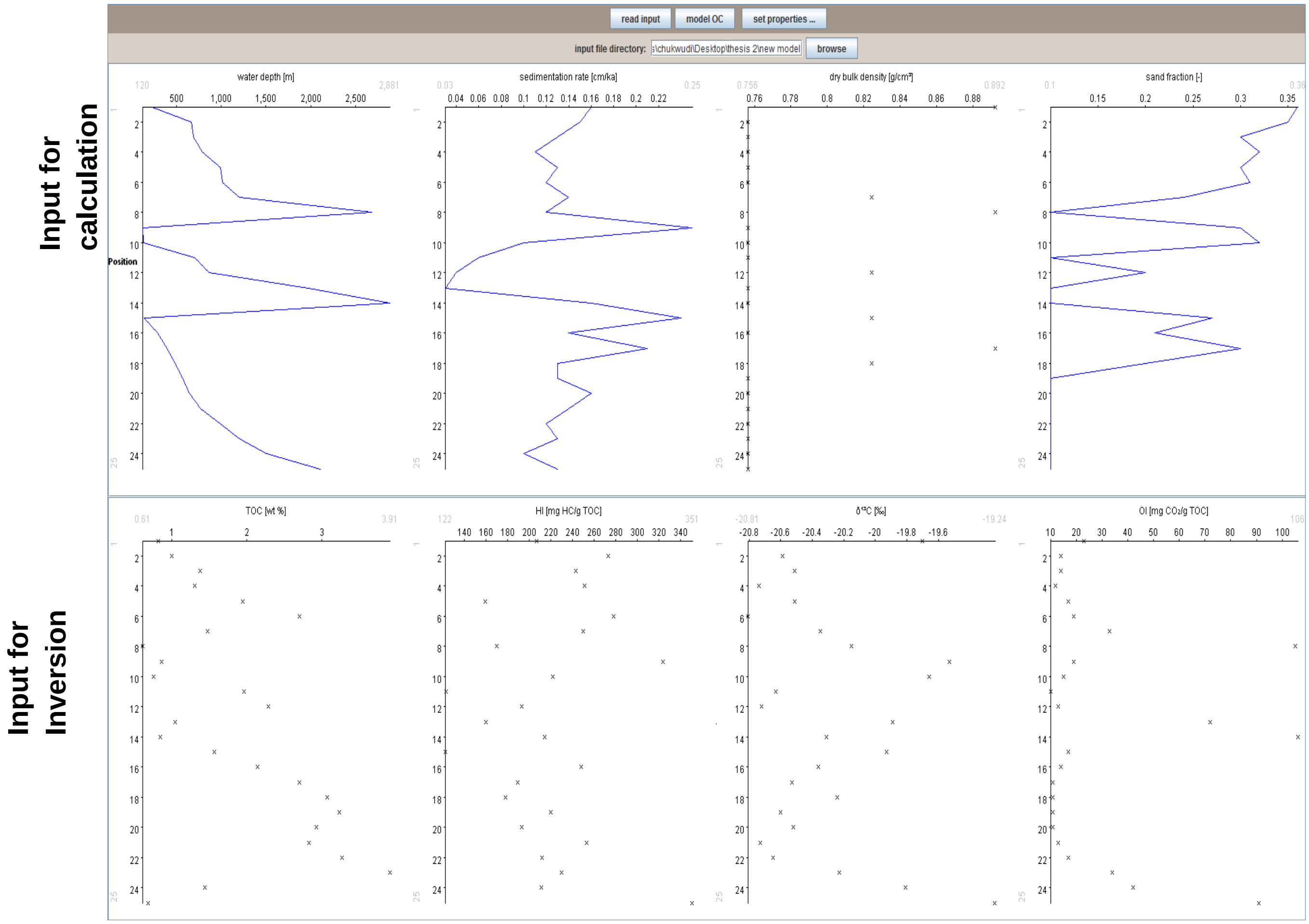


Figure 20 OF-Mod 1D data input panel for calculation of organic carbon fraction and Inversion panel to estimate primary productivity

In organic geochemistry $\delta^{13}C$ values have been successfully used to trace the origin of recent organic matter in coastal oceanic sediments (Westerhausen et al 1993). Samples from marine and terrestrial organic carbon reveal relatively consistent values with the terrestrial sourced organic carbon falling within the lower $\delta^{13}C$ values (-26 to -31), while the marine organic carbon has relatively higher (0 to -23) present day values (Westerhausen et al 1993). Rock Eval analysis reveals that the marine derived organic carbon has higher HI values compared to the terrestrial organic carbon; which is also influenced by the degree of preservation. As a result these values are considered when setting end member values for the 1D modelling processes (Figure 21).

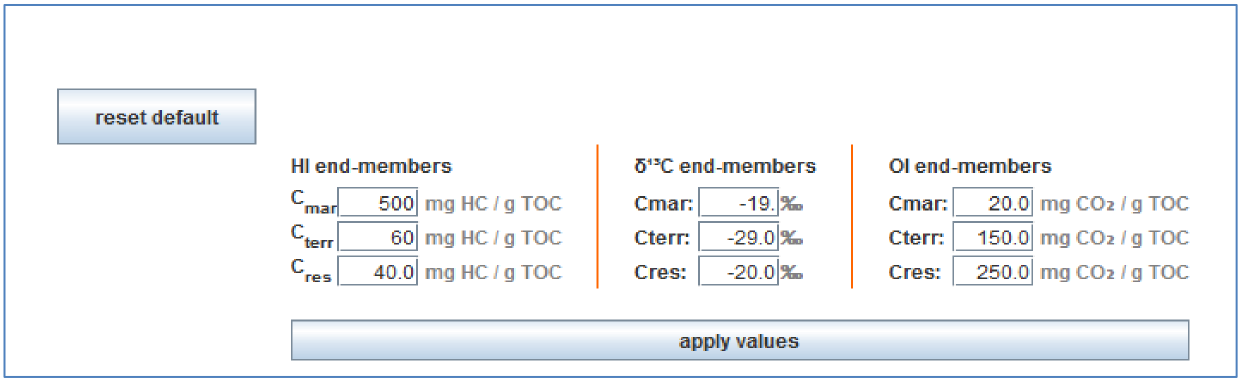


Figure 21 OF-Mod 1D end member values for organic facies modeling

The organic fractions are modeled and if a miss-match between calculated fractions and measured arises (Figure 23), then end member fractions of HI, $\delta^{13}C$ values are adjusted within realistic limits as given above until a good match is achieved between calculated fractions and measured values (Figure 24). When a match is achieved the back calculation process gives the primary productivity and preservation factors required to preserve the marine fractions. In adjusting the end member values the marine organic carbon is placed at the higher end while the terrestrial organic carbon is at the lower end because the marine organic carbon has higher Hydrogen index values (van Krevelen, 1984) and it also has a higher $\delta^{13}C$ value which has been used to trace the organic carbon origin in coastal organic sediments (Westerhausen et al 1993).

Figure 21 shows which are user defined the end member values for each source fraction. Figure 22 is a graph which shows relationship between given end member values and preserved marine organic matter in OF-Mod 3D modeling.

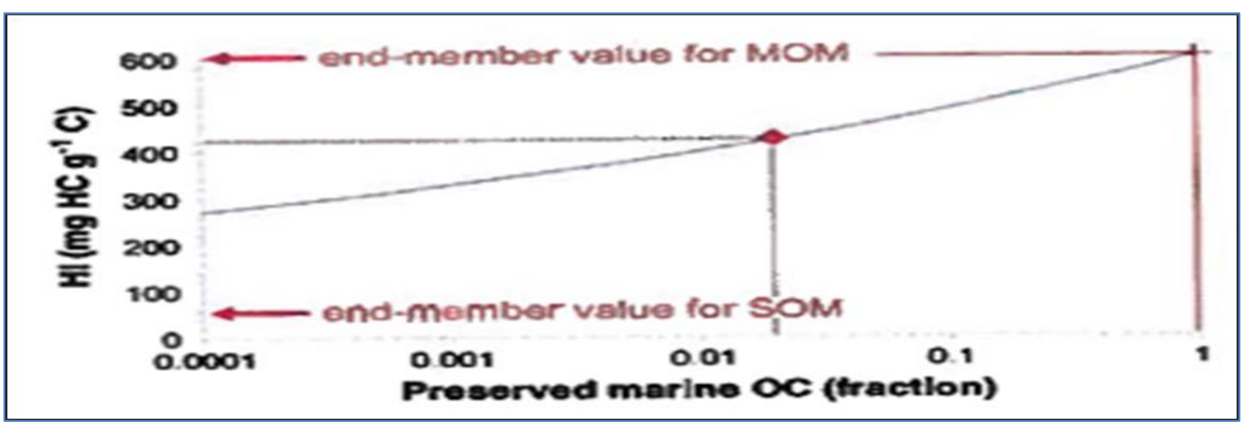


Figure 22 the relationship between end member values for marine organic carbon and preservation factor. (Mann & Zweigel, 2008)

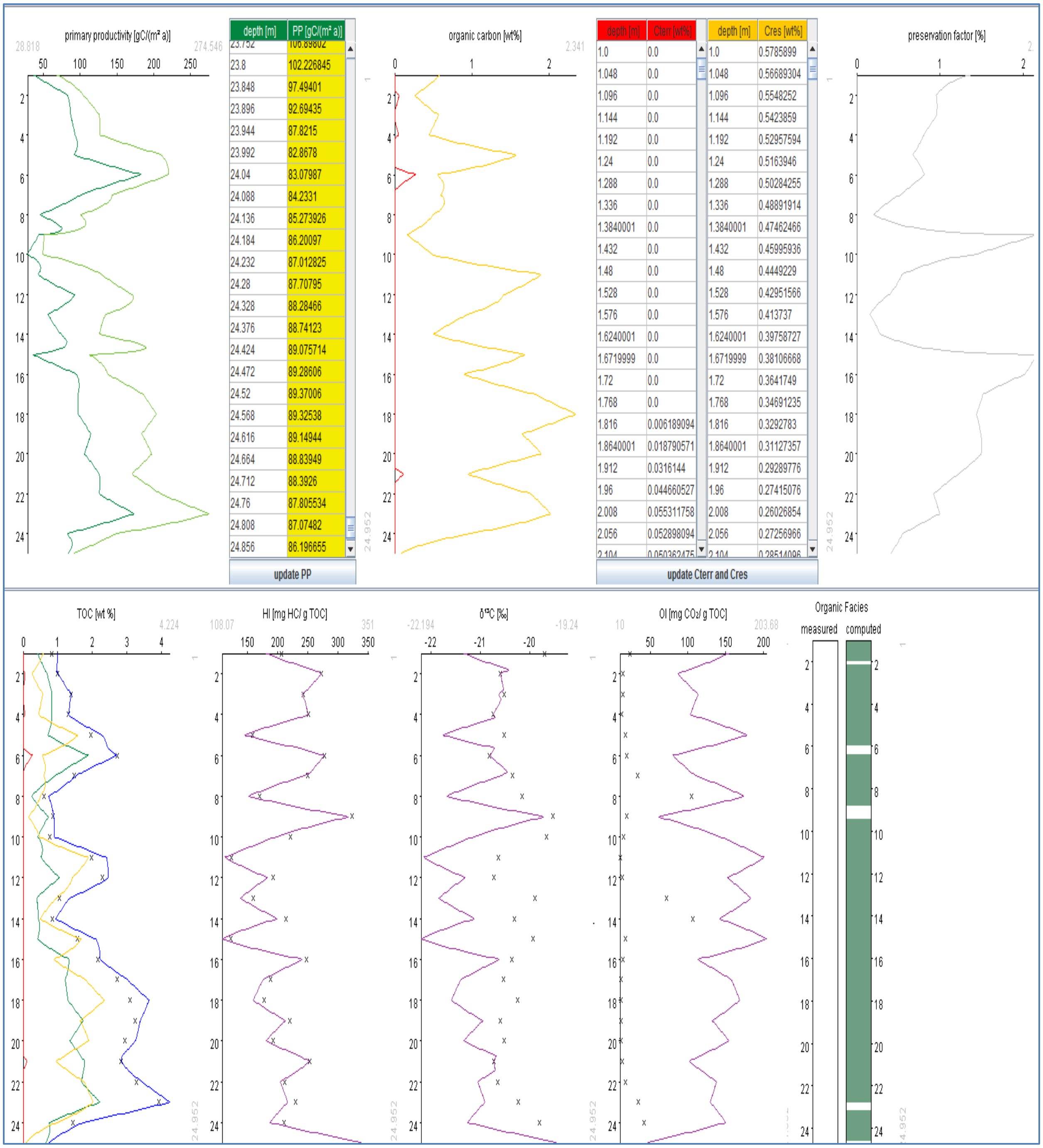


Figure 23 OF-Mod 1D organic carbon modeling panel. (Miss-Match $\delta^{13}C$ values) Calculated values as continuous lines and Measured values as point values.

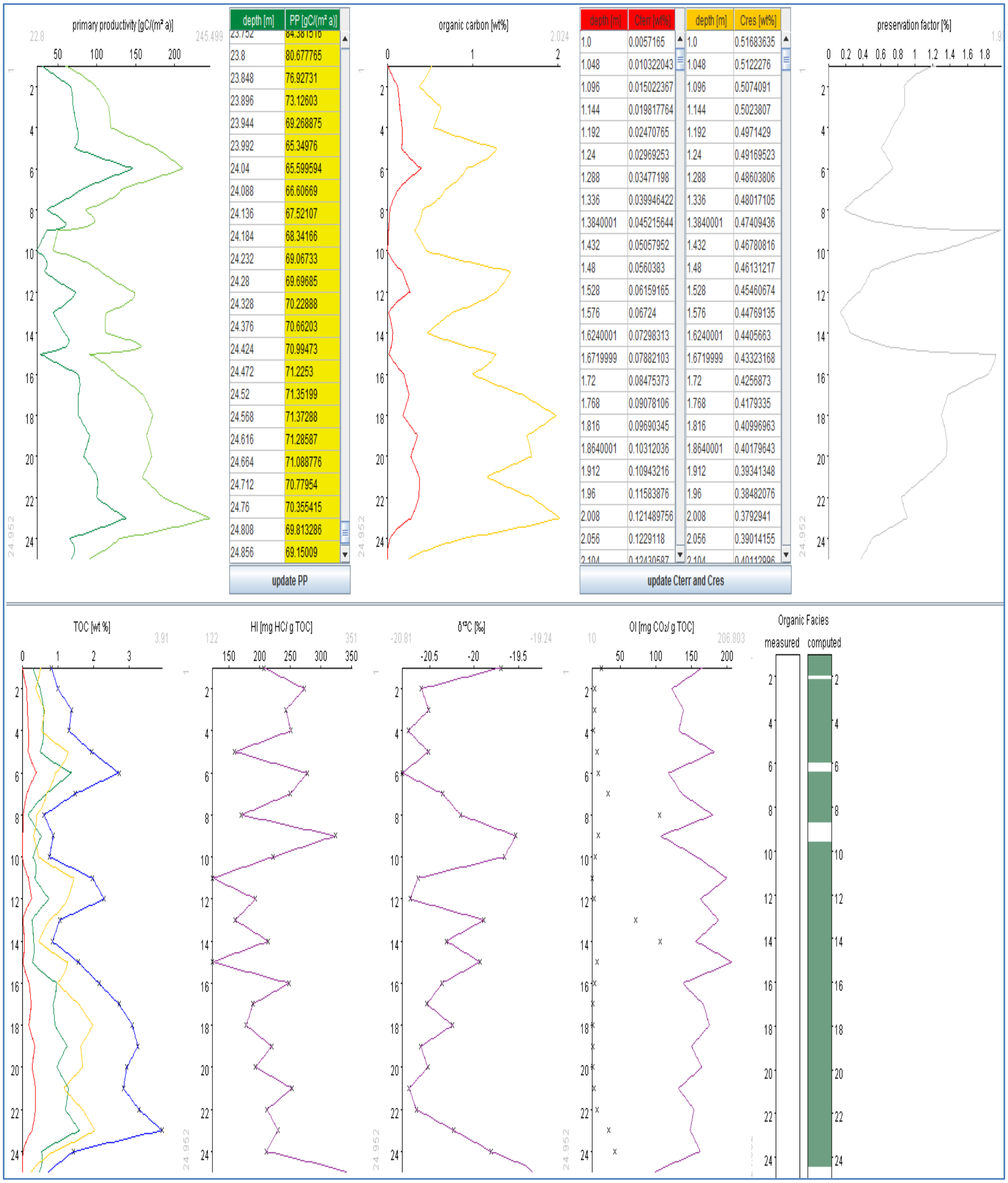


Figure 24 OF-Mod 1D organic carbon modeling panel. Match achieved between calculated and measured value.

5.5 Methodology step 5: 3D organic facies modeling.

OF-Mod 3D enables the spatial modelling of the organic fractions, the process is the same as illustrated in the OF-Mod methodology but here it is carried out across 3D space. In order to achieve this, result from the OF-Mod stratigraphy builder such as water depth maps, sand fraction maps, sedimentation rate maps, DBD maps and distance to shore across the area of interest are used to model the deposited and preserved marine organic carbon over a time period. The primary productivity of organic carbon is a user defined input in 3D modelling but OF-Mod 1D result is used as a guide to estimate the amount of primary productivity applied in the model.

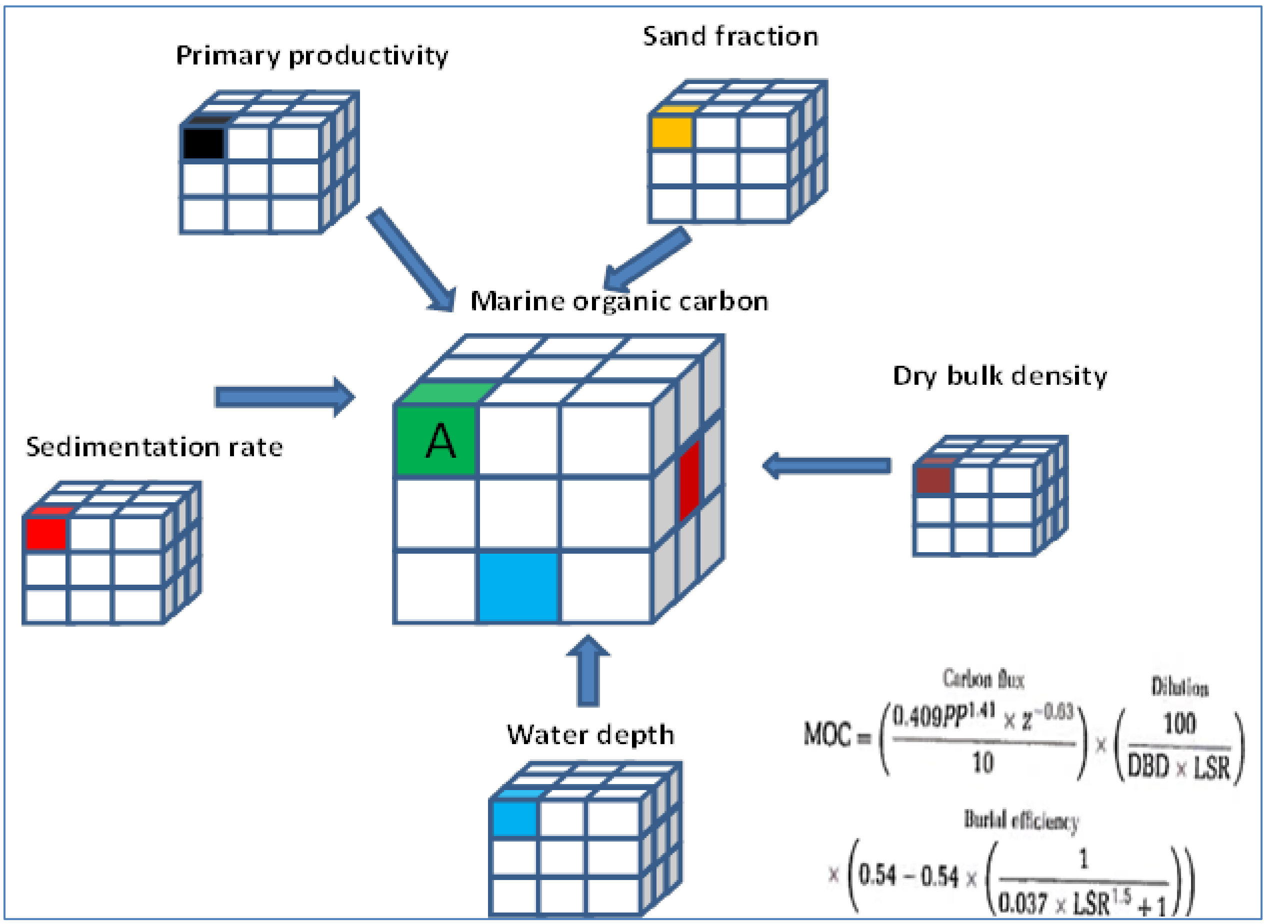


Figure 25 OF-Mod 3D methodology the diagram illustrate how the 3D spatial modeling is carried out

The marine organic carbon (MOC_A) in any grid cell A is given by the input, preservation and dilution equation (IPD) above (Figure 25) associated with that grid cell. (Note in an oxygen rich environment). In calculating the amount of marine organic carbon preserved in grid cell A on the diagram, OF-mod combines all factors and processes acting in grid cell A as shown using the Input, preservation and dilution equation. Using the stated approach the preserved marine organic carbon in the entire grid cell across the cube can be calculated. Note in this project the process was applied to only on one layer.

The terrestrial and residual organic carbon fractions are added to the model and the result of the 1D model was used as a guide in estimating the required amount. In upwelling zones (where biological productivity is relatively higher than background values) additional productivity values were added to simulate the increase (Figure 27). The calibrated 1D point value model across the area is used to adjust the amount of organic matter input in the model to get a more realistic result.

The modeling process was carried out following set of guidelines in order to achieve a good model. Some of the guidelines include honoring the data position when assigning productivity lenses across an area. Productivity lenses are place across an area where data points are available in such a way that a single lens covers a set of closely spaced data point. Another guideline is to ensure that OMZ in OF-Mod is defined in terms of position and intensity as specified in literature.

The conditions and effects of the oxygen minimum zones (OMZ) on preserved organic matter were modeled in OF-Mod 3D. In the OMZ, dissolved oxygen is low and /or absent thus the preservation factor approach is applied in modeling the preserved and accumulated organic carbon. In the OMZ the depth range and intensity of anoxia across the OMZ was based on Schulte et al (2000) oxygen content and depth profile model. They based the degree of anoxia on the presence and absence of oxygen dependent organisms and bioturbation from photo observations and sediment facies from core top sediments see Figure 26.

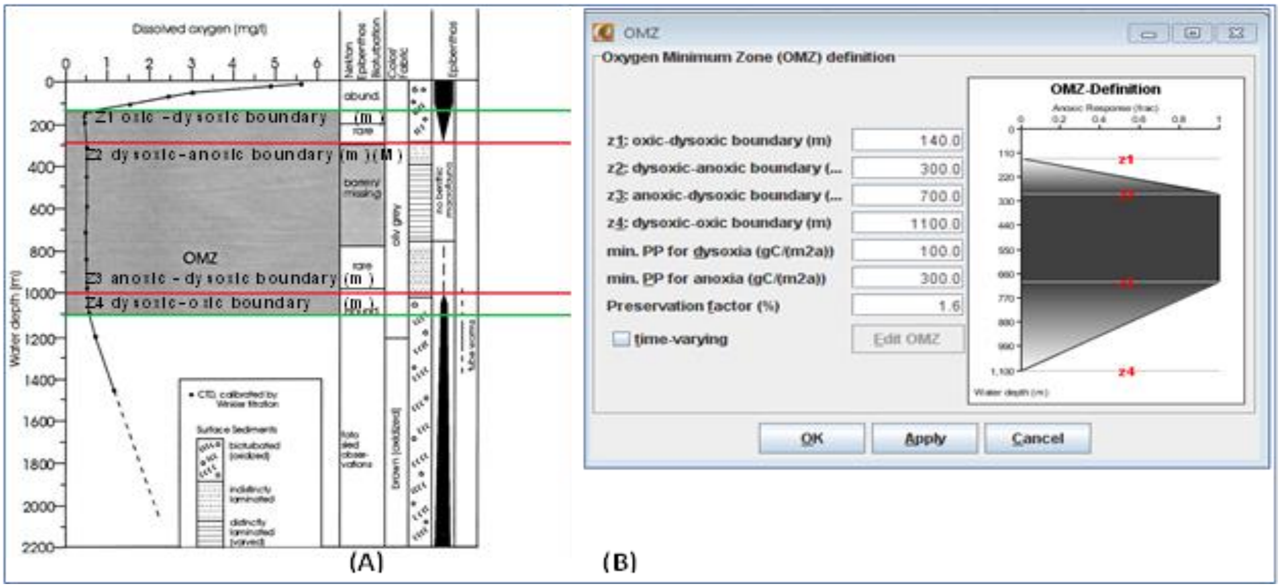


Figure 26 (A) Oxygen concentration in the water column, nekton/epibenthos/bioturbation from photo sled observations, color and sediment facies. Schulte et al (2000) modified after Von Rad et al (1995) (B) Input panel for OMZ where depth values are based on the description of Schulte et al (2000).

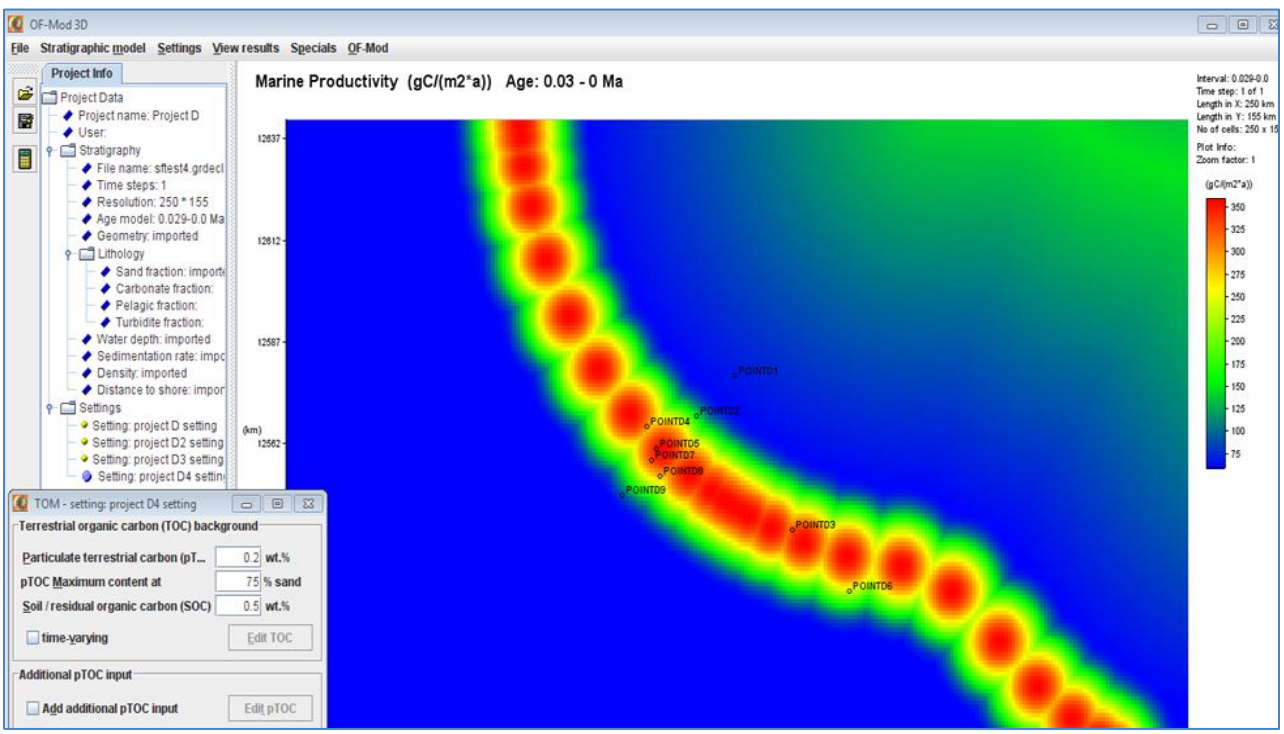


Figure 27 OF-Mod 3D map of Area D showing additional marine productivity, background values and input panel for Terrestrial and residual organic matter.

6 Results

For the model to be representative of the organic carbon present in the area modeled, results from the various modeling steps should match with measured values obtained from the area of interest and should also lie within realistic limits.

6.1 1D organic facies modelling result

OF-Mod 1D organic facies modeling was carried out and calibrated using measured data from the three transects. User defined end member values of organic matter fractions were adjusted to get a good fit between calculated values and measured values. The input data used in OF-Mod 1D modeling include sand fraction data (SF), total organic carbon, carbon isotope data, sedimentation rate (SR), hydrogen index (HI) and calculated dry bulk density (DBD).

Table 1, shows all input data used in 1D modeling to generate the results. The data were acquired from previous studies carried out on the Pakistan margin (See Cowie et al 1999 and Paropkari et al 1991).

Table 1 Input data in OF-Mod 1D modeling.

DATA POINT	sf	sr	oi	TOC	wd	D13c	DBD	HI
POINTA1	0.53	16	23	0.82	228	-19.7	0.7506877	207
POINTA2	0.31	15	14	1	667	-20.59	0.7644153	273
POINTA3	0.23	13	14	1.38	690	-20.51	0.7644153	243
POINTA4	0.16	11	12	1.31	789	-20.74	0.8260608	251
POINTA5	0.12	10	17	1.95	993	-20.51	0.8533912	159
POINTA7	0.11	9	19	2.71	1017	-20.81	0.8533912	278
POINTA6	0.1	7	33	1.48	1204	-20.35	0.8055357	250
POINTA8	0.1	5	105	0.61	2678	-20.15	0.7644153	170
POINTB1	0.33	13	19	0.87	120	-19.53	1.0165	324
POINTB2	0.22	10	15	0.76	134	-19.66	0.9622968	222
POINTB3	0.2	6	10	1.97	704	-20.63	0.74382	123
POINTB4	0.12	4	13	2.29	865	-20.72	0.8533912	193
POINTB5	0.1	3	72	1.05	1970	-19.89	0.74382	160
POINTB6	0.14	6	106	0.85	2881	-20.31	0.7712752	214
POINTD6	0.37	17	17	1.57	136	-19.93	1.0637913	122
POINTD3	0.33	14	14	2.15	287	-20.36	1.0165	248
POINTD1	0.16	15	11	2.71	398	-20.53	0.7849872	189
POINTD2	0.19	13	11	3.08	483	-20.24	0.8055357	178
POINTD8	0.17	12	11	3.24	572	-20.6	0.7918393	220
POINTD5	0.12	15	11	2.93	643	-20.52	0.7575528	193
POINTD7	0.13	11	13	2.83	776	-20.73	0.7644153	253
POINTD4	0.12	9	17	3.27	992	-20.65	0.74382	212
POINTD9	0.11	10	34	3.91	1206	-20.23	0.7506877	230
POINTD11	0.1	8	42	0.69	2111	-19.81	0.74382	211

The output panel (Figure 28) shows modeled primary productivity values (green lines), terrestrial and residual organic fractions (red and yellow lines respectively) and also the preservation factor. The primary producti

vity is shown by two green lines because the back calculated primary productivity using only the marine fractions (dark green line) underestimates measured productivity values from the area found in literature. The primary productivity was recalculated using both the marine and residual organic fractions since the residual fraction were originally part of the marine fraction but currently, are degraded due to poor preservation conditions (light green line). The recalculated value gives a better estimate of measured marine productivity found in literature. Locations are shown in Figure 29. In OF-Mod 1D the input parameters are used to back calculate the primary productivity and preservation factors that will be needed to preserve the measured marine organic carbon. This is achieved by calculating the three organic fractions in the input TOC. The marine fraction is then used to back calculate the primary productivity and preservation factor required to preserve the marine fraction.

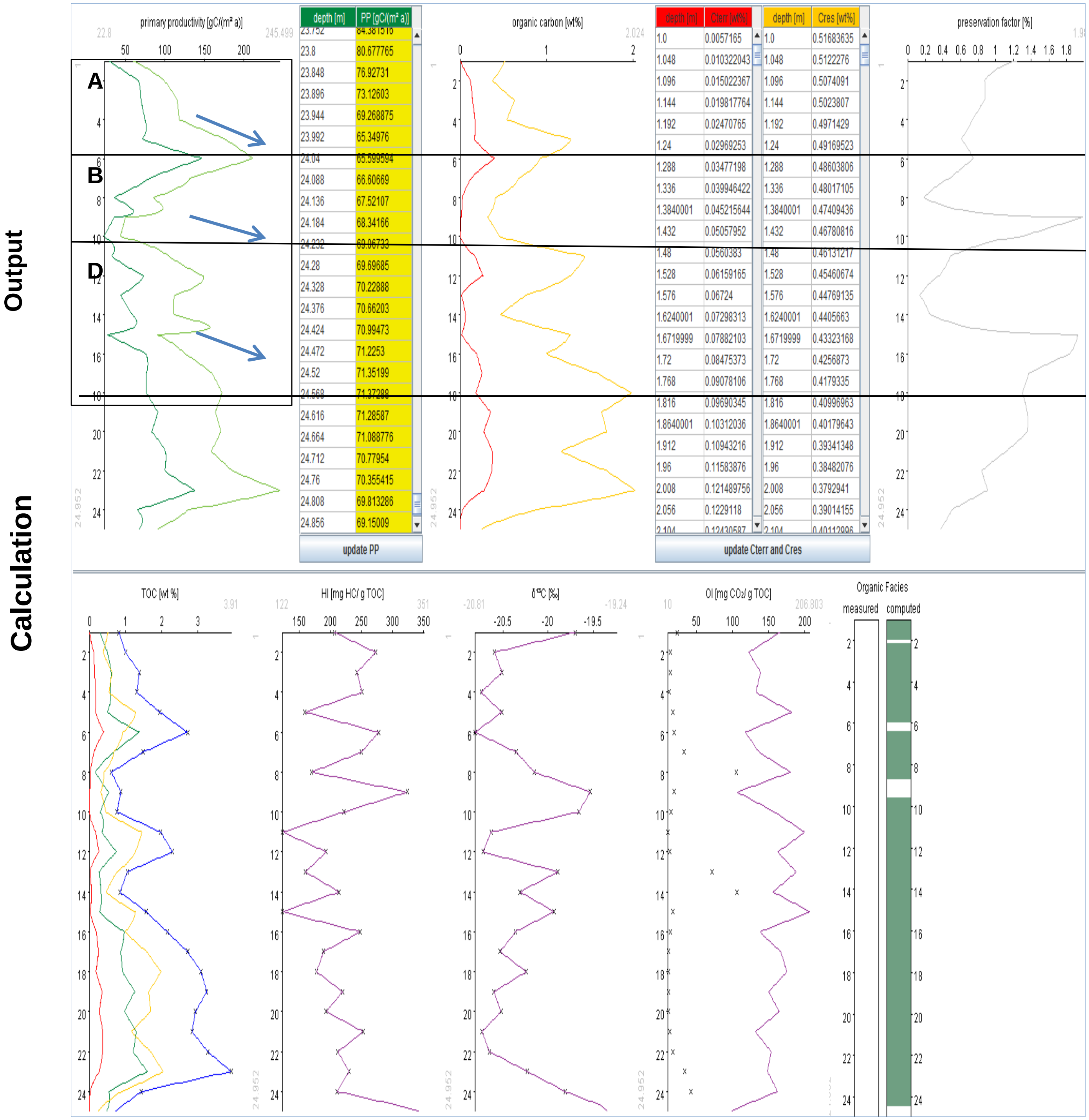


Figure 28 OF-Mod 1D calibrated organic facies model across the three transects A, B, and D and PP trend across each transect (Indicated by arrows)

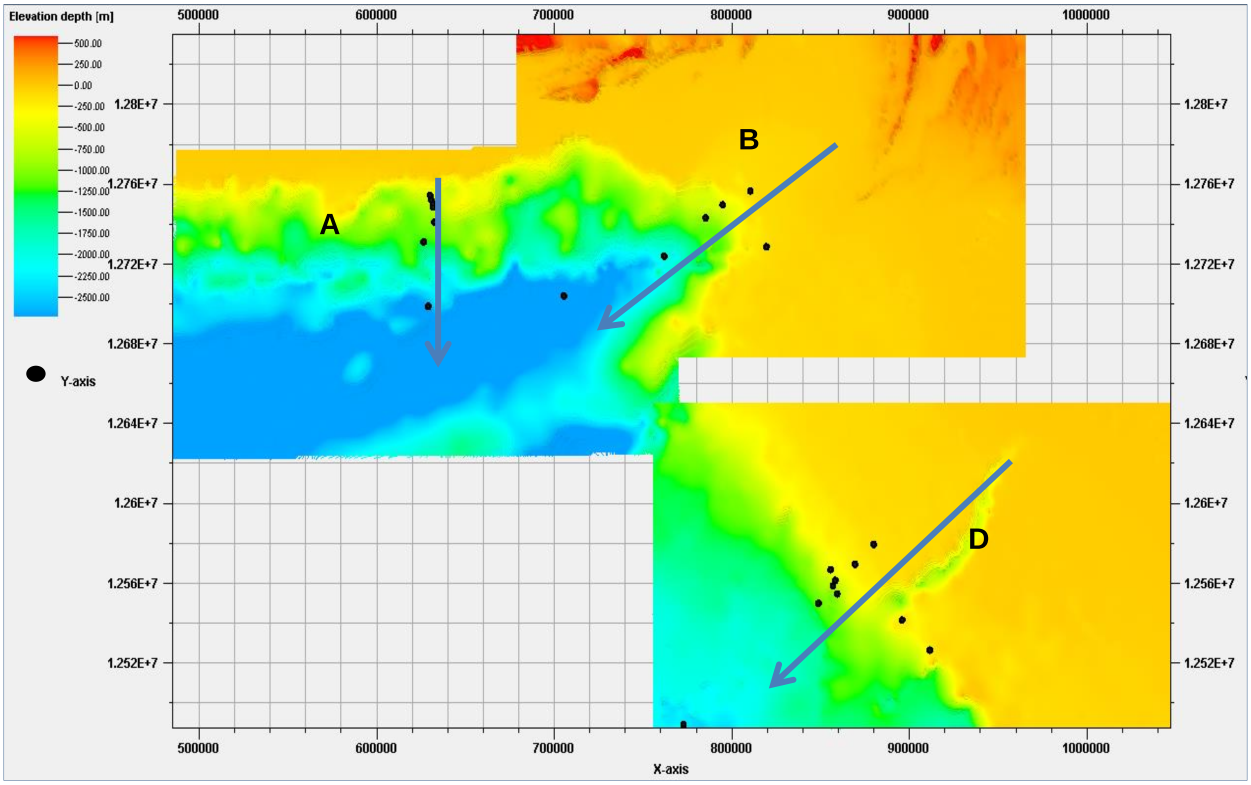


Figure 29 Elevation depth map of area showing measured data locations (black dots) and primary productivity trend arrows based on the 1D model results.

6.1.1 Primary productivity

The model output panel displays the variation of primary productivity (PP) along the three transects (Figure 28). The blue arrows indicate the direction along which the primary productivity value varies, from points near the coastline to points in the deeper parts of the basin (Figure 28 & 29). In the three transects the primary productivity increases from shallow continental shelf and peaks towards the slope and decreases further down onto the abyssal plain (Figure 3132 and 33). This is attributed to the seasonal monsoon and high surface water productivity occurring on and close to the continental shelf (Schulz and von Rad, 1997).

6.1.2 Organic carbon fractions

The organic carbon modeling (Fig 28) shows that residual and marine fractions are dominant while terrestrial fractions are relatively low across the three transects. Carbon isotope ($\delta^{13}C$) values show that the residual organic carbon is of marine origin. This is in agreement with Calvert and Pedersen (1990), who said that the organic carbon content within the Pakistan margin is mainly primarily produced within the marine environment and is due to upwelling of nutrient rich waters. The result of the various fractions will be explained in detail using a graphical plot of organic fraction and distance from shoreline (Figure 30).

6.1.2.1 Marine organic fractions

The 1D results for marine organic carbon show that area D had more marine organic carbon preserved compared to A and B. B had the lowest amount of marine organic carbon. It was observed that the distribution of organic carbon mimics the surface productivity distribution within the area. Sections within areas of high primary productivity had a high amount of marine organic carbon. Sections within the OMZ also had high marine organic carbon values especially where they coincide with high productivity zones along the three transect.

6.1.2.2 Terrigenous organic fractions

The results of organic fraction 1D modelling indicate a general paucity of terrigenous organic matter as compared to marine fractions within the three transects (Figure 30) which agrees with Cowie et al.(1999). The amount of terrigenous organic carbon was relatively higher along transect D especially in areas close to the Indus canyon. Along transect A the terrigenous fractions was lowest compared to other transects.

6.1.2.3 Residual organic fractions

The residual fractions are high within the three transects and result from degraded marine organic fraction due to poor preservation conditions in the environment. The residual organic fraction is higher than the marine and terrigenous fraction along the three transects and also occurs within the OMZ from observations made. Measured values of residual organic carbon exceeded 50% of TOC within the OMZ in transect B (Figure 30).

6.1.3 Preservation factor (PF)

The preservation of organic carbon across the three transects was relatively low form the 1D modeled result. The preservation factor ranges from about 0 to 0.1.8%. The presence of high amount of residual organic fractions and low hydrogen index values supports this result. The 1D result also indicated poor preservation conditions within the OMZ due to low PF values and high amount of residual organic carbon within the OMZ.

The Oxygen minimum zone (OMZ) is indicated by the green coloured bar in Figure 30 and other figures as well. The graph shows variation in organic fractions with distance from shoreline.

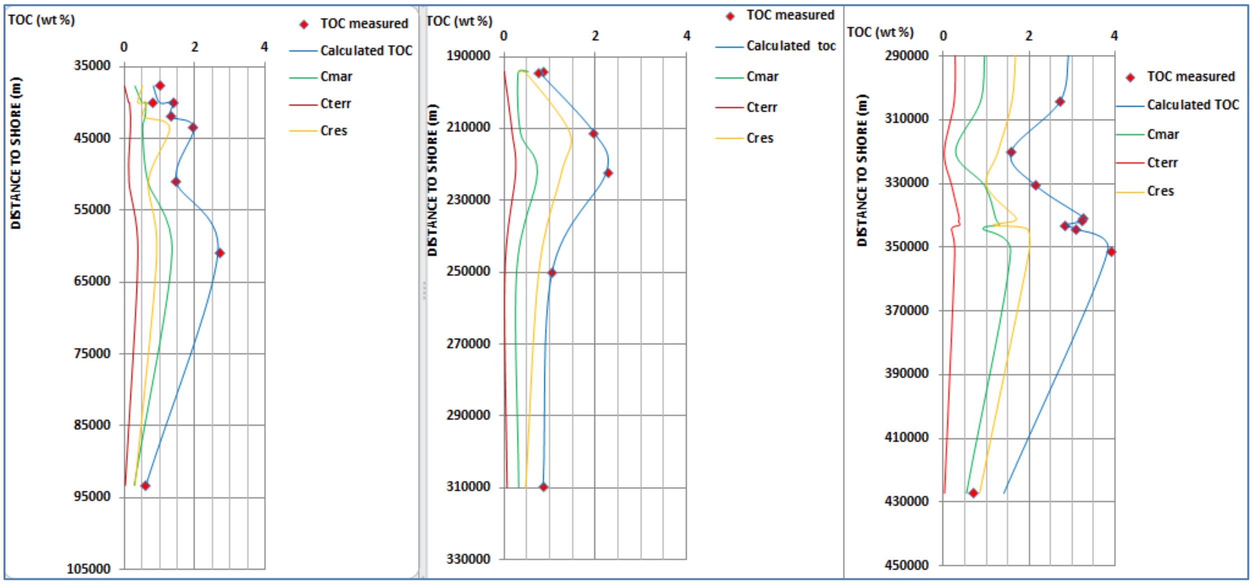


Figure 30 OF-Mod 1D modeling organic matter fractions and TOC calibrated against measured values. Red line shows the terrestrial fraction, yellow line the residual fraction, green line the marine fraction and blue line the total organic matter. Points within the OMZ are marked by the green bar.

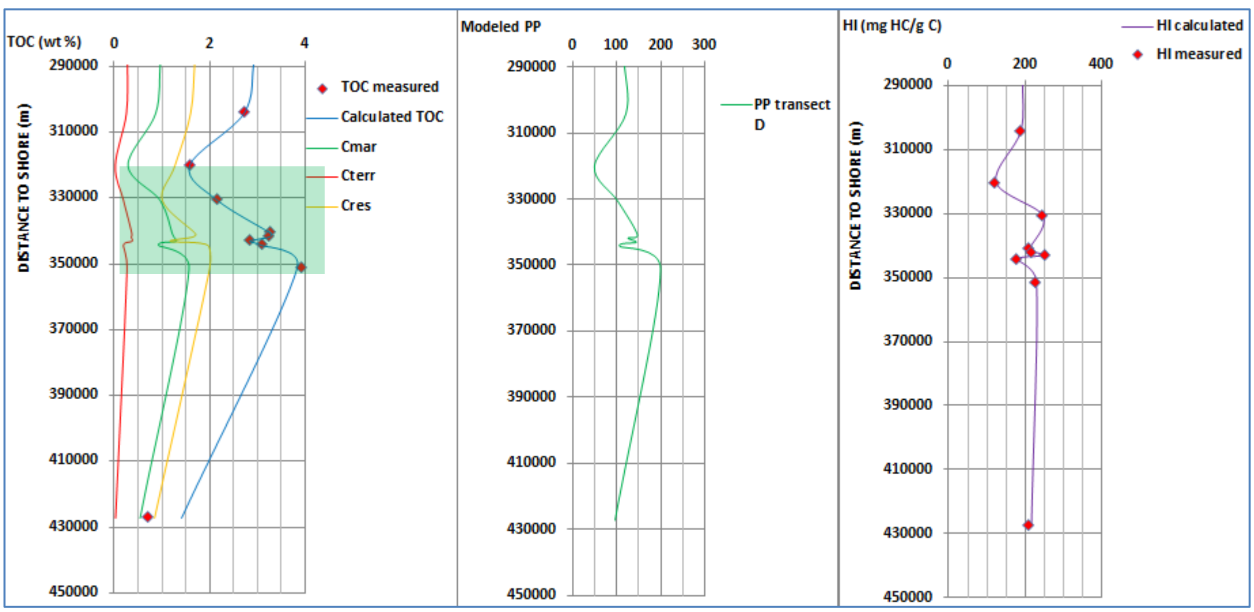


Figure 31 OF-Mod 1D modeled TOC, PP ,HI and measured data points in red (Transect D)

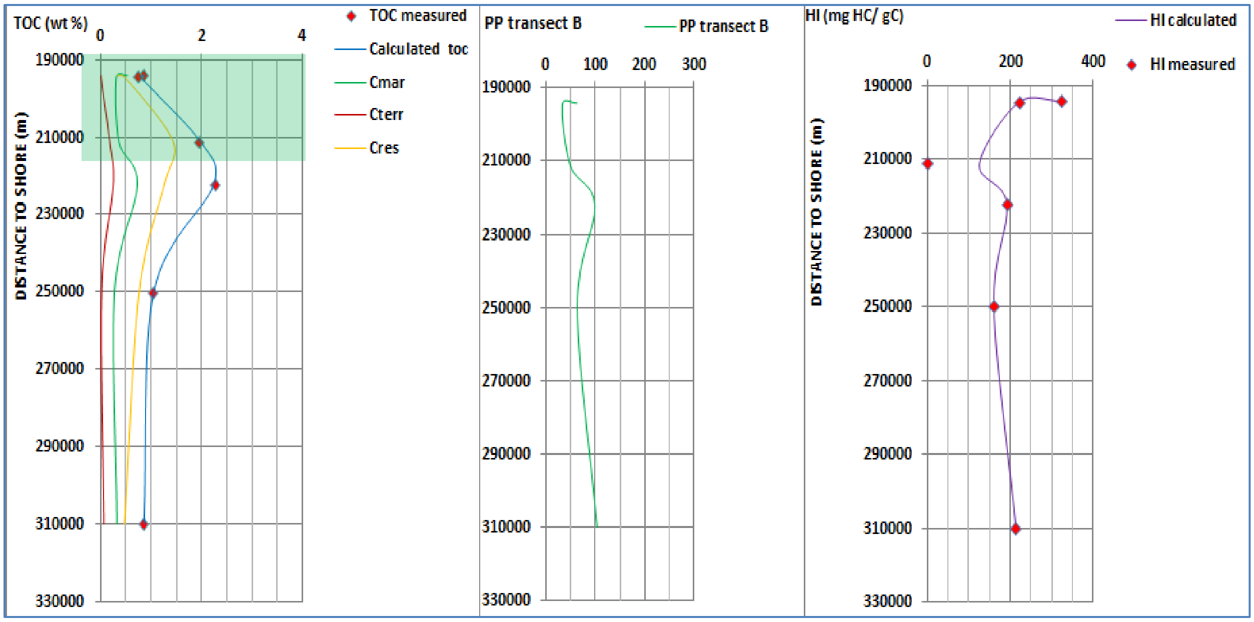


Figure 32 OF-Mod 1D modeled TOC, PP ,HI and measured data points in red (Transect B)

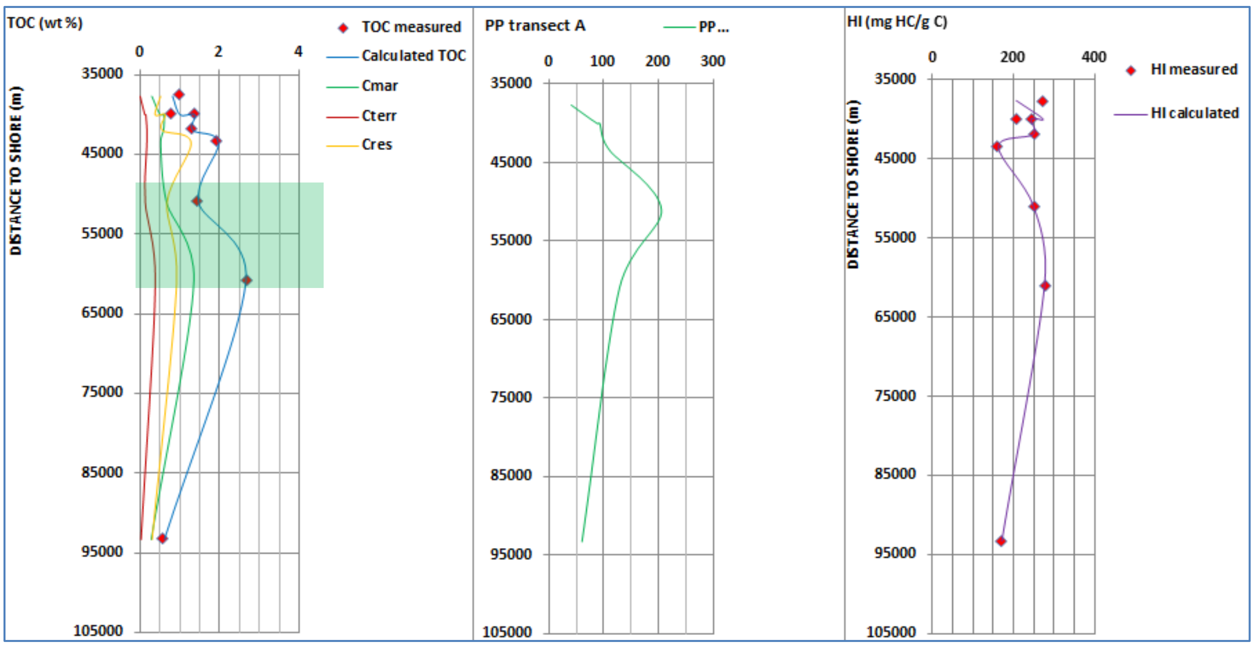


Figure 33 OF-Mod 1D modeled TOC, PP ,HI and measured data points in red (Transect A)

Table 2 shows 1D model results. $\delta^{13}C$ values indicate marine origin, low HI values indicate possible degradation supported by relatively high residual fractions across the Pakistan Margin.

Data position	TOC [wt%]	MOM [wt%]	pTOC [wt%]	SOC [wt%]	Measured HI [mgHC/g]	Measuredδ13C
POINTA1	0.82	0.297447	0.005716	0.516836	273	-19.71722
POINTA2	1.00304	0.502256	0.12149	0.379294	207	-20.58936
POINTA3	1.37888	0.602557	0.145651	0.630672	243	-20.51368
POINTA4	1.32536	0.594003	0.174162	0.557196	251	-20.73448
POINTA5	1.97432	0.519626	0.17172	1.282974	159	-20.5196
POINTA7	2.6608	1.353482	0.384419	0.922899	278	-20.35
POINTA6	1.48	0.669914	0.13199	0.678096	250	-20.7916
POINTA8	0.61208	0.173352	0.029125	0.409603	170	-20.14504
POINTB1	0.869051	0.79794	0	0.071111	324	-19.53208
POINTB2	0.789768	0.486711	0	0.303057	222	-19.69578
POINTB3	1.98024	0.615078	0.173421	1.191741	–	-20.63288
POINTB4	2.2404	1.12169	0.233284	0.885426	193	-20.6868
POINTB5	1.05	0.459135	0.012674	0.578191	160	-19.89
POINTB6	0.85576	0.493294	0.056592	0.305873	214	-20.30696
POINTD6	2.9292	0.965288	0.277044	1.686868	193	-20.52168
POINTD3	2.72184	0.868514	0.253982	1.599344	189	-20.52072
POINTD1	1.57928	0.287538	0.020873	1.27087	122	-19.93688
POINTD2	2.16344	0.963134	0.194533	1.005774	248	-20.36408
POINTD8	3.28536	1.215496	0.368652	1.701212	212	-20.63992
POINTD5	3.24	1.252385	0.355154	1.632461	220	-20.6
POINTD7	2.83704	1.293391	0.373422	1.170227	253	-20.72872
POINTD4	3.0864	0.928912	0.190455	1.967034	178	-20.2544
POINTD9	3.830961	1.565718	0.26615	1.999093	230	-20.21656
POINTD11	0.69	0.540158	0.026679	0.843163	211	-19.7872

6.2 Sedimentation rate

The rate at which sediment is supplied to the sea bed is the sedimentation rate and across the three areas the sedimentation rate varied with location. In the project the sedimentation rate across the three areas was modeled to account for its role in organic carbon distribution and preservation.

6.2.1 Area D sedimentation rate distribution

Sedimentation rate across area D varied from 1.2 to 25 (cm/ka), the SR was higher close to the coastline and reduced towards the deep marine environment. Sedimentation rate at the mouth of the Indus canyon was also relatively high while lower values were observed on the slope and deep marine environment (Figure 34).

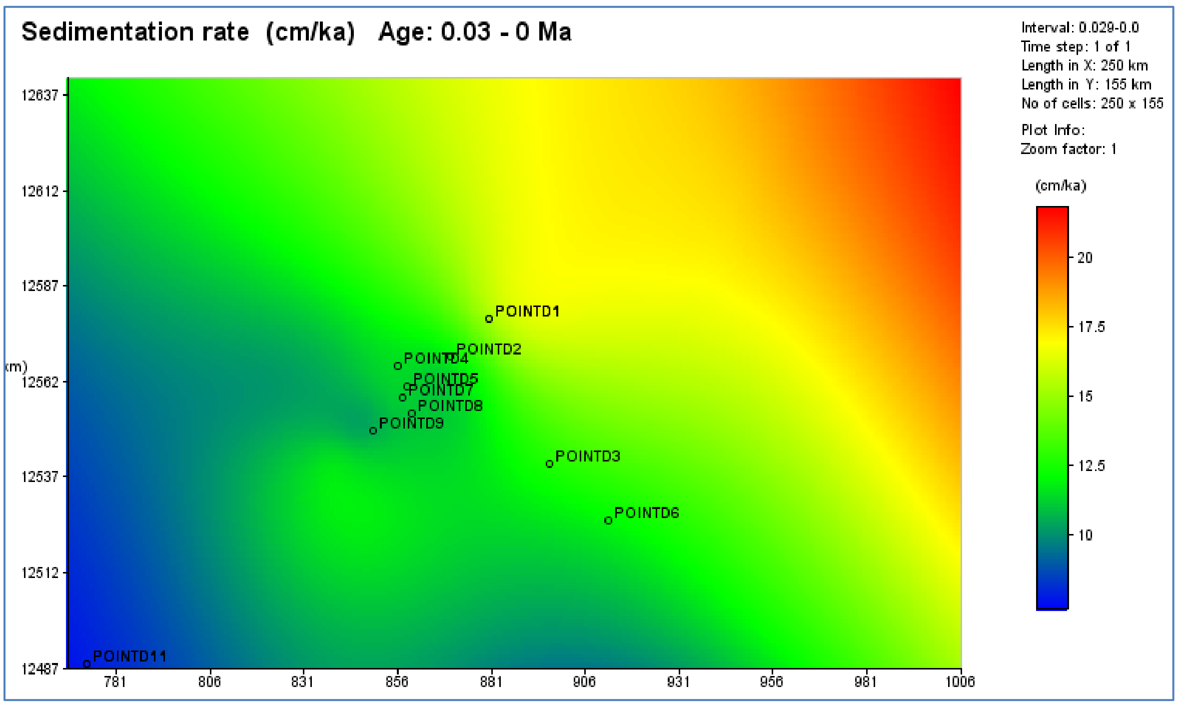


Figure 34 Model of sedimentation rate area D

6.2.2 Area A sedimentation rate result

The sedimentation rate across area A is higher along the coastline and reduces towards the deeper marine environment and the values range from 0 to 35 (cm/ka). Some local variation from the general trend of decreasing SR with increase in water depth noted in D was observed in the area (Figure 35).

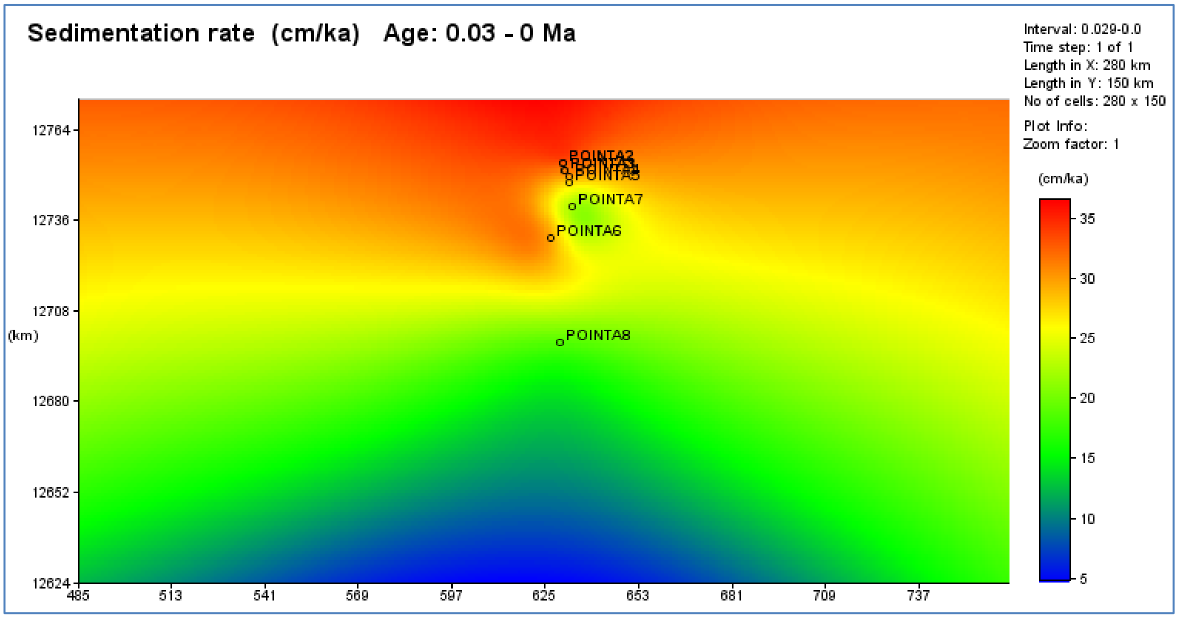


Figure 35 Modeled sedimentation rate in area A

6.2.3 Area B sedimentation rate result

Area B has a similar trend as A with regards sedimentation rate distribution with higher values close to the coastline and lower values in the deeper marine environments. Sedimentation rate values range from 0.2 to 30 cm/ka (Figure 36).

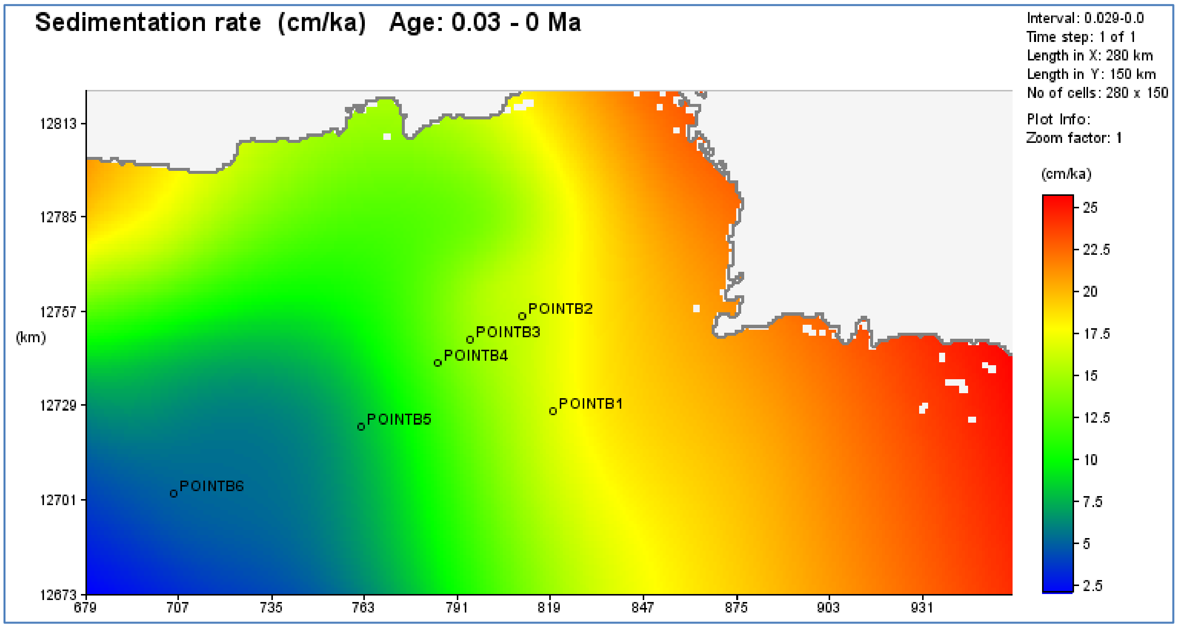


Figure 36 Modeled sedimentation rate in area B

6.3 Sedimentary facies modelling results

The inorganic facies spatial distribution model was represented as five main sedimentary environments:

- Inner and continental shelf facies
- Continental and lower slope facies
- Abyssal plain facies.

OF-mod distinguishes these sedimentary facies based on water depth and distance from coastline using a set of fuzzy logic.

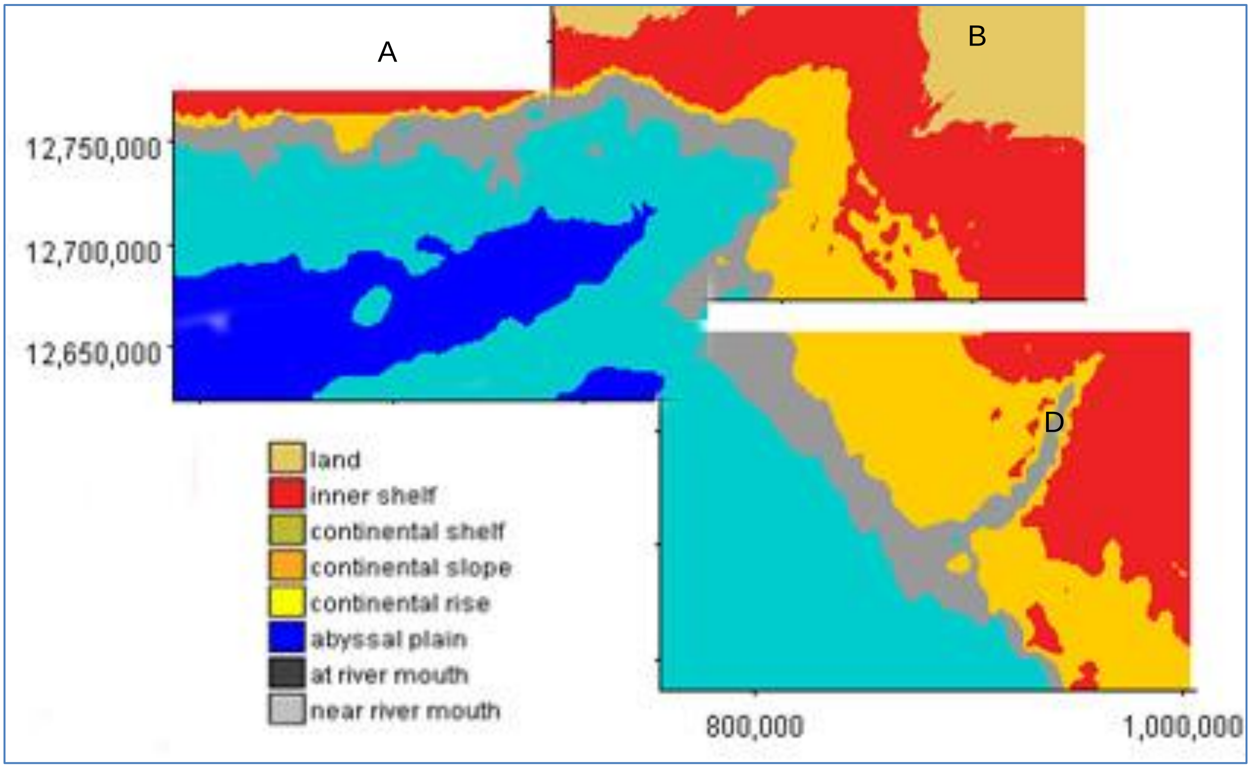


Figure 37 OF-Mod 3D model sedimentary facies distribution across the area of interest.

The facies zonation in the model (Figure 37) runs parallel to the coastline. The area covered by continental shelf sediments in area A is relatively thin compared with transects B and D. This is due to the very steep shelf slope and deep waters within that area. Inner and outer shelves sediments dominate transect D due to the gentle slope, shallow waters and their areal extent. The result was compared with the facies distribution of surface sediments from the Indian-Pakistan continental margin of von Stackelberg (1972) and also of Schulz et al (1996). Von

Stackelberg (1972) divided the surficial sediment into three types based on depositional environment with regards to water depth:

- Shelf sediments;
- Upper slope sediments
- Lower slope sediments

This interpretation of facies distribution was further modified by Schulz et al (1996) where a detailed description of facies distribution was carried out.

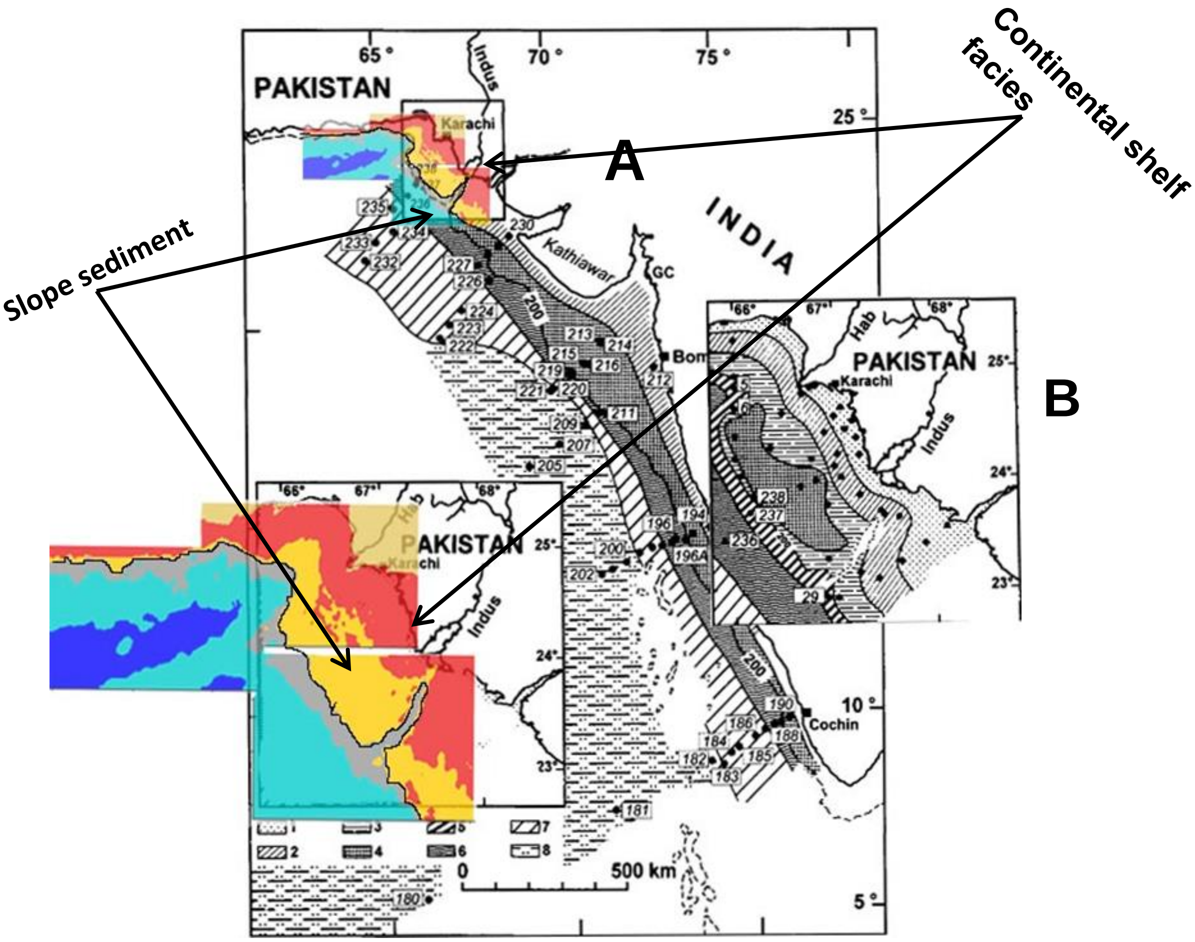


Figure 38 Facies distribution of surface sediments from the Indian-Pakistan continental margin B, (modified from von Stackelberg 1972 Map A). 1, terrigenous sand; 2, micaceous mud; 3, pteropod-rich mud; laminated silty clay; 6, olive-gray silty clay

Comparing the facies model (Figure 37) with the results of Von Stackelberg (1972) as shown in Figure 38, a good correlation with the map of facies distribution is observed. The more detailed version by Schulz et al (1996) (Figure 38 B) shows local facies variations. This is due to the local distribution and trend of the sand fraction which are not considered when creating the model. The difference is probably due to variation in local depositional processes which includes local sands or coarse fragment sources; biogenically derived sediments, and reworked sediments.

6.4 Sand fraction modelling result

Sand fraction modeling was carried out in OF-Mod based on the modeled sedimentary environment as shown in Figure 37 by assigning SF values (Table 3) to the various environments. Sand fraction modeling clearly shows (Figures 39, 40 and 41) a reduction in sand size particle from coastline towards the deeper part of the basin in the three areas. The sand fraction was calibrated using measured sand fraction values from cores collected from the areas (during the Pak-German cruise with R/V Sonne SO-90 (Von Stackelberg (1972). The calculated sand fraction values are subtracted from the measured values and the difference indicates how accurately the model fits the measured values (Figure 42). The closer the difference is to zero the better the model.

6.4.1 Area A

In area A the sand fraction follows the general trend across the margin but a short transition occurs from very high SF at coastline to very low SF in deep marine environment. Data points within this area are located within areas of SF values ranging from 0.1 to 0.4 (Figure 40).

6.4.2 Area B

The transition of SF values from coast line to deeper marine is gradual and follows the general trend. The sand fraction in area B is relatively higher than area A and SF values range from 0 to 0.7 (Figure 41).

6.4.3 Area D

Sand fraction modeling in area D had a similar trend as A and B above. The calibration was better because more data points are available in the area. SF values on the continental slope range from 0.3 to 0.5 while within the shelf slope it ranges from 0 to 0.2 (Figure 39).

Table 3 shows the user defined sand fraction values used in adjusting the calculated sand fraction to fit the measured values.

Table 3 User defined sand fraction values OF-Mod 3D

Sed Facies	Sand fraction
land	SF =0
Inner shelf	SF = 1
Continental shelf	SF = 0.7
Continental slope	SF = 0.3
Lower slope	SF = 0.1
Abyssal plain	SF = 0

sedimentary facies	map colour	sand fraction [-]
land		land
inner shelf		high sf
continental shelf		medium sf
continental slope		low sf
lower slope		very low
continental rise		zero sf
Abyssal plain		zero sf

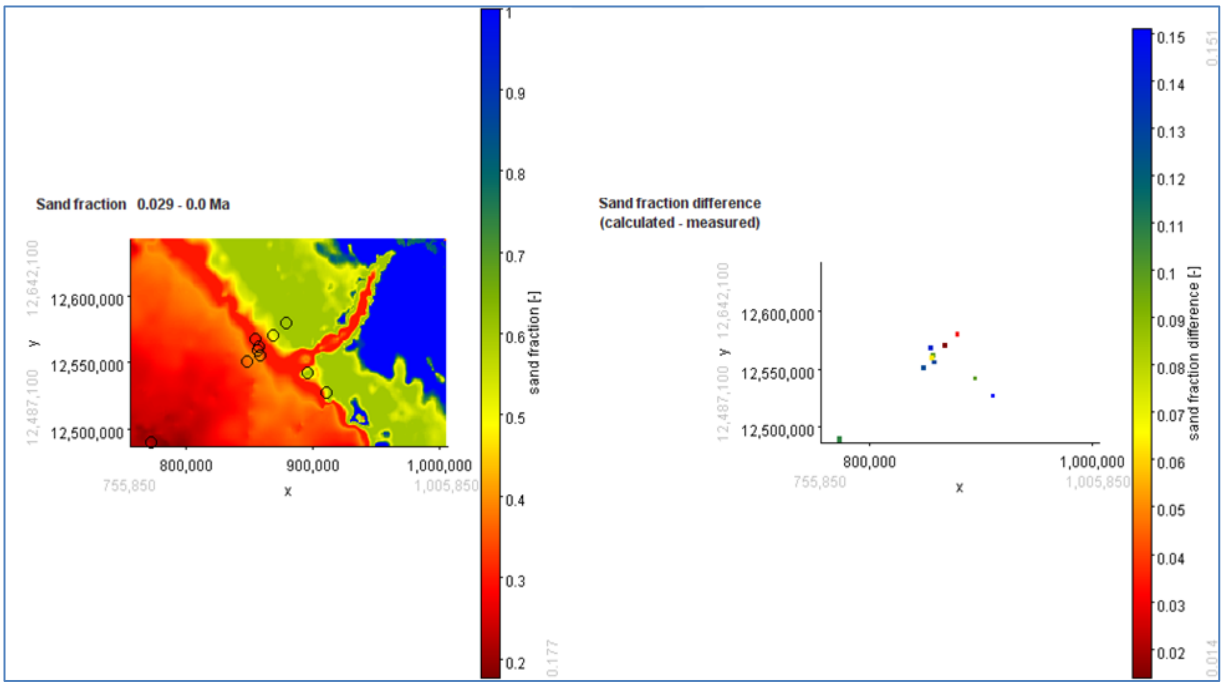


Figure 39 OF-mod 3D modeled sand fraction area D, measured data location points and calibration panel.

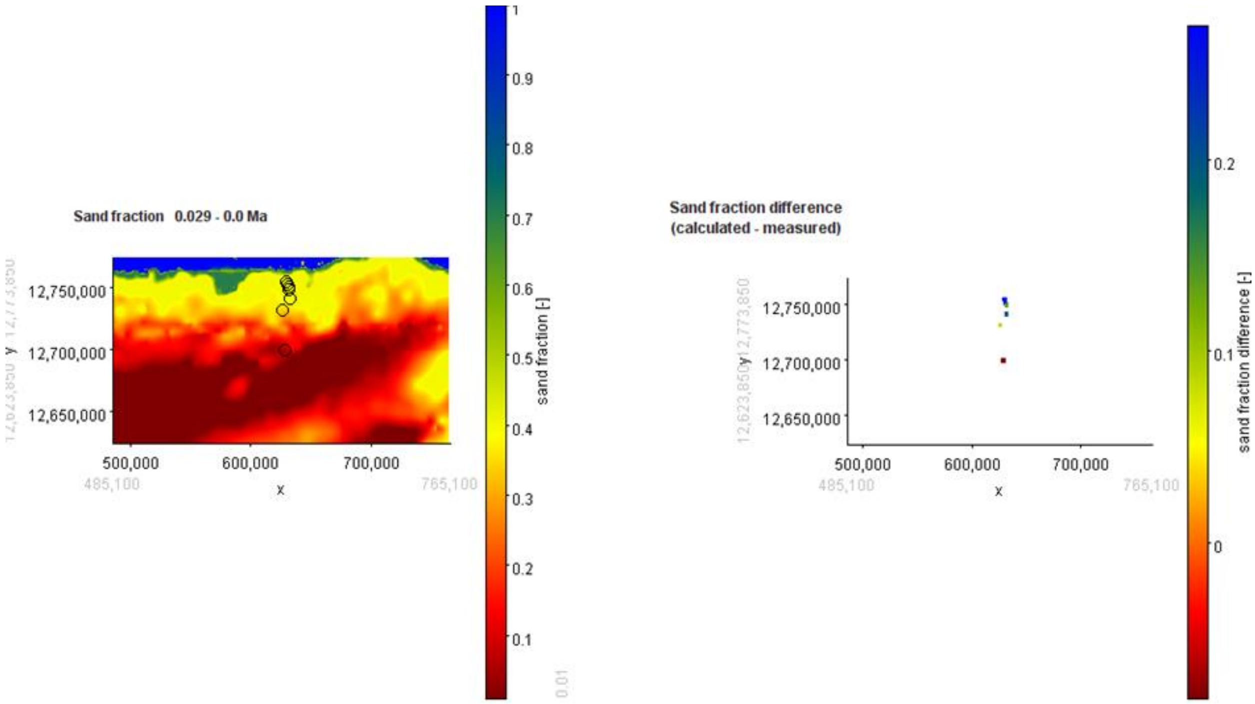


Figure 40 OF-mod 3D modeled sand fraction area A, measured data location points and calibration panel.

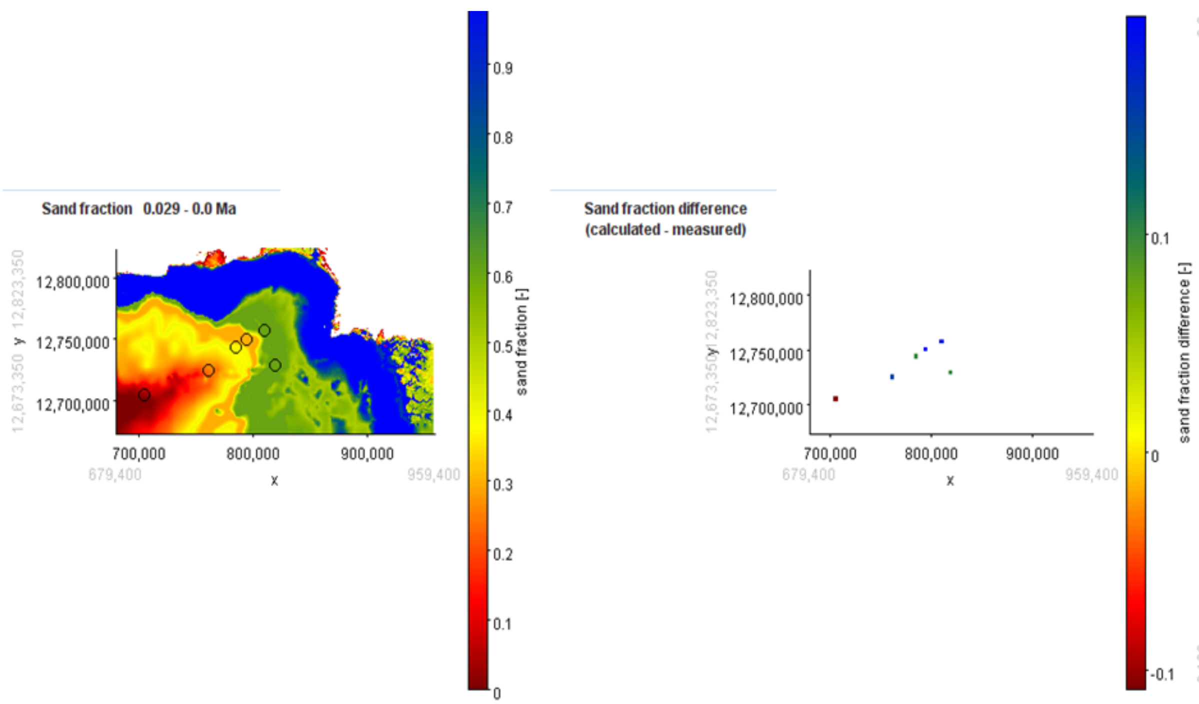


Figure 41 OF-mod 3D modeled sand fraction area B, measured data location points and calibration panel.

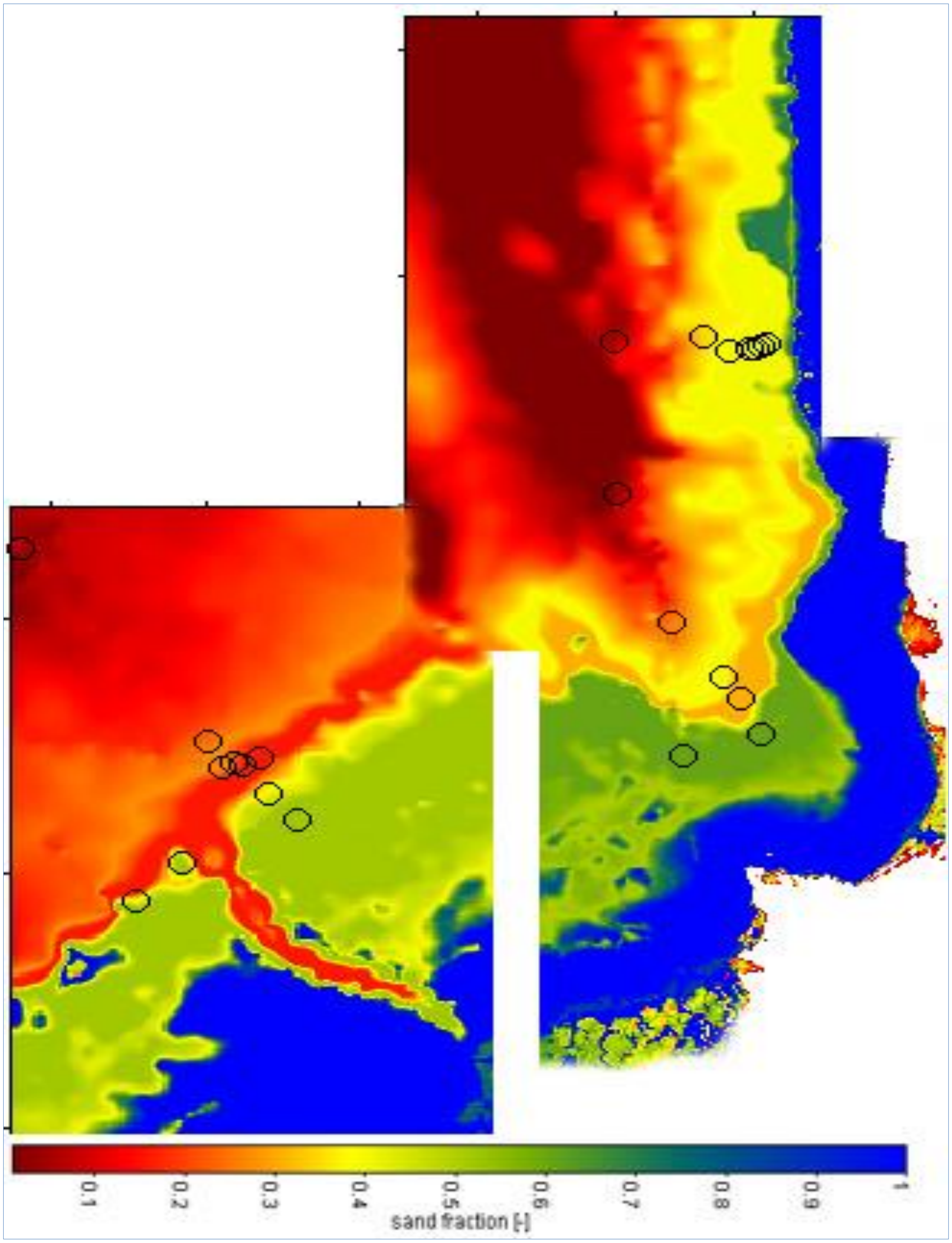


Figure 42 OF-mod sand fraction modeling across in the 3 areas of interest.

6.5 Input parameter estimation for 3D

1D modeling results for terrigenous and residual organic fractions were used to set the amount of the organic carbon fractions used as input in the 3D modeling (Figure 30). Primary productivity values within the upwelling zone and ocean background values were set based on measured values found in Schulte et al. (2000). A preservation factor of 1.8 % was applied in the oxygen minimum zone in the 3D modeling; this value was adopted from the calculated 1D modeling result (Figure 28).

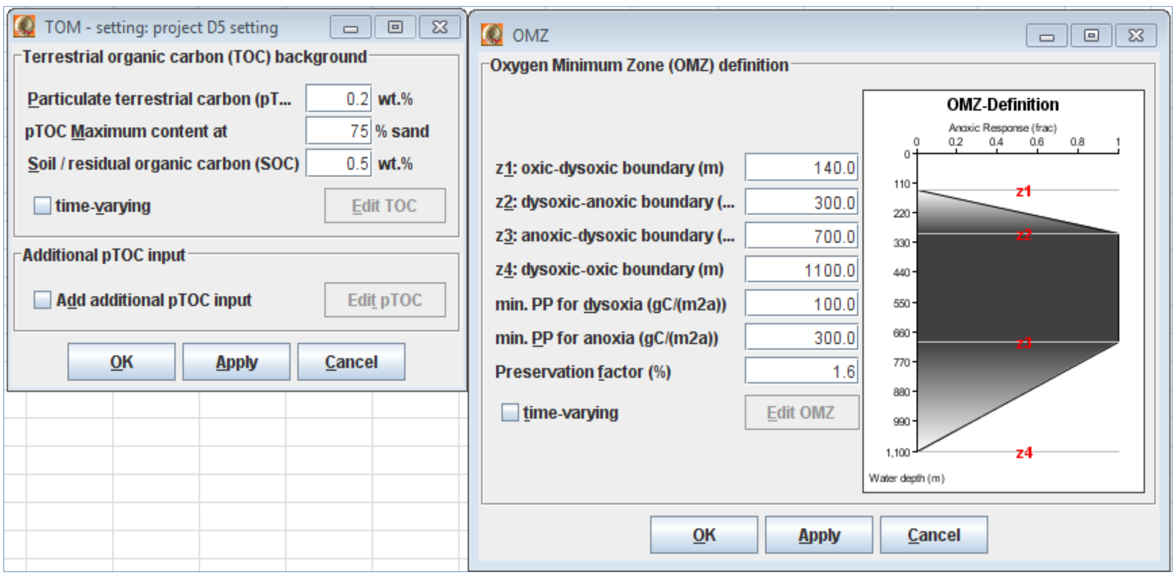


Figure 43 OF-Mod 3D input panel for pTOC, SOC and OMZ properties

6.6 3D organic facies modeling

In this project, spatial modelling of total organic carbon (TOC), effect of the oxygen minimum zone and hydrogen index (HI) was carried out for the three areas. The model was calibrated using measured values obtained from previous work on the area. The 1D model was also useful in adjusting end member values of hydrogen index and carbon isotope ($\delta^{13}C$) values for the marine organic carbon (MOC), terrestrial organic carbon (pTOM), and residual organic carbon (SOC) in 3D modelling. It was necessary to use the 1D modeling result to constrain the modelling process to get a good fit between model and measured data. The 1D model was also used as a guide in estimating the amount of terrestrial organic carbon used as input (note from

1D modelling pTOC was relatively small compared to MOC (Figure 30) and the residual organic carbon.

6.6.1 Oxygen minimum zone

The OMZ was defined based on the Schulte et al (2000) oxygen profile model shown in Figure 26 and the preservation factor adopted was based on OF-Mod 1D results. The OMZ ranges from a water depth of 200m to about 1100m; within this interval dissolved oxygen is relatively low and the water column is anoxic. Seasonal variation in primary productivity within the three areas had some influence on the intensity of the OMZ (Von Rad et al 1995) but was not considered in the model.

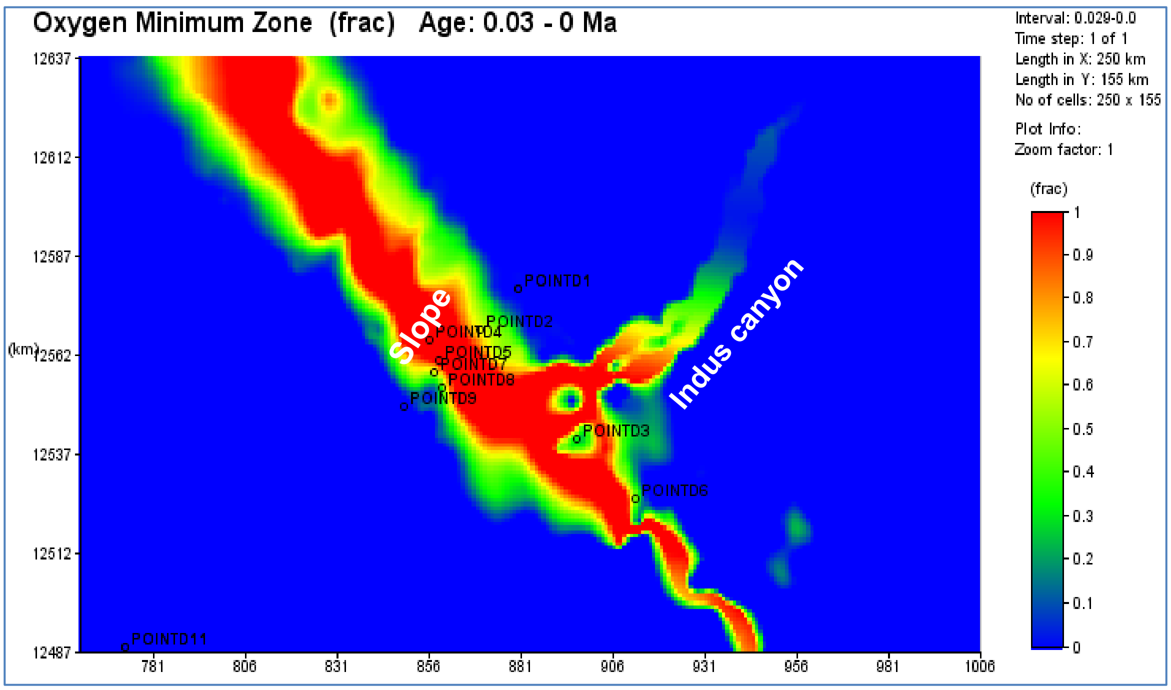


Figure 44 OF-Mod 3D model OMZ area D

Figure 44 shows where in area D, the OMZ impinges on the sea floor; the effect of anoxia extends into the Indus canyon. The OMZ is narrow in the south eastern section due to the steep slope in the area and broadens towards the north western section. A 3D view (Figure 45) of the model of area D sheds more light on why the OMZ is narrow towards the south eastern section. The section is relatively steep compared to the other sections. The intensity of the OMZ has a maximum on the shelf slope and decreases away towards the shelf and abyssal plain.

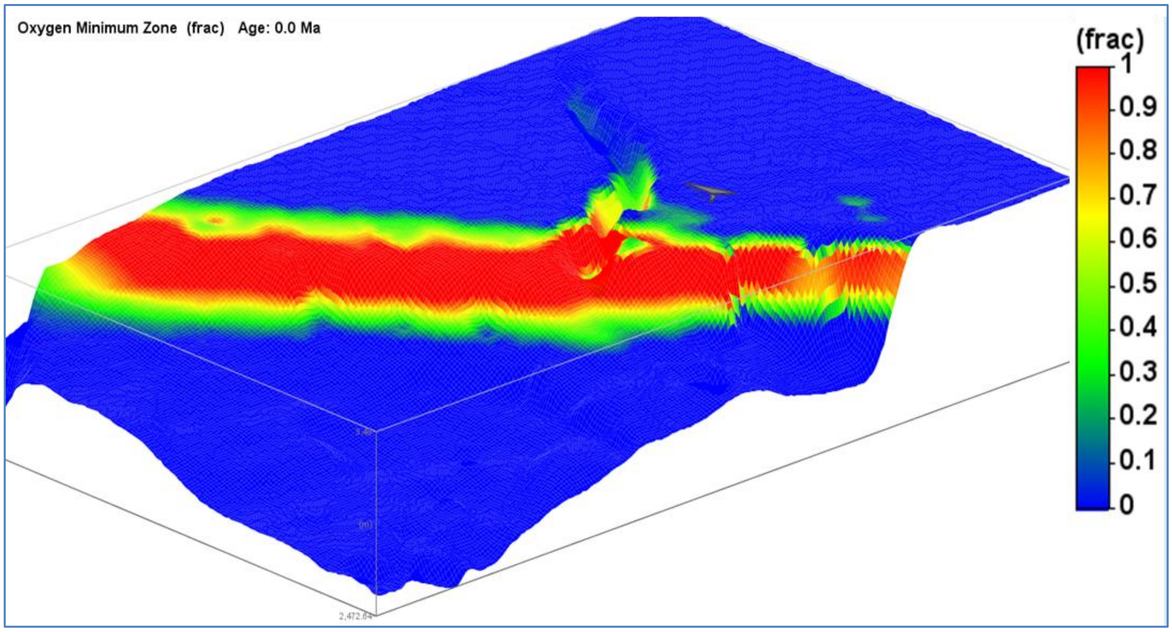


Figure 45 OF-Mod 3D modeled OMZ in 3D view across area D.

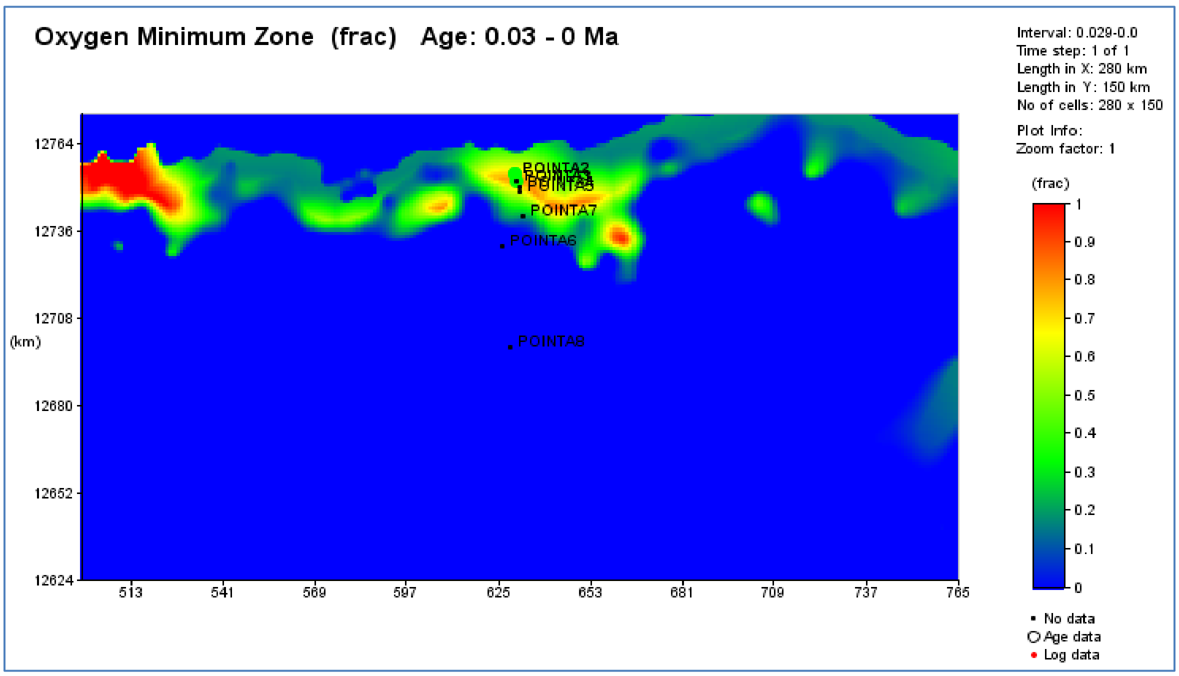


Figure 46 OF-Mod 3D model OMZ area D

In area A the OMZ is located in the northern section of the area and runs parallel to the coastline. The intensity of the OMZ in area A is relatively low compared to area D (Figure 44) though the intensity is high in the north western section.

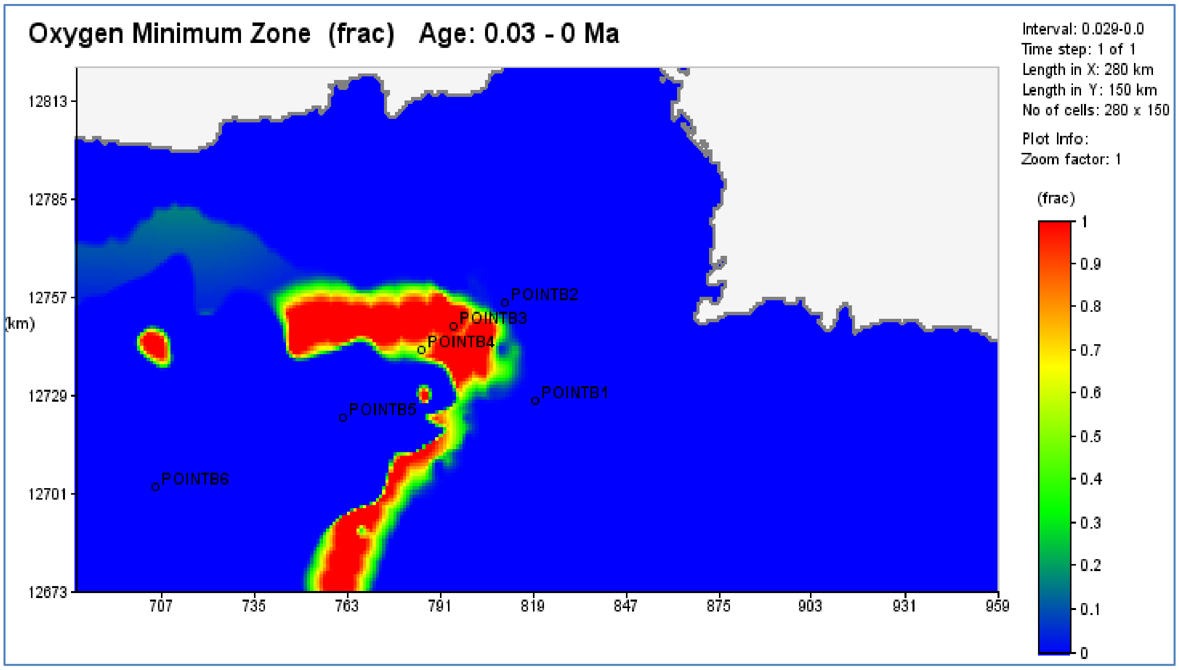


Figure 47 OF-Mod 3D model OMZ area B

The intensity of the OMZ in area B is high in the southern section and reduces in the north western section. The effect of anoxia is observed at a single point in the north western section, which is due to an elevated part of the sea bed intercepting the OMZ.

6.6.1.1 Primary productivity

In applying primary productivity a background value of 60 (gC/m^2/year) was applied to the open ocean and 150 (gC/m^2/year) for the coastline (with a linear decrease between the two). Additional primary productivity values were added to the outer shelf and slope areas to account for the effect of upwelling. Measured values of about 335 to 435 (gC/m^2/year) were described by Schulte et al.(2000) while productivity values of 270 to 365 (gC/m^2/year) were given by Paropkari et al (1992). 1D model results shown inFigure 28 had a peak productivity value well within the range of measured values found in literature, of about 275 (gC/m^2/year) which was adopted in the 3D modeling. The primary productivity levels required to obtain a good fit of calculated TOC with measured TOC in areas D and A were higher than in area B in the model, possibly because the data points were close to the shoreline and could have been influenced by inputs from fluvial systems (Figure 49). In area D maximum primary productivity values were in areas close to the shelf slope, in A maximum primary productivity values were also located close to the shelf slope.

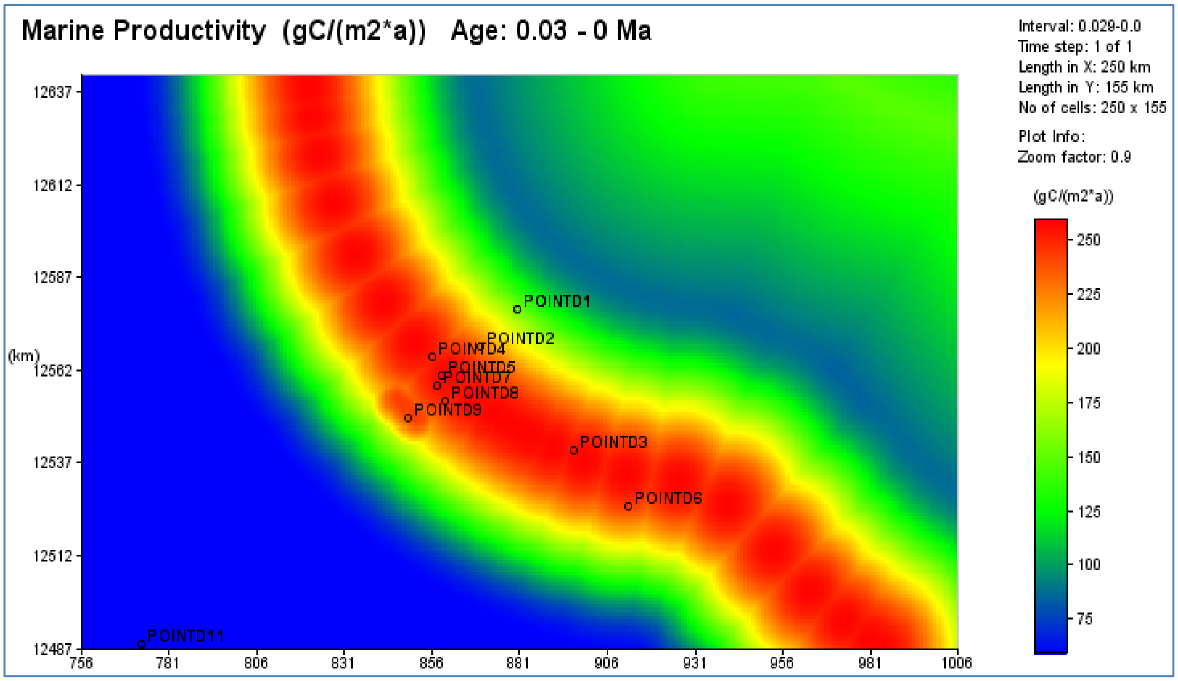


Figure 48 OF-Mod 3D: primary productivity across Area D and data points.

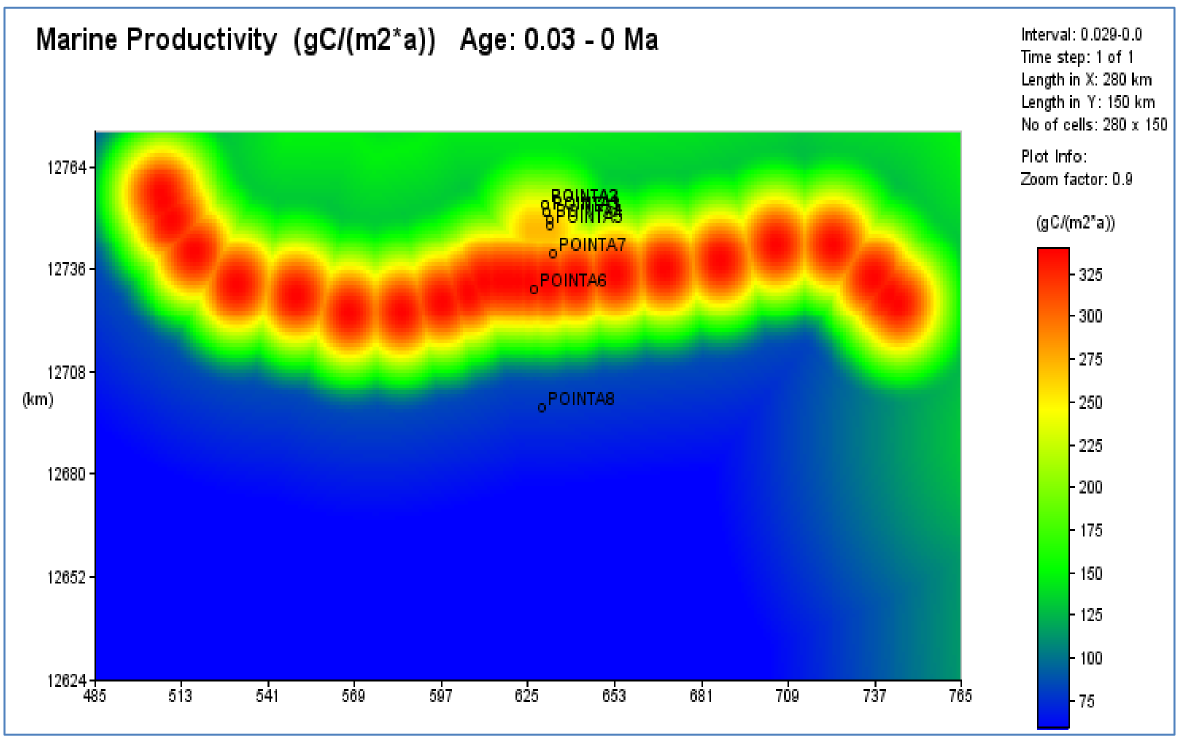


Figure 49 OF-Mod 3D I primary productivity across area A and data positions.

6.6.1.2 Hydrogen index

Hydrogen index (HI, mg hydrocarbons/g Corg) values across the areas were low and ranged from 150 to 300 (mg hydrocarbons/g Corg). HI values within the OMZ were higher compared to most areas outside the OMZ in areas D and B. No HI values were observed close to the coastline in all areas because of the very high sand fraction is assumed to be 100% and highly oxic conditions..

6.6.1.3 Area D HI result

In area D the hydrogen index values were high within the OMZ especially on the slope and reduced linearly away from the slope. The south eastern section of the area had HI values within the range of 200 to 250 (mg HC/g TOC). Figure 50 shows a clear correlation between the OMZ and HI ditribution in area D.

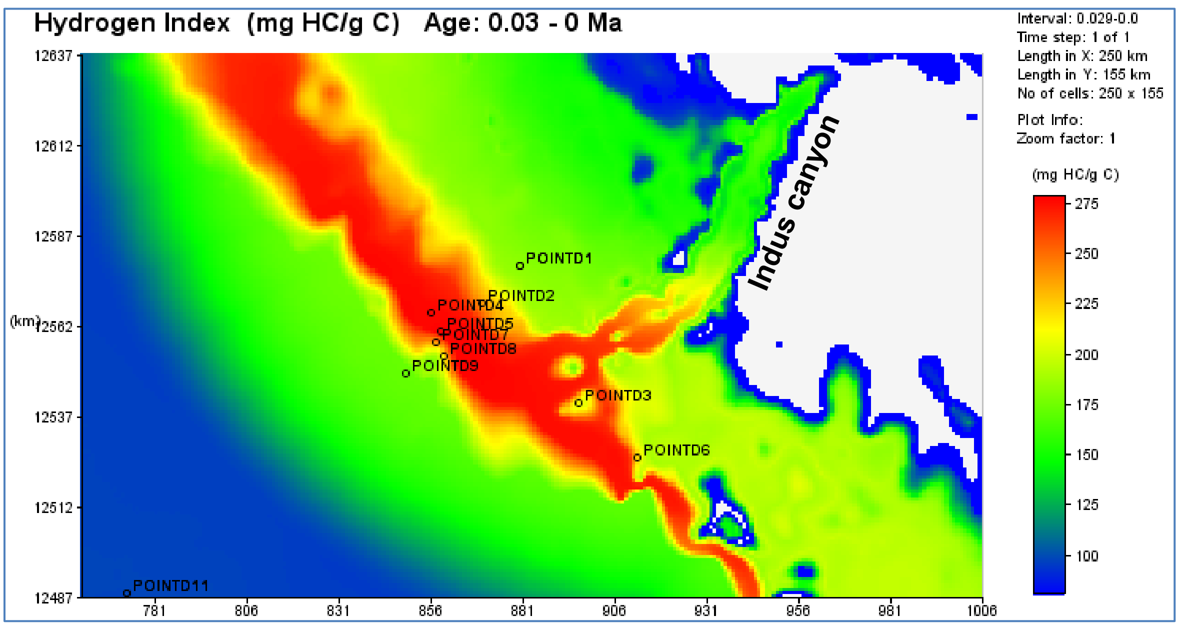


Figure 50 OF-Mod 3D modeled hydrogen index across area D and measured data positions.

6.6.1.4 Area A HI result

Area A had relatively lower HI values and sections within the OMZ had relatively lower values which range from 175 to 200 (mg HC/g C) compared to areas outside the oxygen minimum zone. Within zones in which primary productivity values were high, the HI values ranged from 175 to 250 (mg HC/g C). The HI value in area A had a maximum value in the north western section of the area about 250 mg HC/g C (Figure 51). There is only a poor correlation between OMZ and HI in area A.

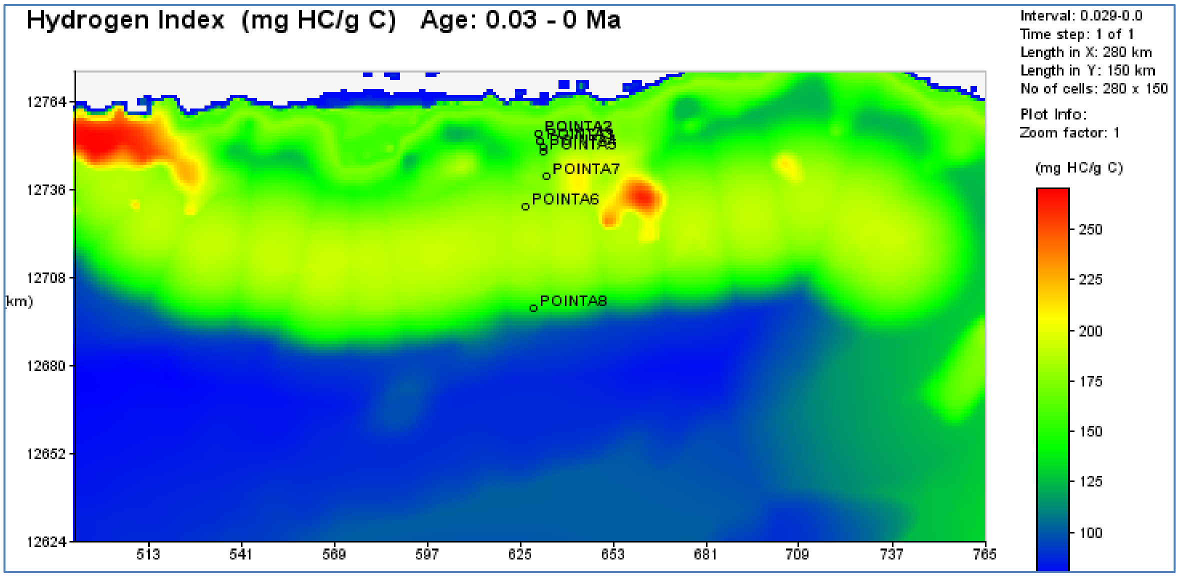


Figure 51 3D modeled hydrogen index (HI) across area A and data positions.

6.6.1.5 Area B HI result

Area B had a similar trend as area D, the OMZ had relatively higher values compared with areas outside it, at points where high productivity values intersects the OMZ. In the eastern areas the hydrogen index values were not high even within the OMZ. HI values within the OMZ range from 200 to 275 (mg HC/g C) with the lower range falling in the north western section of the area (Figure 52).

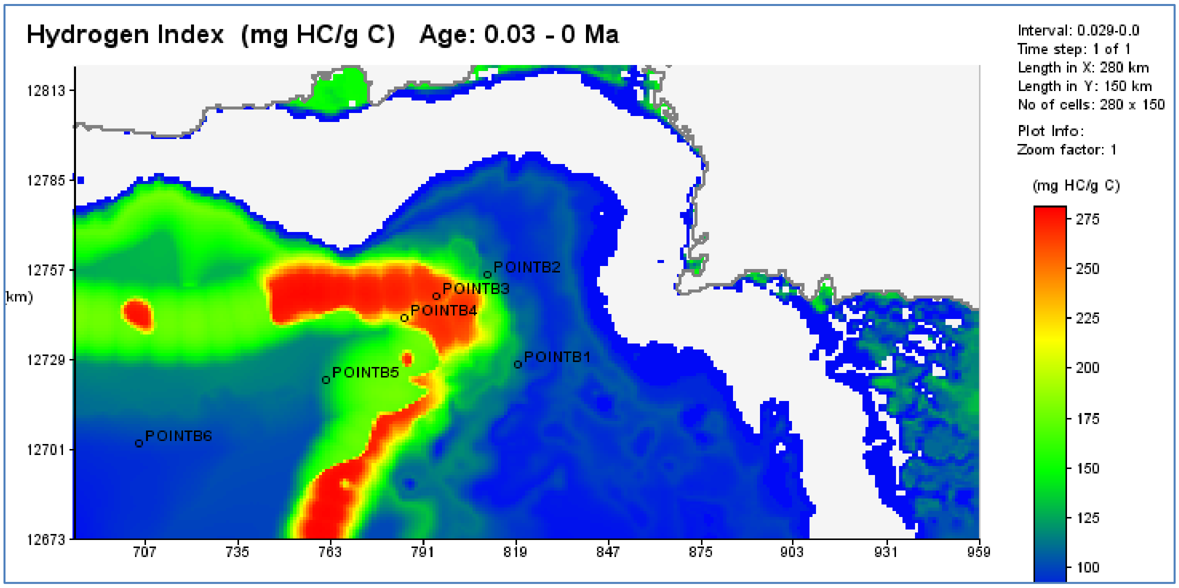


Figure 52 OF-mod 3D modeled hydrogen index (HI) across area B and data positions.

6.6.2 Total organic carbon result.

Total organic carbon result had a good match with measured data found in Cowie et al (1999) see tables 4, 5 and 6. Modeled TOC levels were higher in area D compared to areas A and B. TOC distribution across the area had some correlation with the OMZ and deposited organic matter were also observed in area outside the OMZ especially in D.

6.6.2.1 Area D TOC result

Maximum TOC values were found within the OMZ and values ranged from 3.5 to 4.5 wt %. The south eastern section of the map which falls outside the OMZ had relatively high TOC values ranging from 2.5 to 4.5 wt %. The continental shelf close to shore and abyssal environment had relatively low TOC values as expected (Figure 53).

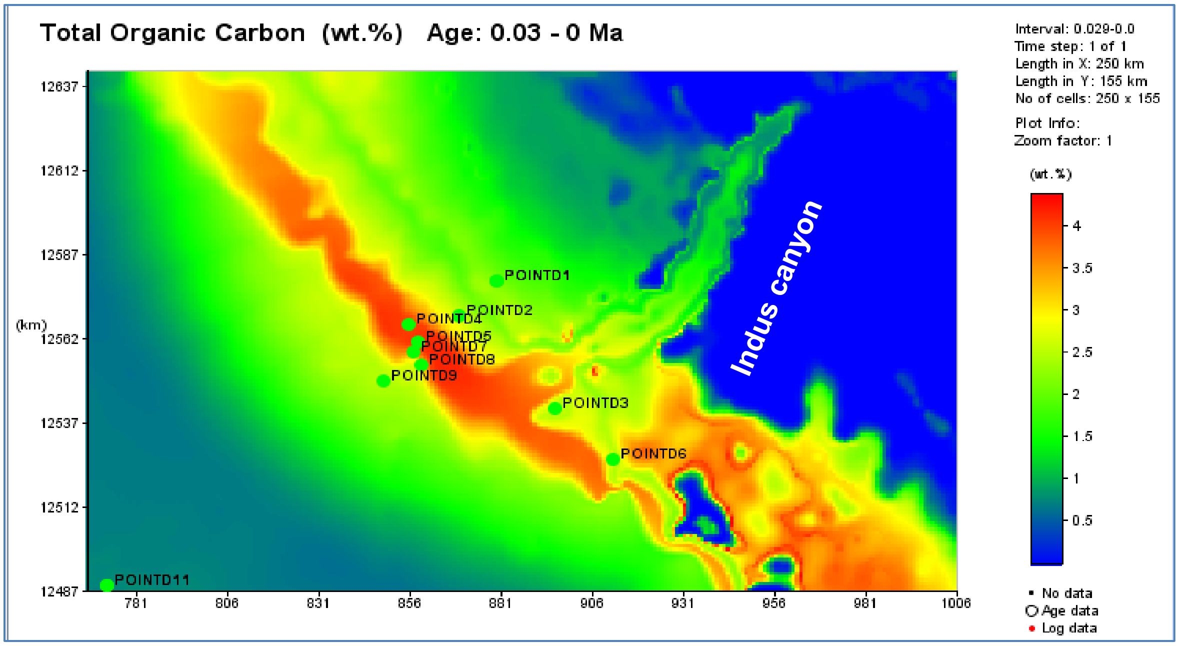


Figure 53 OF-Mod 3D modeled Total organic carbon across area D and data positions.

6.6.2.2 Area A TOC result

Area A had high TOC values stretching along zones of high primary productivity levels, from western to the eastern section of the area and the TOC values range from 2.5 to 3.5 wt %. Zones where the OMZ impinges on the sea floor had high TOC values which range from about 0.5 to 2.5 wt % which were expected (Figure 54).

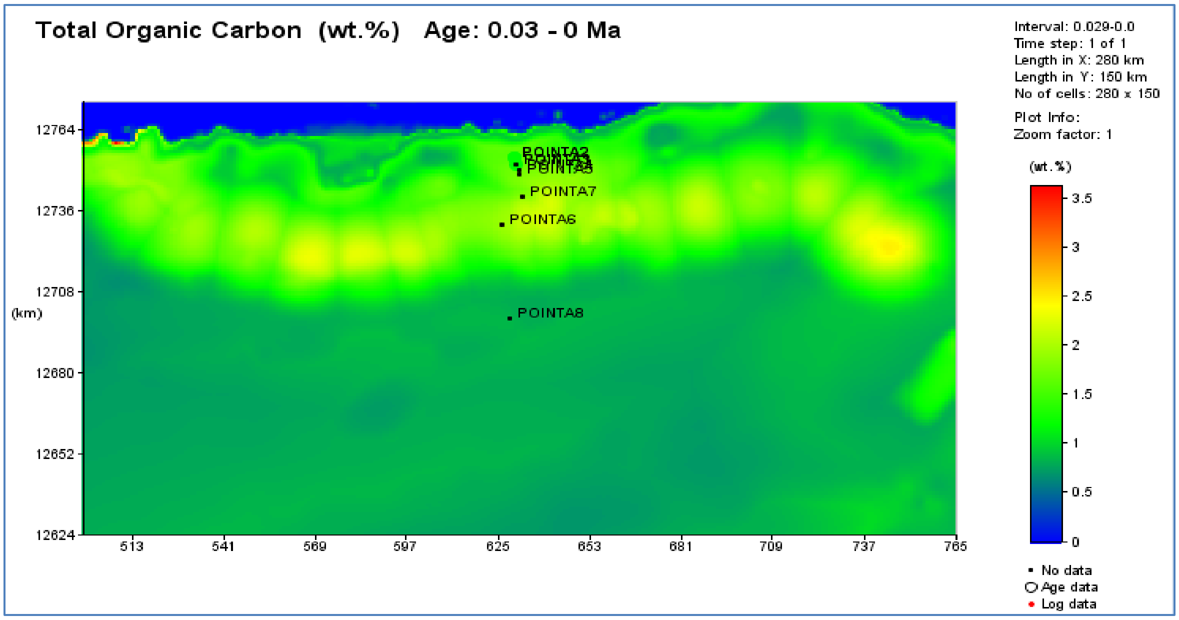


Figure 54 OF-Mod 3D modeled total organic carbon across area A, measured data positions.

6.6.2.3 Area B TOC result

Area B had a narrow band of total organic carbon distributed along the sea bed in the western section. Some of the deposited TOC falls within the OMZ and others outside areas influenced by the OMZ. Significant TOC values within area B range from 0.5 to 5 wt % and maximum values fall within areas influenced by the OMZ and high primary productivity. Sections close to the coastline had little or no TOC present (Figure 55).

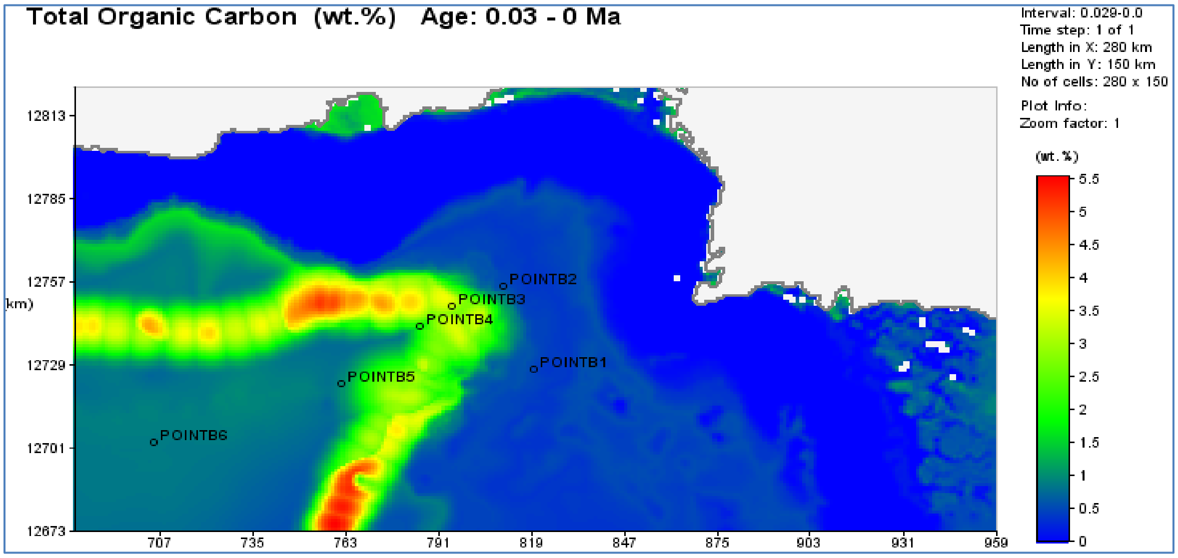


Figure 55 OF-Mod 3D modeled total organic carbon across area B and data position

6.6.3 Preservation factor (preserved marine organic carbon)

The preservation factor is a measure of the absolute amount of primary produced organic carbon deposited and preserved in sediment. The preserved marine organic carbon distribution across the tree areas has a different trend compared to the TOC. The value of preserved marine organic carbon ranges from 0 to 1.75 (%) across the three areas.

6.6.3.1 Area D preserved marine organic carbon result

In area D the value of preserved marine organic carbon was high in the south eastern section of the area and similar values are observed on the continental shelf (Figure 56). Preserved marine organic carbon was relatively low within the OMZ compared to the south eastern section outside the OMZ were preservation was higher.

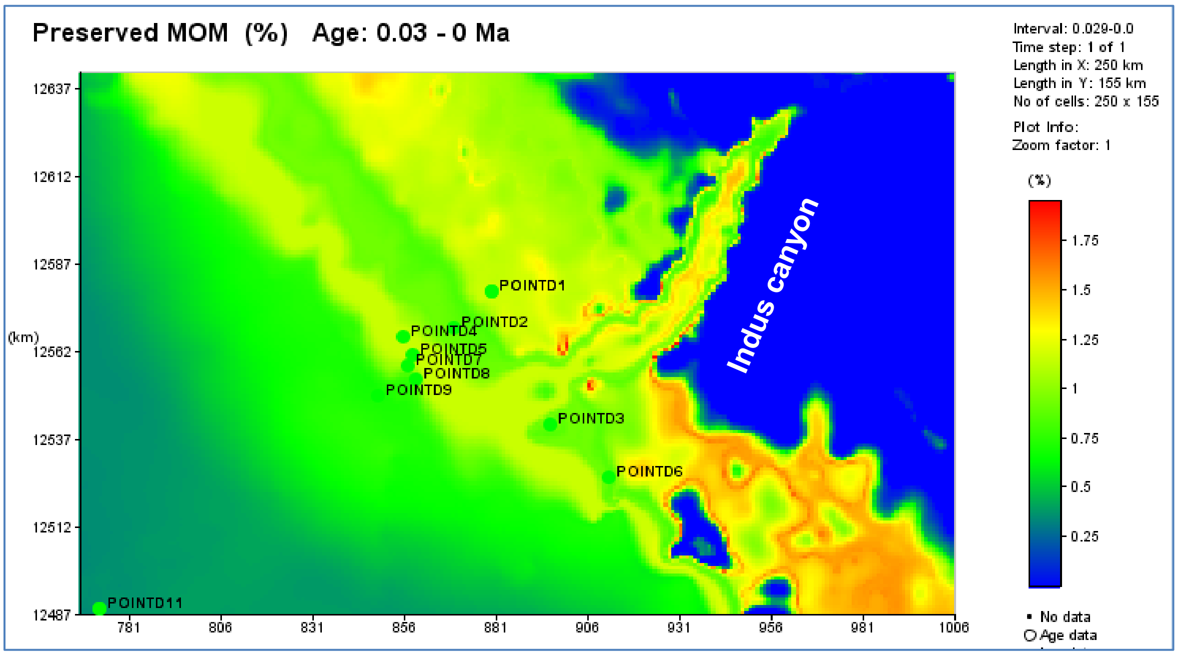


Figure 56 Spatial distribution of preserved marine organic matter in area D.

6.6.3.2 Area A preserved marine organic carbon result

Preserved marine organic carbon in area A is spread across the northern sections in area A from west to east and the values range from 0 to 2% (Figure 57).The preserved marine organic carbon is concentrated on the continental slope and reduces towards the abyssal plain. Within the OMZ the amount of preserved marine organic carbon is relatively higher than areas outside the OMZ with values in the range of 1.5 to 2%.

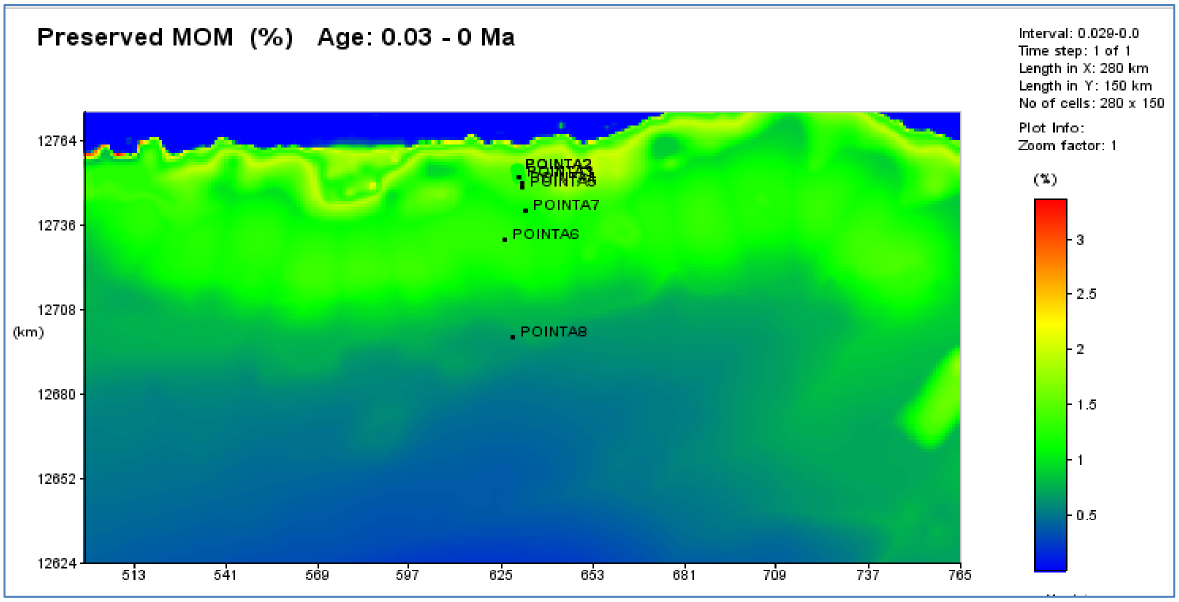


Figure 57 Spatial distribution of preserved marine organic matter area A.

6.6.3.3 Area B preserved marine organic carbon result

In area B the preserved marine organic carbon is higher in western section of the area. Within the OMZ preservation of marine organic carbon was observed to have maximum values and the values range from 0.7 to 1.5 %. The level of preserved marine organic carbon is relatively very low close to the coastline and parts of the continental shelf (Figure 58).

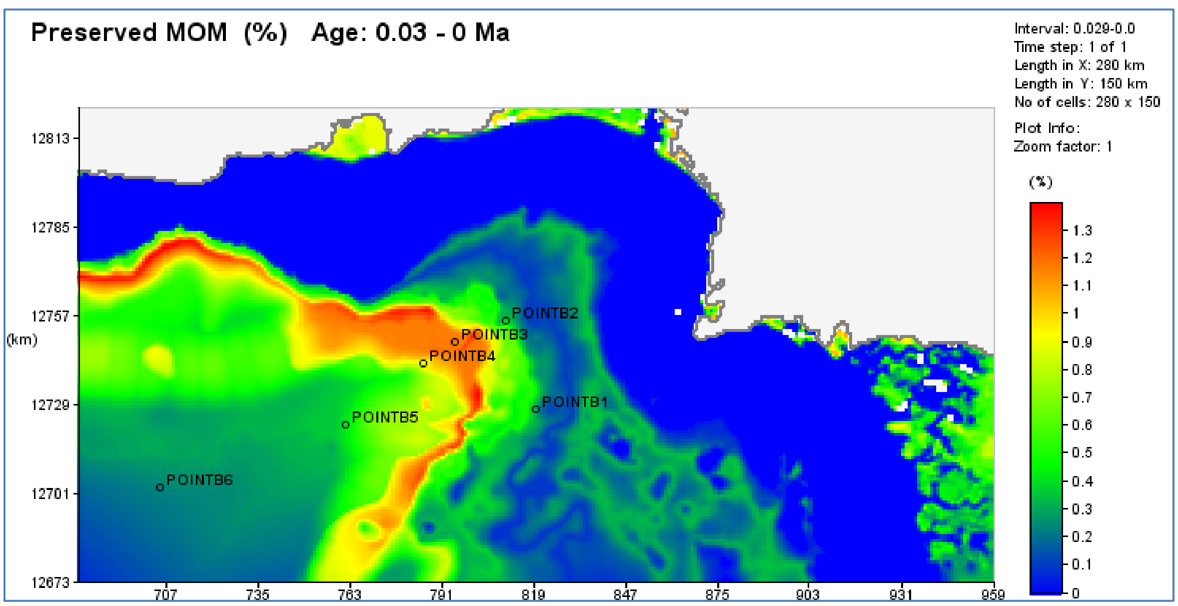


Figure 58 Spatial distribution of preserved marine organic matter area B.

6.6.4 Residual organic carbon (SOC)

Residual organic carbon is the degraded marine or terrestrial organic carbon due to poor preservation conditions in the environment of deposition. The residual organic was modeled across the three areas and the results are presented below.

6.6.4.1 Area D SOC result.

The result showed high values of residual organic carbon along the slope and in the Indus canyon in areas where the OMZ impinges on the sea floor. The observed values in the OMZ are relatively higher than values on the continental shelf. The continental shelf especially the south eastern section had very low values of residual organic carbon. In the deeper marine environment values of SOC are observed to be very high (Figure 59).

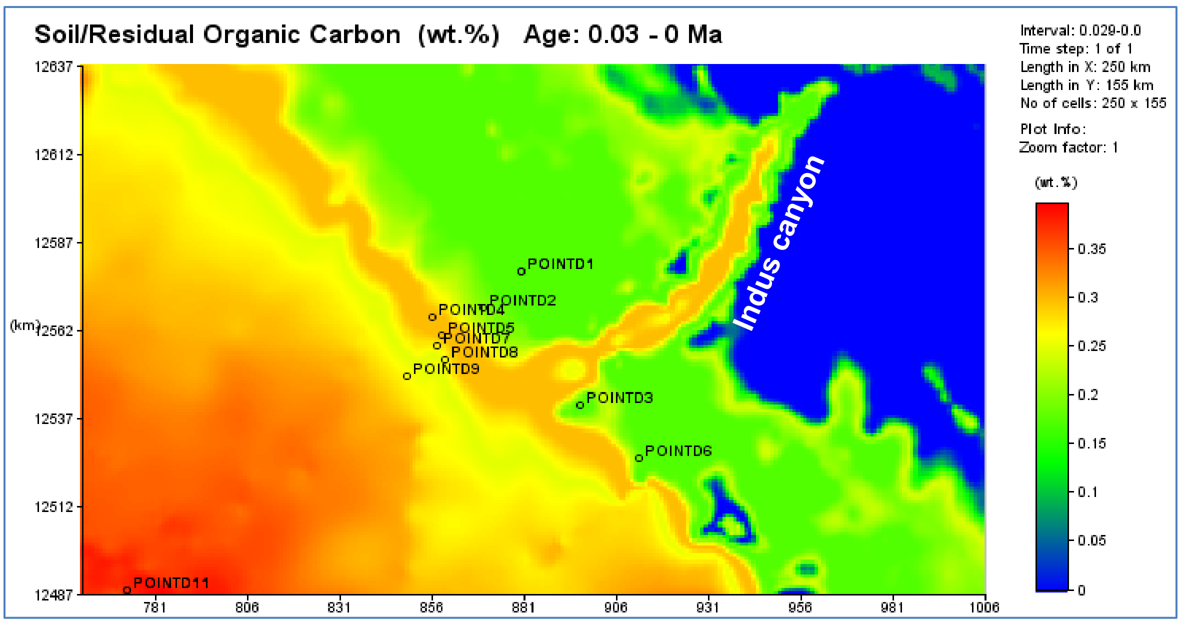


Figure 59 Spatial distribution of residual organic carbon area D.

6.6.4.2 Area A SOC result

In area A residual organic carbon dominates the abyssal plain. Within the OMZ residual organic carbon values are quite low on the lower slope but higher on the upper slope. The narrow continental shelf had very low values of residual organic carbon (Figure 60).

6.6.4.3 Area B SOC result

Area B has more residual organic carbon in the western section of the area and values range from 0.3 to 0.5 (wt %), while in the east the values are lower. The highest values were observed in the deep water abyssal plane (Figure 61).

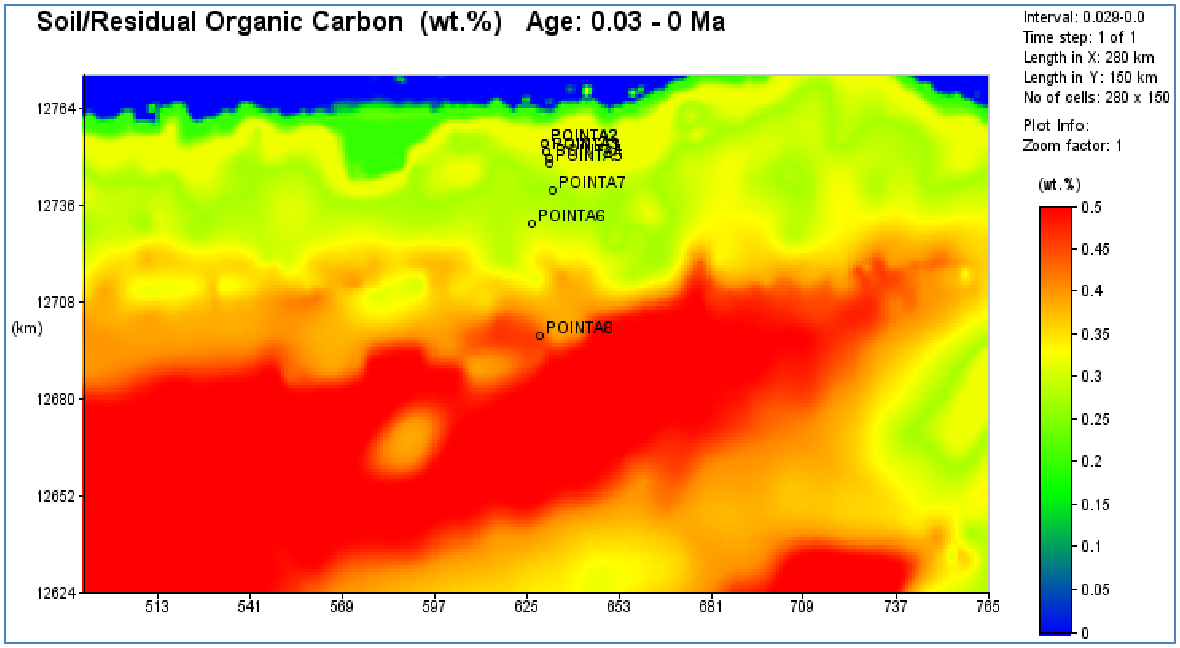


Figure 60 Spatial distribution of residual organic carbon area A

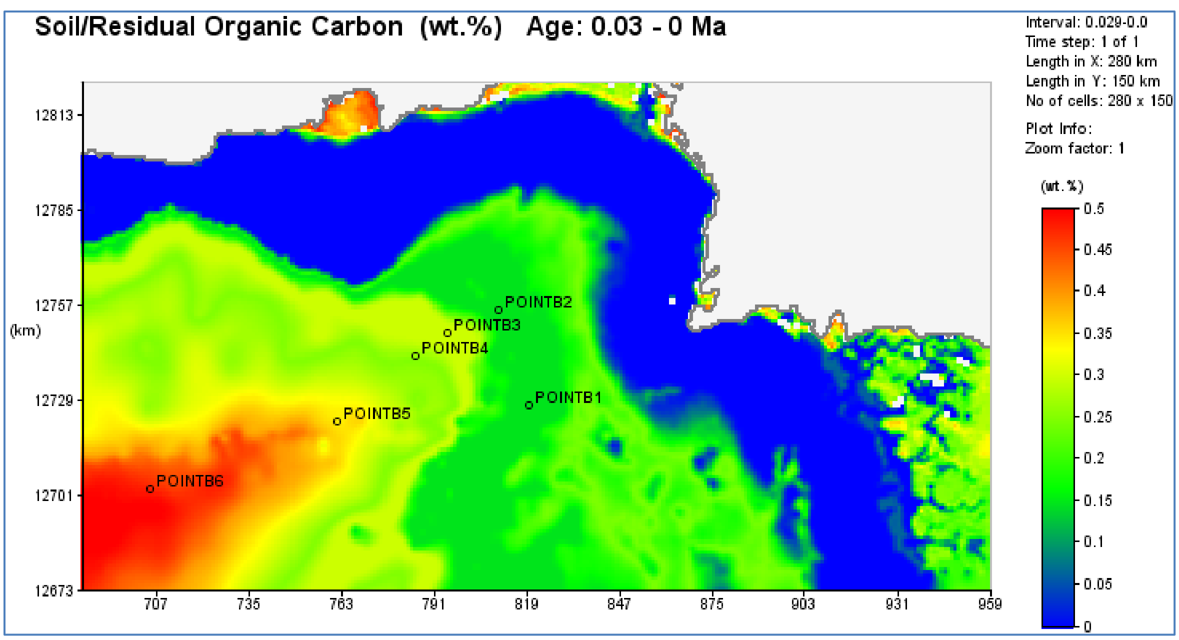


Figure 61 Spatial distribution of residual organic carbon area B

6.6.5 Terrigenous organic carbon result

The terrigenous organic carbon across the area was relatively low compared to SOC and MOC: modeled values range from 0 to 0.2 wt %. pTOC are dominant on the continental shelf and reduces towards the deeper marine environments. In area D terrigenous organic carbon is relative low within the OMZ and the Indus canyon. Higher values are observed on the continental shelf on both sides on the Indus canyon in area D (Figure 62).

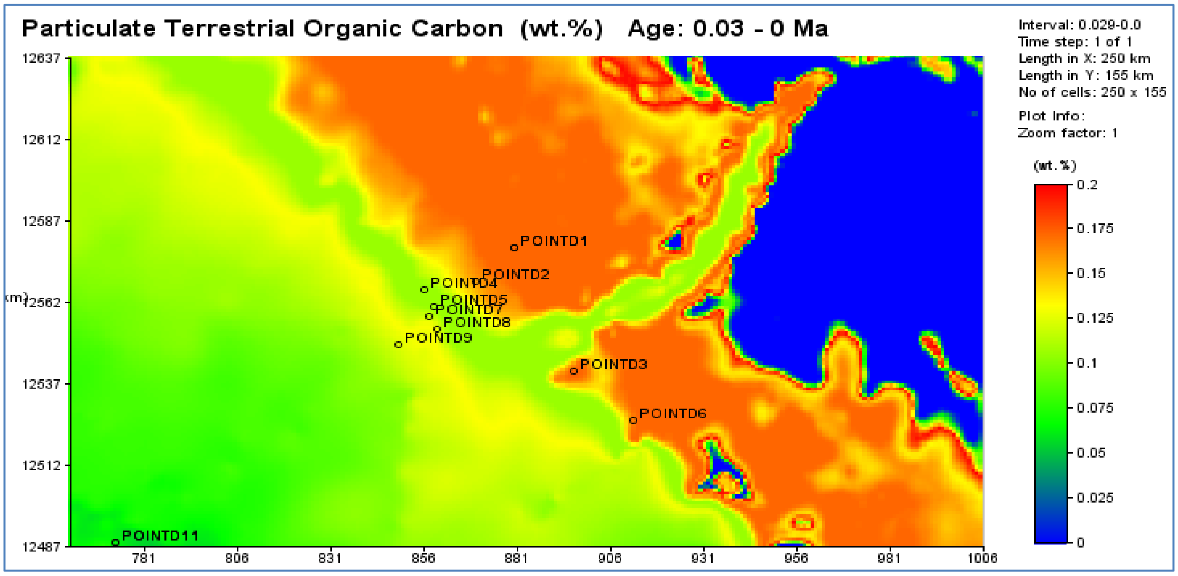


Figure 62 Spatial distribution terrigenous organic carbon area D

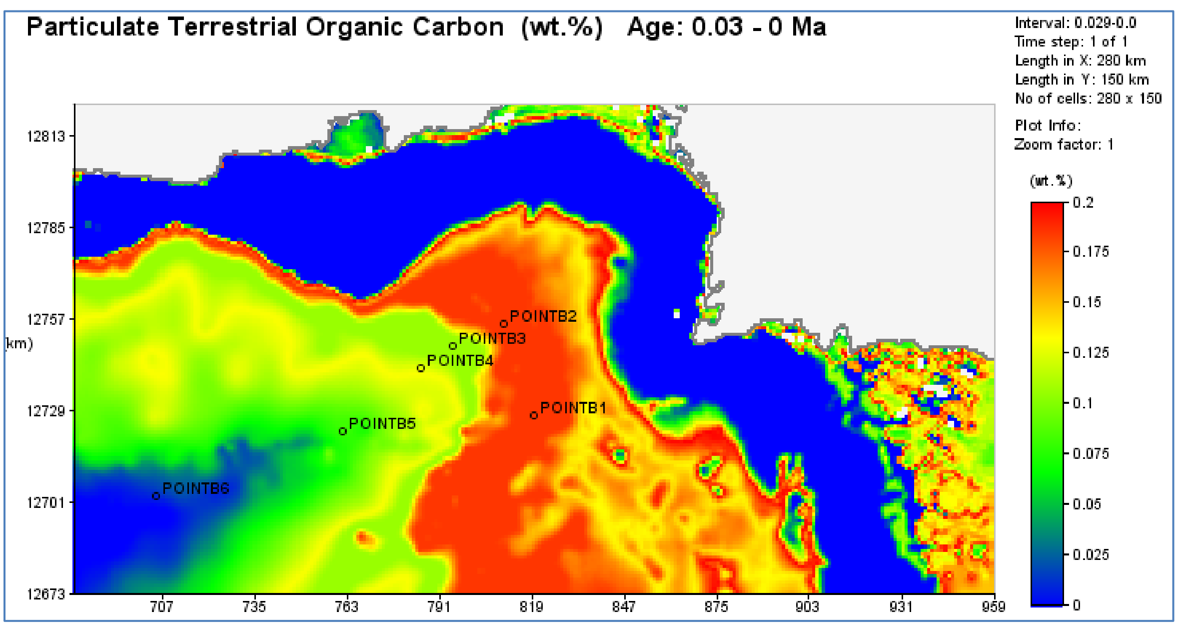


Figure 63 Spatial distribution terrigenous organic carbon area B

In area B the pTOC is higher in the eastern section of the continental shelf and reduces towards the shoreline and deeper marine environment. The pTOC levels are high within the OMZ in area B (Figure 63) compared to D above.

Table 4, 5 and 6 show the modeled result of TOC and HI from the various data locations along transects A, B and D. The modeled values were not always exactly the same as the measured values, but were within a close range when compared with measured values especially for TOC. The measured and modeled TOC values had similar trends along the three transects. TOC values are high within the OMZ and reduce away from it as shown in table 3. It was observed that points with high HI and TOC values correspond to sections were the OMZ intersects zones of high primary productivity.

Table 4 Measured and modeled results across transect B. Points marked with green color lie in the OMZ

	X	**Y**	**Depth (M)**	**Measure TOC (wt%)**	**Modeled TOC (wt%)**	**Measured HI(mg HC/g C)**	**Modeled HI (mg HC/g C)**
Transect B							
POINTB1	819422.10	12728631.00	126	0.87	0.77	324	131
POINTB2	810379.94	12756641.00	124	0.76	0.61	222	135
POINTB3	794812.30	12749693.00	525	1.97	3.29	–	225
POINTB4	785205.40	12743112.00	880	2.29	2.33	193	194
POINTB5	761805.10	12723896.00	1967	1.05	1.67	160	80
POINTB6	705345.40	12703930.00	2880	0.85	0.90	214	55

The modeled TOC values had a similar trend with measured values along transect A with an average difference between measured and modeled value of about 0.13 wt %.

Table 5 Measured and modeled TOC and HI values transect A. Points marked with green color lie within OMZ

	X	Y	Depth (M)	Measured TOC (wt%)	Modeled TOC (wt%)	Measured HI (mg HC/g C)	Modeled HI (mg HC/g C)
Transect A							
POINTA1	630642.10	12752086.00	700.00	0.82	1.24	207	-
POINTA2	630003.90	12754406.00	580.00	1	1.33	273	233
POINTA3	630642.10	12752086.00	704.00	1.38	1.39	243	232
POINTA4	631671.10	12750136.00	778.00	1.31	1.50	251	234
POINTA5	631625.50	12748562.00	807.00	1.95	1.82	159	223
POINTA6	626438.80	12731125.00	1290.00	2.71	1.90	278	194
POINTA7	632587.25	12741029.00	1017.00	1.48	1.93	250	278
POINTA8	628912.30	12698798.00	2730.00	0.61	1.20	170	103

The HI had a slightly different trend from measured HI values along transect A (table 4). Similar trends were observed between measured and modeled TOC values along transect D. Though the modeled values were lower than the measured values, the average difference between measured and modeled TOC value is 0.11 wt %

Table 6 Measured and modeled TOC and HI values across transect D. Points marked with green color lie in the OMZ

	X	Y	Depth (M)	Measured TOC (wt%)	Modeled TOC (wt%)	Measured HI (mg HC/g C)	Modeled HI (mg HC/g C)
Transect D							
POINTD1	879890.06	12579409.00	136.00	2.12	2.1	122	183
POINTD11	772734.70	12489073.00	2279.00	0.69	0.78	211	99
POINTD2	869327.50	12569394.00	250.00	2.15	2.28	248	236
POINTD3	895827.50	12541492.00	197.00	2.71	2.40	189	169
POINTD4	855651.30	12566744.00	430.00	3.08	3.36	178	276
POINTD5	858159.10	12561383.00	630.00	3.24	3.44	220	278
POINTD6	911522.25	12526367.00	232.00	2.93	2.73	193	228
POINTD7	856911.70	12558634.00	799.00	2.83	3.05	253	262
POINTD9	848713.44	12549863.00	1153.00	3.91	2.50	230	172

The graphical display of the modeled and calculated TOC and HI values, it clearly shows the variation between both sets of values. The TOC and HI as earlier stated can be seen to have very good correlation between measured and calculated values within areas A and D, but area B seems rather different.

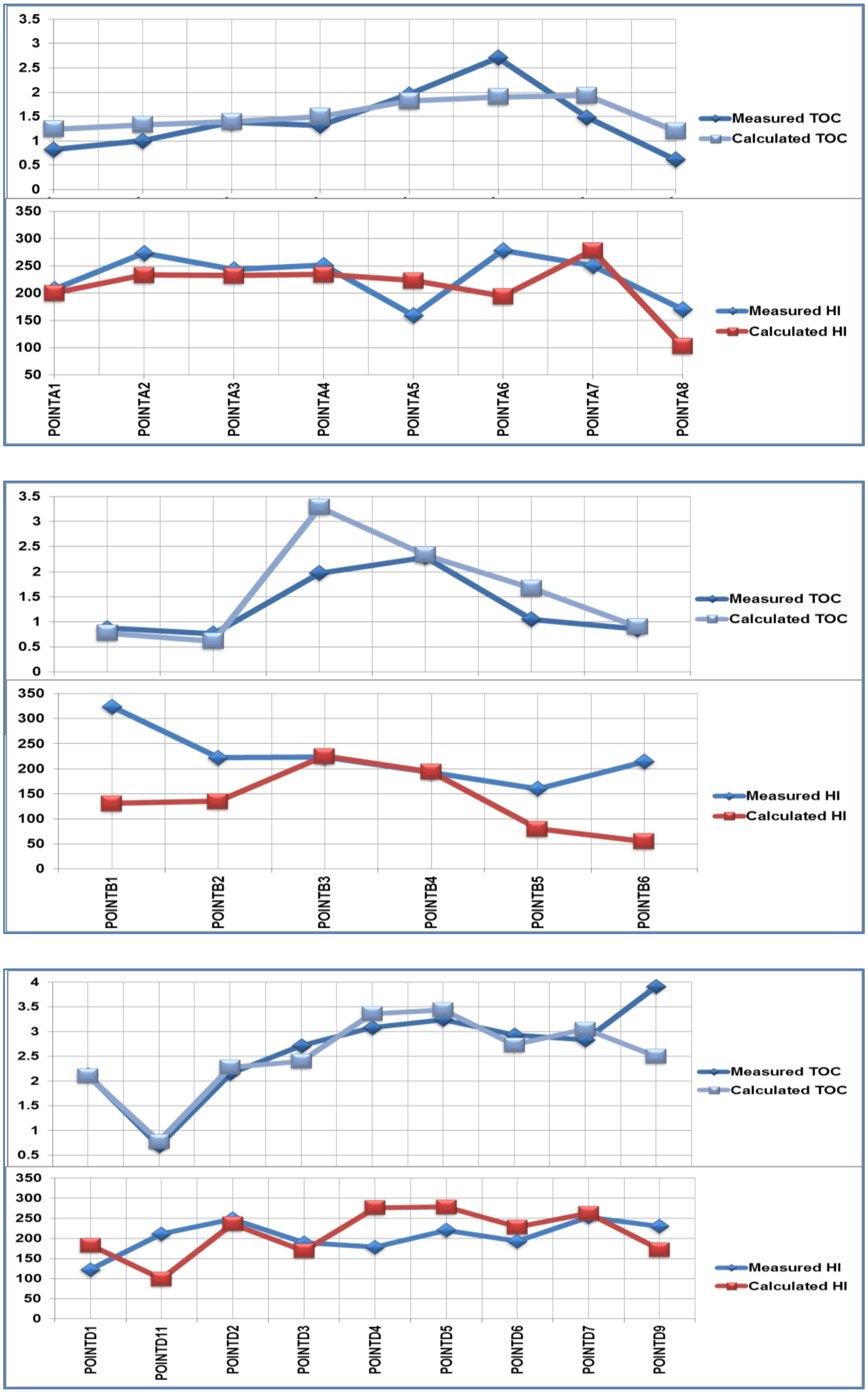


Figure 64 Graphical display of measured and calculated TOC and HI values area A, B and D

6.7 Source rock potential of organic carbon deposit within and outside the OMZ

The result of source rock potential for modeled organic carbon deposit across the three areas was based on source rock definition of Peters (1986) in Table 7. The source rock potential is classed based on TOC values and the potential amount of hydrocarbon thermally generated from the rock (S_2).

Table 7 Source rock potential definition based on Peters (1986)

Very Good	**TOC> 2.0**	**S2>10**	
Good	**TOC > 1**	**S2 >5**	
Fair	**TOC>0.5**	**S2>2.5**	
poor	**Rest**		

The evaluation of source rock properties based on the definition of Peters (1986) show that source rock property across the three area ranges from good to very good. Very good source rock properties are observed within the OMZ as well as outside the OMZ in area B. In other areas as shown in Figure 65, good source rock properties are observed outside the OMZ. In area A the OMZ had very poor source rock potential from the modeled results.

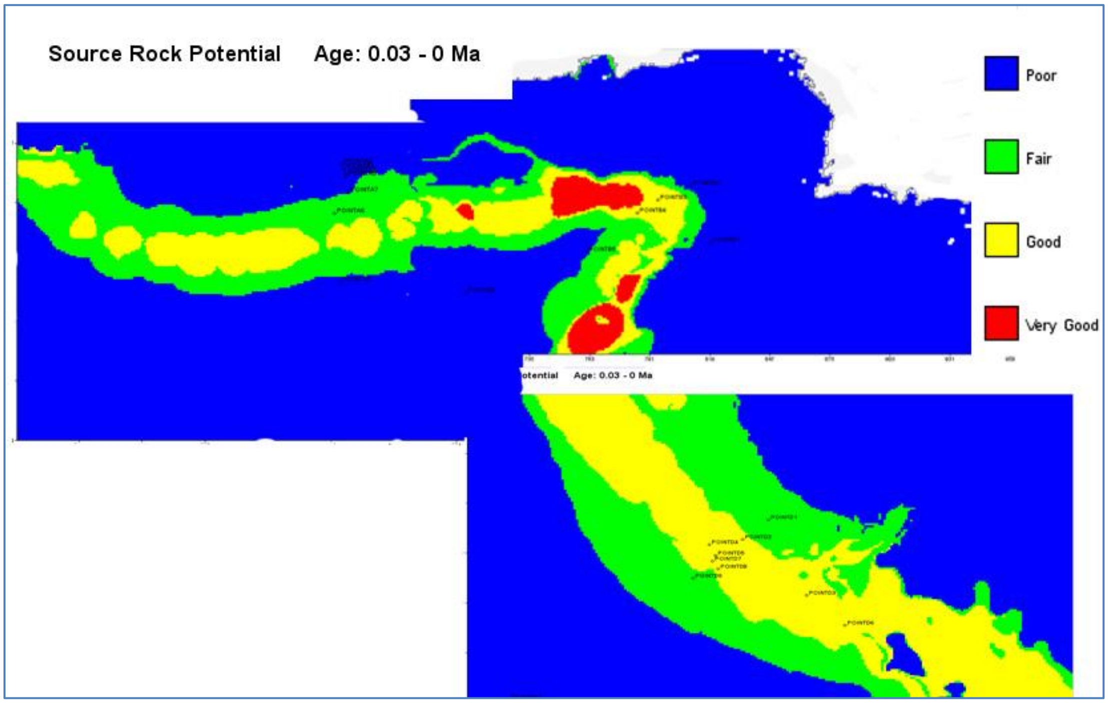


Figure 65 OF-Mod 3D source rock potential across the Pakistan margin.

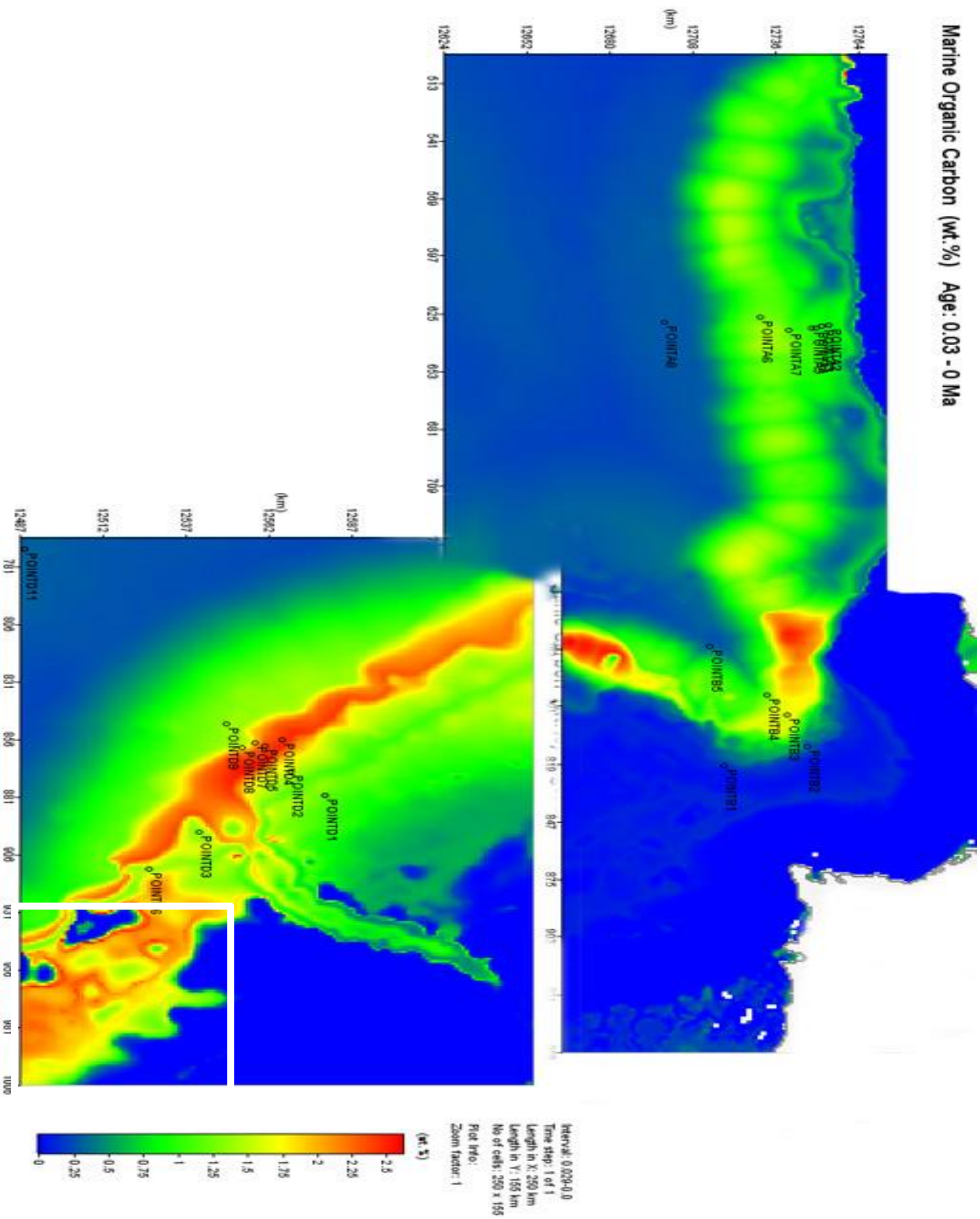


Figure 66 OF-Mod 3D model of spatial distribution of marine organic carbon (MOM) across the Pakistan margin (period 0.03 to 0 Ma).

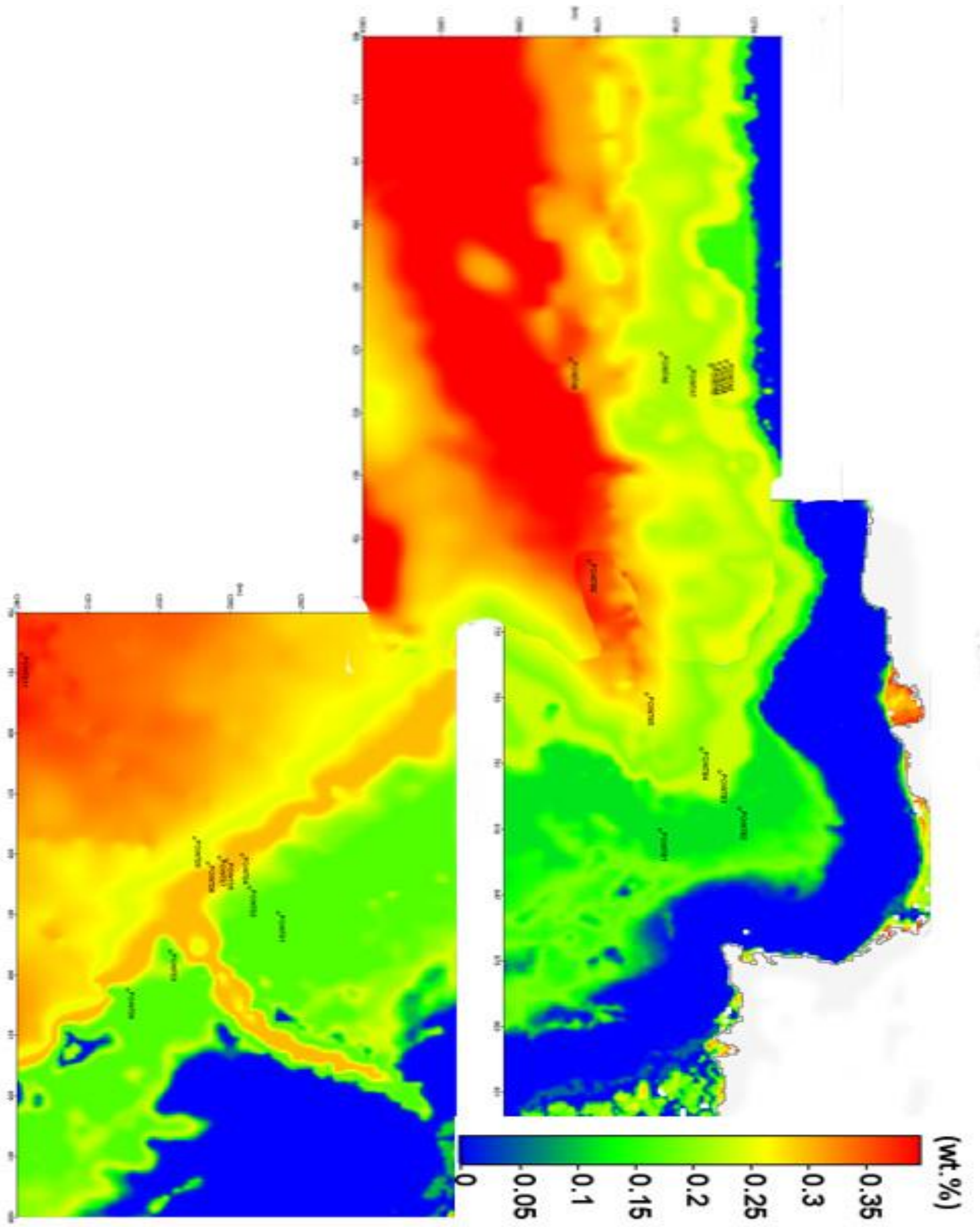


Figure 67 Mod 3D model of spatial distribution residual organic carbon (SOC) across the Pakistan margin.

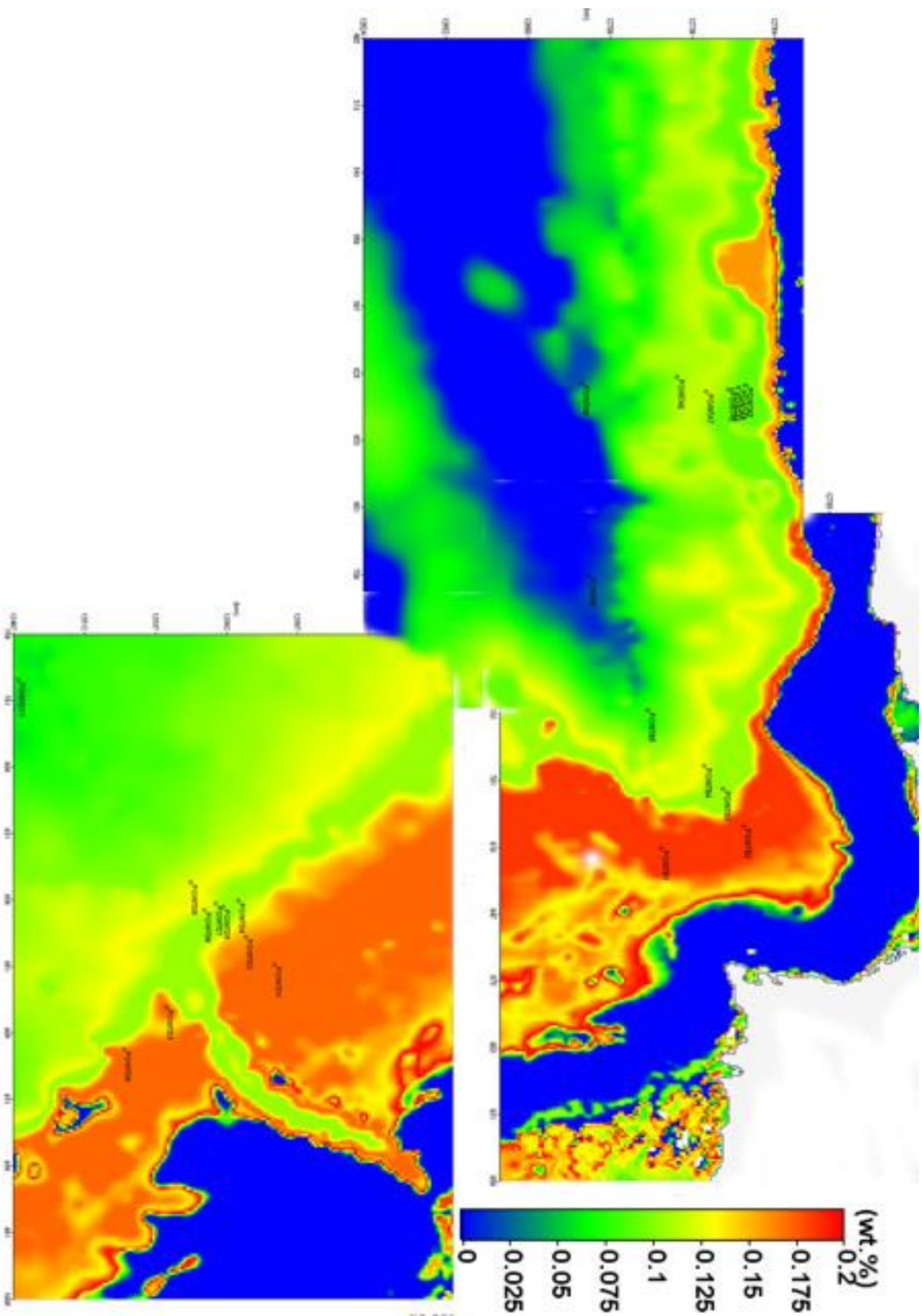


Figure 68 Mod 3D modeled spatial distribution of particulate terrestrial organic carbon (pTOC) across the Pakistan margin.

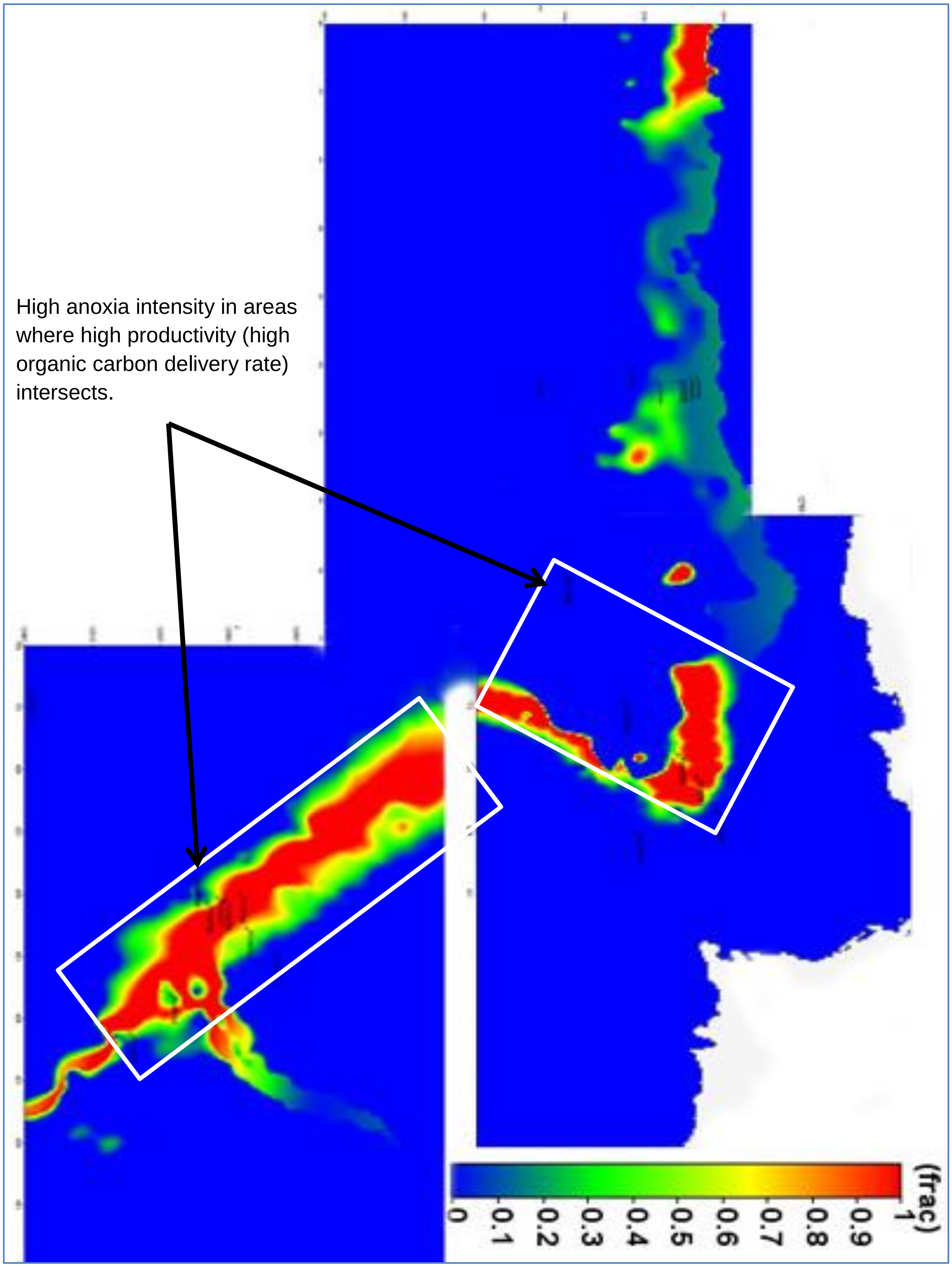


Figure 69 OF-Mod 3D modeled oxygen minimum zone (OMZ) and variation in OMZ intensity

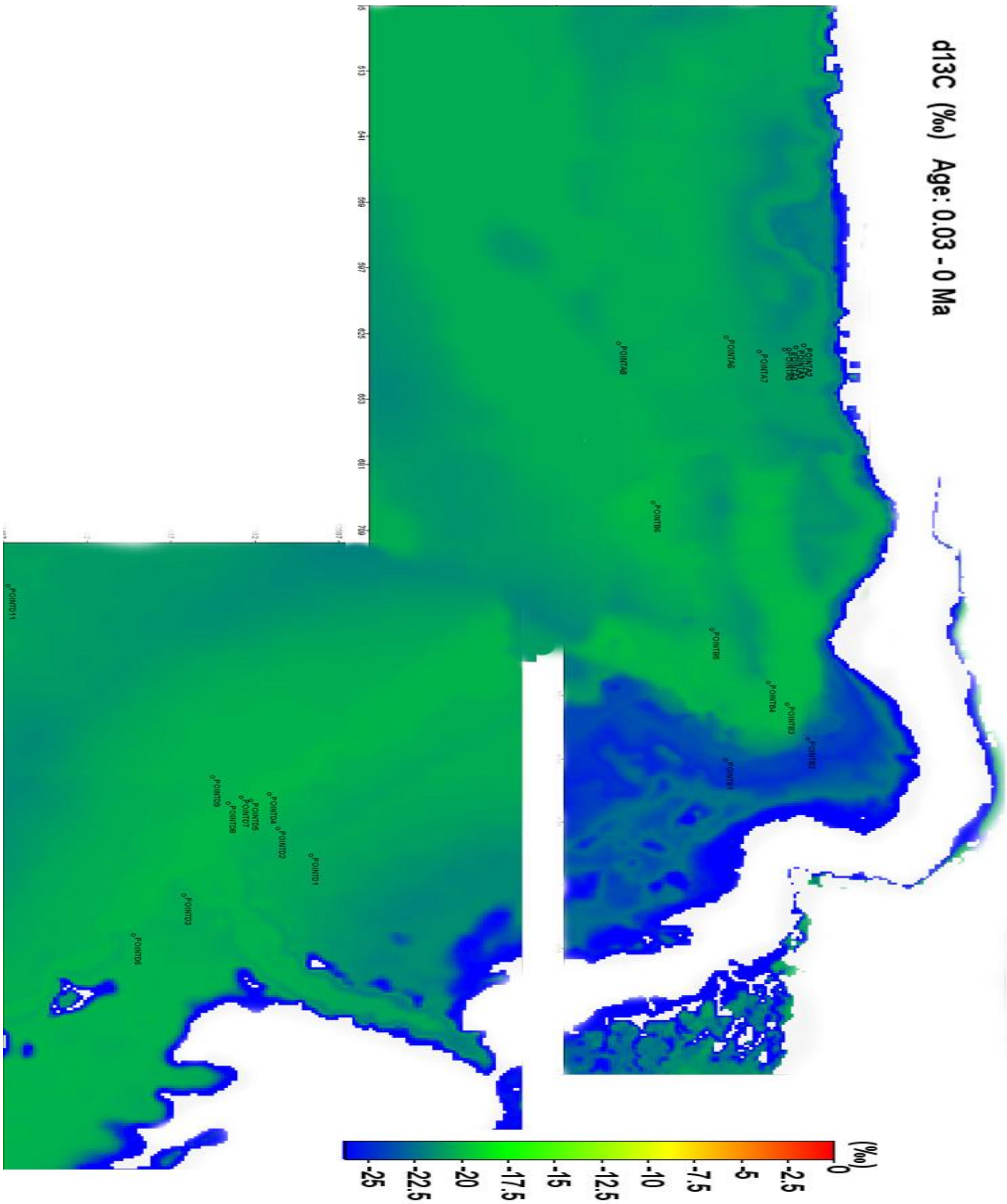


Figure 70 OF-Mod 3D carbon isotope ($\delta^{13}C$) distribution across the three areas.

7 Discussion

In this study, OF-Mod 3D has been used to model the distribution of organic carbon across the Pakistan margin. It is also to understand the influence of anoxia, sedimentation rate and primary productivity on the preservation and accumulation of organic carbon. The project seeks to understand which of these factors influences the preservation factor of primary produced organic materials in a marine environment.

The process of organic carbon distribution and accumulation is greatly influenced by some of the factors mentioned above in sedimentary environment. Identifying the dominant factor has been a source of debate over the years. The relationship between these factors has been puzzling to scientists, who have tried to find out which factor is key to organic matter preservation and accumulation. As suggested by some authors (Bralower and Thierstein, 1984, Meyers, 1997; Menzel et al., 2002) the organic carbon typically preserved in sediments represents a small fraction of the total organic carbon produced by primary producers. Some other authors are of the opinion that the level of dissolved oxygen in the environment (anoxia) determines to a great extent the amount of organic carbon finally preserved in sediment. Thus according to these authors the anoxia has a direct influence on the preservation factor which by definition is the absolute amount of primary produced organic carbon that is deposited is the sediment and preserved (Bralower and Thierstein, 1984). In the Pakistan margin, evidence of deposited and preserved organic carbon has been observed to occur within and outside the oxygen minimum zone (see Cowie et. al. 1999). I will discuss these factors as they relate to the distribution of organic carbon within the Pakistan margin and the role played by anoxia in this area.

7.1 Oxygen Minimum Zone (OMZ), sedimentation rate and preservation factor

The oxygen minimum zone within the Pakistan margin is characterized by low dissolved oxygen levels in the water column and laminated organic rich sediments are found where the OMZ impinges on the sea bed. The low oxygen levels have to some extent prevented redox reaction (oxidation) of deposited organic matter and also reduced the effect of bottom dwelling organisms (these animals most likely depend on oxygen for respiration) from boring and scavenging on deposited organic matter as food (Bralower and Thierstein 1984). Given the above conditions of low oxygen levels and limited activities of benthic fauna, the preservation and accumulation of organic carbon can be enhanced to a certain degree provided other factors such as primary productivity and sedimentation rate are adequate. During periods of high primary productivity (high organic carbon delivery rate) the amount of primary produced organic matter supplied to the sea bed is so much that it uses the available dissolved oxygen in the environment. The system becomes progressively anoxic and this enhances the preservation and accumulation of organic matter supplied to the system.

Figure 69 shows areas where the OMZ intersects with high productivity levels. It can be observed that anoxia level is relatively high while this cannot be said for areas with relatively low primary productivity in the same figure. Figure 66 shows high marine organic carbon content in area B within sections where high primary productivity levels was observed. In Figure 66 the amount of marine organic carbon is lower within the OMZ in area B compared to area D. The preserved marine friction was observed to be more in B (Figure 58) compared to D (Figure 56), thus the amount of deposited marine organic carbon is higher in D but preservation was more effective in B. Comparing the sedimentation rate between the two sections (OMZ in B and D), it is observed that the sedimentation rate in B (Figure 36) is higher than that observed in D (Figure 34) within the OMZ. The model clearly shows that given similar conditions within an oxygen deficient environment higher sedimentation rate would result in the dilution of deposited organic carbon.

In another scenario (Figure 66, area within the box outside the OMZ) the amount of marine organic carbon preserved is higher than values within the OMZ in D. This was due to high primary productivity level and high sedimentation rate within the area. This shows that a similar preservation effect can be observed in an anoxic environment as can occur in an oxic environment. More explanation is given below.

In area D (Figure 56) the preserved marine organic carbon values were observed to be relatively lower within the OMZ compared to sections of the continental shelf e.g. the south eastern section in Figure 56. It was also observed that levels of residual organic carbon were higher in the OMZ indicating an effect of degradation which was observed across other sections within the area. The sedimentation rate values within the OMZ and the south eastern section of the continental shelf outside the OMZ were compared. It is seen that sedimentation rate values was higher in the south eastern section of the shelf and also note that primary productivity levels were the same for both areas. This observation indicates that sedimentation rate had a positive influence on the amount of preserved marine organic carbon on the continental shelf especially the south eastern section. In area B preserved marine organic carbon was relatively higher within the OMZ because sedimentation rate within the OMZ was higher compared to OMZ in area D. Thus sedimentation rate plays an important role in the preservation of marine organic matter within OMZ and also in oxic conditions.

In area A within the OMZ, very low levels of preserved marine organic carbon were observed. This is attributed to the low primary productivity levels in sections of the sea bed impinged by the OMZ in area A. low productivity levels coupled with high sedimentation rate in this section will result in dilution of deposited marine organic matter. Following investigation most sections with relatively high preserved marine organic carbon values in the model had optimum sedimentation rate values especially outside the OMZ. It is observed that sedimentation rate and primary productivity within investigated sections were high. Thus high organic delivery rate coupled with rapid burial of deposited organic carbon enhances preservation within oxic environments and sedimentation rate also plays similar role in the OMZ. This is in agreement with Demaison and Moore (1980). Further observation also showed that in sections where the primary productivity was low and sedimentation rate was also low in the deep marine environment, TOC was relatively low which implies that deposited organic carbon was poorly preserved.

The interplay of these factors actually controls the accumulation and preservation of organic carbon and the amount of organic matter preserved is linked to the amount of organic matter supplied to the system and sedimentation rate. The organic carbon accumulation rate (which is a sub set of the sedimentation rate) can directly influence the preservation factor. In oxic environments, an adequate level of organic carbon supply and relatively high sedimentation rate will trigger the preservation of organic matter via rapid burial in oxic conditions. In anoxic conditions high organic delivery rate would increase the level of anoxia. This will in turn starve benthic organisms of oxygen needed for respiration and reduce oxidation of deposited organic matter.

Though preservation seems to be more effective in anoxic environments given that the anoxia reduces the activities of bottom dwelling organisms, sedimentation rates need to be adequate for effective preservation. Rapid burial of deposited organic carbon (high sedimentation rate) will have a similar preservation effect on organic matter in oxic conditions. So the absolute amount of deposited and preserved primary produced organic carbon to some degree depends on the rate of sediment supply in both anoxic and oxic conditions. This is shown in the model where both oxic and anoxic systems will benefit for adequate sedimentation in other to effectively preserve marine organic carbon.

The residual organic carbon levels in the OMZ (Figure 67) in area B are relatively lower compared to D in the same figure. The high level of residual organic carbon within the OMZ in D is evident of higher levels of degradation compared to B. Higher sedimentation rate in B enhanced the preservation and reduced degradation of organic matter.

The level of terrigenous derived organic carbon was very low within the areas especially in the southern areas. The south had a relatively low amount of terrigenous organic carbon supplied down the Indus canyon. The carbon isotope values also support this argument with measured values within the range of -19 to -22 in the south and lower values in the north. The spatial distribution of carbon isotope values supports a marine origin for deposited organic matter within the area.

Hydrogen index is a good indicator of source rock organic carbon quality (Dean et al 1986). In this project modeled hydrogen index had an average maximum value within the oxygen minimum zone. So the OMZ should have better preservation conditions but this is not the case. Good preservation conditions were observed outside the OMZ in sections where sedimentation rate and primary productivity levels played a major role in preservation. Though outside the OMZ, relatively high HI values were observed at point 11 (see Table 6 and Figure 64). A possible explanation could be the rapid burial of organic carbon by sediment flushed down the Indus canyon.

Source rock potential analysis indicates that good potential source rocks are expected not only within the OMZ but also outside the OMZ. Good preservation conditions are seen to occur in these areas (outside the OMZ) due to the influence of sedimentation rate and primary productivity levels. In areas B within the OMZ very good SRP are expected because of the high sedimentation rate which influences preservation but in D SRP expected within the OMZ is lower because of low levels of sedimentation within this section.

8 Conclusions

The study has shown that the preservation of primary produced organic carbon is influenced by several factors and using OF-Mod 3D the role of these factors have been studied within close proximity for the Pakistan margin and the following inference can be drawn.

The spatial distribution of organic carbon within the Pakistan margin area is mainly influenced by the oxygen minimum zone on the continental slope and by sedimentation rate on the continental shelf. Sedimentation rate from observation has a positive influence on preserved marine organic carbon within the oxygen minimum zone and sections of the continental shelf as well. The model clearly shows a direct influence of sedimentation rate on the preservation factor of primary produced organic matter. Areas of high primary productivity and low sedimentation rate showed low preservation factor and high amount of residual organic carbon. Areas of equal levels of primary productivity and optimum sedimentation rate displayed better preservation and low levels of residual organic carbon.

The area is dominated by marine primary produced organic carbon and degradation over time had converted most of the marine organic carbon to residual or degraded organic carbon. The measured low HI and carbon isotopes ($\delta^{13}C$) values support this augment. Thus the organic carbon deposit within the Pakistan margin is mainly degraded marine organic carbon. The amount of terrigenous organic carbon is relatively low across the Pakistan margin.

The model clearly shows that source rock potential within the areas is positively influenced by optimum sedimentation rate values given adequate productivity and/or level of anoxia. Within the area it is observed that good SRP can be found within the OMZ (anoxic conditions) and also in areas outside the OMZ (oxic conditions).

Preservation factor or the ratio of the absolute amount of primary produced organic carbon deposited and preserved in sediments in the areas is not exclusively dependent on the presence of an oxygen minimum zone but also depends on interplay of sedimentation rate and the organic carbon supplied.

9 Recommendations

Some recommendations on how OF-Mod can be applied and also improved upon include:

- The formation of biogenically derived sediments, for example carbonate can be added to the OF-Mod modeling software to enable the modeling or organic carbon in carbonate environments.
- OF-Mod organic facies modeling software is an invaluable tool for modeling the presence and distribution of organic carbon with regards to quality and quantity in deposited sediments across an area. The process can be applied in modeling TOC and HI distribution across source rocks, in frontier areas to enhance the success and reduces uncertainties associated with source rock quality in petroleum exploration.

9.1 Limitations

Several limitations of the modeling software were observed while carrying out the project which could affect the model results. These limitations can be categorized into two types:

- Event related limitations: This is beyond the control of the modeler and related to events in the geologic past. Several assumptions are made in OF-Mod modeling process such as the relation between, sand fraction, energy and environment of deposition. This is usually true but geologic events such as tsunami and storm deposit (see Alastair et al. 2007) could change this trend and could result in sandy coarse grained sediment deposited in the deep marine environment. Reworking of sediments by localized turbidity currents could also affect the usual trend and hence the model. The inability of the modeler to account for this could give room for errors.
- Limitation based on assumptions: For example in OF-Mod, the sedimentation rate is assumed to be linear over time, in order to make the modeling as simple as possible but realistically sedimentation rate is rarely linear. Storm deposits, debris flow and other instantaneous depositional events are seen in outcrop studies proves otherwise.

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Appendix

von Rad, U et al. (2003):
(Table 1) Carbon14 ages with calibrations to GISP-controlled varve years anchored at the H2/LGM boundary at 23.450 cal kyr BP in sediment core SO130-261KL. doi:10.1594/PANGAEA.127408.
In Supplement to: von Rad, Ulrich; Sarnthein, Michael; Grootes, Pieter Meiert; Doose-Rolinski, Heidi; Erbacher, Jochen (2003): 14C ages of a varved last glacial maximum section off Pakistan. Radiocarbon, 45(3), 467-477,

https://www.uair.arizona.edu/objectviewer?o=http://radiocarbon.library.arizona.edu/Volume45/Number3/azu_radiocarbon_v45_n3_467_477_v.pdf
Coverage:
Latitude: 24.777000
Longitude: 65.819800
Date/Time Start: 1998-04-17T05:07:00 * Date/Time End: 1998-04-17T05:07:00
Minimum DEPTH, sediment: 5.4 m * Maximum DEPTH, sediment: 14.6 m

SO130-261KL * * Latitude: 24.777000 * Longitude: 65.819800 * Date/Time: 1998-04-17T05:07:00 * Elevation: -873.0 m * Recovery: 17.86 m * Campaign: SO130 (MAKRAN 2) * * Basis: Sonne * * Device: Piston corer (BGR type) * * Comment: =SO90-75KL; critical stratigrapic/Paleoclimatological core

Comment:
At 7.67 m core depth we supplemented 1000 varves, assumed to be lost by turbidite erosion. * = four dates in core SO 90-75KL with equivalent core 261KL depths; the actual 75KL core depths are for KIA 3807: 8.97-8.99 m, for KIA 3808: 9.97-9.99 m, for KIA3809: 11.38-11.40 m, and for KIA 3810: 12.48-12.50 m
In Supplement to: von Rad, Ulrich; Sarnthein, Michael; Grootes, Pieter Meiert; Doose-Rolinski, Heidi; Erbacher, Jochen (2003): 14C ages of a varved last glacial maximum section off Pakistan. Radiocarbon, 45(3), 467-477,

https://www.uair.arizona.edu/objectviewer?o=http://radiocarbon.library.arizona.edu/Volume45/Number3/azu_radiocarbon_v45_n3_467_477_v.pdf

Coverage
Latitude: 24.777000 Longitude: 65.819800
Minimum Age: 16.853 ka BP
Maximum Age: 29.498 ka Bp

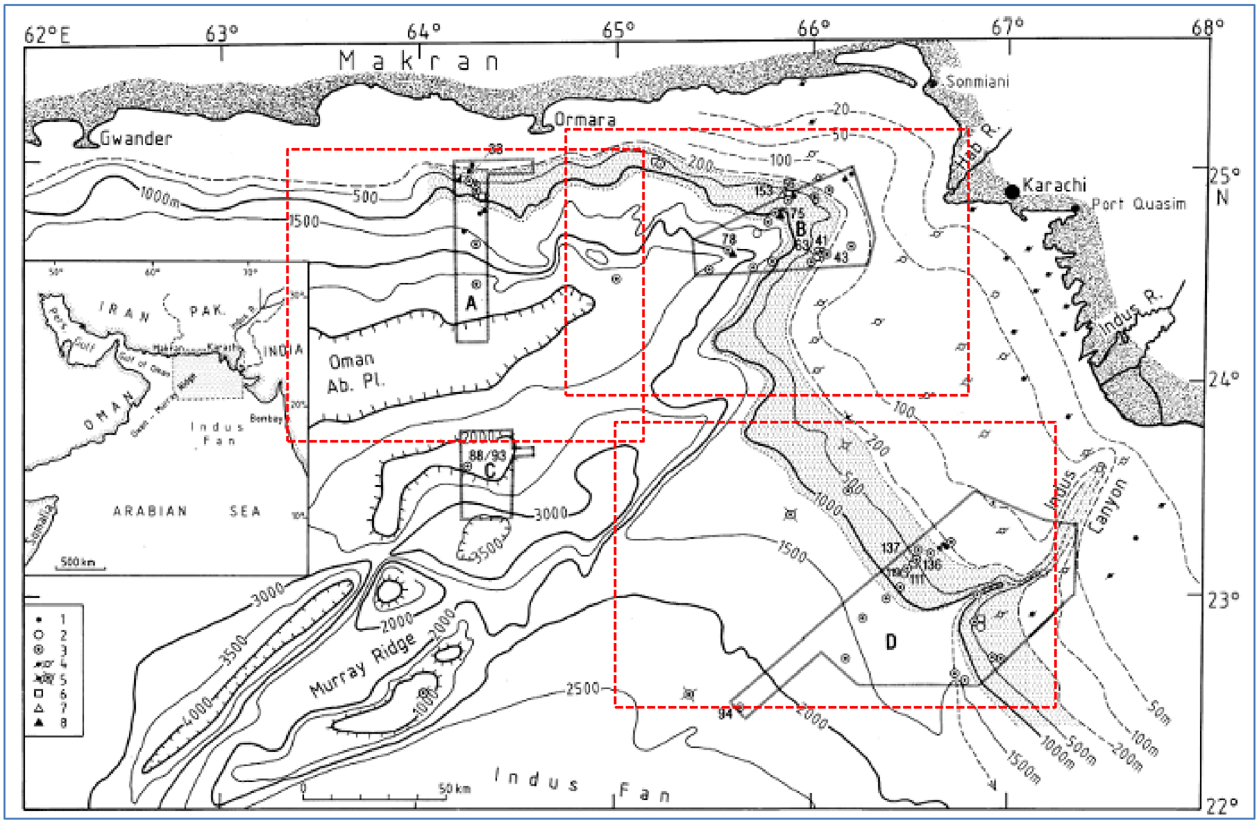
Appendix 1 information on core data acquired from the area (www.pagea.com)

Station locations and analytical results for surficial sediments from the Pakistan margin

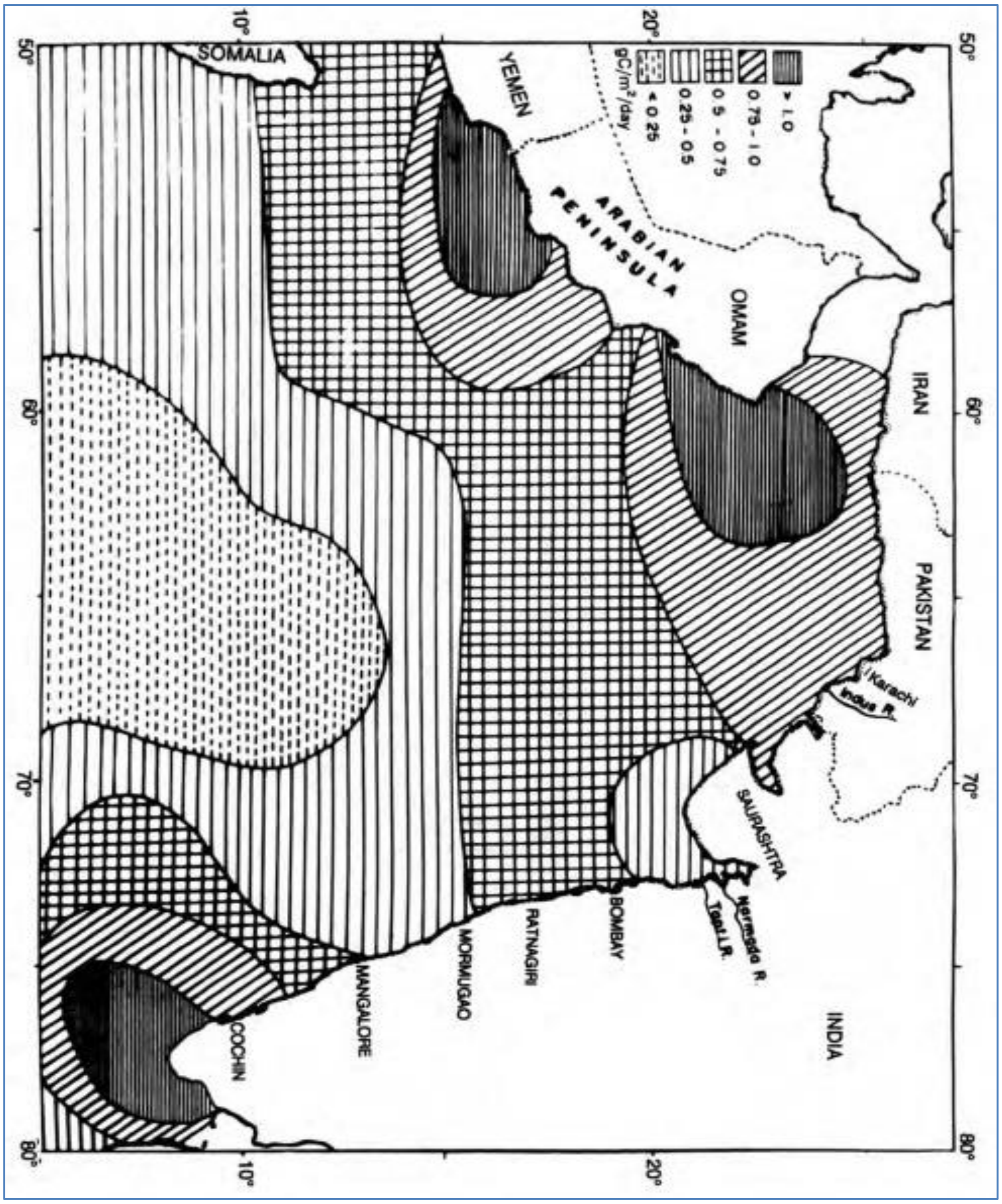
Abbreviations: O_2, bottom water oxygen concentration (µM), average of values observed in proximal hydrocasts (O_2 probe or Winkler titration); C_{org}, organic carbon (wt.%); N_{total}, total nitrogen (wt.%); C/N, organic carbon to total nitrogen ratios (g/g); HI, hydrogen index (mg hydrocarbons/g C_{org}); Σ8, absolute yield of total lignin phenols (sum of 8 vanillyl, syringyl and cinnamyl, mg/10 g dwt); Λ, C_{org}-normalized yield of total lignin phenols (mg/100 mg C_{org}); $\delta^{13}C_{org}$, stable C isotope composition in standard δ notation (‰).

Station	Interval (cm)	Depth (m)	Area	Long. (°N)	Lat. (°E)	O_2 (µM)	C_{org} (%)	N_{total} (%)	C/N (g/g)	$CaCO_3$ (%)	HI	Σ8	Λ	$\delta^{13}C_{org}$ (‰)	I/C_{org}	Mn/Al (×10^{-4})
18 KG	0–2	228	A	24 52.69	64 17.60	23	0.82	0.15	5.41	13.38	207	0.14	0.17	−19.70	15	94
34 KG	0–2	667	A	24 53.95	64 17.23	14	1.00	0.18	5.46	10.73	273	0.12	0.12	−20.59	40	71
23 KG	0–2	690	A	24 52.69	64 17.60	14	1.38	0.23	5.88	11.50	243	0.14	0.10	−20.51	44	73
12 KG	0–2	789	A	24 51.63	64 18.20	12	1.31	0.24	5.44	12.73	251	0.20	0.15	−20.74	49	74
20 KG	0–2	993	A	24 50.78	64 18.16	17	1.95	0.29	6.63	12.02	159	0.20	0.10	−20.51	49	69
28 KG	0–2	1017	A	24 41.36	64 14.99	19	2.71	0.37	7.26	16.48	278	0.20	0.07	−20.81	72	69
24 KG	0–2	1204	A	24 46.69	64 18.69	33	1.48	0.22	6.61	12.63	250	0.14	0.09	−20.35	200	81
1 KG	0–2	2678	A	24 23.83	64 16.28	105	0.61	0.12	5.08	11.49	170	0.11	0.18	−20.15	395	259
65 KG	0–2	120	B	24 38.30	66 09.31	19	0.87	0.10	8.91	65.00	324	0.08	0.09	−19.53	123	110
69 KG	0–2	134	B	24 53.57	66 04.33	15	0.76	0.11	6.59	50.03	222	0.15	0.20	−19.66	117	210
39 KG	0–2	704	B	24 50.00	65 55.01	10	1.97	0.29	6.80	13.12	–	0.24	0.12	−20.63	–	71
142 KG	0–2	865	B	24 46.55	65 49.23	13	2.29	0.34	6.78	12.98	193	0.19	0.08	−20.72	–	71
79 KG	0–2	1970	B	24 36.40	65 35.14	72	1.05	0.17	6.04	11.35	160	0.16	0.16	−19.89	403	874
85 KG	0–2	2881	B	24 26.11	65 01.53	106	0.85	0.17	5.09	10.37	214	0.12	0.14	−20.31	–	351
87 KG	0–2	1782	C	23 35.33	64 13.02	83	0.88	0.15	5.77	20.02	246	0.12	0.13	−19.55	–	333
124 KG	0–2	136	D	23 16.76	66 42.77	17	1.57	0.20	7.85	20.04	122	0.22	0.14	−19.93	280	93
113 KG	0–2	287	D	23 11.49	66 36.44	14	2.15	0.28	7.81	12.89	248	0.25	0.12	−20.36	–	68
180 KG	0–2	398	D	22 56.02	66 51.51	11	2.71	0.35	7.84	15.28	189	0.21	0.08	−20.53	93	76
96 KG	0–2	483	D	23 10.24	66 28.40	11	3.08	0.39	7.86	17.71	178	–	–	−20.24	–	77
112 KG	0–2	572	D	23 07.31	66 29.79	11	3.24	0.40	8.09	17.13	220	0.20	0.06	−20.60	–	71
164 KG	0–2	643	D	22 47.61	67 00.43	11	2.93	0.37	7.87	8.12	193	0.20	0.07	−20.52	116	81
110 KG	0–2	776	D	23 05.84	66 29.02	13	2.83	0.40	7.11	10.29	253	0.20	0.07	−20.73	130	88
107 KG	0–2	992	D	23 03.64	66 30.32	17	3.27	0.42	7.83	18.48	212	0.19	0.06	−20.65	111	78
103 KG	0–2	1206	D	23 01.20	66 24.11	34	3.91	0.48	8.07	23.34	230	0.23	0.06	−20.23	330	213
99 KG	0–2	1506	D	22 55.87	66 20.89	42	1.44	0.22	6.57	26.74	211	–	–	−19.81	538	311
95 KG	0–1.5	2111	D	22 29.16	65 39.04	91	0.69	0.12	5.73	32.58	351	0.17	0.24	−19.24	–	143

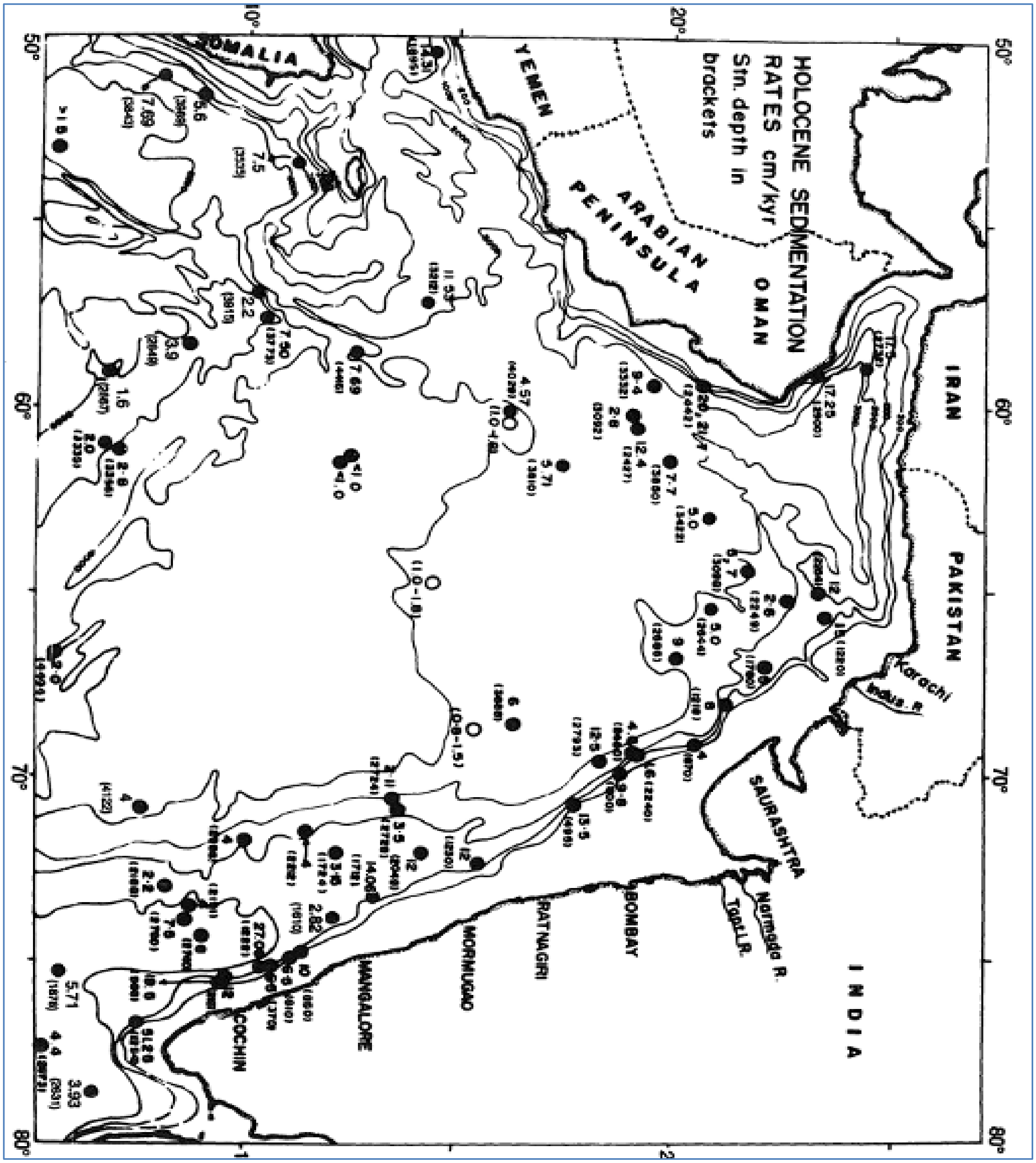
Appendix 2. Data source for surficial sediment, TOC, HI, carbon isotope. (Cowie et al. 1999)



Appendix 3 Map of area (Cowie et al 1999)



Appendix 4 average annual primary productivity in the Arabian Sea (Paropkari et al 1992)



Appendix 5 Holocene sedimentation rates at various locations in the Arabian Sea. Numbers in brackets denote water depth in meters (Paropkari et al 1992).