

Distribution of organic matter and carbonate minerals in surface sediments of Tafiri Bay and the Luiche Platform, Lake Tanganyika: Implications for paleoclimate reconstruction

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Introduction

The relative proportions of organic matter and carbonate minerals in lacustrine sediments reflect processes of carbon cycling, primary productivity, oxycline position, and wave energy, all of which can be related to water depth and climate. In order to elucidate these relationships and thus provide information relevant to paleoclimate reconstruction, this study investigates the proportions of organic matter, carbonate minerals, and shell material in the sediments of Tafiri Bay and the Luiche Platform in Lake Tanganyika with respect to water depth and bathymetry. The two sites exemplify contrasting depositional environments; Tafiri Bay is relatively protected and has no major sediment inputs, whereas the Luiche Platform is exposed to heavier winds and surface waves and drains the Luiche River, which delivers coarse sediments rich in terrigenous organic matter (G. Smith this volume; Morgan 2002). Therefore, I expect to see better correlations of organic matter and carbonates to depth in Tafiri Bay than in the Luiche Platform, and more variable data in the Luiche Platform due to riverine inputs of organic matter and clastics.

Lacustrine sedimentary organic matter is composed of decaying algal remains, zooplankton excretions, and terrigenous material. Because autochthonous primary production tends to contribute the largest portion, the distribution of organic matter in lakes is often controlled by phytoplankton productivity and biomass (Wetzel 1975). However, organic matter particles are soluble in oxic water, so much organic matter is oxidized and degraded in the water column, and if the sediment-water interface is overlain by oxic waters, degradation will continue during and after burial. The amount of organic matter in sediments is therefore largely dependent on water depth (Cohen 2003). Due to these controls I expect that less organic matter will be preserved in shallow waters above the oxycline, below which sedimentary organic matter should increase nonlinearly with depth.

The carbonate fraction of sediments primarily consists of shell material, or biogenic carbonate, and inorganic carbonate precipitated out of the water column as CO_2 is removed by photosynthetic activity (Wetzel 1975). This has led to the use of carbonate abundance to infer primary productivity (cf. Glenn and Kelts 1991). In Lake Tanganyika, the dominant authigenic carbonate mineral is aragonite (Tiercelin and Mondegueur 1991). Biogenic carbonate is formed in shallow, oxygenated waters, whereas aragonite is precipitated both in shallow areas and the photic portion of the pelagic zone. Due to its small grain size, aragonite is heavily affected by winnowing and is not buried in shallow waters with higher wave energy, while biogenic carbonates are larger and are not transported to the same extent (Talbot and Allen 1996; Johnson 1980). Thus, I anticipate finding that shell-derived carbonate is abundant in shallow, nearshore areas and decreases with depth until becoming nonexistent below the oxycline, while the aragonite component of sediments should increase with depth.

Methods

Samples and data were gathered from the *R/V Echo*. Two transects, EW3 and EW4, were sampled in Tafiri Bay on July 17 and 18, and two, North and South, in the Luiche Platform on July 25, 27, and 29. A Ponar grab sampler was used to collect surface sediments, which were placed in Whirl-paks, while water depth was measured with an Echosounder and location determined with a GPS device for each grab sample site.

Loss on ignition was used to determine the organic matter and carbonate mineral content of each grab sample (Dean 1974). Ceramic crucibles to be used were precombusted at 900°C for one hour to clean them, etched with labels, and stored in an airtight bag. After fieldwork, each Whirl-pak was shaken to homogenize the sediment inside, and approximately 2 cm^3 of sediment was measured into a pre-weighed crucible and the combined weight was taken. The sample crucibles were heated for 24 hours in a drying oven at 110°C to remove water, and were then weighed and combusted in a muffle furnace for one hour at 550°C to remove organic matter. Upon cooling, they were reweighed and combusted again for one hour to remove inorganic carbonate (ICO_2) at 900°C , after which they were weighed a final time. Percent water content, organic matter, and inorganic carbonate (ICO_2) were calculated from the weight loss after each combustion, and the following equation was applied to calculate the percent CaCO_3 lost:

$$\% \text{CaCO}_3 = (\% \text{ICO}_2) \cdot 2.27$$

Smear slides were also made for all samples. A small amount of sediment from each Whirl-pak was placed on a clean slide with a metal spatula and spread across the slide with three drops of 95% ethanol using a toothpick. The slides were dried on a hot plate set to low, and three to five drops of Norland mounting medium and a cover slip were placed atop the smeared sediment. They were then left in the sun for five minutes to set the mounting medium. The slides were viewed through a polarizing microscope at 10x or 20x magnification to determine the abundances of aragonite crystals and shell fragments. Abundance estimates were made by establishing the absolute percentage of a field of view covered by the variable to be measured, averaged between five fields of view.

These abundance estimates showed whether the amounts of inorganic carbon measured through combustion were derived from inorganically precipitated aragonite or biogenic carbonate in the form of shell fragments. Additionally, the grain size of aragonite rosettes and single aragonite crystals was estimated in five slides from various depths and averaged to achieve an estimate of 2.86 μm as mean aragonite grain size.

Sample TB5 on Tafiri Bay transect EW3 was a shell lag at the base of a cliff (G. Smith, McGlue, Mischler and Hartwell this volume), and showed an anomalously high aragonite percentage. Although the grain size of TB5 was markedly finer and therefore probably did contain a large amount of aragonite (Hartwell and Daudi this volume), it is likely that smear slide analysis misrepresented the proportion of aragonite to shell material given the impossibility of including an entire shell. Thus, I assumed that the large carbonate percentage of TB5 was actually shell-derived rather than from aragonite, and I did not use TB5 for multivariate statistical analysis.

Results

Transects EW3 and EW4 from Tafiri Bay were approximately 300 m apart and their data showed close agreement; they were therefore analyzed together for statistical significance. The North and South Luiche Platform transects, however, differed significantly in both spatial distribution and depositional environment, and they were treated separately.

Data collected from Tafiri Bay showed the most straightforward relationships. In area plots of the percent composition of sediments versus depth for each transect, EW3 shows the only irregular value, corresponding to sample TB5 (a shell hash at the base of a fault scarp) where aragonite increased at the expense of residue (the primarily siliciclastic material remaining after combustions) (Fig. 1). Depth correlated well to percent organic matter with $r^2 = 0.75$, to percent aragonite with $r^2=0.79$, and to percent shell-derived carbonate with $r^2=0.74$ (Figs. 2-4). Although these variables demonstrated a good relationship to depth, it is visually apparent that these relationships are not always linear. For instance, organic matter abundance would fit a fourth-order polynomial curve better than a line.

The North Luiche data exhibited less distinct trends, although the Luiche transects both included fewer data points than Tafiri Bay. A large peak in siliciclastic residue occurs at 51.4 m replacing aragonite (Fig. 5); this corresponds to the top of a slope and a coarsening of sediment (G. Smith, Hartwell and Daudi this volume). Organic matter correlated best to depth (albeit nonlinearly), with $r^2=0.79$, while percent aragonite correlated with $r^2=0.66$ and percent shell material had a poor correlation (Figs. 6-8).

The South Luiche transect showed the least clear relationships. A plot of percent sediment composition versus depth again showed insoluble residue anomalously replacing aragonite between approximately 100 and 200 m depth (Fig. 9); there is a major channel at 180 m, and sediment grain size coarsens between 100 and 130 m depth (G. Smith, Hartwell and Daudi this volume). Percent organic matter correlated to depth with $r^2=0.79$ (Fig. 10), while percent aragonite and shell material displayed poor correlation.

Discussion

Of all variables assessed, percent organic matter proved the best predictor of depth, and therefore the most robust paleoclimate indicator. Although variables in Tafiri Bay exhibited the best relationships to depth overall, organic matter also correlated to depth in the North and South Luiche transects. Indeed, organic matter abundance could be used to differentiate between these depositional environments: the overall percentages of organic matter in the Luiche Platform were higher than in Tafiri Bay, probably because of riverine inputs of terrestrial organic matter (Figs. 2, 6, 10).

Thus, the hypothesis that organic matter should be sparse above the oxycline and then increase below it is well supported by this study. In fact, organic matter showed a nearly inverse relationship to dissolved oxygen concentration by depth (Fig. 11), which should hold year-round given that oxycline depth in northern Lake Tanganyika is fairly constant (Coulter and Spiegel 1991). It seems likely that the burial and preservation of organic matter in sediments depends most on oxycline depth, and therefore organic matter could exhibit a good correlation to depth regardless of other variables such as depositional environment.

The carbonate portion of sediments generally showed a more ambiguous correlation to depth, although both percent aragonite and shell material correlated well to depth in Tafari Bay. The only exception was sample TB5, where shells and fine sediments accumulated at the base of a cliff, demonstrating the ability of bathymetric features to alter the relationship between sedimentary carbonate and depth.

On the North Luiche transect, then, percent aragonite and shell material both had a weak correlation to depth, and showed poor correlation in South Luiche. It makes sense, however, that the relationships of biogenic and inorganic carbonate to depth would be more ambiguous than in Tafari Bay, because the Luiche Platform is a more complex depositional environment with a major river delta. Shell material was practically a binary variable in these transects; it was generally either present at around 20 % in shallow waters, or entirely absent, and therefore fit a linear regression poorly. Aragonite also fit poorly to a linear regression in the Luiche Platform, in part because of significant outlier points along both transects, where sediment became coarser and depleted in aragonite (Figs. 5, 9). It is probable that in these areas the transects intersect delta levees which transport coarse material and winnow aragonite (Morgan 2002).

Thus, the results of this study support the hypothesis that shell material would be abundant near shore and decrease until vanishing at the oxycline. In Tafari Bay, shell material decreased and disappeared around the oxycline depth of 60 to 70 m (Fig. 1); in the Luiche transects, however, shell material mostly disappeared before the oxycline, at 40 to 50 m depth (Figs. 5, 9), perhaps because of complicating factors to shell growth. Similarly, aragonite increased with depth as initially predicted, with the exception of the coarse outlier grab samples mentioned above where it temporarily decreased.

To estimate the utility of organic matter and inorganic and biogenic carbonate as paleoclimate indicators, multivariate nested regression was used to model the response of depth to these variables. In Tafari Bay, organic matter and shell material responded to depth with $r^2=0.901$ and aragonite and shell material with $r^2=0.896$ (Figs. 12-13). In North Luiche, organic matter and shell material responded to depth with $r^2=0.905$ (Fig. 14), but poorly to other variables, and in South Luiche, all variables responded poorly to depth.

Zhang (this volume) applied a calculation from Johnson (1980) for sediment transport based on wave energy and grain size to predict the abundance of aragonite versus depth, using the mean aragonite grain size measured from smear slides; the calculation predicted aragonite to first appear at 16 m water depth. In Tafari Bay, aragonite appeared sporadically at 10 m and then 19.4 m, but did not become a major contributor to sediments until 46.2 m; in the North Luiche Platform, aragonite first appeared at 29.2 m, and in the South Luiche, at 41.4 m. Thus, with the exception of one sample, aragonite did not exist above 16 m, but appeared significantly below that point on all transects, between 30-40 m water depth, indicating some applicability in Tafari Bay for models from Johnson's 1980 work.

Therefore, sedimentary organic matter and carbonate minerals are useful as paleoclimate indicators to reconstruct water depth in different depositional environments, although the carbonate portion should be analyzed with caution given the limited depth range of shell material and the sensitivity of aragonite to wave energy and bathymetric features as well as depth. Organic matter in particular shows a good correlation to depth that is inversely related to dissolved oxygen content in the overlying water.

Future Work

One of the major difficulties I encountered in this study came from the nonlinear relationship of variables to depth. More powerful results could be obtained by addressing and modeling this nonlinearity. Further, either such

nonlinear models or the regressions generated in this report could be applied to paleoclimate reconstruction in Lake Tanganyika sediment cores, particularly from Tafiri Bay or the Luiche Platform.

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Tafiri Bay

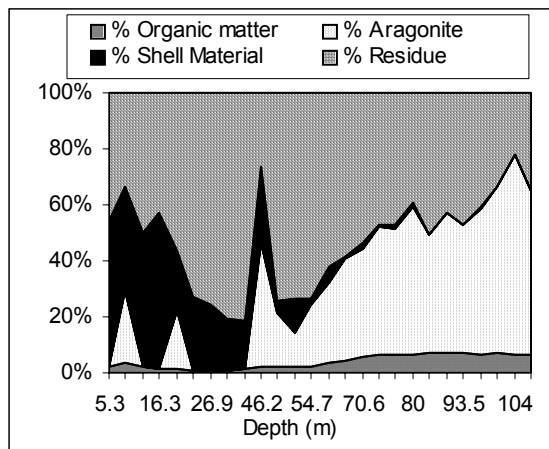


Fig. 1. Area plot of percent composition versus depth for Tafiri Bay; note peak in aragonite at 46.2 m (sample TB5).

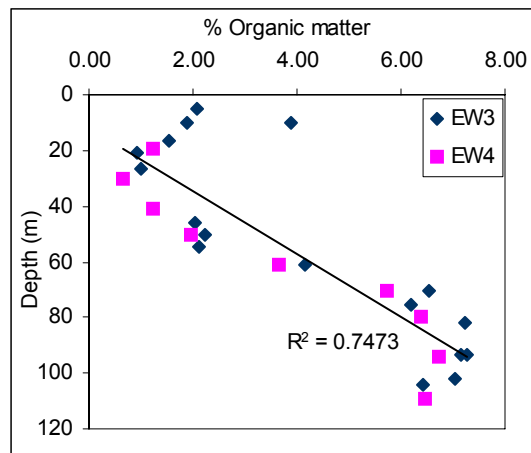


Fig. 2. Bivariate fit of depth by % organic matter; data is not ideally suited to linear regression.

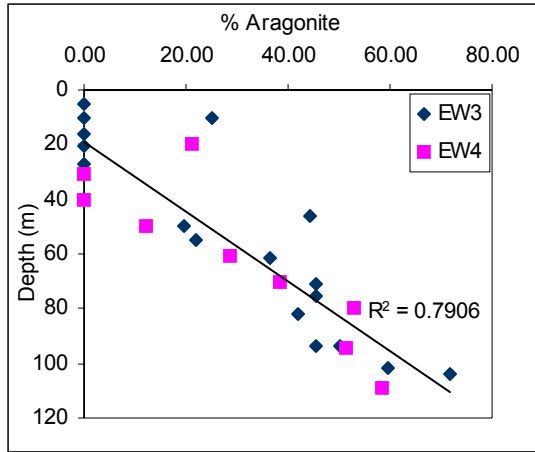


Fig. 3. Bivariate fit of depth by % aragonite.

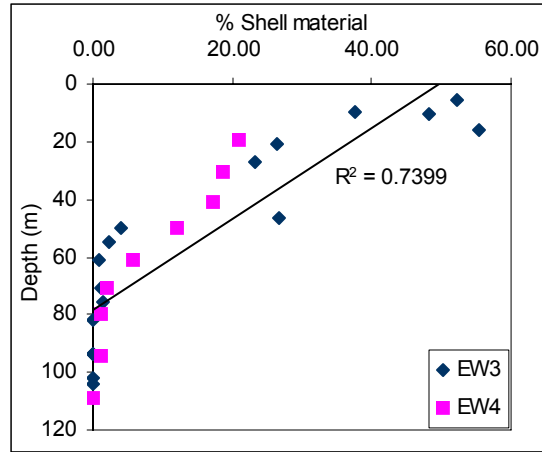


Fig. 4. Bivariate fit of depth by % shell material.

North Luiche

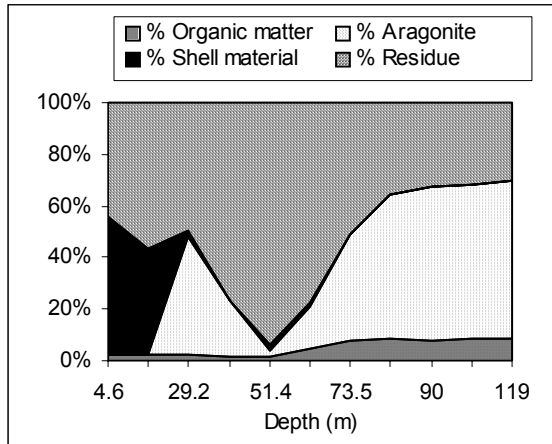


Fig. 5. Area plot of percent composition versus depth for North Luiche transect; note disappearance of aragonite at 51.4 m.

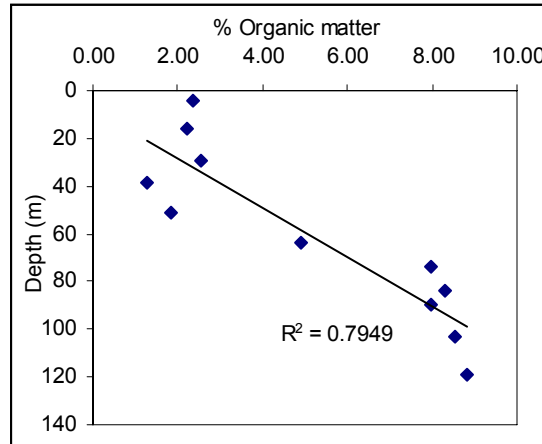


Fig. 6. Bivariate fit of depth by % organic matter; data is also not best modeled by linear regression.

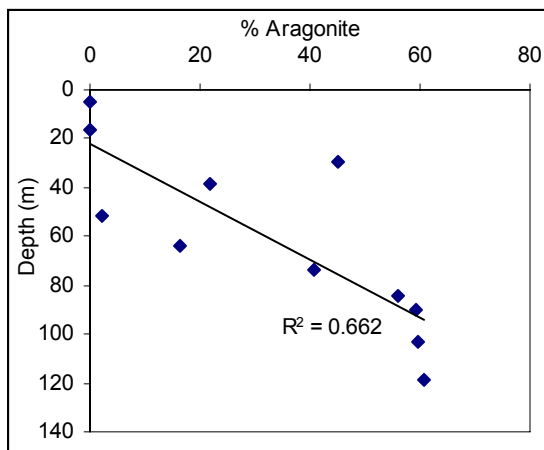


Fig. 7. Bivariate fit of depth by % aragonite.

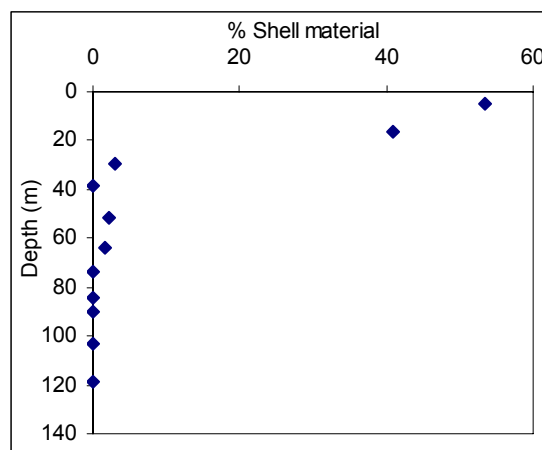


Fig. 8. Bivariate fit of depth by % shell material; data fits a line poorly.

South Luiche

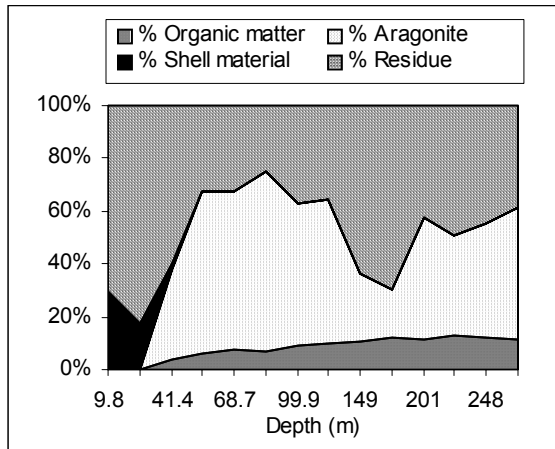


Fig. 9. Area plot of percent composition versus depth for South Luiche transect; note decline and resurgence of aragonite between 100 and 200 m.

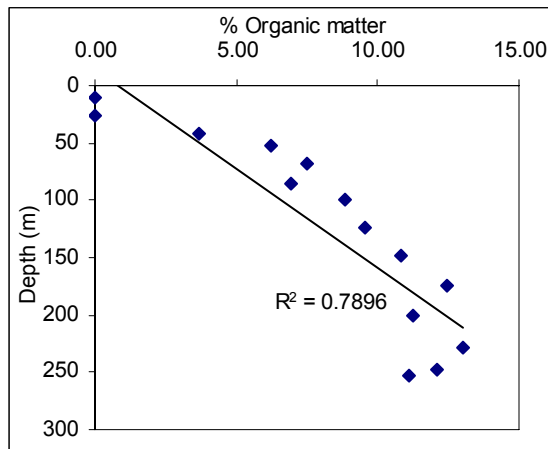


Fig. 10. Bivariate fit of depth by % organic matter.

Paleoclimate Reconstruction

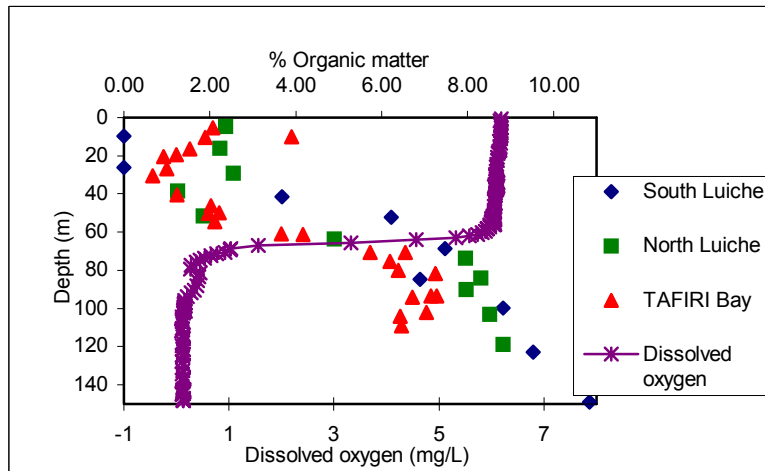


Fig. 11. Depth plotted against percent organic matter and dissolved oxygen in Tafiri Bay and both Luiche Platform transects (three deepest data points from North Luiche omitted). Dissolved oxygen data taken from Kitwe Point (Zhang, this volume). Note inverse relationship of dissolved oxygen and organic matter.

Multivariate Regression

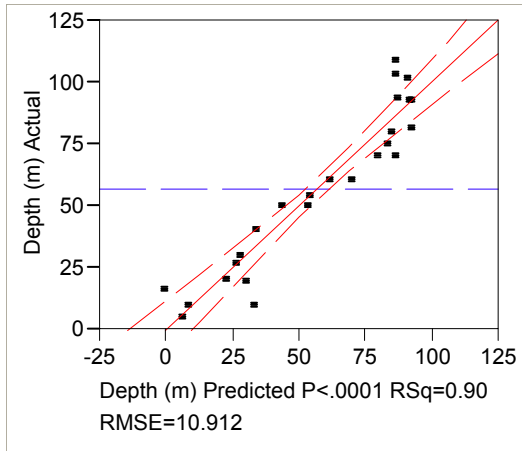


Fig. 12. Response of depth to % organic matter and % shell material in Tafiri Bay.

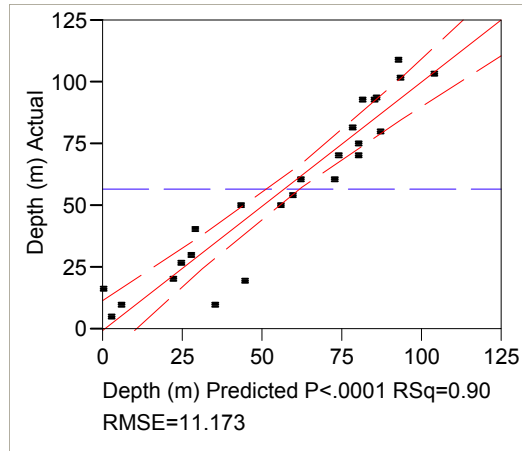


Fig. 13. Response of depth to % aragonite and % shell material in Tafiri Bay.

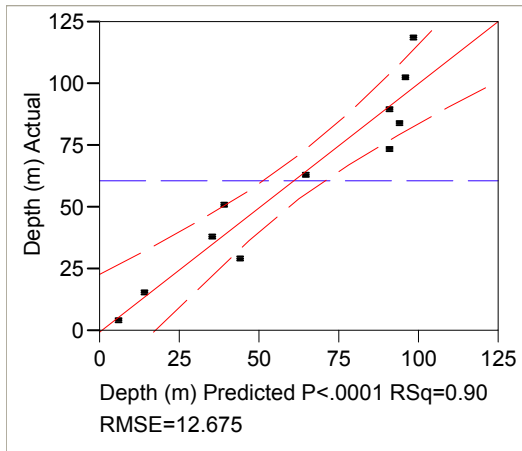


Fig. 14. Response of depth to % organic matter and % shell material in the North Luiche Platform.