

Elucidating the interplay between tectonic and climatic controls on modern depositional processes in the Luiche delta

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Introduction

The Luiche River delta, located in Kigoma, Tanzania, is situated within a complex zone of extensional faulting associated with the evolution of the East African Rift system and the contemporaneous formation of the Lake Tanganyika basin. Active rifting within the East African Rift system over the past 12 million years produced a series of narrow canyons separating sub-lacustrine ridges produced by the pre-rift Precambrian quartzitic horst blocks that characterize the subsurface morphology of the Luiche delta shelf break. The shelf break is a pronounced topographic marker that clearly differentiates the platform, with maximum water depths of 500 meters, from the deep Kigoma basin where water depths extend to 1200 meters (Lambiase, 1990). The small-scale morphological complexity of the Luiche delta platform represents only a small portion of the larger platform margin that extends south of the Luiche delta to the Malagarasi River platform (Lezzar, 2002 personal communication). The geometry of the ridges, and the manner in which they are segmented (described by Morgan, this volume), define the local topography and ultimately control the mechanisms of sediment transport in the region.

The Luiche River is a meandering stream system that terminates at the shoreline of Lake Tanganyika and forms a gradually sloping beach and an isolated offshore delta lobe bounded by northeast-southwest canyons and channel-levee complexes that, theoretically, prograde finer-grained sediment laterally along the platform margin. To the north of the study region, the orientation of canyons and channel-levee complexes is primarily controlled by the placement of horst blocks and secondary faults that complicate attempts to predict variations in grain size and organic matter and carbonate content of the sediments across the platform. Where expressions of sub-lacustrine ridges are not apparent from bathymetric data, the offshore delta lobe extends into the deepest part of the platform, and canyons and channel-levee complexes are apparent even in the absence of faulting, suggesting that other factors are influencing the distribution of sediments throughout the Luiche delta.

Objectives

The ability to predict and interpret the mechanisms for grain size, organic carbon, and carbonate variations in the stratigraphic record of deep-water lacustrine deltaic environments in rift-lakes are complicated by regional tectonic and climatic forcing factors. Results from this investigation will elucidate the interplay between seasonal climatic variations, tectonics, and lake-level fluctuations controlling the bathymetry of the lake floor that influence variations in grain size and organic matter content in the deep-water sediments of a study area of $\sim 550\text{km}^2$ across the Luiche delta (Figure 1). Steep slopes comprising the basin margins permit coarse sediments to be deposited into deep-water environments through gravity-driven transport via canyon and channel-levee systems, and are often interbedded with the fine-grained, organic-rich sediments typically associated with deep-water depositional environments (Huc, et. al., 1990; Wells, et. al., 1999). Seismic interpretation (Morgan, 2002) and evaluations of grain size distribution (Williams, 2002, and this study) will be utilized in determining the relationships between tectonics, lake level and seasonal climatic fluctuations, and the associated variations in the organic matter and carbonate content of sediments representing approximately the past 50 years of sedimentation in the Luiche delta.

Methods

Two research vessels, the *R/V Echo* and the *M/V Maman Benita*, were used in three separate sampling expeditions to collect sediment grab samples from water depths ranging from 20 meters to 583 meters in five northeast-southwest transects covering a $\sim 550\text{km}^2$ area perpendicular to the shoreline of the Luiche delta (Figure 1). Sampling strategies were centralized around the goal of recovering grab samples at 50 to 100 meter depth intervals in water depths greater than 100 meters and sampling intervals of 10 to 20 meters

in shallower waters to permit analysis of TOC, TIC, and water content with distance away from the mouth of the Luiche River. The top 5 centimeters of sediment obtained from the grab sampler was removed and placed in a tightly sealed glass jar to preserve the water content and the integrity of the organic matter content for analysis in the laboratories at the TAFIRI research station in Kigoma, Tanzania. Descriptions of each sample, including color and grain size, were noted in the field before the sediments were refrigerated to ensure that samples remained intact until laboratory analysis could be completed.

Upon returning to the laboratory, approximately 10 grams of the sample recovered was transferred into pre-weighed foil cups, weighed on an analytical balance, and dried in an oven at 60 degrees Celsius for approximately two days to remove all water from the sample. A toothpick-sized sample from the original sample jar was removed and dabbed onto a glass slide, diluted with a drop of distilled water and smeared for smear slide preparation. The slide was placed in the drying oven for approximately 10 minutes before adding Permout glue and a cover slide before sitting on a hotplate for 10 minutes to "cure" the glue and then left to air dry for a 2-day period before analysis could begin.

Following the two-day period, the dry sediments were removed from the drying oven and reweighed to determine the percentage of water in the sediment (wet sediment (g)-dry sediment (g)/ wet sediment*100). In preparation for the loss-on-ignition procedure, the dry sediments were transferred into pre-weighed crucibles, reweighed, and placed into a muffle furnace for one hour at 550 degrees Celsius to burn off organic carbon for determination of TOC. Immediately after obtaining the weight of the sediment without organic carbon, the samples were placed back into the muffle furnace at 925 degrees Celsius for one hour to remove all inorganic carbon from the sediment for determination of TIC. Samples were reweighed and TIC and TOC values were calculated using the following formulas modified from (Zilifi and Eagle, 2000).

$$\text{TOC} = ((\text{dry sediment(g)} - \text{sediment post } 550^0(\text{g}))/\text{dry sediment(g)}) \times 100 \times 0.4$$

$$\text{TIC} = ((\text{sediment post } 550^0(\text{g}) - \text{sediment post } 925(\text{g}))/\text{sediment post } 550^0(\text{g})) \times 100 \times 0.12$$

After mastering the complexities of differentiating between diatoms and sponge spicules using a less than optimal Olympus CH30 E A 100 lens, point counts of siliclastic grains, diatoms, ostracods, sponge spicules, fish bones, plant debris, and estimates of the average percentage of terrestrial organic matter were performed on all samples recovered from greater than 90 meters water depth. Time constraints restricted microscopic analysis of all samples obtained during this study.

Results

On-site observations

Sediment samples recovered with the grab sampler ranged from shell lags with minor amounts of silt and mud to olive-gray fine silt and mud, with many of the mud-rich samples recovered below the oxycline, generally located in waters depths between 100-200 meters, exhibiting a distinctly organic-rich black to greenish-black color. Generally silt-dominated samples exhibited an olive-gray to greenish-black color, and in some cases preserved fine laminations. Sediments recovered from water depths shallower than 90 meters were primarily yellowish-brown to olive-gray in color with varying abundances of shell-hash. The majority of samples recovered below the oxycline were characterized by black to grayish-black highly saturated mud, but some samples exhibited finely laminated black mud with interbeds of fine-grained silt. Water content is noticeably higher in the finest-grained sediments recovered by the grab sampler due to the fact that much of the water is lost from the unconsolidated coarse-sand fraction during retrieval of the grab sampler. The coarse-grained sand and silt cannot retain water as effectively as the fine-grained silt and mud, lowering the relative water content determined following the drying procedure.

Laboratory results and interpretations

Total Inorganic Carbon (TIC)

Values of Total Inorganic Carbon (TIC) obtained in this study are primarily controlled by water depth and distance away from the point source of carbonate production along the shoreline. Rates of carbonate dissolution increase with increasing water depth, resulting in a gradual decrease in TIC concentrations with distance away from the shoreline, an area characterized by high proportions of shells such as mollusks and

ostracods (Van Alstine and Kinyanjui, 2002 this volume) (Figure 2b). Sampling sites along the delta lobe exhibit a gradual increase in TIC values with distance from the shore.

Total Organic Carbon (TOC)

The lowest values of TOC are observed at sample sites concentrated in areas adjacent to the river mouth, reflecting the high proportions of siliclastic sediments transported into the Luiche delta via the Luiche River and its associated tributaries. This inference is supported by the consistent gradual increase in TOC with depth away from the point source of sediment input.

Ostracods

Comparisons between the contour maps of ostracod proportions and TIC data suggest that the predominant source of carbonate may be attributed to ostracod abundances. The high percentages of ostracods located in nearshore transect samples are indicative of the increase in benthic productivity. Observations of ostracod shell fragments in the silts of deeper sample sites suggest that TIC values in these regions are reflective of the transport of ostracod fragments into deeper regions of the delta. The silt-sized fragments of ostracods shells may be carried in suspension for significant distances away from the shallow water environments where they are located in relatively high abundances.

Sponge Spicules

Of particular interest to future studies in Lake Tanganyika are the increases in the abundances of sponge spicules closer to the river mouth, which is the region of the delta associated with the highest proportions of silt held in suspension. Theoretically, sponges, which are filter feeders, would thrive in waters with very little suspended sediment. Proportions of sponge spicules should decrease with closer proximity to the river mouth, but the data generated from this study and other studies performed on these organisms seem to indicate that there must be other hydrodynamic controls on sponge productivity that have yet to be identified (Cohen, personal communication, 2002). Both ostracod and sponge spicule abundances in deeper waters suggest that these organisms living in the oxic zone are transported into deeper waters along with suspended silt-sized sediments.

Diatoms

Values of diatom abundances appear to be inversely proportional to the volumes of siliclastic input in that regions with high siliclastics appear to be associated with reduced diatom percentages.

Terrestrial siliclastics

As expected, terrestrial siliclastic percentages are highest in nearshore samples and in sampling sites in the vicinity of channel-levee complexes. Values decrease significantly in the northernmost region of C1, most probably reflective of short duration, less intense rainy seasons over the last 50 years, limiting the amount of siliclastic input and permitting diatom abundances to increase (Figure 1).

Terrestrial organic matter

Plant fragments and tree bark were predominant in samples located closest to shore near C1, C2, and C3 and decreased significantly with distance from shore (Figure 1). At first glance, it may seem contradictory that TOC values are low in a region with such high terrestrial organic matter input, but remember that the increase in proportions of siliclastics from the shoreline significantly decreases TOC values.

Results and interpretations

The shallowest coastal regions of the Luiche delta system are comprised of fine sand and silt, with the coarsest sands deposited near the river mouth. Sediments on the proximal delta lobe are restricted to this region of the delta by the littoral drift controlled by strong uni-directional seasonal winds during the wet and dry seasons that reworks the sediments back and forth parallel to the shoreline. Finer sands and silts are held in suspension and ultimately deposited on the intermediate delta lobe (Figure 1). Generally, the finest silt and mud is carried out to the most distal and deepest regions of the delta.

The shallowest sites sampled across the delta, all located immediately adjacent to the shoreline, yielded the lowest values of TOC averaging ~0.7%, reflective of the high proportions of siliclastic input from the

minor tributaries of the Luiche River. The TIC values from the shallowest sample sites are generally higher than TOC values, on average ~2.6%, reflecting the high productivity of shallow, oxygenated and nutrient-rich waters with high proportions of shell material accumulating with the sediments. Both the lowest TIC and TOC values in all sediments sampled from the delta are the sample sites directly adjacent to shore, where siliclastic input is undoubtedly diluting both the TIC and TOC values.

In the southernmost sample sites, a noticeable shift from high TIC and low TOC occurs at approximately 50 meters water depth where samples intersect the channel-levee boundary and TOC values are generally higher than values of TIC with increases in depth and distance from shore. At this location, TOC values average 3.4%, with individual values as high as 5.6% in the deepest sample site on the levee at 91 meters, indicating that there are significant decreases in siliclastic input with distance from the shoreline and that these values vary locally with positioning relative to the axis of the channel, most notably on the margin of the levee. Sample sites along the levees bounding the southeastern edge of the proximal delta lobe yield low values of both TOC (0.67%) and TIC (0.49%) and comparisons with values obtained from samples on the margin of the proximal delta indicate that there must be a significant increase in the proportions of siliclastic material on the levee. This inference is supported by the comparatively low water content percentages, suggesting that coarser-grained sediments dominate the levee, most probably due to contributions from the coarse fractions associated with the R5 tributary, located onshore just north of the sampling sites (Figure 1).

The deepest site sampled at 583 meters, located in the northwest region of the delta, is comprised entirely of clastic sediments dominated by sub-angular to angular coarse sands, suggesting a short transport distance and duration most probably related to transport in a debris flow traveling down the canyons passing between ridges on relay ramps. Alternatively, the coarse sands may be erosional products of the west side of the ridge, which are subsequently trapped in the narrow canyons along the ridge. The anomalously coarse grain-size of this deep-water sample is most probably related to the positioning of this sampling site on the basinward side of the platform, where coarse sediments are frequently trapped in narrow canyons.

Discussion

The sample sites in front of the main trace of the Luiche River, R4, appear to be the only region of the delta where a sub-lacustrine channel does not exist in front of an active river system. Analysis of bathymetric data reveals a dome at the northernmost end of the proximal delta lobe, suggesting that there is insufficient energy from the river mouth to transport coarse material across this local bathymetric high, preventing coarse material from accumulating on top of the proximal delta. Instead, the coarse sediments are diverted around the dome into C3 and C4, with C4 accumulating the largest volume of clastic sediments when wind and wave directions prevail from the northwest (Figure 1).

Analysis of seismic data reveals stratigraphic variations between the northern and southern reaches of the distal delta lobe in that non-stratified sediments appear to dominate the northern portion of the distal reaches, most probably related to inputs from the convergence of channels C1, C2, and C3 just a couple of kilometers away from the margin of the distal reaches of the delta. In contrast, the southern edge of the distal portion of the delta appears comprise well-stratified, finer-grained sediments, which may be explained by the comparably long travel distance of sediments transported along C4. In fact, C5 appears to be diverted around the delta as the proximal and intermediate portions prograde laterally to the southeast, most probably related to the manipulation of sediments by littoral drift across this region of the delta.

Conclusions

Seasonal variability in the volume of sediment contributed from minor tributaries, related to the severity and relative duration of wet and dry seasons, may significantly alter the relative proportions of coarse sediments being deposited in all regions of the delta. It is apparent from both seismic and stratigraphic interpretations that tectonics are the primary control on the orientation of the shoreline and positioning of sub-lacustrine channels along relay ramps separated by the rift-related horst blocks. However, sedimentological analyses reveal that climate, and the relative impact of the wet and dry seasonal effects, are the primary controls on the rates of erosion along the watershed and the transport of sediments across

the delta platform. Wind and wave directions generated from the northwesternmost region of the delta over the past 50 years have been the dominant control over the direction of sediment transport. Results from this study reflect the unique controls on sedimentation in the northernmost portion of the delta in that it is sheltered by the headlands when strong winds blow from the northwest, protecting this region of the delta from turbulent waters, permitting fine silt and mud to settle out of suspension and blanket coarse sands deposited when winds are derived from the southeast. The absence of lengthy rainy seasons over the past 50 years limits the relative contributions of sediment from C1-3 and the predominant wind directions from the northwest explains why C4 would be the predominant depocenter for coarse clastic sediments reworked back and forth by littoral drift along the proximal reaches of the delta.

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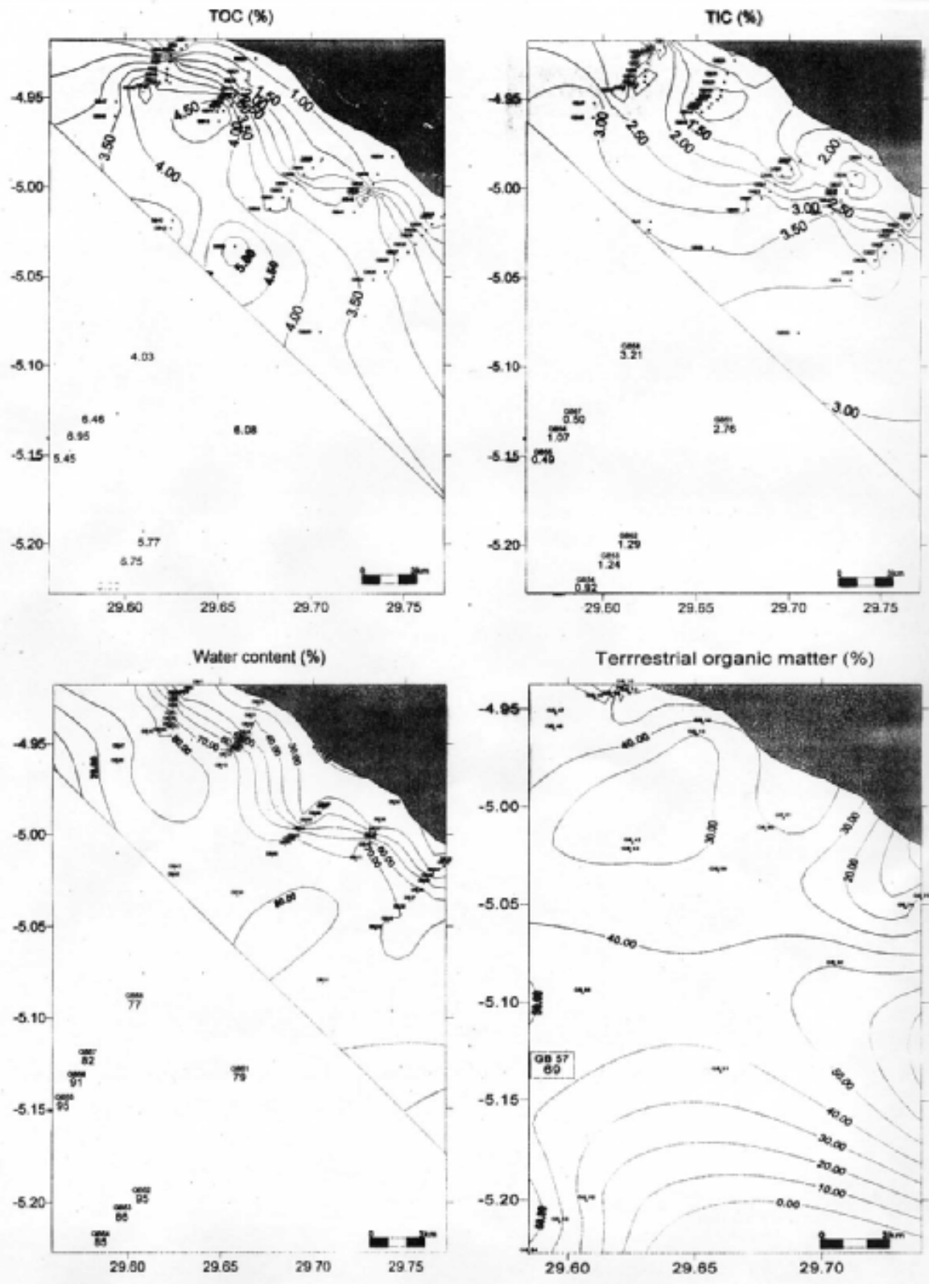


Figure 1: TOC, TIC, Water Content, Terrestrial Organic Matter for the Luiche River Delta. For Grab Samples (GB) location, refer to figure 1 in E. William's Report, this Volume.

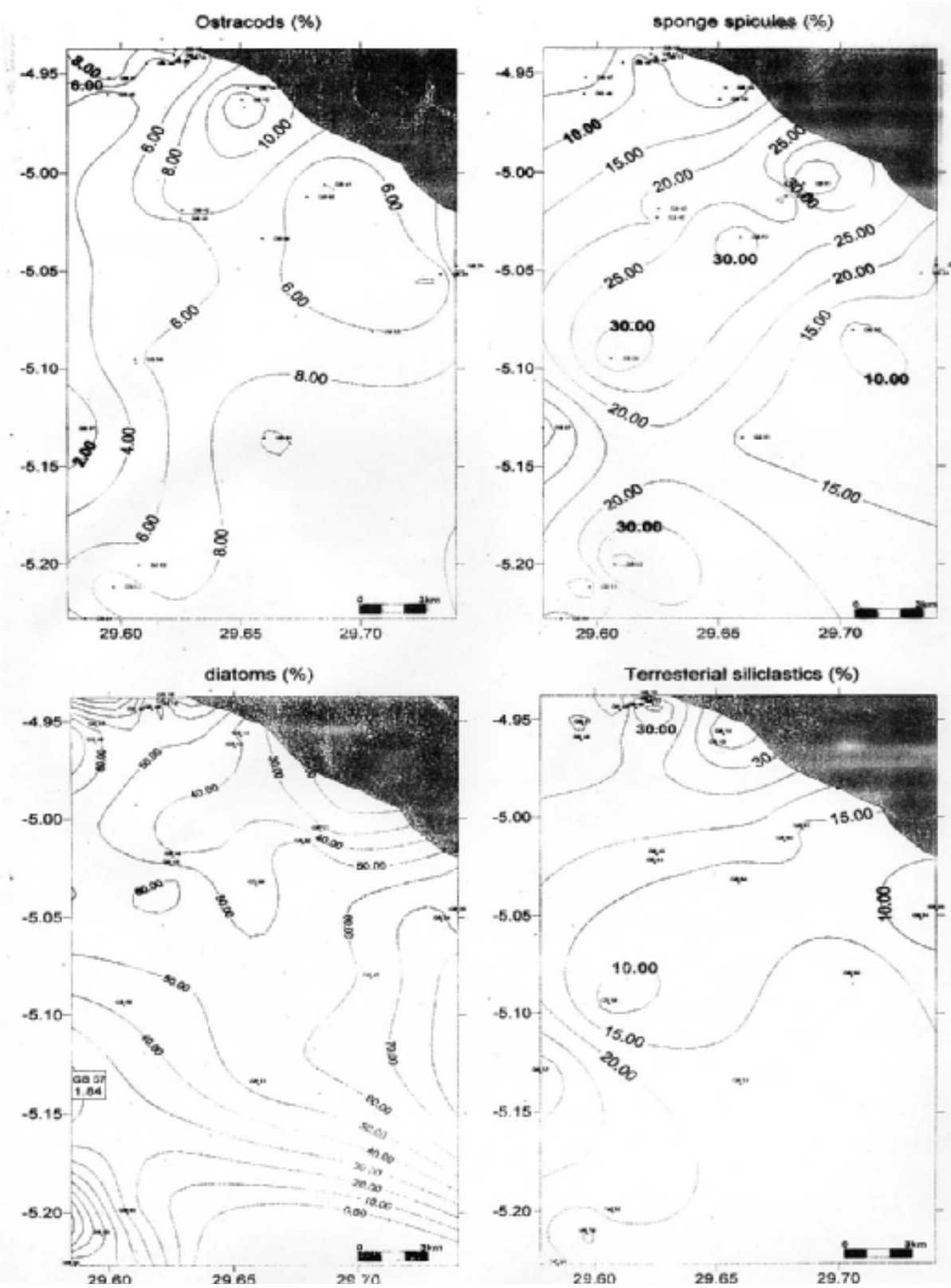


Figure 2: Ostracods, sponge spicules, diatoms, and terrestrial siliclastics for Luiche River Delta. For Grab Samples (GB) location, refer to figure 1 in E. William's Report, this Volume.