Modern water level and sediment accumulation changes of Lake Abaya, southern Ethiopia - A case study from the northern lake area -

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SUMMARY: Lake Abaya is part of a lake system in the southern Main Ethiopean Rift Valley. Since the past ten years water levels of Lake Abaya continuously increased, while in the catchment annual precipitation did not significantly vary and discharge of major tributaries even decreased. By analysis of lacustrine sediments it is pointed out that in the most recent past high input rates of suspended load are due to soil erosion processes in the catchment. Mineralogical and chemical composition of lacustrine and fluvio-lacustrine sediments allow an estimation of sediment body deposited in the most recent past.

1 INTRODUCTION

Since recording started water levels in Lake Abaya, a lake of the southern Main Ethiopean Rift Valley, was subject to repeated changes. But finally, water levels of Lake Abaya since the early 90ties of the 20th century continuously increase (Bekele 2001). Climatic conditions – probably one of the most important factors influencing regional water budget and, thus, lake level - showed high variability during the past 50 years, but lack any trend. Thus, resuming results of climate data time series analysis climatic conditions as the only factor influencing lake level changes have to be excluded.

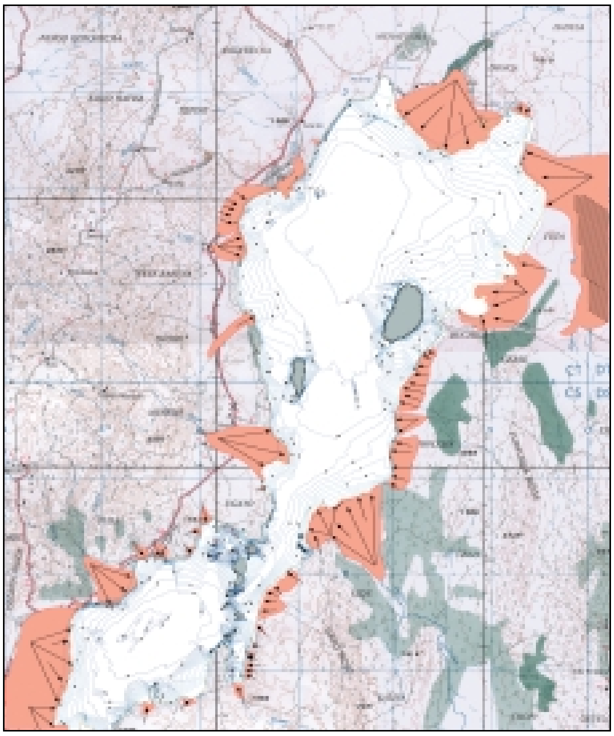

Figure 1 Map of Lake Abaya showing lake's bathymetry, drainage basin topography and distribution of major areas of fan deposits (map source: Topographical Map 1:250'000, sheet Abaya, 1984).

Additionally, analysing Lake Abaya's lake level changes it has to be considered that latest since the 1970ties dramatic population growth, changes in land-ownership, clearing of forests and bush-land as well as changes in cultivation manners caused increasing soil erosion processes and, consequently, rising sediment yield of the Lake Abaya tributaries, possibly influencing basin bathymetry and volume. Because of its shallow depth (maximum depth of 26 m) lake level of Lake Abaya reacts quite sensitive to changes of input factors. Thus, it is an ideal subject-matter to analyse complex pattern of climatic and human impacts on lake level changes. However, as Lake Abaya is located in the

Main Ethiopian Rift Valley, one of the most active tectonic zones of the earth, also possible neo-tectonics at the southern sill influencing outflow to Lake Chamo have to be kept in mind.

To assess the processes of soil erosion as a factor modifying basin volume, sediment cores were extracted from the lake center and the deltas of the major tributaries. Investigating sub-aqueous relief, volume of accumumulation bodies and character of lacustrine and fluvio-lacustrine sediments, the variation in intensity of man's impact on erosion and accumulation processes is pointed out. In the study presented results are shown exemplarily for the northern Lake Abaya where Bilate river deposits its sediments.

2 STUDY SITE

Lake Abaya – Lake Chamo system is a graben fill in the southern section of the Main Ethiopian Rift Valley. A sill covered by swampy forestland of approximately 1 km width separates Lake Abaya from neighbouring Lake Chamo in the south. The altitude difference between the lakes is about 60 m. Altogether, drainage of Lake Abaya – Lake Chamo system covers a watershed of approx. 18,600 km² while lake areas cover approx. 1,550 km². The Lake Abaya can be characterized as a quasi-endorheic basin, with drainage to the southern Lake Chamo only in consequence of overflow. According to this, the possible influence of neo-tectonics to lake level has to be taken into consideration. Most recently, water of Lake Abaya is of a reddish-brown color due to the silty to clayey sediments transported into the lake by its tributaries. Lake Abaya is fed by the major drainage systems of Bilate river from the north, Gidabo and Gelana rivers from the east, and in the west from Hare, Hamessa, and Baso rivers. The catchment of Bilate river is the biggest of the Lake Abaya tributaries, draining 5754 km². High sediment yields of the tributaries cause deposition of extended alluvial fans at the base of the Rift Valley flanks, continuing as deltas into the lake (Figure 1). Lake Abaya is almost shallow with a maximum depth of 26 m. Limnic environment is slightly basic (pH 9.0-9.3) with low salinity (950-1050 µS) and corresponds to a typical tropical lake environment, lacking complete lake circulation.

Climatic conditions in the drainage basin vary between an Aw-climate (after Köppen-Geiger) in the highlands and a Cw-climate (after Köppen-Geiger) in the Rift Valley, both characterised by two annual rainy seasons and a distinctive arid period in winter. Annual as well as monthly sums of precipitation are highly variable (Figure 2a), but do not show a significant trend during the past 20 years. In contrast, time series analysis of annual discharge, executed for the five year moving average (Figure 5), shows for most of the drainage basins tributary to Lake Abaya negative trends (11 gauging stations, covering almost 46 % of the Lake Abaya drainage; gauging period in some places started in the 1970ies). At the same time, growing population in the area with approx. 5 % annual increase since 1970 caused dubling of water consumpion (Bekele 2001).

3 METHODS

Expansion of *Lake Abaya* surface area can be recorded for the time period since 1965 by image analysis such as panchromatic air photographs, CORONA images, RGB images from space crafts, and Landsat TM images. Next to this, data sets available since 1981 from AVHRR-NOAA (*Advanced Very High Resolution Radiator – National Ocean and Atmosphere Administration*) were used to record vegetation cover on a monthly basis by NDVI (*Normalized Digital Vegetation Index*) (Eklundh 1996). Results shown in this presentation are based on monthly average NDVI data provided by *Global Ecosystem Database* with 8*8 km² grid size. Coast lines were received from topographic maps scaled 1:50,000 and 1:250,000 edited in 1990 and 1979. Most recent coastlines were measured by boat using GPS.

Undisturbed lacustrine sediments were taken using a coring plumb line (Figure 6). Analysis of sediments included in a first step description of depositional units to identify stratigraphical units by macroscopic characters (color, lamination, sedimentary structure, facies). Preparation of samples started by drying them at 50°C in a drying cabinet and homogenising them in an agateswing sledge mill. Organic carbon contents were determined by an infrared cell in a LECO high-frequency induction oven (detection limit = 0.02 mass % C). Analysis of mineralogical compounds were carried out by X-ray powder diffraction analysis using a copper k_{α}-tube (Siemens DIFFRAC AT/D5000). Contents of mineral components were recorded as volume-% by the intensity of diffraction at the mineral's major diffraction peak (cps) relatively to the intensity of quartz at its major diffraction peak (d_{101}). To identify composition of clay minerals disaggregated samples were prepared as oriented mounts. Mounts were measured air-dried and after treatment with ethylene glycol and heating up to 550°C and each mount was x-rayed for 2-30 °2θ.

Due to the young age of the sediments (<50 years) conventional dating techniques are not reliable. As in the area of interest up to today pesticides containing persistant organic pollutants such as DDT and Aldrin are used, contents of DDT and Aldrin and its derivates are used for age detection; these analyses are still in progress.

4 RESULTS

4.1 Time series analysis of NDVI

Spatial distribution of NDVI data in the Bilate basin distincly points out differences in development of vegetation due to precipitation and topography. The western exposed flanks of the Rift Valley, which are corresponding to the western part of the Bilate drainage, are affected by orographic precipitation. Thus, vegetation cover here is more dense than in the Rift Valley itself and its western exposed flank. This pattern is also reflected in seasonal variations of NDVI, such as shown for average NDVI in the Bilate drainage for July 2001, representing

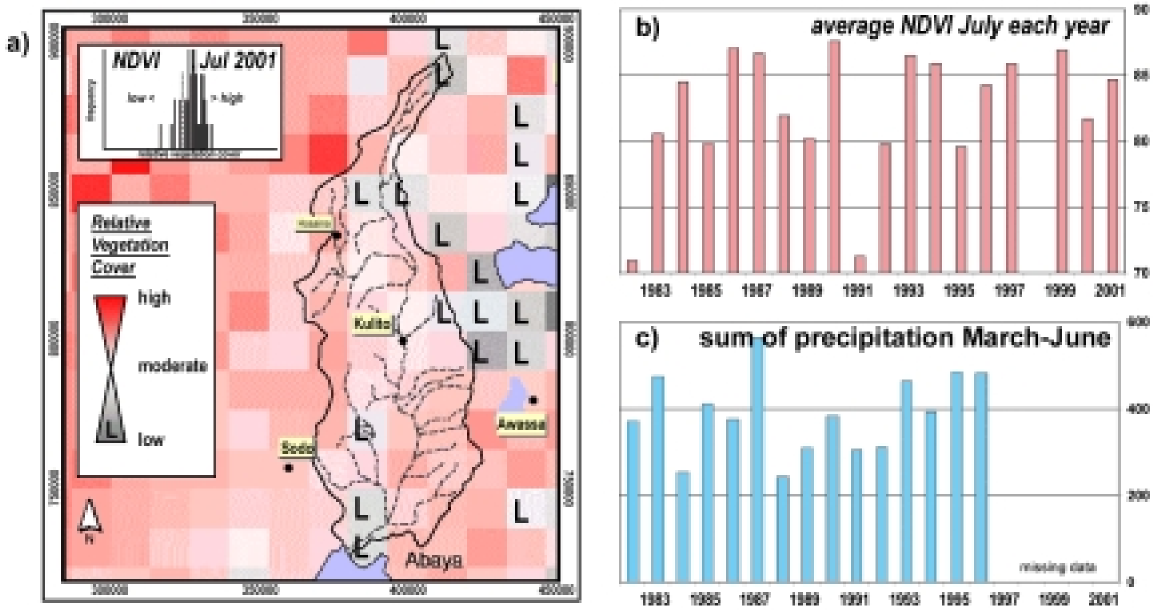

Figure 2 Time series analysis of monthly NDVI in the Bilate River catchment. a) standardised NDVI from July 2001, b) average standardised NDVI for July each year for the time-interval from 1982 to 2001, c) sum of precipitation from March to June each year for the time interval from 1982 to 1996.

vegetation cover for the end of vegetation period (Figure 2a). Time series analysis of average July NDVI of the Bilate drainage (Figure 2b) shows high variability but lacks a trend. Comparison of these data with sum of precipitation of the four previous month (March-June; Figure 2c) indicates dependency between weather and vegetation cover. It is expected that correlations shown get closer while analysing weather conditions.

4.2 Lake level changes and shore-line shift

Analysis of the monthly lake level data from Lake Abaya shows after the spill in the second half of the seventies decreasing lake levels and receding trends until 1992. After a lake level low in the second half of 1992 lake levels increased portraying seasonal variations in precipitation (Figure 3).

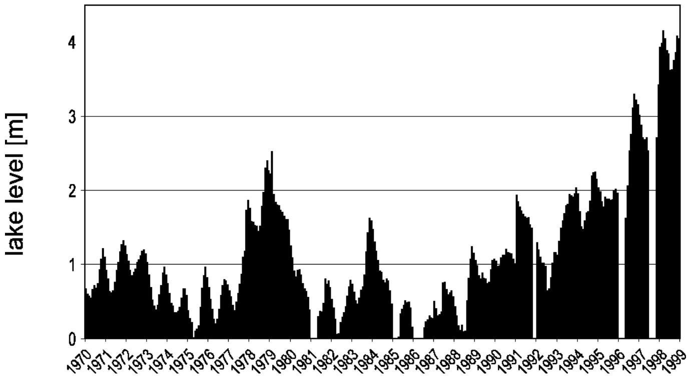

Figure 3 Monthly lake water levels of Abaya Lake at Arba Minch gauging station (data source: Seleshi 2001).

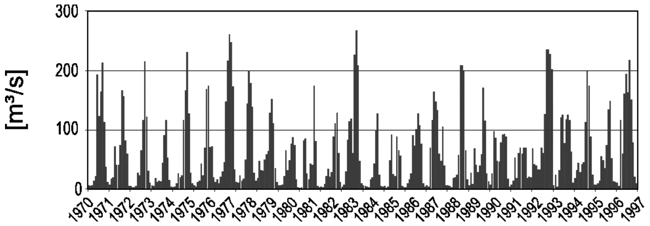

Figure 4 Bilate River at Abaya Outlet Station: Maximum monthly discharge. Gauging period: [1971;1996]. (data source: Seleshi 2001)

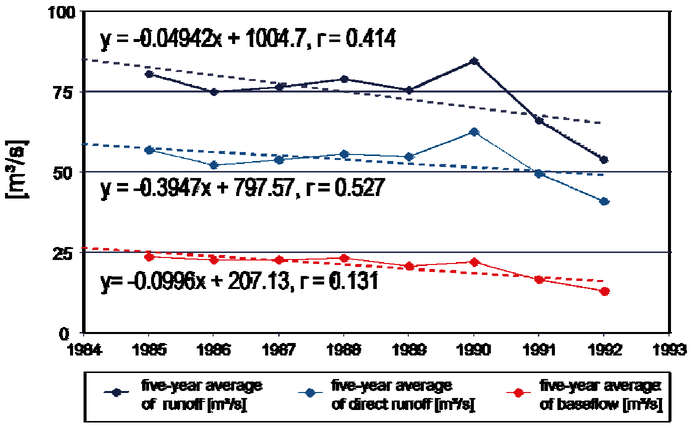

Figure 5 Bilate River, Tena Bailate Station: Five-year running average of runoff [m³/s] and the different discharge components. Gauging period: [1983;1992]. (data source: Seleshi 2001)

Beneath lake levels runoff data of the largest tributaries of Lake Abaya are available for varying gauging periods. Also here monthly discharge data reflect seasonal variations in precipitation whereas increasing discharge data since 1992 such as recorded for the lake levels are missing (Figure 4). In addition for the Bilate river at the Tena Bilate gauging station, located just above the fan-deposits in the lower course of the Bilate river, runoff data analysis of the five-year running average of runoff [m³/s] and the different discharge components for the gauging period from 1983 until 1992 was executed. Trend analysis shows distinct negative trends for the total runoff as well as for runoff originating from baseflow as from direct runoff (Figure 5). Additionally, calculation of the baseflow as percentage of total runoff trend line shows a coefficient of b=-0.905 (r^2=0.873), which points out that baseflow decreases more sharply than direct runoff (Figure 5).

The most recent mouth of the Bilate river is located in a bay at the western fringe of the irrigated and desiccated fan and delta area of the Bilate river. Shore lines moved back during low lake level period in the 1980th (Figure 6). Beyond this, survey of shoreline from February 2002 points out that the most recent Bilate delta is continously growing, causing penetration of the shore line into the lake.

4.3 Sediment analysis

In the Bilate delta area altogether 12 cores were extracted covering the area of most recent fluvio-lacustrine sedimentation (Figure 6). All sediments extracted are finely laminated, changing between brownish, dark and light greyish colors. Grain size of these sediments is clay with frequently occuring silty components. Sediments are soft and only poorly consolidated. At the base of the sediments extracted in all cases highly compacted sandy sediments prevented deeper penetration of coring plumb line.

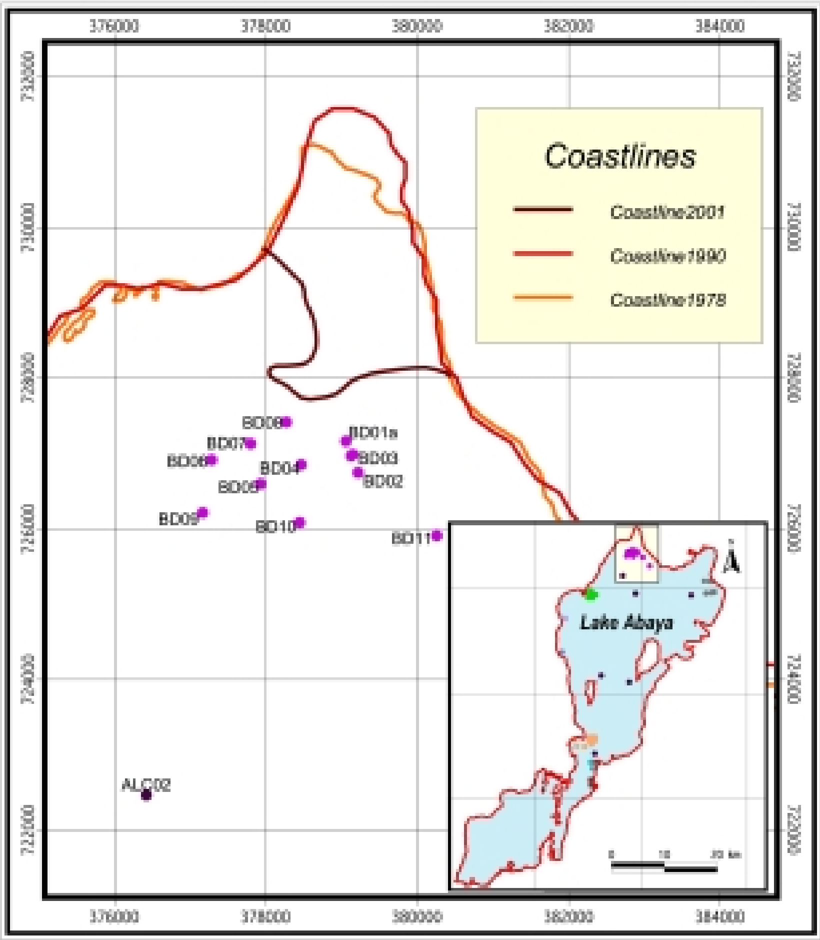

Figure 6 Map of the northern Lake Abaya, showing location of drillings and running of most recent coastlines in the delta areas (map source: Topographical Map 1:250’000, sheet Abaya, 1979, Topographic Map 1:50’000, sheet Bilate State Farm, 1990).

Graphs of organic carbon content for the sediments extracted from the Bilate delta show related shapes (Figure 7): Below lake floor organic carbon content, in general, decreases. In a few centimeters depth of the sediments organic carbon contents increase again; in the sediments extracted close to the mouth of Bilate river this character appears already before 10 cm depth are reached while in the sediments extracted from the delta’s margin increase of organic carbon contents starts off between 10-15 cm depth. In core BD08, extracted in front of the Bilate mouth, there are only 17 cm of clayey sediments before consolidated sandy layers start. The temporal resolution given from fluvio-lacustrine sediments is reduced. In contrast, sediments extracted from the delta’s margin reach down to 40 cm depth and, therefore, go farther back into sedimentation history. In drilling BD02, BD04 and BD07, extracted from the central part of the delta after the increase of organic carbon content in 10-

15 cm depth values remain more or less stagnant before they distinctly increase between 20-25 cm depth (BD02, BD04) resp. in 18 cm depth in BD07. The overall shape of the organic carbon content graphs can also be traced in drillings BD05, BD06 and BD10, all extracted from the margin of the delta, but at least a distinct downward decrease of organic carbon contents is missing (Figure 7).

Next to organic carbon content lake sediments were investigated on their overall mineralogical composition (Figure 8). Showing composition of some selected minerals of drilling BD05 on behalf of the other drillings it gets clear that run of graphs is only poorly connected. Quartz and sanidine are the major mineralogical composits, complemented by augite, analcime, mica, biotite, muscovite, and montbrayite – all components which point out the origin of the sediments from a drainage basin with bedrock due to vulcanic processes. Furthermore, pedogenic minerals (oxides, clay minerals) constitute up to 10 vol.-% of mineralogical composition. While oxides are dominated by goethite, next to kaolinite three-layer clay mineral montmorillionite predominates the composition of clay minerals.

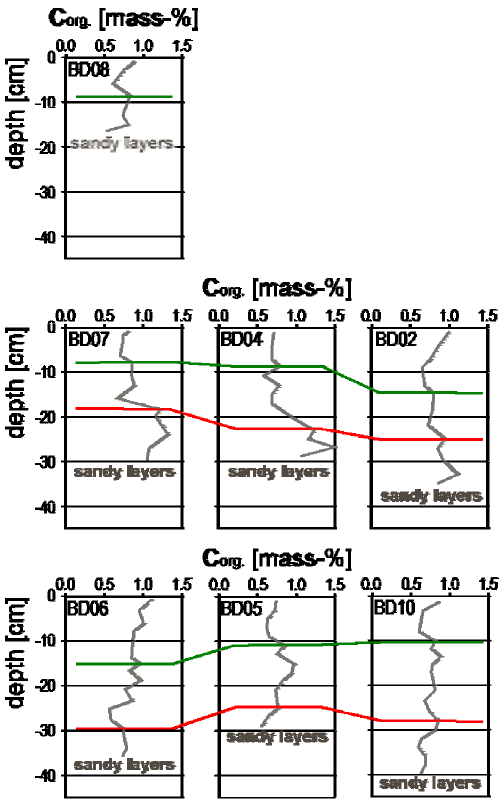

Figure 7 Organic carbon content [mass-%] in the fluvio-lacustrine sediments extracted from the Bilate delta area. Arrangement of graphs corresponds to the location of penetrations (see Figure 6)

Integrating all sediments extracted in the Bilate delta area (n=150) into a statistical analysis it can be pointed out that:

a) oxide contents such as boehmite, hematite and goethite are always positively correlated with each other ($\alpha<0.001$),

b) oxide contents are always positively correlated with clay mineral contents ($\alpha<0.001$),

c) carbonate contents (calcite, dolomite) are always positively correlated with the clay mineral contents ($\alpha<0.001$) as well as with the oxide contents ($\alpha<0.001$),

d) quartz and sanidine contents as well as contents of augite, analcime, mica, and montbrayite are positively correlated with each other ($\alpha<0.05$) and the same time are negatively correlated to the minerals of the carbonate group, the oxide group and the clay mineral group ($\alpha<0.001$).

5 DISCUSSION

Lake-level fluctuations of endorheic basins are among the best indicators for climatic fluctuations during the Holocene, determined by relief, geology, soils, vegetation, and palaeohydrology of their watersheds as the main factors (Street-Perrott 1980). The magnitude and frequency of lake-level fluctuations can be reconstructed from geomorphological and sedimentological analyses (e.g. beach ridges, beach terraces, cliff edges, lacustrine and fluvio-lacustrine sediments) in conjunction with knowledge of the present-day water balance of the lake (Street-Perrott & Harrison 1985). Apart from the deposition of allochthonous detritus,

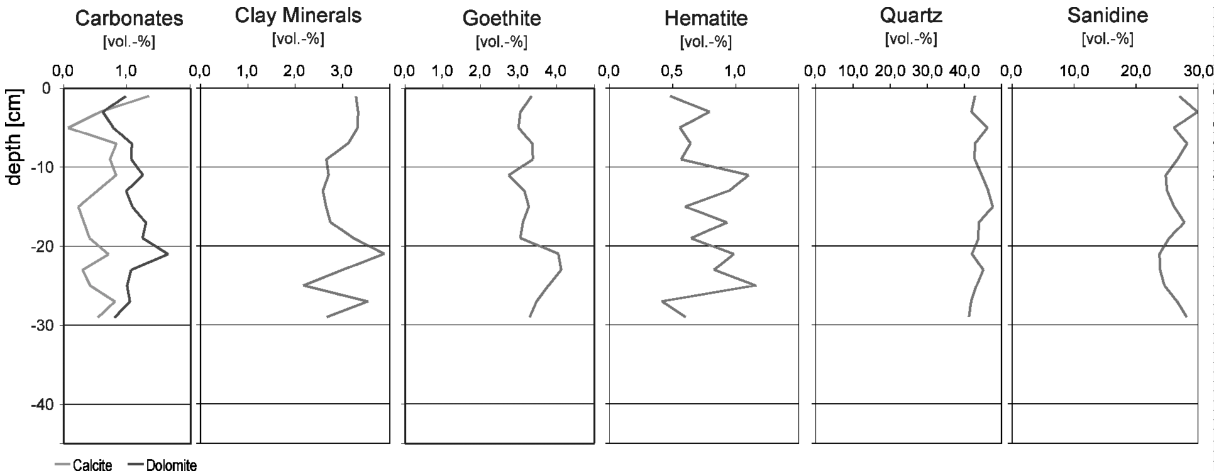

Figure 8 Chemographs of drilling BD05 from Bilate delta.

lacustrine sediments are characterised by precipitation of authigenic minerals from aqueous solutions. Because this process is substantially influenced by lake water salinity and its chemical composition, such sediments are particularly of interest for the reconstruction of the palaeolimnic environments. For this purpose the overall mineralogy, but predominantly the character of carbonates of lacustrine sediments, is of interest to obtain information about the palaeoenvironment of lakes, while composition of its pedogenic minerals obtains information about the synsedimentary environmental conditions in the drainage basin (Schütt 1998).

5.1 Water budget in the drainage basin area

The environmental conditions in the Lake Abaya catchment concerning the overall waterbudget can be summarized as follows: Since 1992 water level of Lake Abaya constantly increases. During the same period of time annual precipitation in the Lake Abaya catchment is of high variability, but does not show any significant trend. Sums of annual outlet of the major Lake Abaya tributaries during the past 30 years predominantly remain stagnant or even show a negative trend. Simultaneously, share of baseflow forming total runoff –as demonstrated for the Bilate river in this paper – constantly decreases.

Under natural conditions during humid phases the vegetation cover obstructs surface runoff and erosion, and infiltration rates increase (Horton 1945). As conditions are reversed during arid phases, surface erosion increases and infiltration rates and subsurface flow are reduced (Dunne et al. 1991, Rogers & Schumm 1991). The same effect is due to soil erosion processes: where vegetation-cover is removed disturbance of soil structure as well as removal of canopy cover protecting against splash-effect and removal of attaching root system favour surface runoff and impede infiltration (Richter 1976, Dunne et al. 1991, Rogers & Schumm 1991).

Analysis of the lake level data shows that after the spill in the second half of the seventies Lake Abaya’s water level constantly decreased until 1988. After 1988 lake system refilled again and until 1996 oscillated within the margins well-known. Since 1996 in southern Ethiopia some very wet years occurred which possibly have been associated to El Niño and which caused significant rise to water level.

Next to these natural and quasi-natural processes of water-balance in the Lake Abaya drainage basin in the most recent past also increasingly direct human impact by water consumption including domestic water use and water use for irrigation and live stock has to be considered. It is assumed that water consumption is steadily increasing due to increasing population number. Domestic use, however, is limited since the average consumption in rural Ethiopia is well below 20 ltr./person/day. Irrigation water demand has been increasing because of large scale cashcrop production in several state farms of the drainage basin (in former times mainly cotton, today preferrably maize). It can be concluded that water consumption was not a major factor for the lake water balance during the last years. It can be expected that the extremely high population growth (average growth rate of 2.23 % of rural and 4.11 % of urban population) will show its effects very soon (CSA 1998).

5.2 Organic carbon content

Organic carbon in lacustrine sediments can be allochthonous, deposited as detritals due to erosion processes in the catchment (Dunne et al. 1991). Additionally, limnic biomass production is an important source of organic carbon in lacustrine sediments (Vallentyne 1962). Limnic biomass production is highly dependent on availability of nutrients and light and, therefore, is reduced when high concentrations of suspended load cause high turbidity (Evans & Kirkland 1988).

Different processes of decomposition and preservation are affecting organic matter in the limnic environment: During process of deposition autochthonous as well as allochthonous organic matter gets decomposed by early diagenitic decomposition (Meyers & Ishiwatari 1993). Early diagenitic decomposition occurs in both the aerobic and anaerobal limnic environment and, in general, under natural conditions can result in the total decay of organic matter (Livingstone 1984). In general, organic carbon contents in the lacustrine sediments are very low. Under normal circumstances, in the uppermost sediments from top to bottom continuously decreasing contents of organic carbon suggest a progressively early diagenetic decomposition of organic matter (Rheinheimer 1974). Thus, increased organic carbon contents of lacustrine sediments indicate deposition rates higher than decomposition rates such as caused by soil erosion processes (Lerman 1979). In lacustrine environments affected directly by fluvial processes as shown for the delta area of Bilate river oscillations of sediment's organic carbon concentrations might reflect deposition of soil sediments from different horizons (top soil: rich in organic carbon, subsoil: poor in organic carbon). Thus, it has to be considered that the increased amounts of organic carbon content in the sediments extracted might be influenced by increasing soil erosion rates in the youngest past (Dunne et al. 1991, Richter 1976). Additionally it has to be considered that subaqueous currency of inflowing surface runoff might vary in location and velocity, causing changes in concentration of sediment's organic matter. Where direct influence of subaqueous currencies is missing concentration of organic carbon in lacustrine sediments reflects the efficiency of decomposition processes in relation to accumulation processes and, thus, shows increased deposition of organic detritals due to erosion and soil erosion processes.

5.3 Mineralogical composition

Apart from allochthonous detritus authigenic carbonates, sulphates, and chlorides make up the mineralogical composition of lacustrine sediments. Detritals originate from decomposition of bedrock in the drainage basin and reflect the mineral fabric of bedrock (i.e., quartz, sanidine, feldspar) and predominating soil forming processes (pedogenic minerals such as clay minerals, hematite, goethite, boehmite). Early diagenetic processes, controlled by salinity and chemistry of lake water can modify the mineralogical properties, especially those of authigenic and pedogenic minerals.

Carbonates

Calcites and dolomites are the only carbonates detected in the sediments extracted. As occurrence of limestone in the drainage area of Lake Abaya is unknown, it has to be concluded that calcites found are authigenic. Calcareous mud is the predominant form of carbonate deposits in the lacustrine sediments investigated. Its origin can be explained by strong mechanical stress on detrital carbonates (Kelts & Hsü 1978) as well as by authigenic calcite precipitation (Schröder et al. 1983). Essentially, the autochthonous development of calcareous mud (=automicrite) in lacustrine environments is due to water chemistry changes effected by decomposition of organic matter, biological assimilation of CO_2, or temperature increases with consequential salinity deviations (Flügel 1978). Warming of the water body in summer and evaporation can also lead to deposition of carbonates, especially in shallow-water areas (Schäfer 1972). Low dolomite contents in the lacustrine sediments correspond to restricted processes of early diagenetic dolomitisation which are due to the low concentrations of magnesium-ions in the limnic environment (Folk & Landes 1975).

As limestones are not likely in the Lake Abaya drainage area the predominant source of calcium bound in the calcites are the weathering products of sanidine ($K_{0.42}Na_{0.58}Ca_{0.03}AlSi_3O_8$). Sanidine is a mineral belonging to the feldspar group and originating from magmatic processes with acid fusion (SiO_2 > 65 mass %) (Deer et al. 1992). Like all feldspars sanidine can easily be weathered, with the earth and alkaline earth metals mobilised and transported away as solutes and the remaining Al- and Si-ions forming clay minerals. The statistical analysis of mineral components show that the higher the clay mineral contents in the lacustrine sediments are the more the carbonate contents increase while contents of geogenic detritals like feldspar and quartz decrease. Thus, the statistical analysis confirm the origin of Ca-ions bond in the carbonates as well as the formation of clay minerals from weathering of feldspars.

Pedogenic Minerals

Clay minerals are generated as a consequence of chemical weathering and soil forming processes.While in acid environments clay minerals get disturbed (Ulrich 1981) in slightly basic and saline environments three-layered clay minerals get meta-stabile and their illitisation might occur (Heim 1990). Also hematite (Fe_2O_3) develops as a consequence of weathering and soil forming processes predominantly under tropical and subtropical climatic conditions with high temperatures and negative soil water balance by dehydration of ferrihydrates ($5Fe_2O_3 \cdot 9H_20$) (Schwertmann & Taylor 1989). In lacustrine environments under reducing conditions hematites are meta-stabile and form goethite (α-FeOOH) (Macedo & Bryant 1989).

In the sediments recorded positive correlation between hematite and clay mineral contents point out their common origin from erosion of soils (Rohdenburg & Sabelberg 1973). The same relation is underlined by the negative trend between contents of pedogenic minerals and quartz resp. feldspar: the higher the degree of weathering of the soil sediments the higher the contents of pedogenic generated clay minerals and the lower the contents of unweathered minerals (Krauskopf 1956). Calcite contents in the lacustrine sediments show a random pattern of trend and quality to contents of other minerals due to its authigenic origin (Schütt 1998).

6 CONCLUSIONS

Concentrations of detrital organic carbon as well as those of pedogenic minerals in lacustrine sediments are excellent indicators to assess intensity of erosion and soil erosion processes in the catchment and the state of the soils eroded. The altogether high concentrations of pedogenic minerals in the lacustrine sediments point out soil erosion, the intensified erosion process due to human impact, as the predominating morphodynamics in the catchment of the Bilate river in the most recent past. Distinct decrease of organic carbon concentrations and of pedogenic minerals in the overlying sediments of the delta sediments show for the most recent past that

a) a distinct change in processes such as a reduction of soil erosion processes or

b) a distinct change in parent material such as erosion of more poorly developed soils for example in areas highly degraded

occurred.

Data for assessing sediment age are still in progress, thus, determining point in time of changes of morphodynamics and its correlation with factors of human resp. climatic impact is yet not possible. Correspondingly, quoting accumulation rates is yet not possible. Nevertheless, run of chemographs (Figure 7) points out that mineral and chemical components of lake deposits are a feasible tool to determine volume of the strata over an extended area independent from facies (lacustrine – fluvio-lacustrine). Comparison of topographical maps and air photographs show that since 1965 the Bilate river deposited an delta-area of approx. 5.5 km^2 at the western fringe of the 'old' Bilate delta which is an amphibian area today. Lakewards of this amphibian area deposition of fluvio-lacustrine sediments covers another approx. 7.5-8.0 km^2. It can be assumed that the clayey, unconsolidated sediments on top of the consolidated sandy strata as the most recent sediments are due to soil erosion processes. Supposing an average depth of 25-30 cm for these overlying layers, a volume of most recent deposited subaqueous sediments due to soil erosion processes of $2.0\text{-}2.5*10^3$ m^3 can be estimated

7 ACKNOWLEDGEMENTS

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