

Spatial patterns of surface sediment variables in the littoral zone of Lake Constance (Germany)

K. Schmieder¹, B. Schünemann² and H. G. Schröder²

With 3 figures and 2 tables

Abstract: A lakewide investigation of littoral surface sediments at Lake Constance gave information on spatial patterns of sediment composition and led to a better understanding of external and internal factors that affect sediment formation on a regional scale. Grain size analyses showed relations between both grain size means and the proportion of the silt and clay fraction at 2 m water depth and the intensity of wave action as described by the effective fetch of the main wind direction. Mean grain sizes of wind exposed northern littoral areas were higher than those of southern protected areas, which also featured higher proportions of silt and clay, resulting in a general north-south gradient of these two sediment characteristics. The sorting effect of the wave action on grain size composition was manifested in a depth gradient of the grain size means. Mineralogical analyses revealed negative correlations between calcite and siliciclastic as well as dolomite minerals. In particular, the linear regression between calcite and clay minerals displayed a high coefficient of determination and significant interactions with depth. The high correlations between the mineral constituents were associated with an east-west gradient in sediment composition. The east-west gradient mainly resulted from two different processes: external input of dolomite, clay, and quartz minerals into Lake Constance from shore erosion and from eastern tributaries in the alpine and prealpine part of the catchment area, and biogenic calcite production by macrophytes and molluscs mainly in the western part. Areas of high sediment calcite content corresponded to the long-term distribution patterns of *Chara contraria*. Littoral areas near the few river mouths in the western part of Lake Constance were exemptions to the general pattern in sediment distribution.

Key words: sediments, littoral zone, granulometry, mineralogy, Geographic Information System (GIS), Lake Constance.

¹ **Authors' addresses:** Inst. of Landscape and Plant Ecology, University of Hohenheim, 70593 Stuttgart, Germany.

² Institute for Lake Research of the Environmental Protection Agency Baden-Württemberg, 88085 Langenargen, Germany.

Introduction

Morphological features and geological composition of the shoreline determine the quality of littoral sediments. Moreover, littoral surface sediments are influenced by external processes such as river transport from the catchment (MÜLLER 1966) and internal lake processes such as shore erosion from wind induced waves (HAKANSON & JANSSON 1983, PETTICREW & KALFF 1991, SCHMIEDER 1995), accumulation of mollusc shells (BROWN et al. 1992), calcite precipitation from pelagic algae (KÜCHLER-KRISCHUN 1989) and littoral macrophytes (BEHBEHANI 1987, SCHNEIDER et al. 1983, SCHÖTTLE 1969, SCHRÖDER 1982).

Littoral sediments are highly influenced by waves according to their exposure and fetch distance to strong winds, resulting in a typical offshore fining of grain sizes (HAKANSON & JANSSON 1983).

Macrophytes reduce currents and wave action during the growing season, thus facilitating particle sedimentation (JAMES & BARKO 1990) and the protection of shore areas from erosion (SCHRÖDER 1988, VERMAAT et al. 2000). The magnitude of these two processes largely depends on plant growth form (VERMAAT et al. 2000) and is especially pronounced near river mouths (WALSER 1995).

During the 1960s Lake Constance was subject of a large sedimentological project (MÜLLER 1966, 1971, SCHMITZ 1971), during which 143 sediment samples from the main basins and 71 samples from the littoral zone were analysed. A more detailed investigation of littoral sediments was undertaken by WAGNER (1968) in the bay of Friedrichshafen in the delta areas of the rivers Schussen and Argen. However, no lakewide, detailed data on the littoral sediment composition have ever been collected.

As part of a lakewide mapping of submersed vegetation in 1993 (SCHMIEDER 1997, 1998) almost 700 samples of littoral surface sediments were analysed. Based on these data, the intent of the current study was to provide a detailed overview of littoral surface sediment composition of Lake Constance on a regional scale and to establish factors and processes that contribute to the observed patterns.

Study area

Lake Constance is the second largest prealpine Central European lake by area and volume after Lake Geneva. Lake Constance is oriented from north-west to south-east and has two main basins, Upper Lake and Lower Lake (Fig. 1, Table 1). The water surface is strongly influenced by wind-activity, occasionally generating large waves especially in the bay of Friedrichshafen (PIEROOTH & PLATE 1992) (Fig. 1). Lake Constance is a

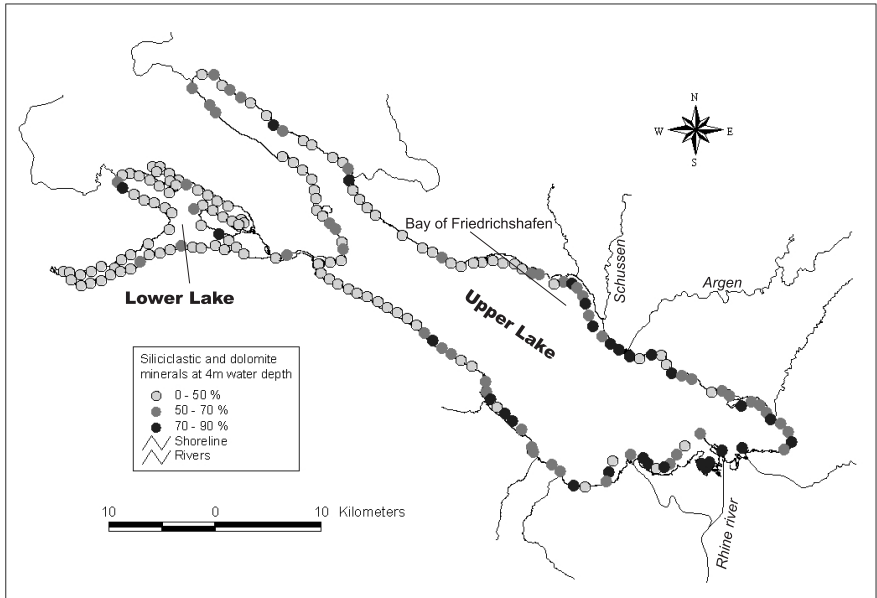


Fig. 1. Spatial patterns in siliciclastic and dolomite mineral contents of littoral surface sediments at 4m water depth.

Table 1. Morphometric data of Lake Constance (47° 39' N, 9° 18' E) and its catchment area according to (BRAUN & SCHÄRPF 1994).

	Upper lake	Lower lake	total
Altitude a. s. l. (m) at middle water level	395.45	395.26	–
Surface area of water (km ²)	500.00	71.5	571.5
Volume (10 ⁹ m ³)	47.678	0.810	48.49
Maximum depth (m)	254	46	–
Mean depth (m)	95	11	85
Mean range of annual water level fluctuation (m)	1.50	1.48	–
Length of shoreline (km)	186	87	273
Littoral zone (area above 10m water depth) (km ²)	57	18	75
Mean outflow (10 ⁹ m ³ /yr)	11.1	11.7	11.7
Theoretical Residence time (yr)	4.3	(0.07)	–
Catchment area (km ²)	10919	568	11487

phosphorus limited, mesotrophic hard water lake with biogenically induced calcite precipitation. The total catchment area of 11,500 km² is approximately 20 times the size of the lake surface area and is distributed over three countries, Switzerland with Liechtenstein (48 % of the area), Germany (28 %) and Austria (24 %). More than 90 % of the water flow originates from the Alps and reaches the eastern part of the Upper Lake via three inflows: Alpenrhein (River Rhine), Bregenzer Ach and Dornbirner Ach.

Geologically, the lake basin is situated in the molasse basin of the northern alpine foothills and was mainly formed by water and ice activity during the last Quaternary glaciation period more than 15,000 years ago (GEYER & GWINNER 1991). After the withdrawal of the ice, eroded material from the alpine and subalpine catchment area entered Lake Constance via the Rhine river and the smaller tributaries. Mesozoic carbonates and metamorphic schists from the northern alpine region as well as Tertiary molasse sandstones are the main sources for suspended matter and gravel deposited in the lake from the catchment area as well as from the littoral bedrocks. In addition to allochthonous mineral inputs, internal lake processes also produce autochthonous sediment material, e. g., organic carbon and biogenic calcite.

Methods

Sediment sampling and analyses

From July to September 1993 approximately 800 samples of surficial sediments (≤ 20 cm depth) were taken with Ekman-Birge samplers at water depths of 1 m, 2 m, 4 m, and 8 m along transects that ran perpendicular to the shoreline approximately 1 km apart. In cases when sample loss was visually obvious or if nonsatisfying results were obtained for other reasons, sediment samples were taken by snorkeling and filled directly into plastic boxes. The samples were transported to the laboratory in closed plastic boxes stored in a cooler and were frozen until further processing.

Grain size analyses were performed by gravimetric sieve analyses for the sand and gravel fraction (RETSCH VE 1000 sieving machine with 200×50 mm sieves according to DIN ISO-3310/1) combined with a laseroptical particle counter analyses for the silt and clay fraction (GALAI CIS 1, L. O. T. Inc.).

To separate the sand and gravel fractions from the finer silt and clay fractions, the wet sample material was suspended in water and quantitatively sieved through a $63 \mu\text{m}$ micromesh sieve under a fine jet of water using a sieve machine. This procedure was continued until the run-off water was clear. The run-off water containing the suspended silt and clay fraction was collected in beakers. After a sedimentation period of 12 hours, the clear supernatant water was carefully decanted. The remaining wet silt and clay fraction was homogenized and transferred into plastic boxes (0.851 volume).

For the laseroptical grain size analyses, an aliquot of 10 ml suspension was transferred into a 100 ml polyvinyl chloride wide-neck bottle, filled with water to which 1 ml of a 25 % ammonia solution was added. The sample was shaken in a Bühler SM 25 shaker at 200 r. p. m. for at least 3 hours to prevent particle aggregation. From the suspended sample an aliquot of 2–5 drops was transferred into a quartz glass cuvette and filled up with 50 % glycerine solution. During the laser measurement the sample was stirred by a magnetic stirrer to keep particles in suspension. Three subsamples were measured by the laseroptical particle counter for one minute each. From all three subsamples a sum curve of different grain sizes was generated. The percent grain size distribution of the fine fraction was related to the total dry weight of the silt-clay fraction to obtain total weights of the different grain size fractions comparable to the results of the sieve analyses of the sand fraction.

The dried sand fraction (drying temperature: 60 °C) was gravimetrically analysed in a RETSCH VE 1000 compound sieve tower with 1.4 mm vertical sieving amplitude using the following 8 sieve mesh sizes: 2000–1600 µm, 1600–1000 µm, 1000–630 µm, 630–400 µm, 400–250 µm, 250–160 µm, 160–100 µm, 100–63 µm. The procedure lasted about 5 minutes for each sample. The single sieve fractions were dried, weighed and stored separately in plastic boxes for further analyses.

The determination of inorganic carbon was performed from the dried silt-clay fraction (drying temperature: 60 °C). Larger grain fractions (>63 µm) were excluded from carbonate analyses. Their usually small sample size could have resulted in strongly biased results, if, for example, single mollusc shell particles or silicate pebbles were present in the sample. To include all grain fractions in the analyses much larger sediment samples would have had to be taken to get representative results.

Samples for inorganic carbon analysis were pulverized and homogenized in a mortar mill (FRITSCH Pulverisette 2). Approximately 500 mg aliquots of the samples were digested in 16 % hydrochloric acid (reaction time about 2 min) and the CO₂ content was measured with a LECO CS-125 infrared detector. The percentage of CO₂ was then converted to inorganic carbon.

Mineralogical analyses were performed with a SIEMENS Kristalloflex D 500 X-ray diffractometer using an angle range of 4 to 70 degrees. By relating the height of the measured reflection peaks to the precise measurements of inorganic carbon content, the portion of the carbonate minerals calcite and dolomite could be quantitatively determined (BEHBEHANI 1987). The amounts of silicate minerals (quartz, clay minerals, etc.) in the sediment samples were semiquantitatively measured by comparing their peak heights to those of the carbonate minerals.

The analytical data were entered into the spreadsheet program MS Excel and integrated into the relational data base of a Geographic Information System (GIS).

GIS-Integration and analyses of data

Lines of sediment sampling transects were digitised from aerial photos with the photogrammetric analyser VISOPRET (Zeiss, Jena) and the CAD-Software Microstation (Bentley Systems, USA). The transect data and a digital depth model of Lake Constance (BRAUN & SCHÄRPF 1994) were imported into the GIS-Software ARC/INFO (ESRI, Kranzberg). From the digital depth model contour lines of sampling depths were created. Both line sets were intersected to get the coordinates of the sample sites. The attribute data entered into a MS EXCEL spreadsheet were combined with geometric data after import into ARC/INFO. Maps of grain size distribution and mineralogical characteristics were created with ARCVIEW (ESRI, Kranzberg). Effective fetch distances (HAKANSON & JANSSON 1983) of sediment sample points at 2 m water depth were calculated with an ARCVIEW script (LEHMANN 1998) and displayed as bars.

Statistics

The mineralogical data were subjected to Analysis of Covariance (ANCOVA) to study the relations between mineral contents with depth. Since the sediment sample con-

sisted in multiple components, autocorrelation of proportions of mineral contents were neglected. The following linear regression model was used:

$$y_{ij} = \mu + \tau_i + \beta x_{ij} + \delta_i x_{ij} + \varepsilon_{ij}, \quad i = 1, 2, \dots, k \quad j = 1, 2, \dots, n_i$$

(y_{ij} – dependant variable, x_{ij} – independant variable, β – slope, $\mu + \tau_i$ – axis intercept + treatment effect, $\delta_i x_{ij} + \varepsilon_{ij}$ – interaction + error term).

In case of significant interactions with depth, separate regression functions were calculated for each depth, respectively.

ANCOVA was done assuming independence of all observations. Analyses were performed with S-PLUS 6.1 (Insightful Corp.).

Results

Spatial patterns in the distribution of siliciclastic and dolomite minerals in the sediments

In Lake Constance siliciclastic and dolomite minerals are generally common in the littoral surface sediments. However, with a range of 10–85 % of weight, the contribution of siliciclastic minerals to sediment weight is highly variable (Fig. 1).

The contribution of siliciclastic and dolomite minerals to sediment composition at 4 m water depth was much higher in the eastern parts of the lake than in the western parts, and reached more than 70 % at many sites (Fig. 1). The highest siliciclastic mineral values were observed near river mouths.

Relations among the mineralogical variables

Table 2 shows the analyses of variance tables for the linear regression functions between calcite and other mineral sediment components. The calcite content is significantly influenced by clay mineral content and depth. In addition, the linear regression function between Calcite and Claymin is significantly different at the 4 depth levels (Table 2).

Relationships of other minerals to Calcite showed no significant interactions with depth (Table 2) and a combined regression function was calculated for all depth levels.

As evidenced from the spatial patterns, in the proportion of sediment constituents, a strong negative association existed between calcite and most other minerals in sediment surface samples at all depth levels. This is reflected by negative regression coefficients in all regression functions (Table 2) with high R^2 for the regression functions of Calcite with clay and Quartz respectively, and low of Calcite with Dolomite.

Table 2. Influence of Claymin-, Quartz-, Dolomite-content and Depth on Calcite-content of surface sediments (Analyses of Co-Variance Tables: Num. d. f. – numerator degrees of freedom; F-value, p-value – probability value of $P > F$). The respective regression functions are listed below the tables.

Variance Source	Num. d. f.	F-value	p-value
A: Calcite ~ Claymin * depth			
(Intercept)	1	5461.891	<0.001
Depth	3	3.916	0.0087
Claymin	1	1737.214	<0.001
Depth : Claymin	3	2.765	0.0411
Linear regression functions of Calcite with Claymin at different depths (y_1 – Calcite at 1 m water depth, y_2 – Calcite at 2 m water depth, ..., x – Claymin):			
$y_1 = 56,929 - 0.62 x$	$R^2 = 0.8804$		
$y_2 = 57,157 - 0.6151 x$	$R^2 = 0.8428$		
$y_4 = 54,213 - 0.5548 x$	$R^2 = 0.876$		
$y_8 = 51,747 - 0.5179 x$	$R^2 = 0.834$		
B: Calcite ~ Quartz * depth			
(Intercept)	1	2117.991	<0.001
Depth	3	2.839	0.0372
Quartz	1	467.535	<0.001
Depth : Quartz	3	0.168	0.9187
Linear regression function of Calcite with Quartz (y – Calcite, x – Quartz):			
$y = 18.8079 - 0.1995 x$	$R^2 = 0.662$		
C: Calcite ~ Dolomite * depth			
(Intercept)	1	1092.376	<0.001
Depth	3	2.078	0.1018
Dolomite	1	160.617	<0.001
Depth : Dolomite	3	2.142	0.0936
Linear regression function of Calcite with Dolomite (y – Calcite, x – Dolomite):			
$y = 11.3790 - 0.1107 x$	$R^2 = 0.415$		

Spatial patterns in distribution of grain sizes

The littoral sediments of Lake Constance varied in total mean grain size between 38 μm and 1000 μm , a range that encompasses the spectrum from the coarse silt to the coarse sand fraction. Mean grain size decreased with increasing water depths (Fig. 2).

Mean grain sizes of more than 330 μm diameter, which are representative for the coarse sand fraction, were more common in south-western exposed shore areas, such as the north shores of the Upper Lake and Lower Lake. The bay of Friedrichshafen and the westernmost part of the Upper Lake represented exceptions to this pattern. At the southern shores of the lake, mean grain sizes were mainly below 330 μm , with only few local exceptions.

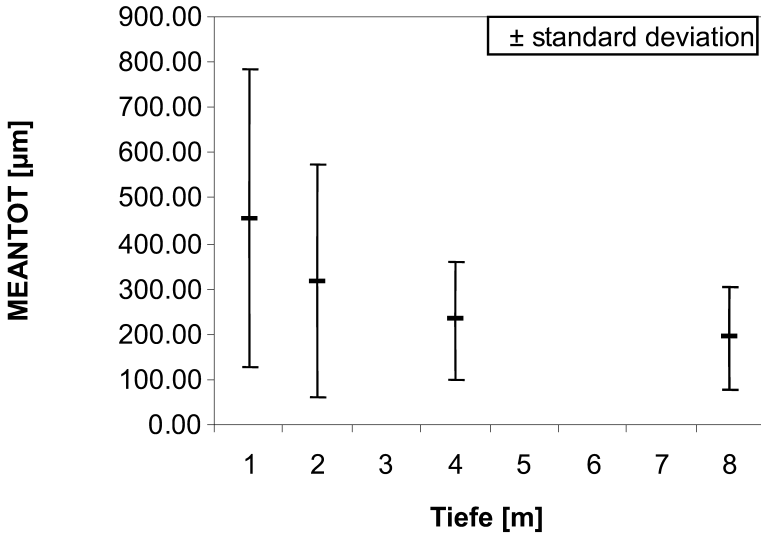


Fig. 2. Mean (\pm SD) grain size of all samples from each of four water depths.

The clay and silt fraction ($< 63 \mu\text{m}$) locally represented up to 92% of the whole sample weight, and was by far the dominant size fraction in littoral sediments of north-eastern exposed shores of Lake Constance (Fig. 3).

In general, the results of the granulometric sediment analyses showed a clear regional division into north-eastern exposed shore areas with mainly fine-grained sediments and south-western exposed shore areas with mostly coarse-grained sediments. Areas within the influence of tributaries represented exceptions to the above pattern in sediment composition.

The effective fetch distances for the main direction of strong winds from south-west show a relation to the proportion of grain fraction $< 63 \mu\text{m}$ (Fig. 3). According to the shape of the lake, the highest fetch distances occurred along the eastern section of the north shore of the Upper Lake, decreasing to the west. For the much smaller Lower Lake analogous results were obtained.

Discussion

Our results indicate that quality and distribution of mineral components in littoral sediments of Lake Constance are the outcome of different formation sources and processes.

Ekman-Birge samplers were used for sampling, even though they sometimes lose proportions of the samples. In cases when sample loss was visually obvious or if nonsatisfying results were obtained for other reasons, sediment

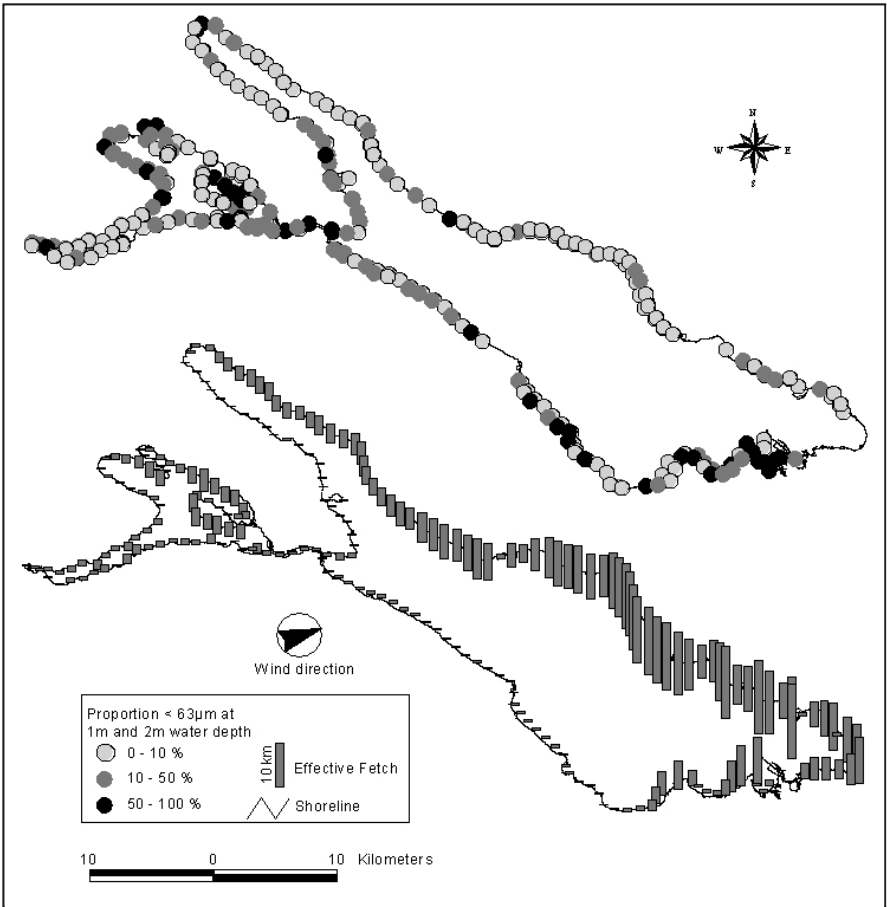


Fig. 3. Spatial patterns of the proportion of grain sizes <math>< 63 \mu\text{m}</math> of sediments at 1 m and 2 m water depth and effective fetch distances of the main direction of strong winds indicated by the wind direction symbol.

samples were taken by snorkeling and filled directly into plastic boxes. Nevertheless, the analyses done could be obscured by the used sampling device.

The observed east-west gradient in the distribution of allochthonous siliciclastic and dolomite minerals can be explained by the location of the main tributaries entering the eastern part of the Upper Lake. The allochthonous mineral spectrum found in the lake sediments directly reflects the geology of the catchment area. Alpine carbonates and metamorphic rocks as well as molasse sandstones and moraine material are the main sources for the allochthonous fraction of Lake Constance sediments and form as well the littoral bedrocks. Therefore, the amounts of allochthonous siliciclastic and dolomite components

are high in the eastern parts of the Upper Lake and lead to a “dilution” of the autochthonous sediment components (MÜLLER 1966, 1971).

The river mouths in the western parts of the Upper Lake and the Lower Lake represent exceptions from this general east-west gradient, but support the interpretation of an allochthonous source of the siliciclastic and dolomite minerals in the sediment.

The west-east gradient of calcite contents in littoral sediments ≥ 4 m depth can be explained by autochthonous processes. The high calcite amounts in Lower Lake and western Upper Lake likely reflects autochthonous carbonate production. In hardwater lakes biogenic carbonates contribute substantially to the calcite minerals in the littoral sediments (SCHNEIDER et al. 1983). The origin of these biogenic calcites cannot be determined by chemical or mineralogical analyses but can be microscopically deduced from the occurrence of characteristic particles. Especially Charophytes seem to be an internal source for sediments and play a major role in autochthonous calcite accretion in the littoral zones of lakes (BEHBEHANI 1987, SCHNEIDER et al. 1983). However, main growing areas of submersed macrophytes and especially Charophytes are situated in the western parts of Lake Constance, particularly in the littoral zone of the Lower Lake (SCHMIEDER 1997, 1998), where biogenic carbonate sediments can reach a thickness of several meters (SCHÖTTLE 1969).

The strong negative correlation between the Calcite and Clay minerals indicates that high sedimentation rates of river borne suspended matter constrain photosynthetic activity, therefore limiting macrophyte growth in the eastern part of the lake (SCHMIEDER 1998). The absence of higher calcite contents in surface sediments of the eastern lake part therefore originates not only from high input of riverborne suspended solids or shore erosion, but also from the longterm absence of macrophytes and particularly of charophytes. In fact, there is a strong relation between the longterm regional distribution pattern of *Chara contraria* (SCHMIEDER 1997, 1998) and the calcite content of littoral sediment surface. However, depending on the exposure of a site, biogenic sediment accretion can be eliminated by winter storms (SCHMIEDER 1995), which may explain why the regional pattern of calcite distribution observed at ≥ 4 m depth is not discernable at ≤ 2 m depth.

Our data from Lake Constance indicate that the regional patterns of the mineral composition can at least be partly explained by both external and internal factors, thus increasing our understanding of natural sources and processes of littoral sediment accretion. However, the shore of Lake Constance is heavily influenced by man. Artificial material deposits and shore constructions superpose natural factors especially at the shallow sites. The regional patterns in the mineral composition of undisturbed littoral surface sediments are therefore most apparent at depths of 4 m and below.

The different sources of sediment particles and internal lake processes must also be taken into account for the interpretation of our granulometric results. Generally, mean grain size decreased with water depth in Lake Constance. The spatial patterns of grain size mean and the proportion of fine material in surface sediment at 2 m depth show a relation to the effective fetch (HAKANSON & JANSSON 1983) for the main direction of strong winds from southwest (MÜHLEISEN 1977).

Generally, wave action causes a sorting process of grain sizes within littoral surface sediments resulting in a typical offshore fining (HAKANSON & JANSSON 1983, MÜLLER 1966). Therefore, the regional patterns of grain sizes in littoral sediments often reflect wave exposure, and can be modeled by factors such as fetch, water depth and slope (PETTICREW & KALFF 1991). The present study revealed regional differences in grain sizes according to fetch distances. These results are in partial contrast to the findings by MÜLLER (1966), who generalised the littoral sediment texture types of Lake Constance as a sequence of "sand" to "siltsand" that extends from the shore to the slope.

An exemption from the general spatial pattern in sediment composition is the bay of Friedrichshafen, which is exposed to the highest fetch distances measured in Lake Constance. Mean grain sizes do not exceed 330 μm , even in the shallowest parts of the bay. However, the sediment sorting process by waves is not only affected by factors associated with wind fetch, but also depends on the extent of the littoral zone. It affects the wave amplitude and wave energy at a distinct depth and shore distance, and therefore the wave erosion potential. The littoral zone of the bay of Friedrichshafen extends more than 1 km from the shore (mean slope 1%) and completely dissipates the energy of even large waves. Furthermore, the tributary "Schussen" entering the bay of Friedrichshafen contains high amounts of fine sediment particles up to 100 mg/l (WAGNER 1976, WAGNER & ZAHNER 1964). Every year 30,000–50,000 t of suspended material are widely distributed in the littoral area of the bay. This occurs mainly during the summerly high water period, when the lower course of the river becomes a backwater of the lake (DITTRICH & WESTRICH 1988). In addition, large fields of submersed macrophytes reduce currents in the littoral of the bay (WALSER 1995). Generally, macrophyte beds increase the sedimentation rate of fine-grained material in littoral zones during the growing season (BARKO & SMART 1986, JAMES & BARKO 1990, PETTICREW & KALFF 1992). Sedimentation in macrophyte beds has been suggested as an important source of nutrient renewal (BARKO et al. 1991, BARKO & JAMES 1997, PETTICREW & KALFF 1992) that stimulates macrophyte growth, thus increasing sedimentation rates. This positive feedback mechanism increases the colonizable surface area for macrophytes (CARPENTER 1981). Macrophyte presence or absence is therefore another factor in the littoral sediment prediction model proposed by PETTICREW & KALFF (1991). However, macrophyte abundance and density in

Lake Constance decreases generally from West to East, so that the shores in the eastern parts of the lake are less protected from erosion by macrophytes.

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