Journal of Paleolimnology **29:** 141–154, 2003.

Classification of lacustrine sediments based on sedimentary components

Douglas Schnurrenberger[1,*], James Russell[1,2] and Kerry Kelts[†1]
[1]*Limnological Research Center, Department of Geology and Geophysics, 220 Pillsbury Hall, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis MN 55455, USA;* [2]*Dept of Ecology, Evolution, and Behavior, University of Minnesota, 1987 Upper Buford Circle, St. Paul MN 55108, USA;* [*]*Author for correspondence (e-mail: schno005@tc.umn.edu)*

Received 2 February 2002; accepted in revised form 3 August 2002

Key words: Core description, Lake sediments, Limnogeology, Paleolimnology, Sediment classification

Abstract

This paper introduces a flexible sediment classification scheme for modern and ancient lake sediments employed at the Limnological Research Center, University of Minnesota. Our classification scheme emphasizes the macroscopic structure and microscopic components of the sedimentary matrix (clastic, chemical and biological) and can be applied to a wide range of lacustrine settings. Such a classification scheme is necessary to i) facilitate communication and collaboration between the highly interdisciplinary community of scientists that study lacustrine archives, ii) create a structure for comparative lacustrine sedimentological studies, and iii) take greater advantage of the great potential information recorded by changing depositional environments. Such a development is needed in light of current and planned Global Lake Drilling efforts and to expedite the creation of on-line, searchable databases of global lacustrine archives. A more comprehensive treatment of the topics discussed in this paper is available at: http://lrc.geo.umn.edu/services/handbook/sedclass.html.

Introduction

Lakes are dynamic response systems that integrate environmental, climatic and tectonic forcings into a continuous, high-resolution archive of local and regional change (Gierlowski-Kordesch and Kelts 2000). A key goal of paleolimnology is to develop continental paleorecords of global change comparable to those available from oceans or ice cores. Lacustrine records can potentially match these records and yield substantially greater temporal and spatial resolution.

Much of our early understanding of continental Quaternary paleoclimate change came from the study of fossil pollen in lakes, bogs and peatlands (e.g., Von Post (1916)). Today numerous additional proxies of past climatic change are routinely applied in the analysis of lacustrine sedimentary records: isotopes (Wolfe et al. 2001; Talbot 2001), diatoms (Stoermer and Smol 1999), sedimentary organic matter (Laerdal and Talbot 2000; Meyers and Teranes 2001), and sediment lithology and facies (Talbot et al. 1984; Verschuren 2001; Valero-Garcés et al. 1997).

The development of lacustrine sedimentology as a global science requires a uniform approach to study the great diversity of continental sediments. A coherent approach to sediment description and classification should form the basis for specialized geochemical and paleoecological studies, and would enhance the quality of paleolimnological and limnogeological studies by providing standardized methods for studying underutilized lithological information on past environmental dynamics (e.g., Gierlowski-Kordesch and Kelts (1994), Valero Garcés et al. (1995), Valero-Garcés et al. (1999)) as well as facilitate comparative studies of lacustrine facies modeling (Verschuren 2001; Talbot and Allen 1996).

This paper presents a flexible classification scheme that is based on the observation of macroscopic features and microscopic observation of sedimentary components for use with recent and ancient (lithified) lacustrine sediments, similar to the component-based classification scheme employed by the Ocean Drilling Program in describing marine sediments. Our effort is stimulated by the recent inception of the Global Lake Drilling Program (GLAD) and the development of a National Lacustrine Core Repository (LacCore: Schnurrenberger et al. (2001)), both of which demand a uniform scheme for describing lacustrine sediments. The goal of this contribution is not to completely revise sediment classifications long in use by investigators working with lacustrine sediments. Rather, we strive to integrate existing classification schemes and practice into a synthetic whole capable of handling the range of sediments possible in lacustrine settings.

Our proposed scheme is intended to serve as a device to be employed in the initial core description (ICD) prior to sampling for specialized paleolimnological studies. A component-based classification system is ideal at this early stage when it is important to understand the full range of sedimentary components available for multiproxy paleolimnological reconstruction, and to develop an understanding of sedimentary structures that may guide sampling strategy. Furthermore, such a system emphasizing sedimentary components can be easily incorporated later into a searchable database such as that developed by LacCore for multi-investigator studies.

The first part of this paper will review the history of conceptual approaches to lake sediment classification, and conclude with a review of classification schemes for lake sediments. The second part of the paper outlines a component-based scheme for lake sediments used in the Limnological Research Center Core Facility in a wide variety of lake types (hypersaline, saline, oligotrophic, etc.). A final section outlining terminology and nomenclature for beds, laminations and sedimentary structures follows the sediment classification section.

History

Lakes - background

Modern lakes exhibit enormous physico-chemical variability, in terms of their origin, size (depth, area), morphology, water chemistry (hypersaline to fresh), trophic state, catchment size, groundwater interactions, and regional climate, all of which act to influence the nature and rate of sedimentation into the various lacustrine environments. This great variety in input conditions produces an astonishing array of potential sediment types for ancient and modern lakes. Furthermore, due to lakes' short residence times and high sedimentation rates, changes in input parameters can produce sudden changes in the sedimentology of lacustrine sedimentary packages over intervals of a few centimeters (Talbot and Allen 1996). The abrupt shifts and astonishing compositional diversity of lacustrine sediments distinguish them from their marine counterparts, and require a special focus on lacustrine sediment classification.

Lake sediment classification

Relatively little interest has been shown with respect to lake sediment classification, particularly when compared with that devoted to other sediments and sedimentary rocks (e.g., marine sediments). Paleoecologists have focused their efforts primarily on fossil components of sediment (e.g., pollen or diatoms) and have often lacked the training or interest to describe the sedimentary matrix in detail. More geologically oriented investigators have borrowed terms from the marine sciences to describe lacustrine sediments.

Tröels-Smith (1955) developed a comprehensive classification for sediments from organic-rich, north temperate lakes and wetlands. The classification was originally designed primarily as a field-based classification but could be expanded to include laboratory study. This classification has been widely applied by European paleoecologists but only rarely outside of Europe, despite the urging of several handbooks of paleoecological techniques (Birks and Birks 1980; Faegri and Iversen 1964).

The advantages of the Tröels-Smith (1955) classification lie in its emphasis on describing sediment components rather than attempting to force a small set of terms onto compositionally diverse sediments. The Tröels-Smith scheme breaks sediment types into major categories based on dominant components (e.g., siliceous, calcareous, organic) and modifies the major term to include the presence of components in lesser abundance. The primary disadvantages of the Tröels-Smith scheme lie in its use of Latin terms (e.g., *Argilla steatodes* for clay), the reliance on macroscopic field description of extruded cores, and its inability to deal with sediment types commonly encountered outside of northern temperate regions. Kershaw (1997) attempted a revision of the Tröels-Smith classification, replacing English terms for Latin and dropping the binomial architecture. Although useful, the system as envisioned by Kershaw (1997) still lacks general applicability for the great variety of lacustrine sediments.

Despite its limited application outside of Europe, a number of non-Latin terms described in the text of Kershaw (1997) paper have come to find widespread application, particularly among North American paleoecologists. For example, the term ''gyttja'' (Faegri and Iverson 1964) can be found as a descriptor in palynological papers where an attempt is made to characterize sediment types. Dean (1981) defines ''gyttja'' as sediment containing more than 20% amorphous organic matter. The Tröels-Smith (1955) equivalent of a ''gyttja'' is a *Limus detrituosus*, a ''mudlike, homogeneous, non-plastic deposit, consisting of particles or colloids $<$ 0.1 mm . . . '' composed of decayed and decomposed microorganisms and higher plants (Tröels-Smith (1955), p. 62).

Unfortunately, others have used the term more as an synonym for organic lake sediments generally, with a profusion of sediment types such as ''sandy gyttja,'' ''calcareous gyttja,'' ''muddy gyttja,'' and so on. For example, Israelson et al. (1997), p. 256 describe a sediment as a ''grayish, carbonate-rich silt gyttja,'' although this sediment in all cases contains over 50% carbonate. Onac et al. (2001) describe Eemian lacustrine deposits from Romania as a succession of lacustrine clays, dark and light brown gyttjas, clay gyttjas, and brown to blackish sandy drift gyttja. While we do not wish to over-emphasize terminology, we fear the term gyttja has been misused so frequently as to have been rendered meaningless. Hence, we follow the advice of Merkt et al. (1971), p. 610 who state that ''Die Bezeichnung, 'Gyttja' wird hier nicht mehr verwendet'' (The term 'gyttja' will no longer be used).

Merkt et al. (1971) proposed a comprehensive lake sediment classification scheme for use in mapping lacustrine deposits. The proposed classification is based on sediment components readily observable in the field and expands considerably the range of sediment types found in lakes, though primarily concentrating on lacustrine deposits in Northern Europe. A number of useful distinctions are proposed in the Merkt et al. (1971) classification. For example, the term ''Seekreide'' is proposed for carbonate-rich lacustrine sediment – a term preferable to ''marl'' which is widely used in North American limnogeology (Dean et al. 1985). Despite its many advantages, this system has been little used, probably as it was published only in the original German and not widely read.

Purpose and concept of the proposed scheme

The LRC sediment classification scheme is based on the recognition that lake sediments are genetically diverse, with components derived from a variety of sources, all of which may potentially yield important paleolimnologic information. Any given lake sediment may consist of a mixture of detrital sediment grains, algal or terrestrial organic matter and inorganically precipitated carbonate and saline minerals, along with numerous other fossil components. The initial description of cores, and application of this classification system is based upon: 1) a general idea of the compositional variability of core material, which may hint at potential paleolimnological variability, influencing the choice of core material to study; 2) the sedimentary composition of major lithologic units, which may assist multicollaborator projects to define what types of specialized studies can be done on which core sections; and 3) the recognition of potential sedimentary unconformities or bedding structures, such as turbidites, which can create spurious data points in specialized studies and must therefore guide core sampling strategy.

Results are best achieved by beginning any project with a multi-component, macro- and microscopic description and classification of the sediments (lithologic units). This crucial step is, to the extent possible, descriptive and devoid of genetic interpretation (with the caveat that the ''simple'' recognition of clastic vs. authigenic minerals is to some extent interpretive). Subsequent steps in data analysis may involve the application of limnogeologic principles and studies of modern sedimentary environments to define facies and subfacies, units which represent more or less dissimilar depositional environments, or directly proceeding to studies of fossil chironomids, diatoms, etc. guided by a robust sedimentology. A fuller discussion of the topics discussed below can be found at: http://lrc.geo.umn.edu/services/handbook/sedclass.html.

The classification scheme

The sediment classification system employed at LRC relies on two primary types of observations: 1) the macroscopic structure of the sediment, i.e., sedimentary structures and textures (bedding features, texture, color) and 2) the identification of the major and minor components of the sediments, e.g., clay, carbonate mud, peat. These two observations are formalized into the scheme below:

1. Color + 2. Bedding + 3. Major Modifier + 4. Principal Name + 5. Minor Constituents
e.g. Dark reddish brown, massive, feldspathic clay with carbonaceous debris and trace gastropod fragments.

Terms 1–2 describe macroscopic features observable on split or cleaned sediment cores or on outcrops; analysis of these features is discussed in the following section. Terms 3–5 describe the nature of the components that comprise the sediments. These components must be analyzed by microscopic observation of smear slides and coarse-fraction sievings, as discussed in the section " Component based analyses". The two types of data, macroscopic structure and microscopic compositional analysis, are integrated into the formalized description above.

Core description

A principal task of the core lab sedimentologist is the bed-by-bed description of the sediments or sedimentary rocks within the cores; this description is recorded on a Visual Core Description form (lrc.geo.umn.edu/services/handbook/VCDform.pdf). In the routine description of a section, the sedimentologist first defines bedding on the basis of variations in sediment lithology, color, sedimentary structures, or other pertinent characteristics, and then proceeds to describe the four major characteristics of each bed: (1) lithology and color, (2) thickness and inclination, (3) sedimentary structures and bedding planes, and (4) degree of disturbance of the core stratigraphy by the coring process. Sets of beds that constitute a sedimentary facies assemblage (e.g., rhythmites, fining-upward sequence) may be identified at this stage.

Macroscopic observation: bed color and texture

Bed color is determined by comparison with Munsell Soil Color Charts. Color should be determined as soon as the core is split and while still wet so that drying and oxidation do not alter its original color. Texture is noted by rubbing small quantities of sediment between the fingers or in the mouth. A rapid grain size estimator may be used to quantify sediment texture. Other aspects of sediment texture (e.g., roundness, sorting) may be estimated macroscopically in coarse-grained sediments or await microscopic smear slide study (see below).

Bed/lamination thickness and other features

Individual beds or laminations may vary substantially in thickness from several meters to only millimeters in thickness. Terminology for these features has been exhaustively covered in several texts (Campbell 1967; McKee and Weir 1953; Reineck and Singh 1980) and will be only briefly discussed here.

Beds are defined as being >1 cm in thickness according to the following terms: **very thick bedded** (>100 cm), **thick bedded** (30–100 cm**), medium bedded** (10–30 cm thick), **thin bedded** (3–10 cm), and **very thin bedded** (1–3 cm) (McKee and Weir 1953). Laminations are less than 1 cm in thickness.

Sets of beds or laminations are repetitive groups of compositionally similar laminations or very thin to thin beds (McKee and Weir 1953) that alternate more or less regularly up the core. Rhythmic or cyclic deposition of laminations or beds is produced by a variety of mechanisms which produce a variable sediment input signal (Glenn and Kelts 1991). Individual beds or laminae within a set should be described according to the sediment classification scheme and a composite description of the set should be formulated which identifies the thickness and cyclicity/rhythmicity of the laminations. When appropriate, it may be possible to identify laminae sets as **varves** when an annual rate of lamination deposition can be independently substantiated (e.g., by radiometric dating).

Laminated sediments are common in lake cores, exhibiting large compositional changes over relatively short intervals. To describe each lamination or bed separately at this stage would not only be time-consuming but also detract from the essential nature of the sediment - the composition and arrangement of laminations. For these reasons, laminated sediments are classed as laminites when indurated and as laminated muds (non-biogenic) or oozes (biogenic) when soft, with major and minor modifiers indicating the nature of the individual laminations (e.g., laminated muds consisting of mm-scale alternating diatom oozes and sapropelic clays).

Sedimentary structures

Sediments or sedimentary rocks may contain one or more sedimentary structures. These structures may be primary (formed during deposition) or secondary (formed after initial deposition of the sediments). Primary and secondary sedimentary structures may result from mechanical processes (e.g., graded bedding, water-escape structures) or may be biogenic (e.g., bioturbation structures, trace fossils) or chemical (e.g., salt) in origin. Sedimentary structures can provide extremely important and diagnostic information about lacustrine depositional environments, such as the recognition of soil features, carbonate breccias, or microbialite structures (Talbot and Allen 1990). Other types of sedimentary structures can represent potentially important sedimentary hiatuses or reworked features such as sediment slumps or turbidites, which if not recognized and described can confound later studies. Types of sedimentary structures are too numerous to recount here and the reader is referred to texts that treat the subject in greater detail (e.g., Reineck and Singh (1980)). Unfortunately few texts or papers treat sedimentary structures typical of lakes in any great detail (see however Last and Vance (1997)).

Bedding planes

The nature of the bedding plane or contacts separating lithologic units holds important information concerning the transition from under-to overlying beds (erosive vs. constant deposition). Bedding planes (contacts) may be described as **sharp** (change noted over less than 1 mm), **diffuse** (change noted over 1 mm – 1 cm) or **indistinct** (change noted over more than 1 cm). The contact between beds may be described as either planar or wavy to gradational, though this distinction may prove difficult in core material vs. outcrops. As noted above, the recognition of bedding planes is extremely important, particularly as sharp bedding planes can often result from processes which leave significant sedimentary hiatuses.

Core disturbance

It is equally important to note evidence for disturbance of the core during the coring or drilling process. Beds and laminations may deform during coring, and single drive piston coring may produce sediment gaps due to the coring process or gas-expansion after core retrieval. Piston coring may also result in bed flexure or bowing from soft sediment deformation under vacuum. Drilled indurated sedimentary rock may show a variety of types of drilling disturbance.

Component-based analyses

The second major part of our sediment classification system involves the identity and estimated abundance of the various components of the sedimentary matrix. For rapid determination of sedimentary component abundance, we employ smear slide analysis. Description of sediment smear slides should be a routine analysis for sediment classification. Crystal morphologies and other optical properties allow the identification of different carbonate (aragonite versus calcite or dolomite), saline (gypsum and halite) and silicate (quartz, clay minerals, plagioclases, volcanic glass) minerals. Biogenic components (diatoms, organic matter, mollusk and so on) are also identified. The approximate percentages of the different components can be estimated. XRD analysis is often employed to identify uncommon minerals.

A component-based sediment classification

The component-based analysis scheme for lacustrine lithology is based on the three basic sediment components common to lacustrine sediments (Figure 1): (1) *Clastic sediment*, (2) *Chemical sediment*, and (3) *Biogenic sediment*. *Clastic sediments* are composed of discrete grains of generally allocthonous (quartz grains, volcanic ash) origin deposited by physical processes of sedimentation (air fall, sub-aqueous currents). *Chemical sediments* are composed of inorganic materials formed within the lake (autochthonous) by inorganic or biologically mediated chemical processes such as precipitation from solution, or recrystallization of detrital evaporites and siliceous, calcareous, or carbonaceous biogenic debris. Examples of chemical components are calcite, halite, pyrite, and gypsum. *Biogenic sediments* can comprise a variety of mineralogies (e.g., CH_2O, $CaCO_3$, SiO_2) but all are essentially the fossil remains of former living organisms (ostracodes, diatom frustules, mollusks or amor-

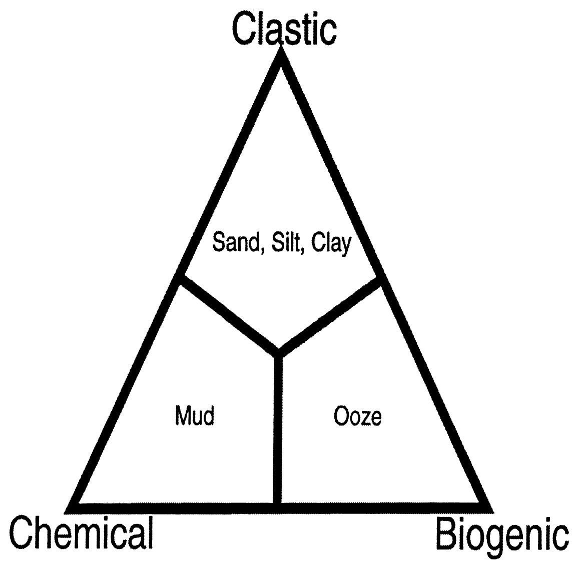

Figure 1. Ternary diagram illustrating principal names for classes of sediment.

phous algal organic matter). Examples of biogenic sediment include peat, coal, diatomites, and shelly hashes or coquinas.

We have followed the spirit of the ODP marine sediment classification (Mazzulo et al. 1988) and that of Tröels-Smith (1955) for lake sediments, both of which are component-based in nature. In these models the most abundant component (>50%) provides the principal name (e.g., sand, carbonate mud, peat) which defines the sediment class (clastic, biogenic, chemical). Major and minor modifiers are employed to further characterize the sediment components that constitute a major (25–50%) or minor (15–25%) component of the sediment. Diagnostic components occurring in trace or rare amounts can be added where appropriate at the analyst's discretion. Where there is no major component, the most abundant component is used as the principal name. Table 1 presents some of the more common sediment types.

Clastic components

Clastic sediment may comprise the bulk of sediment in large, oligotrophic lakes such as the North American Great Lakes (Rea et al. 1999) or glacial lakes (Ashley 1975) and occurs in at least small percentages in virtually all lacustrine settings. Clastic input may derive from aeolian or fluvial input (density currents, deltaic deposits), but also marginal colluvial action, particularly during periods of lake level change. The

Table 1.

Sediment Class	Sub-Class	Series	Principal Name	Major Modifiers
Clastic Sediment			Sand	Grain Size
			Clayey Sand	Roundness
			Silty Sand	Sorting
			Silt	Fabric
			Clayey Silt	
			Sandy Silt	
			Clay	
			Silty Clay	
			Sandy Clay	
			Sand-Silt-Clay	
Chemical Sediment	Evaporites		Gypsite	Mineralogy
			Gypsum	Size
				Fabric
	Carbonates		Limestone	Mineralogy
			Dolostone	Size
			Carbonate Mud	Fabric
				% Carbonate
Biogenic Sediment	Carbonaceous	Coal	Anthracite	
			Bituminous	
			Lignite	
			Peat	Plant Taxon
				Degree of Fragmentation
		Sapropel	Sapropel	
	Fossiliferous		Ooze	Organism Class (e.g., diatom/sponge)
			Hash/Coquina	Organism Class (e.g., gastropod, bivalve)

clastic component of lacustrine sediment can serve as a monitor of landscape changes, yielding signals of varying rates of basinal landscape denudation, strength of regional deflation processes, vegetation dynamics and/or tectonic activity. Clastic grains also constitute an important part of the stratigraphic record in tectonic basins where marginal clastic sediments from fringing marsh, fluvial or alluvial sources interfinger with lacustrine sediments in marginal outcrops (cf. Mediavilla et al. (1994), Armenteros and Corrochano (1994)) or occur in deep profundal sediments as distal turbidites and clay drapes (i.e., Harris (2000)).

Perhaps the greatest caveat is the interpretive nature of the category "clastic" as opposed to the more descriptive categories of chemical and biogenic. Clearly, certain minerals may be either clastic or the result of chemical precipitation (e.g., carbonates, gypsum, silicates, etc.). The only solution to this dilemma is careful geochemical, SEM or light microscopic investigation coupled with knowledge about potential sources of detrital materials within the drainage basin. A related phenomenon in saline lakes is the redeposition of original gypsum or other evaporite minerals by aeolian processes. These analyses are beyond the scope of initial sediment classification; when the origin of a mineral is in doubt we prefer to merely describe its presence and leave the interpretation of its provenance for further study.

Clastic sediment classification scheme

Clastic sediments are classified by designating a principal name describing the major textural component of the sediment (e.g., sand, silty clay; Figure 2) with the addition of major and minor modifiers to either describe less abundant components (e.g., diatomaceous clay) or to provide a more detailed description of the dominant components (e.g., vitric sand), or both. For instance, a major modifier might describe the mineralogy, fabric, or roundness of the major components while minor modifiers describe the mineralogy and texture of components in minor quantities. Major modifiers might also describe the occurrence of non-clastic components, such as chemical or biological components present in minor or major quantities. Minor modifiers (preceded by the suffix with-) describe compositional elements that comprise minor percentages (10–25%) of the sediment or trace components that are diagnostic, e.g., angular quartzofeldspathic sands with abundant molluscan debris.

The Udden-Wentworth grain-size scale (Wentworth 1922) defines the grain-size ranges and the names of

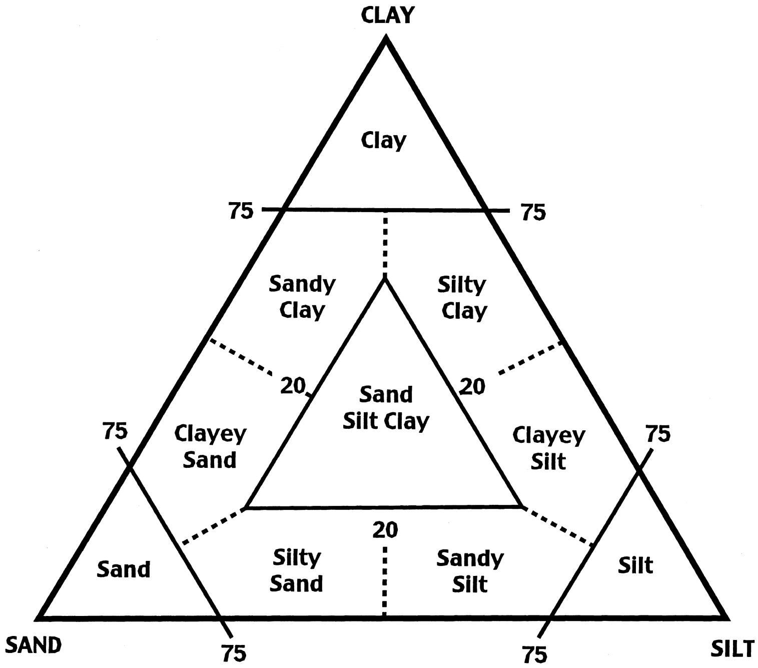

Figure 2. Ternary diagram for clastic textural groups (after Shephard (1954))

the textural groups (gravel, sand, silt and clay) and sub-groups (fine sand, coarse silt, etc.) that are used as the principal names of clastic sediment. We consciously employ the Udden-Wentworth scale rather than others (e.g., Folk (1980)) because of its finer specificity of sediment types and the abandonment of the use of the term ''mud.'' Following the suggestions of Dean et al. (1985) we have dropped ''mud'' and ''mudstone'' as imprecise terms better supplanted by ''silty clay'' or ''clayey silt'' and ''siltstone'' or ''claystone.'' Rather, in our scheme ''mud'' is used to refer to mostly fine-grained, non-lithified chemical sediments.

The suffix -stone can be affixed to the principal names sand, silt, and clay when the sediment is lithified; shale can be used a principal name for a lithified and fissile siltstone or claystone; and conglomerate and breccia are used as principal names of gravels with well-rounded and angular clasts, respectively.

The composition of clastic grains can be described by mineralogy using modifiers such as quartz, feldspar, mica, zeolitic, lithic (for rock fragments), vitric (for glass shards), calcareous, gypsiferous, or sapropelic (for detrital clasts of calcium carbonate, gypsum, and organic matter, respectively); and, in some cases, provenance (e.g., sed-lithic, meta-lithic, gneissic, basaltic, etc.).

The fabric of the sediment can be described by the major modifiers grain-supported, matrix-supported, and imbricated. The shapes of grains can be described by the major modifiers rounded, sub-rounded, sub-angular, and angular. Chemical or biogenic sediments present in major or minor amounts should be appended with percentage estimates based on smear slides where appropriate.

A large number of other important sedimentologic or mineralogic properties may be observed in particular samples (e.g., alteration of feldspars). The observer should feel free to utilize additional features at his or her own discretion.

Examples of clastic sediment

1. Medium bedded, matrix-supported, conglomerate composed of angular, quartzo-feldspathic gravel.
2. Massive, subrounded, quartz silty sand with feldspar and occasional amphibole grains.
3. Massive, black to mottled (white specks), diatomaceous silty clays in beds up to 5 cm thick.

Chemical sediment

The category of *chemical sediment* is defined to include sediments composed primarily of authigenic and diagenetic minerals formed by inorganic precipitation within the water column or post-depositionally in the sediment column. We have consciously elected not to distinguish the two processes (authigenic vs. endogenici Jones and Bowser (1978)) because of the difficulty in making such a distinction in the initial phases of core analysis.

Subcategories of the chemical sediment category are defined as evaporite and carbonate sediments. We fully realize that carbonate sediments also form in evaporative lacustrine basins but elect to divide the two categories for descriptive, not genetic reasons, primarily due to the relative abundance of carbonate sediments. As defined, the chemical sediment category contains the greatest variety of sediment types, as the range of chemical precipitates documented from lakes is quite large (e.g., Picard and High (1972), Eugster and Hardie (1978), Kelts and Hsü (1978)). We propose the term ''mud'' as the principal name for this category of sediments appended to a term describing the mineralogy; e.g., carbonate mud, gypsum mud or calcareous gypsum mud. In instances where the chemical sediment is dominantly composed of larger particles, such as sands or gravel-sized fragments, the term ''mud'' is inappropriate. We suggest that in this case the analyst append a suffix describing more accurately the texture of the particles; e.g., calcite sand, or gypsum breccia.

Evaporites

Evaporite chemical sediments are those produced from saline solutions, either precipitation by evaporative concentration in a closed-basin lake or playa, or by interaction of interstitial brines with groundwater or sediment (Eugster and Hardie 1978; Eugster and Kelts 1983; Rosen 1994). Evaporite sediments may form either by water column precipitation from a residual brine or by intrasediment growth in mud flats (Eugster and Kelts 1983). A great variety of minerals may compose evaporite sediments depending upon original brine chemistry inherited from the drainage basin and climate (Eugster and Hardie 1978; Eugster and Kelts 1983) of the brine. This great range of mineralogies stems from the highly variable salinity (10^1–10^5 mg TDS; Armenteros and Corrochano

(1994)), pH (1.5–11.0; Armenteros and Corrochano (1994)) and range of original ionic compositions. Perhaps more so than other lacustrine systems, the sedimentology of saline lake systems may be one of, if not the most, sensitive proxies for monitoring regional environmental dynamics and climate.

Evaporite sediments are classified according to their mineralogy and their degree of induration. The mineralogy of evaporite sediments may consist of halite or gypsum, in more hypersaline situations, mirabalite and trona, or any of a large number of minerals (Eugster and Hardie 1978; Eugster and Kelts 1983). As with clastic sediments, the category of evaporite sediments can be modified by major terms that describe their macroscopic structure or fabric, such as massive, nodular-mosaic and chicken wire, and/or by microscopic observation of their size, or form (e.g., euhedral, platy), all of which aid in the definition of facies sub-facies, or to describe other components present in major quantities. In all cases describers should note the purity of the chemical sediment: e.g., rounded magadiite (60%) mud. Minor modifiers include descriptions of other sediment classes present, such as clastic sands or diatom frustules, or a description of other evaporite minerals present in minor quantities, e.g., gypsum (50%) mud with aragonite needles and fine quartz sand common. For indurated sediments the suffix -ite is appended to the major modifier, replacing the term ‘‘mud’’, e.g. chicken wire gypsite (90%).

Minerals precipitating within the chemical class my also be reworked from previous deposits and deposited as clastic grains, for example ‘‘detrital gypsum’’ (Sanz et al. 1994). Reworked detrital elements are common in playa settings, resulting from aeolian transport of grains from marginal, desiccated salt flats into central, moist basins. As described before, these sediments are still classed within the chemical sediment category but the suffix to the principal name should reflect the dominant grain-size of the sediment (e.g., gypsum sand) and the subfacies definition will define the depositional history of the sediment.

Carbonates

The class *carbonate sediments* refers to sediments in which the principal component is non-biogenic, authigenic and diagenetic carbonate minerals. Unlike marine sediments, where the vast majority of carbonate consists of tests of foraminifera and calcareous nannofossils (Dean et al. 1985), the majority of endogenic lacustrine carbonates result from chemical precipitation resulting from pH shifts induced by biologic activity or physical changes in the lake waters. In the present classification, the rare, fine-grained muds composed primarily of carbonate microfossils (i.e. *Phacotus* oozes) would be classified as biogenic oozes only when the carbonate particles are biological remains (see below). In practice it may prove difficult or impossible to distinguish biogenic carbonate, for example that produced from charophytes, from inorganically precipitated carbonate, though lacustrine carbonates are rarely dominated by biogenic carbonate (Dean 1981; Kelts and Hsü 1978).

Many lakes precipitate one or more of the carbonate phases, the most common phase being low magnesium calcite (Jones and Bowser 1978; Dean 1981; Eugster and Hardie 1978; Hardie et al. 1978) and (Kelts and Hsü 1978). Many other carbonate phases have been documented as either water column or diagenetic precipitates (dolomite: Last (1990), siderite: Kelts and Talbot (1990), aragonite: Last and Vance (1997), rhodochrosite: Bradbury and Dean (1993)) and often provide diagnostic associations. Extensive reviews of lacustrine carbonate sedimentation can be found in Dean (1981), Kelts and Hsü (1978), Eugster and Kelts (1983), Hardie et al. (1978) and Kelts and Talbot (1990).

As with evaporite sediments, the principal name for carbonate chemical sediments is taken from the mineralogy and relative degree of induration of the sediment according to the following scheme: limestone or dolostone for lithified or indurated sediments, and carbonate mud (or sand/breccia for larger clast sizes) for unconsolidated calcareous sediment. In both cases, the describer should note the purity of the mud by estimating carbonate abundance, e.g., carbonate (70%) mud. Major modifiers may include the mineralogy of the carbonate sediment (siderite, dolomite, aragonite, monohydrocalcite, calcite, or calcareous undefined) or descriptors involving the form/shape/size of the carbonate minerals (e.g., micritic, oncholitic, oolitic, pisolitic, needle, rice grain, etc.), or other sedimentary components present in major amounts. For impure carbonates (<50%) minor modifiers using the suffix with- are used to denote the presence of other authigenic minerals or clastic and biogenic components in major or minor amounts. The case of biogenic carbonate buildings, such as bioherms, stromatolites, and thrombolites, represents a special case of carbonate muds. These structures must be identified by a combination of macroscopic and detailed microscopic investigation, and thus should form part of the subfacies description based upon the combined interpretation of macroscopic and microscopic observations.

In this classification we have taken the tack of (Dean et al. 1985) and avoided some of the more specific terms for carbonate minerals such as 'marl' and 'Seekreide' (Merkt et al. 1971). There will undoubtedly be great resistance to this change but these terms simply express the degree to which carbonate minerals dominate the total sediment. As with ''gyttja,'' given the widespread misuse of some of these terms it seems better to restrict the classes of carbonate sediments and allow their dominance in a particular sediment to be expressed via percentages or by lack of modifiers. For example, in this classification a 'marl' would simply be clayey carbonate (80%) mud.

Examples of chemical sediments
1. Light gray laminated (even beds 0.75–1.0 cm), ostracode bearing, limestone with rare *Chara*-stems. Contacts distinct.
2. Light brown firm, moist, massive micritic calcite (65%) mud with frequent feldspathic clay and diatom frustules.

Biogenic sediment

Biogenic sediment may be composed of the well preserved to highly-degraded remains of organisms (plant and/or animal) that may or may not have shells composed of siliceous, chitinous or calcareous tests and shells. We divide biogenic sediments into carbonaceous sediments, composed of the remains of organisms lacking hard skeletal parts (great range from macroscopic plant fragments, and aragonite-encrusted brine shrimp fecal pellets to highly degraded algal organic matter), and fossiliferous sediments, here termed oozes (*sensu* Mazzulo et al. (1988)) or hashes, depending upon the grain size. ''Oozes'' and ''hashes'' are composed of the remains of organisms with preserved hard (mineralized) skeletal elements. An ooze consists of microscopic skeletal elements (e.g., diatoms) and a hash is composed of macroscopic skeletal elements. Due to the rarity of lacustrine calcareous planktonic forms (cf. *Phacotus* sp.) calcareous biogenic oozes are rare. The more common variety of oozes are diatom oozes, although fecal-pellet or sapropelic *Phacotus* oozes occur in specialized settings. Hashes composed of carbonate skeletal elements of gastropods and mollusks are common components of littoral lacustrine facies (Gierlowski-Kordesch and Kelts 1994).

Carbonaceous sediments

Carbonaceous sediments are derived from the accumulation of organic matter in lacustrine basins. Lacustrine organic matter may derive from organisms inhabiting the lake (cyanobacterial mats, macro- and microphytes, phytoplankton, zooplankton, benthic organisms or feces from aquatic or terrestrial organisms; Kelts (1988)), or from organic matter introduced into the lake from the surrounding drainage basin (terrestrial herbaceous and woody plants), though the latter is generally less common. In cases of extreme alteration of organic matter, the genesis of the material may be difficult or impossible to determine at the ICD stage and will have to await analysis of stable isotopes and hydrogen and oxygen indices (Talbot and Kelts 1986; Kelts and Talbot 1990; Laerdal and Talbot 2000), or biomarker analysis.

As is true for marine basins, carbonaceous sediments typically accumulate in lacustrine basins marked by hypolimnetic anoxia, high salinity, rapid sedimentation rates, or in highly productive shallow macrophyte-dominated systems. Unlike marine basins, lacustrine organic matter as either a dominant or minor component is common due to generally higher sedimentation rates, greater productivity and greater preservation (Kelts 1988).

Most carbonaceous sediments have undergone some degree of alteration by carbonization, bituminization or putrefaction from their original form. These processes generally render fine-grained algal organic matter unidentifiable, leading us to separate carbonaceous sediments into two varieties: the coal series (lithified carbonaceous sediments and peats) and the sapropels.

Much of our understanding of Quaternary paleoecology is derived from the study of components in carbonaceous lacustrine sediments (gyttjas and dys *sensu* Hansen (1959); peats, etc.). Specialized classifications such as Tröels-Smith (1955) have been used successfully and provide a more rigorous classification of carbonaceous sediments than that proposed here.

Coal series

The coal series consist of lithified carbonaceous sediment and are classified according to the degree of alteration or rank. Four ranks are recognized and used as principal names. Because of the importance of the peat categories to the development of paleoecology these classes are substantially elaborated. These subclasses should serve as a prefix to the principal name.

1. Peat: unconsolidated coal (see below)
2. Lignite: few recognizable plant fragments, is soft, dull and brown.
3. Bituminous coal: black and hard, with bright layers, and breaks into cuboidal fragments, along cleats
4. Anthracite coal: bright and lustrous, with conchoidal fractures.

Peat

Peats are soft, earthy, organic materials containing recognizable fragments of mosses or roots of woody or herbaceous plants and aquatic macrophytes. The various types of peats may be subdivided using the major modifiers outlined below that follows closely that outlined by Tröels-Smith (1955) and includes some of the modifications suggested by Kershaw (1997). A distinction is made between ‘‘fragmental peats,’’ consisting of fragments of wood, bark and stems of herbaceous plants, and ‘‘peats’’ which contain the lower portions of the plants (roots), giving indication of *in situ* accumulation.

Moss peat – moss, with *Sphagnum* often the most common peat-former (Kershaw 1997).

Woody peat - Stumps, roots, intertwined rootlets of woody plants, and branches.

Herbaceous peat - Roots, intertwined rootlets, and rhizomes of herbaceous plants ± stems, leaves.

Fragmental woody peat - parts of wood and bark >2 mm.

Fragmental herbaceous peat - fragments of herbaceous plants or parts thereof > 2 mm.

Fragmental granular peat - fragments of herbaceous or woody plants between 2 mm and 0.1 mm.

Minor modifiers of the term peat should include generic identification of individual plant remains (e.g., *Sphagnum* moss peat or sedge herbaceous peat). One can also estimate the degree of humicity (degree of organic decomposition) on a scale of very humic, partly humic, poorly humic, or non-humic (Kershaw 1997).

Sapropel

For fine-grained organic matter we have followed Merkt et al. (1971) and chosen to use the term sapropel instead of gyttja. Sapropel is an aquatic ooze or ‘‘sludge’’ that is rich (>50% of the total organic matter) in amorphous or very fine grained (<0.1 mm) organic matter. The organic matter may originate from either algal or bacterial elements or the decomposition of land and aquatic plants. Major modifiers can describe the dominant taxa composing the sapropel, e.g., *Anabaena* sapropel, or other sedimentary components present in major amounts. It should be noted that although sediment comprised of recognizable dominant taxa could also be termed an ooze, we have elected to use the term sapropel for biogenic oozes composed of organisms lacking biomineralized skeletons. ‘‘Copropel’’ may be used in place of sapropel when a definitive identification of the organic matter as fecal pellets is made.

Fossiliferous sediment

Fossiliferous sediment consists of the remains of pelagic and benthic siliceous, chitinous and calcareous shelled organisms when they comprise more than 50% of the total sediment. In our proposed classification we used two main criteria: size of the biological particles and degree of induration.

Sediments in which the most abundant component consists of fine-grained, unconsolidated microfossils (up to silt size) are described as oozes. The principal name ‘‘ooze’’ should be further refined using modifiers such as diatom (-aceous) or spongaceous, to describe the identity of the microfossil assemblage. For indurated microfossiliferous sediments, the term ooze is replaced by the suffix –ite, e.g., diatomite, and spiculite: lithified sediment composed predominantly of microscopic diatom frustules or sponge spicules.

Biological sediments composed of macroscopic biological remains (e.g., sand and gravel size) are classified to reflect the size of the particles which will often provide information about the sedimentary depositional environment. We propose the principal names hash, for unconsolidated fossiliferous sediments, and coquina for consolidated fossiliferous sediments. These principal names should be modified by a description of the taxa present, e.g., gastropod hash, ostracode coquina. Minor modifiers describing, for example, other components of the sediment or observed features of the fossils, e.g., fragmentation, recrystallization, etc. are also applied. If the macroscopic fossil component is unidentified or is composed of a complex fossil assemblage, we recommend the term 'fossiliferous', e.g., fossiliferous hash. This term should also be applied to fossil-bearing sediments in which fossils comprise a minor component of the sediments.

Examples of biogenic sediments

1. Massive, very moist, black (10YR 3/2), sapropelic diatomaceous ooze with distinct boundaries to over and underlying beds.
2. Diatomaceous ooze
3. *Phacotus* ooze
4. Coquina

Conclusion

Studies of past regional dynamics in the terrestrial environment require high resolution, sensitive records such as those archived in modern and ancient lacustrine sediments. Common goals of understanding past global climate change, whether from planned deep drilling projects recovering thousands of meters of lake sediment or short cores from small lake basins, require a common terminology for the sedimentary matrix, a sensitive and often overlooked proxy for past regional environmental dynamics. The classification scheme outlined here is offered as a first step in this direction, building upon previous models (e.g., Tröels-Smith (1955), Merkt et al. (1971)) and expanding the lexicon to encompass the great variety of sediments reported from lakes. A fuller treatment of the issues discussed in this paper can be found at: http://lrc.geo.umn.edu/services/handbook/sedclass.html.

Acknowledgements

Useful comments to this manuscript were provided by Blas Valero-Garcés, and discussions with Brian Haskell, Herb Wright, Amy Myrbo and Chad Wittkop improved the manuscript. The first two authors would like to acknowledge our tremendous debt to Kerry Kelts (1944–2001) whose inspiration and love for science generally and limnogeology specifically will continue to guide us. Kerry first suggested that such a paper needed to be written and provided the stimulus, encouragement and criticism to see the idea to its conclusion. This is LRC contribution number 584.

References

Armenteros I. and Corrochano A. 1994. Lacustrine record in the continental Tertiary Duero Basin (northern Spain). In: Gierlowski-Kordesch E. and Kelts K. (eds), Global Geological Record of Lake Basins Vol. 1. World and regional geology 4., pp. 47–52.

Ashley G.M. 1975. Rythmic sedimentation in glacial Lake Hitchcock Massachusetts-Connecticut. In: Jopling A.V. and McDonald B.C. (eds), Glacio-fluvial and glaciolacustrine sedimentation. Society of Economic Paleontologists and Mineralogists Special Publication No. 23., pp. 304–320.

Birks H.J.B. and Birks H.H. 1980. Quaternary paleoecology. Edward Arnold, Longon, 289p.

Bradbury J.P. and Dean W. (eds) 1993. Elk Lake, Minnesota: Evidence for rapid climate change in the north central United States. GSA Special Paper 276, 336 pp.

Campbell C.V. 1967. Lamina, laminaset, bed and bedset. Sedimentology 8: 7–26.

Dean W.E. 1981. Carbonate minerals and organic matter in sediments of modern north temperate hard water lakes. Society of Economic Paleontologists and Mineralogists, Special Publication. 31, pp. 213–231.

Dean W.E., Leinen M. and Stow D.A. 1985. Classification of deep-sea, fine-grained sediments. J. Sed. Petrol. 55: 250–256.

Eugster H.P. and Hardie L.A. 1978. Saline lakes. In: Lerman A. (ed.), Lakes: Chemistry, Geology, Physics. Springer, New York, pp. 237–289.

Eugster H.P. and Kelts K.R. 1983. Lacustrine chemical sediments. In: Goudie A. and Pye K. (eds), Chemical Sediments and Geomorphology. Academic Press, London, pp. 321–368.

Faegri K. and Iversen J. 1964. Textbook of pollen analysis. Hafner Publishing Co., New York, 237 p.

Folk R.L. 1980. Petrology of Sedimentary Rocks. Hemphill, Austin, 187 p.

Gierlowski-Kordesch E. and Kelts K. 1994. Global geological record of lake basins. Cambridge University Press, Cambridge, 427 p. 1.

Gierlowski-Kordesch E.H. and Kelts K. (eds) 2000. Lake basins through space and time AAPG Studies in Geology 46. American Association of Petroleum Geologists, Tulsa, OK. 648 p.

Glenn C. and Kelts K. 1991. Rhythms in lacustrine deposits. In: Einsele G., Ricken W. and Seilacher A. (eds), Cyclic and Event Stratigraphy. 2nd edn. Springer Verlag, Berlin, pp. 188–221.

Hansen K. 1959. The terms gyttja and dy. Hydrobiologia 13: 309–315.

Hardie L., Smoot J. and Eugster H. 1978. Saline lakes and their deposits: a sedimentological approach. In: Matter A. and Tucker M. (eds), Modern and Ancient Lake Sediments Vol. 2. Spec. Publs. Int. Ass. Sediment., pp. 7–41.

Harris N.B. 2000. Evolution of the Congo rift basin, West Africa; an inorganic geochemical record in lacustrine shales. Basin Research 12: 425–445.

Israelson C., Svante B., Hawkesworth C.J. and Possnert G. 1997. Direct U-Th dating of organic- and carbonate-rich lake sediments from southern Scandinavia. Earth and Planetary Science Letters 153: 251–263.

Jones B.F. and Bowser C.J. 1978. The mineralogy and related chemistry of lake sediments. In: Lerman A. (ed.), Lakes: Chemistry, Geology, Physics. Springer-Verlag, New York, pp. 179–235.

Kelts K. 1988. Environments of deposition of lacustrine petroleum source rocks: an introduction. In: Fleet A., Kelts K. and Talbot M.R. (eds), Lacustrine Petroleum Source Rocks. Geological Society Special Publication No. 40., pp. 3–26.

Kelts K. and Hsü K. 1978. Freshwater carbonate sedimentation. In: Lerman A. (ed.), Lakes: Physics, Chemistry and Geology. Springer, New York, pp. 295–323.

Kelts K. and Talbot M.R. 1990. Lacustrine carbonates as geochemical archives of environmental change and biotic-abiotic interactions. In: Tilzer M.M. and Serruya C. (eds), Ecological Structure and Function in Large Lakes. Springer-Verlag, Berlin, pp. 290–317.

Kershaw A.P. 1997. A modification of the Tröels-Smith system of sediment description and portrayal. Quaternary Australasia 15: 63–68.

Laerdal T. and Talbot M.R. 2000. The Late Pleistocene - Holocene palaeolimnology of Lake Victoria, East Africa, based upon elemental and isotopic analyses of sedimentary ogranic matter. J. Paleolim. 23: 141–164.

Laird K.R., Fritz S.C. and Cumming B.F. 1998. A diatom-based reconstruction of drought intensity, duration, and frequency from Moon Lake, North Dakota: a sub-decadal record of the last 2300 years. J. Paleolim. 19: 161–179.

Last W.M. 1990. Lacustrine dolomite – an overview of modern, Holocene, and Pleistocene occurences. Ear. Sci. Rev. 27: 221–263.

Last W.M. and Vance R.E. 1997. Bedding characteristics of Holocene sediments from salt lakes of the northern Great Plains, Western Canada. J. Paleolim. 17: 297–318.

Mazzulo J.M., Meyer A. and Kidd R.B. 1988. New sediment classification scheme for the Ocean Drilling Program. In: Mazzullo J. and Graham A.G. (eds), Handbook for Shipboard Sedimentologists. ODP Tech. Note 8., pp. 45–67.

McKee E.D. and Weir G.W. 1953. Terminology for stratification and cross-stratification. Bull. Geol. Soc. Amer. 64: 381–390.

Mediavilla R., Martin-Serrano A., Dabrio C.J. and Santisteban J. 1994. Cenozoic lacustrine deposits in the Duero Basin (Spain). In: Gierlowski-Kordesch E. and Kelts K. (eds), Global geological record of lake basins Vol. 1. World and regional geology 4., pp. 53–59.

Merkt J., Lüttig G. and Schneekloth H. 1971. Vorschlag zur Gliederung and Definition der Limnischen Ledimente. Geologischishes Jahrbuch 89: 607–623.

Meyers P.A. and Teranes J.L. 2001. Sediment organic matter. In: Last W.M. and Smol J.P. (eds), Tracking Environmental Change using Lake Sediments Volume 2: Physical and Geochemical Methods. Kluwer Academic Publishers, Boston, pp. 239–269.

Onac B.P., Björkman L., Björck S., Clichici O., Tamas T., Peate D. et al. 2001. The first dated Eemian lacustrine deposit in Romania. Quat. Res. 56: 62–65.

Picard M.D. and High L.R. Jr. 1972. Criteria for recognizing lacustrine rocks. In: Rigby J.K. and Hamblin W.K. (eds), Recognition of Ancient Sedimentary Environments. Society of Economic Paleontologists and Mineralogists Special Publication No. 16., pp. 108–145.

Rea D.K., Moore T.C. Jr., Lewis C.F.M., Mayer L.A., Dettman D.L., Smith A.J. et al. 1994. Stratigraphy and paleolimnologic record of lower Holocene sediments in northern Lake Huron and Georgian Bay. Can. J. Earth Sci. 31: 1586–1605.

Reineck H.E. and Singh I.B. 1980. Depositional Sedimentary Environments. Springer-Verlag, Berlin.

Ricketts R.D. and Johnson T.C. 1996. Early Holocene changes in lake level and productivity in Lake Malawi as interpreted from oxygen and carbon isotopic measurements from authigenic carbonates. In: Johnson T.C. and Odada E.O. (eds), The Limnology, Climatology, and Paleoclimatology of the East African Lakes. Gordon and Breach, Newark, N.J., pp. 475–494.

Rosen M.R. 1994. The importance of groundwater in Playas: A review of playa classifications and the sedimentology and hydrology of playas. In: Rosen M.R. (ed.), Paleoclimate and Basin Evolution of Playa Systems. Geol. Soc. Of Am. Spec. Pap. 289., pp. 1–18.

Sanz M.E., Alonso Zarza A.M. and Calvo J.P. 1995. Carbonate pond deposits related to semi-arid alluvial systems: examples from the Tertiary Madrid Basin, Spain. Sedimentology 42: 437–452.

Schnurrenberger D., Kelts K., Johnson T., Shane L. and Ito E. 2001. National lacustrine core repository (LacCore). J. Paleolim. 25: 123–127.

Shephard F.P. 1954. Nomenclature based on sand-silt-clay ratios. J. Sed. Pet. 24: 151–158.

Stoermer E.F. and Smol J.P. 1999. The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, 469 pp.

Talbot M.R. 1988. The origins of lacustrine oil source rocks - evidence from the lakes of tropical Africa. In: Fleet A.J., Kelts K. and Talbot M.R. (eds), Lacustrine Petroleum Source Rocks. Geological Society Special Publication, London, 40., pp. 29–43.

Talbot M.R. 2001. Nitrogen isotopes in palaeolimnology. In: Last W.M. and Smol J.P. (eds), Tracking Environmental Change using Lake Sediments Volume 2: Physical and Geochemical Methods. Kluwer Academic Publishers, Boston, pp. 401–439.

Talbot M.R. and Allen P.A. 1996. Lakes. In: Reading H.G. (ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Science, Oxford, pp. 83–124.

Talbot M.R. and Kelts K. 1986. Primary and diagenetic carbonates in the anoxic sediments of Lake Bosumtwi, Ghana. Geology 14: 912–916.

Talbot M.R., Livingstone D.A., Palmer P.G., Maley J., Melack J.M., Delibrias G. et al. 1984. Preliminary results from sediment cores from Lake Bosumtwi, Ghana. Palaeoecology of Africa and the Surrounding Islands 16: 173–192.

Tröels-Smith J. 1955. Karakterisering af løse jordarter Danmarks Geologiske Undersøgelse Series IV. 3(10), 73 pp.

Valero Garcés B.L., Kelts K. and Ito E. 1995. Oxygen and Carbon Isotope Trends and Sedimentological Evolution of a Meromictic and Saline Lacustrine System: The Holocene Medicine Lake Basin, North American Great Plains, USA. Palaeogeogr. Palaeoclim. Palaeoecol. 117: 253–278.

Valero-Garcés B.L., Laird K., Fritz S., Kelts K., Ito E. and Grimm E. 1997. Holocene climate in the northern Great Plains inferred from sediment stratigraphy, stable isotopes, carbonate geochemistry, diatoms, and pollen at Moon Lake, North Dakota. Quat. Res. 48: 359–369.

Valero-Garcés B.L., Grosjean M., Kelts K., Schreier H. and Messerli B. 1999. Holocene lacustrine deposition in the Atacama Altiplano: facies models, climate and tectonic forcing. Palaeogeogr. Palaeoclim. Palaeoecol. 151: 101–125.

Verschuren D. 2001. Reconstructing fluctuations of a shallow East African lake during the past 1800 yrs from sediment stratigraphy in a submerged crater basin. J. Paleolim. 25: 297–311.

Von Post L. 1916. Om skogsträdpollen i sydsvenska torfmosselagerföljder. Geologiska Föreningens i Stockholm Förhandlingar 38: 384–390.

Wentworth C.K. 1922. A scale of grade and class terms for clastic sediments. J. Geol. 30: 377–392.

Wolfe B.B., Edwards T.W.D., Elgood R.J. and Beuning K.R.M. 2001. Carbon and oxygen isotope analysis of lake sediment celluose: methods and applications. In: Last W.M. and Smol J.P. (eds), Tracking Environmental Change using Lake Sediments Volume 2: Physical and Geochemical Methods. Kluwer Academic Publishers, Boston, pp. 373–400.