Chemostratigraphy - A tool for understanding transport processes at the continental margin off West-Africa

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PREFACE

This study was funded by the Deutsche Forschungsgemeinschaft (DFG) within the DFG Research Center and Excellence Cluster "MARUM – The Ocean in the Earth System" as part of the Project C2 "Sediment transport at continental margins: processes, budgets and models". The project integrated seismo-acoustics, sedimentology and geochemistry to investigate sedimentation processes on the continental margin off NW-Africa. The study has been proposed and supervised by Prof. Dr. Horst D. Schulz and Dr. Martin Kölling at the Fachbereich 5 – Geowissenschaften (Department of Geosciences), University of Bremen, Germany.

The present thesis focuses on the aspects of (i) pore water geochemistry and (ii) inorganic solid phase geochemistry from sediment records of two submarine canyon systems. The study aims to (i) detect young slide events invisible from the sediment record and estimate their age and (ii) correlate turbidite sequences in a chemostratigraphic approach. The key results of this work are presented in two first-author manuscripts submitted for publication in international peer-reviewed scientific journals and are for the most part based on my own sampling, analyses, data evaluation and interpretation. Figures and tables within the manuscripts are considered with independent numbering. References have been removed from each paper and all references are cited in a single reference list at the end of this thesis. All data presented in this study are available through the Pangaea database (http://pangaea.de).

The first chapter of the thesis includes an introduction into the investigation area and its sedimentation processes, the scientific rationale of this study and the methodological approaches followed. The second chapter comprises the two manuscripts: (i) Schnieders et al. (submitted a) shows an the basis of pore water concentration profiles that pore water geochemistry not only documents sediment transport processes but also provides the possibility of estimating the age of these events. (ii) Schnieders et al. (submitted b) presents the results of a geochemical fingerprinting on turbidite sequences in order to correlate sediment deposits in a chemostratigraphic approach. This is scientifically relevant for subsequent reconstructions of sediment transport pathways and for gaining background information about sediment mixing and possible sediment sources. Following the manuscripts, a third and concluding chapter will summarize the most important findings and gives perspectives for future research.

CONTENT

ABSTRACT

Continental margins as multiform and complex interfaces between the continents and the ocean basins play a significant role as accumulation, storage and bypass areas for sediments. They display a variety of globally important gravity-driven depositional environments and their related transport processes. As continental margins are natural palaeoclimate archives, represent regions of natural geohazards and their sediment regimes contain major energy resources, they are of great interest for both scientific and socio-economic reasons.

Understanding the interaction of external and internal controlling factors of the sediment transport processes of those environments is an important scientific aim in order to reconstruct the sedimentary history of the continental slopes and to quantify the sediment budgets.

This study focuses on the geochemical imprints left in the sediment material and its corresponding fluid phase by gravity-driven sediment events and the related transport processes. Such events control the sediment composition and its stratification pattern during deposition, re-deposition and on the transit along- and downslope. High resolution geochemical investigations of marine sediments and their pore waters provide detailed insights into the sedimentation history of different depositional environments and document the various subsequent transport processes. The geochemical analyses provide a more detailed characterization of the material allowing conclusions on possible changes in the depositional environment and the related processes.

The chemical composition of pore water, an indicator of processes between pore water and sediment may document recent changes in the sedimentation pattern caused by to young slide events, as long the original sediment strata remains intact. Geochemical modelling of these pore water concentration profiles helps estimating the age of such an event. Geochemical fingerprinting of turbidite sequences in a redefined chemostratigraphic approach allows for a more precise separation of the different events which in turn facilitates a reconstruction of their transport pathways and characterizes the sediment material and the corresponding sources more precisely.

In this thesis we focus on sediment cores from two submarine canyons at the passive continental margin off NW-Africa showing the characteristic pattern of hemipelagic sedimentation intercalated with turbidite sequences. Submarine Canyon Systems represent one major pathway responsible for significant volumes of gravity driven transport of sediment downslope, subsequently acting as important storages for clastic sediments. Deposits of both, ancient Canyon Systems and the modern analogues are of great scientific interest.

The first paper presents a pore water study on a sediment core from a bayou of the Cap Timiris Canyon offshore Mauritania, demonstrating that the pore water chemistry records sediment transport events, and therefore can reveal and document young transport events although the pattern of the solid phase composition show no valuable hint regarding such an event. Data from an additional sediment core of the Angola basin highlights that the investigated pore water feature is not just a local phenomenon, restricted to the submarine canyon setting, but is likely to occur also elsewhere on continental slope systems.

In a second investigation, we obtained high-resolution records of bulk sedimentary element data from sediment cores of the Dakar Canyon further south. We statistically assessed the dataset with Discriminant Function Analysis (DFA). Our combined approach showed a great potential to the precision of the identification, tracking and correlation of the deposits from submarine canyon systems over long distances. We are confident that it is particularly useful when lack in material, uncertain bed boundaries, stacked deposition, or thin turbidite occurrences complicate stratification by means of conventional age dating methods or element stratigraphy.

ZUSAMMENFASSUNG

Kontinentalränder sind vielschichtige, komplexe Bindeglieder zwischen den Kontinenten und ihren Ozeanen. Sie spielen eine wichtige Rolle, als Akkumulation-, Speicher- und Transportbereiche für Sedimente. In ihrem Einzugsbereich befinden sich eine Vielzahl, durch gravitative Sedimentationsprozesse gesteuerte, global bedeutende Ablagerungsmilieus. Da Kontinentalränder natürliche Paläo-Klima Archive sind, geologisch gefährdete Gebiete repräsentieren und große Speicherbereiche für fossile Energie Ressourcen darstellen, sind sie sowohl wissenschaftlich als auch sozioökonomisch von großem Interesse.

Ein wichtiger wissenschaftliches Ziel ist es, die externen und internen Steuerprozesse der gravitativen Sedimentbewegungen zu verstehen, um die Sedimentationgeschichte zu rekonstruieren und das Sediment Budget der kontinentalen Hänge quantifizieren zu können.

Die vorliegende Studie beschäftigt sich mit den geochemischen Auswirkungen, die gravitativ gesteuerte Ablagerungsereignisse und die hiermit verbundenen Transportprozesse auf das Sediment und dessen fluide Phase haben. Solche Sedimentbewegungen kontrollieren die Zusammensetzung des Sediments und sein Sedimentationsmusters während seiner Ablagerung, Umlagerung und des Transports am Hang und in die Tiefe. Hochauflösende geochemische Untersuchungen an marinen Sedimenten und ihren Porenwässern geben detaillierte Einblicke in die Sedimentationgeschichte verschiedener Ablagerungsmilieus und dokumentieren die verschiedenen untergeordneten Transportprozesse und ihre Steuerungselemente. Die geochemische Analyse des Materials ermöglicht eine detailliertere Charakterisierung des Sediments und erlaubt so Rückschlüsse auf mögliche Veränderungen in den einzelnen Ablagerungsmilieus und den verbundenen Sedimentationsprozessen.

Die chemische Zusammensetzung des Porenwassers, als ein Anzeiger für die Prozesse zwischen Sediment und fluider Phase, kann aktuelle Veränderungen im Sedimentationsmuster aufgrund junger Rutschungsereignisse dokumentieren, solange die interne Struktur des rutschenden Sedimentkörper intakt bleibt. Über die geochemische Modellierung der Porenwasser Konzentrationsprofile kann so der Ereigniszeitraum abgeschätzt werden.

Geochemisches Fingerprinting an Turbidit-Sequenzen mit Hilfe eines neu definierten chemostratigraphischen Ansatz erlaubt eine präzisere Trennung der verschiedenen Ereignisse, was wiederum eine genauere Rekonstruktion ihre Transportwege und der verbundenen möglichen Sedimentquellenermöglicht.

Die Untersuchungen im Rahmen dieser Arbeit konzentrieren sich auf Sedimentkerne aus zwei verschiedenen submarinen Canyons am passiven Kontinentalrand vor NW-Afrika, die das charakteristische Ablagerungsmuster aus hemipelagischen Sedimenten mit eingeschalteten Turbidit-Sequenzen zeigen. Submarine Canyon-Systeme bilden einen verantwortlichen Transportweg für eine beträchtliche Menge von gravitativ transportiertem Sediment am Hang hinunter und fungieren dabei außerdem als Speicher für klastische Sedimente. Diese Ablagerungen aus fossilen Canyon Systeme und ihren rezenten Vertretern sind von großem wissenschaftlichem Interesse

Das erste Manuskript zeigt eine Porenwasser Studie an einem Sedimentkern aus einem Altarm des Cap Timiris Canyons vor Mauretanien. Es wird gezeigt, dass die chemische Zusammensetzung des Porenwassers Sedimentbewegungen anzeigt und damit junge Rutschungen sichtbar dokumentieren kann, obwohl sich in der Sedimentabfolge kein verwertbarer Hinweis auf dieses Ereignis zeigt. Die in diesem Zusammenhang zusätzlich dargestellten Daten eines Sedimentkerns aus dem Angola Becken sollen verdeutlichen, dass das untersuchte Porenwassersignal nicht nur ein lokales, an das Canyon System gebundenes Phänomen ist, sondern das es sehr wahrscheinlich auch in anderen Bereichen am kontinentalen Hang auftritt.

In einer zweiten Untersuchung haben wir mit hochauflösenden Festphasen-Elementdaten von Sedimentkernen aus dem weiter südlich gelegenen Dakar Canyon gearbeitet. Diese Daten wurden mit Hilfe der Diskriminanzanalyse statistisch erfasst und ausgewertet. Unser kombinierter Ansatz zeigte ein großes Potential für die präziserer Identifikation, Verfolgung und Korrelation von Ablagerungen aus submarinen Canyon Systemen über weite Distanzen. Wir können zeigen, dass dieser Ansatz besonders sinnvoll ist, wenn das Material unvollständig ist, die Schichtengrenzen nicht eindeutig sind, Ereignishorizonte in direktem Kontakt miteinander liegen, oder wenn das auftreten von sehr geringmächtigen Sequenzen die Stratifizierung durch konventionelle Datierungen oder Element-Stratigraphie kompliziert.

1. INTRODUCTION

1.1. The role of continental margins

Continental margins represent about 20% of the surface area of the global marine system. They form an essential transitory area to accumulate, supply and transfer sediments from the continental hinterland into the ocean, with shelf and slope regions both acting as a temporary storage and bypass area.

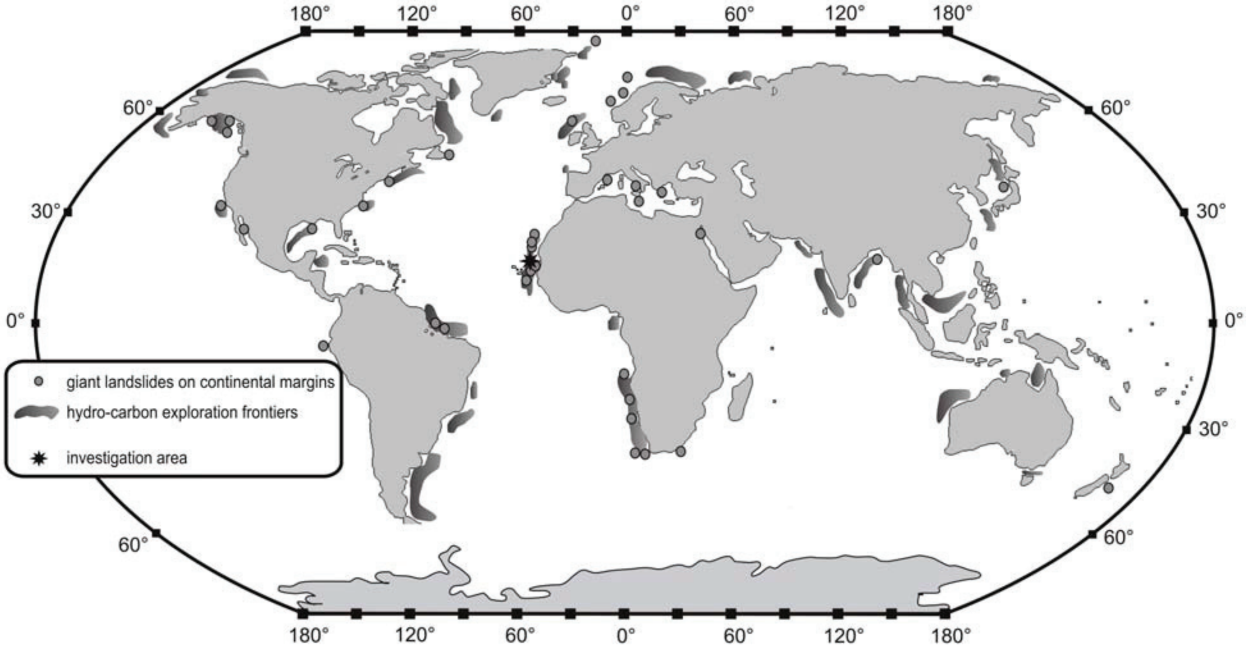

Fig. 1: *Global distribution of major gravity-driven mass flow deposits and the mostly coinciding areas of recent hydrocarbon exploration (from Mienert et. al., 2003).*

Many different factors and processes control the evolution of these submarine slope systems. The most important factors are the slope system morphology, the sediment input and load, the composition of the terrigenous material, climate variability, sea level changes and variations in the oceanographic conditions. The continental margins are often subject to large-scale gravity-driven sediment transport, such as submarine landslides (cf. Fig. 1), occurring on all scales and located on all types of margins (passive, active and sheared).

Numerous studies on these slope systems have revealed a wide spectrum of sediment transport processes including both along slope (bottom current) and downslope (gravity-driven) transport (e.g. Wynn et al:, 2000a; Antobreh & Krastel, 2007; Henrich et al., 2008). Hereby their shelf areas und subsequently the slopes act as temporary storages and transport areas. The three principal groups of sediment deposits due to gravity-driven transport processes are generally identified as slides / slumps, debris flows and turbidity currents (McHugh et al., 2002; and references therein).

The composition and texture of the sediment records depends on the magnitude of marine biological productivity, the input quality of terrigenous material, and on the underlying transport processes and their determining factors. These factors control the change in sediment material composition on its way downslope, due to current sorting, winnowing, bypassing, selective removal or addition of further sediments due to mixing during deposition and re-deposition and degree of mass- wasting (Henrich et al., 2008). In addition, numerous external factors potentially affect sediment pattern and deposition such as seabed morphology, climate conditions, sea-level fluctuations and slope stability. In order to reconstruct and evaluate the behaviour of slope systems as linkages between continents and ocean basins, understanding of the determinant imprints in the sediment record is crucial.

1.1.1. Submarine canyons: geological significance and economic and scientific relevance

Submarine canyons are one major part of the globally important gravity-driven depositional environments on continental margins. They are important conduits that are responsible for the transport of both, marine and terrestrial sediments from shallow shelf marine areas into the deep marine basins (Weaver et al., 2000), mainly in form of turbidity currents. In addition, they act as important storage systems for the terrestrially derived clastic sediments and thus play a significant global role as potentially major hydrocarbon reservoirs (Emery & Myers, 1996; Weimer & Slatt, 1999; Stow & Mayall, 2000). During the last decades, the interest in submarine canyon systems, their sediment transport processes and the related deposits of gravity driven transport in general has increased considerably (Masson et al., 1996).

The importance of submarine mass wasting events and their resulting effects became first evident only indirectly when high-velocity turbidity currents damaged marine telecommunication infrastructure at continental slopes, (e.g. Heezen & Ewing, 1955; Pickering et al., 1989; Nichols, 1999; Einsele, 2000). Since then, those systems have become a major research focus due to their economic significance as energy storages and potential geo-hazardous areas.

Both fossil and modern deposits of this kind of depositional environment are of scientific interest. Outcrops of ancient deep-water clastic systems are studied to reconstruct and predict reservoirs, providing essential inputs for 3D geological models used for further predictions of the reservoir behaviour (Pollock et al., 2002; Eschard et al., 2003; Satur et al., 2005). It became evident that outcrops may provide valuable information on the developments of deep water transport sediment systems (Chapin, 1998). Vice versa modern canyon systems can be useful analogues to understand fossil submarine canyon systems. Therefore detailed multidisciplinary investigations of modern systems, such as geophysical approaches using side-scan sonar interpretations, combined with high-resolution seismic are likely to reveal important information (e.g. Twichell et. al., 1991, 1995; Bouma, 2000). In the same manner sedimentological investigations (e.g. Wynn et al., 2000a; 2000b, 2002) and geochemical approaches using standard piston and gravity coring (Pearce & Jarvis, 1995) have provided valuable insights into structure, architecture and evolutionary developments of submarine canyon systems in sedimentary regimes.

1.2. Gravity-driven sedimentation processes along continental margins: a brief overview

Though deepwater sedimentary classifications are changing rapidly (Shanmugam, 2000) there is a general consensus on the description of various schemes of gravity-driven processes and their depositional end-members. The main depositional processes and their deposits are briefly introduced (cf. Fig. 2 below) to clarify the terms used in this study (after McHugh et al., 2002).

In general gravity-driven mass flow deposits are referred to as:

(1) slides / slumps (cohesive flow),
(2) debris flows (transitional hybrid flows) and
(3) turbidity currents (non-cohesive flow), all representing different floe regimes.

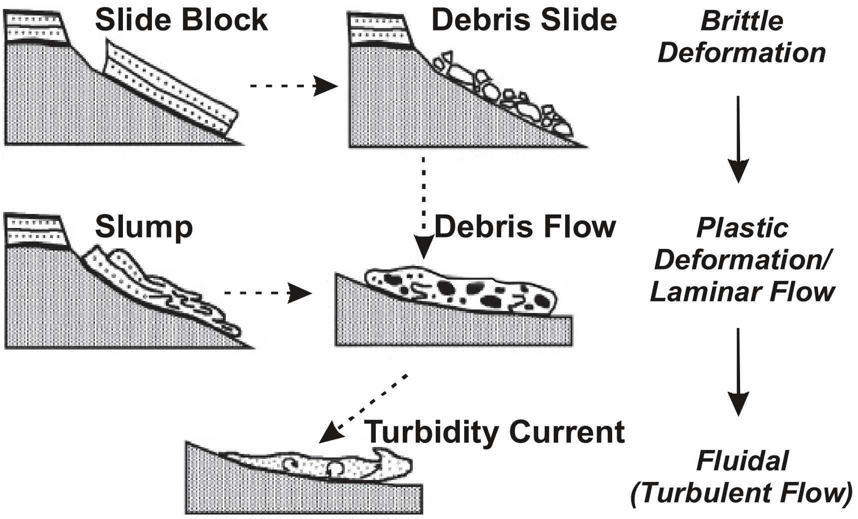

Fig. 2: *Schematical illustration of gravity-driven mass transport processes and the corresponding deposits (from McHugh et al. 2002).*

Several authors have discussed the definition of these terms as well as their usage (e.g., Embley & Jacobi, 1977; Shanmugam et al. 1994 and 1995; McHugh et al., 2002). Each term represents a classified group of sediment transport processes and the resulting characteristic depositional pattern. The groups are mainly distinguished with respect to transport velocity, characteristic internal flow (laminar or turbulent) and the internal structure of the deposits during transport and after deposition.

The schematical illustrations in Figure 3 give an overview of the evolving interrelationship between the various sub-aqueous density flows and their transportation of sediment. The diagram demonstrates how cohesive/laminar flow changes into non-cohesive/turbulent flow, while passing through different transitional stages of a hybrid flow. Once initiated, the sediment movement is not consistent in shape and form but may transform continuously dependent on triggering factors, both external and internal. These may comprise sediment load, morphology and internal structure of the material. The sediment deposits from these different flows are co-genetic and slurry flows accumulates as a mix of both cohesive and non-cohesive material. The degree of disaggregation of the sediment material increases with velocity during the flow process. The sediment deposits evolve from debrites (cohesive flow) to non-cohesive high-density turbidity (HDT) to low-density turbidity currents (LDT).

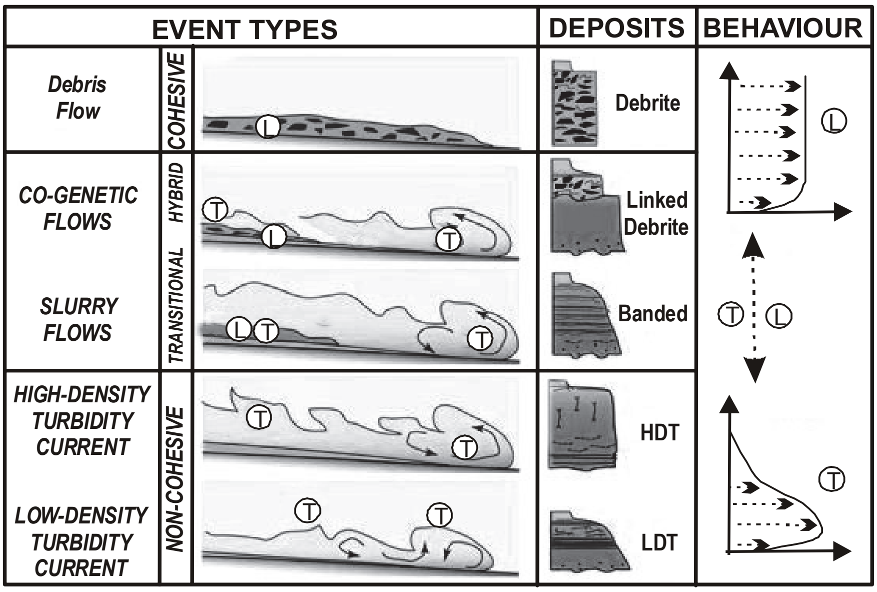

Fig. 3: *Simplified scheme for the classification of event type behaviour and corresponding deposits after Mulder & Alexander (2001) from Houghton (2006).*

The first classification of deepwater systems was based on the observation of beds of sandstone in which the sediment grain size decreased upward. Sandstone beds with such texture became known as deepwater "turbidites" based on the recognition that deposition from a waning turbidity current had a matching decrease in grain size (Kuenen, 1957).

Later, this characteristic structure of upward fining grain size distribution was termed "Bouma Sequence" (Bouma, 1962). Today, it is acknowledged that while not every deepwater sedimentary cycle has the fabric of the complete Bouma Sequence turbidite (Shanmugam, 2000); process driven interrelationships exist between most deepwater sediment processes and their associated sediment pattern (Shanmugam, 2000).

1.3. Setting of the investigation area off NW-Africa

The NW-African continental margin is a key location in order to understand the variations in climate history, past oceanographic changes as well as slope failure mechanism, documented occurrences and the impact on the environment.

This investigation area is an environment that offers unique records of variations in climate and oceanographic conditions. But in particular, its highly dynamic sedimentary setting makes it a prime region to investigate mass transport processes, slope failure mechanisms and their documentation in the sediment record, and the impact of these events on the marine environment. The most important control factors for sedimentation processes (cf. Fig. 4) along this margin are the effects of the different climate zones of the continent, the width of the shelf, the morphology of the slope, the hemipelagic sediment load, seasonal upwelling, sea level changes and aeolian and fluvial input (McMaster & Lachance, 1969; Seibold & Fütterer, 1982; Weaver et al., 2000; Wynn et al., 2000a; Zühlsdorff et al., 2007 b).

The Quaternary and Holocene climate history of NW-Africa has been reconstructed from marine and terrestrial sediment records which suggest significant changes from an arid glacial to a more humid climate during the early Holocene (Sarnthein et al., 1982; Rognon & Coudé-Gaussen, 1996; deMenocal et al., 2000 a; Moreno et al., 2001; Kuhlmann et al., 2004). Most of these studies and the related sediment archives are located off Mauritanian and the Canary Islands, whereas only few investigations have been conducted in the southward region off Senegal and Guinea-Bissau.

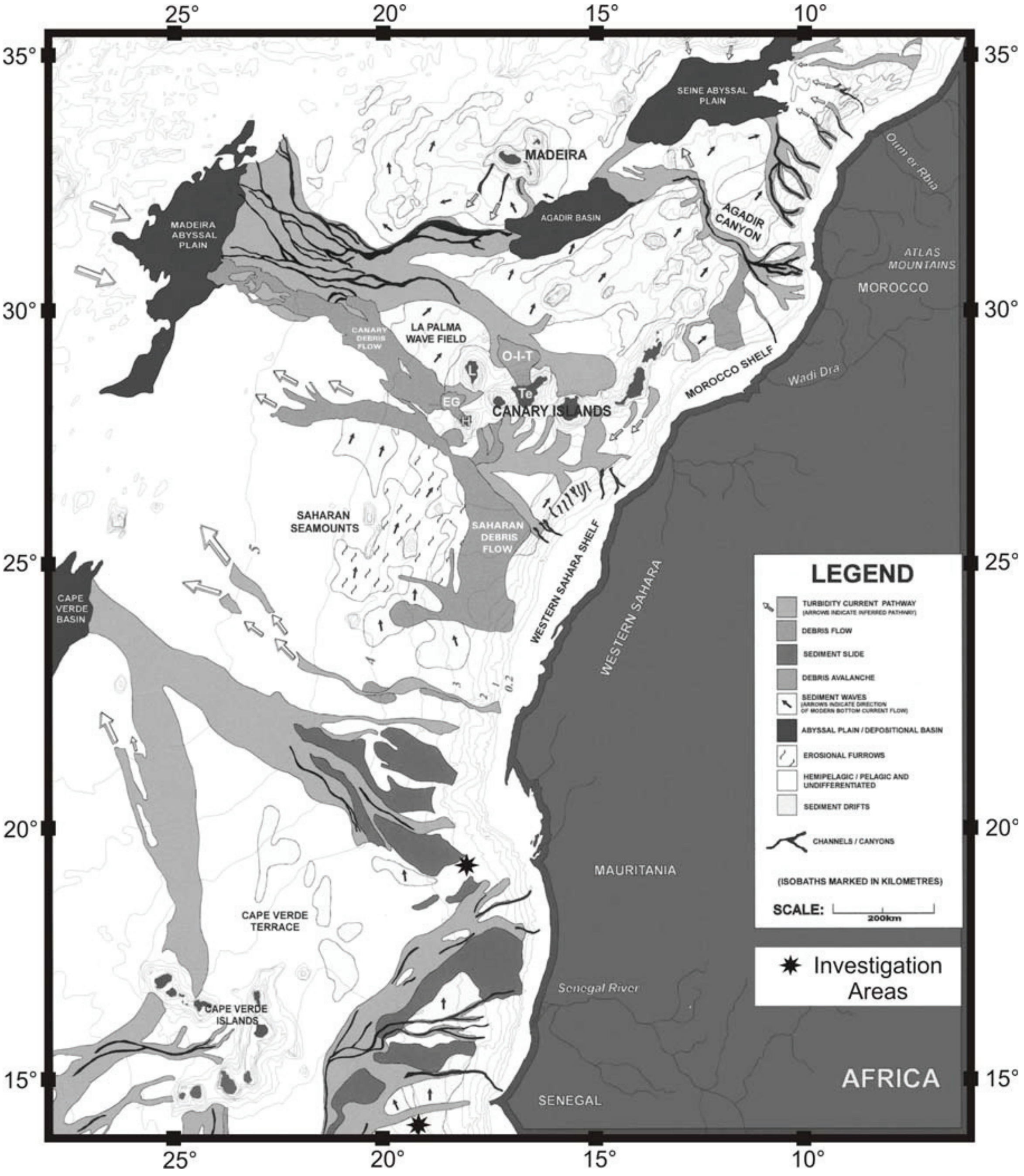

Fig. 4: *Sediment processes and features along the NW-African margin (from Wynn et al., 2000 a).*

In addition, several submarine canyons incise the slope along the margin (Dietz et al., 1968; Dietz & Knebel, 1971; Jacobi & Hayes, 1982; Wissmann, 1982; Weaver et al., 2000; Krastel et al., 2004). These canyons are responsible for significant volumes of gravity-driven sediment transport from the shallow coastal zone into the deep ocean basins, and are therefore associated with turbidite activity.

The submarine Cap Timiris Canyon offshore Mauritania and the Dakar Canyon offshore Senegal are both effective pathways for gravity-driven sediment transport at the passive continental margin off NW-Africa as well as some canyon systems south of the study area (Dietz et al., 1968; Wynn et al., 2000 a; Babonneau et al., 2002; Antobreh & Krastel, 2006; Zühlsdorff et al., 2007 b, Pierau et al., 2010 and 2011).

1.3.1. The Cap Timiris Canyon System, offshore Mauritania

The Cap Timiris Canyon, discovered in 2003 during Meteor cruise M58/1, is a submarine, meandering channel system incising the continental margin offshore Mauritania. It is 2 to 3 km wide, about 300 m deep, and runs about 400 km into the deep ocean basin. It appears to be the first of its size to be described from offshore a present-day hyper-arid desert region. Although it shows continuous turbidity current activity (Holz et al, 2004), there is no evidence for a recently linked, active drainage system in the hinterland. Therefore, the sediment supply is mainly aeolian from the Saharan Desert. The Cap Timiris Canyon consists of up to 150 m deep tributaries cutting back into the continental shelf merging into one main channel further downslope. It shows a characteristic alternation between a relatively straight channel pathway and meandering sections in the more distal part of the system (Krastel et al., 2004).

1.3.2. The Dakar Canyon System, offshore Senegal

The Dakar Canyon is a 3-4 km wide and in average 350 m deep submarine channel off the Senegalese coast, southwest off the City of Dakar. The canyon incises the strata of the proximal slope 700 m in depth and the depth of the channel decreases in its distal part down to less than 20m. Terrigenous sediment supply to the Senegalese continental shelf is primarily accomplished by fluvial and aeolian transport. The deeper area of the slope shows clearly indication for large scale mass wasting. The canyon runs relatively straight downslope in a NW-SE direction to about 4000 m water depth, with several terraces at the canyon flanks. The canyon floor shows a small U-shaped profile, indicating a sandy infill due to recent sediment transport through the canyon. The coastal part of the canyon shows a complex pattern of smaller tributaries and older buried canyons (Krastel et al., 2004; Pierau et al., 2010 and 2011).

1.4. Methodological and analytical approach

Deep-water sands and their depositional environment, such as submarine fans or turbidite systems, are recognised as very important hydrocarbon reservoirs and have become a major focus of both academic and industrial interest during the last decades. This is generally the result of intensified exploration, accompanied by intensified research and the discovery of large hydrocarbon accumulations in fine-grained, mud-rich turbidites systems (e.g. Stelting et al., 2000; Lomas & Joseph, 2004). Many studies have emphasised the fundamental differences between the thoroughly studied coarse-grained, sand-rich systems and the still poorly understood fine-grained, mud-rich systems (e.g. Shanmugan & Moiola, 1988; Normark, 1989; Bouma, 2000). In order to improve knowledge in this field, a number of detailed and comprehensive studies have focused on channel classification and morphology, and depositional processes of both individual channels and regional systems in modern settings and ancient analogues (e.g. Damuth et al., 1983; Clark & Pickering, 1996 a, 1996 b; Cronin & Kidd, 1998; Babonneau et al., 2002; Browne & Slatt, 2002; Pirmez & Imran, 2003).

Sediment deposits recovered from modern submarine canyons are not only useful for the reconstruction of terrigenous sediment supply from the continent to the ocean (Normark et al., 1998; Prins et al., 2000; Weber et. al., 2003; Mullenbach et al., 2004; Talling et al., 2007). The sediment material also bears a unique imprint of the prevailing dynamics of sedimentation, climate, and oceanography of the investigation area. Several external forces have a strong influence on the sediment material and on the development of turbidite deposits: tectonics, climate, sediment, and sea-level fluctuations (e.g. Prins & Postma, 2000; Hasiotis et al., 2005; Pierau et al., 2010).

But these factors do not only leave signatures on the sediment material, but also alter the composition of the pore water surrounding the sediment solid phase. Therefore, the investigation of both sediment solid phase and pore water should enable a more thorough reconstruction of the development of the sediment deposits sampled in the core. It has been shown that pore water geochemical analyses may be used to reveal sediment transport events (Zabel & Schulz, 2001; Hensen et. al, 2003).

1.4.1. Pore water geochemistry: Proxy for transport processes

Because the specific characteristics of early diagenetic processes are documented in pore water concentration profiles, it is possible to identify a disturbance of this pattern due to a gravity-driven transport. This is possible as long as (i) the internal structure of the sediment and therefore its original pore water pattern stays intact and (ii) the fluid phase of the participating sediment packages show distinguishable different pore water concentration profiles. In an 'undisturbed' sediment record, pore water concentrations reflect the local prevailing conditions and influences like early diagenetic reactions and diffusive transport processes.

In pore waters of high productivity areas for example sulfate profiles document the downward diffusion caused by sulfate reduction in the discrete zone of Sulfate-Methane-Transition (SMT) at a distinct depth below the sediment surface. The resulting gradient in concentration of the pore water constituents is then controlled by the original position of the sediment sequences. After sediment sequences have been re-deposited their characteristic pore water concentration pattern will adjust over time to the new local geochemical conditions of the environment towards new quasi steady-state conditions. This readjustment of the different gradients in concentration profiles gradually evolves and typically requires several hundred years to equilibrate. Modelling the intermediate stages of the smoothing of the different geochemical profiles offers excellent potential to estimate the age of the sediment re-deposition.

1.4.2. Geochemical fingerprinting: A chemostratigraphic approach

The sedimentary record of the cores of both canyons investigated in this thesis consists of hemipelagic sediments with intercalated centimeter to decimeter thick turbidite beds at distinct intervals. Such a depositional pattern is characteristic for submarine canyon systems (Bouma, 1962 and 2000; Stow & Shanmugam, 1980; Bouma et al., 1985). For the investigation area off NW-Africa all scales of turbidite deposition have been recognised from large scale mass transport represented by megaturbidites down to cm-thin event layers. Regardless of the thickness a stratigraphic classification or at least assignment to one another, of these deposits is needed in order to obtain information on depositional frequency, emplacement time and to correlate events and be able to reconstruct the sedimentation history.

Chemostratigraphy offers useful working approaches in this context. Chemostratigraphy is the application of sedimentary geochemistry to stratigraphy and it is based on the theory that different internal and external control parameters interact with one another in varying ratios and that these changes leave chemical imprints on the sediment record. This working environment covers several disciplines in earth sciences (e.g. engineering, geophysics, geochemistry) and many different fields of expertise like stable isotope approaches (e.g. oxygen, radiocarbon but also sulphur and strontium) focussing on the undisturbed pelagic facies of transport induced sediment records. These conventional dating methods of age dating with oxygen or radiocarbon isotopes not only require a sufficient amount of undisturbed pelagic sediment separating the turbidite sequences, but these methods are also a time consuming and expensive.

Another chemostratigraphic focus lies on geochemical high resolution solid phase investigations either on the pelagic sequences of the sediment record or, in a direct approach on the turbidite sequences themselves. The downcore element variations of the pelagites provide indirect age models by correlation to available dated reference cores and help to determine emplacement time of intercalated gravity mass flow deposits and asses emplacement to sea-level stand and climate conditions (Wien et al., 2006 a). The direct element contents of turbidite sequences may provide also a reliable pattern to correlate deposits over distance (e.g. Pearce & Jarvis, 1995; Reeder et al., 1998). The limiting factors to these methods is always the availability of pelagic or turbidite material in a sufficient amount. The different sequences have to be thick enough to provide a meaningful element content pattern that allows for a precise separation, comparison, and assignment of units of different sediment records to one another.

For the sediment cores investigated in this study other approaches have to be considered as the sediment records display only centimetre to a few decimetres thickness of both, turbidite events and intercalated pelagites. Most of the signals of the thin deposits are further obscured by bioturbation and by a stacked deposition, which impedes their separation. Due to the narrow depositional time frame the sedimentological characteristics of the material are expected to be very similar (Krastel, 2006 a; Pierau et al., 2011).

In addition, for some of the deposits only a few samples were available. This all leads to gaps with a lack of information in the sediment signal making correlation even more difficult. For material like this assessing the geochemical element data with statistical methods in order to correlate seemed to be a good approach. The application of statistics such as discriminant function analysis (DFA) to limited geochemical element data is a common approach to distinguish between known groups in order to define their characteristics to separate them precisely and to be able to correlate them. This technique is used in many fields, e.g. tephrachronology, or stratigraphy of barren strata. To apply DFA to a high resolution multi-element data set of all major, trace and REE-elements provides an objective approach, which uses the full complement of the geochemical data. Since even small differences in transport and subsequent storage of the material may be imprinted in the sediment DFA is the method of choice to compare all data simultaneously and filter differences as well as similarities that are not obvious by visual comparison.

1.4.3. Chronological framework

For the age model of the sediment core Geo 9622 from the Cap Timiris Canyon at least 10 mg of carbonate from planktonic foraminifera G. ruber (white/pink), G. sacculifer and O. universa were used as sample specimen for accelerator mass spectrometry (AMS) radiocarbon dating. Carbonate hydrolysis and CO2 reduction was carried out at Bremen University and AMS dating was done at the Leibniz Laboratory for Radiocarbon Dating and Isotope Research in Kiel. For the age model of the gravity core GeoB 1023-4 from the Angola Basin all raw data used in this context are derived from the publications of Kölling (1991), Schneider et al. (1992) and later Shi et al. (2000).

AMS radiocarbon ages providing the loose stratigraphic frame and constraining post LGM ages for the turbidites sequences of the studied sediment cores from the Dakar Canyon, off the Senegalese coast, are published in Pierau et al. (2011). A standard reservoir age of 400 yrs is assumed for calibration as suggested for the study area off the NW-African margin. All radiocarbon age determinations were calibrated with CalPal-2007online (Danzeglocke et al., 2008).

1.5. Scientific aims of this study

The Northwest African slope apron is one global important modern analogue for deep-water sedimentation systems. It displays various possible depositional environments and their related deposits from large-scale mass wasting to small-scale gravity driven sediment transport. One recent scientific key objective in this context is to develop models for the sedimentary history of the continental slopes and to quantify sediment budgets. The research project in which this thesis is imbedded, deals with the various transport processes on this passive continental and their determinants respectively, from (1) re-deposition of sediments from the shelf, (2) their deposition on the continental slope, or (3) transport and final deposition in the deep-sea basin. A significant aspect of the work is to reveal and understand the interaction of external and internal controlling factors of the sediment transport processes along the slope.

The main topics of this thesis arose out of the interest to reveal and decipher the potential of geochemical studies of marine sediments and their fluid phase. Because a more detailed characterization of the material may provide essential insights on possible changes in this depositional environment.

During the project related research expedition RV Meteor cruise M65/2 in 2005 one gravity core recovered from the bayou of the Cap Timiris Canyon off the Mauritanian coast, was chosen for the first part of this study. The pore water analysis onboard indicated some kind of movement in the sediment at certain depth whereas the expected respective signals in the sedimentary record (e.g. glide plane or a change in sediment material) were obscured. Subsequent evaluation of data from sediment material from earlier research expeditions showing the same pore water feature, offered the additional possibility to investigate if this is just a local anomaly or likely to be happen also in different depositional settings.

The other focus of this thesis lies on high resolution geochemical sediment phase investigations to correlate modern strata only on the basis of their geochemical element variations. Especial in cases when conventional dating methods or indirect geochemical stratigraphic approaches on the basis of the pelagic material are difficult or impossible because of a short depositional time frame were the sediment pattern is expectedly difficult to decipher.

The field of today's chemostratigraphy offers several multi-disciplinary approaches as stratigraphic tools. During the last decade geochemistry in general and inorganic high-resolution element geochemistry in particular has become a crucial topic in stratigraphy, along with the more conventional approaches. Various high-resolution strata studies focus now on a geochemical approach, but mostly concentrate on barren strata of ancient material and fossil outcrop. The diagenetic overprint of those ancient deposits provides an important additional geochemical signal to this material. Modern deposits are more likely to provide the full imprint of the primary source signal as represented by rare earth elements (REE). By studying modern turbidite systems to understand the evolution of deep-water systems, it becomes more and more obvious that recent chemostratigraphic approaches still have the potential to be improved and enhanced. In this context, a high resolution multi-element solid phase analysis, combined with multivariate statistics appears to be more efficient in order to approach the gravity cores investigated in this part of the study. It may provide the characteristic geochemical fingerprint of these gravity-driven transport events and reveal it from what seems to be a geochemical overall similar pattern of the investigated sediment records.

In the course of this study, the analytical concept, applied to these hemipelagic and gravity-driven deposits (i) combines the essential pore water data with supporting sediment data and (ii) concentrates on high resolution solid phase investigations assesses with statistics. Both topics uses radiocarbon analysis to provide a time frame that (i) further support the sediment history as indicated by pore water and (ii) gives a relative time frame in order to evaluate the reasonability of the selected sediment records in order to investigate the scientific aim. The following investigations should emphasise inorganic pore water and sediment geochemistry as two equally important to document and decipher sedimentation dynamics of global relevant depositional environment.

2. MANUSCRIPTS I

2.1 Identification and dating of repeated slide events revealed from pore water geochemistry: An example from the Cap Timiris Canyon off North-West Africa

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(submitted to Marine and Petroleum Geology)

Abstract

We present three cores from two different locations, showing kinks in the pore water profiles of sulfate, ammonium and alkalinity a few meters below the sediment surface. These signals are interpreted to be the result of recent (approx. 20 yr) slide events. However, the sedimentological record does not show any indication of a non-continuous sequence in this part of the record. The age model of the cores determined from several radiocarbon dates only shows a change in sedimentation rate, but no young surface below the displaced package as described by Zabel & Schulz (2001) and Hensen et al. (2003) has been detected. This study presents a model concept which unites all measurements and observations from pore water and solid phase samples, yielding in a coherent overall picture. Modelling the diffusive flows in the pore water fraction resulted in an age determination of the slide event. It becomes clear that the slide event would neither have been recognized nor understood without this study and without an appropriate understanding of the concentration profiles in the pore water. A comparable study with a sediment core previously recovered from the shelf off the coast of Angola exemplarily shows that such recent slides are not just a phenomenon locally limited in their occurrence to the canyon, instead, they are likely to happen anywhere on continental slopes.

Keywords: submarine canyons; turbidites; pore water; slides.

Introduction

A great number of sediment cores were recovered and analyzed during the last decades to achieve a better understanding of the processes taking place in the present-day oceans and, particularly, those which have taken place in the past. To reconstruct oceanographic history, successions of sediment layers which must be unperturbed as much as possible and derived from the most various water depths, have been processed and analyzed. However, the published data relating to these cores are rather few relative to the number of cores sampled. The core archives all over the world are filled with cores that document some kind of “incomprehensive irregularity” in their sediment sequences and, for this reason, have not been further processed and published.

Turbidite layers are irregular structures easily recognizable in the sedimentological record. They were already described in the 1960s and often occur on the slopes of passive continental margins (e.g. Bouma, 1962; 2000; Bouma et al., 1985; Mulder & Cochonat, 1996; Nichols, 1999; Einsele, 2000; Mienert et al., 2003). For quite a long time, it has been an unanswered question whether turbidity currents only transported sediments, or whether they also eroded the substratum. Recent publications were able to reveal that such erosions are of negligible consequence. As a result, an almost unperturbed succession of (hemi)pelagic sediments is encountered between the layers of turbidites, wherefore an age determination of the series of strata automatically also produces the age of the turbidite layers (Wien et al., 2006a). However, turbidity currents only represent one special form of gravitational sediment transport occurring on the continental slopes. Others forms are landslides and debris flows or avalanches (e.g. Mulder & Cochonat, 1996; Einsele, 2000). The three major types of sediment transport are:

In a *slide* or *slump*, the greater part of the sediment layers remain unperturbed and slides a certain distance down the continental slope. We assume that the material transport rate is rather low in such process. The plane on which this slide event occurs is narrowly defined in its thickness and preconditioned through the existence of a soft sediment layer that functions as a slipping agent (e.g. Mulder & Cochonat, 1996; Masson et al., 1998).

In a *debris flow* or an *avalanche*, the structural association of the sediment is destroyed and fragmented into blocks being decimeters or meters in size. These blocks are finally embedded into a fine-grained matrix. Unlike sediment slides, debris flows are easily recognizable on account of their distinctive albeit disrupted stratification characterized by blocks being displaced towards each other. The transport rate in a debris flow is higher than in a slide event and lower than in a turbidity current.

A *turbidity current* is a sediment-laden water mass which moves with a high velocity. The material in suspension is consequently dispersed down to a level of grain sizes. The high velocity and the dissolution of the material's coherence consequentially associated with it, do not remain constant during transport but may vary between the locations of origin and deposition (McHugh et al., 2002; Mienert et al., 2003).

Several years ago, we succeeded in identifying submarine landslides and debris flows by evaluating pore-water concentration profiles (Zabel & Schulz, 2001; Hensen et al., 2003). The age determinations of recent landslides and debris flows were then accomplished for the first time by the method of numerically modelling diffusion-controlled, non-steady-state concentration profiles in pore water.

Consequently, pore-water data, in combination with geochemical solid-phase analytics and radiometric age determinations, provide important information needed for reconstructing the sedimentation history of a core. Particularly in case of landslides, which are mostly difficult to identify visually in a sediment core, a combination of sedimentological observation, radiometric age determinations and complex pore-water profiles is needed to gain a coherent model concept. In this article we demonstrate this combined approach and show its potential on 2 examples.

Study site

Both coring sites GeoB 9622 and GeoB 1023 are located in the Atlantic, on the continental slope of Africa (cf. Fig. 1 and Tab. 1).

Tab. 1: *Location and core information*

RV Meteor cruise	GeoB station	Longitude	Latitude	Water depth [m]	***Core length***
M 6/6[a]	1023	11°00.6'E	17°09.7'S	1965	10.20
Angola Basin; no significant disturbance due to turbidites					
M 34/2[b]	3714	10°59.9'E	17°09.6'S	2060	12.27
Angola Basin; no significant disturbance due to turbidites					
M 65/2	9622	18°33.2'E	19°14.9N	2881	10.45
Cap Timiris Canyon; several turbidity sequences are intermitting the sediment stratigraphy					

[a] Data from (Schulz et al., 1994), [b] Data from (Niewöhner et al., 1998)

Position GeoB 9622 is located off Mauritania, at about 19° N, in a cut-off loop of Cap Timiris Canyon at a water depth of almost 3000 m (see Fig. 1-A). This canyon was only discovered and first surveyed during Meteor expedition M58/1 in 2003 (Schulz et al., 2003; Krastel et al., 2004).

We believe that the canyon developed at a time when the nowadays dry Tamanrasset River System (Schulz et al., 2003), through which it continues on the continent, used to carry plenty of water from the once rain-laden Sahara. Nowadays, the sediment freight of the canyon mainly consists of dust imported from the Sub-Sahara and Sahel region (Tetzlaff & Wolter, 1980; Pye, 1987; Wefer & Fischer, 1993). Additionally it consists of biogenic sediments whose import into this area is favored by upwelling and the high rate of marine productivity associated to it, particularly in the near coastal regions of the canyon (e.g. Fütterer, 1983; Bertrand et al., 1996; Martinez et al., 1999).

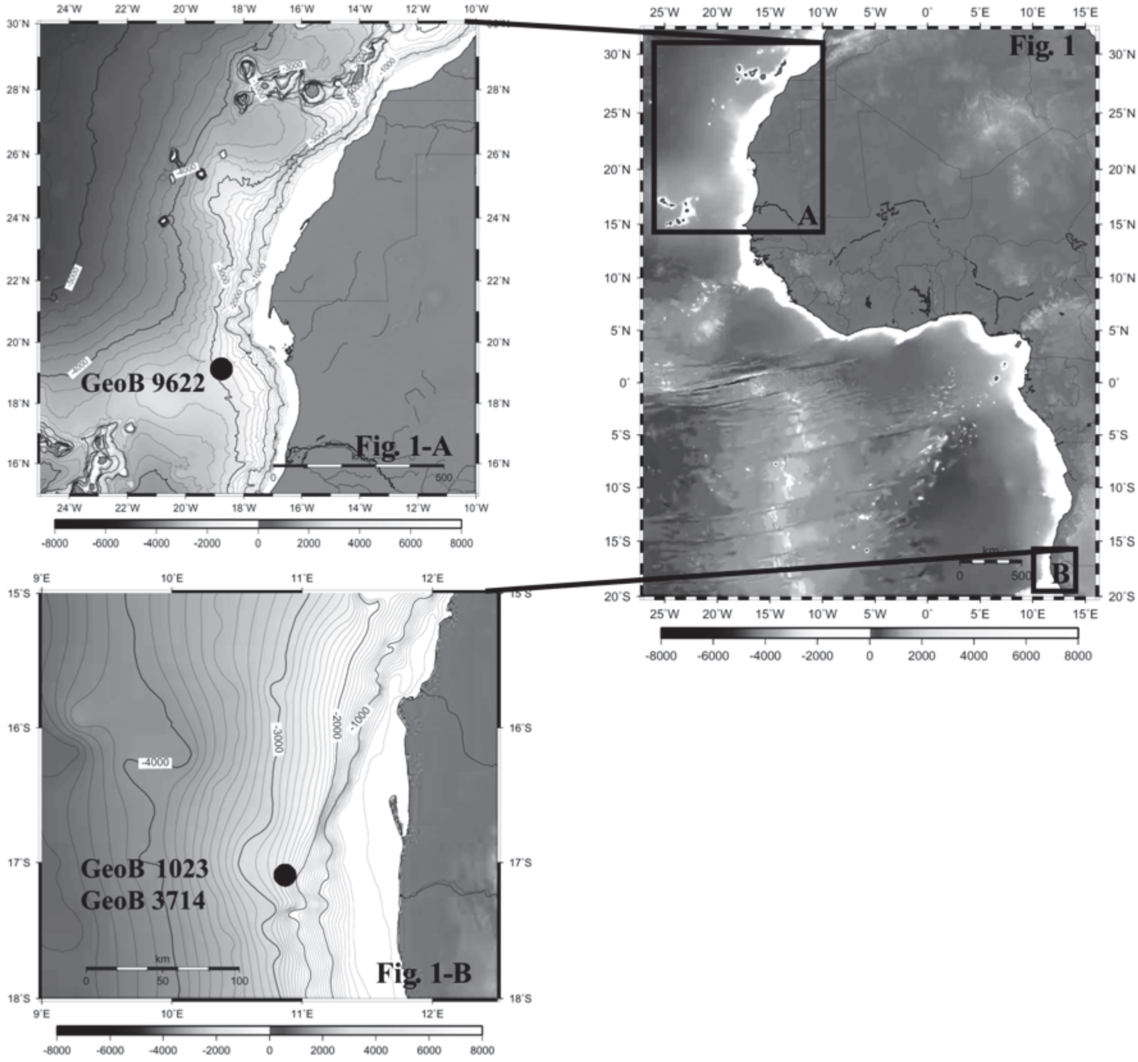


Fig. 1: *Core locations of the studied GeoB gravity cores; map A shows the core position of GeoB 9622 from the Cap Timiris Canyon (RV Meteor cruise M 65/2; map B displays the core position of core position of GeoB 1023 as well as 3714 (RV Meteor cruises M 6/6 and M 34/2).*

Gravity core GeoB 9622 reveals a succession of hemipelagic sediments which are repeatedly interrupted by turbidite sequences. This is a succession of deposits characteristic of a core station located in a canyon system (e.g. Bouma, 1962; 2000; Stow & Shanmugam, 1980; Bouma et al., 1985).Coring station GeoB 1023 is situated in the South Atlantic, on the passive continental slope off the coast of Angola, a short distance north of Walvis Ridge in the southern Angola Basin. The gravity core was taken during the M6/6 Meteor expedition in 1988. The pore-water concentration profiles previously analyzed represented a specialty not yet fully understood at that time (Schulz et al., 1994).

For this reason, sampling was repeated during Meteor expedition M34/2 in 1996 at position GeoB 3714, lying in the immediate vicinity to station GeoB 1023. The continental slope of coring stations GeoB 1023 and 3714 (see Fig. 1-B) which belongs to the southern part of the Angola Basin is a high-productivity area in the southern Atlantic. Its sediments are characterized by high sedimentation rates and great amounts of organic matter. The clastic proportion of the sediments is mainly imported by the Kunene River.

The hemipelagic sediments in this dynamic deposition area are frequently interrupted by turbidite layers (Schneider, 1991). Headwalls of landslides common to this continental slope distinguish the topography of the seafloor. Glide planes were not macroscopically identifiable in the gravity cores GeoB 1023 and 3714. They could only be identified indirectly by characteristic kinks in the depth profiles of certain pore-water concentrations (particularly sulfate, ammonium, and alkalinity), as first described by (Zabel & Schulz, 2001) for a core from the continental slope in the estuary of the Congo River.

Materials

Solid-phase recovery and pore water extractions

The gravity core from position GeoB 9622 was dissected offshore into 1m-long segments within approximately. 30 minutes after recovery and then brought into the laboratory. Here, pore water was extracted from the yet unopened core within the next 30 to 60 minutes, at intervals of 50 cm using rhizones, a fast and non-destructive pore water sampling method (e.g. Seeberg-Elverfeldt et al., 2005; Dickens et al., 2007). Sampling usually produced 10 – 20 ml pore water per rhizone.

Several hours later, the core GeoB 9622 was split lengthwise. The solid phase was then continuously sampled by using titanium U-channels. The complete U-channels were sectioned in 4 cm increments and oven-dried at 200°C for 60 min. Then each 4 cm section was ground in a mortar. Element contents were determined from the in total 257 samples by energy-dispersive polarization X-ray fluorescence (EDP-XRF) spectrometry, using a Spectro Xepos instrument, within the next 1-2 days. We therefore applied a method designed for pulverized sample material. The XRF analytical method employed is described in detail elsewhere (Wien et al., 2005; 2006 b; Schulz, 2006 a). The sediment cores GeoB 1023 and GeoB 3714 were also dissected into 1m-long segments within an interval of 30 minutes and then brought to the ship's refrigerated laboratory (4° C). The pore water was extracted with the aid of PTFE pore water squeezers under an argon atmosphere, using 0.2µm membrane filters and a pressure of about 5 atmospheres (for further details cf. Schulz et al., 1994 and Niewöhner et al., 1998).

Methods

Geochemical pore water Analytics

The pore-water samples of all three cores were measured onboard during the research expedition within one day after coring. The alkalinity of all the cores was determined by pH titration (according to Grasshoff et al., 1983) within 5 hours after sampling, using a sample volume of 1.5ml and a 0.01 molar HCL solution as reagent for analysis. The ammonium concentration of cores GeoB 1023 and GeoB 3714 was determined photometrical in an autoanalyzer, applying the standard procedure described by Grasshoff et al. (1983). Pore water ammonium from position GeoB 9622 was analysed by conductivity measurements, applying the flow-injection technique (Hall & Aller, 1992). Ion-chromatography was applied to determine the sulfate concentration in cores GeoB 1023 (Schulz et al., 1994) and core GeoB 3714 (Niewöhner et al., 1998). Pore water sulfate of GeoB 9622 samples was determined photometrical with a quick test from Merck® (Krastel et al., 2006a). More information about the analytical methods used is available in Schulz (2006 a) and at: http://www.geochemie.uni-bremen.de/koelling/MGCmain.html. All data related to the cores GeoB 1023, 3714 and 9622 presented here are published in the generally accessible PANGAEA database (http://www.pangaea.de).

Radiocarbon dating

Radiocarbon dating of sediment core GeoB 9622 (cf. Tab. 2) proceeded at the Leibniz Institute of Radiometric Age Determinations and Isotope Research (University of Kiel, Germany) by applying the AMS method (Ref. No.: HB 939-941, 944, 945, 947, 948, 979). For the 8 samples approximately 10 mg carbonate from planktonic foraminifera was used as sample specimens. Eight radiocarbon age data points are available from initial analyses of the organic carbon of sediment samples taken from gravity core GeoB 1023-4 (cf. Tab. 3). The samples were measured at the University of Bremen, applying benzene synthesis and liquid scintillation counting. All data used in this context were derived from the publications of Kölling (1991), Schneider (1991) and Shi et al. (2000) later, who used carbonate profiles to correlate GeoB 1023-4 with the parallel core GeoB 1023-5 to adjust the proper sampling depth. We used the original sampling depths of core GeoB 1023-4. All radiocarbon age determinations in this paper (cf. Tab. 2 and 3) were calibrated with CalPal-2007online (Danzeglocke et al., 2008).

Determination of the Kf Value

In order to estimate the probability of an entry of lateral pore water at certain sediment depths, we estimate permeability coefficients Kf (in m/s) after Beyer (1964), for the sandy substrate of two turbidite sequences, T4 (4.54 – 4.55m), located directly within the zone of the distinctive pore water concentration changes and the next turbidite sequence T5 (6.36 – 6.37m). Only grain sizes greater than 0.063mm were included in the grain-size analysis.

Modelling of pore water concentration profiles

The age estimation of the sediment slide event documented by the pore-water profiles proceeded by application of EXPLICIT (Zabel & Schulz, 2001; Schulz, 2006 b). This is a computer program which permits the calculation of Fick’s second law of diffusion for one-dimensional transport processes controlled by diffusion or by advection and dispersion, each in combination with simple reactions. As such, it produces an explicit numerical solution. The program is available as a MS Excel® worksheet at http://www.geochemie.uni-bremen.de.

Results

Pore water data

All pore-water concentration profiles showing alkalinity, sulfate and ammonium (cf. Fig. 2) of the sediment cores GeoB 9622, GeoB 1023 and GeoB 3714 displayed so-called 'kink type' profiles. These 'kink-type' profiles have been described before (Borowski et al., 1997, 1999; Haese et al., 1997; Niewöhner et al., 1998; Pruyser, 1998). They are characterized by a distinctive concentration gradient change which emerges at a certain depth.

Modelling of pore water concentration profiles

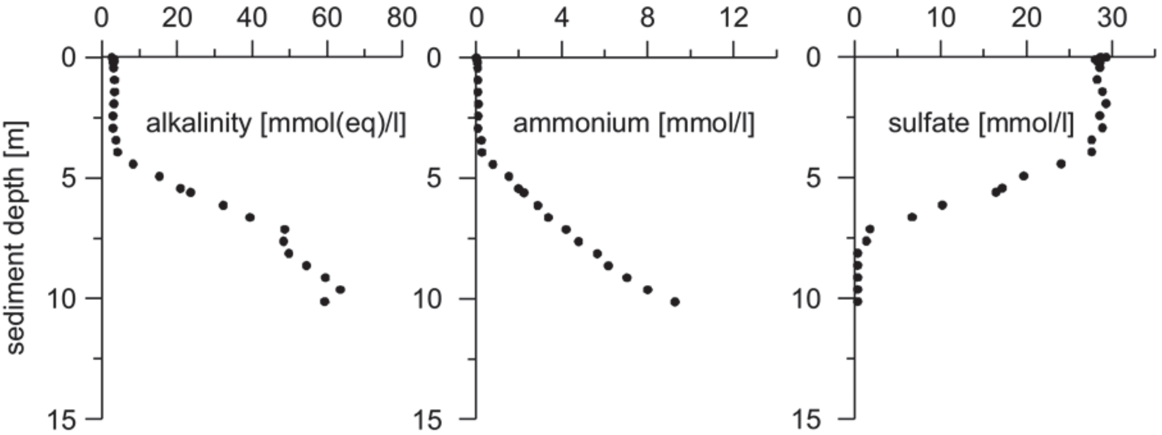
The interaction of diffusion and simple reactions (degradation, release) was used to numerically model the pore-water profiles in order to determine the age of slide events. Figure 3 shows the results obtained for the parameters of ammonium and sulfate in cores GeoB 1023 and GeoB 9622. Modelling procedures were based on the following assumptions:

A sequence of sediment strata which had been originally developed further up on the continental slope is located at positions (GeoB 1023 and GeoB 9622). This is the result of a slide event over an older sediment surface. The upper sequence of the sampled cores contains a lower amount of reactive organic matter as reflected by shallow pore-water concentration gradients. The thickness of this block amounts to 4.0m (GeoB 1023) or 4.5m (GeoB 9622).

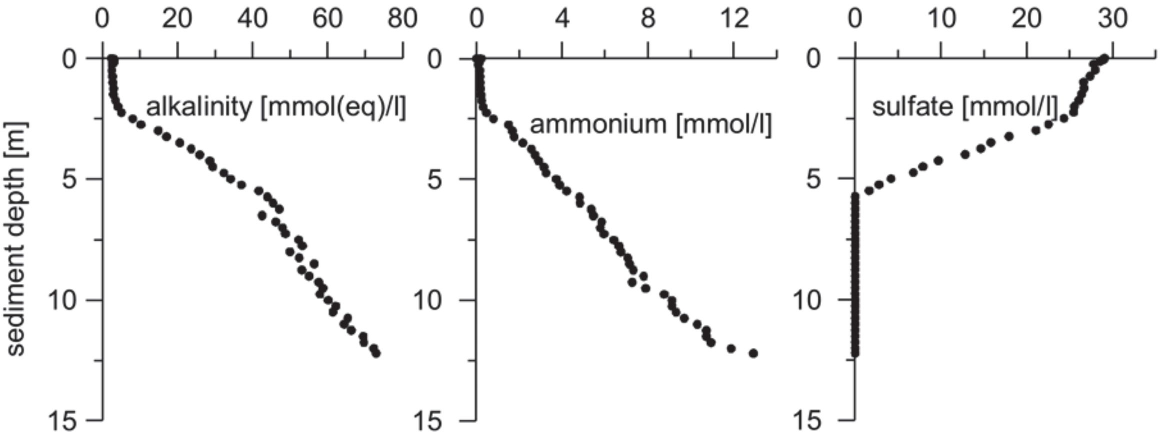
- The lower series of strata contains higher concentrations of organic matter in the substratum which is displayed in the shape of a steep concentration gradient.

- At a greater depth (8 m in case of GeoB 1023; 11 m in case of GeoB 9622) ammonium (alkalinity demonstrating similar behaviour) is released and sulfate is reduced in the narrowly defined sulfate-methane transition zone.

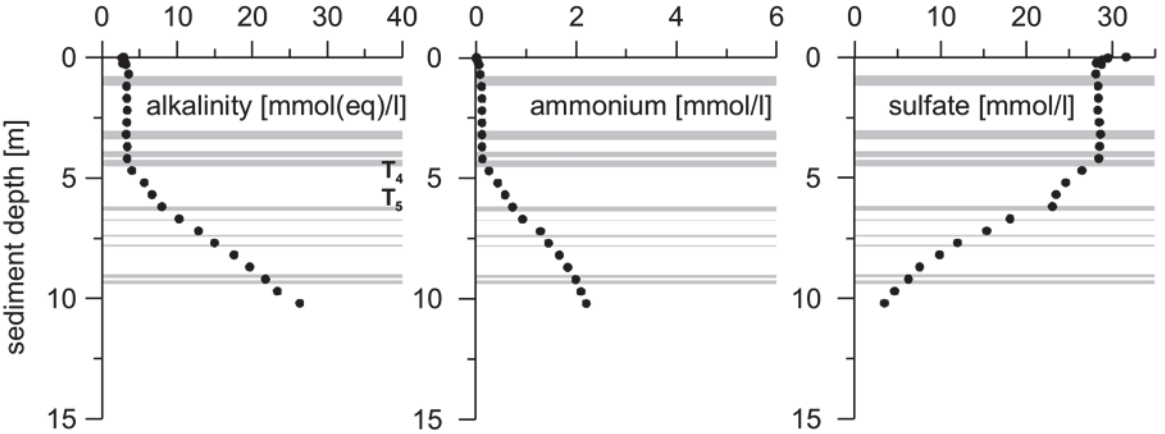
Once a slide event is over, the concentrations at the sediments surface will be controlled by the concentrations in seawater. In the deep parts of the sediment, release and degradation reactions continue to control the concentrations. The entire intermediate part of the profile is determined by diffusion processes, with well-known diffusion coefficients (Schulz, 2006 a), beginning at time after the slide.



(a) GeoB 1023



(b) GeoB 3714



(c) GeoB 9622

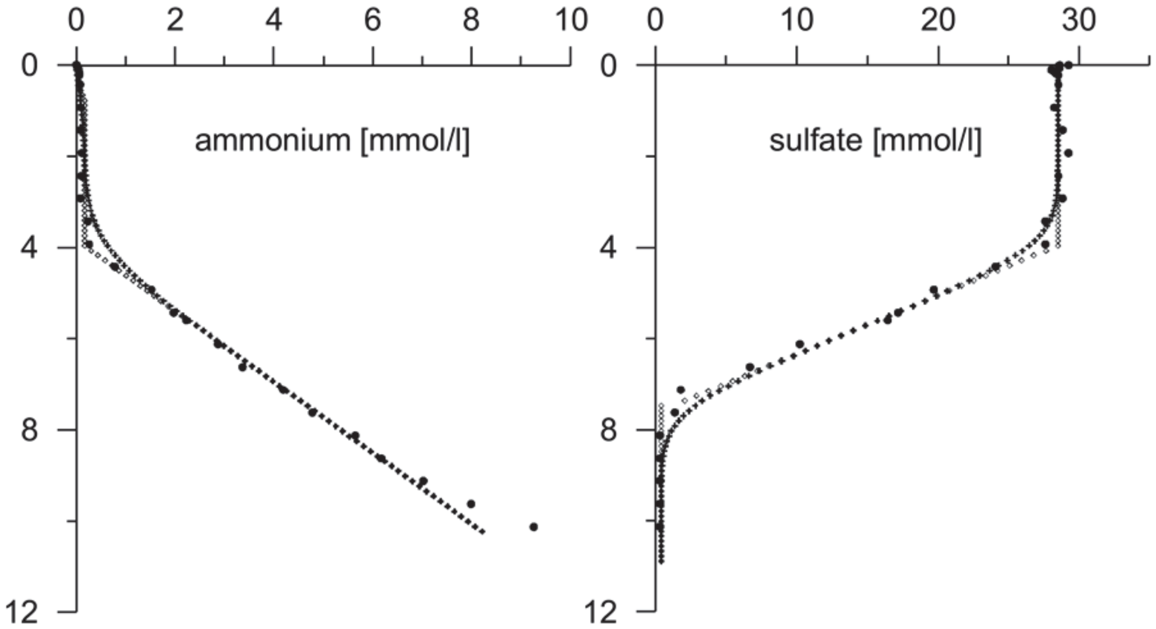
Fig. 2: *Pore water results of alkalinity, ammonium and sulfate from;*

(a) GeoB 1023 (data from Schulz et al., 1994);

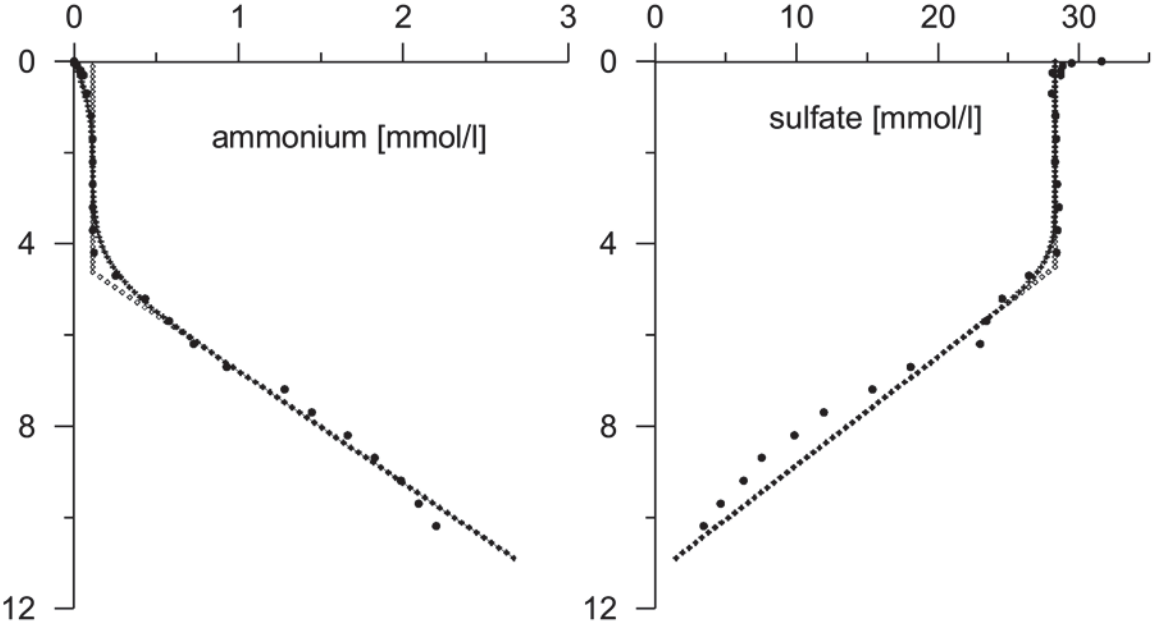
(b) GeoB 3714 from the southern Angola Basin (data from (Niewöhner et al., 1998));

(c) GeoB 9622 from the Cap Timiris channel system (data from this study).

Figure 3 shows the anticipated concentration profiles of both stratigraphic sequences which are marked by small open diamonds. Such profiles were measured at various locations on the continental slope.



(a) GeoB 1023



(b) GeoB 9622

Fig. 3: *(a)-(b) Black dot: Pore water concentration profiles of ammonium and sulfate, Open rhombus: Modelled pore water profile, start situation direct after, relocation (time T0 yrs). Black cross: Modelled pore water profile, recent situation (time T20 yrs).*

The start of the model is set at the time immediately after the slide event occurred. Diffusion smoothes the original sharp-edged kinks progressively. Modelling is terminated once the model curve (black crosses) reflects the measured values (round dots) as good as possible. The time covered by the modelling represents the number of years that have passed since the slide event. It comprises a few decades according to the two examples shown in Fig. 3. There is certainly only little tolerance for a subjective adjustment of the model to the measured concentration profiles. We therefore assume that the slide events had occurred more than 10 and less than 50 years before the concentration profiles were measured.

Solid phase data

After opening the core, the solid phase of core GeoB 9622 displayed a succession of turbidite sequences which were deposited in alternation with normal hemipelagic sediments as expected from a canyon system (e.g. Bouma, 1962, 2000; Stow & Shanmugam, 1980; Bouma et al., 1985). The depth location of the glide planes could be expected to lie in a rather limited range. However, there was nothing recognizable macroscopically which would have allowed us to draw any conclusions concerning the potential existence of a glide plane. Although the elemental distribution in the sediment core measured on board by XRF did reveal markedly deviant concentrations in the zone of the turbidite sequences, an obvious signal appearing in association with the anticipated slide event was not discernible. Neither did the solid phase of the sediment core GeoB 1023 retrieved from the Angola Basin reveal any macroscopically visible alterations of the sediment's composition in the proximity of the pore-profile 'kinks' which could have indicated the existence of a glide plane (Gingele, 1992) .The same also applied to sediment core GeoB 3714 which was extracted in the immediate vicinity to the previous core location of GeoB 1023.

In order to estimate the probability of an entry of lateral pore water, e.g. by means of weakness zones such as sandy turbidite deposits, we determined permeability coefficients Kf (in m/s). A mean Kf value of 4.5 10-5 m/s was obtained for the sandy substrate of the turbidite sequence T4 (4.54 – 4.55m), located directly within the zone of the distinctive pore water concentration changes. The next turbidite sequence T5 (6.36 – 6.37m) revealed a mean Kf value of 4.5 10-5 m/s. The real Kf value, however, is much lower, since only grain sizes greater than 0.063mm were included in the grain-size analysis. The fine fraction (< 0.063mm) of T4 in fact accounts for 1/3 of the entire sample, and even ¾ in case of T5, i.e. the obtained Kf value is overestimated in both cases. Considering the obviously too high values, a pressure gradient within these layers would have to be postulated in the event that any critical lateral advection had occurred. However, there has neither been any theoretical nor any practically measured indication of such a condition as far as we know.

Radiocarbon dating

The results of the radiocarbon dating of the cores GeoB 9622 und GeoB 1023 are compiled in Table 2 and Table 3 and Figure 4. The diagrams of Figure 4 reveal that two zones are recognizable for which sedimentation rates, clearly differing from each other by a factor of 2, were calculated on the basis of the radiocarbon dates.

Tab. 2: Radiocarbon: GeoB 9622 **Tab. 3:** Radiocarbon: GeoB 1023

Depth in core 9622 [m]	Age (^{14}C yr B.P.***) a***	Age range at 2σ (cal yr B.P.) ***c***	Depth in core 1023 [m]	Age (^{14}C yr B.P.) b	Age range at 2σ (cal yr B.P.) c
0.74	9550 ± 55	10775 – 11048	1.43	1860 ± 60	1731-1866
3.06	17960 ± 110	21262 – 22015	2.47	5940 ± 150	6600-6978
3.90	20050 ± 130	23642 – 24309	3.46	9710 ± 350	10638-11754
4.19	18270 ± 100	21628 – 22288	3.97	10790 ± 110	12668-12887
4.56	20540 ± 110	24207 – 24796	5.46	11470 ± 190	13150-13570
4.62	20950 ± 150	24694 – 25478	6.96	14160 ± 140	17136-17672
6.13	28930 ± 320	32976 – 33835	9.14	15940 ± 280	18826-19464
8.90	49750 ± 4200	49361 – 60630	10.16	18650 ± 260	21843-22745

a Data provided Leibniz Institut Kiel, Germany
b Data from gravity core GeoB 1023-4 from station GeoB 1023 (Data from Kölling, 1991).
c Data calibrated with CalPal-2007$^{\mathbf{online}}$ (Danzeglocke et al., 2008)

The upper 4 meters of the sediment in core GeoB 1023 displays a markedly lower sedimentation rate of merely 0.3 m kyr-1, whereas a sedimentation rate of somewhat more than 0.6 m kyr-1 results for the layer below. The sedimentation rates in the upper 4 meters of core GeoB 9622 are higher. A sedimentation rate of approximately 0.3 meter kyr-1 characterizes the upper part, whereas the lower revealed a rate of approximately 0.15m kyr-1.

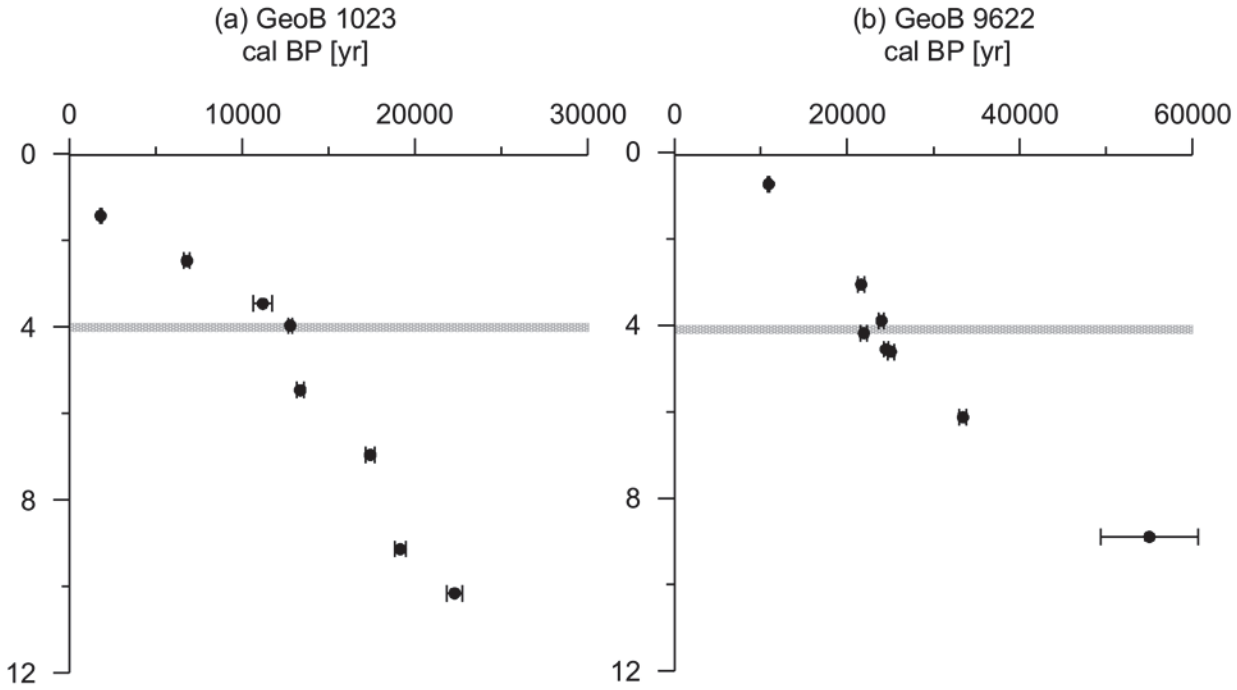


Fig. 4: *(a)-(b)   Black dot: Radiocarbon ages ;*

(dashed line: average trend of data, grey line: area of kink in pore water data.)

(a) GeoB 1023: data from Kölling (1991);

(b) GeoB 9622: data provided by the Leibniz Institute Kiel, Germany;

(a)- (b) Calibrated with CalPal-2007online (Danzeglocke et al., 2008)

It is also evident from Figure 4 that the zones displaying the disparaging sedimentation rates meet exactly at a point where the existence of a glide plane had to be postulated according to the depth profiles of the pore-water concentrations. However, the data also reveal that the lower stratigraphic sequences lying immediately below the postulated glide plane do not reflect a situation typical of a young sediment surface prior to a slide event. Here, the data revealed a small discontinuity in the age sequence only. This result needs to be considered as essential to developing a model concept.

Data evaluation and model concept

The concentration profiles shown in Figure 2 relating to alkalinity, ammonium and sulfate of the three analyzed cores are to be understood as an image reflecting geochemical processes which are controlled by the redox reaction known to describe the mutual decomposition of sulfate and methane at the zone of the "sulfate-methane transition" (SMT) (e.g. Niewöhner et al., 1998).

$$SO4 + CH4 \rightarrow CO2 + 2\ H2O$$

In an undisturbed profile, this process is represented as a stead-state condition with very characteristic profiles (e.g. Schulz et al., 1994; 2006 a).

Pore Water Sulfate

Sulfate reduction in the SMT zone is equivalent to the gradient of the concentration which extends from a value of approx. 28 mmol/l in the sediment surface, to a concentration of 0 mmol/l in the SMT zone. This sulfate gradient also mirrors at a ratio of 1:1 the diffusive methane flow from the bottom to the SMT zone. It is often used to estimate the turnover of methane released in a deeper sediment zone by fermentation.

Kinks in the concentration profiles encountered above the SMT zone — such as we observed in all three sulfate profiles (cf. Fig. 5) — would indicate under given steady-state conditions the presence of a sulfate source. The existence of the latter can be ruled out without any doubt in this particular case. Consequently, such kinks in the concentration profile and/or alterations in the concentration gradient are likely to merely reflect conditions of a non-steady state.

Pore Water Alkalinity

The release of CO_2 as indicated in the above chemical equation will lead to higher carbonate concentrations in the pore-water fraction, which is recorded in the concentration profile of alkalinity. This contribution to the pore water produces a steeper alkalinity gradient in the SMT zone as is evident in Figure 2; especially with regard to position GeoB 1023 at a depth of 1900 m WD. There is no kink in the alkalinity depth profile at position GeoB 9622. This is due to the fact, that the SMT zone lies below a depth of approximately 10 m and is not reached by the cored material. A constant gradient from the SMT zone to the low alkalinity at the sediment's surface would establish itself under steady-state conditions. Here as well, the distinct alterations in the concentration gradients discovered at a depth of 4-5 m can only be understood as the result of non-steady-state conditions.

Pore-Water Ammonium

Ammonium rising from the depth to the sediment surface by diffusion is not linked to the process of methane oxidation through sulfate. Hence it does not display any alterations in its concentration gradient at the SMT zone (particularly visible in the high-resolution depth profile of core GeoB 3714, Fig. 2). The ammonium released in the depth originated from the decomposition of organic matter in the course of methane fermentation.

Under steady-state conditions, ammonium is therefore characterized by a continuously constant gradient from the depth up to a concentration which is practically zero at the sediment's surface. Here as well, the kinks in the concentration profiles shown in Figure 2 definitely reflect non-steady-state conditions.

Slide Ages

(Zabel & Schulz, 2001) and (Hensen et al., 2003) were able to demonstrate that the profiles of the so-called "kink-type" could have been the result of a slide event, provided that the original pore-water signal had been retained in the sediment. They also demonstrated that the time that passed since the slide event had taken place could be estimated by the diffusion-dependent disappearance of the kinks from the profile.

We conducted a similar estimation for the profiles obtained from the positions GeoB 1023, GeoB 3714 and GeoB 9622 (cf. Fig. 3) and came to the conclusion that the slide events documented in the pore water of all three cores had occurred only a few years or decades before the cores were sampled, as the various pore-water gradients had hardly adjusted themselves to each other by way of diffusion. Figure 3 shows the results of the model calculations, which have led to this age estimation. The open symbols designate the initial situation in the pore-water fraction immediately after termination of the slide event.

The solid symbols represent the concentrations which would have been obtained after approx. 20 years of diffusion. The modelled smoothing of the concentration profile kinks by diffusion after this period of time reflects the best representation of the measured concentration profiles at GeoB 1023 / GeoB 3714 and GeoB 9622 (cf. Fig. 3).

This value of 20 years resulted from terminating the diffusion calculation as soon as the modelled concentration distribution revealed an as good as possible match with the concentration distribution measured. A process of diffusion which had been effective over a period of 10 years only would have resulted in kinks overly pronounced, whereas a diffusion process over 30 years would have produced kinks that were too flat. Nevertheless we speak with all cautiousness only of age “estimation” and limit ourselves to a statement of “few decades”, which already means a very narrow time span in the context of the sedimentation history of such sediment.

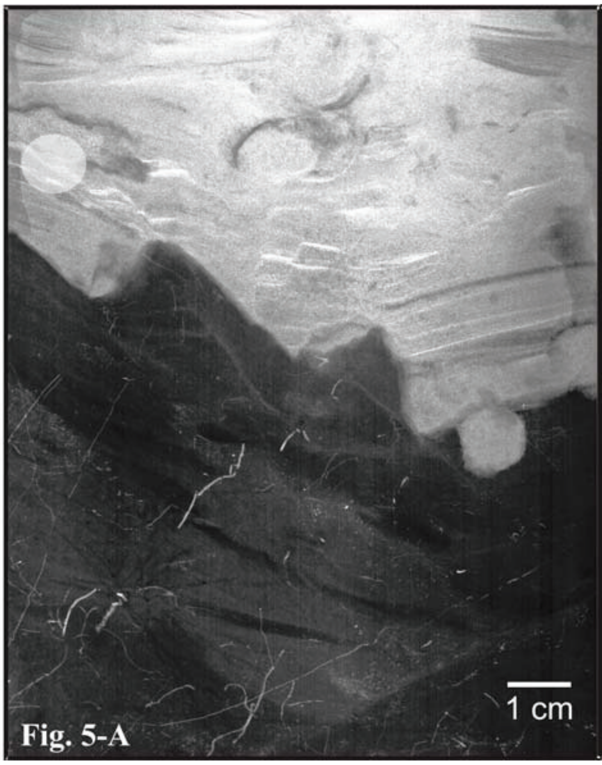
Identification of a Glide plane at Position GeoB 9622

According to the pore-water profiles and their modelling (cf. Fig. 3 and 4), the location of the postulated slide could be specified within narrow margins and assumed not to extend much deeper than 4m below the sediment’s surface. In the solid phase of GeoB 9622 there was no signal (e.g. a glide plane) unequivocally allocatable to the slide event within the range of concentration gradient alterations at a sediment depth of 4.55m.

But what is a glide plane expected to look like in such a material? There are hemipelagic sediments intermitted with turbidite layers above and below the expected glide plane within the range of pore-water gradient alterations at the sediment depth of 4.55m. The plane itself very probably might be embedded in a rather low-friction layer and hence be very limited in space, running essentially parallel to the stratification. If we also were to assume that such a slide of the entire layer sequences does not proceed at a particularly fast rate, noticeable disruptions of the adjoining sediments will not have to be expected in the proximity of the slide. In most cases, such a glide plane will therefore be difficult to identify.

Still, we believe that we were able to identify not only by pore-water profiles but also in the sedimentological record, the area of sediment depth in which the postulated glide plane can be expected. Figure 5 shows a radiography representing a sediment depth ranging from

4.515 m down to 4.625 m, in which Turbidite T4 is placed as well. It can be clearly seen that the base of T4 (cf. Fig. 5-B, hatched areas) displays a blocky broken structure indicative of lateral stress exposure (e.g. movement) subsequent to the original deposition of sediment. We assume the actual glide plane to be located in the directly underlying dark, fine-grained layers.



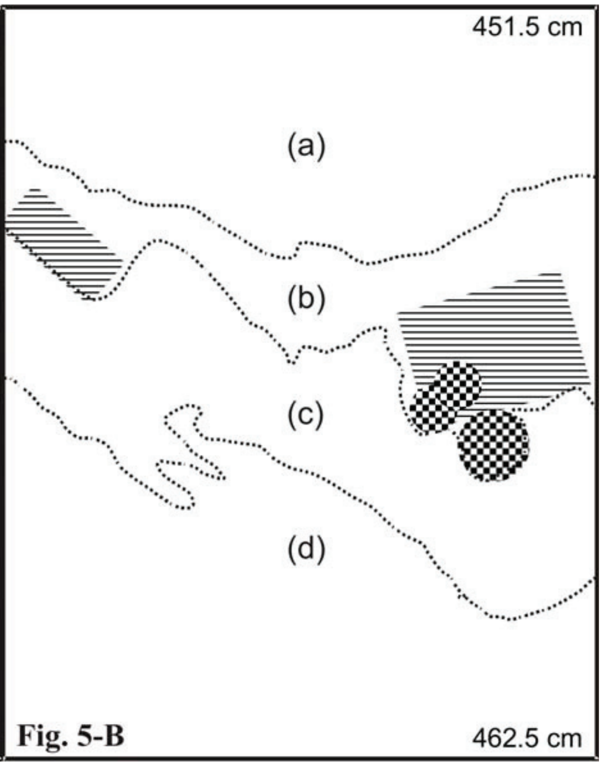


Fig. 5-A: *Radiography of gravity core GeoB 9622 from 451.5 - 462.5 cm sediment depth; showing the sandy base of turbidite sequence T4 on top and underlying sediment sequences.*

Fig. 5-B: *Scheme of Fig. 5-A, showing the important features; (a) top to 453 cm : lower part of the turbidite sequence T4; (b) 454 to 456 cm: sandy base of the turbidite; (checkered area: slightly bioturbated, dashed area: blocky structured sandy base of the turbidite); (c) 456 to 459 cm: pelagic sedimentation (foraminifera bearing mud); (d) 459 to bottom: pelagic sedimentation (foraminifera bearing mud); (all information according to Krastel et al, 2006).*

In general such slight perturbations are often considered to be caused, for example, by the process of core removal. So if pore-water concentration profiles had not been available, the glide plane would most likely have been overlooked.

The Situation at Position GeoB 9622

If we identified a slide as such, then the question ensues, why did an entire layer package slide at this particular site, and why did the disruption of the sediment's coherency not proceed as a debris flow or turbidity current? If we want to develop the whole process as a coherent model concept then we also must know the path and the distance of the layer sequence's movement.

Figure 6 shows a cross-section through the region of Cape Timiris canyon in which position GeoB 9622 is located. The core position lays a cut-off loop of the canyon, where the sediment surface lies approximately 120m higher than in the active course of the canyon.

The seismological profile clearly shows that the cut-off loop used to be just as deeply incised as the active canyon. Consequently, the sediment filling was certainly deposited only after the canyon had lost its active function at this site. The sediment filling of the cut-off loop consists of hemipelagic sediments and several turbidites.

Looking more closely at the sediment echography of the material filling at the cut-off loop, it is noticeable that the upper layers of this sediment filling display a marked decline from the central peak towards the steep edges of the loop. The deeper, still recognizable layers of cut-off loop sediments display a distinctly horizontal orientation as is characteristic of the sediments in the active branch of the canyon. This can only be explained with the sediment transport across the vast and steep altitude differences between high plateau and the active canyon regularly being associated with dissolution of the stratification, resulting in a turbidity layer of similar thickness all over. Even the older deposits in the cut-off loop apparently came into existence this way. Only in case of the upper part of the sediment filling the height difference between the central peak and the base of the cut-off loop was small enough to allow a sediment sequence to slide with the necessary slowness to the base without disturbing the original strata.

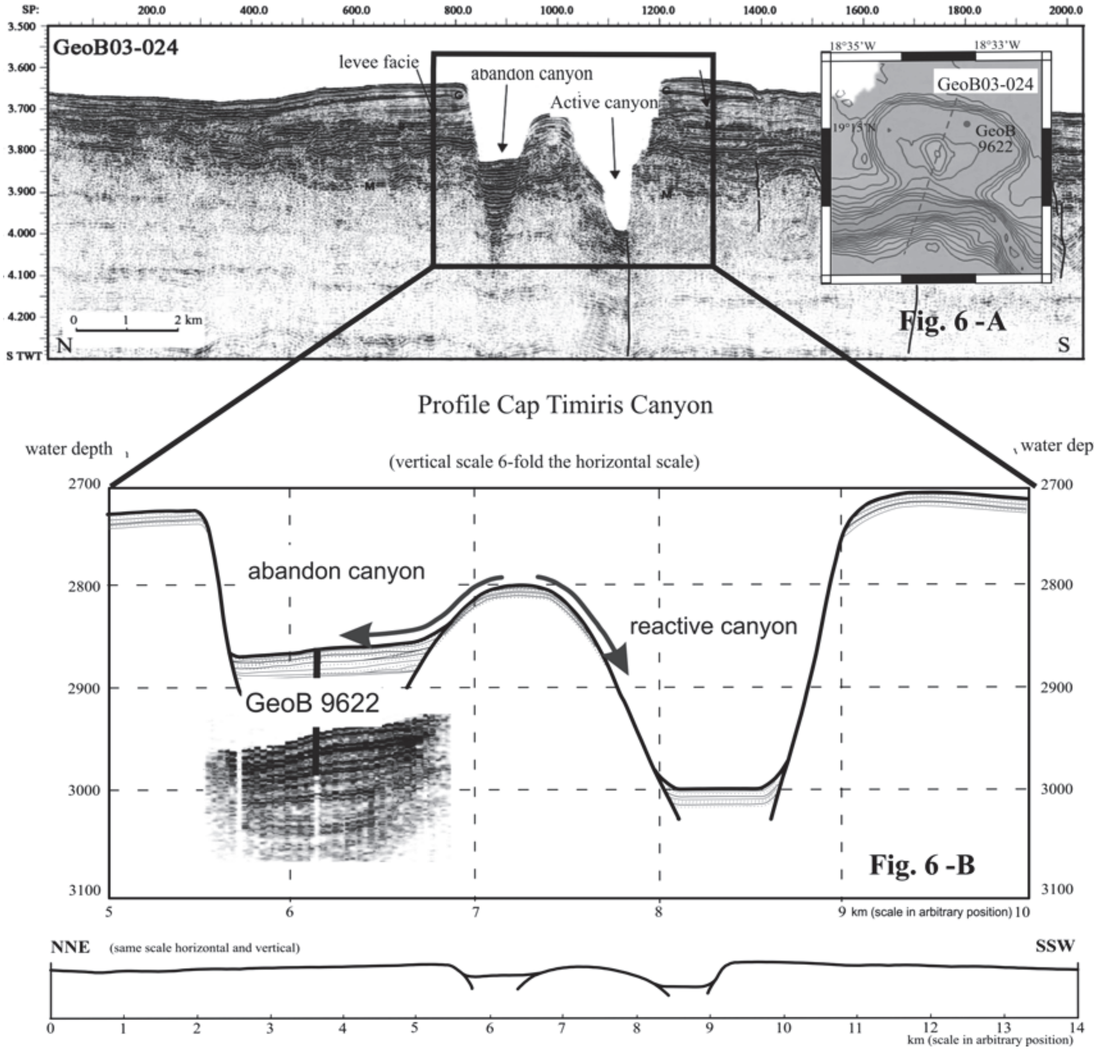


Fig. 6-A *: Multi-channel seismic reflection profile GeoB03-024 recorded in the lower canyon domain of the Cap Timiris Canyon during RV Meteor Cruise M58/1 (modified after (Antobreh & Krastel, 2006). To the north the cut-off loop is partly filled with younger sediments (location of GeoB9622).*
Fig. 6-B: *Sketch based on the seismic profile showing schematically the sedimentation settings at the core location of GeoB 9622 with a detail out of a parasound profile from RV Meteor cruise M58/2 showing the sedimentation in the cut-off-loop and a non-inflated sketch of the local situation below.*

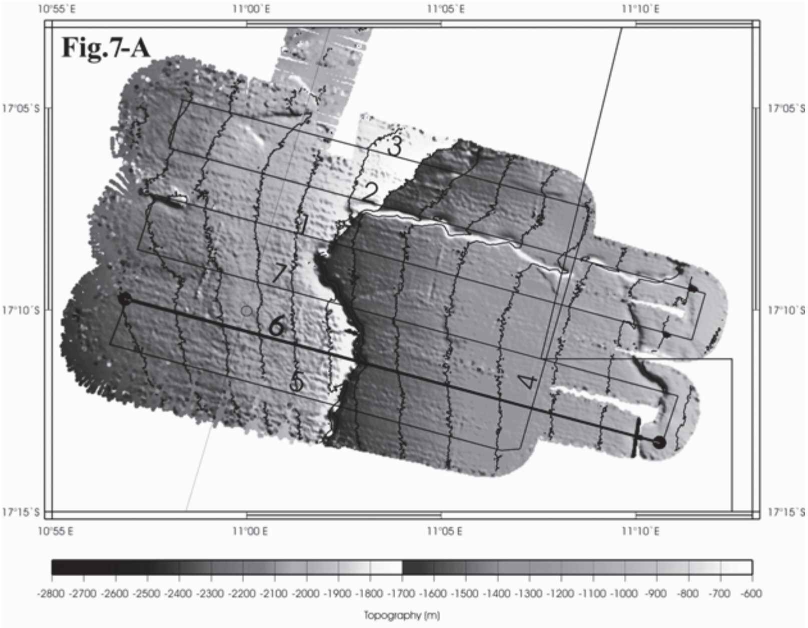
The Situation at Position GeoB 1023/GeoB 3714

As far as location GeoB 9622 is concerned, we could argue that the cut-off loop of the marine canyon represents a rather specific situation. However, positions GeoB 1023 and GeoB 3714 were recovered from a quite normal, passive continental slope which is distinguished by a rather high sedimentation rate and high concentrations of organic matter in the sediments.

Neither could any glide planes be unequivocally identified in the sedimentological record of GeoB 3714, nor have they been described / mentioned for the sediment strata of GeoB 1023 (the original core itself is no longer available) in earlier studies (Kölling, 1991; Schneider, 1991; Gingele, 1992), even though its depth is described quite precisely again by the high-resolution pore-water profiles. We therefore assume that the glide plane is rather sharply defined and concordant in its layers here as well, lying in a zone of enhanced sliding properties. Once again, we are certain that no one would have ever suspected to find a glide plane in these cores if it were not for the pore-water profiles.

As mentioned before, it is well known that in this area of the Angola Basin sediment transport frequently occurs, in form of slides, debris flows and turbidity currents (Embley & Morley, 1980; Schneider, 1991). Also in this area having hemipelagic sedimentation intermitted by Turbidite layers is a common finding (Schneider, 1991). Figure 7-A shows a bathymetric map of the position's surrounding recorded with a Hydrosweep® fan depth finder, while Figure 7-B shows profiles which were measured with a Parasound® sediment acoustic system. An almost 200 m high headwall is also clearly visible in both the map and the profiles.

We point out to the fact that the headwall shown in Figure 7 is by two orders of magnitude larger than the thickness of the slide we identified and dated in our cores by evaluating the pore-water profiles. The slumped series of strata identified in our cores only measure 2.5 to 5m in thickness. However, Figure 7 and the information concerning this part of the Angola Basin delineate this area to be a dynamic system. It demonstrates that slides of any type and dimension are likely to be expected to occur and that they may be considered as "regular events" on this particular kind of continental slope.



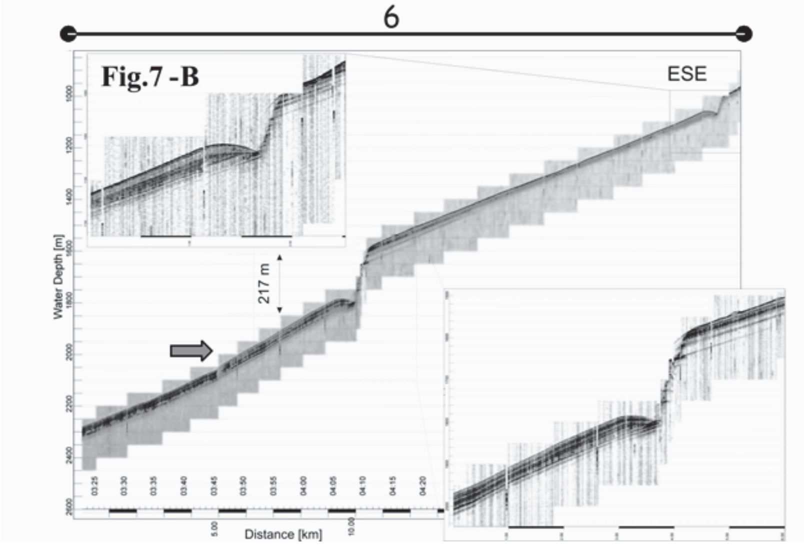


Fig. 7-A: *Bathymetric map showing the core location (Red dots) of GeoB 1023 and GeoB 3714 at the continental slope of the Angola Basin (see also Fig. 1-B) (Hydrosweep data of RV Meteor cruise M 34/2 from 1996).*

Fig. 7-B: *Parasound profile 6 located near coring station (cf. Fig. 7-A). Arrow marks the position where Geo B 1023/3714 is located between the profiles 6 and 7 in a water depth of about 2050 m (Parasound data of RV Meteor cruise M 34/2 from 1996).*

Radiocarbon Age Determination and Slide Model Concept

Initially, we expected an old sediment surface to lie below the sediment strata that slipped down the continental slope. However, this is ruled out by the depth profiles obtained from the radiocarbon dating (Fig. 4, Tab. 2 and 3). They reveal an alteration of the sedimentation rate in the glide plane area, as well as small but distinct discontinuities within the profile, but fail to show that there is a very young surface lying below the glide plane.

We see the solution to this apparent contradiction in a glide plane which was repeatedly used by several intact sediment strata sequences on the continental slope. Blocks of a few metres of sediment slide downslope and – after some time of exposure – get replaced by a package from further up-slope. The replacing block one represents almost the same period of time, but due to its different origin, a different pore-water geochemical fingerprint, as well as a different sedimentation rate.

In Figure 8 we show a schematic developmental history of the stratigraphic sequence as it documents itself in the three cores we analyzed. Much importance was given to consider the results obtained from the pore-water profiles and from the radiocarbon age determination to the same extent.

In the uppermost panel of Figure 8 we see the initial situation before a slide event and observe the two positions A and B on the continental slope. The sulfate profiles of A and B are shown exemplary for the pore water profiles at the different positions of the involved sediment strata in general. Additionally, the profiles of the radiocarbon age determinations that apply to the positions A and B. The sulfate profile at position B is distinctly steeper than is the case at position A.

A somewhat higher methane flow is the reason for the SMT zone lying in a lesser depth at position B. Such differences are by no means unusual, even in various water depths, on account of the invariably pockmarked distribution of methane fermentation turnovers in the deeper substratum. The various gradients in both radiocarbon profiles reflect various sedimentation rates. The sedimentation rate at position B is higher than at position A.

In the central panel of Figure 8, a series of strata has now slipped further downslope on a low-friction layer. This slide event affects position B, but not position A.

For this reason, the sulfate profile and the radiocarbon profile are identical with position A in the upper panel. At position B, however, the upper parts of the profiles are missing immediately after the slide event (continuous curve).

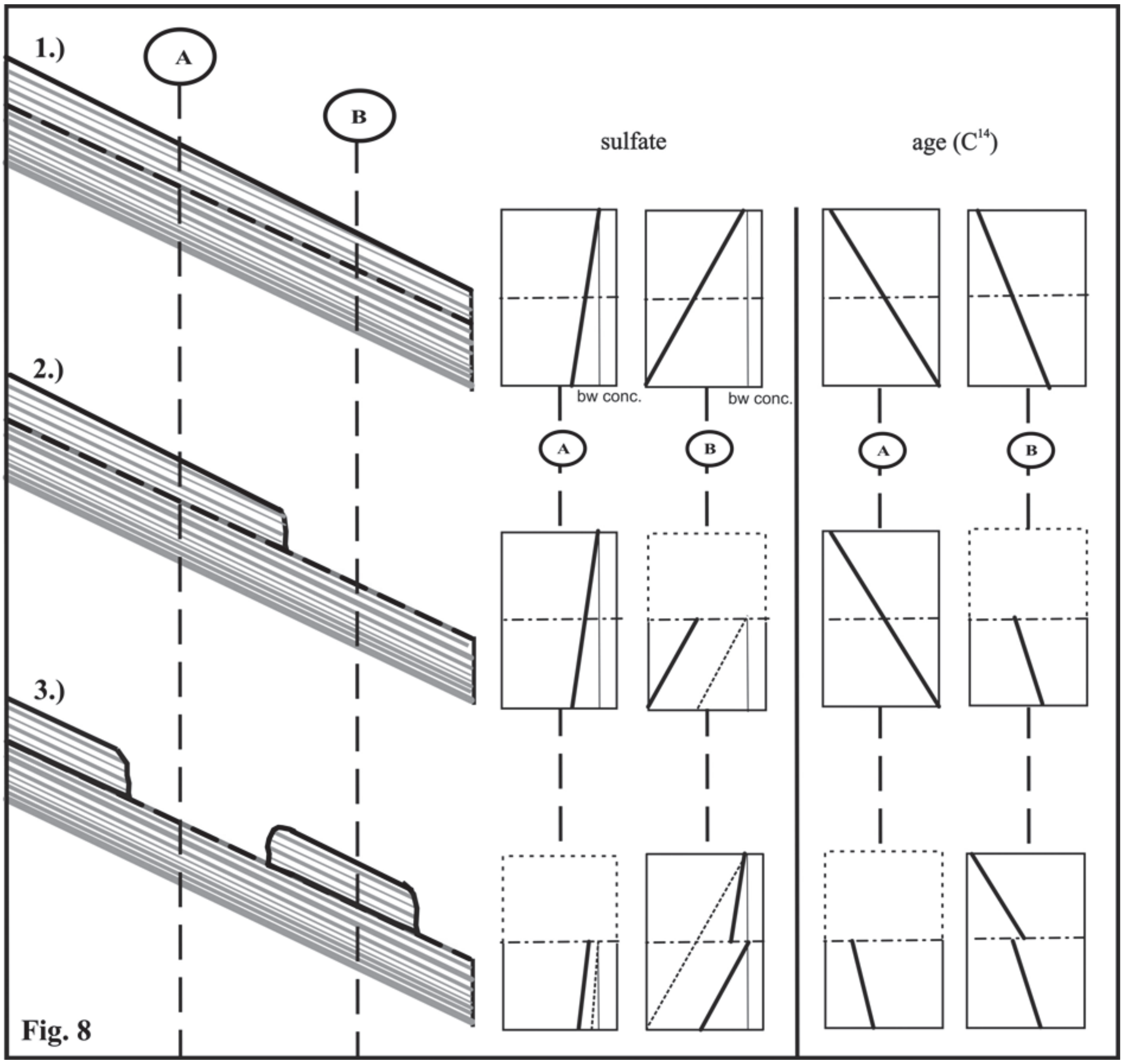


Fig. 8: *Model concept for slides of sediment blocks on the continental slope. Several slides occurred on the same glide plane. Diagrams show the concentration profiles of sulfate in pore water as well as the radiocarbon age determinations at two different locations.*

The upper panel (1) describes the situation before a slide event;
The center panel (2) describes the situation immediately after the slide;
The lower panel (3) reflects the situation after a second slide

(general remarks: ***dashed upper half diagram****: slided sediment series,* ***thick solid lines in diagrams****: concentration profiles of sulphate conc. profile as well as the radiocarbon ages,* ***dashed sulfate profiles****: steady state is once again reached (several centuries after the slide);* ***thin line in sulfate profiles****: concentration in bottom water)*

Several centuries later, the sulfate profile in the pore water adjusted itself by diffusion to the new situation and the seawater concentration above the new surface. It assumes an appearance which resembles the situation before the slide event (dashed curve). Such an adjustment certainly does not occur in the radiocarbon profile, as the solid phase is not affected by diffusion.

In the lower panel of Figure 8, another series of strata moved downwards along the same glide plane several centuries later. Now the upper part of position A has shifted to position B, thereby cutting off the upper part of the profiles at position A (continuous curves – situation immediately after the slide). The pore water will adjust itself to the new situation by way of diffusion once again after several centuries (dashed curve).

After this slide, we now obtain the shapes of the curves which we had previously obtained by measurement (continuous curves) of both pore water and radiocarbon age determination profiles. The pore water adjusts itself to the new situation by diffusion. We exploited the time course of this adjustment in order to determine the age of the slide event. A steady-state condition will be reached again after several centuries (dashed curve).

Conclusions

From the presented results and their evaluation several conclusions ensue, which need to be considered in the seismological, stratigraphic and paleo-climatological interpretation of sediment cores:

Various forms of sediment transport often appear on the continental slopes in many regions. Mostly, depositions occurring in association with turbidity currents and debris flow are easily recognized. However, if there is no visible change in material or a clearly distinguishable glide plane, the identification of slide events from unperturbed sediment sequences in sediment cores at a later point in time is of great difficulty. Older slide events are most often only recognizable on account of minor “disturbances” in the radiocarbon age profile and/or in an abrupt alteration of the sedimentation rate.

Slides with ages ranging from a few decades to a maximum of 100 or 200 years will mostly be well represented in the pore-water concentration profiles, if the upper series of sediment strata display a different geochemical regime than the one lying below. Diffusion produces a progressive adjustment of the pore-water concentrations in the transition area between both stratigraphic sequences, until a steady-state condition is reached after many centuries. The extent of the adjustment reached by the time the coring takes place, permits estimating the age of the slide event. Consequently, pore water analyses seem necessary to fully understand the sediment record and its history and should therefore not be omitted particularly in regions where other forms of sediment translocations are expected to occur as well.

Compared to the numerous cores taken to find the answers to sedimentological and stratigraphic questions, there are actually only a small number of cores for which the corresponding results have been published. Only some type of stratigraphic discrepancy, problems with age determinations, or similar ‘incomprehensible inconsistencies’ have been discovered in the vast number of these cores. We hold the opinion that the slides of intact sediment sequences occur much more often than hitherto anticipated. One or the other disagreeable and problematic core would be better understood, if an occurrence of sediment slides had been taken into consideration more often.

Acknowledgements

We are indebted to Karsten Enneking und Jan Hoffmann for assisting with the laboratory work during the RV *Meteor* cruise M 65-2. We likewise owe thanks to the Captain and crew members. We likewise owe thanks to Silvana Pape and Susanne Siemer for analytical support. This research was supported by a grant from the DFG Research Centre Ocean Margins at Bremen University.

2. MANUSCRIPTS II

2.2 Correlation of Turbidites in a Submarine Channel using Geochemical Fingerprints and Discriminant Analysis
(Dakar Canyon NW-Africa)

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(submitted to Sedimentary Geology)

Abstract

Chemostratigraphy has been applied to three cores within the Dakar Canyon System offshore NW Africa using the geochemical element data of the sediment successions in order to distinguish and correlate their turbidite sequences. This submarine canyon system has been studied using joint sedimentological, geophysical and geochemical approaches during Meteor expedition M65/2 in 2005. The solid phase of the cores was microwave digested and 41 elements were measured using both, ICP-AES and ICP-MS at a depth resolution of 1 cm. In this paper, we present a chemostratigraphic correlation resulting from the geochemical fingerprinting analyses. The sample dataset of in total 274 samples has been assessed statistically with discriminant function analysis (DFA) in order to first characterize and separate hemipelagites and turbidites. In a second step the use of DFA on the inorganic geochemical data provided a reliable correlation of the turbidites across the cores at the three positions along the canyon thalweg. This combined approach shows, that with this large number of elements measured, the precision of DFA assisted correlation is much better than with all other methods. Especially like in the present case of a high number of especial thin and even stacked modern turbidite sequences showing no significant digenetic overprint.

Keywords: submarine canyons; turbidites; Chemostratigraphy; discriminant function analysis

Introduction

At present identification, separation and correlation of turbidite sequences in sedimentary records rely largely on radiography-assisted visual description of the sediment, grain size analyses and radiocarbon dating. Correlation between cores has been performed using different proxies, including solid phase element concentrations or element concentration ratios. It has been shown that even in hemipelagic sediments strongly affected by turbidites, element stratigraphy is a useful tool for correlation if the turbidite deposits are clearly identified and removed from the sediment record. Useful downcore element profiles can be tied into a stratigraphic framework by correlating them with comparable geochemical profiles from reference cores with reliable age models (Wien et al., 2006 a). In this way, reliable age models for both the hemipelagites and the intercalated turbidites may be established.

This geochemical correlation method requires that turbidite boundaries are clearly identified in the respective cores, using detailed core description and radiographs of core slabs. This is, however, often complicated especially in the upper, finer part of turbidites. Separating thin turbidity beds from overlying pelagites is particularly difficult if primary depositional features like lamination are obscured by intense bioturbation (Weaver et al, 1992). Also thin muddy turbidites are hard to distinguish from the background sedimentation. However, if turbidites are successfully separated from the background material, this method allows single turbidites to be successfully correlated and indirectly dated (by dating the embracing sediments). For this purpose, hemipelagic layers have to be sufficiently thick, and erosion by the turbidite event should negligible at the core location. In this study, we are not focussing on the element stratigraphy of the hemipelagic sediments, but we are using the geochemical fingerprints of the turbidite layers themselves for correlation. This method is especially useful where turbidites dominate the sediment succession and the probability for erosive turbidite events is high.

Chemostratigraphic approaches are mainly used in hydrocarbon reservoir exploration for provenance studies (Pearce & Jarvis, 1992 a, 1992 b; Pearce & Jarvis, 1995; Pearce et al., 1999), in particular to correlate both offshore sequences (Pearce et al., 1999) and sandstones (Preston et al., 1998). Stratigraphic correlation is often performed by visually comparing downcore element profiles or element ratio profiles.

Both major and trace elements as well as several other proxies are established for the geochemical characterisation and correlation of strata, using downcore profiles or binary and ternary plots of selected element ratios for a chemo-stratigraphic comparison of turbidity beds (e.g. Roth et al., 1972; Bhatia & Taylor, 1981; Bhatia, 1983; Bhatia & Crook, 1986; Roser & Korsch, 1988, Pearce & Jarvis, 1995; Pearce et al., 1999; Wien et al., 2006a). The more chemical elements data are available for chemostratigraphy, the more precisely different layers may be characterized. On the other hand, a dataset of 41 downcore parameters as presented in this study may not be successfully correlated visually. Element ratios are commonly used to reduce large datasets, but calculating a ratio includes losing potentially useful information about the actual single element concentrations. An appropriate analysis of a large data set with multiple variables (here: element solid phase contents) in multiple samples may only be performed in a multidimensional space.

For the separation and grouping of samples from large data sets, discriminant function analysis (DFA) is the method of choice (e.g. Fisher, 1936; Roth et al., 1972; Bhatia, 1983; Roser & Korsch, 1988, Pearce & Jarvis, 1995; Pearce, 1999).

We demonstrate our approach at the example of three sediment cores from the Dakar Canyon offshore NW Africa, where a large number of different turbidites are deposited with only minor amounts of hemipelagic sediments between them (Pierau et al., 2010). Single turbidites have been deposited directly on top of older ones. Neither the stratigraphic position nor sedimentological or geophysical methods allowed a direct correlation of single turbidite layers. Only the youngest turbidite could be radiocarbon-dated and correlated across the cores (Pierau et al., 2011)

Study site

The Dakar Canyon incises the passive continental margin off Dakar, Senegal (NW-Africa) (cf. Fig. 1 and Tab. 1). It follows an almost straight downslope course to the Southeast and at its most distal part splits into a main channel and an inactive southern parallel channel (Pierau et al., 2011). The canyon was investigated by a combination of seismic and hydroacoustic as well as sedimentological and geochemical approaches (Krastel et al., 2006a) during RV Meteor cruise M65/2 in 2005.

Tab. 1: *Location and core information*

Core No.	Longitude	Latitude	Water depth [m]	Core length [m]	General remarks
GeoB 9610-1	18°32.68' W	13°45.27' N	3268	2.46	Canyon axis
GeoB 9611-1	18°52.60' W	13°32.30'N	3983	1.47	Canyon axis
GeoB 9615-1	19°06.25' W	13°23.65'N	4180	9.30 (total)	Canyon axis
				0 - 1.21 (sampled)	taken into account for this study

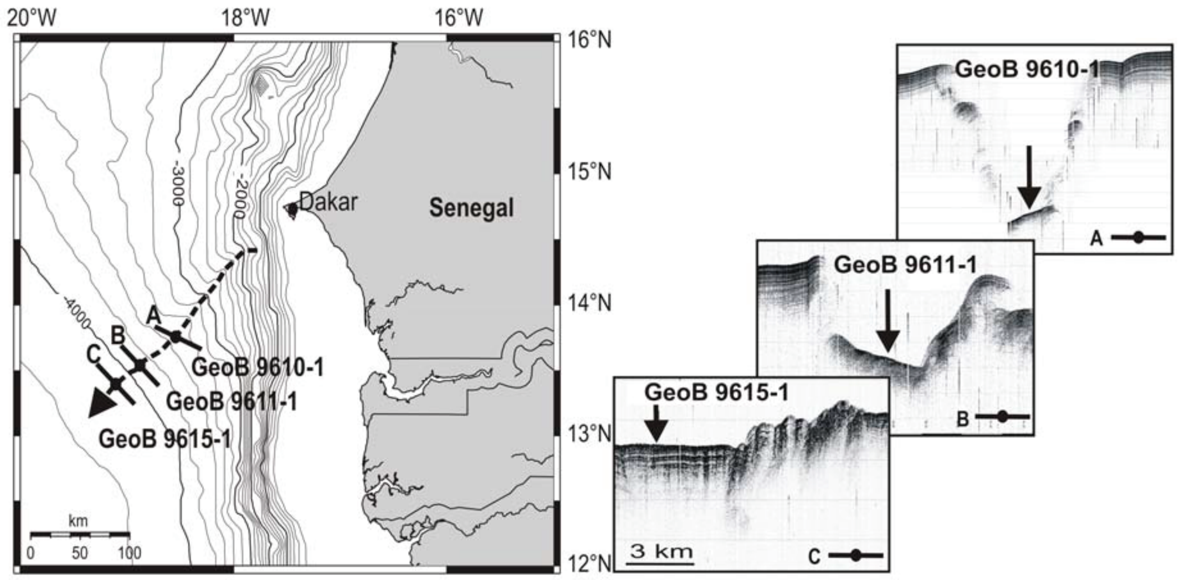

Fig. 1: *Overview map of the study area (Dakar Canyon); showing the canyon axis (dashed arrow; with position of studied cores (black dots) and parasound profiles (solid lines A, B, C).*

Figure 2 shows the modern oceanic and climatic settings in the study area off NW-Africa. The seasonal migration of the Intertropical Convergence Zone (ITCZ), separating dry conditions in the North from equatorial wet monsoonal conditions, is the main present-day climatic feature across NW-Africa (Nicholson, 2000). The ITCZ shifts northward during boreal summer, accompanied by the humid SW monsoon in the south.

During boreal winter, after the ITCZ has migrated to its southernmost position (5°N) the NE trade winds dominate the atmospheric circulation in the study area. The Canary Current is the major surface current along the NW-African coast (Mittelstaedt, 1991), while the Guinea Dome dominates the surface water masses south of 20°N (Stramma et al., 2005).

In boreal winter, a southward current affects the coast of Mauritania and Senegal (Stramma & Schott, 1999), whereas the northward flowing Mauritania current prevails during summer. The trade winds and the overlying Saharan Air Layer (SAL) are the most important wind systems over NW-Africa, causing both upwelling and major dust transport from the Sahara-Sahel zone towards the Atlantic Ocean (e.g. Koopmann, 1981; Sarnthein et al., 1982; Prospero & Lamb, 2003). The dust plumes are important for the terrigenous sediment supply along the Northwest African continental margin (Koopmann, 1981; Holz et al., 2004; Stuut et al., 2005). Riverine input in the study area is restricted to the Senegal River north of Dakar, and it only plays a minor role in sediment supply (Redois & Debenay, 1999). The Senegalese shelf varies in width from 50 - 100 km (Hagen, 2001). The average water depth south of 15°N is about 100 - 150 m (McMaster & Lachance, 1969).

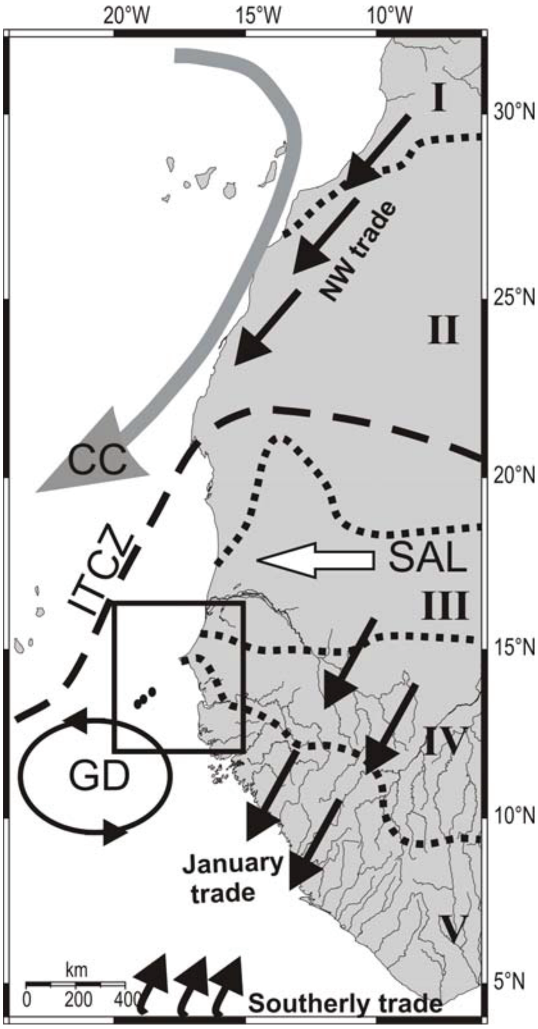

Fig. 2: *Overview map of NW-Africa with the most important oceanographic and atmospheric features (CC - Canary Current, GD - Guinea Dome, ITCZ - Intertropical Convergence Zone, SAL - Sahara Air Layer). I – V: Major vegetation zones;*

I - Mediterranean vegetation, II - Saharan desert, III - Sahelian vegetation, IV – Sudanian savannah, V - Guinean rain forest (redrawn after Hooghiemstra et al., 2006)

The surface sediments on the shelf mainly consist of aeolian quartz sands and carbonate shell fragments (McMaster & Lachance, 1969; Barusseau et al., 1988; Redois & Debenay, 1999). During the Last Glacial Maximum (LGM), overall increased wind strengths caused a seaward migration of active desert dunes over the exposed shelf areas (Matthewson et al., 1995; Rognon & Coudé-Gaussen, 1996; Martinez et al., 1999). Remnants of paleo-dunes are preserved on the shelf south of Dakar (Barusseau et al., 1988).

This study focuses on three gravity cores (GeoB 9610-1, 9611-1 and 9615-1; 3752 m to 4108 m water depth) from the Dakar Canyon main channel (cf. Tab. 1). The cores consist of hemipelagic sediment with intercalated, sometimes stacked turbidites. Pierau et al. (2011) published radiocarbon ages from the lower part of the cores (cf. Tab. 3) that generally constrain post-LGM ages of the turbidites studied in this paper.

Material and Methods

Sampling and Analysis

An overview of the sampled core intervals and the number of samples from the each core is shown in Table 2. In general, all samples are 1 cm thick sediment slides that was freeze-dried, then milled and homogenised using an agate mortar. For total digestion, 50-52 mg sediment splits were digested using a microwave system (MLS – MEGA II and MLS – ETHOS 1600) in a mixture of 3 ml HNO3, 2 ml HF and 2 ml HCl. Dissolution of the sediments was performed at 200°C at a pressure of 30 bar. After the digestion program, the acid mixture was fully evaporated, and the remaining sample powder was re-dissolved with 0.5 ml HNO3 and 4.5 ml bi-distilled water (MilliQ). Finally, the solution was filled up to 50 ml with bi-distilled water. Major and trace elements were measured by ICP-AES (PE Optima 3300R). Rare earth elements (REE) and some additional trace elements were analyzed by ICP-MS (Thermo Element 2) (cf. Table 3). The standard deviation of the analyses for each sample was < 3% for ICP-AES and < 5% for ICP-MS. The accuracy of the measurements was verified using standard reference material USGS-MAG-1. The reference material concentrations were within certified ranges. For detailed information on the lab methods see (Schulz, 2006 a) and http://www.geochemie.uni-bremen.de/koelling/index.html. The data set of solid phase measurements presented in this paper is available at http://www.pangaea.de.

Tab. 2: *Sample compilation of the sediment cores in regard to this study (n.s. – not sampled; grey areas: lack in turbidite samples (cf. Fig. 5))*

GeoB 9610-1			GeoB 9611-1			GeoB 9615-1		
sediment depth top-bottom [m]	**sample interval**	**number of samples**	**sediment depth top-bottom [m]**	**sample interval**	**number of samples**	**sediment depth top-bottom [m]**	**sample interval**	**number of samples**
0.00 - 0.81	0.05 m	**16**	**0.00 - 0.51**	0.05 m	**12**	**0.00 - 0.41**	0.10 m	**5**
0.81 - 2.45	0.01 m	**127**	**0.56 - 1.25**	0.01 m	**59**	**0.47 - 1.15**	0.01 m	**48**
0.83 - 0.84	n. s.		0.57 - 0.60	n. s.		0.41 - 0.47	n. s.	
T 2 0.93 - 0.94	n. s.		0.64 - 0.65	n. s.		0.53 - 0.59	n. s.	
1.02 - 1.05	n. s.		0.69 - 0.70	n. s.		0.80 - 0.81	n. s.	
T 4 1.13 - 1.15	n. s.		0.75 - 0.76	n. s.		0.94 - 0.96	n. s.	
T 5 1.16 - 1.20	n. s.		**T 4** 0.79 - 0.80	n. s.		1.04 - 1.15	n. s.	
1.22 - 1.25	n. s.		0.83 - 0.84	n. s.		1.16 - 1.20	n. s.	
1.34 - 1.35	n. s.		1.10 - 1.11	n. s.		**1.15 - 1.21**	0.05 m	**2**
1.36 - 1.40	n. s.		1.24 - 1.25	n. s.				
T 7 1.41 - 1.45	n. s.		**1.25 - 1.41**	0.05 m	**4**			
1.98 - 2.00	n. s.							
2.03 - 2.05	n. s.							
2.06 - 2.10	n. s.							
2.37 - 2.38	n. s.							
T12 2.39 - 2.41	n. s.							
2.42 - 2.45	n. s.							
2.45 - 2.46	0.01 m	**1**						
[total		**144]**	**[total**		**75]**	**[total**		**55]**

Why 41 elements?

The selection of elements applied in this study is a compromise between the best chemical characterization possible and the analytical possibilities.

The geochemical composition of continental slope sediments may be roughly classified with four main components: 1) marine/biogenic, 2) terrigenous, 3) diagenetic/transport-influenced, and 4) primary source rock. Table 3 shows which elements constitute the fingerprint of each of these components. This classification, of course, is a simplification, as no element can solely be confined to one of this group.

The distribution of elements as Si, Al, K, Fe or Mn in clastic sediments is controlled by weathering, transport and diagenesis. Clays typically have higher contents of trace elements than sands (Taylor & McLennan, 1989; McLennan et al., 1989; Johannessen & Andsbjerg, 1993). These processes change the primary signature of the source rock.

Feldspar weathering may influence the content of elements like K, Mg, Pb, Rb und Sr (Nesbitt & Young, 1984; McLennan et al., 1989; Preston et al., 1998). Ca and Si are often found in the tests of marine organisms. Ba, Mg and Sr are incorporated in small amounts in marine carbonate-producing organisms (e.g. Stoll et al., 1999; Henderson, 2002). Especially an elevated Sr/Ca ratio is a typical marine signal. P and S are indicative of the activity of certain marine microorganisms degrading organic matter on the sea floor (Schulz & Schulz, 2005). Ba may be used as palaeoproductivity indicator (e.g. Berger et al., 1989).

Tab. 3: *Element compilation in regard to this study*

	Element group				
Elements	**marine / bioactive**	**terrigenous**	**primary sources**	**diagenetically influenced**	**Analytical device**
Ca, Mg	*				ICP-OES
Sr	*	*		*	ICP-OES
Ba	*	*		*	ICP-OES
P, S	*			*	ICP-OES
Na	*				ICP-OES
Al, K, Ti		*		*	ICP-OES
Fe, Mn		*		*	ICP-OES
V, Ni, Cu, Zn, Mo, Cd		*		*	ICP-OES
Cr, Co, As		*	*	*	ICP-OES
REE		*	*	*	ICP-MS
Sc, Th, Y		*	*	*	ICP-MS
Hf, Zr		*	*	*	ICP-MS
Rb		*		*	ICP-MS
Pb		*		*	ICP-MS

The rare earths elements (REE) are among the most intensely studied trace elements (Stosch, 1998). The REE content of sediments is controlled by the nature of the source rock and, for clastic sediments, also by the grain size distribution. Felsic and mafic rocks differ in their ratios of La / Sc and Co / Th (Taylor & McLennan, 1985), and metamorphic rocks in their ratios of Th / Sc and La / Cr (Piovano et al., 1999). Diagenetic redox processes control the mobility and reactivity of trace elements such as P, As, Cu, Fe, Mn, Mo, Pb, Zn (e.g. Froehlich et al., 1982; Haese, 2000). Sediments derived from several sources or affected by multiple reprocessing cycles may be distinguished based on heavy minerals, especially the stable mineral zircon (Owen, 1987: Morton, 1985). This mineral consists of approximately 50% Zr and 0.6 - 3% Hf (McLennan, 1989), and has a characteristic Zr / Hf ratio for each source rock (Owen, 1987). If the mineral is not affected by sedimentation processes, this ratio remains constant (Bauluz et al., 2000).

Discriminant Function Analysis (DFA)

Discriminant function analysis (DFA) is a multivariate statistical method that was first described by Fisher (1936). This method allows for the analysis of large data sets for both, changes within variables as well as changes between variables (Davis, 1986). In our case, the characteristic distribution of the element contents of predefined groups is analyzed by DFA. In a second step, single samples may be assigned to one of these groups with a probability defined by DFA. In the statistical analyses, all the geochemical information is used simultaneously.

As a result of the DFA we get (e.g. Roth et al., 1972; Davis, 1986; Long et al., 1986; Graham et al., 1990; Charman & Grattan, 1999):

- A number, representing how well single predefined groups may be separated based on the variables used (Mahalanobis distance).
- The contribution of single variables to the grouping selectivity.
- Numbers representing the probability that a single sample belongs to a predefined group. These probabilities may be also determined for unknown samples (that have not been used to define the groups).
- A degree of homogeneity within the groups. Single misassigned samples may be reanalyzed. Groups with a larger number of misassigned samples may indicate a non-adequate initial group definition.

In this study, we used a custom-made FORTRAN code using the sediment samples as "samples" in the statistical sense, and the measured solid phase content of chemical elements as variables. The FORTRAN worksheet used in this study can process 30 variables (elements) at the same time. In order to cover all the 41 element information available simultaneously, we reckoned the total content of the REE element group (LREE (La to Sm) and HREE (Gd to Lu)) for each sample instead of using their single elements contents while assessing DFA. So from the dataset of 41 chemical elements, 27 variables that represent single elements and one mixed variable that represents the total REE content was used.

Groups were created from sedimentological definable hemipelagites and from parts of the turbidites that were identified visually in the sedimentary record. Samples with an unknown grouping were assigned to the above groups using DFA. In DFA step I (cf. Fig. 5)**;** the separation of single sample groups (turbidites) from each other and from the background sediment is shown for each of the three cores (cf. Tab. 5). In a second step (DFA step II, Fig 6), the turbidites identified statistically in the cores were compared among the cores in order to correlate single events using assignment probability data derived from the DFA (cf. Tab. 6).

Results and Discussion

The three cores GeoB 9610, GeoB9611 and GeoB9615 (cf. Tab. 1 for general information) are all located in the thalweg of the Dakar Canyon 180 km off the coast of Senegal (cf. Fig.1 and Fig. 2). The core positions are approximately 50 km apart from each other, with the deepest water position located at the end of the main channel (Krastel et al., 2006 b). The sedimentary record in this area shows a complex pattern of upper slope and canyon sediments. The Dakar Canyon is currently not active as a turbidite conduit, as expressed in hemipelagic sediments of up to 50 cm thickness at the top of the succession.

Below the youngest hemipelagic layer, all three cores show a series of partially very thin turbidites within their total thickness of 2.5 m (GeoB9610), 1.4 m (GeoB9611) and 1.2 m (GeoB 9615). The lower turbidites of GeoB 9610 (T 9 and T 11) and GeoB9611 (T5 and T6) have a coarse sandy base, but only one of them (T9, GeoB9610) shows a complete Bouma sequence (Bouma, 1962).

Because of their positions along the canyon axis and their proximity to each other, these cores and core parts (in the case of GeoB 9615) seemed to be suitable for this investigation. This was confirmed by the radiocarbon ages from Pierau et al. (2011) providing a relative stratigraphic framework (cf. Table 4).

Tab. 4: *AMS radiocarbon ages important for the stratigraphic frame of the sediment cores for this study (* Data from Pierau et al., in review b)*

Core No.	AMS radiocarbon ages sample depth (top - bottom [m])*	Calib. Age [kyr BP] *
GeoB 9610-1	0.82	14.4
	2.46	16.3
GeoB 9611-1	0.56	14.2
	1.14	18.0
GeoB 9615-1	0.30	11.9
	1.21	15.8

It is important to recognize that a general correlation of the turbidite sequences based on the age determination can just be an approximation *(*Pierau et al., 2011*)*. Only the uppermost turbidite could be correlated throughout the cores and radiocarbon-dated precisely. The other turbidites do not show any sedimentological or geophysical patterns that would allow a correlation Krastel et al., 2006 b; Pierau et al., 2010, Pierau et al., 2011).

General geochemical information

Looking at the depth profiles of single elements, it is obvious that single elements (e.g. Al) do not show a distinct traceable pattern in the single turbidites (Fig. 3). As the complete turbidite packages have been deposited within a short time period between 12 kyr and 18 kyr (Pierau et al., 2011), they include only thin layers of pelagites. Although some of the turbidites can be sedimentological separated from the pelagites, mixing processes like bioturbation might obscure the boundaries between turbidites and pelagites, leading to a geochemistry-based separation that differs from the sedimentological one (cf. Fig. 5 and Table 5).

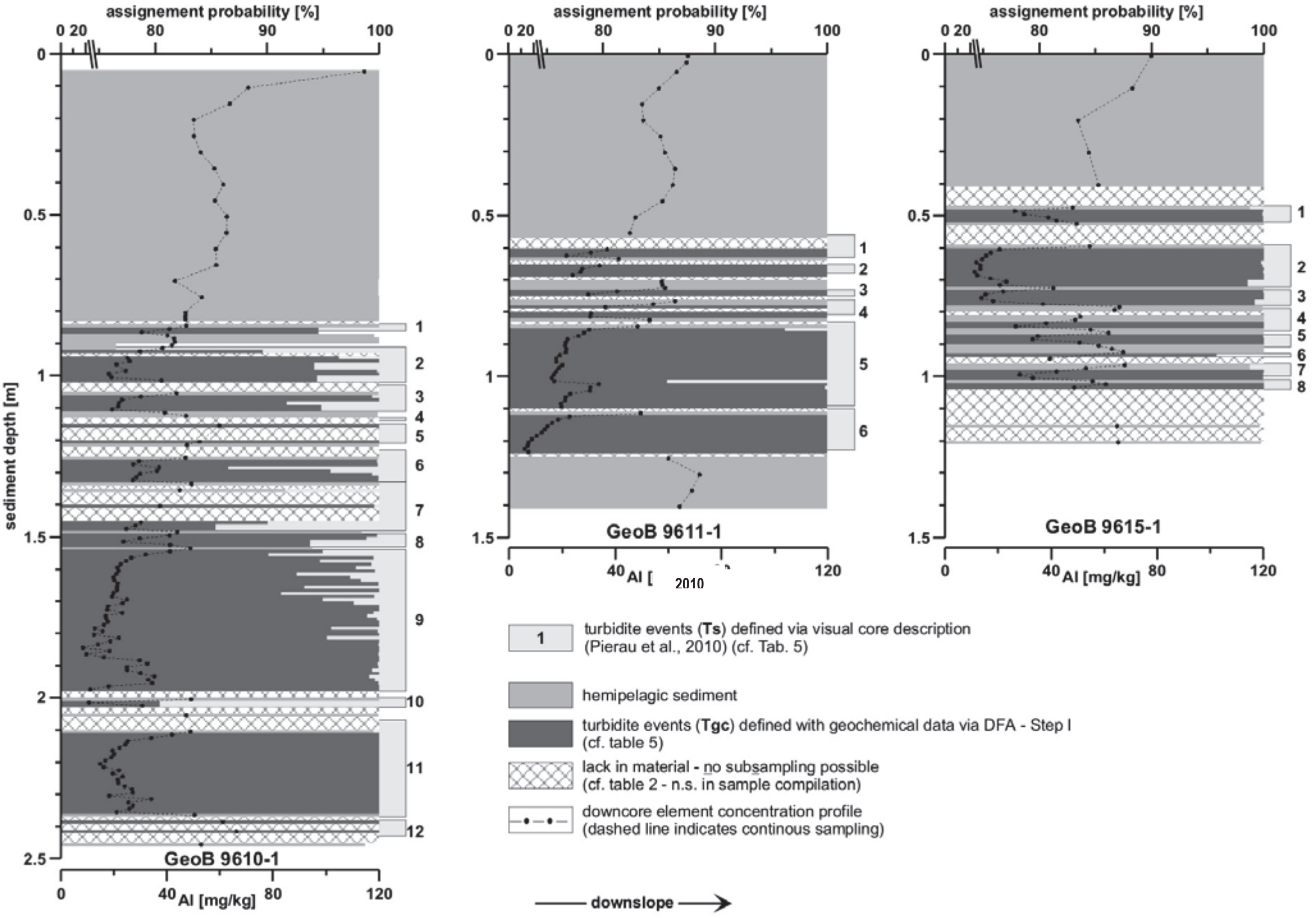

Fig. 3: *Exemplary downcore concentration plot of aluminium for all three cores*

The chondrite-normalized REE patterns show that both within the cores and between cores most of the sediment material is originating from similar terrestrial sources (cf. Fig 4-A). The REE variability shows patterns intermediate between clay schist and sandstones (Taylor & McLennan (1985), and is related to grain size variations (Stosch, 1998). The ratio of light rare earth elements (LREE, La to Sm) to heavy rare earth elements (HREE, Gd to Lu) and the negative Eu anomaly are typically larger in marine sediments than in their magmatic source rocks (e.g. Cullers & Graf, 1983).

Solid phases containing Al and Ti are mainly concentrated in the silt and clay fraction of sediments (Fralick & Kronberg, 1997). Sr is found mainly in carbonate sediments, but also in clastic sediments containing plagioclase (Van de Kamp & Leake, 1995). Plagioclase is also a source of elevated Rb contents in sediments. Dinelli et al. (1999) used the Rb/Sr ratio as an indicator for the separation of siliciclastic and carbonate sources of sediments.

Therefore, the Rb / Sr ratio and the Al / 10 + Ti ratio of the samples were plotted against each other (cf. Fig. 4-B) to obtain a simplified lithological classification. For this figure it should be noted that the grain size ranges have smooth transitions and the boundaries of the carbonate influence is only suspected. Since detailed information on the grain size was not available for all samples, we included data from Taylor & McLennan (1985) to verify our assumptions. The plot shows that the geochemical signature of the samples is typical of sandy to silty sediments, and there is only minor influence of marine carbonates.

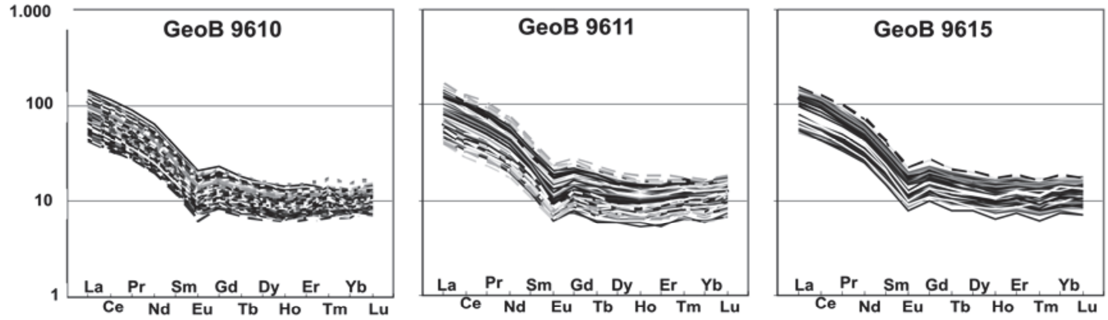

Fig. 4-A

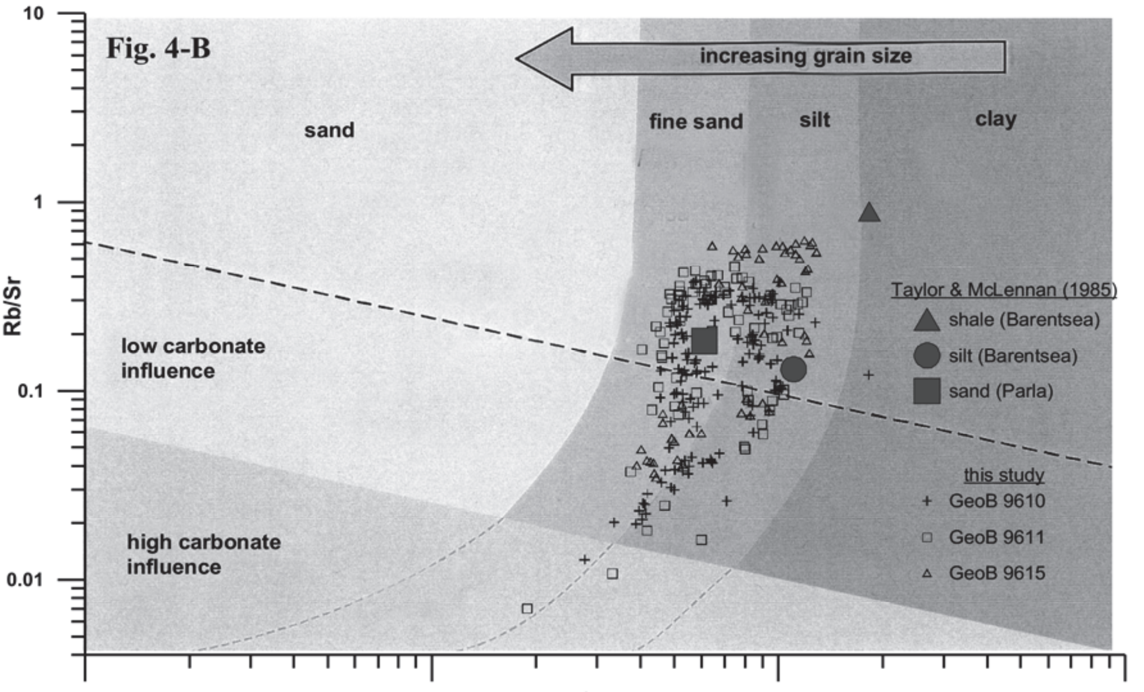

Fig. 4-A: *REE overview plots for all three cores, including all samples; samples vary in between the range from shale to sandstone (according to Stosch, 1998).*

Fig. 4-B: *Lithological division of the analysed samples with references from Taylor & Mclennan (1985); General remark: transition between schematical grain size boundaries is smooth; areas of carbonate influence are only estimated.*

Binary and ternary diagrams of ratios such as La/Sc, La/Co Th/Sc and Th/Co (e.g. Cullers et al., 1975; McLennan et al., 1980; Bhatia, 1983; Bhatia & Crook, 1986; Wronkiewicz & Condie, 1990; Cullers, 1995) have been produced from the data set are not shown here, because they do not display any diversity among the samples that could indicate differences in the sediment sources. All samples plot in between continental island arcs and active / passive continental margins. In a Zr/Hf diagram, all samples plot on a straight line with correlation coefficients greater than 0.99 for both single cores and the whole data set. This indicates that both Zr and Hf are controlled by the mineral zircon, and their ratio is not significantly altered by sedimentary processes (Bauluz et al., 2000).

The results of the DFA-Step I

The separation of the sediment samples into turbidites and pelagites was first carried out independently of the sedimentological analyses, which separated 12 turbidite events (Pierau et al., in review a) indicated by light grey bars and numbers from 1 to 12 (cf. Fig. 5). The shipboard core description of GeoB9610 separated only 9 turbidites, while our statistical analyses as well as the detailed description onshore revealed that some layers are actually two separate events (e.g. T11 and T12). When defining the whole sequence between 2.10 m and 2.40 m in Core GeoB 9610 as one turbidite, step 1 of the DFA clearly excluded the lower part of the sequence (<55% probability) and grouped an intermediate sample (2.37 m to 2.38 m) with the hemipelagites (>93% probability). This is clear indication for two separate events. These preliminary tests confirmed our application of the DFA as appropriate.

In order to separate pelagites from turbidites, step 1 of the DFA – Step I (cf. Fig. 5 and Tab. 5) was carried out for each sediment core individually. Turbidite groups were defined based on detailed sedimentological onshore descriptions. All samples described as hemipelagites were grouped together in order to get good selectivity between turbidites and background sedimentation. The dark grey bars in Figure 5 show the turbidite layers detected by the geochemical statistical analysis. Note that in the figure, the axis is subdivided and all samples have been assigned to the groups with a probability of more than 80%.

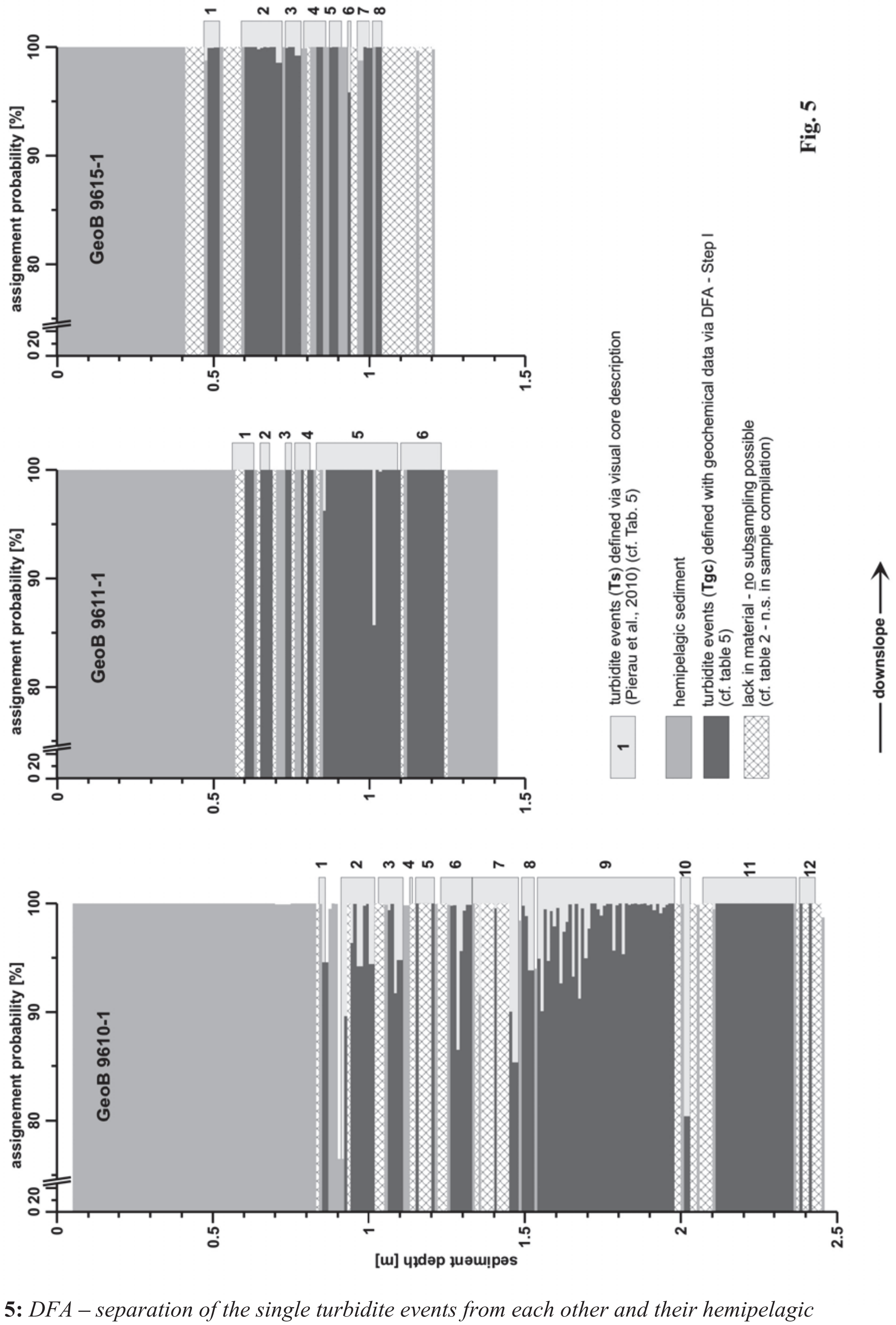

Fig. 5

Fig. 5: *DFA – separation of the single turbidite events from each other and their hemipelagic sedimentation; DFA-treatment carried out for sedimentary strata of every single sediment core individually.*

(Turbidites detected visibly (Ts): from Pierau et al. (2010); turbidites detected geochemically (Tgc): emplacement defined via geochemical data processed through DFA – step I; hemipelagic sedimentation: defined via geochemical data processed through DFA – step I)

On average, the assignment probabilities of samples to groups were 95% (GeoB9610), 99% (GeoB9611), and 97% (GeoB9615). The average probability of assignment of background sediments to the hemipelagic group was 95 to 99% as well. For GeoB9610, the assignment probability is lower than in the other two cores. This is due to an increased number of thin turbidites, where bioturbation of the upper part might become a significant disturbing factor. Note that the statistical separation between single turbidites and background sediments is very similar, but not always identical to the detailed sedimentological analysis. In contrast to the sedimentological evidence, the statistical analysis shows that the upper and the lower parts of T11 are not grouped with the turbidite sediments. This is remarkable, since in contrast to main component analysis (MCA) (Roth et al., 1972) DFA is not designed to detect natural groups, but tests the assignment of samples to predefined groups (Fischer et al., 1936; Roth et al., 1972). In case of GeoB9611, turbidite succession Tgc 5, one sample at 1 m depth has an assignment probability of only 85%, although the remaining samples show an almost 100% probability to belong to one group. This outlier sample might indicate a significant disturbance in the sedimentary signal at this depth, maybe documenting e.g. a mixed signal due to bioturbation.

Tab. 5: *DFA – Step I: Turbidite emplacement depth and thickness; Ts* - information from sedimentological record; Tgc - geochemical data, processed via DFA – Step I (cf. Fig. 5)*

	GeoB 9610-1		**GeoB 9611-1**		**GeoB 9615-1**	
Turbidite No.	**Ts * top-bottom [m]**	**Tgc top-bottom [m]**	**Ts * top-bottom [m]**	**Tgc top-bottom [m]**	**Ts * top-bottom [m]**	**Tgc top-bottom [m]**
1	0.84 - 0.86	0.85 - 0.87	0.56 - 0.63	0.60 - 0.63	0.47 - 0.52	0.48 - 0.52
2	0.91 - 1.02	0.92 - 1.02	0.65 - 0.68	0.65 - 0.69	0.59 - 0.72	0.60 - 0.72
3	1.03 - 1.11	1.06 - 1.11	0.73 - 0.75	0.73 - 0.75	0.73 - 0.78	0.73 - 0.78
4	1.13 - 1.14	-	0.76 - 0.81	0.78 - 0.82	0.79 - 0.86	0.83 - 0.85
5	1.15 - 1.21	1.15 - 1.21	0.83 - 1.09	0.85 - 1.10	0.87 - 0.91	0.87 - 0.90
6	1.23 - 1.33	1.26 - 1.33	1.10 - 1.23	1.12 - 1.24	0.93 - 0.94	0.93 - 0.94
7	1.33 - 1.48	1.40 - 1.48			0.96 - 1.00	0.98 - 1.01
8	1.49 - 1.53	1.50 - 1.53			1.01 - 1.04	1.02 - 1.04
9	1.54 - 1.98	1.54 - 1.98				
10	2.00 - 2.03	2.01 - 2.03				
11	2.07 - 2.37	2.11 - 2.36				
12	2.38 - 2.43	2.38 - 2.42				

* *Data from (Pierau et al., 2010) Turbidite thickness from onshore core description and by means of X-ray radiographies*

The results of the DFA-Step II

In the second part, DFA – Step II (cf. Fig. 6 and Tab. 6), the correlation of the groups (single turbidites) defined in DFA - Step 1 between the three cores was established. First we tested if the background sediments of all three cores carried similar geochemical information. Therefore, we defined the upper, hemipelagic sediments above T 1 of each core as one group. In this test, all background sediments of all three cores were successfully reassigned to this group with probabilities between 98.9 and 100%. Subsequently, the upper background sediment package of each core was defined as a group and the remaining samples from all cores were assigned to groups by the DFA without predefinition. In this test, the turbidite groups were also defined, so there were different choices for assignment. For all three cores, the background sediments were successfully assigned to the predefined hemipelagic sediment group with more than 98% probability. This test proved that the background sediments are significantly different from the turbidites due to their more dominant marine signature on top of the terrestrial fingerprint.

In order to correlate the turbidites across the cores, both background and turbidite groups of the first core (GeoB 9610) as analyzed in DFA - Step I were assigned as known groups for the DFA. Then all turbidite sequence samples of the next core (GeoB 9611) were defined as a sequence of single samples that need to be assigned / assorted to these predefined groups of GeoB 9610 by DFA - Step II. The robustness of assignment was tested by randomizing the sequence of unknown samples in several independent runs. This procedure was performed for all possible pairs of cores: GeoB 9610 – GeoB 9611 and GeoB 9611 – GeoB 9610, GeoB 9610- GeoB 9615 and GeoB 9615- GeoB 9610, GeoB 9611- GeoB 9615 and GeoB 9611- GeoB 9615 (with the first core given the predefined groups and the second one the sequence of single samples to be assigned to).

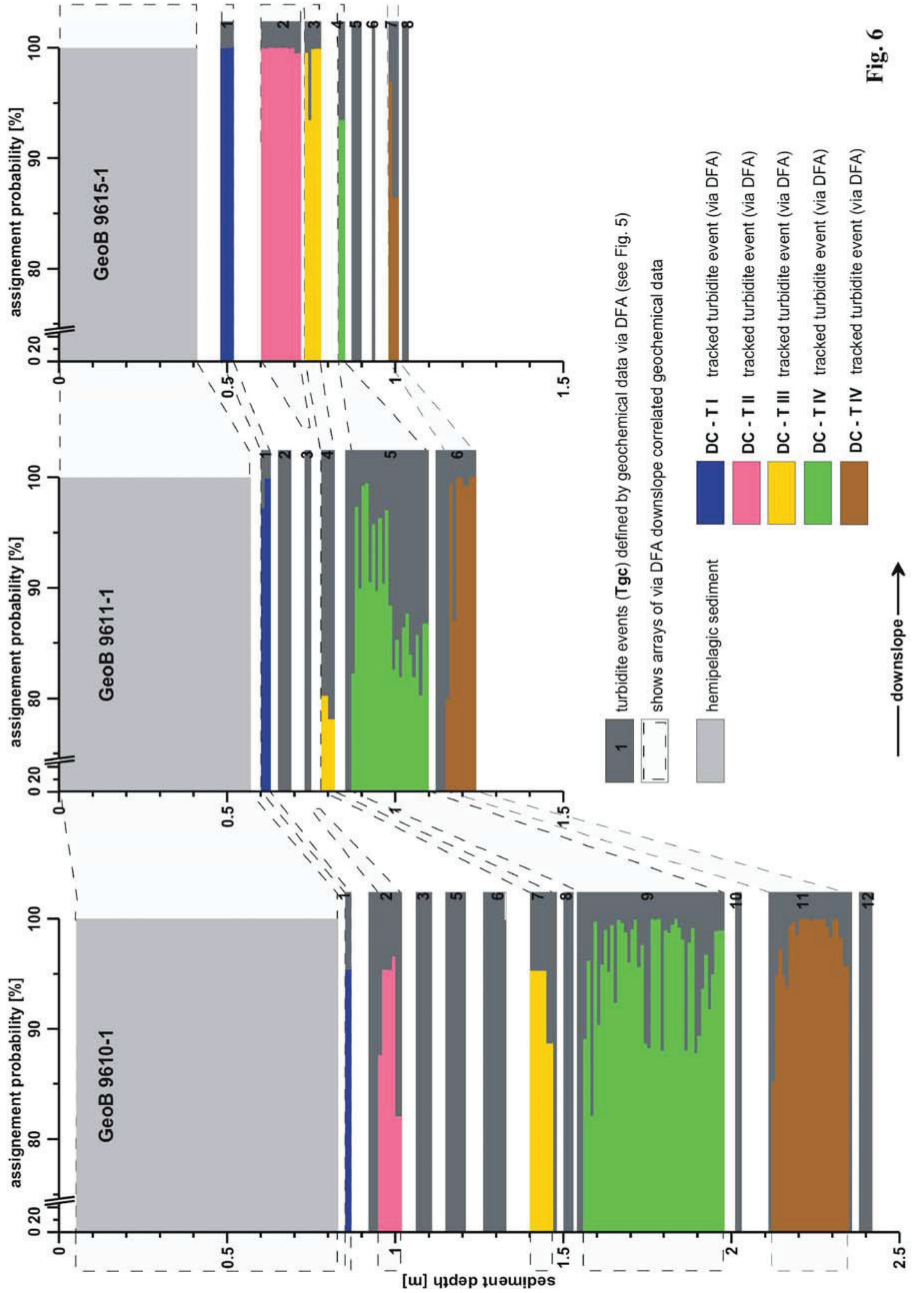

Fig. 6

Fig. 6: *DFA – Step II: tracking and combination of single turbidite events across the three cores via geochemical data processed through DFA – Step II, single turbidites (Tgc): detected from core via DFA – Step I (cf. Fig. 5) with upper hemipelagic sediment used as reference group*

DC – T I to DC – T V: correlated turbidite events tracked downslope the canyon; processed through DFA – Step II

Turbidite event samples (marked with coloured bars, cf. Fig. 6) were successfully correlated across the cores with a mean assignment probability between 80% and 99.9%. Samples that were assigned in more than one run with less than 80% were assigned with mean probabilities of only 45% to 65%. These samples were often non-systematically assigned to different turbidite events in different runs, or even assigned to the background sediment group with similar low probabilities. The samples that were difficult to assign were mainly located in the upper fine-grained parts of the turbidites, where possible bioturbation causes a mixture of turbidite and background sediment signals resulting in perturbed geochemical signatures. An assignment to any correlated turbidite events (DC – T I to DC – T IV) is therefore not certain.

Tab. 6: *DFA – Step II: Turbidite correlation along the axis of the Dakar Canyon Tgc all* - information from DFA – Step I Tgc - geochemical data, processed via DFA – Step II*

	GeoB 9610-1		**GeoB 9611-1**		**GeoB 9615-1**	
Turbidite No.	**Tgc all* top-bottom [m]**	**Tgc correlated parts top-bottom**	**Tgc all* top-bottom [m]**	**Tgc correlated parts top-bottom**	**Tgc all* top-bottom [m]**	**Tgc correlated parts top-bottom**
1	0.85 - 0.87	0.85 - 0.87	0.60 - 0.63	0.60 - 0.63	0.48 - 0.52	0.48 - 0.52
2	0.92 - 1.02	0.95 - 1.02	0.65 - 0.69	-	0.60 - 0.72	0.60 - 0.72
3	1.06 - 1.11	-	0.73 - 0.75	-	0.73 - 0.78	0.73 - 0.78
4	-	-	0.78 - 0.82	0.78 - 0.82	0.83 - 0.85	0.83 - 0.85
5	1.15 - 1.21	-	0.85 - 1.10	0.87 - 1.10	0.87 - 0.90	-
6	1.26 - 1.33	-	1.12 - 1.24	1.15 - 1.24	0.93 - 0.94	-
7	1.40 - 1.48	1.40 - 1.47			0.98 - 1.01	0.98 - 1.01
8	1.50 - 1.53	-			1.02 - 1.04	-
9	1.54 - 1.98	1.56 - 1.98				
10	2.01 - 2.03	-				
11	2.11 - 2.36	2.13 - 2.33				
12	2.38 - 2.42	-				

Conclusions

In a usual chemostratigraphic approach, multivariate statistical methods are assessed to a data set of a few variable parameters to define discriminant parameters or a combination of discriminant variables describing specific characteristics of a group (e.g. turbidites, sediment formation, barrel sequences). Thus, statistics make compositional differences visible and allows distinguishing them better.

This approach may be of little value if - as in the presented case - preliminary results indicate that the sediment materials under study display no significant differences from each other. The signal patterns of turbidites, as well as those of the hemipelagic sediment can therefore be very likely not be sufficiently described with a few variables.

Our study shows that the approach of assessing DFA to a geochemical data set of a large number of elemental variables is a useful tool to separate sediment transport events from background sedimentation, and - despite very similar sediment characteristics - to differentiate events from each other by using their geochemical fingerprints. The single events may then be easily correlated across cores. With a careful selection of parameters, this is possible even despite e.g. downslope grain size changes within a turbidite layer representing a single event. In many cases, only a few samples were needed to clearly correlate a turbidite layer to a corresponding layer from a core further upslope. The correlation allows for constructing a detailed stratigraphy of transport events, shows the extension of turbidites, and the downslope development of the sediment thickness for each event.

Acknowledgements

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3. CONCLUSIONS AND PERSPECTIVES

In this work we use the great potential of pore water as a proxy to detect young transport events. Their natural adjustment to local environmental conditions over time provides a tool to estimate the age of this event by geochemical modelling.

The use of pore water as an indicator for these events not only supports the evidence of those transport events clearly documented in the sediment record, but actually documents slide events which are invisible in the sediment pattern at first sight. This provides new insights into internal sediment structures and the history of development. It and may give new insights in sediment record histories that had already seemed resolved. The detailed knowledge of both pore water and solid phase geochemistry of a gravity core enables us to reveal the whole development of the sediment record. This work clearly shows that this pore water feature out of a bayou of the Cap Timiris Canyon, off NW-Africa, is not just a local anomaly due to the restricted depositional frame offered by a canyon system. In contrast these young transport events leave their signature in the pore water pattern in various kinds of depositional frames. The results suggest taking pore water even more seriously into account especially when discrepancies in sediment records to corresponding pore water profiles arise during investigations, and confirm that pore water data is even more useful than already commonly anticipated.

The second study based on three gravity cores out of the canyon axis of a submarine canyon applies a redefined chemostratigraphic approach in order to correlate their turbidite sequences. The present combined approach of a high-resolution geochemical multi-element data set of the bulk sediment material statistically assessed by discriminant function analysis (DFA) allows us to identify and precisely separate the single deposits from on another in order to then correlate the turbidites. Especially as the correlation of gravity-driven events is limited by the availability of a reliable stratigraphic framework, this redefined chemostratigraphic approach becomes all the more important for sediment records, which do not provide the requirements necessary for a stratigraphic reference.

The combination of the multi-elemental data set assessed by DFA enabled us to use the full implement of geochemical elemental data in a fast efficient way. The approach provides the opportunity of a geochemical fingerprinting on the turbidite sequences despite the lack in material and therefore in information. The application of DFA allows ‘filtering’ the characteristic sediment signal for each turbidite signal from geochemical data and certainly improves and enhances the correlation of small scales gravity-driven transport deposits.

The results of this study lead to some potentially important recommendations (i) in regard to the extent of the scientific potential of pore water as a proxy to identify and assess young gravity-driven transport events and for (ii) chemostratigraphic investigations. We offer one reliable approach to the frequently raised demand in recent chemostratigraphic studies to expand the commonly used direct or indirect stratigraphic approaches, in order to broaden the knowledge and the extent of opportunities in correlation of ancient and modern barren strata.

Although we have presented a further step in extending regional correlation of gravity-driven transport deposits, future evaluation of high resolution data sets should also concentrate on:

(i) using this approach to correlate more cores from different micro-depositional spaces of the canyon system, such as cores from the levee and the more coastal part. In addition, cores from the shelf should be taken into account to follow the sediment material upslope, back-tracking the bypass area and the temporary storages to correlate / link the distal cores to one of the main subsequent storage areas on margins, the shelf. This will be necessary not only to gain more insights on the different transport stages but to provide information about material distribution and variability and their local interconnections. Another main scientifically interesting focus (ii) should concentrate on further work on the high resolution data to fingerprint sources if reference material from the shelf or the hinterland is available.

The frequently arising questions about the origin of sediment material, the underlying transport processes in both ancient and modern depositional environments, even if they are globally recorded, is still not satisfactorily answered yet and knowledge of those systems has to be expanded for both industrial and socio-economic reasons.

Our study on pore water features and bulk inorganic geochemistry data presents an additional tool to asses and understand the processes and their determinants, respectively, of a highly complex mosaic of sedimentary evolution of, and interaction in, a globally relevant depositional environment like the investigated submarine canyon systems, to a further extent.

The present results show the wide range at opportunities in inorganic geochemistry of solid phase and pore water respectively. It is a key discipline not only to decipher the record of marine archives and therefore the highly relevant palaeoenvironmental processes, but also to reveal the complex history of a sediment record and its related fluid phase. This shows once again that the up to now developed and successfully utilized approaches based on geochemical data, in the widespread field of chemostratigraphy still have a great potential for further development and even more thorough investigations.

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