SEDIMENTATION IN LARGE RIFT LAKES : EXAMPLE FROM THE MIDDLE PLEISTOCENE – MODERN DEPOSITS OF THE TANGANYIKA TROUGH, EAST AFRICAN RIFT SYSTEM

Jean-Jacques TIERCELIN, Michael SOREGHAN, Andrew S. COHEN,
Kiram-Eddine LEZZAR and Jean-Luc BOUROULLEC

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La sédimentation récente dans le deuxième plus grand lac de rift du monde, le lac Tanganyika, Rift Est-africain, a été étudiée au cours du Projet GEORIFT de Elf Aquitaine (1983-1986). Cette étude repose essentiellement sur plusieurs centaines de kilomètres de sismique haute résolution (5 kHz), des carottages de type Kullenberg et des dragages. A la même période, le Projet PROBE (Duke University) a réalisé une sismique réflexion multitraces qui a permis l'identification de la structure profonde du fossé ainsi que de plusieurs séquences sismiques au sein de la série de remplissage. Parallèlement d'autres projets de recherche se sont développés, concernant en particulier la sédimentation carbonatée (University of Arizona) et l'hydrothermalisme (GROUPE TANGANYDRO).

Le lac Tanganyika est divisé en deux bassins, nord et sud, eux-mêmes constitués d'une mosaïque de sept sous-bassins fortement asymétriques, qui sont structuralement des demi-grabens séparés par des seuils transverses d'importance variable. Cette disposition tectonique résulte en plusieurs environnements morphologiques, escarpements de failles bordières, plate-formes littorales, seuils transverses, bassins axiaux profonds, qui influencent le réseau d'alimentation et l'hydrologie du lac, et par conséquence la sédimentation.

Les sédiments associés aux failles bordières sont des dépôts de piedmont, des glissements de terrain, cônes alluviaux, barres de bas de pente, et, plus localement, des sédiments hydrothermaux et minéralisations. Les plate-formes littorales sont essentiellement caractérisées par une sédimentation deltaique, deltas latéraux ou axiaux reliés à des systèmes complexes de chenaux sous-lacustres empruntés par des courants de turbidité. Sur ces plate-formes se développe également une sédimentation carbonatée, sables oolitiques, lumachelles, stromatolites. Sédimentation gravitaire en bordure du littoral et sédimentation biogénique « offshore » sont typiques des abords des seuils transverses, qui contrôlent également le tracé de chenaux sous-lacustres.

Les bassins axiaux profonds sont essentiellement le lieu d'une sédimentation de type organique (maximum 12 % COT), favorisée par l'anoxicité des fonds lacustres. Ces dépôts s'avèrent être des roches mères potentielles, comme le prouve les indices d'hydrocarbures du Cap Kalamba. Les courants de fond qui se développent dans ces bassins contribuent à une sédimentation de type turbiditique et à la génération de rides migrantes.

Ces différents environnements sédimentaires sont discutés en termes de climat, tectonique et volcanisme. Les notions de roches mères et de réservoirs sont évoquées dans l'optique de l'exploration pétrolière de séries synrift.

Jean-Jacques Tiercelin, Kiram-Eddine Lezzar, Groupe Riftogenèse, URA 1278 "Domaines Océaniques" et GDR 910 "Genèse et Evolution des Domaines Océaniques", Université de Bretagne Occidentale, 6, avenue Le Gorgeu, F-29287 Brest; Michael Soreghan, Andrew S. Cohen, Department of Geosciences, University of Arizona, Gould-Simpson Building, Tucson AZ 85721, USA; Jean-Luc Bouroullec, Elf Aquitaine, Direction Exploration, Tour Elf, F-92078 Paris La Défense, CEDEX 45. – April 3, 1992.

Mots-clefs : Sédimentation lacustre, Sédimentation deltaïque, Quaternaire, Sédiments carbonatés, Sédimentation détritique, Contrôle tectonique, Afrique Est, Lac Tanganyika.

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ABSTRACT

Recent and Modern sedimentation of the second largest rift lake in the world, Lake Tanganyika, East African Rift System, has been studied during the GEORIFT Project of Elf-Aquitaine (1983-1986). This study was mainly based on several hundreds of kilometres of high-resolution (5 kHz) seismic profiles, associated with multiple gravity coring and dredging. At the same time, the PROBE Project of Duke University collected multifold reflection seismic profiles, which have permitted the identification of several seismic discontinuities and sequences, as well as the deep tectonic structure of the trough. Onshore and offshore tectonic structures can now be related with the aid of field and satellite imagery observations. Other cooperative research programs were also developed, mainly concerning the carbonated sedimentation (University of Arizona) and the hydrothermal activity (TANGANYDRO GROUP).

The modern geomorphology of Lake Tanganyika is characterized by two main bathymetric basins, North and South, subdivided in a mosaic of seven strongly asymmetric sub-basins, which are all normally half-grabens. These sub-basins are separated by more or less developed and/or sediment-buried ridges of basement rocks. Such tectonic arrangement defines several morphological elements within the Tanganyika structure such as **border fault margins, littoral platforms, midlake structural highs** and **axial-deep basins.** Such present geomorphology strongly influences the drainage pattern as well as the hydrology of the lacustrine domain. Analyses of Recent-Modern sediments indicate that the sediment has two main origins, allochthonous and autochthonous. Particular facies geometries and occurrences can be related to the particular tectonic-geomorphic settings cited above.

Sedimentation associated with border fault margins includes piedmont deposits, colluvial rockfalls, fan deltas and downslope bars, and locally, at N-S/NW-SE crossing faults, hydrothermal sediments and mineralization. Sedimentation related to littoral platforms is characterized by fan deltas and deltas associated with lateral littoral platforms, as well as by prograding deltas associated with axial littoral platforms. High density underflows generated by cold, sediment-rich streams are characteristic of most Tanganyika deltas and are related to sublacustrine canyon and channel systems which deeply incise platforms and slopes. Peculiar carbonate deposits, ooids shoals, coquinas, stromatolites, are also associated with such littoral platforms. Sedimentologic processes along midlake structural highs are dominated by the interacting of gravity-driven sedimentation nearshore and biogenic sedimentation offshore. Deltas also develop, characterized by poorly sorted delta front sediments. Channel and canyon systems associated with such deltas are generally confined by the structural grain of the midlake highs.

Sedimentation related to axial-deep basins is mainly of autochthonous origin. Wide "sheet drape" sequences are formed by homogeneous or laminated organic-rich muds. A maximum TOC of 12 % found in modern sediments of the Northern Tanganyika Basin is explained by anoxic conditions which are present over most of the bottom of the lake. Locally, such sediments have a high petroleum potential, possibly explaining the oil occurrence in the area of Cape Kalamba, Northern Tanganyika. Deep currents at the bottom of the lake result in distal turbiditic sedimentation and also generate sediment waves, resulting in alternating clastic and organic layers.

Such sediments and sedimentary bodies related to particular tectonic-geomorphic settings are discussed in terms of the influences of climate, tectonism and volcanism. Implications for hydrocarbon exploration in synrift series are analyzed, mainly in terms of source rocks and reservoirs.

Key-words : Lacustrine sedimentation, Deltaic sedimentation, Quaternary, Carbonate sediments, Detrital sedimentation, Structural controls, East Africa, Lake Tanganyika.

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INTRODUCTION

Bottom sediments of the largest lake of the East African Rift System, Lake Tanganyika (length 650 km; surface area 32600 km^2; volume 18800 km^3; maximum depth 1470 m) (COULTER, 1991) (Fig. 1), were first studied during the Belgian "Mission hydrobiologique au lac Tanganyika" (1946-1947) led by E. LELOUP (LELOUP, 1949). Sedimentary facies were identified using echosounding supplemented in places by sediment dredging. Sediment cores were successfully obtained from the lake bed in 1961 (LIVINGSTONE, 1965) and 1970 (DEGENS *et al.,* 1971).

Our present knowledge of Recent and Modern sedimentation in Lake Tanganyika is largely based on high-resolution (5 kHz) seismic surveys associated with multiple gravity coring and dredging, made during the GEORIFT Project of Elf-Aquitaine (1982-1985) which was supported by the European Economic Community (EEC) and the "Fonds de Soutien aux Hydrocarbures". Multifold seismic profiles collected during the PROBE Project (Duke University) have permitted the identification of several seismic discontinuities and associated sequences in the sedimentary pile, which were interpreted in terms of sedimentary processes and paleoenvironments (ROSENDAHL *et al.*, 1986; BURGESS *et al.*, 1988; SCHOLZ & ROSENDAHL, 1988). Other research programs were developed at about the same time along the lakeshores of Burundi, Tanzania and Zaire, mainly concerning

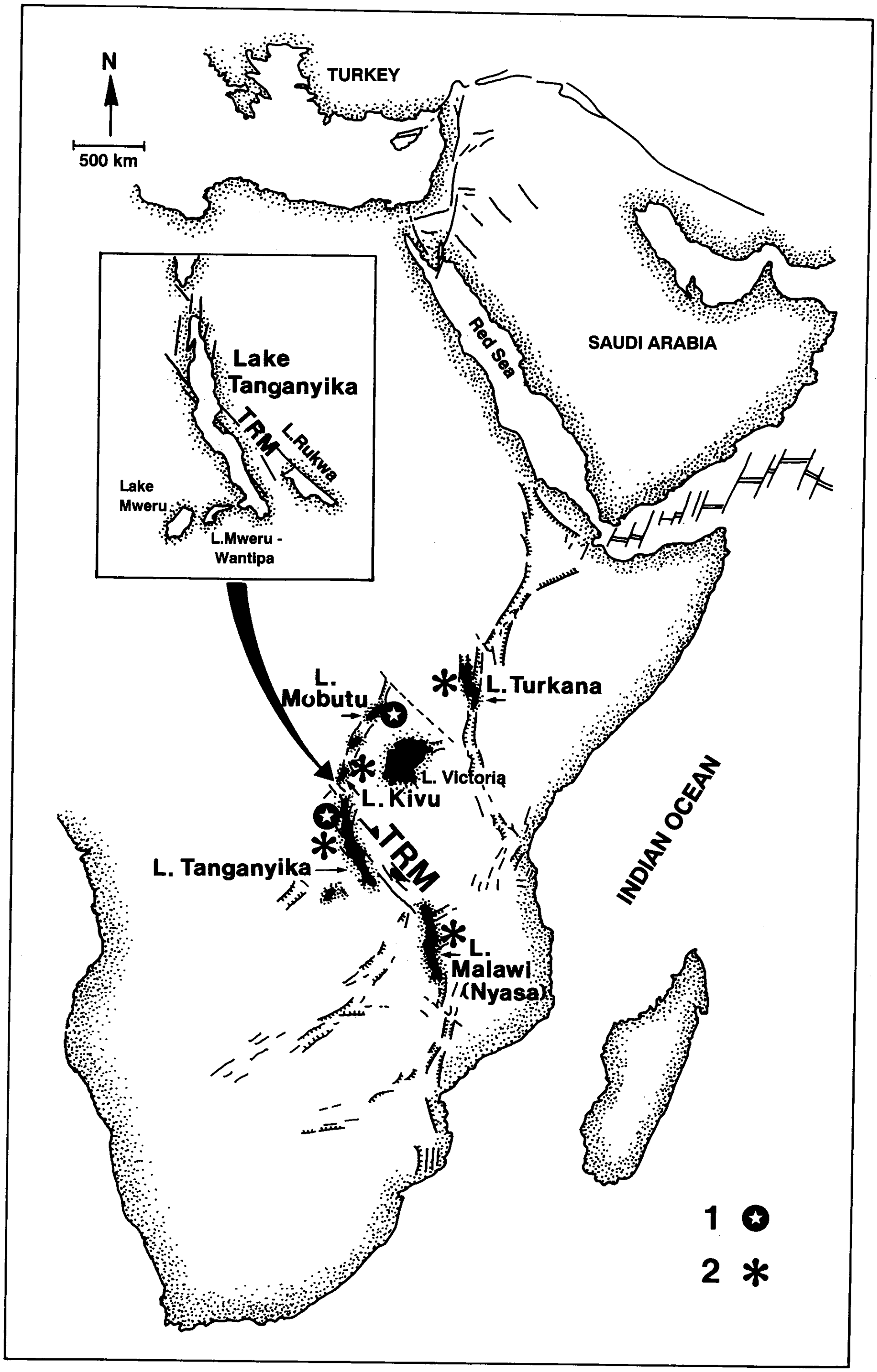


FIGURE 1

Lake Tanganyika, the second largest rift lake in the world, belongs to the western branch of the East African Rift System. Hydrocarbon occurrences within the EAR System : 1) Modern oil seeps; 2) Methane and other hydrocarbon gases.

surveys of littoral carbonate sedimentation (University of Arizona) (Cohen & Thouin, 1987; Casanova & Thouin, 1990) and sublacustrine hydrothermal activity (Tanganydro Project) (Vaslet *et al.*, 1987; Tiercelin *et al.*, 1989a; Tanganydro Group, 1992; Tiercelin, Boulègue & Simoneit, in press). Data presented here are a compilation of published or unpublished results acquired during these various research projects.

1. — THE MODERN GEOMORPHOLOGY OF THE TANGANYIKA TROUGH. ITS INFLUENCE ON DRAINAGE PATTERNS

The deep structure and stratigraphy of the Tanganyika Trough have been investigated by multifold reflection seismic studies (PROBE Project) (Rosendahl *et al.*, 1986; Rosendahl, 1987; Burgess *et al.*, 1988). Structural field and satellite imagery observations have been used to relate onshore and offshore tectonic structures (Chorowicz *et al.*, 1987; Tiercelin *et al.*, 1988a; Rolet *et al.*, 1991) (Fig. 2 A). During its early history, Lake Tanganyika appears to have consisted of three large depositional basins, the Ruzizi, Kigoma and Southern Basins, which were separated by the Ubwari and Kalemie-Mahali horst blocks respectively (Burgess, 1985; Burgess *et al.*, 1988) (Fig. 2 B).

The modern geomorphology of Lake Tanganyika is characterized by two main bathymetric basins, that of the North (3° 20' to 5° 40' S) and that of the South (6° 50' to 9° S) (Fig. 2 C, D). In detail, the lake basin comprises a present-day mosaic of seven "en touches de piano", strongly asymmetric, rectangular-shaped sub-basins, mainly oriented NNE-SSW to NW-SE. From North to South, these are : the Bujumbura, Rumonge, Kigoma (Eastern and Western), Kalemie, Moba, East-Marungu and Mpulungu sub-basins (Ebinger, 1989; Rolet *et al.*, 1991; Tiercelin & Mondeguer, 1991) (Fig. 2 C, D). These sub-basins are internally faulted and separated by more or less developed and/or sediment-buried ridges of basement rocks, which serve as barriers to sediment spillover. The two main ridges are respectively (Fig. 2 B, D) :

— the Ubwari shoal, which forms the lakeward extension of the N20° Ubwari horst block and divides the Bujumbura and Rumonge sub-basins;

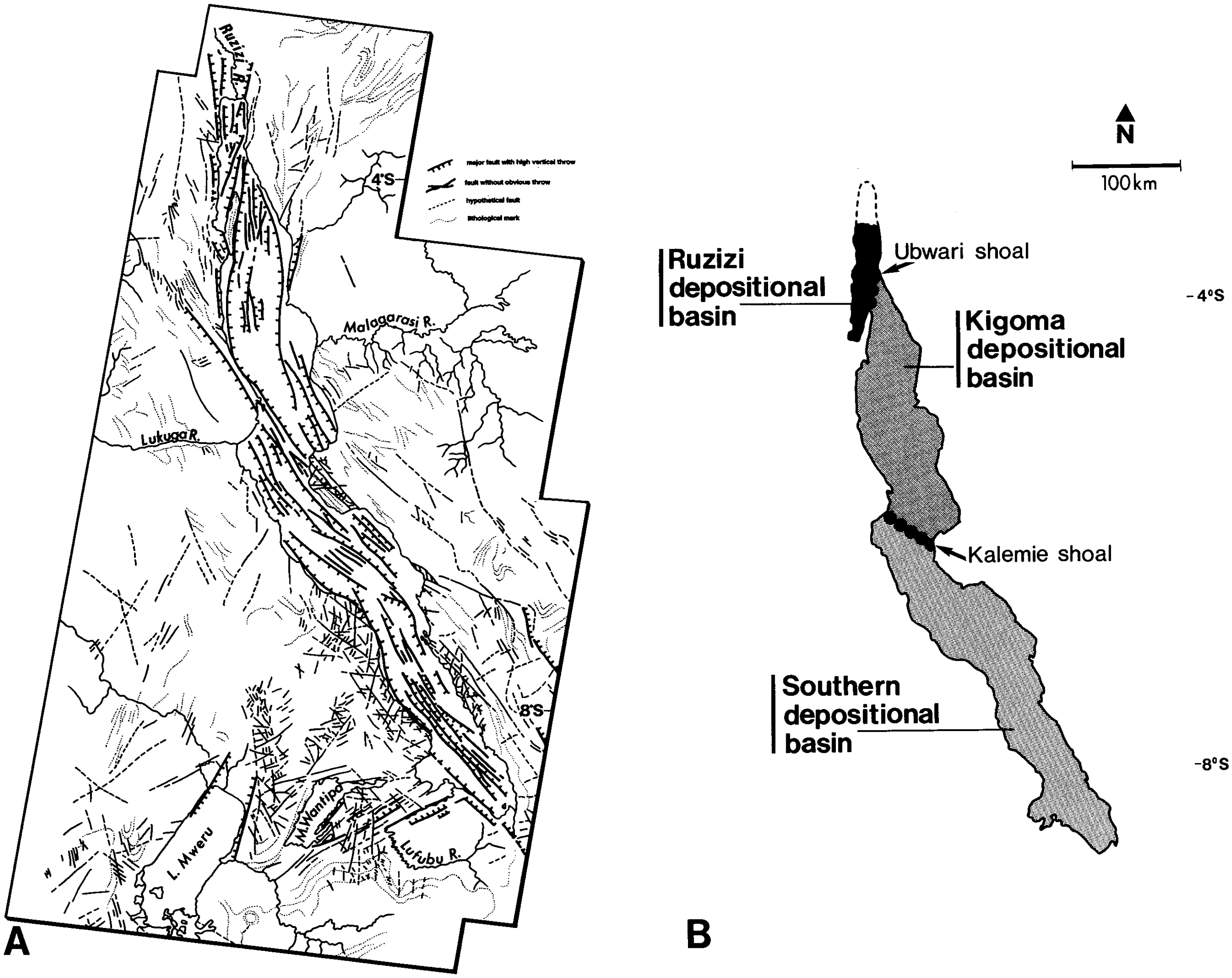


Figure 2

A : Fault map of the Tanganyika Trough deduced from MSS Landsat imagery and PROBE seismic profiles (from Morley, 1988; Mondeguer, 1991); B : Early depositional basins of the Tanganyika Trough (from Burgess, 1985);

— the Kalemie-Mahali shoal, a N130-140° complex block-faulted structure belonging to the Tanganyika-Rukwa-Malawi transcurrent Fault Zone (TRM FZ) (Tiercelin *et al.*, 1988a) that divides the Kigoma and Kalemie sub-basins.

The deepest areas of Lake Tanganyika are located in the Kigoma sub-basin, with a maximum water depth of 1310 m at the "Baron Dhanis Deep", and in the East-Marungu sub-basin with a maximum depth of 1470 m at the "Alexandre Delcommune Deep" (Fig. 2 C).

These depositional basins are all normally half-grabens with one dominant system of normal faults bounding each half-graben. Where basin troughs widen (> 30-50 km), they may comprise half-graben to full graben geometry (Morley, 1988). The present throw of the boundary faults reaches as much as 8 km, which has allowed the deposition of more than 4 km of sediment in the deepest parts of these basins (Rosendahl *et al.*, 1986; Burgess *et al.*, 1988). Such tectonic arrangement defines several morphological elements within the Tanganyika structure such as **border fault margins, littoral platforms, midlake structural highs and axial-deep basins** (Fig. 3A).

The marked tectonic trends and asymmetry of the sub-basins strongly influence the drainage pattern along the rift margins. Among the four main permanent tributaries to Lake Tanganyika, the largest tributary to the basin is the Malagarasi River, flowing into the lake on the eastern shore after a 475 km long circuitous course in Western Tanzania, which has been interpreted as the result of a capture after a fall in the lake-level (Salée, 1927) (**platform margin drainage** of Cohen, 1990) (Fig. 3A, B). The Lugufu and Luegere Rivers (160 km and 95 km long respectively) are both **backshed drainage reentrants** (Cohen, 1990) which ultimately enter the lake along the Malagarasi Platform. The Lufuko and Lufubu Rivers (190 km and 290 km length respectively) are backshed drainage reentrants on the west side of Lake Tanganyika. The Lufubu River flows into the southern Mpulungu sub-basin via a fault-oriented downstream course controlled by the N70° Mweru-Mweru Wantipa fault zone, a conjugate structure to the TRM FZ (Mondeguer *et al.*, 1989;

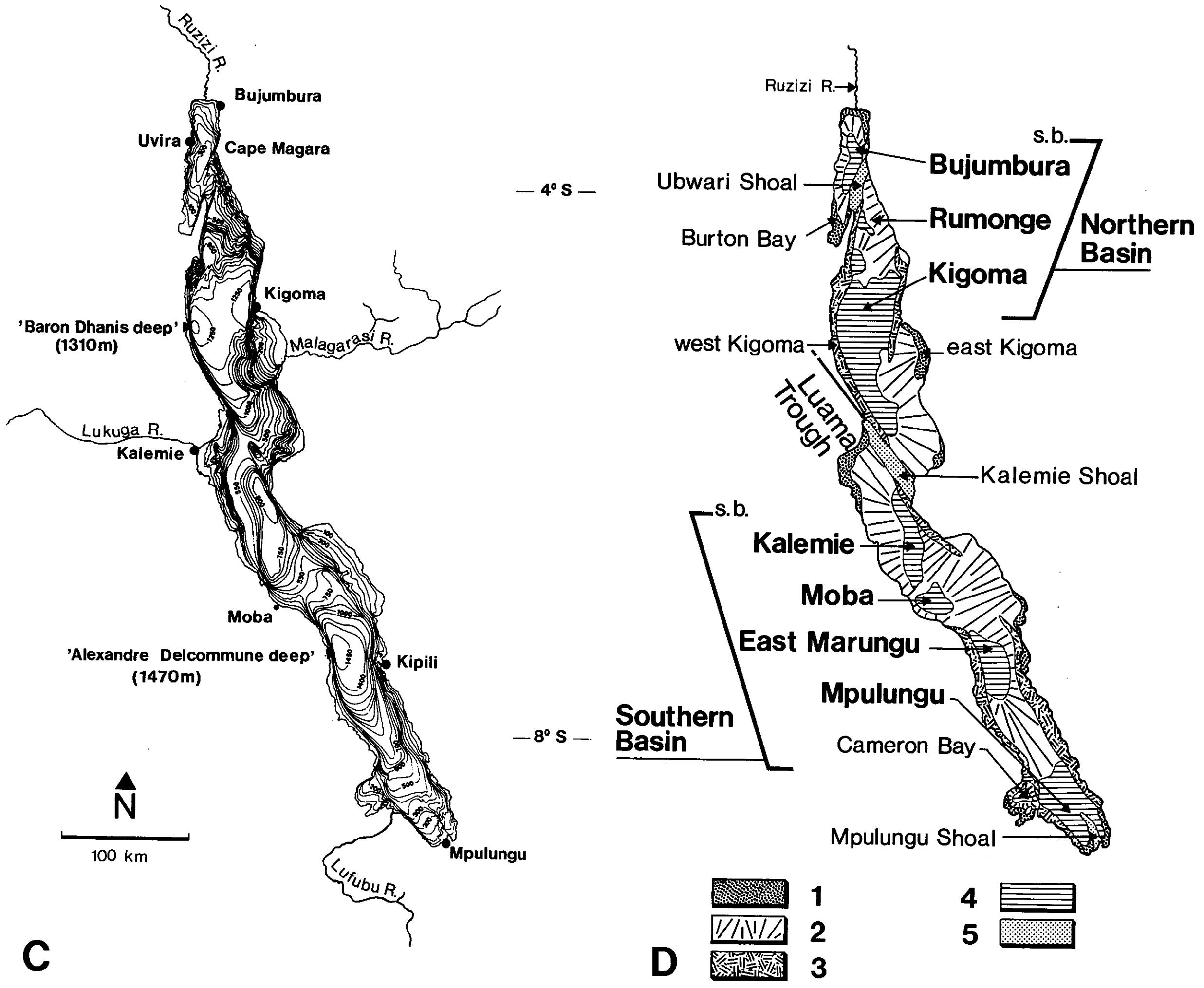


Figure 2 (continued)

C : The bathymetry of Lake Tanganyika. Bathymetric data are from Capart (1949) and from Project GEORIFT; isobaths in metres; D : Present-day geomorphology of the Tanganyika Trough; 1) Littoral platforms; 2) Talus; 3) Escarpments (> 10°); 4) Sub-basin deep zones; 5) Transverse shoals; s.b. : sub-basin (from Mondeguer, 1991; Tiercelin & Mondeguer, 1991).

MONDEGUER, 1991) (Fig. 2 A; 3 A, B).The Ruzizi River drainage is the only longitudinal stream which is strictly controlled by the NNW-SSE then N-S Kivu-Ruzizi Trough extending from the Lake Kivu Basin to the Bujumbura subbasin (**axial margin drainage** of COHEN, 1990) (Fig. 3 A, B).

The minor lateral drainage pattern to Lake Tanganyika is also mainly controlled by the gradient of the rift margins (**escarpment margin drainage** of COHEN, 1990). Catchment areas are generally small (median 2.7 km^2) (COHEN, 1990), particularly where the slopes are steep, as along the main, active border faults such as the Uvira Border Fault (Fig. 2 A). Here, tributaries are either permanent or temporary, and characterized by high and sporadic sediment/water discharge, mainly during the rainy season.

2. — THE HYDROLOGY OF LAKE TANGANYIKA

Modern Lake Tanganyika (latitude 3°-9° S) experiences a semihumid, tropical climate (1000-1200 mm/yr precipitation). The region has a strong seasonal climate, with a 4-month "dry season" (May through August) with cooler dry conditions and a fairly constant southerly wind, and a "wet season" during the rest of the year, with lighter and mainly northerly winds (COULTER, 1991). The lake is hydrologically open via the Lukuga River outlet (2.7 km^3/yr) (Fig. 3 B). Nevertheless most water loss is by way of evaporation (1700 mm/yr) (BULTOT, 1965). Chemically the lake is mildly alkaline and non-saline. Its anomalous high Mg/Ca ratio is the result of upstream low-magnesium calcite precipitation in Lake Kivu, whose waters enter Tanganyika via the Ruzizi River (3.2 km^3/yr) (COHEN, 1990). Other influents have uniformly low-salinity.

Despite high water temperatures (23-27 °C), thermal stratification is well-marked and varies seasonally above an apparently permanent anoxic hypolimnion at depths of 50-100 m in the north to about 240 m at the southern end (COULTER, 1991). COULTER & SPIGEL (1991) have shown that internal circulation is primarily effected through internal wave oscillations which generate a lakewide seiche which remains active througout the wet season. Because of the lake's low altitude and narrowness, Coriolis circulation is of little or no importance in generating lateral currents. Gases (carbon dioxide, hydrogen sulphide and methane) are present in the hypolimnion in appreciable quantities (RUDD, 1980; CRAIG & CRAIG, 1981). Deep-water upwelling appears to take place near the southern shore (Mpulungu sub-basin) during the dry season (COULTER, 1991) and also along the northern Zaire coast (COHEN, 1990). Sublacustrine geothermal discharges have been identified on the western shore of the lake at Pemba, Cape Banza, Luhanga and Mbemvi (Fig. 2 D) (TANGANYDRO GROUP, 1992; GROUPE TANGANYDRO, in press). Fluids at temperatures of 60-100 °C are released from the Precambrian basement at a depth of 50 m (the maximum depth of diving investigation). Methane and heavier hydrocarbon gases as well as hydrogen sulphide and carbon dioxide are present in these fluids. The flow of ther-

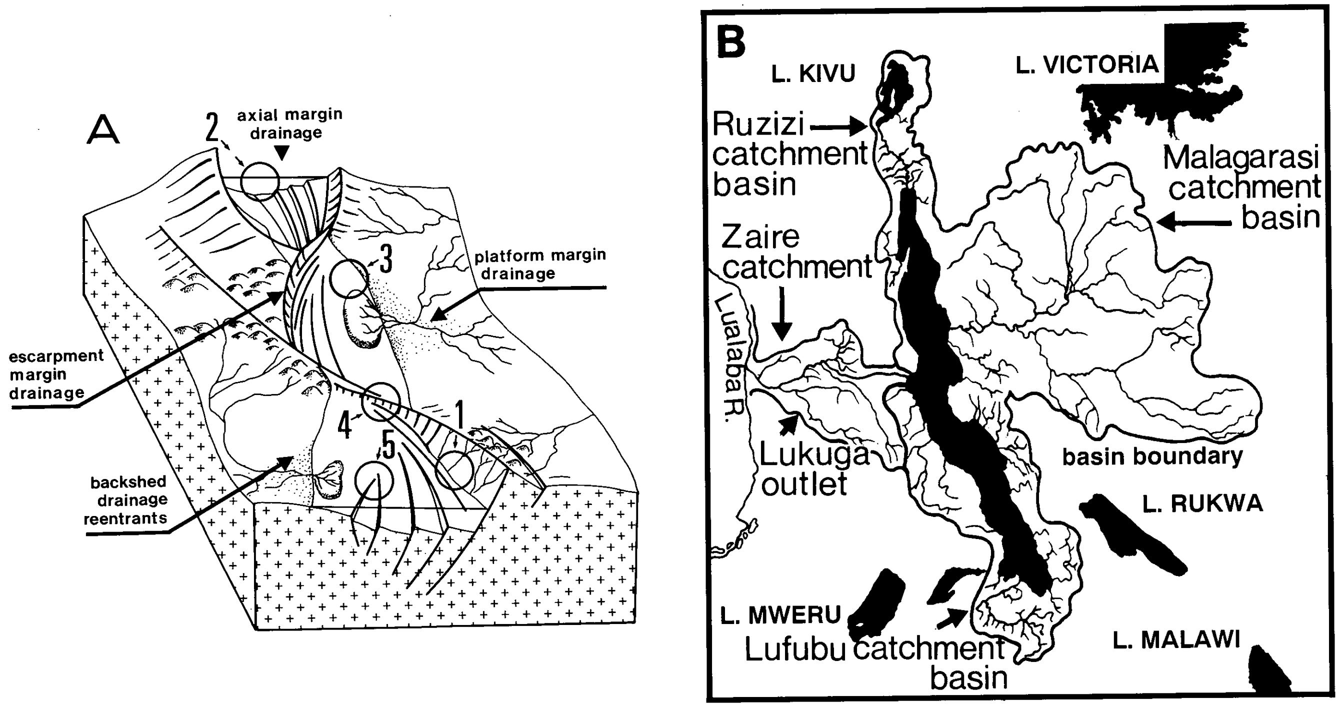


FIGURE 3

A : Block diagram illustrating alternating half-grabens linked by transverse structural highs and their related rift-basin morphologies and drainages (modified after COHEN, 1990); 1) Border Fault Margin; 2) Axial Littoral Platform; 3) Lateral Littoral Platform; 4) Midlake Structural High; 5) Axial-deep Basin.

B : Drainage pattern of Lake Tanganyika showing the Ruzizi, Malagarasi and Lufubu influent catchment basins, and the Lukuga-Zaire effluent catchment basin (from SINGH, 1975).

mal waters is estimated to be at least 0.002 km^3/yr for the studied areas at Pemba and Cape Banza. Fluid emissions at higher temperatures (250-270 °C) are suspected to occur in the deep waters of Lake Tanganyika (Craig *et al.*, 1974; Tiercelin *et al.,* in press), and may significantly heat the hypolimnion layer and increase its gas content (Coulter, 1991).

3. — MIDDLE PLEISTOCENE - MODERN SEDIMENTATION IN LAKE TANGANYIKA

The most recent research on Middle Pleistocene – Modern sedimentation in Lake Tanganyika has been carried out by the GEORIFT Project of Elf-Aquitaine and the Department of Geosciences of the University of Arizona. The upper 100 metres of the infill sequence of Lake Tanganyika, possibly representing the last 500 000 years, was studied using 5 kHz seismic reflection profiling. The Cameron and Mpulungu seismic sequences identified within the Mpulungu and Bujumbura sub-basins (Fig. 4) have been interpreted in terms of sedimentary environments and processes (Mondeguer *et al.*, 1989; Tiercelin *et al.*, 1989b; Bouroullec *et al.*, 1991, 1992; Mondeguer, 1991). Kullenberg cores up to 10 m long representing Upper Pleistocene-Holocene period were recovered from the Northern and Southern Basins (Tiercelin *et al.*, 1988b; Mondeguer *et al.*, 1989; Baltzer, 1991). Direct underwater observation and sampling was carried out by the University of Arizona, Department of Geosciences (Cohen & Thouin, 1987; Cohen, 1989a, 1990) and the Tanganydro Group (Tanganydro Group, 1992).

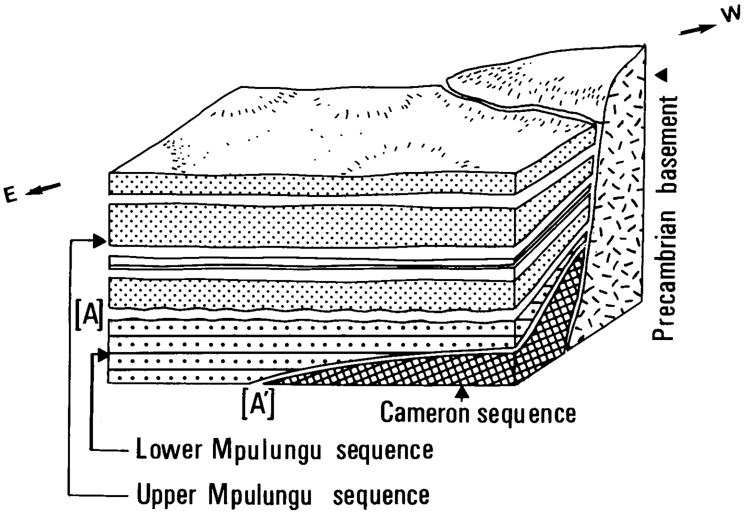


Figure 4

High-resolution seismic stratigraphy of the recent deposits in the southern Tanganyika basin (Mpulungu sub-basin). Two main seismic sequences, the Cameron and Mpulungu Sequences, are separated by a major unconformity [A']. The Cameron Sequence, identified as the acoustic basement, appears to be of sedimentary origin. The overlying Mpulungu Sequence is divided into Lower and Upper Sequences separated by the unconformity [A] (after Mondeguer, 1991). The Cameron and Mpulungu Sequences as well as the [A'] and [A] unconformities correlate with the B and C Sequences and the [W] and [X] unconformities in the Northern Tanganyika basin (after Bouroullec, 1990; Bouroullec *et al.*, 1992).

Analyses of Recent-Modern sediments indicate that the sediment has two main origins : an allochthonous origin which is linked to the whole lake catchment basin, and an autochthonous origin peculiar to the lake basin. Particular facies geometries and occurrences can be related to the particular tectonic-geomorphic settings within the Tanganyika rift basin, border fault margins, littoral platforms, midlake structural highs and axial-deep basins.

3.1. SEDIMENTATION RELATED TO BORDER FAULT MARGINS

Deposits related to border fault margins are dependent on the morphology of the half-graben basins which is characterized by an extremely strong asymmetry, particularly marked in the Bujumbura and Kigoma sub-basins of Northern Tanganyika (Fig. 2 A, D; 5). Within the Bujumbura sub-basin, the elevated and steep western margin (Zaire) corresponds to the line of the major, seismically active Uvira Border Fault (Wohlenberg, 1969, 1975; Zana & Hamaguchi, 1978). Here, a steep hinterland forms an extremely reduced catchment. Sediments built in such tectonic-geomorphic conditions consist mainly of coarse to very coarse detrital deposits (breccio-conglomerates to coarse sands) originating directly from the steep slope.

Other types of deposits are dependent on structural characteristics of border faults. Present-day tectonic activity in areas of N-S (normal) and N130-140° (strike-slip) crossing trends leads to open fault formation. Thermal fluid circulation is known from such areas, which has resulted in the formation of hydrothermal deposits (Tanganydro Group, 1992).

3.1.1. Piedmont deposits and colluvial rockfalls

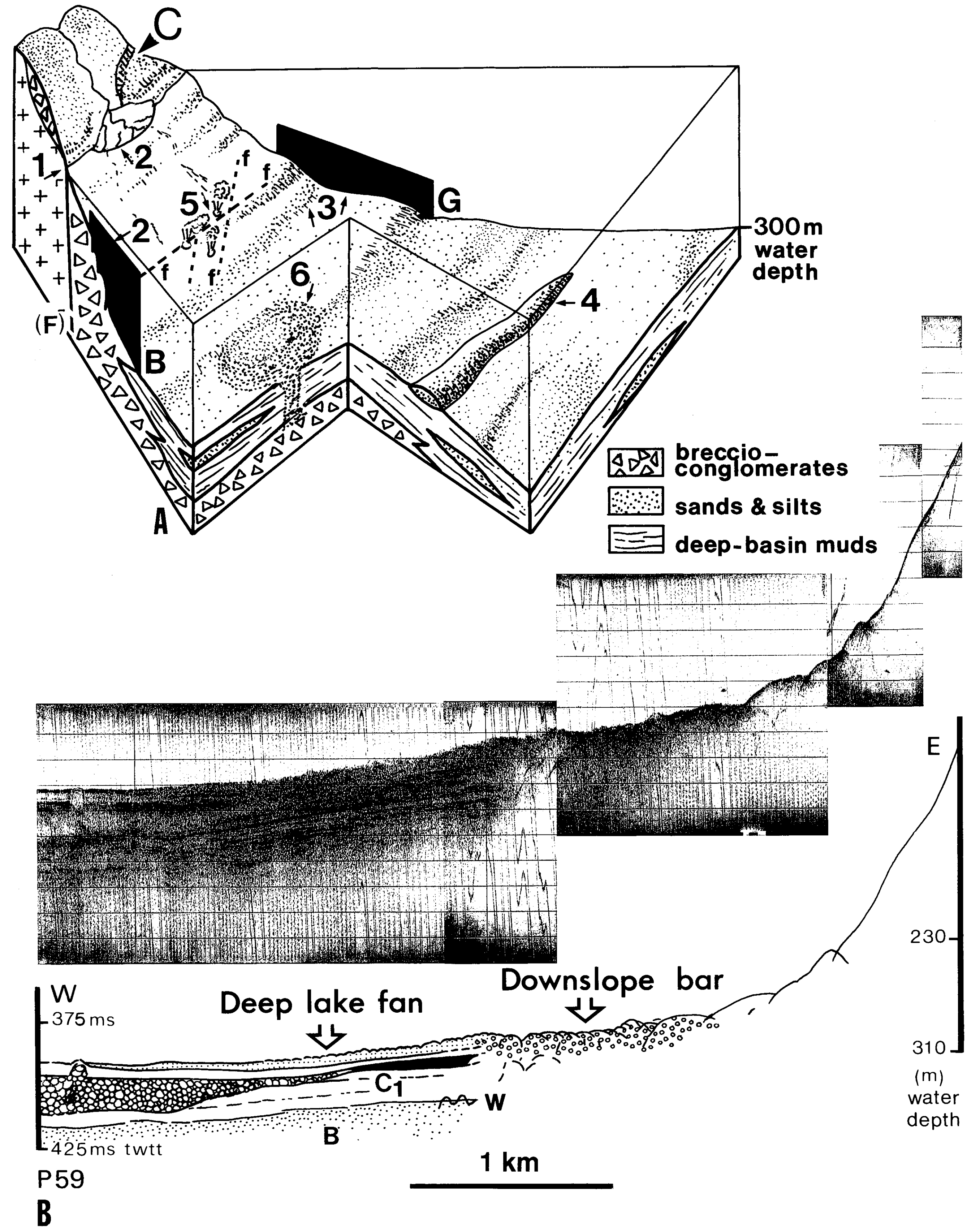
These deposits consist of very coarse colluvium (up to 5-m-diametre blocks, irregular in shape), generally within an abundant sandy-muddy matrix. Such deposits may form subaerial bodies hundreds of metres long and several tens of metres thick. They may also be shed directly down the escarpments into the deep lake basin (Fig. 5 A, B, C). These catastrophic debris flows and landslides are generally ini-

Figure 5 (see next page)

Sedimentation related to border fault margins.

A : Block-diagram illustrating the border fault margin environment : 1) Border Fault escarpment deeply incised by streams; 2) Fan deltas; 3) Mass wasting deposits; 4) Downslope sedimentary bars; 5) Sublacustrine hydrothermal seeps at N-S and NW-SE crossing fault lines (f); 6) Hydrothermal mounds.

B : Debris flow deposits at the foot of the Cape Magara escarpment, Bujumbura sub-basin, Burundi; GEORIFT high-resolution seismic line 59; C : Huge landslide at Port Kalundu, Uvira, possibly originated by strong rains on the Uvira Border Fault escarpment, Bujumbura sub-basin, Zaire; D : Fan delta at the foot of the Uvira Border Fault escarpment; E : Proximal fan deposits formed by pluri-metric blocks along the Uvira Border Fault escarpment; F : Distal fan deposits formed by interfingered sands and conglomerates, Burundian coastline; G : Mass-wastings deposits developed at the foot of the Mpulungu Border Fault, Mpulungu sub-basin, Zambia; GEORIFT high-resolution seismic line 9 (after Mondeguer *et al.*, 1989); H : Downslope sedimentary bars in the Bujumbura sub-basin, North Tanganyika (after Bouroullec *et al.*, 1991).


C
1
2
2
5
f
f
f
f
3
G
300m water depth
6
4
(F)
B
A
breccio-conglomerates
sands & silts
deep-basin muds
E
230
310
(m) water depth
W
375ms
Deep lake fan
Downslope bar
C1
W
B
425ms twtt
1 km
P59
B