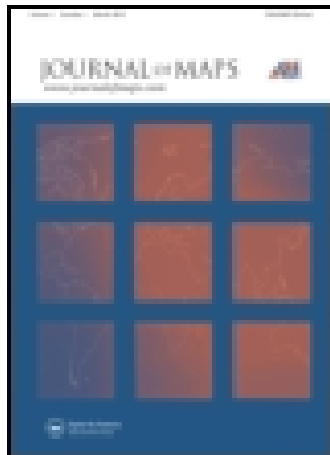


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Geology and stratigraphy of the south-eastern Lake Edward basin (Petroleum Exploration Area 4B), Albertine Rift Valley, Uganda

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SCIENCE

Geology and stratigraphy of the south-eastern Lake Edward basin (Petroleum Exploration Area 4B), Albertine Rift Valley, Uganda

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The Lake Edward basin lies within the Albertine Rift Valley of Uganda and the Democratic Republic of Congo which forms the northern end of the western arm of the East African Rift System. It is a frontier petroleum prospective area, which, at the outset of this study, had no exploration wells drilled within it or any deep reflection seismic surveys. There have been some previous studies in the basin, but none produced a geological map subdividing the onshore rift-fill sediments or established a workable stratigraphic framework for them. Between 2007 and 2010, Dominion Uganda Ltd., in collaboration with Trinity College Dublin and the Petroleum Exploration and Production Department of the Ministry of Energy, Uganda, undertook a geological mapping survey of the south-eastern onshore part of the basin, known as petroleum 'Exploration Area 4B' (EA4B). Five rift sediment formations were identified and mapped across the area to produce a new geological map of EA4B. Palynological analyses suggest that all exposed rift sediments are (Late to Mid) Pleistocene–Holocene. EA4B is dominated by a north-east to south-west trending fault zone which underwent significant extension within the last 130,000 years to produce a trough, or sub-basin, to the south-east against the rift margin. This trough subsequently filled, initially with ponded swamp clays, followed by coarse fluvial and alluvial clastics. There is field evidence for minor inversion and 'pop-up' structures along some footwall crests, suggesting that the neotectonic phase is compressional or transpressional, and this has caused stream rejuvenation and incision.

Keywords: East African Rift System; Lake Edward; structure and stratigraphy; petroleum exploration

1. Introduction

The Albertine Rift Valley forms the northern of three sectors which comprise the Western Arm of the Miocene to Recent East African Rift System, with the national border between Uganda and the Democratic Republic of Congo (DRC) passing along the centre of the valley. The

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Albertine Rift is structurally segmented into a series of asymmetric graben depocentres, or domains, each separated by NW–SE or W–E trending basement highs or ‘Accommodation Zones’ (AZs), many of which are also associated with volcanics (Rubondo, 2005). For the purposes of petroleum exploration, each of the rift basins on the Ugandan side of the border has been subdivided into blocks, or ‘Exploration Areas’ (EA). EA 4 covers the Ugandan Lake Edward–Lake George basins at the southern end of this northern rift sector (Figure 1). Lakes Edward

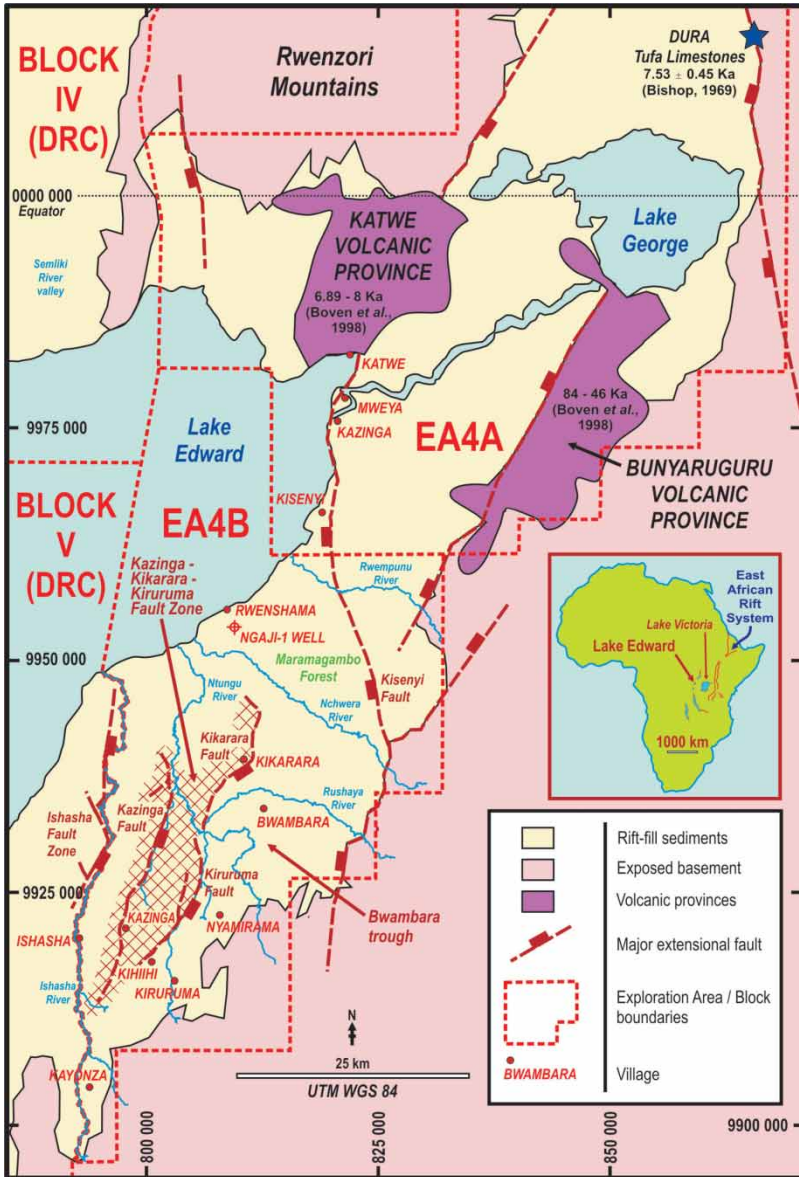


Figure 1. Geographical position and main features of EA4B. The figure shows the extent of EA4B during the initial phases of petroleum exploration by Dominion Uganda Ltd., between 2007 and 2010. Also shown are the two volcanic provinces in the basin, the location of dated Dura limestones, and the position of the Kazinga–Kikarara–Kiruruma Fault Zone and Bwambara trough.

and George are separated from the Lake Albert basin by a complex combination of an AZ marked by the alkali basalt Katwe tuffs, and the Rwenzori Mountains, which are flanked along their eastern margin by further sporadic volcanics including rare carbonatite lavas. Exploration Area 4 was originally split into two further EAs, one to the north (EA4A) and the other to the south (EA4B). EA4B included the onshore rift sediments to the south-east of Lake Edward and a large proportion of the Ugandan side of the lake (Figure 1). At the time that the present study was undertaken, no petroleum exploration wells had previously been drilled in the Lakes Edward and George basins, and only a shallow penetrating seismic reflection survey (depth \leq 50 m) had been carried out on Lake Edward (see below). Consequently, EA4 to the south of the Rwenzori Mountains remained a virgin frontier area unexplored for hydrocarbons.

EA4B is bounded to the south-east by the faulted edge of the rift valley, which exposes basement schistose gneisses along the rift shoulder. To the south-west, its onshore boundary follows the national border with the DRC along the Ishasha River, and follows it westwards as this passes offshore and diagonally across the centre of the lake. To the north-east, EA4B adjoins EA4A within an elevated plateau region covered by the dense Maramagambo rain forest. Within these confines, onshore EA4B physiography and vegetation effectively subdivide it into two halves; to the north-west towards the lakeside, the area is flat with open savannah grasslands of the Queen Elizabeth National Park and Kigezi Game Reserve, which are home to many large African mammals such as elephants, hippos, water buffalo, various antelope, and most famously prides of tree-climbing lions. The south-eastern half of the area, however, consists of gradually raised and subsequently incised topography covered with dense vegetation in parts and is cultivated for coffee, tea, bananas, and papaya.

Initial geological mapping in the region was undertaken by the Geological Survey of Uganda in the late 1950s, mainly to identify mineral resources in the Proterozoic basement (Geological Survey of Uganda, 1961). Although the Late Pleistocene–Holocene Katwe and Bunyaruguru volcanics were identified, the remaining rift-fill sediments were left undifferentiated. However, some lineations on aerial photographs were recognised as potential faults trending NE–SW across the onshore area. Subsequently, a period of academic research in conjunction with some preliminary geological field mapping and combined with a prior gravity survey, conducted by the Petroleum Exploration and Production Department (PEPD) of the Ministry of Energy and Minerals Development, Uganda between 1960 and 2000 in the Lake Edward–Lake George region, identified up to approximately 13 informal lithological formations in various litho- and chrono-stratigraphic schemes (see Bishop, 1969; Byakagaba, 1997; Musisi, 1991; Pickford, Senut, & Hadoto, 1993; Senut & Pickford, 1994) (Figure 2). These were typically assigned an age range of anywhere between Late Miocene and Holocene. However, such informal schemes did not clearly identify or define formational bounding surfaces or internal facies characteristics. Consequently, the lateral correlation of these units was, and has remained, impossible. In addition, the primary biostratigraphic constraints used in these schemes relied on correlation between a combination of gastropod and mammalian faunal provinces in the Albertine Rift and similar assemblages amongst dated tuffs in Ethiopia. This correlation is in itself problematic, as it does not allow for palaeo-biogeographical differences across the East African region at this time, and assumes that the species concerned appeared simultaneously in both areas.

The International Decade for the East African Lakes (IDEAL) marked a period of renewed research on Lake Edward. A limited, shallow-penetration reflection seismic survey (depth \leq 50 m) was carried out by Syracuse University in 1996, accompanied by some shallow piston coring on Ugandan Lake Edward. This was subsequently followed by a more extensive IDEAL Lake Edward shallow seismic survey in 2003, the results of which appeared in a series of publications (Laerdal, 2000; McGlue, Scholz, Karp, Ongodia, & Lezzar, 2006; Russell & Johnson, 2005; Russell, Johnson, Kelts, Laerdal, & Talbot, 2003). High-resolution ^{14}C dating

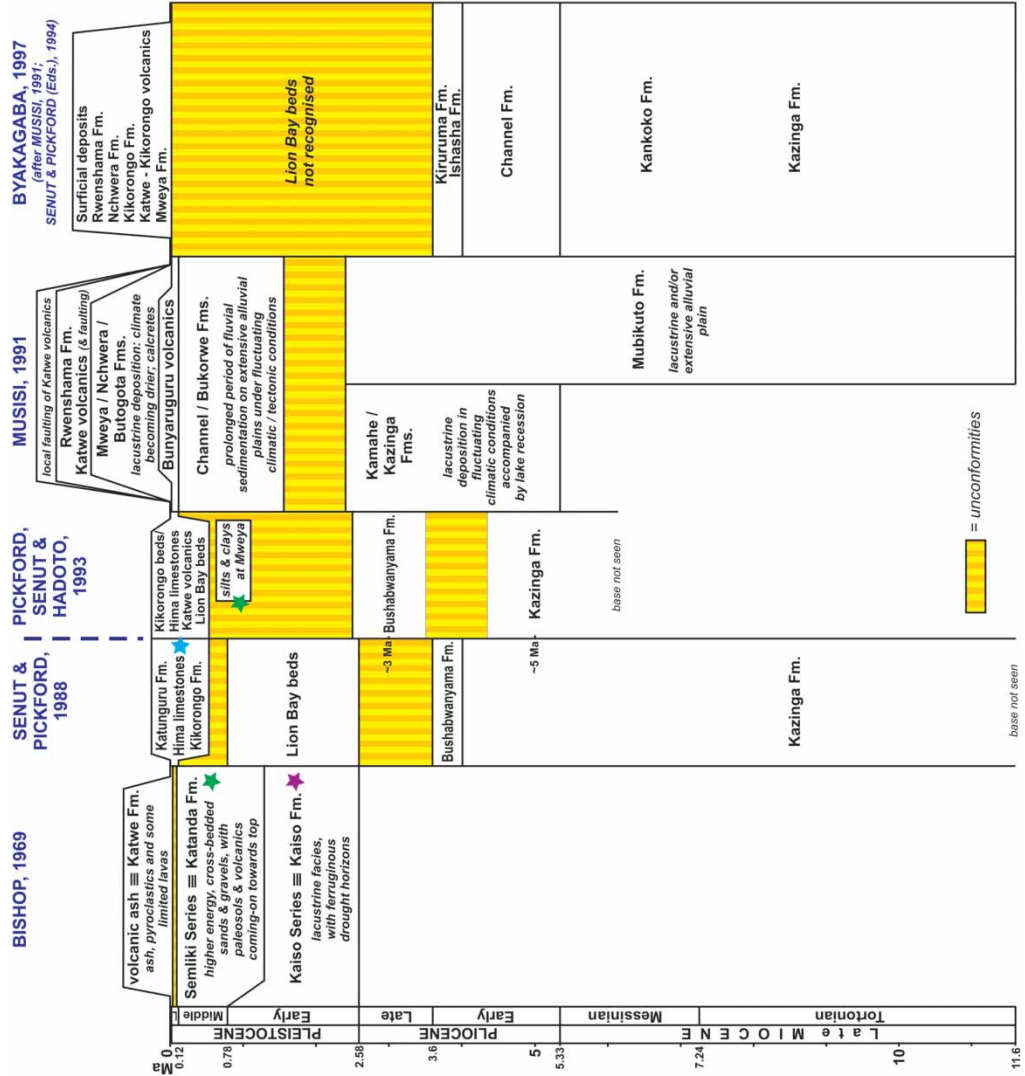


Figure 2. Lithostratigraphic schemes produced in studies of the Lake Edward–Lake George basin between 1960 and 2000. A variety of informal formations were recognised at individual exposures across the area, ranging in age from Late Miocene to Holocene.

of plant material within short cored intervals of lake sediment, combined with sequence stratigraphic interpretation of seismic sections, led to a new chrono- and event-stratigraphy for the eastern Lake Edward area and the recognition of a neotectonic framework. This new stratigraphic scheme presented a much younger chrono-stratigraphy for eastern Lake Edward than those studies undertaken prior to 2000, mainly due to the accuracy of absolute ¹⁴C age dating (Russell & Johnson, 2005; Russell et al., 2003). Identification of arid intervals, wet phases, and their correlation with an oscillating East African climate during glacial/interglacial episodes indicate that the near-surface sediments of present-day Lake Edward are latest Pleistocene–Holocene in age (~20,000 years BP to the present day) (Laerdal, 2000; McGlue et al., 2006; Russell & Johnson, 2005; Russell et al., 2003) (Figure 3).

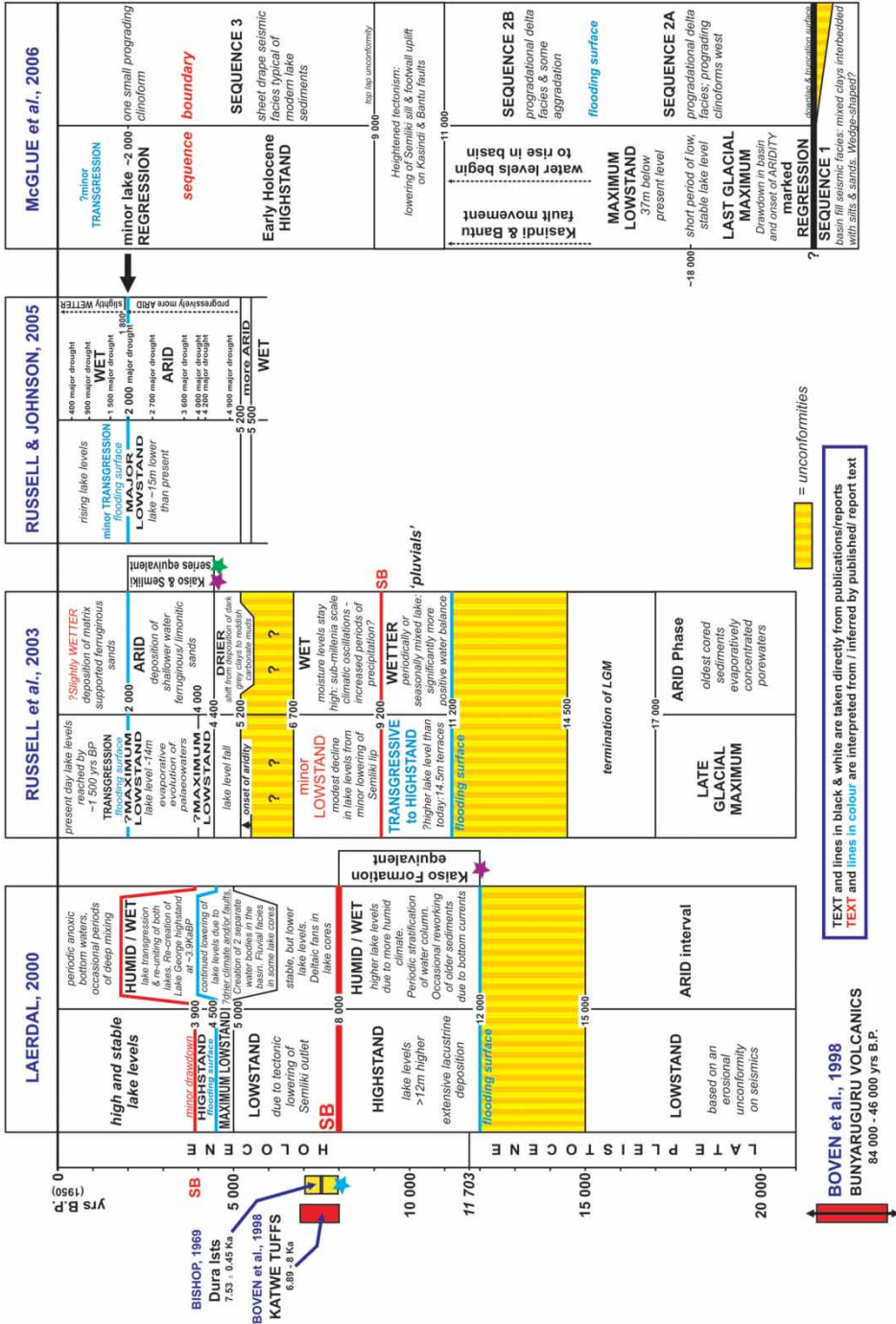


Figure 3. Stratigraphic summary chart of shallow cored sediments in eastern Lake Edward based on IDEAL studies, correlated against age dates from Katwe and Bunyaruguru tuffs and previous age attempts on sporadic occurrences of hot spring tufa limestones within the basin. Coloured stars indicate where units identified in Figure 2 would plot in this stratigraphic scheme. Although the Lake Edward cored sediments are likely to be younger than most onshore exposures, the Kikyere swamp clays may correspond to one or more of the wet phases indicated during the Holocene.

Upon signing a Production Sharing Agreement for EA4B with the Ugandan Government in 2007, Dominion Uganda Ltd. (a subsidiary of Dominion Petroleum Ltd.) began an extensive geology and geophysics field research programme in collaboration with Trinity College Dublin and PEPD. One of the principal results of this new phase of geological field surveying was a geological map sheet of onshore EA4B, presented here at 1:66,666 scale (1.5 cm = 1 km) ([Main Map](#)). This map not only subdivides the stratigraphy of rift-fill sediments for the first time but also identifies relatively recent normal faults which have controlled the style and architecture of sedimentation in the basin. In addition, as this map records the first petroleum exploration in this basin, it is also something of a historical document, in that additional features, such as the course of the original seismic lines through the bush, have been shown, as well as sites where ~80 m deep upholes were drilled to help process the seismic data, and where lithofacies were recorded in samples collected from the bottom of drilled 9 m shot holes ([Main Map](#)).

2. Mapping strategy and attempts to establish the stratigraphy in EA4B

The Dominion field programme began with an initial field reconnaissance of the EA4 Lakes Edward and George area, undertaken in September 2007. As part of this reconnaissance, attempts were made to revisit the key localities at which informal formations had been described previously by [Musisi \(1991\)](#) and [Byakagaba \(1997\)](#). However, problems were encountered not only in relocating some of these ‘type’ localities but also in making any kind of lithostratigraphic correlation between isolated, short, logged sections. In essence, the crux of the problem lay in the fact that exposed rift-fill sediments in EA4B were originally deposited in dominantly fluvial and/or alluvial depositional environments by north-westerly prograding complexes from the SE rift margin. As such, a change in sediment can be expected to occur over very short distances both laterally and distally down-dip from source area, as well as establishing complex stacking patterns in what can be thin stratigraphic intervals of only a few metres in thickness.

In order to circumvent this problem, yet continue mapping until the stratigraphy could be resolved, a lithofacies approach was adopted. Using this method, at each exposure, the component lithofacies were identified and described separately, followed by an interpretation of their lithofacies associations and depositional environments. In the field, five broad lithofacies types were recognised (‘Lithofacies A–E’; see ‘Key to Intraformational Lithofacies’ on [Main Map](#)), each associated with a particular suite of depositional environments related to factors such as water energy and distance from the south-eastern rift margin scarp. Each characteristic lithofacies was assigned a specific colour code for the map representing each of the five main lithofacies (see ‘Key to Intraformational Lithofacies’ on [Main Map](#)), and all individual exposures visited are shown delineated and coloured, accompanied by the original locality code which corresponds to its description in field notebooks. Exposure of rift-fill sediments in EA4B is generally poor compared with, for instance, equivalent areas of the Albertine Rift in Ugandan Lake Albert to the north. Thus, many of the smaller exposures simply consisted of one lithofacies type. However, larger cliff exposures, most of which have been visited by previous authors and logged as formation ‘stratotypes’, were a combination of stacked lithofacies. This approach proved to be far more flexible and realistic in describing precisely what was observed in the field. Eventually, multiple sampling from hand augering along road sections meant that each lithofacies could be subdivided further (for instance, D^I, D^{II}, D^{III}), to reflect more specific differences in local depositional environments leading to sedimentation of beds with roughly similar physical properties, and this further division is shown in the ‘Key to Road Section Lithologies’ which accompanies the road section correlation panel at the bottom of the [Main Map](#). Samples from clay intervals of lithofacies ‘D’ and ‘E’ were taken from a variety of stratigraphic intervals and road sections, and processed by RPS Ltd. (UK) following the method of [Shaw, Logan, and](#)

Weston (2008) for their palynological assemblages. Biostratigraphic analysis of these samples indicated that all exposures were Pleistocene–Holocene in age (i.e. ≤ 2.59 Ma). Correlation with the IDEAL ^{14}C results from shallow lake-floor sediments just offshore on Lake Edward (Figure 3) would make this age range more likely to be Middle or Late Pleistocene–Holocene (i.e. ≤ 0.78 Ma). However, without further age constraints, a more detailed synthesis with shallow lake bottom data remains problematic.

Whilst geological surveying was in progress, Dominion conducted both an onshore and offshore deep seismic reflection survey within EA4B. As a necessary precursor to shooting the seismic lines, shot holes for dynamite were drilled along lines at 25 m intervals, and up to a depth of about 9 m. The drillers were asked to take a sediment sample from the base of each hole. Sample coverage was unfortunately not complete, but yielded further information on lithofacies variation across the area in places where no exposure was present. Despite these additional data, at the end of this process, the recognition of formational stratigraphic units was still unclear, with no distinct pattern emerging from lithofacies distributions across the area. However, what the exposure and shot hole lithofacies data amply demonstrated by their colour distribution on the accompanying geological map was that the comment above, regarding rapid fluvial and alluvial lithofacies changes both laterally and over time, holds true for the rift-fill sediments in Lake Edward. In essence, this lithofacies approach views the stratigraphy at too high a resolution perhaps for distinct sedimentary packages to become clear. Consequently, following on from this lithofacies mapping, a slightly different approach was needed. This involved attempting lateral correlation across the area by bundling characteristic lithofacies packages together with the recognition or inference of under- and overlying significant bounding surfaces. This takes the original goal of mapping lithostratigraphic formations towards the establishment of a sequence stratigraphic framework of distinct chronostratigraphic sedimentary packages or units, separated by time surfaces.

Throughout the EA4B region, a general observation which holds true is that the rift sediment strata are in almost all cases very shallowly dipping to the horizontal ($\leq 10^\circ$), reflecting their original angle of repose during deposition in their respective fluvial environments. Making the assumption that over large lateral distances, localised differences in angles of dip and direction broadly cancel each other out to give an approximately horizontal regional angle of dip to sedimentary packages means that altitude (height above sea level in metres) would correspond directly to true stratigraphic height in a sedimentary section. In reality, of course, where strata are dipping gently, this equivalence of difference in altitudes to true stratigraphic thickness will be a slight over-exaggeration. Consequently, key road or track sections were identified which traversed areas of stratigraphic complexity and with the maximum altitude variation. A hand auger was used to drill below the soil along stretches of no exposure and recover sediment samples, generally at 20 m vertical intervals along each section, and incorporating any data from roadside exposures. Using the assumption of horizontal dip gives a maximum thickness in each road section equivalent to the difference in altitude. Despite the obvious shortcomings of these assumptions, it should be remembered that there are very few thick exposures in EA4B, and that short of continuous coring in boreholes, this method remains the best way to stack together or correlate between road sections and finally build a lithostratigraphic framework for EA4B. This framework is shown across the lower half of the [Main Map](#).

3. Coupled structural and stratigraphic framework in EA4B

Seismic sections combined with aero-gravity and magnetic data demonstrate that the Lake Edward basin is a highly asymmetric graben or asymmetric half-graben, with the major controlling fault bounding the western edge of the lake in the DRC. It became clear early on in the

geological mapping that the surface topography of EA4B reflected this underlying structure of the region. Linear or slightly sinuous, low, asymmetric hills are common with pronounced scarp slopes along one side and a flat, gentle dip-slope on the other. The base of scarp slopes thus mark the surface expression of underlying faults and the scarp face approximates to the fault plane. This interpretation was confirmed by observing fault drag on beds exposed along scarps at some localities. Given that all exposed sediments in EA4B are Mid–Late Pleistocene–Holocene in age, faults which have produced a scarp at the surface must have had comparatively recent movement within tens of thousands of years.

Mapping revealed the presence of a ~7 km wide NE–SW trending, east-facing extensional fault zone exposed across the centre of onshore EA4B. Within this zone, particularly well-developed exposed fault geometries are seen at Kazinga, Kikarara, and Kiruruma. The major faults seen at Kikarara and Kiruruma trend towards each other and the likelihood is that they are in fact the same fault which has had its scarp breached and eroded in the centre by the Ntungu River. This scarp-breaching appears common in many of the faults seen in EA4B and is also accompanied by recurved, eroded fault scarp surface terminations. Some minor west-facing antithetic reverse faults can be seen, and these have a curving trace at the surface which bifurcates from the main fault scarp. This is particularly well developed along the Kazinga Fault at Katookye Gate (UTM 802300 9935300 on the [Main Map](#)). Here, where antithetic faults join the main fault at either end, the area in the centre can be observed to be an upstanding hill or raised ‘pod’ on the footwall crest with an accompanying pronounced ‘shoulder’ on the dip-slope. Such raised ‘pop’-up hills in the central area of footwall blocks on major faults suggest that the neotectonic phase in EA4B is compressional or transpressional.

The presence of the Kazinga–Kikarara–Kiruruma Fault Zone (KKK-FZ), and the comparatively recent extensional movement across it, has had a profound effect on the sedimentary rift-fill of this portion of the Lake Edward basin. The low-energy, distal fluvial floodbasin plain and marginal lacustrine deposits of the comparatively older Kisenyi Formation form the footwall of these major faults and is exposed in their scarps. However, to the south-east of this fault zone, the sedimentary fill has altogether a different style and architecture, reflecting rapid deposition from higher energy fluvial and alluvial systems. Although these sediments are clearly more proximal to the rift margin, and therefore would be expected to be coarser clastics, the change from these into the Kisenyi Formation is abrupt across the fault zone and not gradational. This suggests that extensional movement along the KKK-FZ has created a sub-basin, or trough, trending NE–SW through the district of Bwambara and along the south-eastern rift margin (hence it is referred to here as the ‘Bwambara trough’) ([Figure 1](#)). This has subsequently become filled with relatively immature clastics shed directly from the exposed basement to the south-east. Seismic interpretation indicates that there is a gently dipping shallow unconformable surface present which separates a gently dipping near-surface sedimentary package from underlying tilted fault block reflectors in the onshore part of the Lake Edward basin. This surface marks the onset of KKK-FZ extension and subsidence of the Bwambara trough, and as a significant bounding surface, it separates the Kisenyi Formation from overlying trough fill ([Figure 4](#)).

The Bwambara trough contains three recognisable stratigraphic units. The lowermost of these, the Kayonza Formation, is a fluvial unit with well-developed channel conglomerate lenses and thick, laterally persistent clay intervals. These clays represent formation of extensive ponded floodbasin swamps developed during initial subsidence in the trough as reorganisation of drainage pooled river systems to the south-east of KKK-FZ scarps. In addition, it seems likely that this also represents a period of deposition during a wet climatic period, such as would be experienced in the equatorial tropics of East Africa during northern and southern hemisphere interglacials (for instance, see [Trauth, Deino, & Strecker, 2001](#)) ([Figure 4\(b\)](#)). In Section IXa, at the Kiruruma River Quarry close to the base of the Kayonza unit, a thin, ~15 cm thick, hard, white ‘clay’

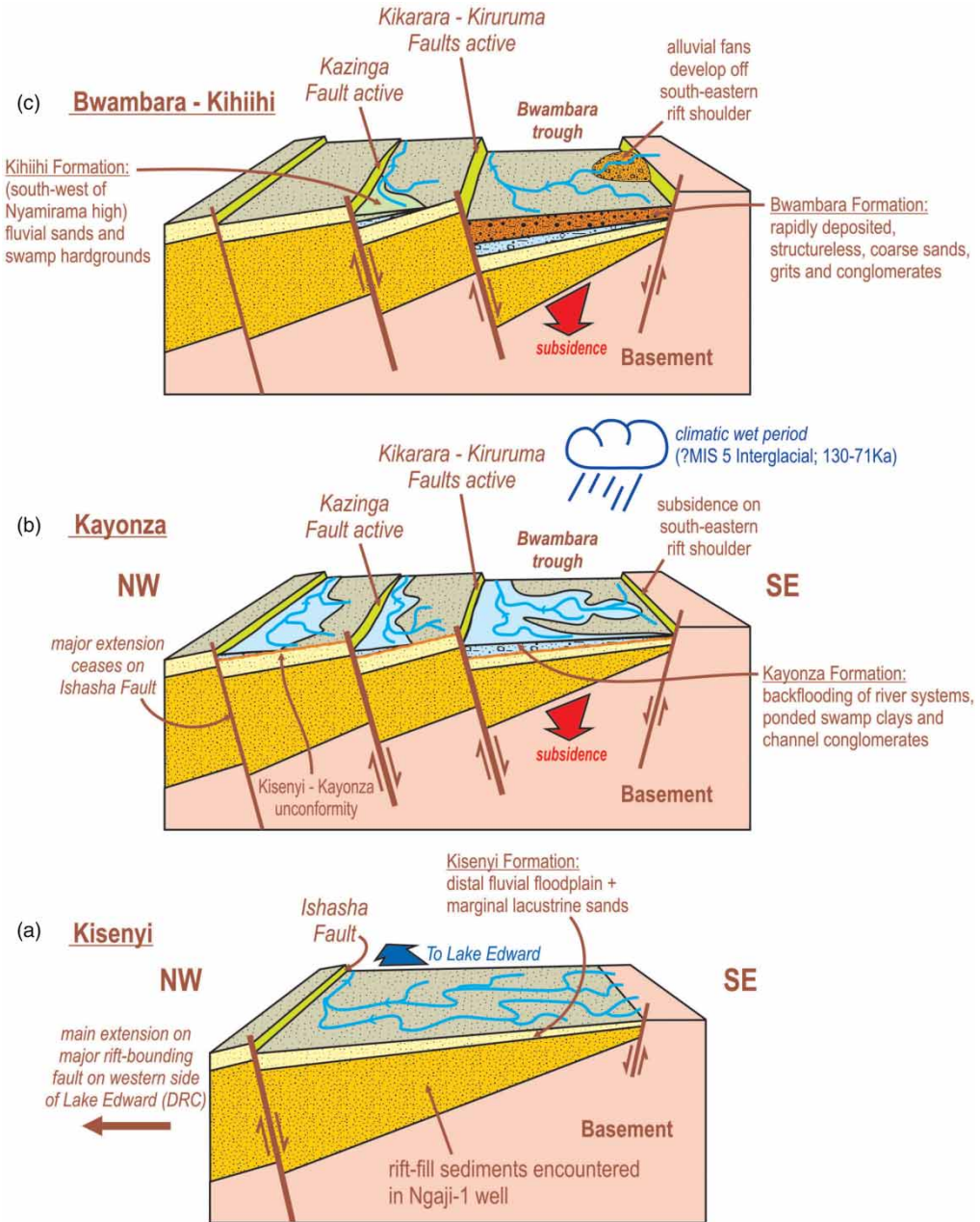


Figure 4. Block cartoon to illustrate the main phases of extension and subsidence which developed the Bwambara trough and its associated sedimentary rift-fill. The cartoon broadly corresponds to the line of section L8, NW–SE across the onshore part of the basin, and also incorporates features from further to the south-west. As such, the cartoon is not drawn to any scale and should be considered schematic only.

horizon is present. This is similar to diatomites found elsewhere in the Lakes Albert and Edward basins. If it were indeed a diatomite, then it supports the idea of drainage ponding behind the KKK-FZ, with the formation of a temporary lake in the trough. The alternative possibility is

that it is a volcanic ash bentonite horizon. The base of the Kayonza Formation can be defined as the basal surface of the lowermost laterally persistent clay horizon lying with angular unconformity upon the Kisenyi Formation below.

The Kayonza Formation is overlain by laterally variable clastics which can be subdivided either side of a structural high, or divide, across a basement spur at Nyamirama. Thus, the top bounding surface to the Kayonza Formation can be defined as the lowermost stratigraphic occurrence of thick, structureless sands, which is actually an easily recognised marked change in many road sections. The Kihiihi Formation, developed to the south-west of the area, is characterised by low-energy fluvial sediments and occasional swamp hardground horizons with freshwater gastropods. This unit effectively developed on the flank of the main Bwambara trough (Figure 4(c)). To the north-east of the Nyamirama high, the main area of subsidence accumulated the Bwambara Formation, which is composed of thick, comparatively structureless, dominantly coarse sands, grits and conglomerates, representing the immature, relatively rapid, sub-basin fill (Figure 4(c)). The youngest unit which can be recognised in sporadic occurrence across the whole area, the Kikyere Formation, is composed of swamp clays which have formed, or are currently forming, typically along the hanging walls of fault scarps due to the present-day interglacial wet phase. This would then be equivalent to Marine Isotope Stage (MIS) 1; from 14 ka to the present day. A more detailed formal description of each of these new stratigraphic formations will be published elsewhere. In addition, however, it is worth noting that because the significant bounding surfaces between formations correspond to unconformities caused by changes in tectonics and climate, they also represent time surfaces. Formations, therefore, also serve as chronostratigraphic units.

Age constraints on timing of KKK-FZ movement and associated Bwambara trough sedimentary fill are difficult, given the lack of any further indication from palynology. The Kisenyi Formation is exposed in the Kisenyi Fault scarp and can be correlated with confidence to the uppermost section in the Ngaji-1 well nearby. Neither the Kisenyi Formation nor any of the sediments in Ngaji-1 contain recognisable tuff horizons, or reworked tuffaceous material, and therefore these must have been deposited prior to any volcanism in the Lake Edward basin. However, if the white clay at the Kiruruma River Quarry (Section IXa) is indeed a bentonite ash band, lying close to the base of the Kayonza Formation, then it must have originated from air fall ash erupted during the Bunyaruguru volcanic episode (Boven, Pasteels, Punzalan, Yamba, & Musisi, 1998), as the Katwe tuffs are too far to the north to have produced the thickness of bentonite observed here. Bunyaruguru tuff cones and maars are exposed approximately 50 km to the north-east of Kiruruma and are dated as having formed anywhere between 84,000 and 46,000 years BP (Boven et al., 1998). This date plus the characteristic feature in the Kayonza unit of interglacial wet phase ponded swamps and a possible lake forming in the Bwambara trough allow tentative correlation to deposition during interglacial MIS 5 ('Eemian', from 130 to 71 ka). The shallow unconformity which can be identified on seismic sections across the onshore area of EA4B, and which corresponds to the surface between Kisenyi and Kayonza Formations, is most likely to have been formed by a forced regression and lake lowstand event during a climatic dry phase caused by a glacial maximum. If the Kayonza unit was deposited during MIS 5, then this glacial maximum must have occurred during the MIS 6 glacial sometime between 191 and 130 ka. If so, then extension along the KKK-FZ, formation of the Bwambara trough and its sedimentary infill all occurred relatively rapidly, certainly within the last ~ 130,000 years.

4. Conclusions

The geological map presented here represents the first attempt to subdivide the stratigraphy of rift-fill sediments of the south-eastern Lake Edward basin and explain their sedimentology as a consequence of the relatively recent structural evolution of this part of the basin. Hand augering a

series of road sections yielded composite stratigraphic logs which could be correlated to produce a robust framework of five sedimentary formations exposed across the EA4B area. The oldest of these, the Kisenyi Formation, predates the Bunyaruguru volcanics of 84,000–46,000 years BP, and forms the footwall blocks of the extensional Bwambara trough. Subsidence in the trough began during MIS 5 before or during Bunyaruguru volcanism and was marked initially by deposition of the interglacial wet phase Kayonza Formation. This represents a fluvial unit with lenses of channel conglomerates, but dominated by ponded swamp clays. Continued subsidence caused the accumulation of thick, fluvial and alluvial sands and conglomerates as the laterally equivalent Kihiihi and Bwambara Formations, either side of a basement high. The present neotectonic phase across this part of the basin appears to be compressional, or transpressional, and this has caused some inversion, marked by drainage rejuvenation and incision of the recent topography and rift-fill sediments.

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Software

Topographic base map tiles were imported into CorelDRAW 11, along with scanned field maps and reduced to 1:50,000 scale for digital drafting and final map production.

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