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Early Continental Rift Basin Stratigraphy, Depositional Facies and Tectonics in Volcaniclastic System: Examples from the Miocene Successions Along the Japan Sea and in the East African Rift Valley (Kenya)

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Additional information is available at the end of the chapter

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1. Introduction

There are numerous stratigraphic studies regarding rift valley fill successions. The major understanding of the rift basins' filling process was obtained from the Basin and Range regions and Rio Grande Rift, USA (for example, [1-4]); East African Rift Valley (for example, [5-7]); Suez Rift, Egypt (for example, [8-10]); Corinth Basin, Greece (for example, [11-13]) and so on. The initial stage of the rift basin evolution is characterized by the development of a series of small half-grabens. Basins become larger through the linkage of border faults of individual half-grabens [14]. Even after basin mergers, topographic lows of footwall among basins (accommodation zones before basin mergers) play an important role for sediment supply. The relay ramp developed between two normal faults dipping in the same direction (Figure 1), and its evolution, is crucial because it acts as the major entry point of the water and sediments to the basins [14-15]. The manner of sediment entry to the basins and the subsidence pattern strongly affect the architecture of basin-fills (for example, [16-17]), resulting in the formation of different systems tracts in different places within a basin at a given time [18]. In case of continental rift basins with lakes, the strata formation is much more complicated than in marine basins (for example [19-20]). The differences in sedimentation process between lake and marine basins are summarized in [21], suggesting that the terrestrial basin fills are not miniature marine basins because there were different amplitude base-level variations, linkage of climate

and sediment supply and so on. Pre-rift basement structures also affect the evolution of the basin as well as fills of the early rift basins (for example, [13, 22-23]).

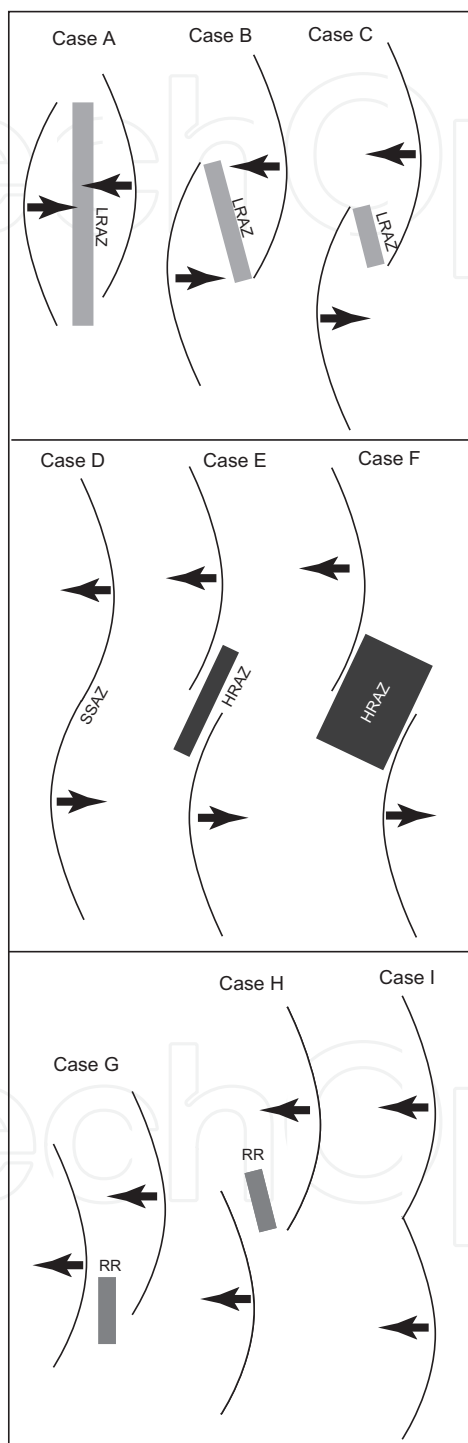


Figure 1. Various types of linked half-grabens and characteristics of accommodation zones modified from Figure 6a-c in Rosendhal (1987). Arrows indicate the direction of normal fault displacement. LRAZ: Low relief accommodation zone, HRAZ: High relief accommodation zone, SSAZ: Strike-slip accommodation zone, RR: Relay ramp.

However, studies of the rift basin fills with active volcanism have been limited and their basin-fill processes are poorly understood (see [24]). Pyroclastic fall may supply sediments from the air nearly evenly within a basin if the basin size is small relative to the pyroclastic fall area. The reworked volcaniclastics (mainly ash) supplied via rivers can be more widely spread in the lake than is the case of the siliciclastic system. This is because of smaller grain density (for example [25]), resulting in faster sedimentation even in parts of a basin starved of sediments transported by streams. Such faster sedimentation may provide opportunities to decode the high-resolution tectonic and basin-fill history through the reconstruction of environmental changes. Some examples of the basin-fill successions affected strongly by sediment supply via pyroclastic fall are, therefore, shown to discuss the evolution of the early rift basin fills. Early rift basins are expected to experience a complicated history in association with merging small basins when border fault tips propagate laterally to the next basin [14] or when one basin is filled out and sediments and water spill over to the next basins beyond the accommodation zone [16]. Examples of studies discussing such events are also limited to a small number [4]. The basins filled rapidly with pyroclastic fall are suitable for detecting such basin-merging events as well as another type of tectonic events such as subsidence.

The Miocene successions exposed along the Japan Sea on the Japanese main island contain the early rift basin fills, which were formed when the Japan Sea was opened; they are now exposed on the land because of tectonic inversion (for example, [26]). One of the basin fills was targeted in this study—the Miocene Koura Formation, exposed in SW Japan. Other targets here were the Miocene half-graben fills in Kenya (Namurungule Formation in Samburu Hills and Nakali Formation in Nakali, northern and central Kenya, respectively). The basin fills adjacent to the volcanoes must be strongly affected by the supply of volcaniclastics and lava flow, as well as subsidence/uplift related to volcanism (for example [24, 27]). However, the local volcano-related tectonics (such as caldera formation) are excluded in this study for simple discussions. Because the centre of the eruption or intrusion of magma during the deposition of the Namurungule and Nakali Formations has not been discovered around the target basins, it is considered that the tectonic subsidence or uplift induced by local volcanisms (see [24, 28]) can be ignored for these cases. The Koura Formation example is unclear for the strong tectonic control from local volcanoes, but its effect can be ignored as well, because lava has not been found and only pyroclastic fall or flow deposits have been described from the formation.

2. Case studies of the early rift basin fills

2.1. Koura formation

The Miocene successions associated with the Japan Sea opening widely spread along the coastal region of the Japan Sea. The Miocene Koura Formation is exposed in the Shimane Peninsula, on the western part of the main island of Japan (Honshu Island) (Figure 2). The Koura Formation distribution is elongated E–W—which is almost parallel to faults in and around the western Japan Sea (ENE–WSW)—and dips mainly to the north, allowing observation of axial facies changes in the basin (Figure 2). The basin fill thickness exceeds 600 m [29-30].

The basement rock of the basin has not been confirmed yet, but granitic or metamorphic rocks are inferred to be the basement on the basis of the gravels contained in the formation [31].

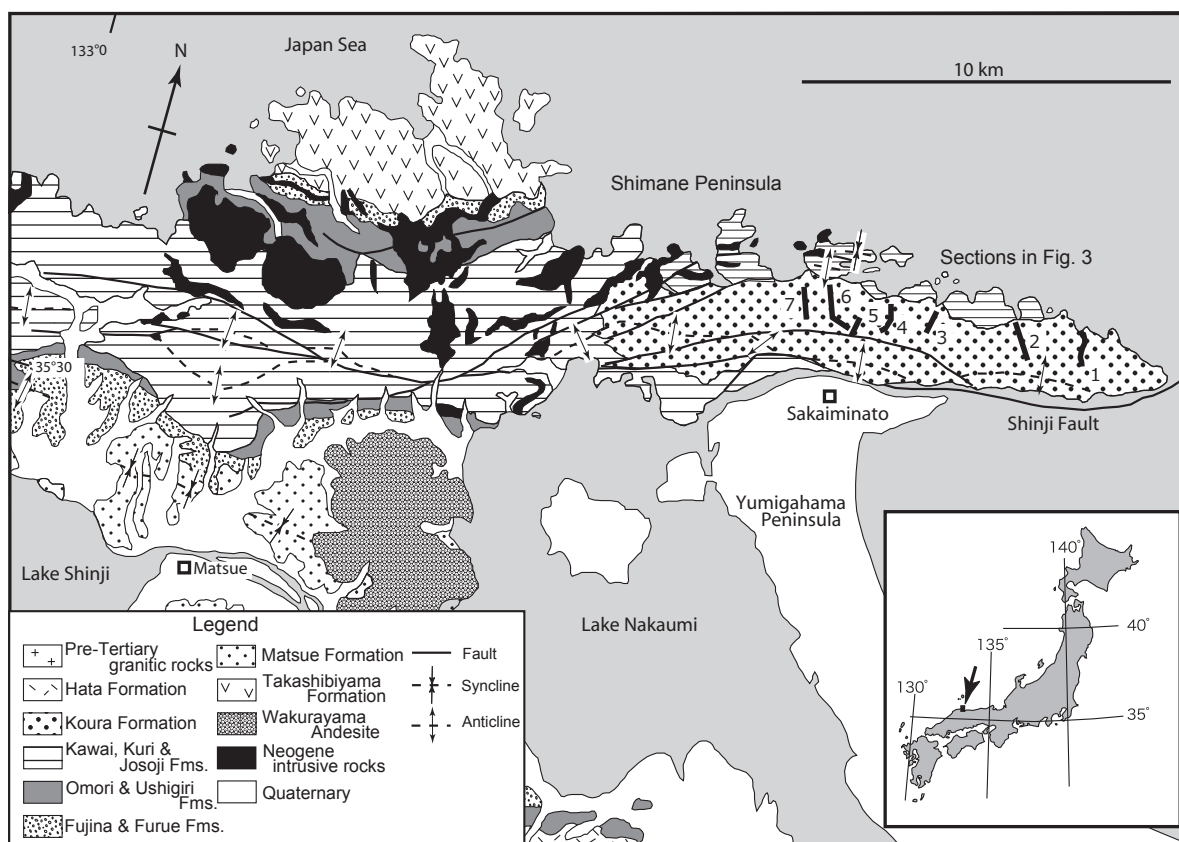


Figure 2. Location and geologic map of eastern Shimane. 1–7 in Figure 4 show the sections.

It is difficult to discuss the basin morphology at the time of deposition because of the limited extent of exposure. However, the seismic cross-sections of this area show the presence of a series of half-grabens under the bottom of the Japan Sea [32], suggesting that the Koura Basin fills a half-graben. Although the border fault of this basin has not been confirmed either, one of the major faults of this region, the Shinji Fault (or Kashima Fault), running just south of the distribution area of the Koura Formation (Figure 2) and acting presently as a right-lateral strike-slip fault [33], is most probably the border fault of the basin.

The Koura Formation consists of three members (Sakai et al., 2013). For simplicity, these three members are referred to as “lower”, “middle” and “upper” formations. The lower formation consists of conglomeratic sandstone beds (alluvial fan origin [30]) and the overlying alternation of the sandstone and mudstone beds (meandering and braided streams, floodplain, marsh and shallow lake origin [34]) (Figures 3 and 4). The middle formation consists of andesitic volcanoclastics deposited in a shallow (probably fresh) lake and floodplain (Figures 3 and 4). The sediments in this interval are predominated by those from pyroclastic fall and small-scale gravity flows (Kano, 1991; Sakai et al., 2013). The upper formation is characterized by alternations of tuffaceous sandstone and mudstone beds (fan delta deposit; Figures 3 and 4) and

conglomerate interbeds filling small sublacustrine channels developed on the fan delta slope – which were deposited in a blackish lake, as suggested by the presence of *Ostrea* and *Corbicula* fossils and burrows by *Teredo* sp. as well as geochemical data [29, 34, 36-37]. The upper Koura Formation contains hummocky cross-stratified (HCS) sandstone beds, implying that the lake size became wide enough for generating large waves. The sediment supply to the basin was mainly from the east during the deposition of the upper formation [30, 35]. Three thick lapilli tuff beds (T3–T5) are strong tools for correlation within the basin (Figure 3). The chronology of the Koura Formation has been insufficient. Ages of 16–24 Ma were obtained from the upper formation through fission-track dating [38], and the age of the base of the overlying Josoji Formation (i.e. the top of the Koura Formation) was estimated to be 20–18 Ma or younger [39].

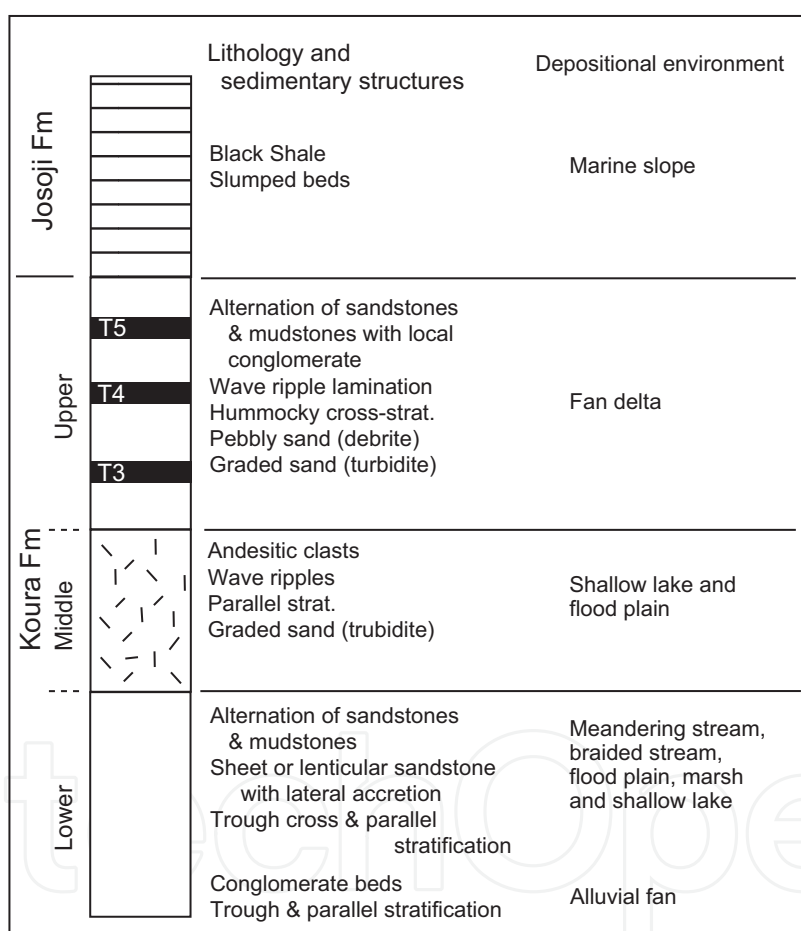


Figure 3. Lithostratigraphy of the Koura and lowest Josoji Formations. T3–T5 indicate lapilli tuff beds in the upper Koura Formation.

The boundaries of the lower-middle and middle-upper formations are marked by a surface that is then overlain by an up to 10 m sediment interval consisting of cross-stratified sandstone or conglomerate beds (Figure 5). It is interpreted that each cross-stratified interval was deposited from a basin-wide flood-flow incoming from another basin, and subsequent lake-level rise occurred when this and the other basin were merged [34], on the basis of the following

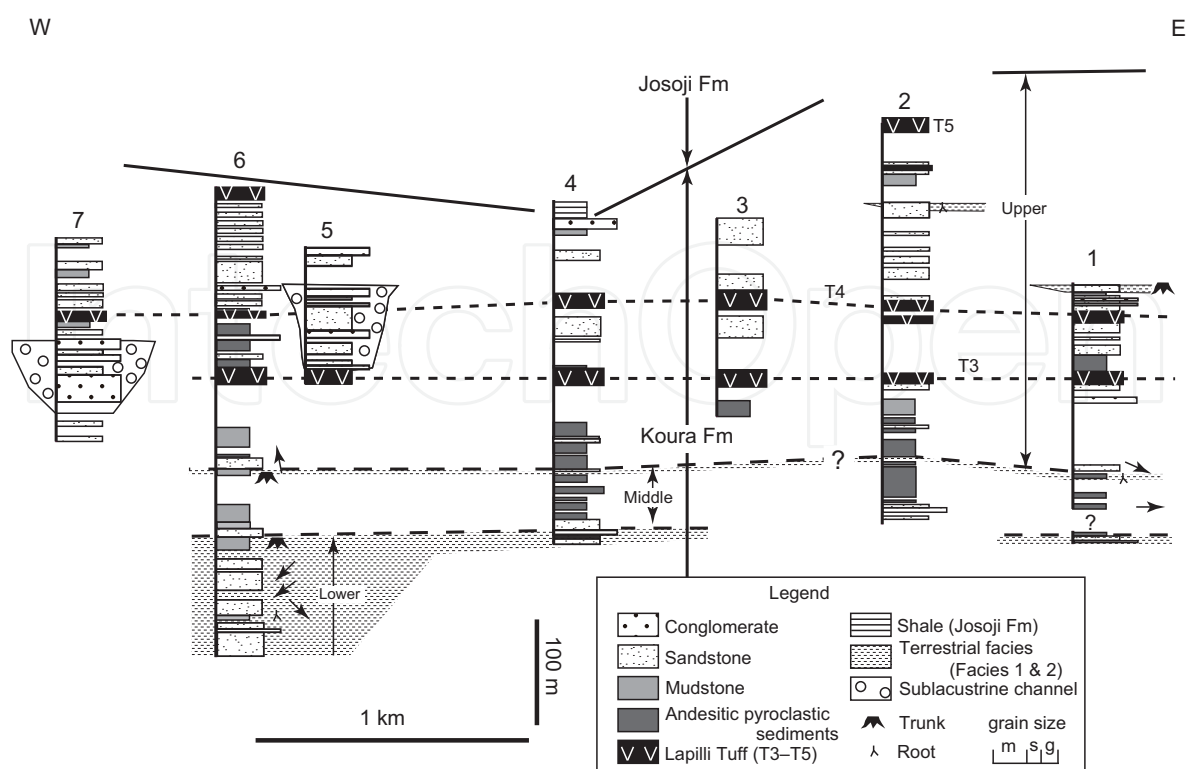


Figure 4. Columnar cross-sections of the Koura Formation (modified from [34]). m: mud, s: sand, g: gravel.

reasons: (1) absence of a major erosion surface within both cross-stratified intervals and homogeneous lithology imply their deposition within a short period; (2) both the cross-stratified intervals cover terrestrial deposits with tree trunks, and change upward into the alternations of sandstone and mudstone bed and the andesitic volcanoclastic beds containing both pyroclastic fall, turbidite and beds with small-scale slump structures (lake deposit) (Figure 5). The rapid lake-level rise suggests the merger with a basin having a base level higher than that of the Koura Basin. The second event may record the merger of this basin with a marine one to become a blackish lake basin.

The top of the Koura Formation is marked by a major flooding surface below the black marine shale of the Josoji Formation. The Josoji Formation is interpreted to consist of sediments of the climax phase of the Japan Sea opening. In the context of sequence stratigraphy, the lower and middle formations are interpreted to be the lowstand systems tract (LST). The base of the upper formation is interpreted to be the first flooding surface and the upper formation is interpreted to be the transgressive systems tract (TST) together with a part of the overlying Josoji Formation.

The upper Koura Formation hosts sediment cycles (Figure 6). The thickness of each cycle ranges from 5 to 20 m. Some of the cycles are bounded by flooding surfaces (see [40]) (Figure 6A). Such cycles mainly consist of sediments with an upward-shallowing trend. The basal flooding surface is covered with a massive mudstone bed (outer shelf equivalent deposit of the fan delta) or an alternation of HCS sandstone and mudstone beds of inner shelf equivalent

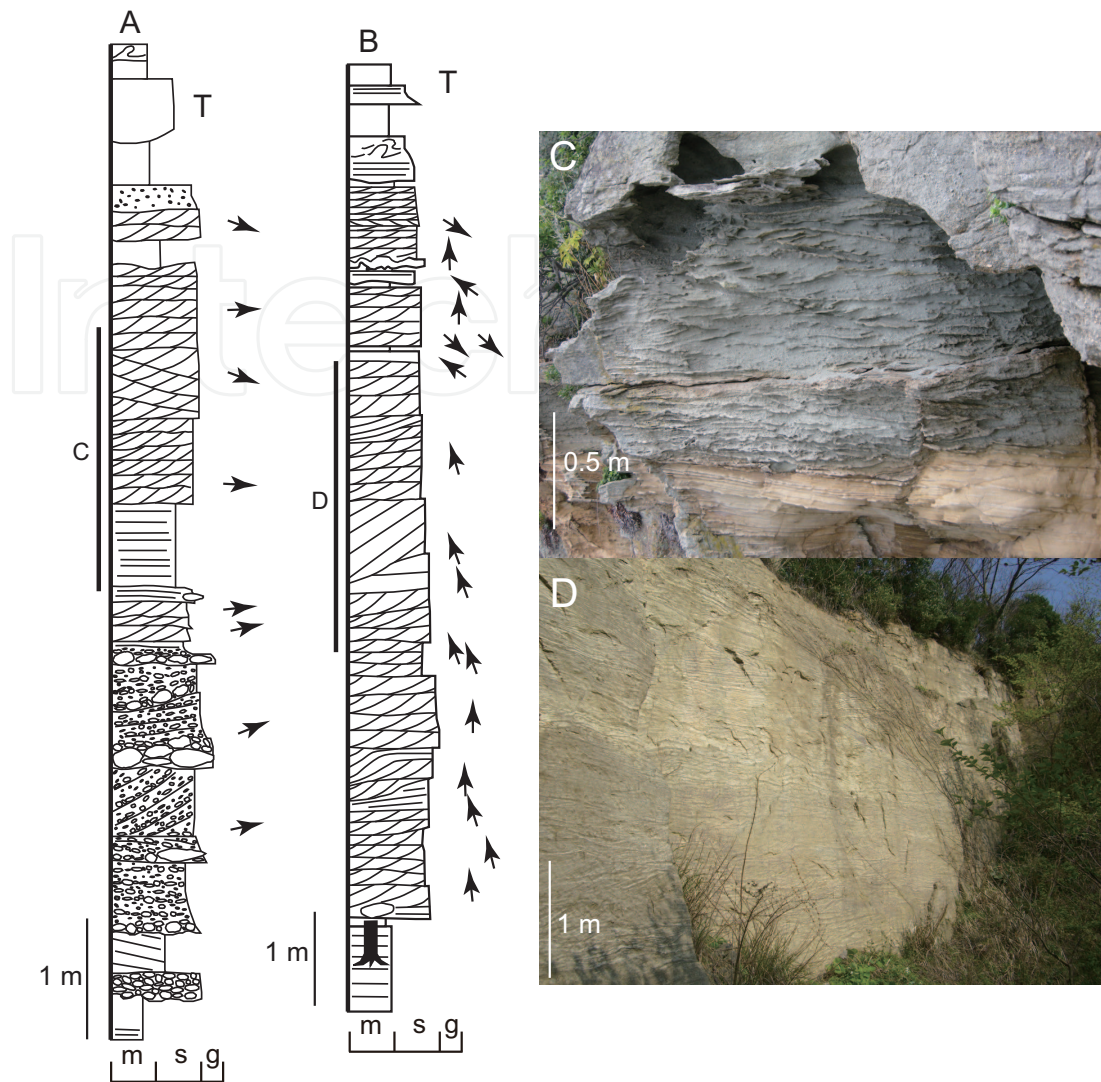


Figure 5. Columnar cross-sections of the event beds. Each event bed is interpreted as having been deposited from an outburst flood associated with a basin merger, followed by a lake-level rise (modified from [34]). A: event beds at the base of the middle Koura Formation. Arrows indicate the palaeoflow direction (up = north). B: event beds at the base of the upper Koura Formation. Both horizons grade upwards into the lake deposits containing turbidite (T) and slumped deposit. See Figure 7 for legend. C: outcrop photograph of a part of the event beds (cross-stratified beds) at the base of the middle formation. D: photograph showing the wide view of the event beds at the base of the upper Koura Formation.

deposits of the fan delta [34]. On the other hand, most of the cycle bases are represented by a surface covering a slumped deposit (Figures 6B–D). Each surface is undulating (i.e. erosional) (Figures 6B and 6D), and is then covered with facies beds shallower than those below the surface (Figure 6). Parts of the sediments just above the surface are also dragged into the slumped deposits in some places (Figure 6C), indicating that sediment accumulation above the surface occurred almost simultaneously with slumping. The sediment overlying the surface is then punctuated by the flooding surface (Figure 6), covered by a shallowing-upward succession. The cycle boundaries are, therefore, interpreted to have been formed by relative uplift of this area at the time of deposition.

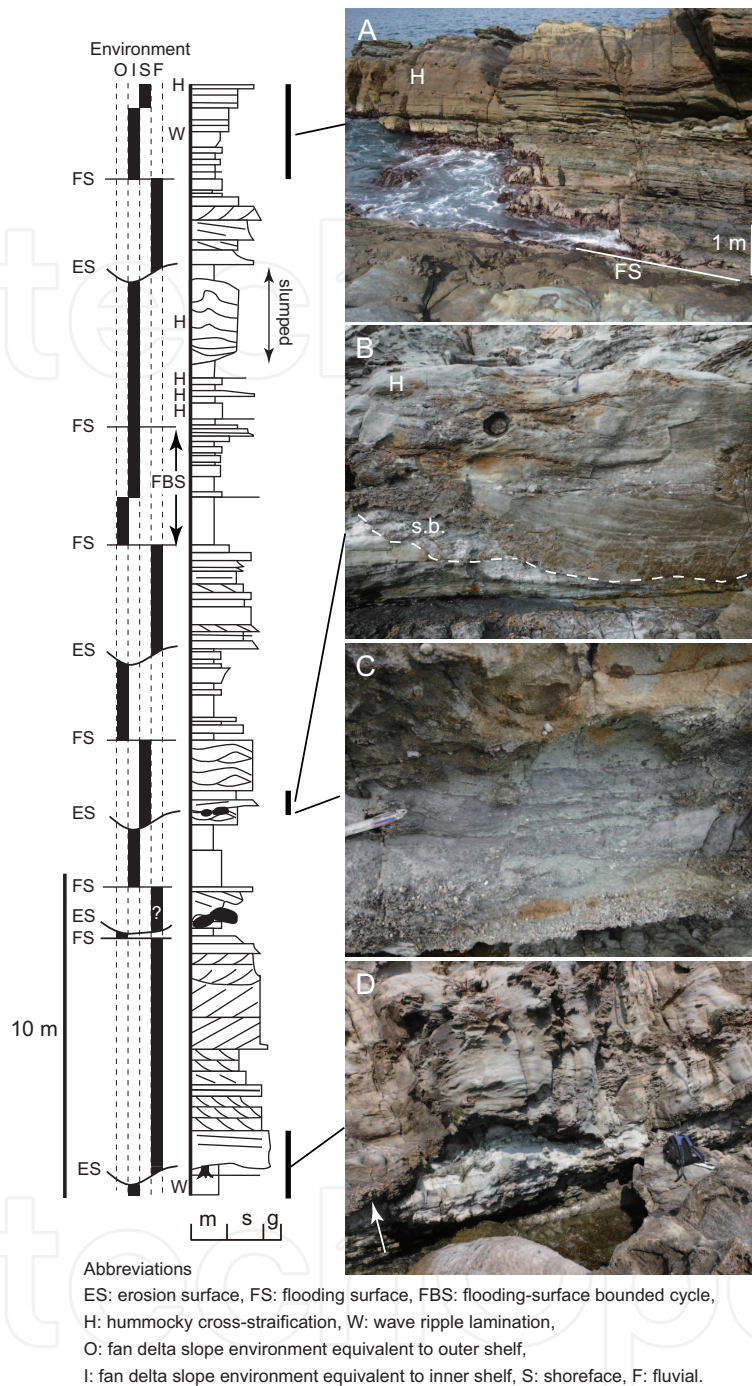


Figure 6. Columnar cross-section of a part of the upper Koura Formation and changes in depositional environment. A: a sediment cycle showing an upward-shallowing trend. The cycle base is represented by a flooding surface. B: an erosion surface truncating the inner shelf equivalent deposit, and is then covered with HCS sandstone beds of the shoreface origin. s.b.: slump block. Note the hammer for the scale. C: a close-up photograph of the sediment just below the erosion surface (cycle boundary). There are several slip surfaces of the slump in the sediments. Coarse-sediment grains, which can be found only above the surface, are also incorporated (probably dragged) into the slumped horizon. The scale is 0.2 m long. D: a basal erosion surface of the cycle, truncating the inner-shelf-equivalent deposit and being covered with fluvial channel deposit. The white arrow indicates the surface. See Figure 7 for the legend of the columnar section.

Such sediment cycles were not identified in the lower and middle formations. The detailed outcrop observations in the lower formation revealed that either the top or the base of the sandstone intervals (fluvial channel facies) is marked by a surface associated with minor sliding (Figure 7); the former case is the most common (Figure 7). The surface is then covered with a thin poorly sorted silty sandstone bed (up to 0.1 m thick)(Figure 7A). Some of the silty sandstone beds contain pebble-sized sandstone or mudstone clasts of the underlying beds (Figure 7). In some places, the very small syndepositional faults extending almost parallel to the bedding plane are recognized below the silty sandstone beds. The silty sandstone beds are then covered with a massive or a laminated mudstone bed of a small and shallow lake origin (Figure 7B), showing a lake-level rise immediately after the sliding event. The slide may have been associated with subsidence of the basin.

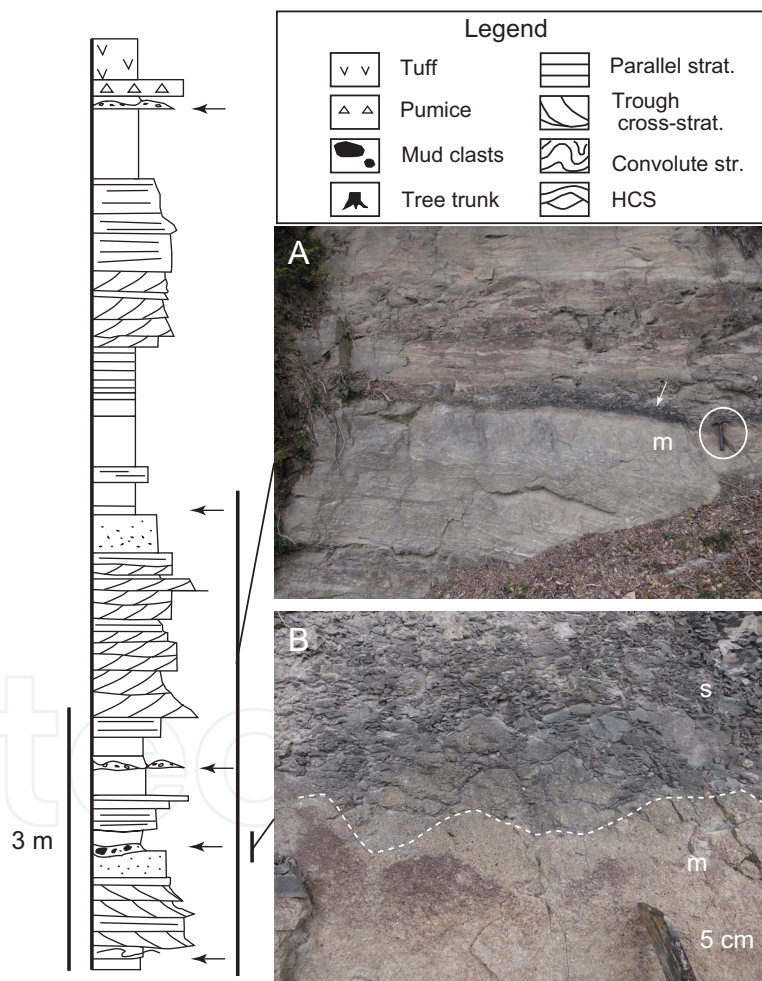


Figure 7. Example of the columnar cross-section of the lower Koura Formation taken along section 6. The arrows indicate the horizons showing evidence of a small-scale slide. A: outcrop view of the fluvial deposit. The arrow indicates the horizon of Figure 7B. The scale (hammer) is 0.3 m long. B: close-up photograph of the top of the fluvial channel fill sandstone beds. The dotted white line indicates the surface of the slide, which is then overlain by a silty sandstone bed with abundant sand clasts originating from the underlying sandstone bed. The scale (a part of the hammer head) is 0.05 m long. m: massive sandstone bed, s: shallow lake deposit, HCS: hummocky cross-stratification.

2.2. Examples from the East Africa rift valley

In the Kenya Rift, the Miocene rift basin-fill successions are exposed (Figure 8). The activity of the rift system started in the Oligocene and attained its maximum in the middle to late Miocene [41]. We targeted the half-graben fills exposed in the Samburu Hills, northern Kenya [42-44], and Nakali, central Kenya [45]. The target sediment successions of both areas (Namurungule and Nakali Formations) have not been classified into members based on the international stratigraphic nomenclature, although each formation can be divided into three units. Therefore the terms, the lower, middle and upper formations, are used for three units of each formation in the present study.

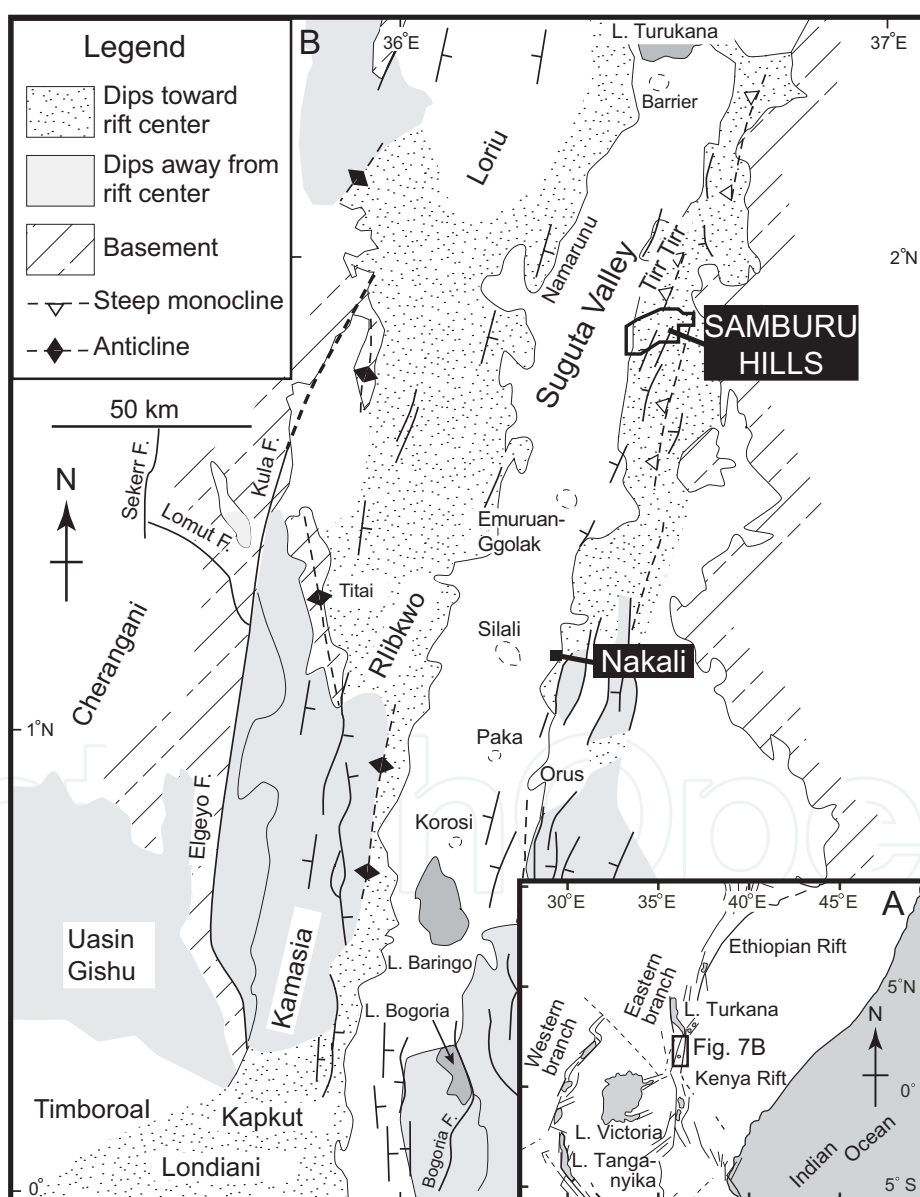


Figure 8. Location map of Samburu Hills and Nakali in central and northern Kenya.

a. Samburu Hills

Samburu Hills are located in the eastern shoulder of the eastern branch of the East African Rift Valley system, northern Kenya (Figure 8). The Nachola, Aka Aiteputh, Namurungule and Kongia Formations (ca. 20–5.3 Ma [43]) make up the Miocene succession, which covers the Precambrian Mozambique Belt rocks (gneiss and granitic rocks)(Figure. 9). The upper Aka Aiteputh to the Namurungule Formations’ phase (ca. 10–9.3 Ma) was one of the major rifting periods in this area, as suggested by the development of a series of small half-grabens, which is indicated in the geologic map as the scattered distribution of the Namurungule Formation [42] (Figure 9). Each formation body has a lenticular plan view and one or both sides of the body are punctuated by faults (Figure 9).

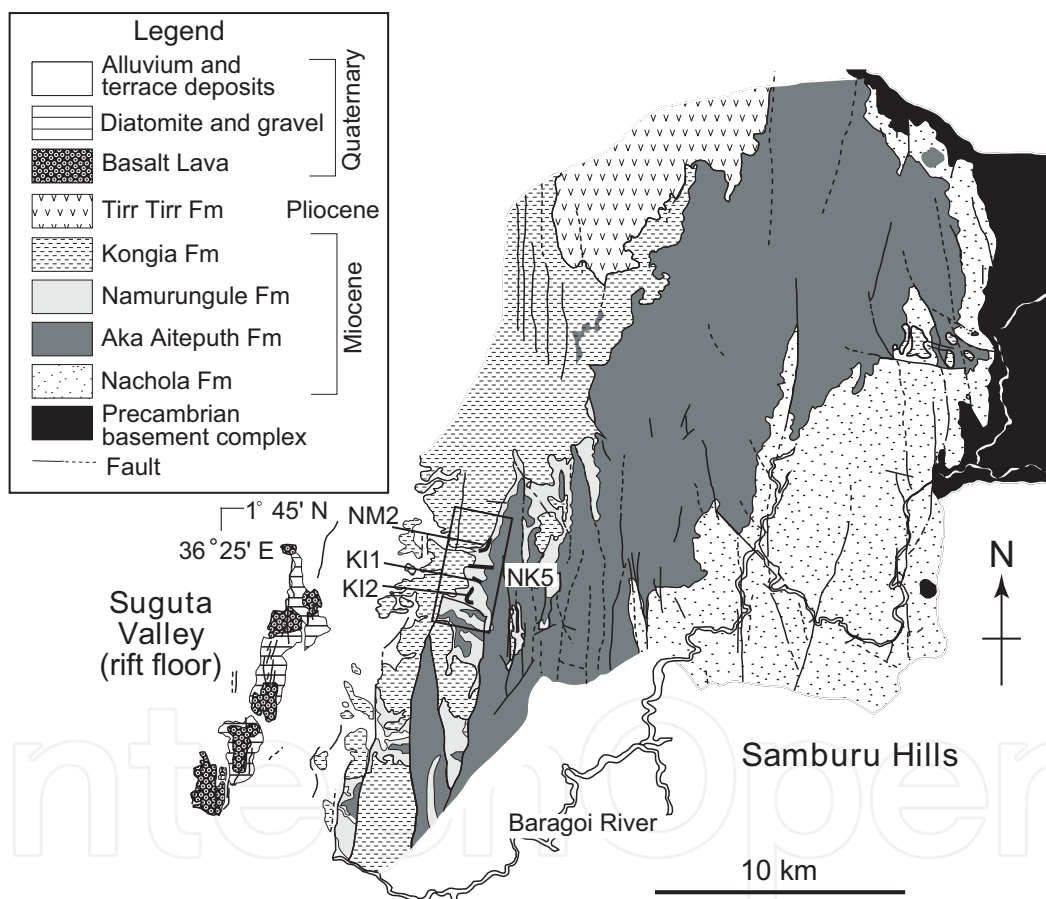


Figure 9. Geologic map of the Miocene in Samburu Hills. The enclosed part is the studied area. K11, K12, NM2 and NK5 are locations of columnar cross-sections in Figure 10.

The target basin has a lenticular shape extending N–S (Figure 9). Although the western margin of the basin is truncated by the overlying Kongia Formation— which is interpreted as having been deposited during the rejuvenated phase of the rift after 7 Ma (see [43])— the border fault of the basin runs in the western margin, as suggested by the Namurungule sediments thickening to the west [42]. There is a gap in fault location in the northern and southern halves

of this basin. In the earliest phase of basin evolution, there may have been an accommodation zone in the boundary between the northern and southern halves of this basin.

The northern half of the basin, where spectacularly well exposures allow sediment correlation among outcrops, was targeted in the present study. A half-graben fill consists of the upper Aka Aiteputh Formation, which is characterized by red soil beds with abundant calcrete layers and basalt lavas with basalt conglomerate layers [44]. The overlying Namurungule Formation consists of four parts: the basal conglomerate beds of alluvial fan origin, the alternations of tuffaceous mudstone and sandstone beds (mudstone-dominated) of the lower part (both parts form the lower formation) and an about 20-m-thick lahar deposit of the middle formation (Figure 10). The upper formation is represented by a pile of sediment cycles, each of which consists of a sandstone-dominated and an overlying mudstone-dominated interval, as mentioned below. The age of the Namurungule Formation ranges from 9.6 to 9.3 Ma [43], and the rapid sedimentation rate was estimated to be 1.52 m/ky for the lower formation and 0.24 m/ky for the upper formation [42].

From the viewpoint of sequence stratigraphy, the red soil beds and basalt lava interval of the upper Aka Aiteputh Formation and alluvial fan interval of the basal Namurungule Formation are interpreted as the LST; most of the lower Namurungule Formation, except for its basal and uppermost part, is the TST showing retrogradational succession. The remaining part is the highstand systems tract (HST) (Figure 10: see also [44]).

The TST is characterized by a rapid lateral facies change from the thick lake facies in the southern part to the terrestrial facies represented by the alternations of root-bearing mudstone and sandstone beds in the northern part. The up to 20-m-thick terrestrial sediments in the TST contain a few stream deposits represented by an up to 0.5 m of sheet sandstone beds with parallel and trough cross-stratification. Other sandstone beds in the terrestrial deposits are associated with temporary lake expansions, as suggested by the wave-generated sedimentary structures (wave ripple lamination and small hummocky cross-stratification) in sandstone beds [42] (Figure 11). There are local slide deposits, represented by pebble- and cobble-sized mudstone breccia in the succession (Figure 11).

On the other hand, the HST is represented by a pile of sediment cycles [42]. Each cycle consists, from the base to the top, of the conglomeratic sandstone beds of fluvial channel fill origin, root-bearing mudstone beds of floodplain origin, laminated mudstone beds of lake origin and tabular cross-stratified sandstone beds of delta front origin (Figure 12). The cycle boundaries are sharp and undulating, and truncate the underlying sediments (delta front and lake deposit) (Figure 12).

Individual cycles tend to thicken to the west, which are interpreted to be owing to tectonic subsidence in the western part of the basin. The basal surface truncates the underlying sediments in each cycle, indicating a lake-level fall probably because of the migration of lake water to the basin centre when the basin subsidence occurred (for example, [2]).

Petrographical analysis indicates that the sediments (feldspar and rock fragments, mainly basalt grains) were supplied only from the adjacent area during the deposition of the upper Aka Aiteputh and lower Namurungule Formations (Figure 10), showing the poor develop-

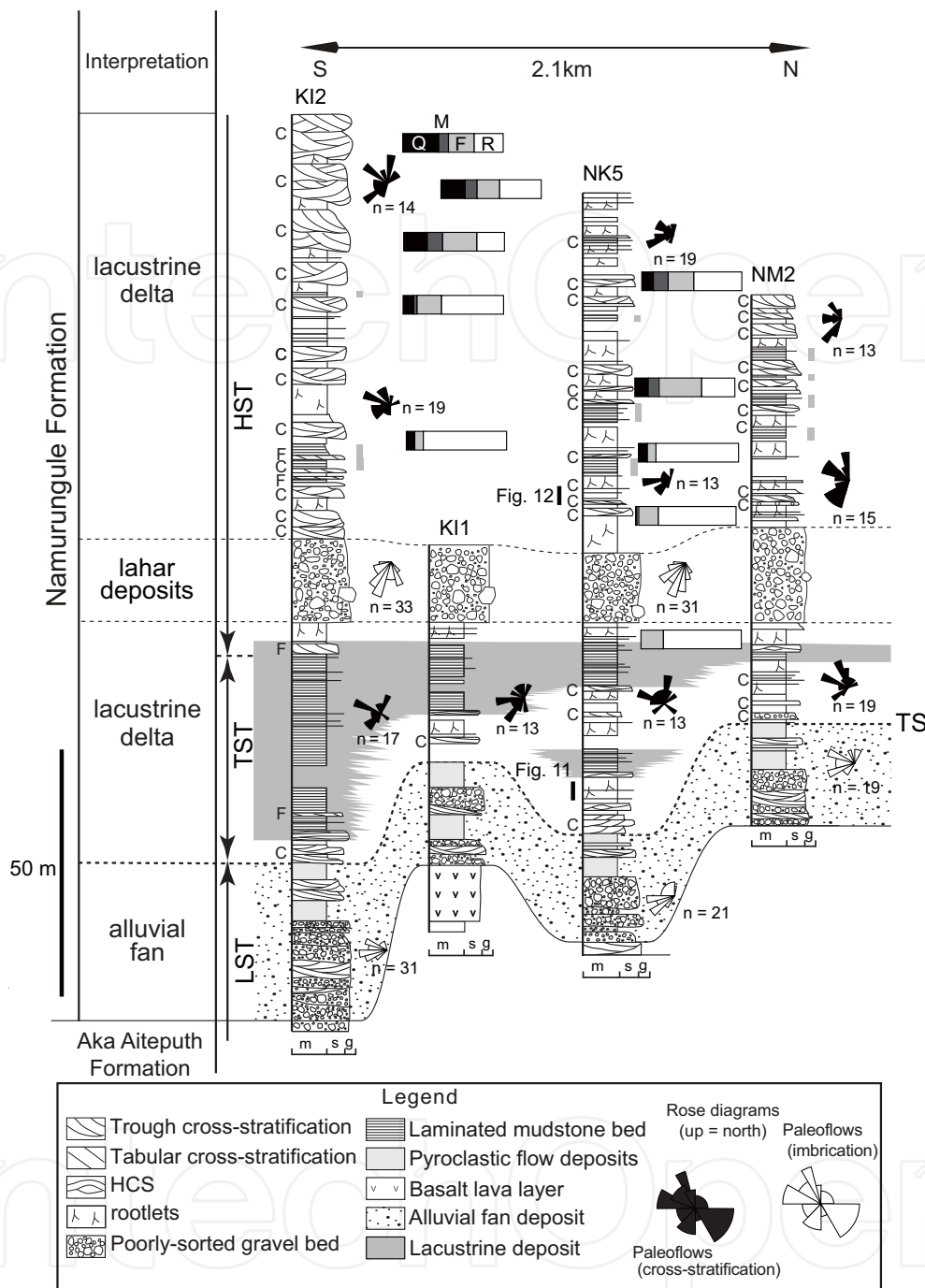


Figure 10. Columnar cross-sections of the Namurungule Formation (modified from [44]). Graphs indicate the petrographical analysis results. Grey bars indicate the horizons of lake deposits. C: fluvial channel fill, F: delta front deposit. Q: quartz, M: microcline, F: alkali-feldspar, R: rock fragment.

ment of the drainage system. On the other hand, the sediment grains in the upper formation supplied from the basement (Mozambique Belt), such as quartz and microcline, suggest that the drainage basin became wider through time [46]. This trend, later appearance of the grains originating from basement rocks, has been reported from other rift basins (for example, [46]).

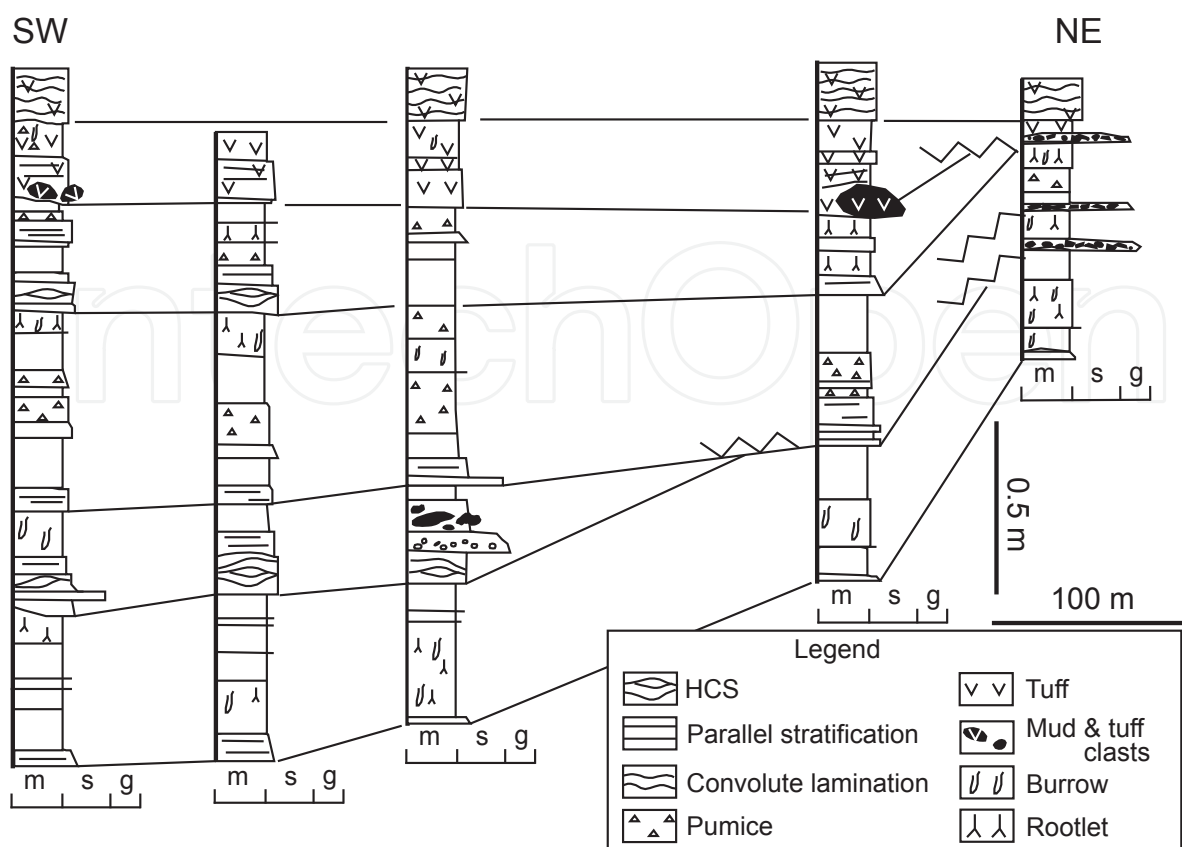


Figure 11. Example of the columnar cross-sections from the lower Namurungule Formation (modified from [42]). The zigzag line indicates an erosion surface that can be seen only in the northern part of the measured area.

b. Miocene Nakali Formation

Nakali is located about 50 km south of the Samburu Hills (Figure 8). The Miocene Nakali and Natorut Formations are distributed in this area [45] (Figure 13). The lower part of the lower Nakali Formation is characterized by the alternations of tuffaceous sandstone and mudstone beds, which are interpreted to be turbidite and slumped deposits (delta front deposit), and the overlying thick lapilli tuff beds that bury the lake (Figure 14). The fluvial channel fill, floodplain and shallow lake deposits (conglomerate, tuffaceous sandstone and mudstone beds) characterize the upper part of the lower formation. The middle formation is represented by thick pyroclastic flow deposits (ca. 40 m). The lower part of the upper formation shows sediment characteristics similar to the upper part of the lower formation. The upper part of the upper formation is represented by tuffaceous mudstone beds and conglomerate and sandstone interbeds with slump structures. The slumped deposits in this interval indicate that this is of the lake slope origin (Figure 14). One of the important hominoid fossils, *Nakalipithecus* [45], was discovered near the top of this interval. In terms of sequence stratigraphy, most of the formation forms the LST—except for the upper part of the upper formation, where deeper lake mudstone facies predominates. This part is interpreted as the TST. The Nakali Formation is then overlain by trachitic or basaltic lava and volcanoclastics of the Natorut Formation (Figure 14). The magnetostratigraphic reversed polarity zone in the middle portion of the Nakali

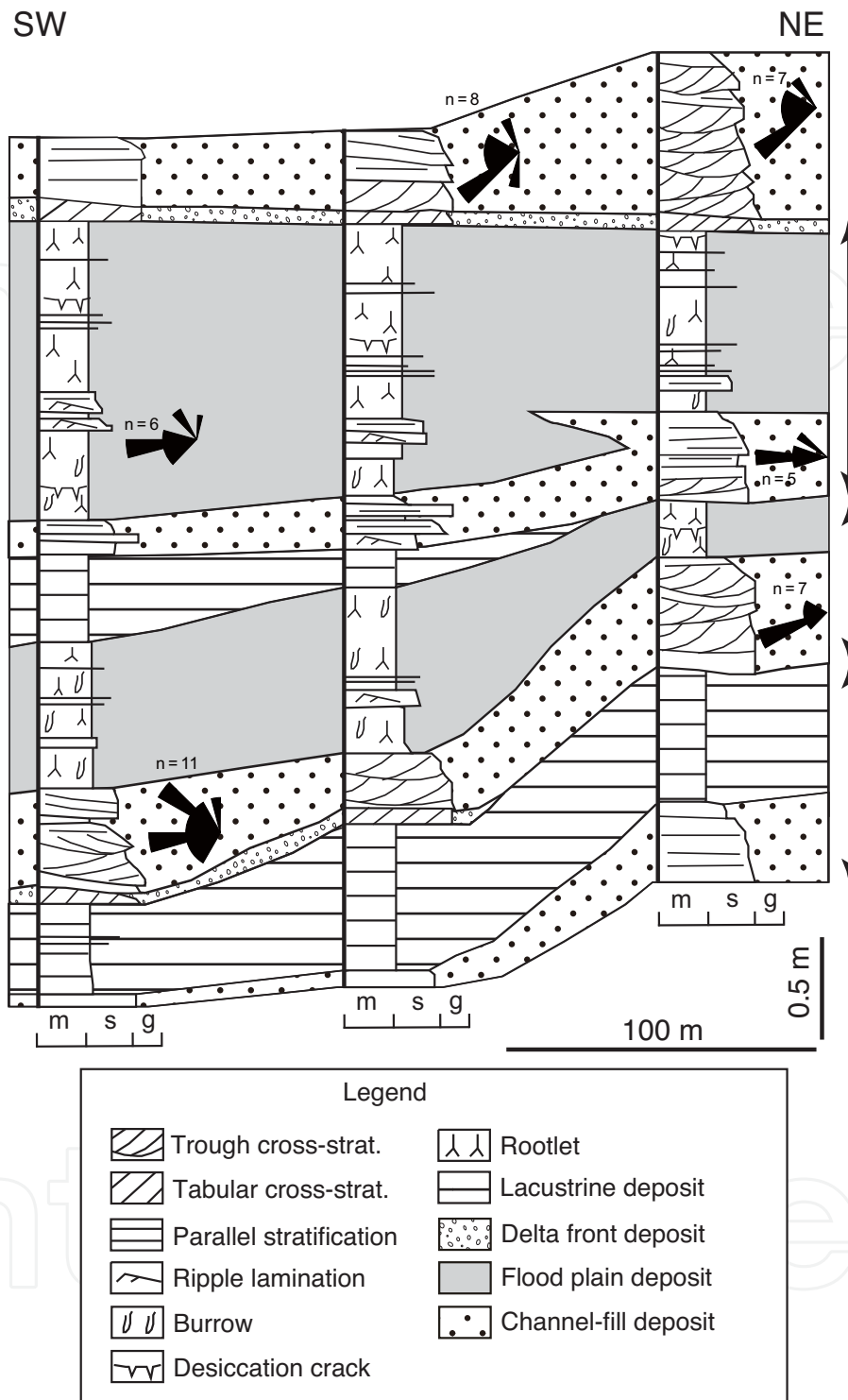


Figure 12. Example of the columnar cross-sections from the upper Namurungule Formation (modified from [42]). The arrowed intervals show individual cycles. The rose diagrams indicate palaeoflow directions shown by cross-stratification (up = north).

Formation was correlated to the Chron C5n.1n (9.88–9.74 Ma [46]) on the basis of the Ar–Ar ages [45].

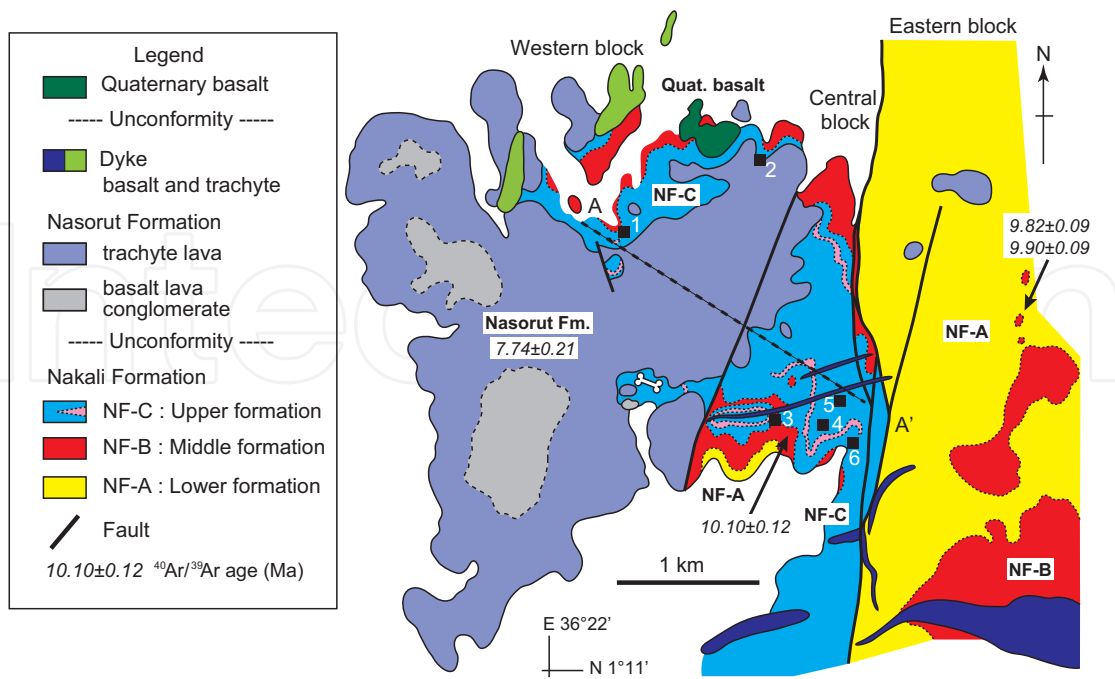


Figure 13. Geologic map of the Nakali Formation (modified from [45]). A-A' is the trend of the columnar cross-sections obtained from locations 1–6 in Figure 15.

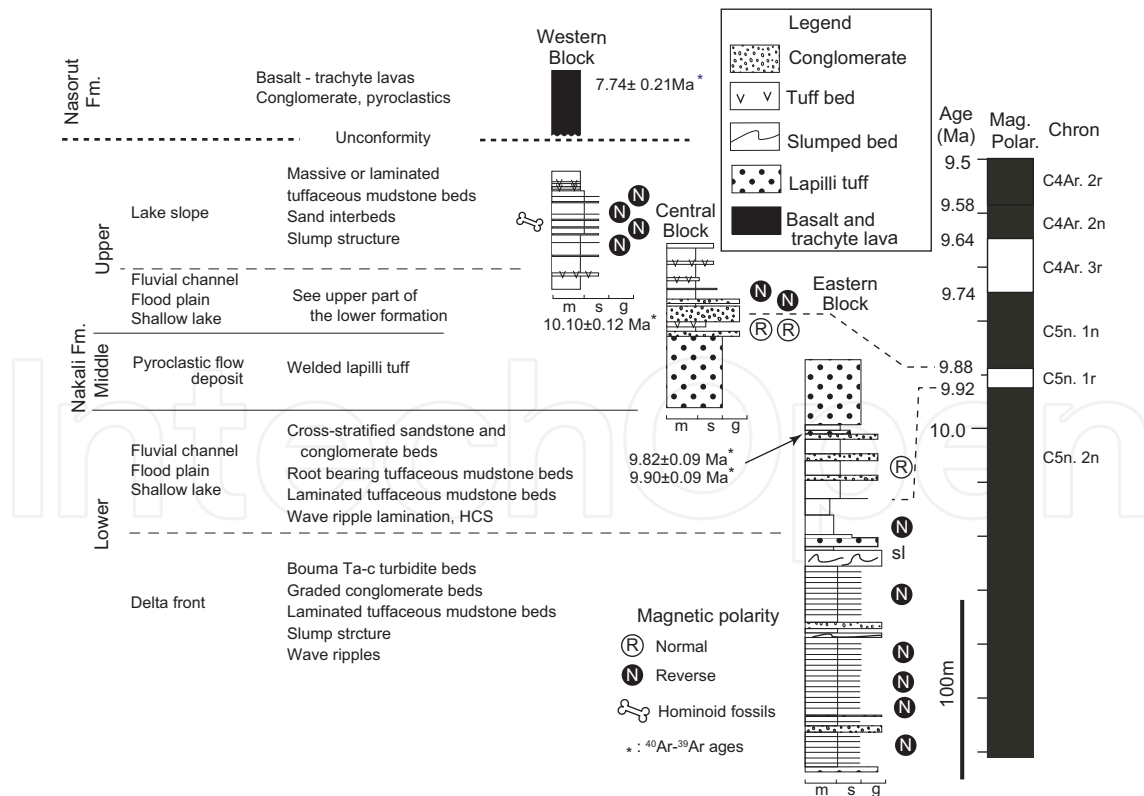


Figure 14. The generalized litho- and chronostratigraphy of the Nakali and Nasorut Formations (modified from [45]) and facies description and interpreted depositional environments.

Two normal faults extending N–S separate the rocks of this formation into three blocks (eastern, central and western) (Figure 13). The displacement of the eastern fault is larger than those of the others and is estimated to be about 200 m on the basis of the altitude gap of the middle formation between the eastern and central blocks.

c. Subsidence history of the upper Nakali formation

The good exposures of the lower part of the upper formation and the frequently interbedded tuff beds allow observation of lateral facies changes in the field within and among blocks (Figure 15). Six tuff beds were identified in this horizon, and are named Twin (two white tuff beds), Exo (white tuff bed containing abundant trachyte fragments), Pum (pumice tuff), Fu (poorly sorted pumice tuff bed), Mfu (poorly sorted pumice and accretionary lapilli tuff bed) and Ma (white tuff bed containing accretionary lapillis) (Figure 15). The thick cemented beds with weakly weathered soil beds (termed ‘terrace forming bed’ in Figure 15, because this bed forms a wide terrace in this place); the White beds, represented by the sandstone and conglomerate beds rich in small breccia of white tuff, and the Red beds, characterized by red conglomerate and sandstone beds of fluvial channel fill and floodplain origin (Red beds), can be used for the correlation as well. The bases of the lake deposits, flooding surfaces, were also used as one of key horizons (Figure 15).

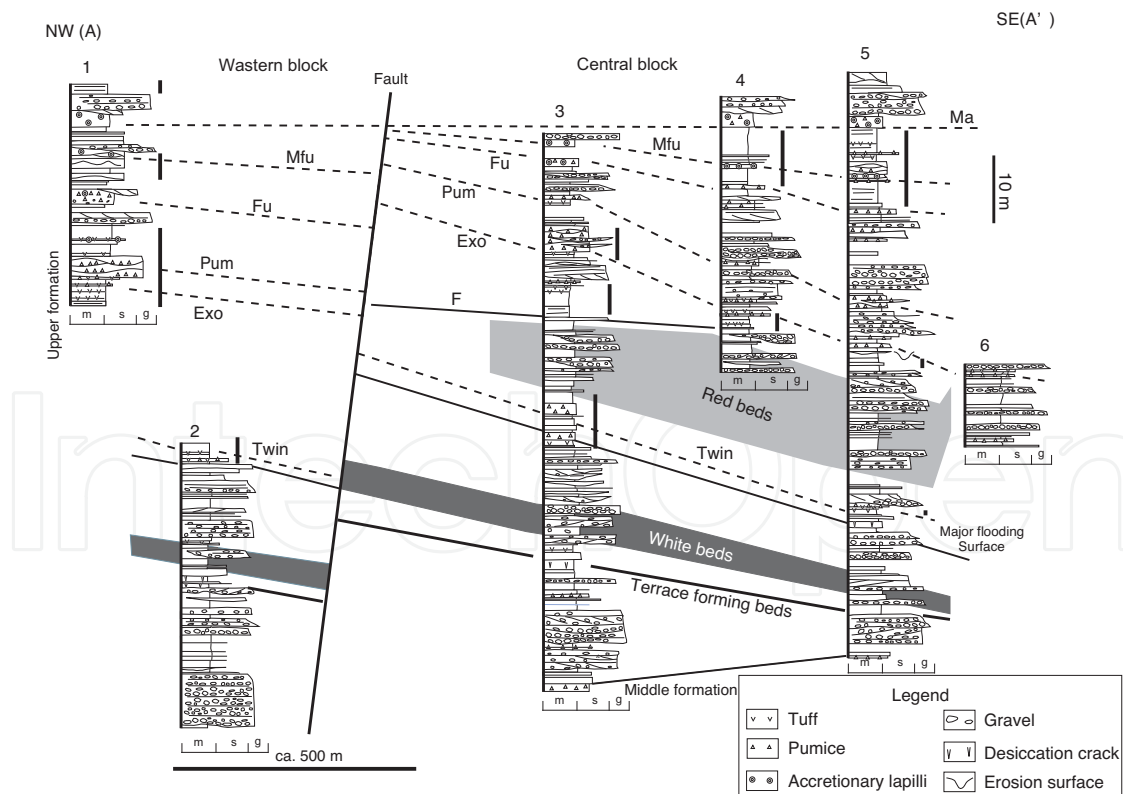


Figure 15. Columnar cross-sections of the lower part of the upper Nakali Formation. The black bar indicates the horizon of lake deposit. The dotted and solid lines indicate correlated tuff beds and flooding surface, respectively. A bold line indicates “the terrace forming bed”. See text for tuff names. F: local flooding surface.

The correlation results (Figure 15) show thicker sediments in the western part of the central block below the Twin Tuff bed. The thickness of sediments between the base of the upper formation and Twin Tuff bed consistently increases from section 5 to section 2, even though section 2 is located in the west of the fault separating the western and central blocks. This may show that the fault was inactive before the Twin Tuff deposition, and another fault, which is not indicated on the geologic map and is running west of the study area, was active instead.

Thickness of the sediments between the Twin and Pum Tuff beds is almost constant in the central block. However, the Red beds tend to be thicker to the east, and the sediments between the local flooding surface (F in Figure 15) and Exo Tuff bed tend to be thicker to the west, suggesting a temporary seesaw subsidence during the deposition between the Twin and Pum Tuff beds (Figure 15).

The sediments above the Pum Tuff bed (Figure 15) tend to be thicker in the eastern part of the central block. This thickness change and the appearance of the thicker lake deposits in the eastern part clearly indicate that the depocentre was shifted in the eastern part of the basin. The seesaw subsidence seems to have ceased just before the Pum Tuff deposition. The thicker sediments to the east indicate that the fault separating the central and eastern blocks may have been formed in this phase. Note the thickness variation between the Pum and Ma Tuff beds—which tend to be thicker from section 3 to 5, but have thicker sediments in the same horizon in section 1, indicating larger subsidence around section 1 than section 3. This suggests that the fault separating the central and western blocks also became active after the Pum Tuff bed deposition.

Such a seesaw subsidence pattern suggests that the study area was located on the accommodation zone [3, 5] during the deposition of the lower part of the upper Nakali Formation. The Case C fault linkage and accommodation zone proposed in [5] (Figure 1) is inferred for this case.

Seesaw subsidence was reported from the Santo Domingo Basin in the Rio Grande Rift system [3], which has been long lived from the Oligocene to Pleistocene, because of changes in the shift of the active part of the faults forming the accommodation zone. This study showed a gradual facies shift because of such long-term seesaw subsidence (Figure. 8 in [3]). In case of the Nakali Formation, the movement's scale is much smaller and shorter than the case in [3]. This seesaw subsidence may have been related to the development of the block-bounding faults, which propagated either from the south or north. Such a temporary seesaw subsidence pattern may be the typical subsidence pattern of the Case C accommodation zone (Figure 1) when the zone is incorporated into a larger basin because of the merger of smaller basins. This result additionally suggests that the constant thickness sediments within a half-graben fill could be the consequence of the seesaw subsidence happening in a short period.

3. Discussion

3.1. Effects of supply mainly by pyroclastic fall on stratigraphic architecture

Samburu Hills provide a good example of a basin that was strongly controlled by sediment supply from pyroclastic fall. The target basin did not seem to experience a complicated tectonic history during the Namurungule phase (interaction with another basin, such as a basin merger) like other examples, so it is a suitable place to discuss the contribution of fine volcanoclastics supplied by falls or streams on stratigraphic architectures. Because the border fault of this basin runs along the centre of the rift basin, sufficient sediment supply from the footwall slope would not have been expected, and the basin should have been starved in terms of sediment supply (particularly siliciclastic sediments). However, the supply by pyroclastic fall or by streams that transported reworked pyroclastic fall sediments to the lake contributed to the high rate of sedimentation. The total thickness of the lake deposit (TST) at the southern end of the study area becomes almost double that at the northern end of the basin. This suggests that the newly formed accommodation space was rapidly filled even near the basin centre.

The presence of different systems tracts within a half-graben in the same period was expected on the basis of computer simulations [18]. The study simulated marine basins, but its results are also applicable to continental basins, except for a different response of the lake- or sea-level changes compared with the tectonic subsidence (see [21]). As expected in [18], a high rate of sediment supply might have resulted in a progradational stacking pattern in the northern end of the target basin, where the subsidence rate was small. The absence of the progradational unit in this place can be explained by dispersion of the eroded sediments into the basin due to the larger mobility of fine volcanoclastics. However, we need more tests to evaluate the effect of the higher mobility of volcanoclastics compared with siliciclastic sediments on the stratigraphic architecture.

Another two basin sediments (Koura and Nakali Formations) were dominated by volcanoclastics, and show high sedimentation rates [44-45]. The high-resolution tectonics related to basin evolution are discussed as follows.

3.2. Record of basin mergers

Both Koura and Nakali Formations record that terrestrial or shallow lake environments were finally changed to deep-water environments (Figures 4 and 14) after several periods of rapid environmental change. As mentioned in Sakai et al. (2013), it is highly possible that the Koura Formation experienced at least two periods of outburst floods and subsequent lake-level rise as a result of merging basins.

The major flooding surface of the upper Nakali Formation is also interpreted as having been associated with a basin merger event. The hummocky cross-stratified beds and conglomeratic sandstone interbeds just below the flooding surface may be a record of strong waves and currents just before this basin was deeply submerged (Figure 16). Another basin merger event is expected to have occurred when the subsidence centre jumped from the western to eastern part of the central block around the deposition of the Pum Tuff bed. However, distinct evidence

of basin merger cannot be found in the sediments. This was probably because of lower topographic relief in the accommodation zone (Figure 1), which was not high enough to cause the major shift in lake water when two basins were merged.

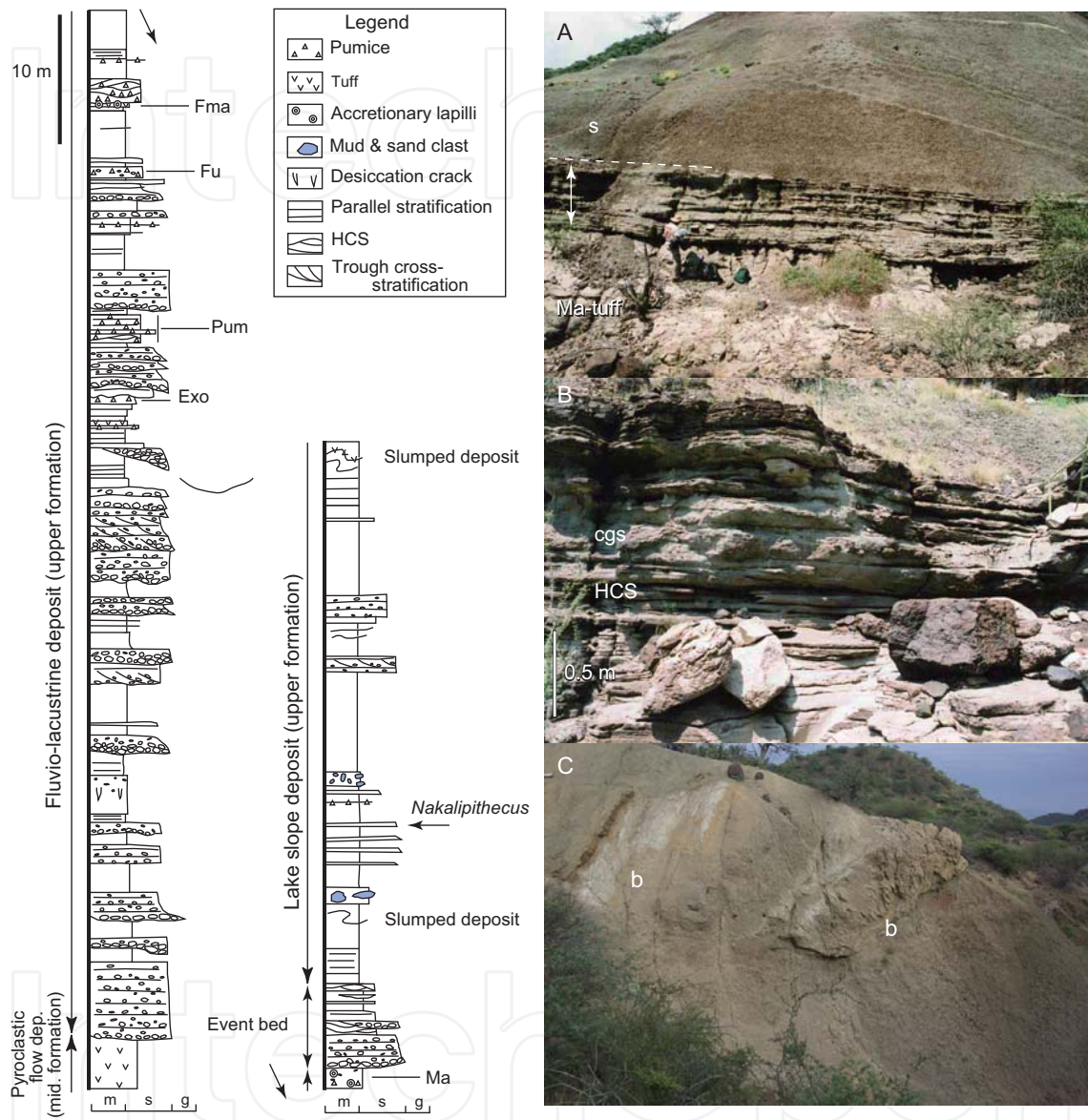


Figure 16. Example of the columnar cross-section of the upper formation, showing the boundary of the upper and lower halves of the upper formation. A concave-up solid line indicates an erosion surface. A: outcrop photograph of the boundary of the lower and upper halves of the formation. B: close-up photograph of the boundary. HCS: hummocky cross-stratification, cgs: conglomerate beds, s: slope deposit. C: an example of the slumped beds in the upper half of the upper formation. b: large slump block.

The process of the basin merger and related basin fill has been modelled in some previous studies [4, 16], which emphasized the hydraulic connection between two adjacent basins after one basin reached the over-filled condition (see [19]). In the present examples (Koura and Nakali cases), each event seems to have been related to the outburst flood and associated with

a rapid deepening event. Both basins finally submerged into the Japan Sea or deep lake in short periods, implying a high subsidence rate in these basins. Therefore, the tectonic merger of the basins (i.e. connection of border faults of adjacent basins) is strongly expected for these cases. Because the Japan Sea was opened rapidly during the middle Miocene, evidence of such basin mergers is expected to be found from many basins along it.

3.3. Appearance of cycles in the upper Koura and Namurungule formations

In the Namurungule and Koura Formations, sediment cycles appear in their upper parts [34, 44]. Similar types of cycles have been reported from other areas, and some of the cycle formation was explained simply by migration of the fluvial system ([47]). Strong pulse of pyroclastic sediment supply could form small cycles as well. The Namurungule case, thickening of individual cycles to the west, indicates that the cycle formation is controlled by subsidence within the basin [42].

The Koura Formation example shown here is only a one-dimensional section, and is not enough to discuss the origin of the cycles. However, some of the erosion surface formation is clearly associated with tectonics. The shallower facies covering basal cycle surfaces without sedimentation gaps (Figures 6B and 6C) implies a lake-level fall induced by a relative uplift against the basin centre around the measured section. Although it is impossible to know the quantity of the relative uplift, the estimated uplift might be a few metres on the basis of the facies gap above and below the surface. The formation of the flooding surface and some of the cycle boundaries may be related to eustatic sea-level rise and fall.

On the contrary, both formations do not contain such cycles in their lower and middle parts. The lower parts of both formations, however, show evidence of small-scale sliding in the sediments (Figures 7 and 11). There is a small gap in the environment above and below the slide interval of the lower Koura Formation, indicating that a small-scale subsidence occurred. However, the subsidence was not of sufficient amplitude to form a cycle boundary like the case of the upper formation.

This matches with the general understanding of the rift basin evolution, where the displacement of the border fault becomes larger through the basin enlargement (for example, [14, 16]). The absence of the poorly developed drainage system also contributed to the absence of sediment cycles in case of the Namurungule Formation, because streams do not have enough strength to form an erosion surface when the relative uplift occurred. Therefore, the earliest phase of the rifting is not favourable for generating small sediment cycles related to tectonics because of smaller fault displacement.

The Nakali Formation does not contain such small sediment cycles, which indicates that the uplift or subsidence associated with fault displacement was not distinct in this place. Because the area we observed may have been situated near the accommodation zone when the upper formation was deposited, the fault displacement causing subsidence/uplift may have been smaller than that near the basin centre and was not enough to form sediment cycles.

4. Conclusions

Three examples of the early rift basin fills from the Koura Formation in SW Japan, and from the Namurungule and Nakali Formations in central and northern Kenya, have been indicated. The three basin fills consist mainly of volcanoclastics and are represented by rapid sediment accumulation. The Namurungule Formation's succession may be strongly affected by the wide dispersal of volcanoclastics in the lake resulting in a single systems tract within the basin, although a progradational unit is expected to be formed from the marginal part of the basin with a smaller subsidence rate during the TST formation in the central part of the basin. The longer-lived Koura and Nakali Basin fills may record basin merger events followed by lake-level rises probably associated with tectonic basin mergers. The appearance of the cycles only in the upper part of the Koura and Nakali Formations is interpreted to have been associated with the larger displacement of the border faults than when their lower and middle parts were deposited. Absence of the cycles in the lower part of the upper Nakali Formation can be explained by insufficient relative uplift/subsidence of the basin for cycle formation.

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