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The role of inherited crustal structures and magmatism in the development of rift segments: Insights from the Kivu basin, western branch of the East African Rift

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ABSTRACT

The study of rift basin's morphology can provide good insights into geological features influencing the development of rift valleys and the distribution of volcanism. The Kivu rift segment represents the central section of the western branch of the East African Rift and displays morphological characteristics contrasting with other rift segments. Differences and contradictions between several structural maps of the Kivu rift make it difficult to interpret the local geodynamic setting. In the present work, we use topographic and bathymetric data to map active fault networks and study the geomorphology of the Kivu basin. This relief-based fault lineament mapping appears as a good complement for field mapping or mapping using seismic reflection profiles. Results suggest that rifting reactivated NE-SW oriented structures probably related to the Precambrian basement, creating transfer zones and influencing the location and distribution of volcanism. Both volcanic provinces, north and south of the Kivu basin, extend into Lake Kivu and are connected to each other with a series of eruptive vents along the western rift escarpment. The complex morphology of this rift basin, characterized by a double synthetic half-graben structure, might result from the combined action of normal faulting, magmatic underplating, volcanism and erosion processes.

1. Introduction

The western branch of the EARS consists of a series of elongated half-graben basins, which developed in a Precambrian basement and which are separated from each other by transfer zones (e.g., Ebinger, 1989a,b; Morley, 1989; Lærdal and Talbot, 2002; Corti et al., 2007). The Kivu rift, corresponding to the central part of the western branch of the East African Rift System (EARS), differs from other rift segments. First, it is flanked by large volcanic provinces, namely the Virunga Volcanic Province (VVP), in the north, and the South Kivu Volcanic Province (SKVP), in the south (Fig. 1). Next, Lake Kivu shows a complex shape subdivided into five basins, including two elongated ones separated by the central Idjwi Island. Additionally, irregular shorelines are observed, along which several minor islands extend topographic ridges into the basin. This complex lake shape is assumed to result from the combination of a rift depression and a former hydrologic system that flowed northward. The system was flooded due to natural damming by the Virunga lavas (Boutakoff, 1933; Peeters, 1957), triggering a lake-level rise and a southward flowing of the Kivu waters, towards Lake Tanganyika (Hecky, 1978; Ross et al., 2014). As highlighted by Wood et al. (2015), this latest stage in the evolution of the Kivu basin is very recent. Recent studies date the main lake level rise at 12.2 ka BP (Zhang et al., 2014) and the first deposition, in Lake Tanganyika, of sediments coming from Lake Kivu at 10.6 ka BP (Felton et al., 2007). Finally, the Kivu rift segment is located in the centre of a regional topographic uplift called the Kivu dome (Fig. 1b), which is possibly related to melting and lithospheric thinning processes in the mantle (Chorowicz, 2005; Wallner and Schmeling, 2010; Schmeling and Wallner, 2012) or to a local effect of the mantle upwelling located beneath the Tanzanian craton (Furman and Graham, 1999).

Several geological and structural maps of the Kivu rift exist in the scientific literature (Boutakoff, 1939; Degens et al., 1973; Pouclet, 1977; Villeneuve, 1978, 1980; Ebinger, 1989b; Yamba, 1993; Wood et al.,

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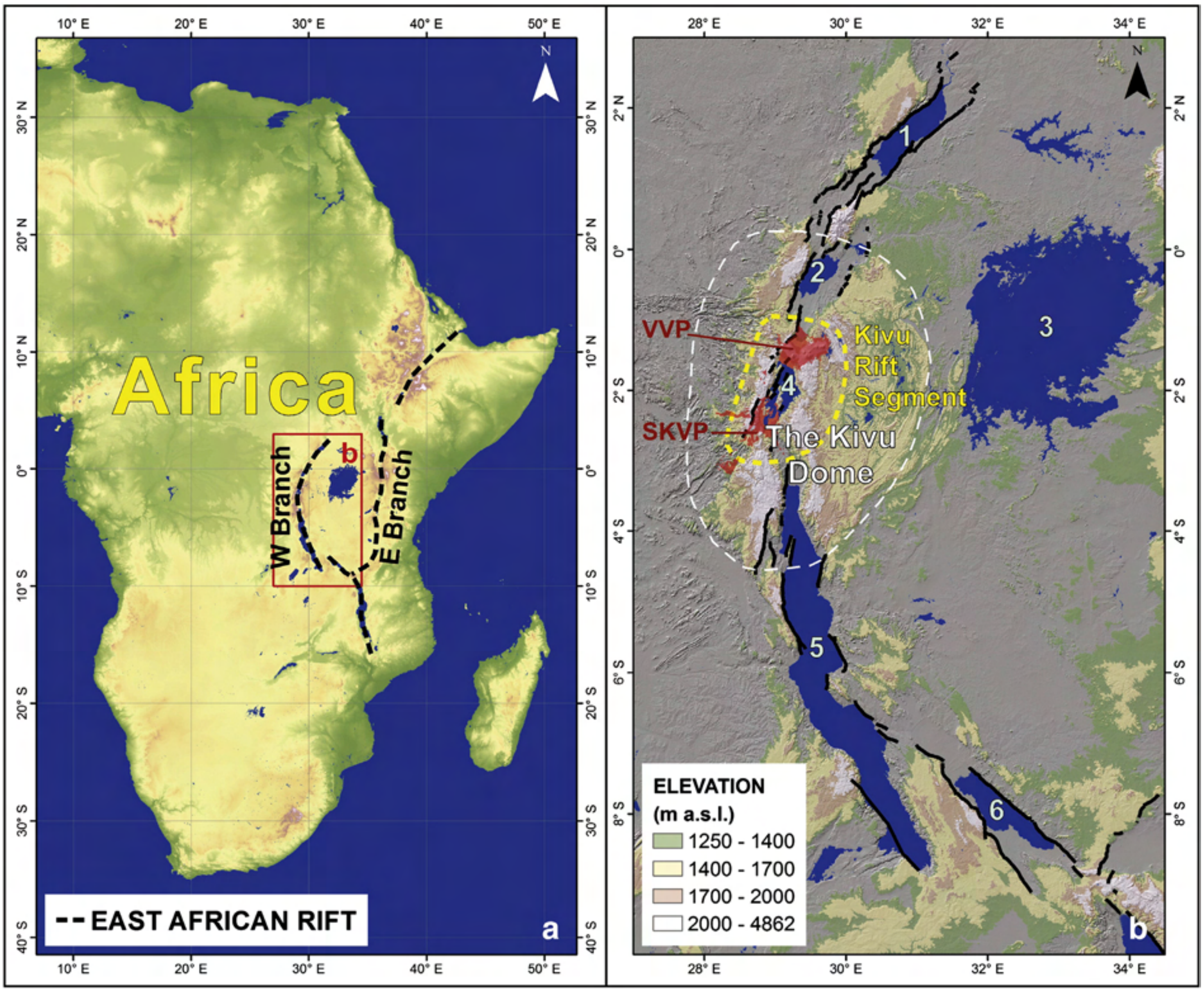

Fig. 1. Location of the Kivu rift segment within the East African Rift System (EARS). Frame "a" shows the location of the EARS in the African continent and its separation into two branches. The black dashed lines highlight the rift valleys. Frame "b" zooms into the western branch of the EARS. The Kivu rift segment is surrounded by a yellow dashed line. Red areas are volcanic provinces surrounding the Kivu basin, namely the Virunga Volcanic Province (VVP) and the South Kivu Volcanic Province (SKVP). The white dashed line highlights the presence of a topographic zone, called the Kivu Dome; centred on the Kivu rift segment. The black lines are the main rift fault escarpments mapped according to the topography on the SRTM-3 DEM (NASA) and the mapping of Ebinger (1989a). 1 = Lake Albert; 2 = Lake Edward; 3 = Lake Victoria; 4 = Lake Kivu; 5 = Lake Tanganyika; 6 = Lake Rukwa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2015). Rift faults on these maps were mostly mapped using photo-interpretation of aerial and satellite optical images, sometimes complemented with field observations. However, these fault maps often differ from each other (e.g., Fig. 2), which makes difficult to interpret the geodynamic context. Besides insecurity and recurrent civil unrests, which most of the time prevent ground-truthing of observed fault lineaments, the main difficulties in neotectonic fault mapping in the Kivu region are the strong weathering and erosion rates, landslides along rift flanks and sometimes vegetation. In addition, faults in the Kivu rift depression are mostly hidden by the presence of Lake Kivu's waters and recurrent lava flows resurfacing in the VVP. Hence, the contact between these surfaces and the main highly eroded rift escarpments does not necessarily represent the exact position and orientation of the main rift faults.

A better understanding of the fault distribution in the Kivu segment is however required, as active faults play a role in the distribution and occurrence of the main natural hazards encountered in this region, i.e. landslides (e.g., Moeyersons et al., 2004; Trefois et al., 2007), earthquakes (e.g., d'Oreye et al., 2010; Mavonga et al., 2010) and volcanism (e.g., Wadge and Burt, 2011; Smets et al., 2015). In the present work, we propose a new mapping of fault escarpments, as well as a geomorphological and structural analysis of the Kivu rift segment. Fault lineament mapping was realized independently of existing mappings, using digital elevation models (DEM) and two sets of bathymetric data. This mapping was restricted to straight escarpments that clearly suggest the existence of faults. However, we preferred the term "fault lineament", which is here defined as the surface expression of a potential or confirmed fault at depth. The main lithologies were locally mapped using field data available in the scientific literature and changes in the topographic texture. The fault mapping technique was validated in the southern lake Edward basin and in the eastern part of Lake Kivu using mappings of Nicholas et al. (2015) and Wood et al. (2015), respectively. Results were compared with other existing fault maps, with the aim of re-interpreting active fault networks and the local geomorphology that characterize the Kivu rift. Finally, implications for rifting processes and volcanism are discussed.

2. Material and methods

2.1. Topographic analysis

In this work, we used the SRTM-1 DEM (~30 m/pixel; NASA/NGA; Farr et al., 2007), and two sets of bathymetric data. In the vicinity of the Kabuno Bay, a DEM derived from the TanDEM-X SAR imagery (Albino et al., 2015) was used to interpret topographic features missing in the SRTM-1 DEM. The first bathymetric dataset was acquired between March and October 1998 over the entire Lake Kivu (blue area in Fig. 3)

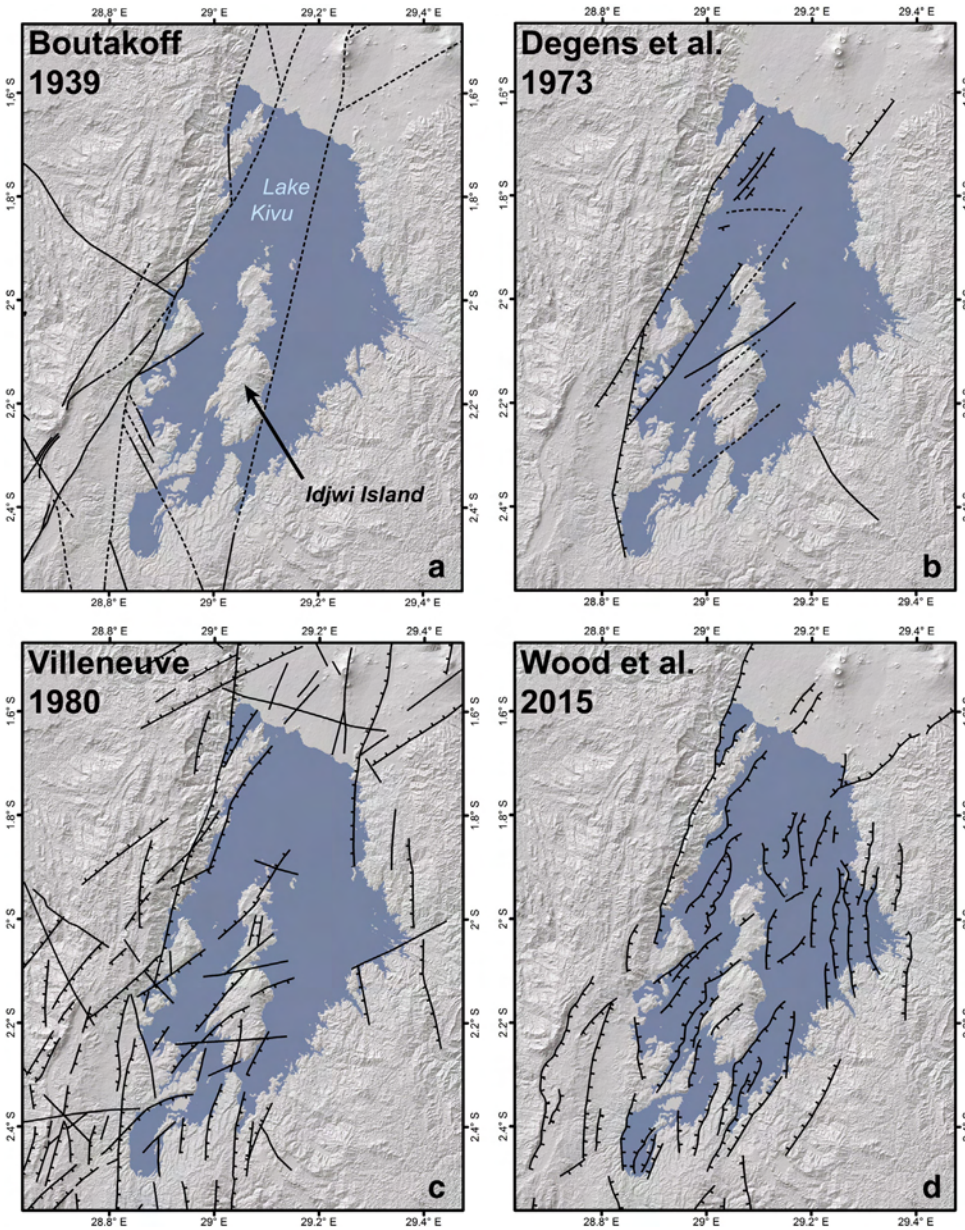

Fig. 2. Comparison of different structural maps available in the literature. This Figure illustrates the diversity of fault networks and orientations, depending on the map used. Ticks along fault lines indicate the dipping, when reported. Dashed lines are probable faults.

and was exported into a 10 m grid. Data acquisition and processing methods are detailed by Lahmeyer and OSAE (1998). Unfortunately, E-W striping artefacts affect this dataset, which makes the interpretation of small reliefs difficult. In order to reduce the impact of these anomalous values in images, the 1998 bathymetry was smoothed using a low-pass 3×3 pixels filter. The second bathymetric data set was acquired in October 2010, using a 50 kHz high-resolution system, and covers the major part of the Lake Kivu northern basin (red area in Fig. 3). Data were exported into 5 and 10 m grids. Ross et al. (2014) give more information about the data acquisition and processing of this bathymetry.

Two types of images were derived from the DEM and the bathymetric data, i.e. hillshade and slope images. Hillshade images (or shaded reliefs) allow an apparent 3D visualization of the relief, using an artificial sun-like lightning for which the user determines the elevation and azimuth. Indirectly, hillshade images also provide information on slope aspects. This kind of images helps interpret the structural and morphological characteristics of the relief, but may be misleading depending on the chosen illumination. In order to avoid as much as possible misinterpretation, we produced Mutlidirectional Oblique Weighted (MDOW) hillshade images (Mark, 1992), using the DEM Surface Tools extension for ArcGIS developed by Jenness (2011), as they provide better details for reliefs in the shadow. Slope images are the first derivative of the elevation image and provide information on the maximum slope at each pixel. This kind of DEM-derived image help highlight contrasted reliefs and escarpments.

Fault lineaments were mapped using the combination of elevation, slope and MDOW-hillshade images, merged using transparency functions (Fig. 4). These lineaments were restricted to the lower break of slope of straight escarpments that clearly suggest normal faulting, and/or topographic and geological discontinuities that translate strike-slip movements. Misinterpretation cannot be totally excluded in the Precambrian basement, where faults sometimes merge with landslide scarps or rock layering, and in Lake Kivu, where turbidite channels might be misleading. Despite the relatively high resolution of bathymetric data (i.e. 5 to 10 m), several minor faults in Lake Kivu were also missed, as highlighted by seismic profiles in the northern part of Lake

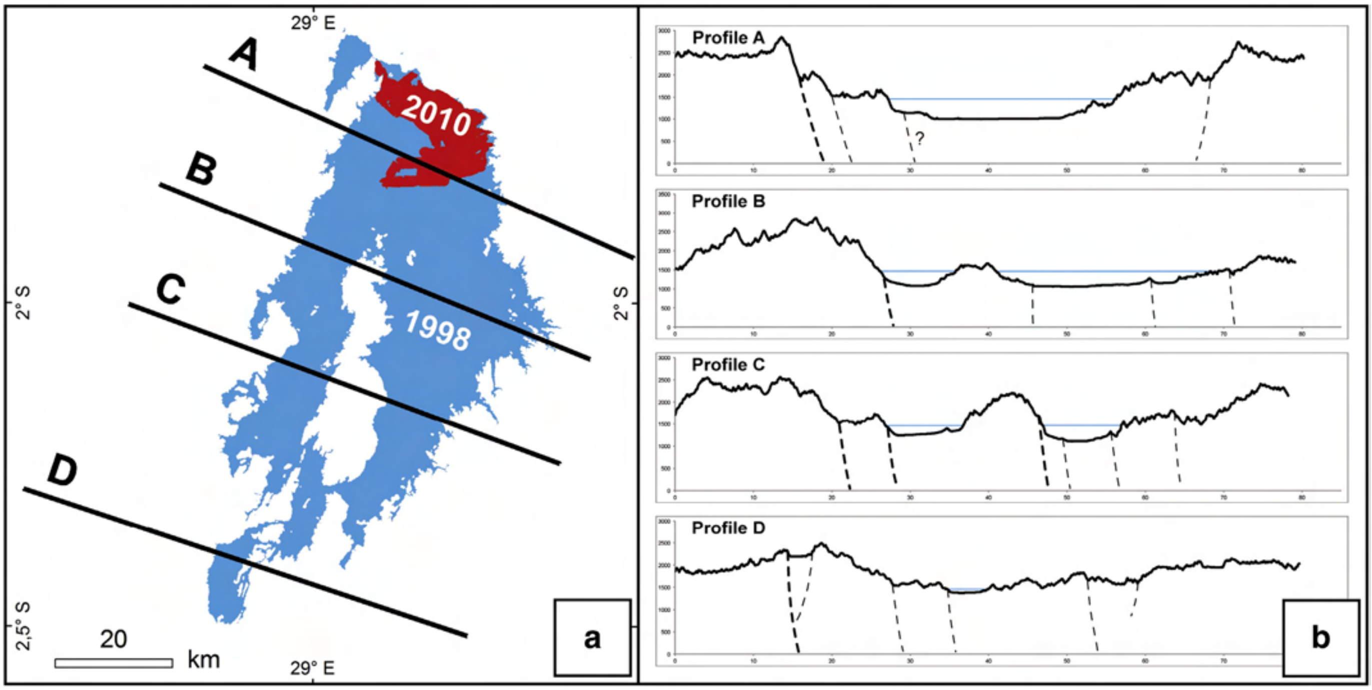

Fig. 3. (a) Map showing the coverage of the two bathymetric data sets of Lake Kivu used in this work. The red zone corresponds to data acquired in 2010 by Ross et al. (2014) over the northern basin of Lake Kivu. The blue zone, which covers the entire lake, corresponds to the bathymetry acquired in 1998 by Lahmeyer and OSAE (1998). Black lines A to D are topographic profiles described in frame (b). (b) Topographic profiles across the Lake Kivu rift basin. Black dashed lines represent the main assumed normal faults. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Kivu (Ross et al., 2014, 2015). Fault orientations were illustrated in rose diagrams using Polar Plots for ArcGIS, a plugin developed by Jenness (2014). We preferred length-weighted fault orientations, as they enhance the main orientations in the rose diagram.

Eruptive fissures in the VVP volcanic field were mapped using high to very-high resolution optical images (i.e., SPOT-5 and Pléiades images), a TanDEM-X DEM (Albino et al., 2015) and GPS field mapping.

By comparing DEMs and derived images with the geological maps of Yamba (1993), Fernandez-Alonso et al. (2007) and Smets et al. (2010), three main different geological units can be easily determined, based on changes in the relief texture: Precambrian rocks, which correspond here to the Mesoproterozoic Karagwe-Ankole Belt (Tack et al., 2010; Fernandez-Alonso et al., 2012), 2) the lava fields of VVP and SKVP, and 3) recent Quaternary sediments corresponding to alluvial and colluvial deposits. In Lake Kivu, elevation and hillshade images were both used to map these geological units and identify volcanic cones. A first mapping was realized using the 2010 bathymetry (see Ross et al., 2014), which offers the best quality and resolution. Then, by comparing the 2010 and 1998 bathymetric data in the Lake Kivu northern basin, the mapping was extrapolated to the entire lake basin.

2.2. Data from scientific literature

The existing scientific literature contains information that can either complement our mapping or serve as point of comparison. Hereafter, we describe data extracted from literature and relevant for this work. Table 1 summarizes the exploited maps coming from the literature.

2.2.1. Structural maps

We used ground-controlled (i.e.,. using seismic reflexion profiles and field observations) maps to locally validate our fault mapping technique performed using the SRTM-1 DEM and the bathymetric datasets. For this, we used the maps of Nicholas et al. (2015) and Wood et al. (2015), which cover part of the southern Lake Edward basin and Lake Kivu, respectively (Fig. 5). For the data from Wood et al. (2015), only faults in the eastern side of Lake Kivu were used, as they are the only faults mapped independently of previous mappings, using seismic reflection profiles. The results show a good correlation between the two mapping approaches and indicate that our mapping technique allows the detection of all significant normal faults in sedimentary deposits. In the Lake Edward basin, the comparison highlights the complementarity of the mapping techniques. Hence, our method for fault lineament mapping appears reliable for studying the fault distribution in the studied rift basin.

Several structural maps covering the Kivu Rift Zone, or part of it, were also digitized for comparison over each section of the studied area. In the southern Lake Edward basin and in the northern part of the VVP filling the rift depression, we used the field-controlled mappings of Yamba (1993) and Nicholas et al. (2015). In the VVP and the Kabuno Bay, we compared our mapping with Boutakoff (1939), Pouclet (1977) and Villeneuve (1980). For Lake Kivu and the SKVP, faults lineaments were compared with those from Villeneuve (1978, 1980), Degens et al. (1973), Ebinger (1989b) and Wood et al. (2015). The work of Ebinger (1989b), which mapped the southern part of Lake Kivu and the SKVP, is considered as the best existing mapping for this part of the rift, as it is based on photo-interpretation of satellite images, literature review and ground truthing through detailed fieldworks.

2.2.2. Geological maps

Existing geological and lithological maps were used to complement the mapping. In the VVP, the mapped lava field corresponds to an updated version of Smets et al. (2010). In the SKVP, the mapped lava field was compared to Meyer (1954) and Villeneuve (1978). The volcanic cones located at depth in Lake Kivu were compared to the location of cones in the SKVP mapped by Villeneuve (1978) and Ebinger (1989b). The detailed geology of the Kabuno Bay area was mapped using field mappings of Pasteels (1961) and Buchstein et al. (1967). Despite the rigorous geocoding of these existing maps, the accuracy of the geological features digitized from literature remains dependent on the quality and scale of the published maps, as well as on the quality of publication reprint and scanning.

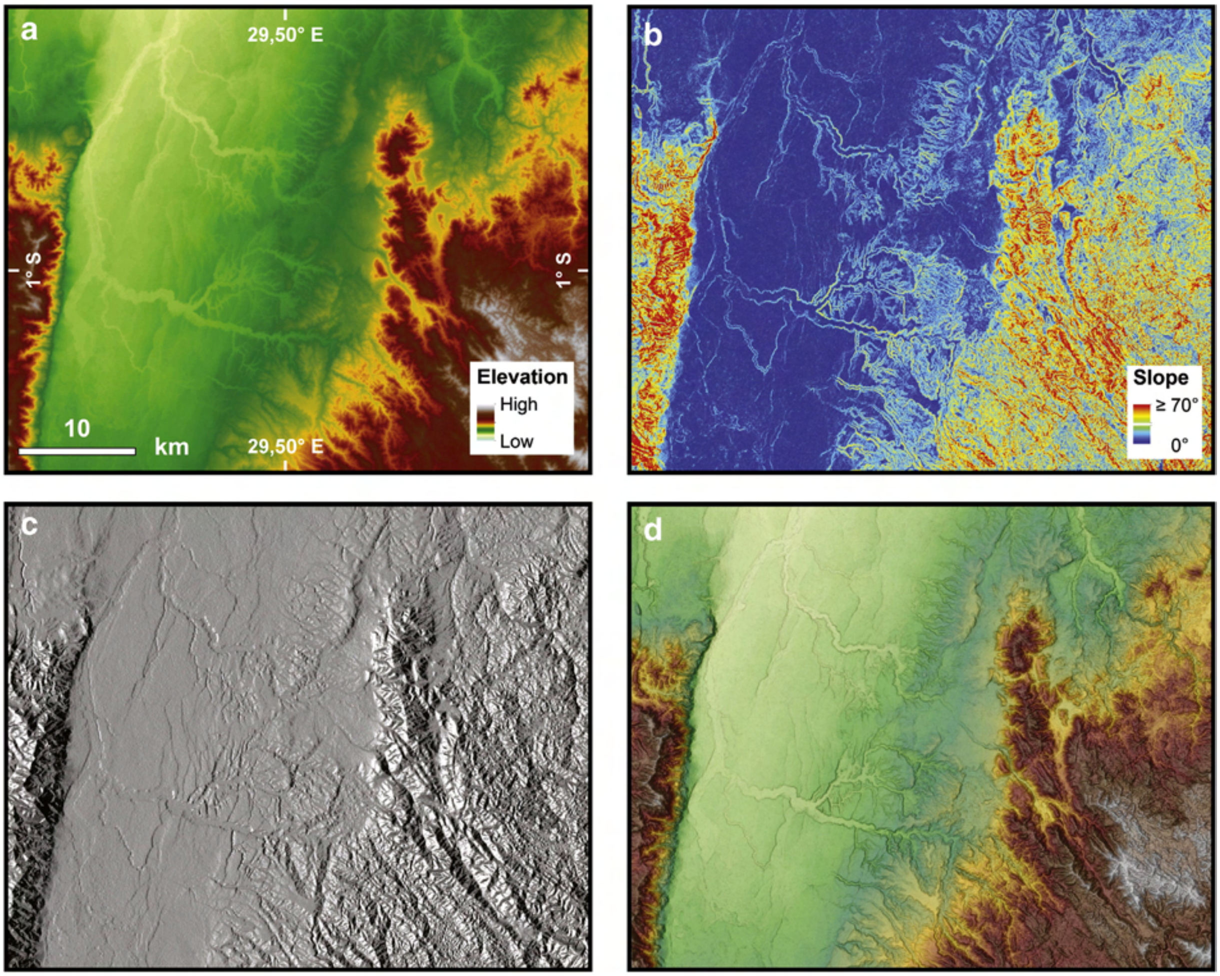

Fig. 4. Types of images derived from topographic data used in this work. The rift section illustrated here using the SRTM1-DEM is located in the southern part of the Lake Edward basin. (a) Colour-scaled elevation image. (b) Colour-scaled slope image derived from elevation data. (c) Mutlidirectional Oblique Weighted (MDOW) hillshade image. (d) Combination of images illustrated in frames (a) to (c) using transparency options. Similar image processing is applied to bathymetric data.

3. Fault lineaments and geomorphology of the Kivu rift segment

3.1. The southern Lake Edward basin

In order to highlight changes linked to the transition between the Lake Kivu basin and the rift segment located north of it, we included the southern part of the Lake Edward basin in our mapping. This section of the rift appears as a half graben, with the main escarpment forming the western shoulder (Fig. 6). Within the rift depression, a network of segmented and anastomosed escarpments visible in the recent sediment deposits clearly depicts the dominant fault structures at ground surface. Most of the faults appear east dipping. Heading southward,

Table 1
List of maps exploited in this work.

Source	Type	Covered area	Mapping methodology	Exploited information
Boutakoff (1939)	Geological map	Kivu	Sparse field observations	Faults
Meyer (1954)	Geological map	South Kivu Volcanic Province	Field observations	Lava field, volc. cones
Pasteels (1961)	Geological map	Kabuno Bay	Field observations	Lithological units
Buchstein et al. (1967)	Geological map	Kabuno Bay	Field observations	Lithological units
Degens et al. (1973)	Structural map	Lake Kivu	Field observations and seismicity	Faults
Pouclet (1977)	Volcanological/structural map	Virunga Volcanic Province	Field observations, volc. cone alignments	Faults
Villeneuve (1978)	Structural map	Kivu rift basin	Photo-interpretation, field observations	Faults
Villeneuve (1980)	Structural map	Kivu rift basin	Photo-interpretation, field observations	Faults
Ebinger (1989b)	Volcanological/structural map	South Kivu Volcanic Province	Photo-interpretation, field observations, literature review	Lava field, volc. cones, faults, dykes
Yamba (1993)	Structural map	Southern part of Lake Edward basin	Field observations	Faults
Fernandez-Alonso et al. (2007)	Geological map	Karakwe-Ankole Belt	Field observations, literature review	Lithological units
Smets et al. (2010)	Volcanological map	Virunga Volcanic Province	Remote sensing, photo-interpretation	Lava field, volc. cones, erupt. fissures
Nicholas et al. (2015)	Geological map	Southern L. Edward basin (Uganda)	Field observations, seismic reflection profiles	Faults
Wood et al. (2015)	Structural map	Lake Kivu	DEM analysis, seismic reflection profiles	Faults

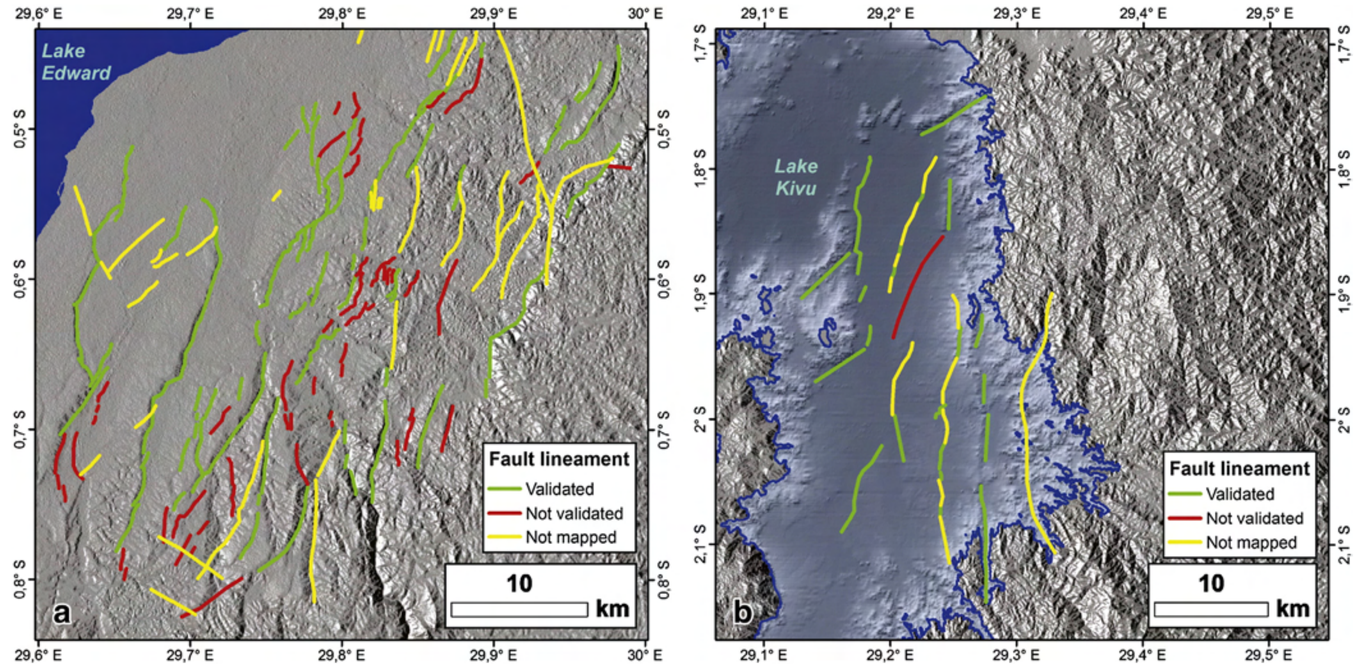

Fig. 5. Local comparison between the DEM-based mapping of fault lineament presented in this study and the field-based (field observations, seismic reflexion profiles) mappings of Nicholas et al. (2015), in frame (a), and Wood et al. (2015), in frame (b). In frame (a), not-validated and missed (i.e., not mapped) fault lineaments mostly appear as extensions of validated faults, which suggest that both mapping approaches are complementary. Some of not-mapped faults, in the NE part of the map correspond to W-dipping faults that are not visible in the topography. In Frame (b), faults mapped using seismic reflexion profiles complement fault escarpments visible in the bathymetry of Lake Kivu. Only one fault lineament was not validated as an actual fault.

the rift depression becomes narrower and the main escarpment is transferred eastward through an en-echelon transition. Two main fault orientations are observed and correspond to N0°E and N30°E. Contrary to its central part, the southern section of the Lake Edward basin does not show a marked antithetic eastern rift escarpment (Fig. 6a).

3.2. The Virunga Volcanic Province

Approaching the VVP, the N-S-oriented main rift escarpment abruptly shifts to a NE-SW strike (Fig. 7a). Fault traces become less obvious or even impossible to map accurately, as volcanic products hide the base of the main escarpment and cover the rift depression. The main escarpment on the western side of the rift depression appears highly eroded, with gullies and several landslide scarps. This complex eroded structure was first evidenced by Pouclet (1976). Heading towards southwest, the ridge of the main escarpment decreases in elevation and disappears below the lava plain. Both the topography and the hydrographic network suggest that this depression in the rift escarpment is a former river valley that was invaded by the lava flows of Nyamulagira. Wood et al. (2015) interpret it as the possible consequence of the loading pressure coming from the main volcanic edifices of the VVP.

Although no fault is visible in the Virunga lava field, eruptive cone and fissure alignments may highlight at ground surface the presence of faults at depth (e.g., Smets et al., 2015). However, it is worth mentioning that, if all these cone and fissure alignments may indeed indicate the orientation of a fault located below the ground surface, the real location of the fault may differ, as dikes may be diverted from the fault plane during their upward propagation (Connor et al., 2000).

Various volcanic cone alignments and fissure orientations dominate in the VVP. In the central and eastern VVP, where are located the oldest main volcanic edifices (Pouclet, 1977), they mostly have a NE-SW orientation, similar to the strike of the main rift escarpment located west of the Virunga volcanoes (Fig. 7a). This is for example the case for the Rusayo chain, in the SW volcanic field of Nyiragongo (Fig. 7a), for which Evrard and Jones (1963) suggest that they represent the trace at ground surface of an east-dipping normal fault, based on a gravimetric profile performed along the northern shoreline of Lake Kivu. At the scale of the entire volcanic province, the main edifices at the exception of Nyamulagira, and monogenetic cones between Nyiragongo and Muhavura, align along a similar NE-SW orientation. In the western VVP, additional fissure orientations dominate, even if recent eruptions of Nyamulagira suggest possible NE-SW faults beneath the Nyamulagira lava field (Smets et al., 2015). The eruptive fissure network that crosses Nyiragongo and Nyamulagira edifices indeed has a contrasting NNW-SSE orientation, and eruptive fissures along the southern flank of Nyiragongo have a rift-parallel N-S orientation.

3.3. Kabuno Bay

Despite interpretations commonly found in the literature (e.g., Boutakoff, 1939; Pouclet, 1977; Villeneuve, 1980; Wood et al., 2015), there is no escarpment possibly associated with normal faulting in the topography and bathymetry along the shorelines of Kabuno Bay (Fig. 8). Instead, the morphology of the Kabuno basin is typical of a flooded valley. Steep slopes in the relief, west of the bay, start about 2 km west of the shoreline (yellow dashed line, Fig. 8). By comparing the topography with the detailed lithology of the area (Fig. 8), it appears that variations in the relief match with lithological contrasts. Granites and carbonates indeed form the highest reliefs, while schist interbedded with quartzite layers compose the lower reliefs (Fig. 8). NE-SW fault lineaments are also observed in the steep slopes, extending southward the western rift escarpment through an en-echelon arrangement (Figs. 7 and 8). South of the bay, fault lineaments match with the N-S oriented rock layering (Fig. 9).

3.4. The Lake Kivu basin

Ross et al. (2014) described in detail the bathymetry of the northern Lake Kivu. Results show that the lava field of the VVP extends into the lake (Fig. 9). Volcanic cones, lava flows and a small topographic dome of a probable magmatic origin (not shown here) are clearly visible in

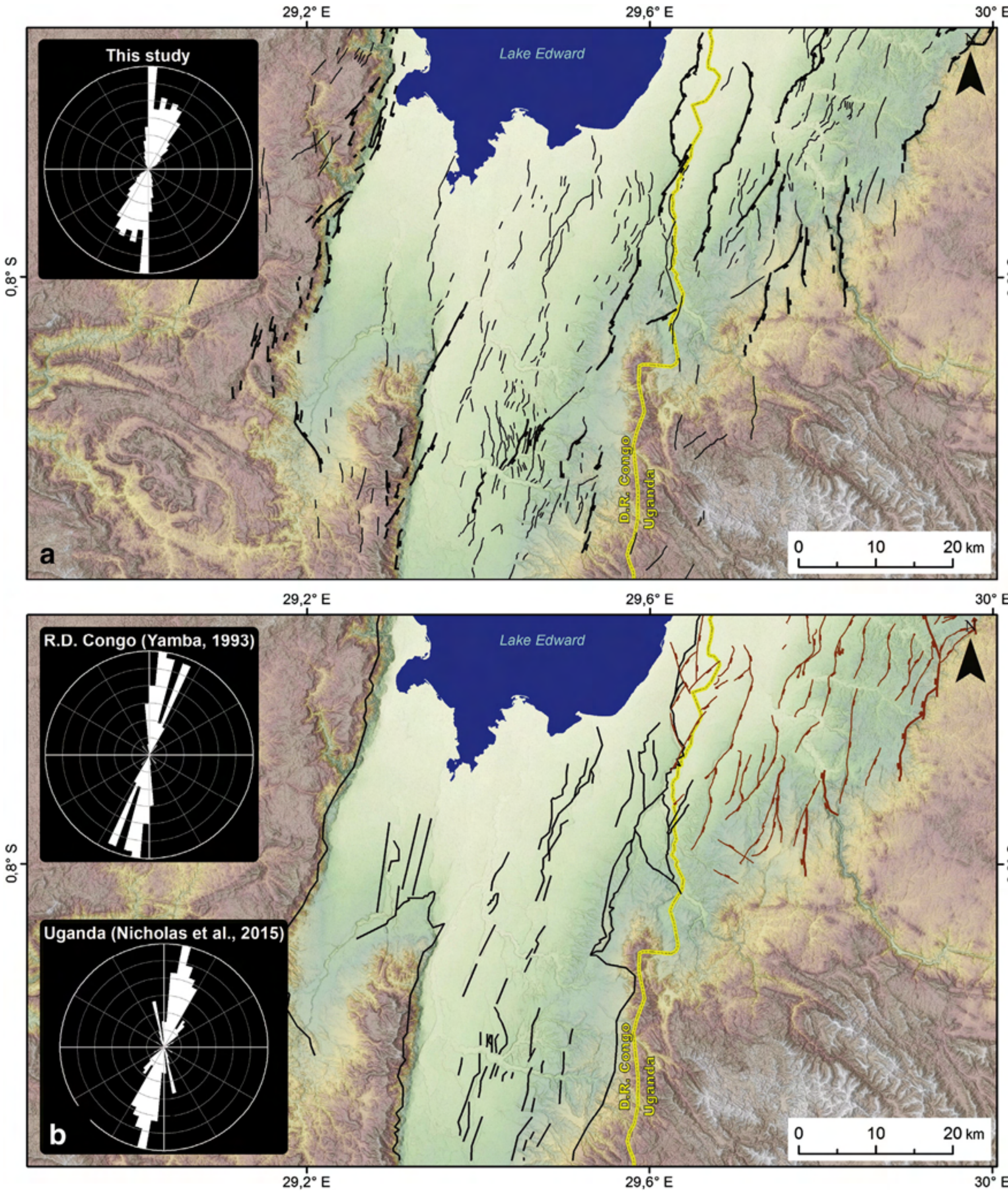

Fig. 6. Fault maps of the southern Lake Edward basin. (a) Map of fault lineaments realized in the present study. Thick black lines are the major normal fault lineaments. Black boxes along the lineaments indicate the slip direction. Thin black lines are other E-dipping fault lineaments. (b) Map showing faults mapped by Yamba (1993), in black, and Nicholas et al. (2015), in brown. Brown boxes along the faults of Nicholas et al. (2015) indicate the slip direction. Rose diagrams in black insets show the length-weighted orientation of mapped faults. The yellow line in both frames correspond to the political boundary between D.R. Congo and Uganda. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the NW part of the northern basin of Lake Kivu. Phreatomagmatic cones, i.e. maars, tuff rings and rootless cones (red and green triangles; Fig. 9), as well as a dendritic lava flow (not shown here), which all result from the interaction of magma or lava with water or water-saturated substrate, suggest a volcanic activity at a time period where the lake level was probably 250 to 315 m below the current one. Ross et al. (2014) roughly estimated the age of tuff rings and maars to ~9–14 ka, using a mean sedimentation rate and the sediment thickness inside four craters. The active hydrothermal springs detected by the same authors (Fig. 9), and spatially related to the submerged volcanic cones, probably indicate that magmatism is still active in this zone. Only one ~N-S oriented fault escarpment was clearly identified in the 2010 bathymetry. This fault is located in the northern underwater extension of Idjwi Island (Fig. 9) and is confirmed by several seismic reflection profiles (Ross et al., 2014; Wood et al., 2015).

By extrapolating the geological mapping to the entire Lake Kivu basin using the 1998 bathymetry and geomorphological similarities with the 2010 bathymetry, several observations provide new insights into the characteristics of the Kivu basin (Fig. 9). First, the volcanic field of the VVP extends southward, along the western shoreline of Lake Kivu, east of the Mbuzi Peninsula (Fig. 9). The volcanic field of the SKVP also extends into Lake Kivu and topographic mounts, interpreted as volcanic cones, link the two volcanic provinces. Second, Precambrian rocks of Idjwi Island extend into the lake, especially

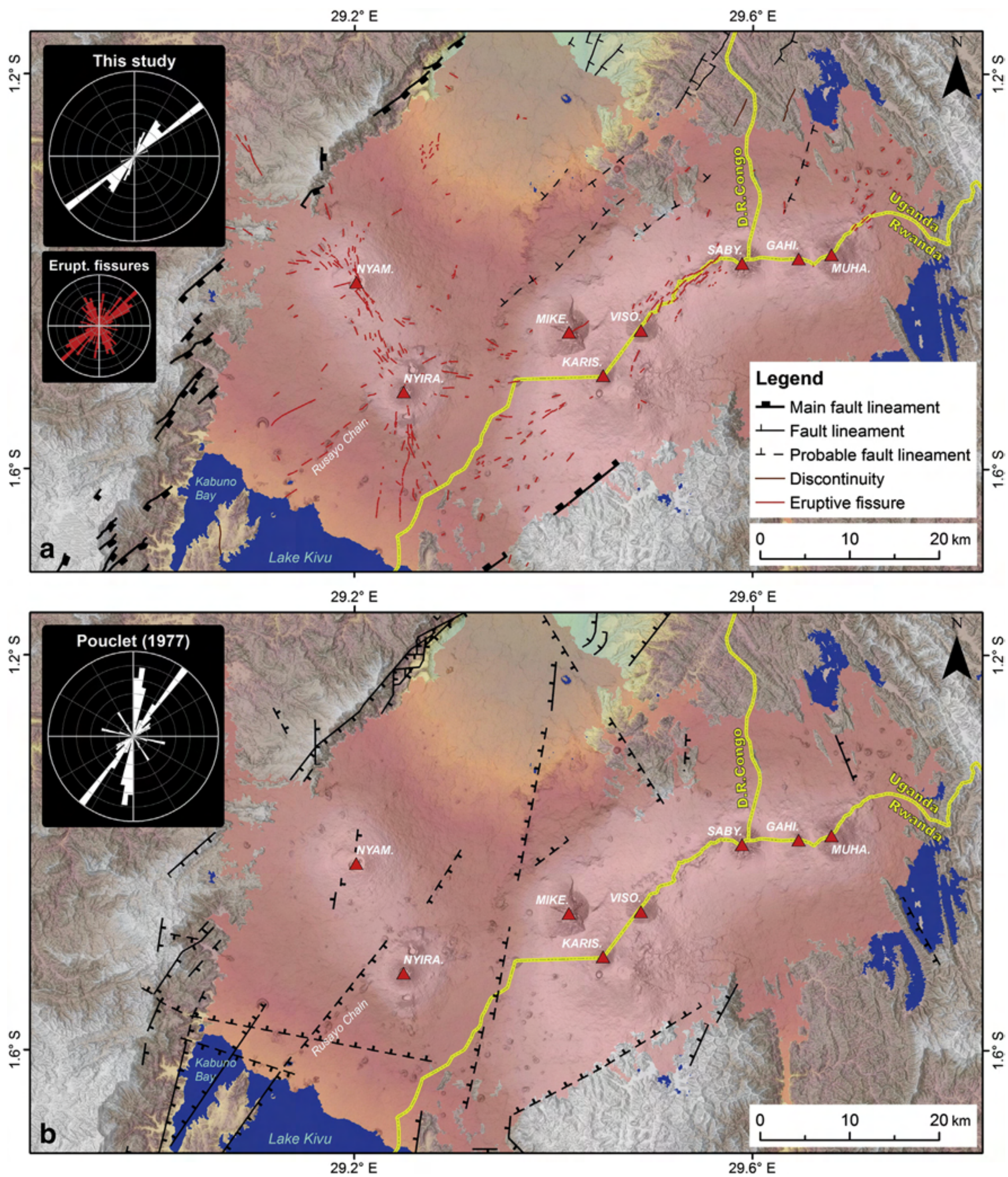

Fig. 7. Simplified geological maps of the Virunga Volcanic Province (VVP). (a) Fault-lineament map realized in the present study. Black boxes and ticks along fault lineaments incicate the slip direction. (b) Faults (black lines) and probable faults (dashed black lines) mapped by Pouclet (1977). The ticks along fault lines indicate the dipping. The red area represents the VVP lava field mapped by Smets et al. (2010). Rose diagrams in black insets show the length-weighted orientation of mapped fault lineaments and eruptive fissures. The yellow lines are political boundaries. The red triangles locate the main volcanic edifices of the VVP. NYAM = Nyamulagira; NYIRA = Nyiragongo; MIKE = Mikeno; KARIS = Karisimbi; VISO = Visoke; SABY = Sabinyo; GAHI = Gahinga; MUHA = Muhavura. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

northward, where Precambrian outcrops in the lake bottom delimit an isolated eastern sub-basin (Fig. 9). Finally, several fault escarpments were detected and mapped in the eastern, western and southern parts of Lake Kivu (Fig. 9). As previously mentioned, additional rift faults probably exist, but are not visible in the bathymetry. The presence of these additional faults is confirmed by seismic profiles (Ross et al., 2014; Wood et al., 2015). Faults are mainly oriented N-S and NNE-SSW, but some have a NE-SW orientation similar to faults in the VVP.

Four NW-SE topographic profiles crossing Lake Kivu were produced in order to see the N-S evolution of the basin morphology (Fig. 3). The northernmost Profile A shows a graben structure with a more sharply marked western escarpment. Southward, the rift depression evolves towards a clear half-graben structure with, from west to east, an elevated western shoulder delimited by a sharp escarpment in the Lake Kivu basin, the progressive appearance of Idjwi Island as a westward-tilted block, and an eastern border characterized by a gentle slope (Profiles B and C; Fig. 3). In Profile C, Idjwi Island becomes an important relief delimited in the east by a sharp escarpment. The topography of the rift depression in this profile roughly draws a double half-graben structure. Profile D shows the disappearance of this structure and the evolution towards a smooth and much less marked rift depression filled by lavas of the SKVP.

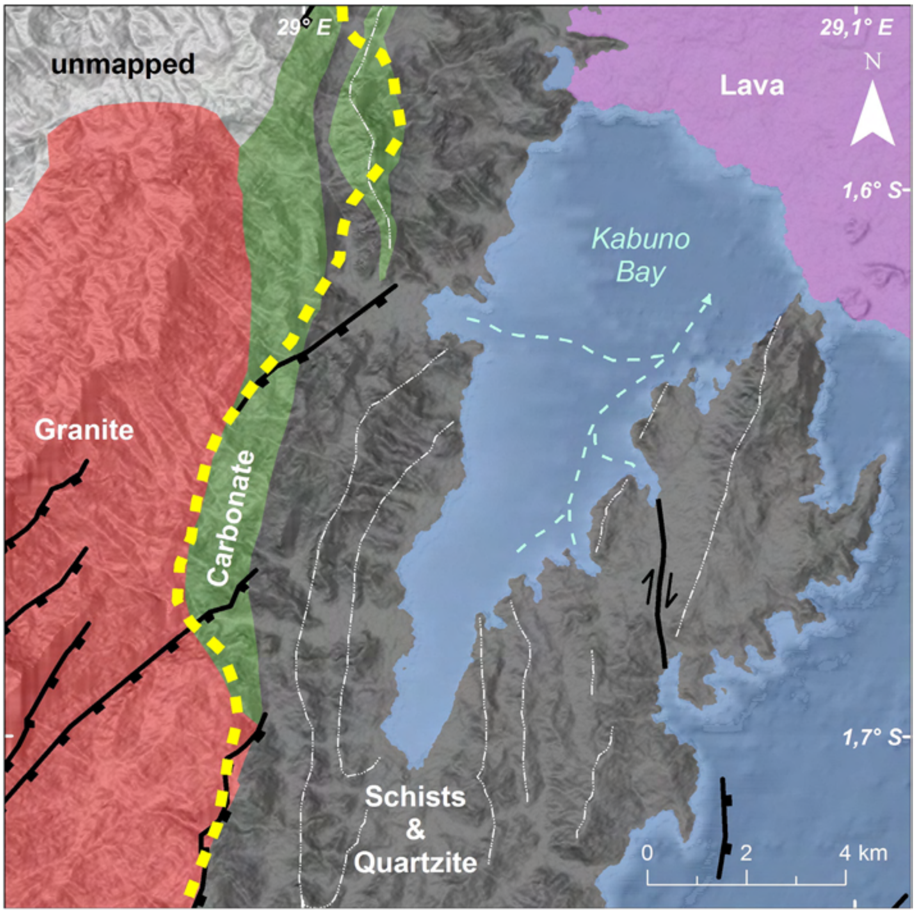

Fig. 8. Simplified geological map of Kabuno Bay, based on the topography and field investigations of Pasteels (1961) and Buchstein et al. (1967). The yellow dashed line highlights the topographic break-in-slope, which marks the base of a topographic escarpment. Black lines are fault lineaments mapped in this work. Black boxes along fault lineaments indicate the slip direction. Thin white dashed lines highlight the topographic ridges corresponding to quartzite layers interbedded with schist. The light-blue dashed lines in Kabuno Bay highlight the underwater paleo- hydrographic network. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.5. The South Kivu Volcanic Province

The morphology of the SKVP is different to what is observed in the VVP. There is no main volcanic edifice or monogenetic cone identifiable on available DEMs, and the lava field is highly affected by faulting, corresponding mostly to eastward-dipping escarpments (Fig. 10). The presence of faults in the volcanic field suggests that no major recent volcanism occurred in the SKVP. Fault escarpments are mostly N-S or NNE-SSW. Dyke intrusions observed by Ebinger (1989b) in the central and eastern parts of the SKVP (Fig. 11) however have a NE-SW strike, similar to the eruptive fissures in the central and eastern VVP.

3.6. Comparison with the existing fault maps

In the southern Lake Edward basin, faults mapped in the present work and those from the maps of Yamba (1993) and Nicholas et al. (2015) show the same fault arrangements and the same distribution of fault orientation (Fig. 6). The absence of a distinct and continuous eastern rift escarpment was confirmed in the field by Asselberghs (1938) and Nicholas et al. (2015). The southward narrowing of the rift valley, with an eastward transfer of the main rift escarpment, appears where the rift meets the well-layered and highly folded mesoproterozoic rocks of the Karagwe-Ankole Belt (Tack et al., 2010, Fig. 12).

In the VVP, our mapping suggests the main influence of a NE-SW-oriented fault network across the volcanic province. The NNW-SSE fissure alignment that crosses Nyamulagira and Nyiragongo volcanoes can either be explained by the stress interaction between the magmatic systems of both volcanoes (Wauthier et al., 2012), the reactivation of Mesoproterozoic faults similar to those observed in Rwanda (Smets et al., 2015) or both. The presence of faults with other orientations, such as those suggested by Pouclet (1977), were not identified in our geomorphological analysis (Fig. 7b). Along the Kabuno Bay, mapped faults are located 2 km west of the western shoreline, contrary to previous mappings, the latter works commonly locating a fault along the western shoreline of the bay (Figs. 2 and 8). In Lake Kivu, faults orientations globally fit with the main existing mappings. Faults from Villeneuve (1978) do not fit well with faults mapped in the bathymetry, mainly in terms of location, but also sometimes in terms of orientation. In contrast, our mapping in Lake Kivu align relatively well with the maps of SKVP realized by Ebinger (1989b) and Wood et al. (2015), and with faults escarpments detected on the SRTM-1 DEM (Fig. 11).

The geological mapping in the Lake Kivu basin fits well with all mappings of the surrounding area. In the northern basin of Lake Kivu, the southward extension of the Virunga volcanic field seems to correspond to the en-echelon continuation of the Rusayo chain (Fig. 7). Further south, cones detected in the bathymetry align with a series of cones in the SKVP (Villeneuve, 1978; Ebinger, 1989b; Fig. 9). All these observations suggest that our geological mapping in Lake Kivu using the existing bathymetric datasets is accurate enough to be representative of the actual geology.

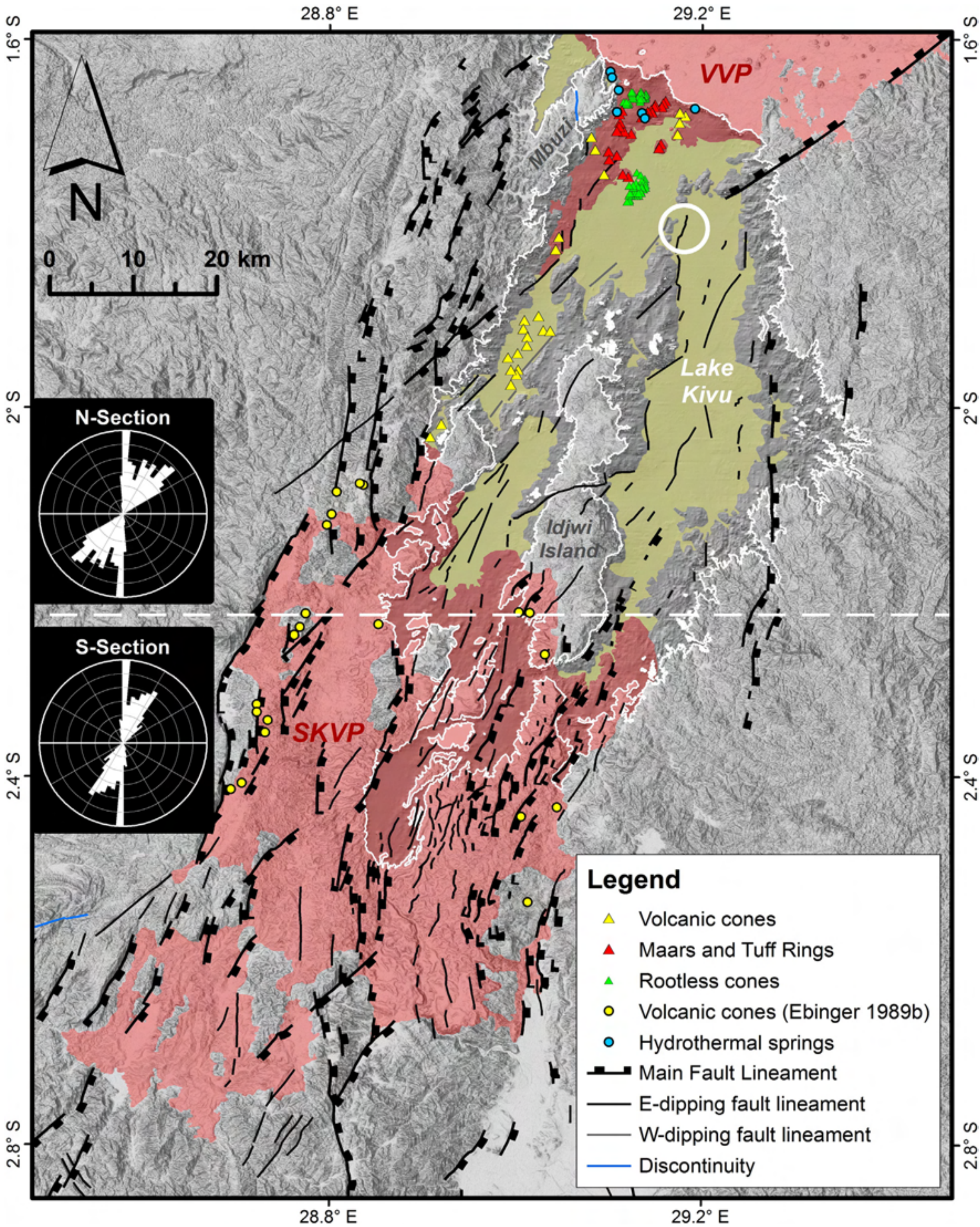

Fig. 9. Simplified geological map of the Lake Kivu basin realized in this work. Lake Kivu is contoured in white and underwater terrains are darkened. Areas coloured in grey, red and yellow are Precambrian rocks, lava fields and lacustrine sediments, respectively. The discontinuity (blue line) in the SW part of the map corresponds to a faulted fold axis in the Precambrian basement. Black boxes along the main fault lineaments indicate the slip direction. The white circle highlights the only fault visible on the 2010 bathymetry (Ross et al., 2014). Rose diagrams in black insets show the length-weighted orientation of mapped fault lineaments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Interpretation and discussion

4.1. Fault networks and possible origins

As highlighted by the new fault lineament mapping of the present study, three main fault orientations characterize the Kivu rift segment (Fig. 11). The N-S and NNE-SSW orientations are observed throughout the studied rift section and mostly affect recent lithology, i.e. lacustrine sediments and lavas. Hence, these two fault orientations seem directly related to the rift process, suggesting an E-W to ESE-WNW direction of rift extension and confirming former studies (e.g., Villeneuve, 1978, 1980; Rosendahl, 1987; Morley, 1988, 1989, 2010; Ebinger, 1989a,b; Boven et al., 1998; Foster and Jackson, 1998; Calais et al., 2006; Stamps et al., 2008; Delvaux and Barth, 2010; Saria et al., 2014). According to field observations, the faults with a N-S to NNE-SSW orientation are normal faults with a – mostly eastward – dip angle of 70 to 80° (Villeneuve, 1980).

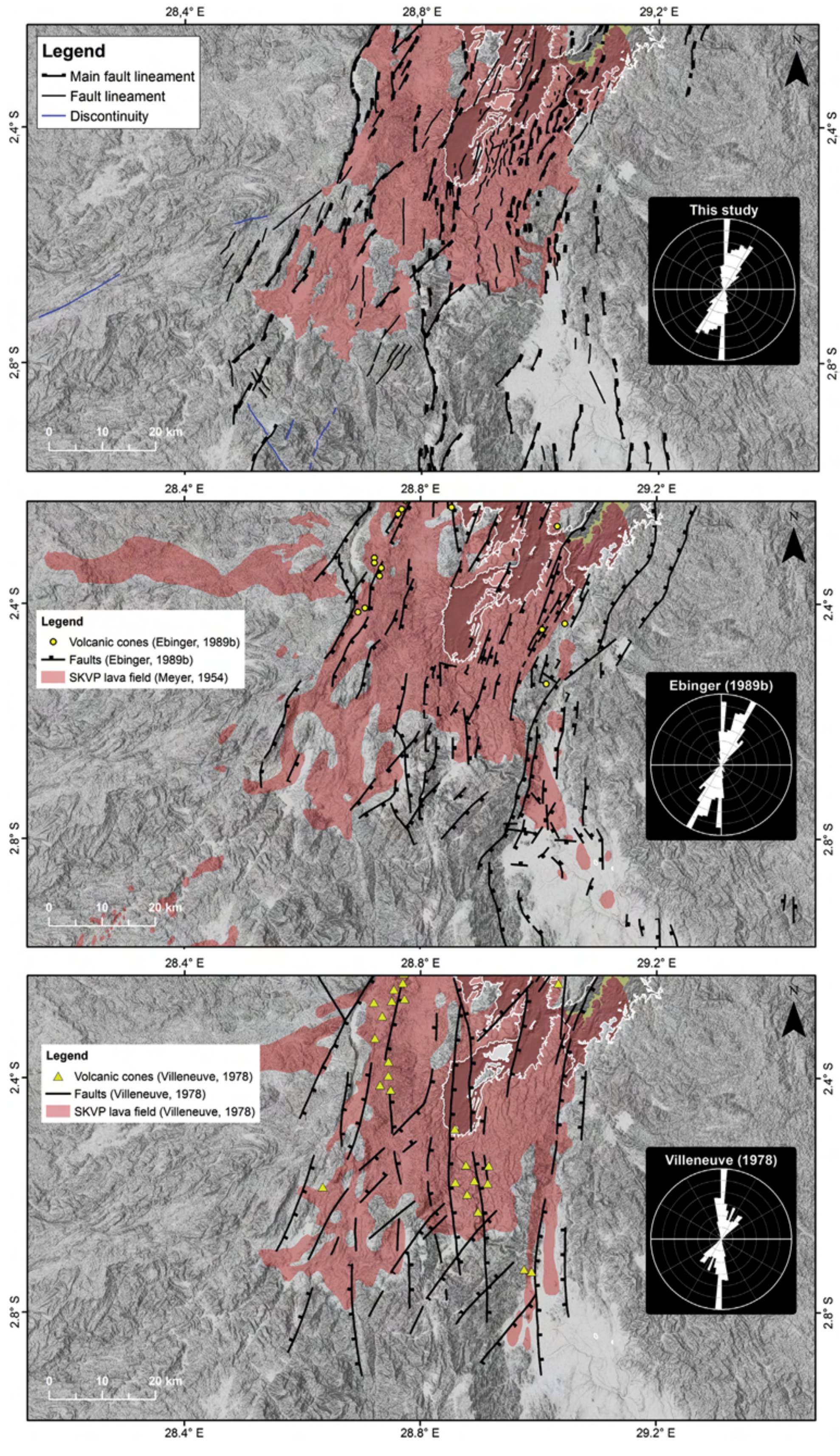

Fig. 10. Simplified geological maps of the South Kivu Volcanic Province (SKVP). (a) Fault lineaments and lava field mapped in this work. Black boxes along the main fault lineaments indicate the slip direction. All other normal fault lineaments are E-dipping. (b) Map showing the lava field of SKVP mapped by Meyer (1954), and faults and volcanic cones mapped by Ebinger (1989b). The ticks along fault lines indicate the dipping. (c) Map from Villeneuve (1978). The ticks along fault lines indicate the dipping. Rose diagrams in black insets show the length-weighted orientation of mapped faults lineaments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

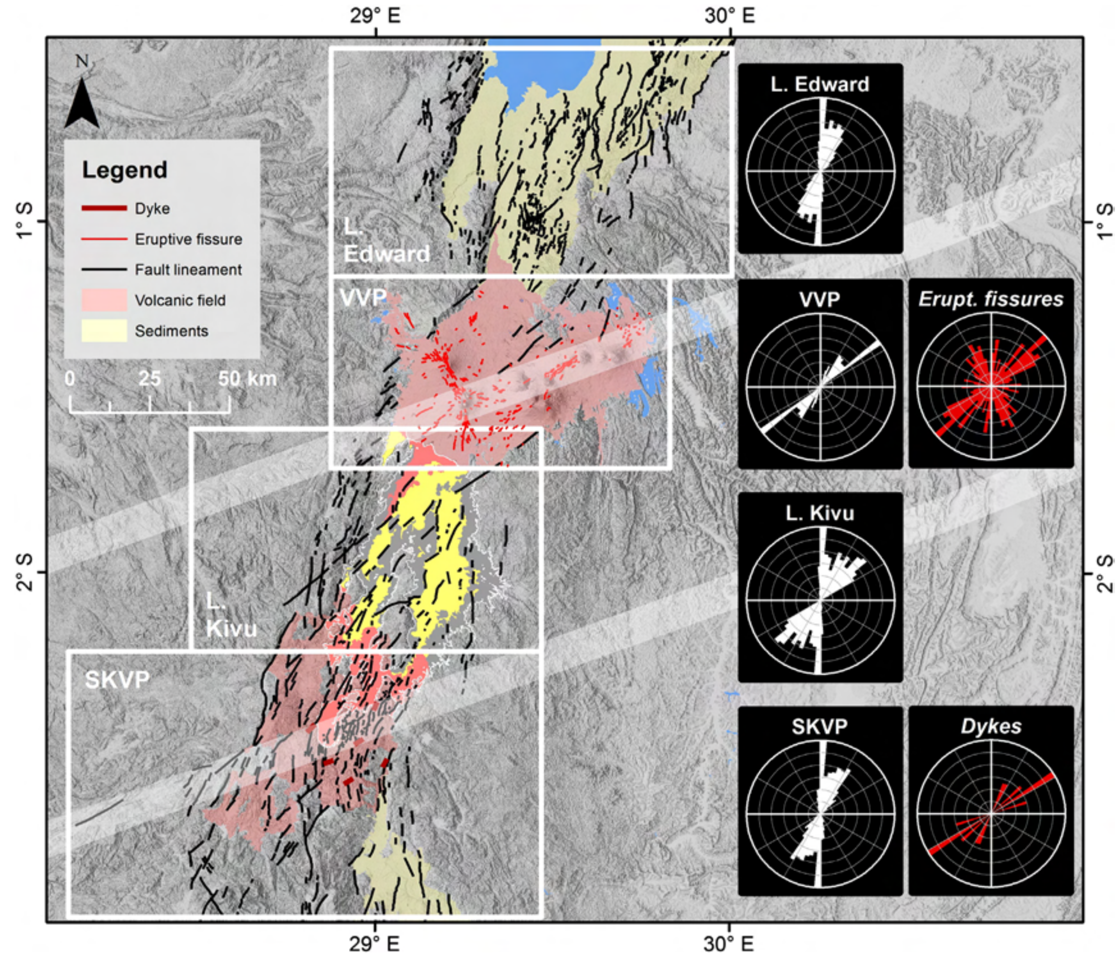

Fig. 11. Map showing the entire fault lineament and lithological mapping realized in this work. Dykes in SKVP are those mapped by Ebinger (1989b). Lake Kivu is contoured in white. The thick and transparent white lines crossing the map highlight the assumed regional fold axes that might have influenced the development of transfer zones and the distribution of volcanism. Rose diagrams in black frames show the length-weighted orientation of mapped fault lineaments, eruptive fissures and dykes. For the slip direction of normal fault lineaments, please refer to Figs. 6 to 10. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The NE-SW orientation mainly appears in transfer zones, when volcanic zones developed, but some fault lineaments in the Lake Kivu basin have a similar strike. In the VVP, they appear as a N-S en-echelon fault network extending the main western rift escarpment southward, and as a main eruptive fissure orientation. In the SKVP, such orientation corresponds to a few fault escarpments, a faulted fold axis located west of the volcanic province, in the Mesoproterozoic basement (Fig. 8; Ebinger, 1989b), and the main dyke orientation observed by Ebinger (1989b) (Fig. 11). The inconspicuous presence of the NE-SW orientated faults in the lava field of the SKVP suggests that the most recent rifting activity concentrated along faults oriented N-S to NNE-SSW. According to Villeneuve (1980), the NE-SW orientated faults are normal faults with a dip angle of 70–80°, similar to N-S/NNE-SSW oriented ones. As these faults are much more marked in the Mesoproterozoic rocks of the Karagwe-Ankole Belt than in recent sediments, they were probably mostly active during an earlier stage of the rift development. By looking at the topographic ridges related to lithological layering, both VVP and SKVP appear to be located along regional fold axes with a similar strike, in the Precambrian Karakwe Ankole Belt (Fig. 12), suggesting a structural inheritance. These fold axes and the related faults, which initially result from a succession of Proterozoic compressional events (Fernandez-Alonso et al., 2012), may consequently have influenced the alignment of the main volcanic edifices in the VVP and the orientation of dyke intrusions in SKVP. The influence of inherited crustal structures on the development of the rift and on the distribution of volcanism are also found elsewhere in the EARS (e.g., Lærdal and Talbot, 2002; Corti et al., 2007; Fontijn et al., 2010; Aanyu and Koehn, 2011; Albaric et al., 2014).

As these NE-SW orientations are mostly illustrated by the oldest volcanic edifices of the VVP and former dykes in the SKVP, we also suggest that these weakness structures, which were probably reactivated at the initiation of rifting in this part of the western branch of the EARS, promoted the development of transfer zones and the concentration of volcanism at these locations. This interpretation is supported by numerical and analogue modelling, which indicate that inherited crustal structures control the location and development of rift segments, rift faults in transfer zones being preferentially sub-parallel to inherited structures (Corti, 2004; Corti et al., 2007).

4.2. Characteristics and origin of the Lake Kivu morphology

The topographic profiles realized across the basin reveal a complex half-graben structure. The southward extension of the main rift escarpment in the western part of the VVP seems progressively transferred into Lake Kivu, through an en-echelon fault succession (Profiles and B, Fig. 3). The steep escarpment forming the western edge of Lake Kivu, which is characterized at depth by an alignment of volcanic cones and faults (Fig. 9), indeed strongly suggests the presence of a main active rift fault at this location. The relief of Idjwi Island separates the Lake Kivu basin into two en-echelon synthetic half graben sub-basins; the steep eastern border of Idjwi Island relaying the western lake escarpment southward. This interpretation is not perfectly delineated by

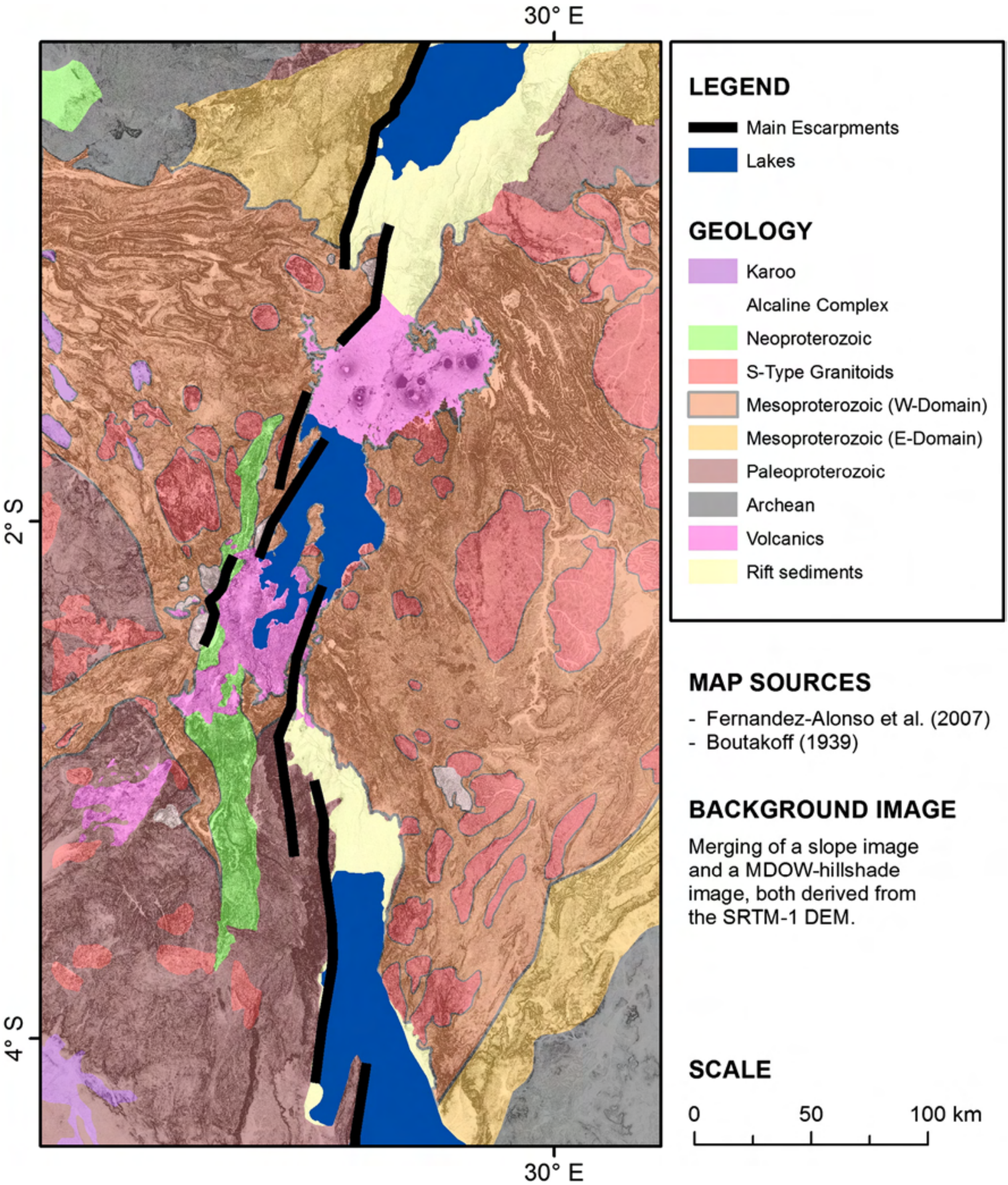

Fig. 12. Regional geological map of the central part of the western branch of EAR, based on maps of Fernandez-Alonso et al. (2007) and Boutakoff (1939). This map clearly highlights the en-echelon arrangement of the western rift escarpments in the Precambrian basement. All main rift escarpments are E-dipping.

mapped faults lineaments, but both lacustrine sediments and lavas from the SKVP probably hide part of the structures in the eastern and southern part of Lake Kivu. In addition, this interpretation is consistent with the fault structures reported by Ebinger (1989b).

According to Wood et al. (2015), at least 1.5 km of thick recent sediments, cut by at least three unconformities, fill the eastern Lake Kivu, suggesting a roughly estimated age of 3–5 Ma for the development of the Kivu basin. The current state of the rift basin, with a deep Lake Kivu and a southward flowing of its waters through the Ruzizi river, only represents the most recent phase in the evolution of the basin.

The continuity between the VVP and SKVP, characterized by volcanic cones continuing into Lake Kivu, strongly suggests that volcanism in this region has a common origin. This observation is consistent with the hypothesis of a magma underplating below the Kivu region. The distribution of volcanism indeed fits with results from Corti et al. (2003), who suggest that underplating magma beneath the Kivu rift basin tends to create this complex basin morphology, with (half-) grabens and horsts, but also transfer zones at the tips of the basin, recalling ductile materials and, hence, concentrating volcanism at these locations. It is worth mentioning that, despite the geomorphological evidences and results from analogue modelling, there is no geophysical data to support or deny the presence of underplating magma beneath the Kivu basin. A similar interpretation on the role of transfer zones in dike-driven strain accommodation has been reached in other places of the EARS (Muirhead et al., 2015 and references therein).

4.3. Implications for volcanic activity

The contrasting geomorphologies between the VVP and the SKVP strongly suggest that volcanism is currently restricted to the VVP only. First, fault escarpments are clearly detectable in the SKVP, while there is no direct topographic evidence of fault at ground surface in the VVP lava field. This means that faulting in the SKVP is not hidden by lava flows anymore. Next, the extension of volcanic provinces in Lake Kivu is different. The abrupt wall drawn by the VVP lavas and forming the Lake Kivu northern shoreline is likely to be related to the lava-water interaction. As suggested since the first scientific investigations in the Kivu region, this lava wall has stopped any water flow towards the north, and is presumably the main reason for the current lake level (e.g., Boutakoff, 1939; Peeters, 1957; Ross et al., 2014). On the contrary, the South Kivu volcanic field in Lake Kivu shows gentle slopes and an irregular invasion of the basin by lavas. This invasion of the Kivu basin probably occurred when the lake water level was too low for it to reach this area, as no morphology related to lava-water interaction is observed. The present interpretation is consistent with the observations of d'Oreye et al. (2010) and Wauthier et al. (2012) who suggest that magmatism in VVP accommodates the extensional stress, while normal faulting plays that role in the SKVP.

As reported by Smets et al. (2015), recent historical eruptions of Nyamulagira still occurred along NE-SW oriented cone alignments, suggesting that Precambrian structures with such orientation are still able to influence magmatic intrusions and eruption location.

The young age of tuff rings, maars and lava flows observed at the bottom of the Lake Kivu northern basin (Ross et al., 2014), as well as the presence of active hydrothermalism in this zone (Ross et al., 2014, 2015) suggest that the possibility of a new eruption inside Lake Kivu cannot be neglected. Magma propagation beneath Lake Kivu was also highlighted by the deep dyke intrusion linked to the Nyiragongo 2002 flank eruption, modelled by Wauthier et al. (2012).

5. Conclusions

The Kivu rift basin displays an atypical morphology in the western branch of the EARS. The study of the lake bathymetry and the surrounding topography offers new insights into the main geological features that characterize this rift section. The proposed fault lineament mapping based on topographic and bathymetric data offers reliable results to interpret fault arrangements and should be considered as a technique complementary to mappings based on field surveys and seismic reflection profiles.

Results suggest that rifting have reactivated NE-SW oriented weakness structures of the Mesoproterozoic Karagwe-Ankole Belt, which represent the Precambrian basement in which the rift propagated. These inherited structures would be responsible for the development of the transfer zones observed north and south of Lake Kivu. Their influence on the distribution of volcanic activity is clearly highlighted by the preferential alignment of volcanic edifices in the VVP, and by the orientation of dyke intrusions observed in the SKVP. Next, N-S and NNE-SSW oriented fault networks developed in recent lithology, confirming an E-W to ENE-WSW extension in this part of the EARS.

The unusual geomorphology of the Kivu rift segment appears to result from a complex mixing of inherited Precambrian structures, differential erosion linked to the Precambrian lithology, and the hypothetical presence of magmatic underplating beneath the Lake Kivu basin, with the concentration of volcanism at transfer zones and, in a lesser extent, along the western rift fault escarpment. The main rift fault escarpment in the VVP is progressively transferred southward, in Lake Kivu, through a series of en-echelon NE-SW–oriented faults located west of Kabuno Bay. This structure is partly hidden by lavas of Nyamulagira and by the advanced erosion of the Precambrian basement.

Both the VVP and the SKVP extend into Lake Kivu and are linked to each other by an alignment of volcanic cones at depth, along the western lake shoreline. As previously highlighted by Ross et al. (2014), the presence of young phreatomagmatic cones and active hydrothermalism in the northern part of the lake, suggests that a volcanic eruption under Lake Kivu is possible, although the probability that this type of event occurs remains unknown.

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