Drone aerial imagery and digital terrain models as tools in resolving contested borders: The case of Zambia and the Democratic Republic of the Congo

Ali El Husseini, Ph.D., CEO, Medici Land Governance

Keywords: border disputes, Zambia, Democratic Republic of the Congo, aerial drone survey imagery, digital terrain model, spatial data products

SUMMARY

More than 90 percent of the intra-state conflicts on the African continent in the last three decades have involved a border dispute. One of those disputes involves the border between Zambia and the Democratic Republic of the Congo which has been imprecisely defined and has led to confusion and contention between both countries for decades. Recently, both nations agreed to have a modern, accurate survey conducted to document physical features, which define a portion of the boundary line in remote and rural areas near Lake Tanganyika.

The project involves Medici Land Governance and the German development organization, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), which has been conducting an aerial imagery survey to demarcate in detail the contested border line between Zambia and Democratic Republic of the Congo. With the survey imagery, MLG is tasked with building a digital terrain model (DTM) to visualize the contested area accurately so that both countries can then proceed on a diplomatic path to resolve a long-standing dispute regarding the boundary lines. The objectives and deliverables of this project focus on delineating topographic prominences (peaks and ridges) in a remote, rural area. The process includes aerial surveys using drone aircraft and ground survey equipment, along with deriving orthoimagery and digital terrain models and conducting terrain analysis of derived digital terrain models to identify and map mountain peaks in the affected area. Careful analysis of the DTM has identified a set of peaks and delineated the watershed anchored at one end by Cape Kipimbi, but the most consequential finding in the present context is that the steep, tall landforms referred to as Kipimbi Mountains or Kipimbi Range are not mountains in a formal sense, but rather the shoulder and face of an escarpment (or multiple escarpments). As such, they have no natural objective crestline as would be the case for the ridge connecting a series of peaks, and Medici Land Governance cannot delineate the course of a non-existent feature. Both countries will receive the data in preparing for the next phase of diplomatic negotiations.

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1. INTRODUCTION

In 2020, the African Union identified nearly 100 active border disputes on the continent, many of which are legacies of the colonial era and continue even 60 years after many African nations achieved independence. The border limits dispute between Zambia and the Democratic Republic of the Congo (DRC) had its roots in the 1894 treaty signed by Britain (on the Zambian side) and Belgium (on the Congolese side).

Early in the independence era, both countries had talked about a bilateral commission to resolve the problem, as early as 1966 but it never materialized. Finally, in 1982, Zambia and DRC picked experts to review the border limits of the 1894 treaty. In the interim, there were periodic skirmishes with several casualties, accusations of territorial violations, and incidents of smuggling and robbery but there also were no moves on either side to organize larger military operations. The hot spots appeared to be concentrated in the area of Kaputa, as well as along the Luapula River and in the Copperbelt region.

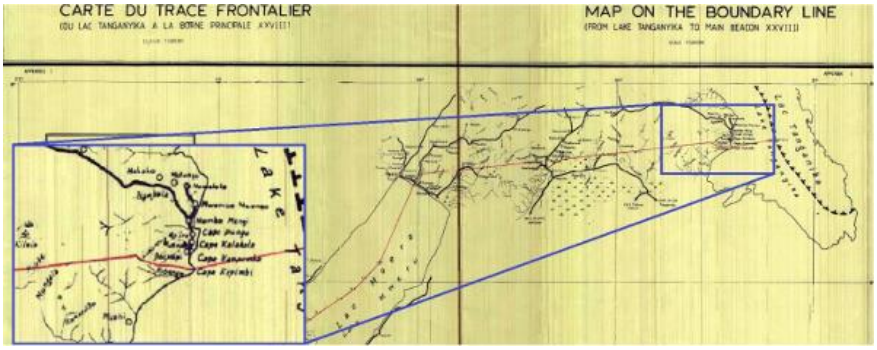

Figure 1. Excerpts from the Appendix map to the 1989 Treaty.

By 1987, Zambian government officials had drawn up the framework for resolving the dispute. In 1989, both countries agreed that the borders should be specified along 200 kilometers running from west to east between Lake Mweru and Lake Tanganyika. The portion of the lake boundaries has not yet been definitively resolved, mainly because there was no logistical resources or technology to draw the border on the specific terrain interests. This particular case illustrates the continent-wide challenges of resolving border disputes, precisely because of a lack of verifiable demarcation and delimitation. The broader issue is one of the most critical in Africa, where countries such as Zambia, Rwanda and Liberia have turned their attention toward using advanced technology to handle domestic and geopolitical concerns surrounding land

governance. To summarize, “these conflicts have revolved around issues of trans-boundary minorities, transboundary resources, unclear frontiers, and the contestation or difficulty of implementing existing colonial and post-colonial boundary agreements” (Amupanda, 2021).

In 2020, the Southern African Development Community said in a report that the best tools to resolve the dispute should involve geodetic inspection as well as a capacity to acquire aerial images to lay the groundwork for border demarcation and topographical mapping (Amupanda, 2021).

The treaty was signed on September 19, 1989 by President Mobutu Sese Seko (representing Zaire as the DRC was then known) and Zambia’s President Kenneth Kaunda. “The signing of this treaty is truly a proud moment for Africa,” Kaunda said at the time. “It shows that left to themselves, African countries are sufficiently mature to resolve even the most serious of problems in an amicable manner.” The only public details associated with the treaty that were ever announced, came from the following press release: “Tanzania-Zaire-Zambia tripoint in Lake Tanganyika may no longer be indefinite since it is reported that the indefinite section of the Zaire-Zambia boundary has been settled.”

Despite the visible diplomatic success, the issue remained unresolved for various reasons. Zambia is a landlocked country where capital improvements in roadways and railways would be expected to be prioritized, especially as the population was, for a long time, primarily concentrated in the capital of Lusaka. The financial resources, especially as they might involve obtaining the technical expertise and tools to resolve the boundary questions, were limited. Also, relations between the two states have tended to be inconsistent, given whatever governments were in power in each of the respective countries. Access to the terrain in question is complicated by the geographical and topological features of the affected area. “This would include mountainous regions; waterways; overgrowth in natural fauna; unpaved roads; and climatic challenges, when the rainy season makes fieldwork impracticable” (UNOWAS 2019). In fact, these issues often were cited by experts at various African Union conferences, such as a 2008 symposium on land, lake and river boundaries management.

2. MEDICI LAND GOVERNANCE (MLG) and GIZ: ZAMBIA AND DRC

Recently, GIZ engaged the two respective national governments to clarify how the border should be delineated of the shared boundary near Cape Kipimbi, on the shore of Lake Tanganyika. As mentioned above, the dispute epitomizes the large areas of uncertainty in interpreting how the delimiting and demarcating of the border in question should be resolved. Reiterating a point made earlier. both countries had signed a treaty in 1989 but numerous reasons, including those of technical expertise and access to the technology required to carry out a proper aerial survey, prevented both countries from putting forth the treaty terms into tangible results. Accordingly, GIZ engaged Medici Land Governance (MLG) as a technical partner to conduct a modern survey of the area and to analyze the resulting terrain model. The goal of the survey and analysis is to resolve the identity and location of key features mentioned in the treaty text, thus facilitating the national partners’ efforts to finalize demarcation of the boundary.

Medici Land Governance has produced a state-of-the-art digital terrain model (DTM) of the project area using Lidar data captured in an aerial survey of the Cape Kipimbi/Cape Pungu project area. The DTM delivered is in the WGS84 UTM Zone 36S coordinate system. It is gridded at 30-centimeter resolution, has positional accuracy of 30 centimeter (horizontal) and 40 centimeter (vertical). The DTM represents a significant improvement in detail and accuracy over previous spatial data for the portion of the DRC/Zambia boundary that runs from Lake Mweru to the Tanzanian tricorner.

The following sections explain how MLG analyzed the new terrain model, along with a high-level description of the terrain features found in the project area. Also, there are comprehensive breakdowns and discussions of the geographic references, as they have been noted in the text of the 1989 treaty. This leads to the critical takeaways of the analysis.

3. DIGITAL TERRAIN MODEL ANALYSIS

One of the most crucial findings in the digital terrain model (DTM) was that the landscape feature referenced in the 1989 treaty as "Kipimbi Mountains" and "Kipimbi Range" do not constitute a mountain range per se (discussed in Sections 6 and 7). The project area, in the northernmost corner of Zambia and southeastern corner of the DRC, is underlain by an inclined series of geological terraces or escarpments that step down in a sequence towards the northeast with individual terraces being largely flat. Although the terraces are largely parallel and run from northwest to southeast, the rim of each terrace is dissected by erosion into rounded lobes and the terrace rims are quite irregular. The westernmost terrace is at the highest elevation and lies entirely outside the project focus of interest. The middle terrace runs largely along the west edge of Cape Kipimbi. Peaks on the exposed margin of this terrace are at ~1170 meters - ~1190 meters above sea level and sit ~100 meter higher than the elevations at its base. The easternmost terrace is anchored by Cape Kipimbi itself and runs along the eastern edge of the project area . Peaks on this terrace area are at ~1060 meters – ~1120 meters above sea level and the top rim sits ~ 300 meter higher.

In summary, there is no ridgeline forming a crest anywhere within the region as described by the treaty. Understandably this makes delineating a "crest line of the range of mountains from Kipimbi in form of a points line with coordinates (X, Y, Z) every 5 meters; vector data format (ESRI Shape file)", as specified in the original GIZ tender, very problematic. Instead, MLG has provided a framework for interpreting the de facto terrain in light of the binding treaty language, suggesting several alternatives that conceptualize the crucial and problematic treaty element of the "crestline of the Kipimbi Range" in various ways.

4. IDENTIFYING POINTS REFERENCED IN THE 1989 TREATY

The precise locations of key points can be resolved. But, the interpretation of the official treaty text delimiting the border between the two countries is complex because the descriptions of topographical features in the treaty do not always correspond to the reality on the ground. In some cases, this means the challenge extends beyond measuring locations of fixed points – that

is, the nature or identity as well as the precise locations of the features must be agreed upon bilaterally by the national parties.

The treaty text explicitly mentions eight geographic points individually and references one further set of points collectively. Together these nine points combine to define four boundary segments, as well as three other key line features (referred to as “construction lines” hereafter) that accompany those definitions. The English translated text of the relevant treaty section with the nine points is quoted verbatim here:

The boundary between the Republic of Zambia and the Republic of Zaire starts from:

A. the median on Lake TANGANYIKA at 08d 17’ 00” South Latitude and proceeds in a straight line, passing through
B. the furthermost point of Cape KIPIMBI up to
C. the summit of KIPIMBI mountains. It thereafter follows
D. (Dn-1…Dn) the crest of these mountains up to
E. its intersection with the median line drawn from
F. an equidistant point between
G. the summits of Capes PUNGU and
H. KIPIMBI and running in a straight line in the direction of
I. the point where River LUVUA issues from Lake MWERU (MOERO).

A schematic diagram illustrating how the points relate to one another is given in Figure 2 below.

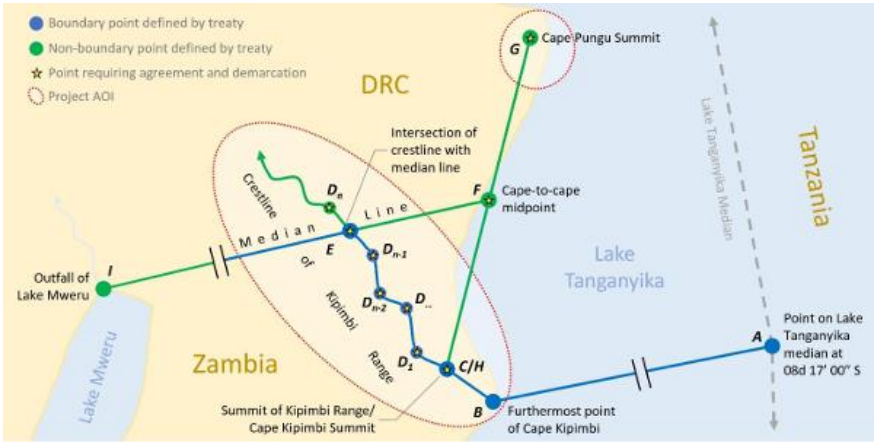

Figure 2.. Schematic map of the points defining the boundary, as described by the treaty text.

Using this taxonomy, the four boundary segments intersecting the project area of interest then are:

A to B, running from the Tanzania tri-corner on the Lake Tanganyika median into the AOI to the furthermost point of Cape Kipimbi;

B to C/H, running from the furthermost point of Cape Kipimbi to the summit of Kipimbi Range;

C/H to D1...Dn-1 to E, from the summit of Kipimbi Range to intersection of the Kipimbi crestline and the median line; and

E in the direction of I, following the median line out of the project area of interest.

The other three construction lines are:

1. G to C/H, the cape to cape line;
2. F to I, the median line;
3. D, the last segment of the Kipimbi crestline, part of which (E to Dn) falls on the north side of the median line.

MLG can now make several important observations about eight of the nine points referenced in the treaty, which in the current context are well-defined and unlikely to become a subject of disagreement between the national partners:

Points A and I: First, the terminal points A and I lie far outside the study area and cannot be delineated via this study. Their locations must be identified via other means. While A may be delineated independent of all other points discussed here, I must be known to precisely locate E.

Point B: MLG was informed by the Zambian authorities in February 2021 that the identity and location of point B has been bilaterally resolved already. MLG accordingly defers to the national partners, rather than suggesting a location for this point.

Point C: "The summit of KIPIMBI mountains" is straightforward to identify geographically. The clear implication of the treaty text is that C is the nearest summit to Point B (otherwise, why would the boundary proceed from B to C to D). The nearest meaningful summit to Point B stands 301 meters above the shoreline of Cape Kipimbi and ~800 meters from the next-nearest prominence. These two summits are separated by a saddle that drops ~50 meters. There are no other peaks with anything like this degree of prominence anywhere nearby.

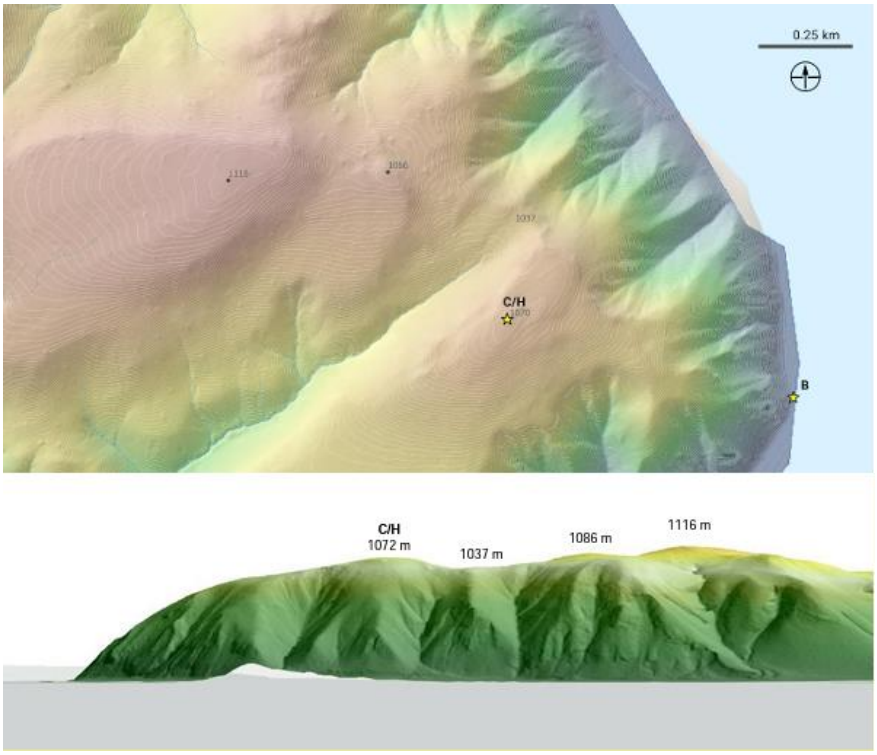

Figure 3. Cape Kipimbi, from above (top) and as viewed from lake level, looking towards the southwest (bottom).

Points G and H: Next, MLG notes that points G and H (the summits of Capes Pungu and Kipimbi, respectively) are relatively easy to delineate because their identities as geographical features are unambiguous and not subject to credible debate. Point G is easily identified as the taller of two summits within the Cape Pungu area of interest, as shown in Figure 4**.** Point H is also easily matched with a physical feature, namely the peak closest to and rising directly from Point B, the furthermost extent of Cape Kipimbi (see discussion of Point C and Figure 3). In other words, points C and H represent the same geographical feature and are referred to as Point C/H throughout this report.

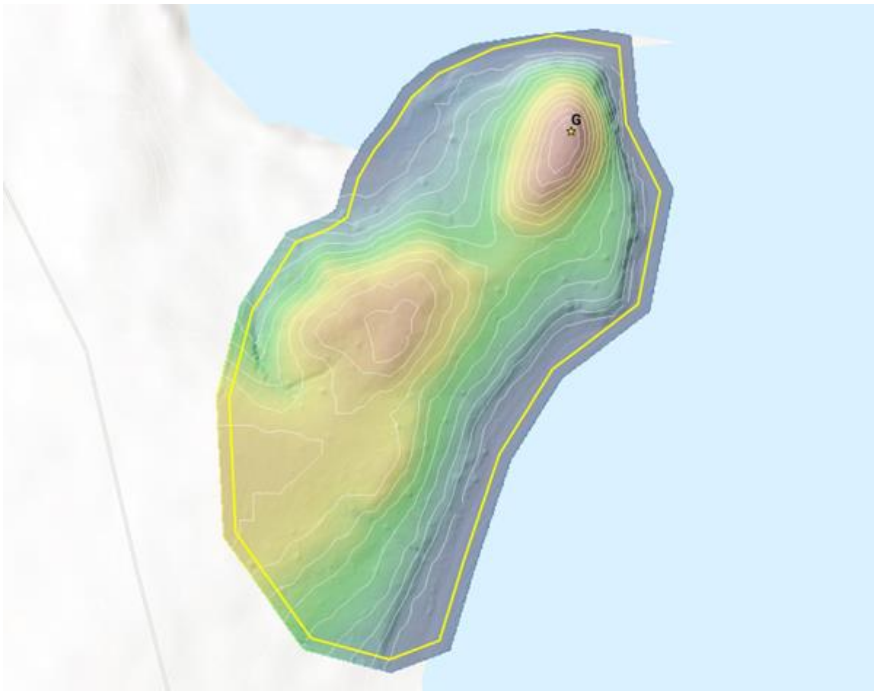

Figure 4. Cape Pungu and its summit.

Point F: Points E and F are special cases in contrast to all other points, whose locations may each be determined independently. The location of Point F is dictated by the joint locations of G and C/H, as shown below in Figure 6. Because Points G and C/H are easily located as discussed above, it necessarily follows that Point F is easily known as well. Point F, at the equidistant point between the summits of the Pungu and Kipimbi capes, is the midpoint on a line joining the horizontal locations of the two summits in the planar (i.e. projected) coordinate reference system used for this project.

Point E: The location of Point E is dictated by the joint locations of five different points: Dn-1, Dn, I, G and C/H.

Points D1...Dn: Crestline of Kipimbi Range: The points discussed above suffice to define and locate the first two segments of the boundary, plus the two long construction lines involved in defining the last two segments, as shown in Figure 6 above. Because the boundary line segment C/H to Dn-1 to E stops at the median line, analysis of the southern half of the Kipimbi area of focus is sufficient to identify and locate points D1...Dn. However, locating points D1...Dn themselves is challenging because of a mismatch between the nature of the landforms in the area of interests and language the treaty uses to describe them.

The remainder of the boundary and the most challenging problems posed by the treaty text entail this question of points D1...Dn. These problems include a) identifying what physical features are meant by the “Kipimbi Range”, and b) further identifying the “crestline” of this range (i.e. delineating points D1...Dn). These issues are discussed in the following section.

5. KIPIMBI RANGE AND DEFINING LANDFORM TERMS

The Kipimbi Range is the most difficult element of the treaty definition to operationalize because of the specific geomorphology of the prominent landforms dominating the Kipimbi area of interest in the project. It is helpful to define some terms to describe the landforms of the Kipimbi Mountains and consider how to operationalize a definition for the crest of these mountains.

A *peak* is a landform defined by a singular high point surrounded by lower land. Peaks can be identified analytically in a DTM by computing where water would flow to from each pixel; a pixel with no flowlines coming from any other pixel is a peak (although perhaps a very minor one).

A *ridge* is a linear landform that is higher than land on both sides of the line; water falling on either side of a ridge will flow away from the ridge in different directions.

An *escarpment* is a landform where a relatively flat upland drops steeply down to another, lower, largely flat lowland. The top edge of an escarpment is a linear landform, referred to as a *shoulder* – unlike a ridgeline, the land is lower on only one side of a shoulder; on the other side the land is relatively flat. Because of this water falling on opposite sides of a shoulder may end up flowing in the same direction. Shoulders do not typically form watershed boundaries and cannot be delineated using hydrological flow analysis. However, they can be identified and mapped from digital terrain data using the measures of curvature, including the Topographic Position Index (TPI). TPI has the advantage of highlighting all convex features including peaks, ridges, and shoulders, regardless of whether or not they correspond with watershed features.

The landforms within the project area are not ridges connecting a series of peaks and therefore do not form watershed boundaries. Rather, they are largely the rims of flat highlands bounded by escarpments whose edges are a series of lobes with prominent headlands, incised by stream valleys running perpendicular to the escarpment.

There are three such landscape features near Cape Kipimbi (see Figure 5). They descend to the east like roughly parallel steps. The escarpments each run northwest to southeast and are spaced a few kilometers apart from one another in a sequence that climbs to the southwest, following the shoreline of Lake Tanganyika to the south of Cape Kipimbi. The escarpment anchored by Cape Kipimbi has the greatest vertical relief of the three features, climbing 300 meters from foot to shoulder at its southeast end, where it terminates into Lake Tanganyika and forms Cape Kipimbi.

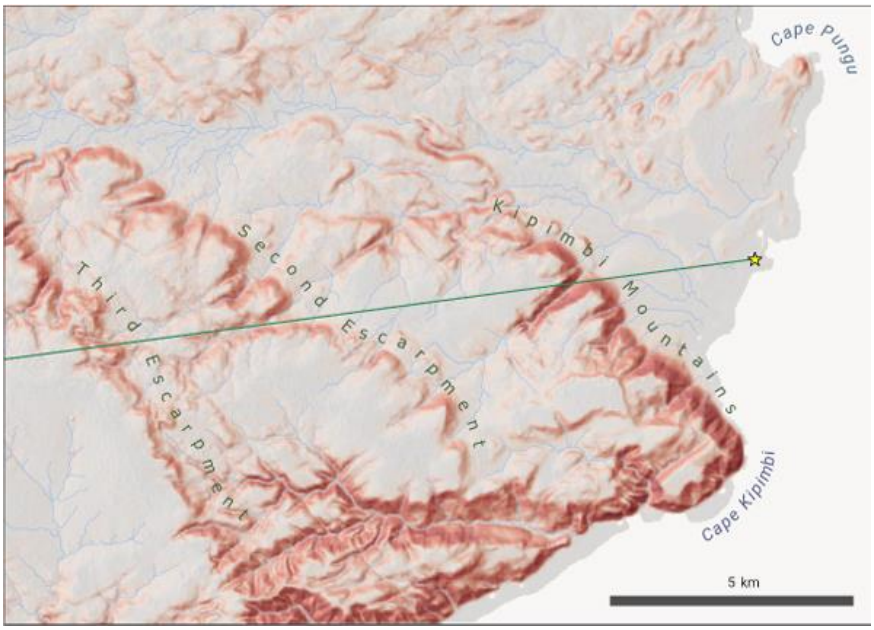

Figure 5. Kipimbi Mountains and two adjacent escarpments that form a series of flat steps, rising to the SW. Here terrain is shown with an increasingly steep slope rendered in darker red to illustrate the flat terrain on the back side (SW) of the crest.

Because the Kipimbi Mountains consist of headlands from an eroded escarpment rim rather than a ridge joining a chain of peaks, the shoulder of the escarpment is the natural definition for the mountains' crest. There is no ridge joining a series of peaks to correspond with what an observer on the ground below naturally perceives as a range of mountains, and the crest of the Mountains is not a drainage divide. This means that the flat highland above the escarpment (and even a substantial portion of the land above the next escarpment) drains to the northeast, despite being on the southwest side of the shoulder (Figure 6 below). Because of the headland lobes formed by the dissecting stream valleys, this shoulder itself is sinuous despite the escarpment's (Kipimbi Mountains') clear linear trend to the northwest.

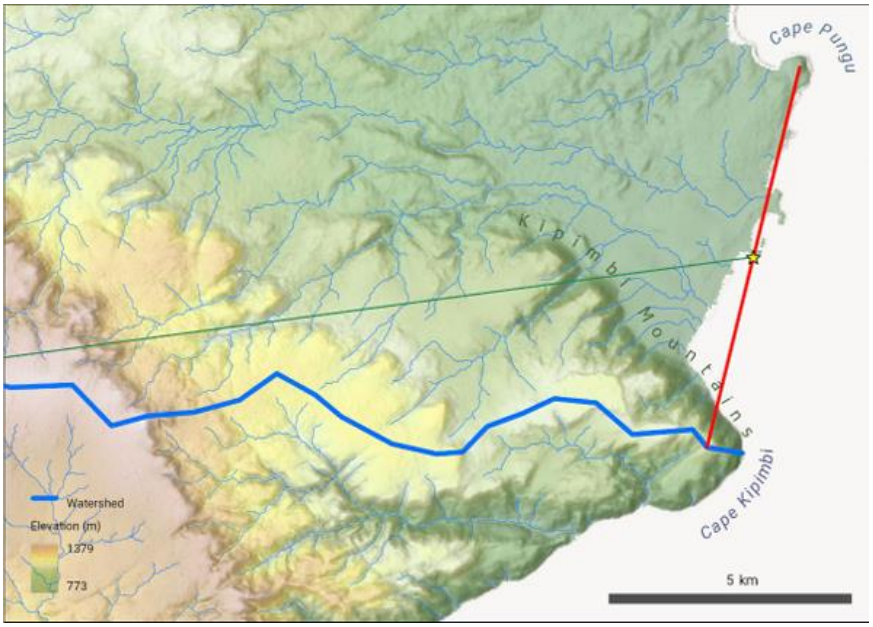

Figure 6. Drainage divide of the Kipimbi Mountains. This drainage pattern is counter-intuitive because streams flow through, not to either side of the range. This is characteristic of escarpment shoulders but not of a ridge

6. DELINEATING A CRESTLINE

The crestline is not a ridge. In each of the following four options, the treaty's "crestline of the Kipimbi Range"is conceptualized in a different way. MLG applied the interpretations via analysis of the DTM and resulting points D1...Dn are shown as a red line. Point E is the point of intersection between the green median line and the red crestline in each scenario.

Option 1 interprets the crestline as a watershed. Figure 7 above shows the scenario crestline on top of the TPI, as computed from the new DTM: convex landforms are red, concave landforms are blue, and flat areas are gray. Areas that drain to the north of Cape Kipimbi (Point B) are on the Congolese side of the crestline; areas that drain south of Cape Kipimbi are on the Zambian side. Point E1 is not shown on the map as it falls outside the project focus, ~5 kilometers to the west. The crestline in this scenario has an objective existence defined by the terrain in the project area, but it does not correspond with what a viewer would perceive as a ridgeline. It is easy to see that over most of its course, the watershed boundary traverses very flat ground (i.e. TPI near 0; gray or pale pink above) that peaks or crests only very marginally.

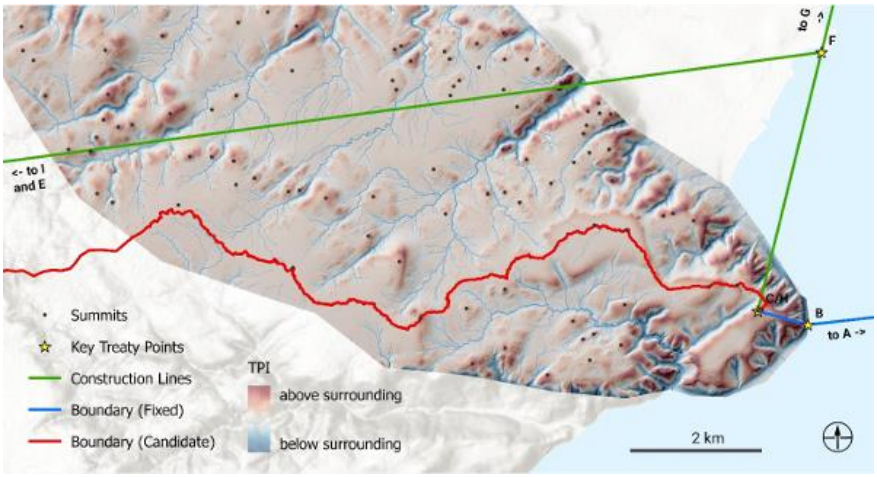

Figure 7. Crestline as the watershed anchored by Cape Kipimbi.

Option 2 treats the crestline as a sequence of summits, cutting through the area being studied, while following high points. Figure 8 shows the scenario crestline on top of terrain colored by elevation, ranging from red in the highest areas down to blue in the lowest areas. This option of the crestline runs from the summit of Cape Kipimbi through the intermediate table-land lying between the two escarpments falling within the project area, and then onward following the highest summits lying closest to the western escarpment. Because the chain of high points does not constitute a watershed boundary this line does not thread between drainages but may cross canyons and stream channels at right angles. Further, because the key landforms are escarpments and not a chain of mountains, the high points conceptually representing summits here are generally not noticeable peaks, exhibiting relatively small prominence above surrounding land. For the same reason, the highest points do not always correspond with an escarpment shoulder, as seen in peak points lying to the southwest of the line. Accordingly, one could imagine variations on this concept that deviate from lobes of the escarpment shoulder to touch higher points further to the west.

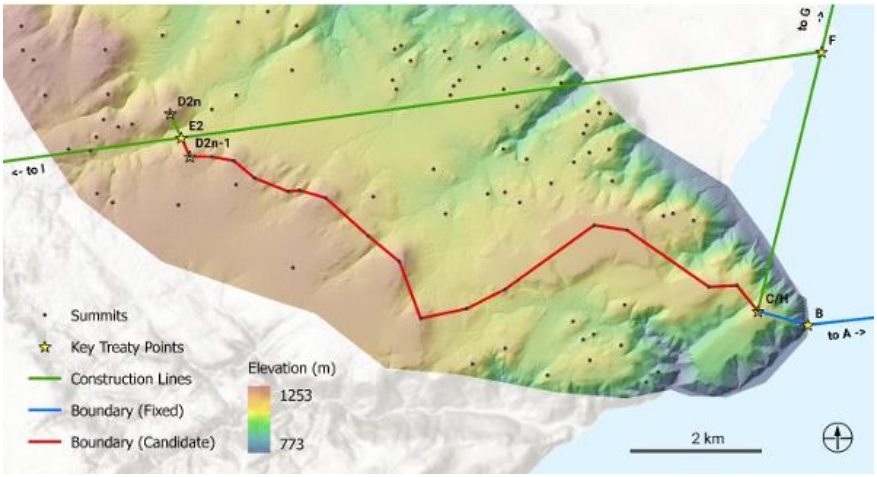

Figure 8. Crestline as a series of summits along the middle escarpment.

Option 3 treats the crestline as the shoulder of the most prominent landform within the project area— that is, the eastern escarpment. Figure 9 shows the scenario crestline overlaid on TPI computed from the new DTM: convex landforms are red, convex landforms are blue, and flat areas are gray. Beacon points are defined as points of greatest TPI – "shoulder points" – along the face of each escarpment lobe, which when connected represent the shoulder of the escarpment (while ignoring the dissections from streams that drain down off the highland above). Notably this shoulder does not always coincide with the highest points nearby, which differentiates this line from the Option 2 line. Of the three options, this line corresponds most closely with a viewer's impression of a "ridge of the Kipimbi Mountains," as viewed from a lower vantage (e.g., from lake level). However, MLG also notes that identifying shoulder points also makes it possible to delineate other lines that follow other shoulders than the one illustrated above.

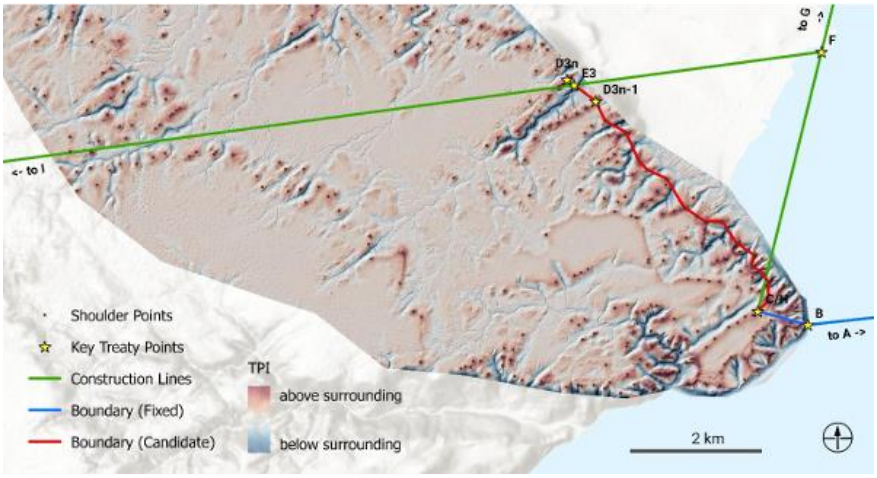

Figure 9. Crestline as shoulder of the most prominent landform, the easternmost escarpment.

Because there is literally no ridge line within the project area, any final set of points must ultimately involve a broadened understanding of what constitutes the treaty's conceptualization of an acceptable "crestline". The previous three options each present a different but internally consistent conceptual definition. However, hybrid lines that mix concepts from Options 1, 2, and 3 are certainly possible, and the national partners may wish to consider such strategies for delineating the boundary.

Option 4 illustrates one of many possible hybrid lines. As with Option 2, Figure 10 above shows the scenario crestline on top of terrain colored by elevation, ranging from red in the highest areas down to blue in the lowest areas. This projected hybrid line follows the watershed boundary from Point C/H up to that line's closest approach within the project area to the median line (Point D4n-2 in the figure above). It then runs to the nearest high point to the north (Point D4n-1 above) and from there to the nearest high point on the far side of the median line (Point D4n above).

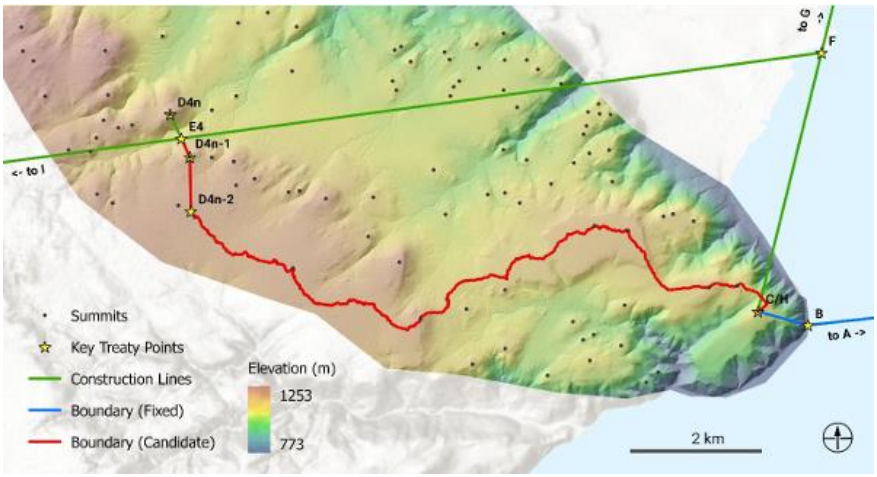

Figure 10. Crestline as a hybrid combining elements of the previous three options.

7. CONCLUSION

The significance of resolving border disputes that have sat in limbo for long periods, sometimes a result of changing political circumstances and priorities and other times a pragmatic realization of not having the resources or technology to demarcate and delineate the boundaries to mutual agreement, is now possible. It is precisely this sort of analysis that can assist the parties involved in border disputes to now see the possibilities of transforming what previously were barriers to bridges of interstate integration and cooperation. The hope is that resolving these disputes diplomatically with concrete data, as represented in the possibilities of digital terrain modeling, will reduce and potentially eliminate the borders from being seen as spots for conflict, crime and violence.

The DTM represents a region on the ill-defined border between Democratic Republic of the Congo and the Republic of Zambia and embodies a new and unprecedented tool for these sovereign neighbors as they seek to resolve long-standing uncertainty about the delineation and demarcation of their shared boundary. Careful analysis of the DTM has identified a set of peaks and delineated the watershed anchored at one end by Cape Kipimbi, but the most consequential finding in the present context is that the steep, tall landforms referred to as Kipimbi Mountains or Kipimbi Range are not mountains in a formal sense, but rather the shoulder and face of an escarpment (or multiple escarpments). As such, they have no natural objective crestline as would be the case for the ridge connecting a series of peaks, and Medici Land Governance cannot delineate the course of a non-existent feature.

Recognizing this, MLG has formalized a framework for the nations of Zambia and the DRC for discussing, locating, and negotiating an agreement on the various elements of the treaty text. MLG hopes this framework will assist the national partners in their effort to reach a shared understanding of where this boundary runs. To that end, MLG has presented a set of possible interpretations that conceive the treaty's "crestline" as features that *are* found in the region's terrain.

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BIOGRAPHICAL NOTES

Ali El Husseini, Ph.D., is the CEO of Medici Land Governance (MLG), a company established in 2018. MLG's mission is focused on applying emerging technologies, including blockchain, to empower developing countries' governments at the local and national levels to verify and validate land rights for their citizens and to develop interactive transparent, secure platforms and mobile applications that provide new economic opportunities for landowners.

CONTACTS

Ali El Husseini, Ph.D
Medici Land Governance
Address
Salt Lake City, Utah
USA
Tel. 801-266-6662
Email: info@mediciland.com
Web site: https://mediciland.com/