

Master Thesis

"Generation of a high-quality physiographic map as a basis for nature conservation and land planning"

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Task Description

Generation of a high-quality physiographic map at a scale 1:100,000 for the entire Kilimanjaro Massif. Besides a highly accurate relief representation (with elevation contours, spot-heights, hill-shading and rock-drawing) the map has to show the complete infrastructure of the National Park (incl. climbing routes, potable water sources, camp-sites), infrastructure outside the national park (incl. roads, railroads, major power lines), certain points of interest, as well as the current vegetation distribution and land-use. The map will include all research plots and their surrounding areas of the KiLi project. With this the map would represent an important tool for land and nature management and planning, e.g. for the National Park authorities and the rural land planning division as well as an important scientific and logistic base for the KiLi-project regarding implementation and data analysis. The quality shall be such that the final map product can well compare with other high-quality maps published in Germany, like the map series of the Consortium for Comparative High-Mountain Research.

Methods

Based on a digital compilation of the existing and available Tanzanian 1:50,000 toposheets, vegetation and climate maps the various layers for the map have to be generated using the current version of ArcGIS. By means of the most recent available high-resolution satellite imagery, the resulting geodata have to be up-dated. Doubtful or questionable spots or areas have to be clarified in field trips during a two-month field campaign. Subsequently the ArcGIS data sets have to be finalized using the cartographic OCAD software.

Abstract

Mt. Kilimanjaro is located on the northern border of Tanzania in East Africa. Its highest point reaches to 5,895 meters above sea level. This makes Mt. Kilimanjaro the highest mountain on the continent of Africa and it ranks as the highest stand-alone mountain in the world. Mt. Kilimanjaro and is an attractive tourist destination, with an average of 50,000 people coming to climb its slopes every year (TANAPA, 2014). Many maps have been made of Mt. Kilimanjaro; most either concentrate on the hiking trails on the mountain and neglect the surrounding area, or they depict the area surrounding the mountain but neglect the hiking routes on the mountain itself. This thesis is an accompaniment to a multi-use map that shows the area surrounding Mt. Kilimanjaro but also details the hiking routes on the mountain. Additionally, land use and vegetation will be included in order to create a basis for further use in nature conservation and land planning. Unfortunately, the map could not be completed within the allotted time given for a master's thesis.

Statement of Authorship

Herewith I declare that I am the sole author of the thesis named

“Generation of a high-quality physiographic map as a basis for nature conservation
and land planning”

Which has been submitted to the study Commission of Geosciences of the Faculty of
Environmental Sciences of TU Dresden today.

I have fully referenced the ideas and work of others, whether published or
unpublished. Literal or analogous citations are clearly marked as such.

Dresden, 15/09/2016

Signature

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Abbreviations

CMYK	Cyan, Magenta, Yellow, Key (Color model)
D.O.S.	Department of Overseas Surveys
FID	Figure Identification
GIMP	GNU Image Manipulation Program
HMFS	Half-Mile Forestry Strip
KINAPA	Kilimanjaro National Parks Authority
JPG	Joint Photographic Experts Group (digital image file format)
OID	Object Identification
OSD	Ordnance Survey Directorate
TANAPA	Tanzanian National Parks Authority
TIF	Tagged Image File Format (digital image file format)
TSD	Tanzania Surveys and Mapping Division

1 Background

Mt. Kilimanjaro is a dormant volcano located in the East African country of Tanzania on the northern border with Kenya. Mount Kilimanjaro is comprised of three volcanic cones, resulting in three peaks: Shira, Mawenzi, and Kibo. Shira and Mawenzi are the remnants of former volcanic peaks (much of which have eroded away). Kibo is the highest of the peaks at 5,895 meters above sea level and the only to retain its volcanic cone shape. Although its altitude is such that it is not among even the top 100 highest peaks in the world, it is the highest mountain on the African continent and the tallest free-standing

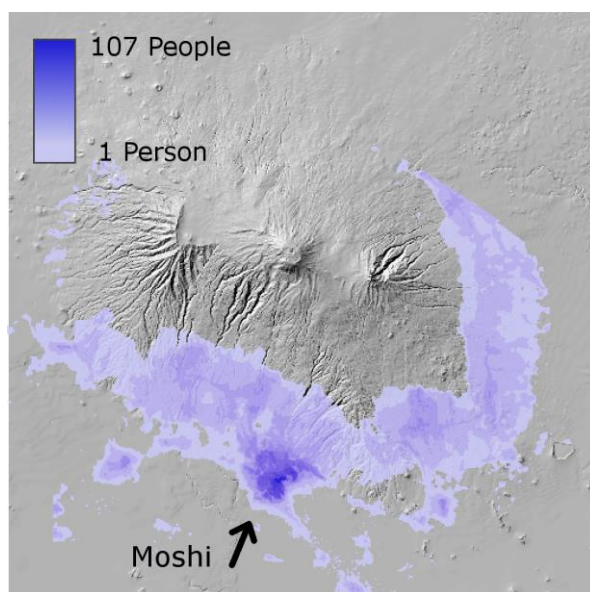


Figure 1.1 Estimated Population Density by grid cell (100m² at the equator) (WorldPop)

mountain in the world (i.e. not a part of a mountain chain). Because of its status and more importantly, its beauty, Mt. Kilimanjaro is an enticing tourist destination; every year, an average of 50,000 people come to climb the mountain (TANAPA, 2014). Over 1.2 million people live on the southern and eastern slopes of the mountain (figure 1.1). The town of Moshi to the south of the mountain is the largest town in the area with 184,292 inhabitants (National Bureau of Statistics et al., 2013)

1.1 Map Review

Most maps of Mt. Kilimanjaro seem to fall into two categories depending on their intended audience. There are maps that detail the hiking trails sufficiently enough for a tourist hiking the mountain (figure 1.2), but they often leave out important areas around the mountain, such as the town of Moshi (figure 1.3) or Lake Chala. The other type of map adequately depicts the topography of the mountain and includes the surrounding region (e.g. Moshi, figure 1.4) but often neglects to adequately detail the hiking paths found on the mountain (figure 1.5).

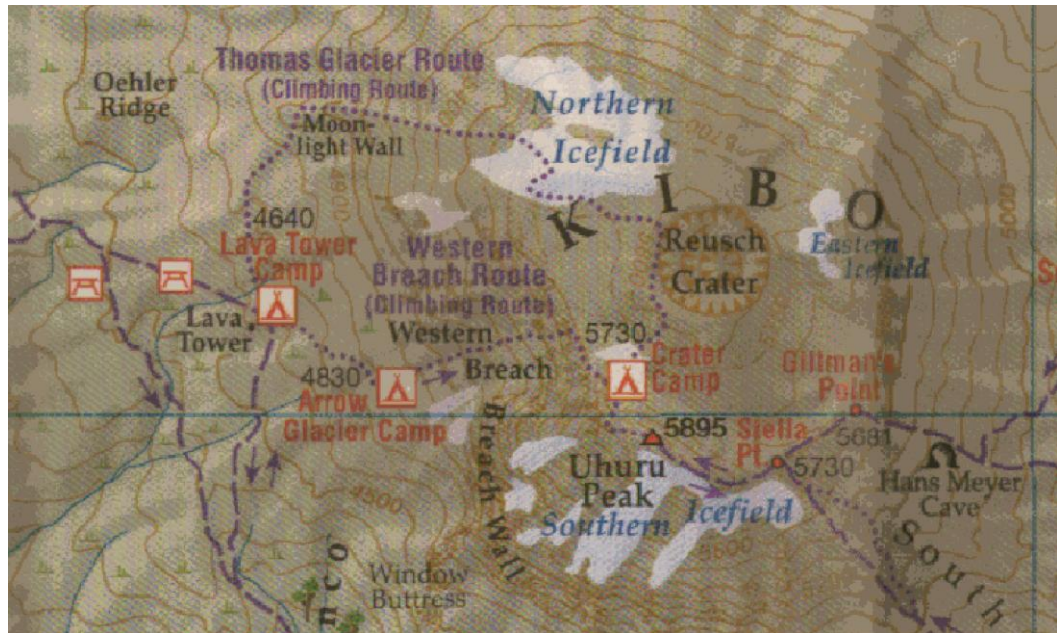


Figure 1.2 Detail of a tourist map showing many hiking trails and related features.

(Harms-ic-verlag, 2011. [1:100,000])

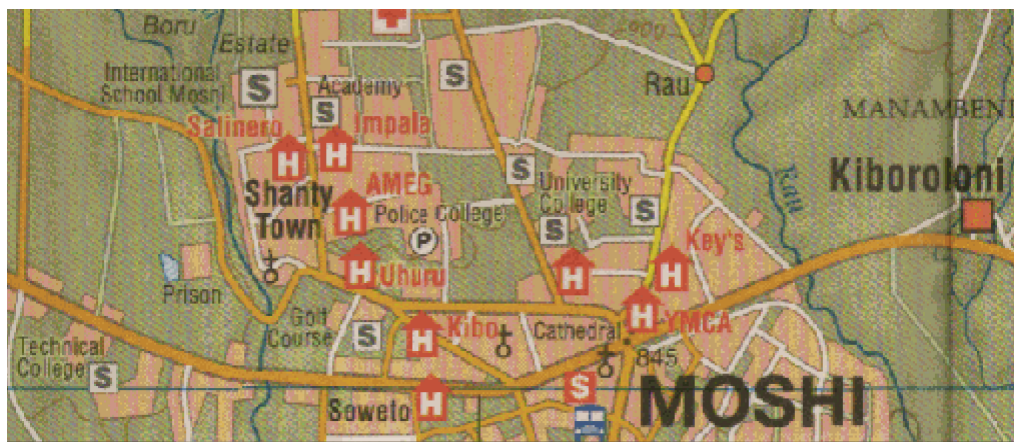


Figure 1.3 Detail of a tourist map which includes only the northern portion of Moshi.

(Harms-ic-verlag, 2011. [1:100,000])

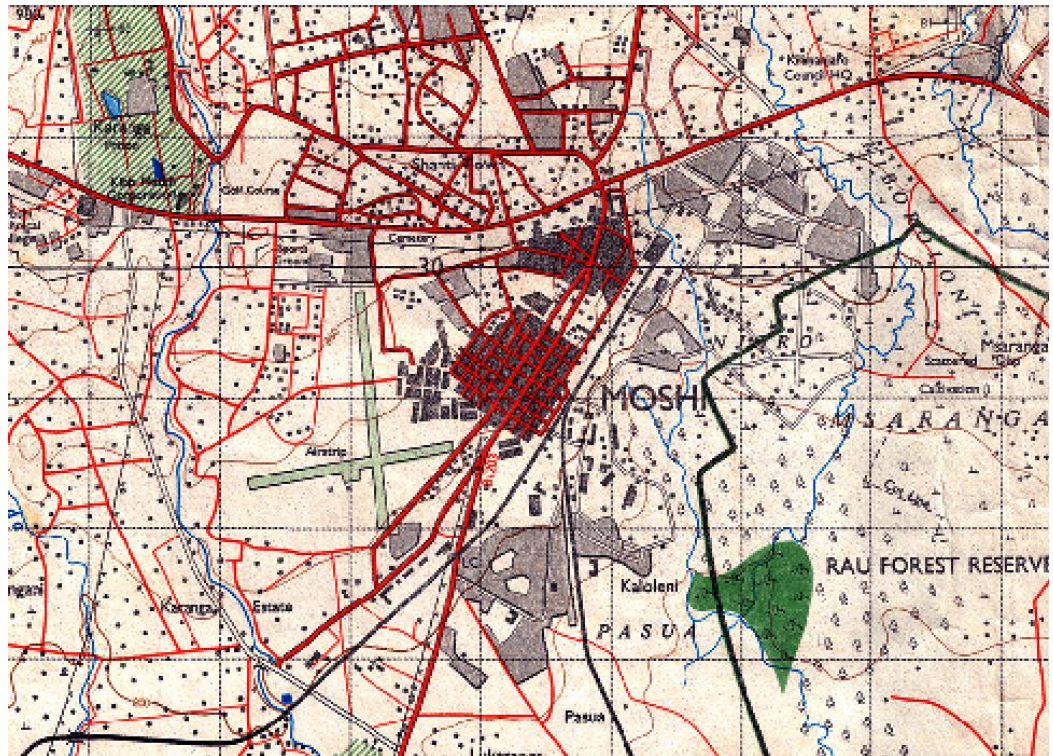


Figure 1.4 Detail of a topographic map that includes the town of Moshi in its entirety.

(Ordnance Survey, 1990 [1:50,000])

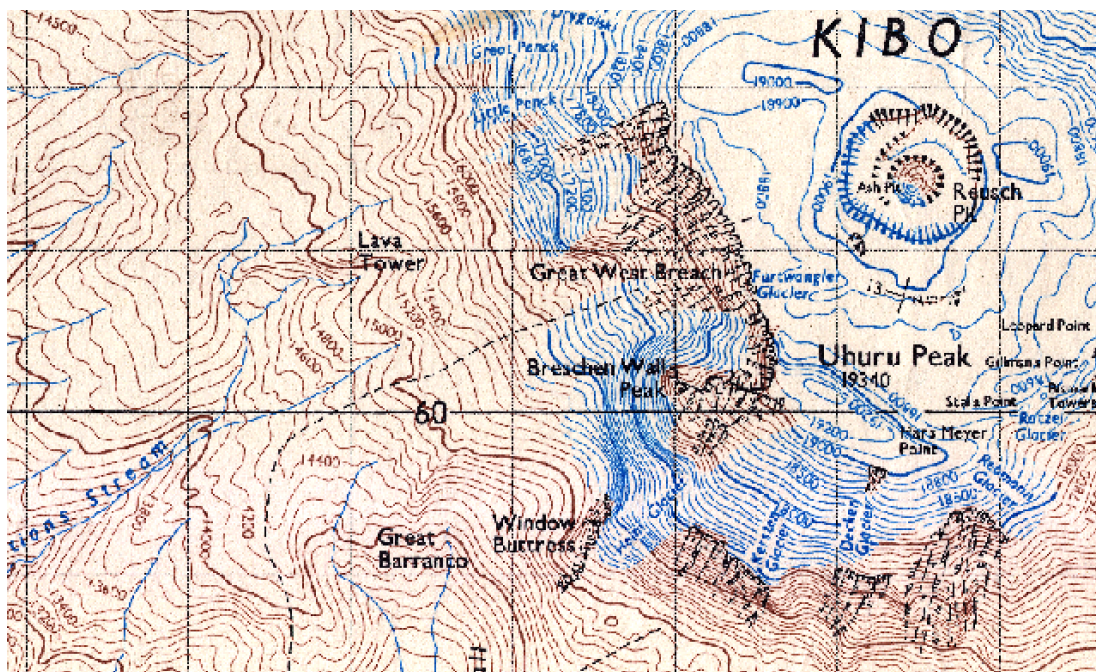


Figure 1.5 Detail of a topographic map showing limited climbing routes and related features

(D.O.S., 1964b. [1:50,000])

The assigned task is to create a map of Mt. Kilimanjaro with a scale of 1:100,000 that includes the surrounding region and to depict the hiking trails and associated features in adequate detail. Essentially, to take the advantages of each type of map, and try to reduce the disadvantages as much as possible. As this will be a multi-use map meant for tourists among others (those who wish to hike Mt. Kilimanjaro are almost exclusively international tourists), the map will also include certain points of interest in the surrounding area. Additionally, land use and vegetation types will be displayed in order to create a basis for nature conservation and land planning. This map will be referred to throughout this thesis as “the final map”.

2 Sources

2.1 Maps

The main source materials for the foundation of the final map consisted of nine topographic sheets tiled into a 3x3 grid at the scale of 1:50,000. For the remainder of the thesis, these nine maps, taken together, will often be referred to as the “source maps” or “the 3x3 grid” and partially or individually as “tiles” (e.g. “the metric tiles”, “the Rongai tile”). They’re placed in the 3x3 grid in the order shown in figure 2.1 and the map sheet information is given in table 2.1. The Olkaria tile is missing its legend. It is similar in style to the maps made in the 1960s, so it is assumed to be a first edition Directorate of Overseas Surveys map rather than the second edition made after 1990. With the edition assumed, the series and sheet number could be inferred from connecting tiles of the same edition, but the year is unknown, and citation in general impossible to complete.

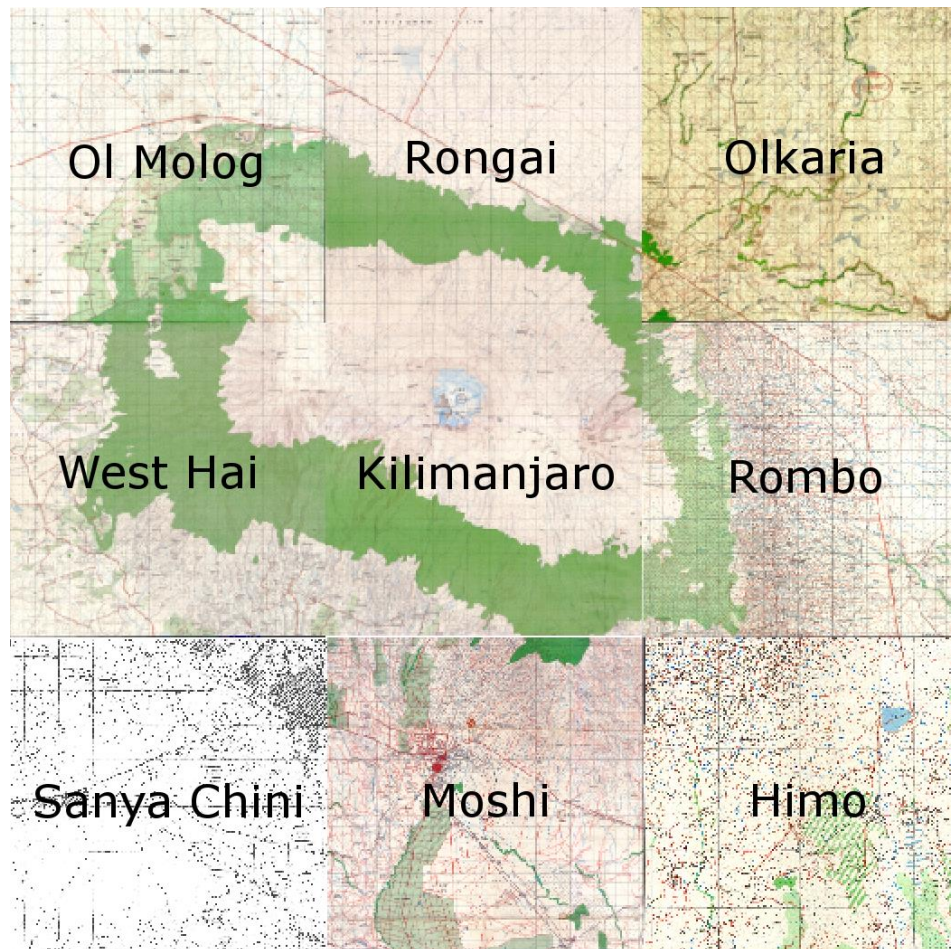


Figure 2.1 Layout of the individual map tiles

Table 2.1 Source maps' metadata

<i>Ol Molog</i> Series: Y742 (D.O.S. 422) Sheet: 42/3 (Kenya 181/3) Edition: 2-TSD/OSD 1990	<i>Rongai</i> Series: Y731 Sheet: 181/4 (Tang 42/4) Edition: I-D.O.S.	<i>Olkaria</i> (supposed) Series: Y731 (D.O.S. 423) Sheet: 182/3 (Tang. 42E/3) Edition: I-D.O.S.
<i>West Hai</i> Series: Y742 (D.O.S. 422) Sheet: 56/1 Edition: I-D.O.S.	<i>Kilimanjaro</i> Series: Y742 (D.O.S. 422) Sheet: 56/2 Edition: I-D.O.S.	<i>Rombo</i> Series: Y742 (D.O.S. 422) Sheet: 57/1 (Kenya 188/1) Edition: 2-TSD/OSD 1990
<i>Sanya Chini</i> Series: Y742 Sheet: 56/3 Edition: I-D.O.S.	<i>Moshi</i> Series: Y742 (D.O.S. 422) Sheet: 57/4 Edition: 2-TSD/OSD 1990	<i>Himo</i> Series: Y742 (D.O.S. 422) Sheet: 57/3 (Kenya 188/3) Edition: 2-TSD/OSD 1990

From these source materials, many shapefiles were digitized. These included contours, roads, rivers, trails, lakes, springs, dams, water holes, cattle dips, urban areas, settlements, shops, land use, and labels. Not all of the digitized layers turned out to be necessary for the final map, but these shapefiles served as a foundation for field truthing.

Although these source maps served as the basis for much of the final map, the age means that for the most part, information retrieved from them could not be used directly. The population of Tanzania as a whole has greatly increased since the 1990s when half of these topographic maps were made, and extremely so since the 1960s when the other half were created. This rise in population has brought about many changes. A higher rate of agriculture, many more housing structures, and better infrastructure are needed to sustain this larger population. Therefore, land use has changed, villages have come into existence, and roads have been built, fallen into disuse, or improved since the creation of the source topographic maps. In addition, since the maps were created, the upper parts of Mt. Kilimanjaro have been put under the protection of the Tanzanian National Parks Authority (TANAPA), and much of the lands which were previously a forest reserve have been merged with the Kilimanjaro National Park. The border of the Kilimanjaro National Park was changed, and given much greater importance in the name of preservation of the park (the general populace is not allowed in the park without permit, logging or poaching is strongly forbidden within the park). Certain branches of the hiking trails have become established as official, and some trails that formerly branched off of the now-official routes have been closed. Logging roads and unofficial trails have fallen into disuse, and will not be included in the final map, as they are closed to public (and perhaps overgrown to the point of being unusable).

Also used as source material were some tourist maps of the mountain. They are more recent maps than the 3x3 grid, but they concentrate on the mountain and trails. This means they were great sources for the hiking trails and other features of interest along the trails (camps, picnic areas, caves, etc.) but were of little to no use for the majority of layers in the final map. These maps included Kilimanjaro-Kibo (Greulich & Wettstein, 2008) and Kilimanjaro National Park, Tourist Map & Guide (Harms-IC-Verlag, 2011). One other map was consulted: Kilimanjaro (Ordinance Survey, 1989). However, because it was created with the same sources of information as the 3x3 grid and does not cover the entire

desired area (Moshi is off the southern edge of the map), it was only consulted infrequently and after creating the foundation from the 3x3 grid.

2.2 Field Work

As a part of the map creation, I conducted field research in Tanzania from November 4th to December 20th, 2015. I was stationed in the village of Kidia (Old Moshi) on the slopes of Mount Kilimanjaro. While there, I was able to closely work with one of my advisors and source of local knowledge around Kilimanjaro, Andreas Hemp. Andreas Hemp was the source of much information and due to our proximity, much of the information sourced from him was acquired during my field work. During my stay, I was able to visit many areas on the southern side of the mountain. It was planned that I would circle the mountain on a trip which would include an ascent up to the Shira Plateau. Unfortunately, my permit to enter the national park did not arrive until days before my departure from Tanzania. This left me with enough time to enter the park once but not enough time to acquire any meaningful data from within the national park, and no time to complete the planned circuit and ascent of Mt. Kilimanjaro. As such, I spent much of the time travelling over the southern slopes and savannah checking for any discrepancies between the source maps and what was seen all around me.

3 Layers

The final map is a product of multiple layers which were worked on in no particular order. Often, work was paused on one layer to work on another depending on any new information that was received. Because of this, rather than detail the work performed on the map chronologically, I will detail the work performed on each layer chronologically (the layers themselves listed in no particular order), which in aggregate, shows the work completed on the map in toto.

3.1 Contour Lines

Of the nine tiled source maps, five use metric units with a contour interval of 20 meters ("Ol Molog", "Olkaria", "Rongai", "Moshi", and "Himo") and four use imperial units with a contour interval of 50 feet ("Rombo", "Kilimanjaro", "West Hai", and "Sanya Chini").

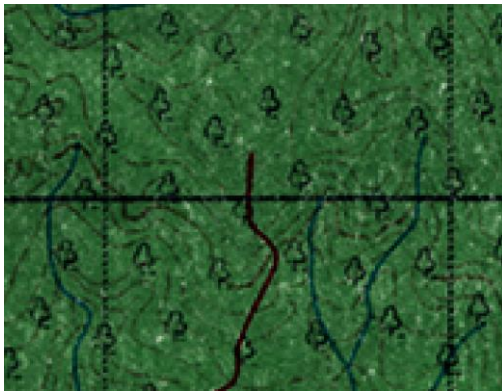


Figure 3.1 Faint contour lines on the
"Moshi" tile (Ordnance Survey, 1990)

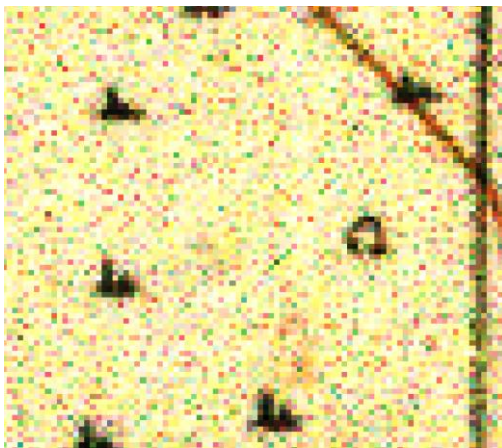


Figure 3.2 Extreme speckling present on
the "Olkaria" tile (D.O.S., unknown)

Due to an early misunderstanding between Manfred Buchroithner, Andreas Hemp and myself, I received only inferior versions of each map from which all features were then digitized (not knowing that higher resolution scans were available). The contour lines were the only features with which it would have been beneficial to have the higher resolution copies, but even so, only two of the nine map tiles had major problems that made digitization more difficult. The "Moshi" tile (Ordnance Survey, 1990) contained a single forested area in which the contour lines were faded and hard to distinguish (figure 3.1), but there were multiple issues with the "Olkaria" tile (D.O.S., unknown, probably 1960s). There was an extreme speckling in the raster image and a yellow tint to the entire map (Figure 3.2) which sometimes made it difficult to differentiate between different colored lines.

The darkness of the green forested areas made it nearly impossible to visually discern the color of line features within. As seen in figure 3.3, normal and thick contour lines, two different types of road, and river line features all look very similar when on the green forest background.

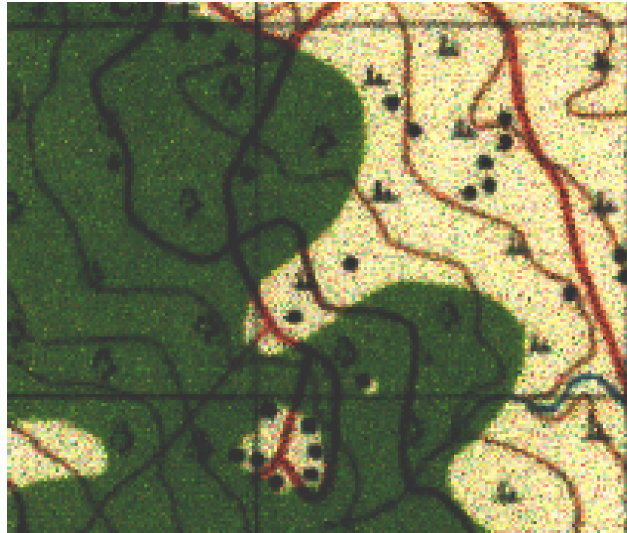


Figure 3.3 Detail of the dark green forest patch in the “Olkaria” tile.

As for the contours themselves, there were two types of unexpected interruptions found in the contour lines. First, in particularly steep areas on the source maps, the contour lines were interrupted to aid legibility (figure 3.4). Theoretically, in extremely steep areas, multiple contour lines might occupy the same space on the map, resulting in an illegible cluster of lines. These interruptions were preserved during digitization.

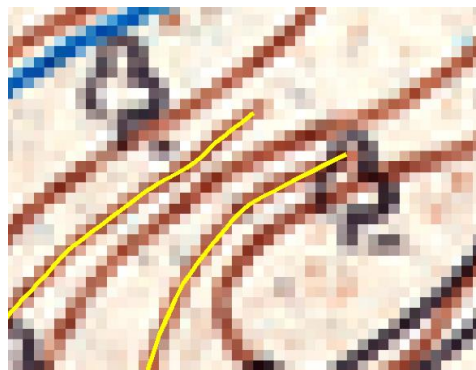


Figure 3.4 Interrupted contour lines present in the “Moshi” tile (Ordnance Survey, 1990).

Other interruptions were found which existed for no observable reason (Figure 3.5). The contour lines were not in a particularly steep area (there would have been no graphic conflicts), there actually were no other important features in the area, and satellite imagery showed nothing special in that location. It was suggested that the interruptions were merely mistakes, so they were simply ignored. Digitization was simply continued over the gap.

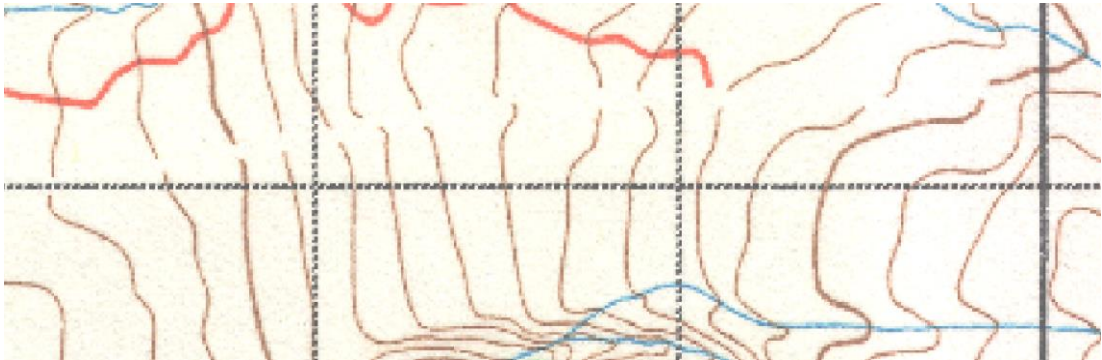


Figure 3.5 Erroneous interruptions present on the "Ol Molog" tile (Ordnance Survey, 1991a)

3.1.1 Digitization

Since completely manual digitization would likely take many months, each map tile was processed to use ArcScan's interactive vectorization tools. In order to use ArcScan, the input must be a binary raster with the foreground to be digitized. This meant the contour lines needed to be extracted from the raster images. Originally, classification tools had problems with the speckled background of each tile (especially the "Olkaria" tile). Low pass kernel filters were used in an attempt to smooth out the speckles, but the one-to-three-pixel-wide contour lines proved to be too fragile to withstand the smoothing (classification tools extracted much less of the contour lines after smoothing). With much experimentation and tweaking of training samples, an adequate classification was created for each tile. Because the classification tool depends on the color of the pixel, classes needed to be created with every different color of contour line pixel. Whereas the unnecessary non-contour classes were simply "black", "grey", "red", "blue", etc. (optimally containing all features of that specific color), contour lines consisted of many different classes. These classes had to account for the normal color of contour lines and also the slight color differences imparted when intersecting differently colored features. There were three types of contour lines: normal contour lines, thick contour lines (at a regular interval there was a thicker contour line with a darker color), and blue contour lines (used to show the existence of ice at higher elevation). A class was created for each contour line type where they crossed over other feature types. That is, classes included normal contours on a green background (forested areas), thick contours crossing a river, blue contours crossing a grid line, and every other combination of contour line type and feature type.

Through the use of the “con” tool, only those classes which contain the contour lines were isolated and merged. This resulted in a raster image, which, in the best case scenario, would contain only contour line pixels. In the case of all nine tiles, however, they contained many non-contour pixels. Training samples were tweaked until there was an acceptably low amount of non-contour pixels erroneously classified as contour line pixels. The ArcScan interactive vectorization tool was very often thrown off by nearby erroneously classified pixels. Digitization would continue towards the erroneous pixels instead of the actual contour line. The erroneous digitization was deleted and manual digitization performed past the problem area, then the interactive vectorization tool could be used once again.

3.1.2 Processing the Digitized Contour Lines

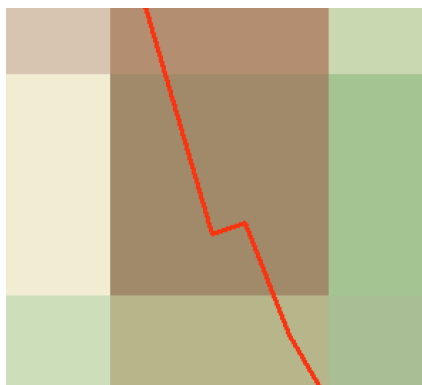


Figure 3.6 Example of a sub-pixel deviation introduced by the interactive vectorization tool.

When every contour line was digitized for all nine map tiles, artefacts introduced by the vectorization tool were attended to. Whenever a section of automatic generalization begins, the tool would digitize from the starting point to the center of the contour line, then continue. This created many pixel- or subpixel-length lateral deviations of the contour line (figure 3.6). As this was done automatically, and the viewing frame was shifted to the end of the automatic digitization section, the only way to check

this error was to stop digitization, scroll to the beginning of the automatic digitization (if the beginning could be found), and check and correct any mistake. Luckily, smoothing the contour lines (which was to be done anyhow) should theoretically resolve any problems with lateral deviations. Unfortunately, due to the size of the deviations, it is impossible to completely confirm whether they all disappeared or not. There were very many of them, but they did not appear in any regular pattern, so the only way to find one would be to zoom in to a contour line and search along its length. Doing this for every deviation is infeasible. It was merely assumed that the smooth line tool dealt with every deviation (as the tolerance was much higher than the average subpixel deviation). To further check and correct any possible errors, a dataset was created from the two contour

shapefiles, and a topology was created. The rules for the topology were: "cannot intersect", "cannot self-intersect", "cannot overlap", "cannot self-overlap" and "cannot have dangles". Contour lines that terminate at the edge of the map will be dangles, but there should be no dangles in the interior of the map besides those interruptions due to steepness present in the source maps. With all these rules, topological errors which were not fixed by prior smoothing were found and manually corrected.

3.1.3 Changing Foot Contours to Meter Contours

The next task was to create meter contour lines from the existing foot contours. To do this, a DTM was created from the foot contours. Unfortunately, there were initially too many vertices in the foot contour shapefile for the "topo to raster" tool. The lines of the foot contours needed first to be simplified. To do this, the "simplify line" tool was used with the point remove variation and a tolerance of .1 meter. Using these parameters, the lines would hardly change, but it would remove any unnecessary vertices. The next attempt to create a DTM was successful. This process was then repeated with the meter contours. After months of vectorization, a 3d model of Mt. Kilimanjaro could be created out of the DTMs using ArcScene. Although not necessary, it was a matter of curiosity. Scanning the 3d model, one inevitable issue with the DTM stood out. There was a stair-stepped pattern from contour line to contour line. This must have come directly from the DTM, and it must have been an artefact of the "Topo to Raster" tool. Unfortunately, any other methods to create a DTM would have taken much longer than could be spared for this thesis. Although the stairstep artefacts are a major problem for any hillshade sourced from this DTM, any contours created from the DTM should contain only minimal errors.

To then create the meter contours from the foot DTM, the "contour" tool was used. New meter contours were created with a 20 meter contour interval to emulate the existing meter contour lines. Unfortunately, something was wrong with the contour data; the new meter contour lines did not line up neatly with the original meter contours whatsoever. Upon further inspection, it became apparent that although the original foot contours lined up with the foot contours from other tiles and the meter contours lined up with meter contours from other tiles, there was a disconnect between the foot tiles and meter tiles. It was expected that the foot and meter contour lines would not line up across the border due to differing units, but there was more error than simply unit conversion. For example,

there was a foot contour line of 3,600 feet that should theoretically meet at the border very near the 1,100 meter contour because it converts to 1,097.28 meters. Instead, it lines up almost exactly with the 1,120 meter contour, and the 1,100 meter contour lines up with the 3,550 foot contour, which converts to 1,082 meters (figure 3.7).

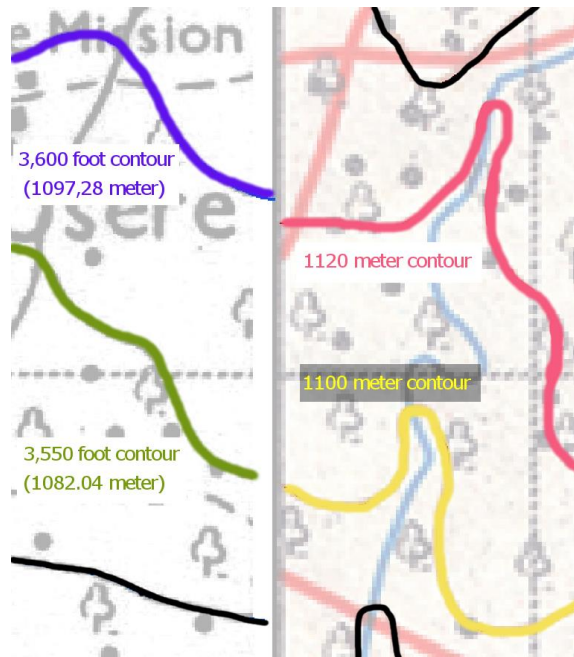


Figure 3.7 Example of the disconnect present between foot and meter contours. left: "Sanya Chini" (D.O.S. 1969) right: "Moshi" (Ordnance Survey, 1990)

Unfortunately, there is no systematic shift in elevations; some contours meet where they should but most do not. Because this error came directly from the source maps, it was advised that we find a way to negate the error along the border of the foot and meter tiles. This was early in the mapmaking process, so further work on the contours was postponed until another work approach was found.

3.1.4 Second DTM

As another part of the misunderstanding between myself and my advisors, when I got to Tanzania, Andreas Hemp said that the contour vectorization that was performed was unnecessary because he actually already had a DTM of the area (produced by J.A. Ong'injo, C. Lambrechts and A.Hemp, henceforth referred to as the "new DTM"). Luckily, that meant that there was one usable consistent DTM rather than two disjointed ones. Out of each of the DTMs (foot-cum-meter, meter, and the new DTM), hillshades were created

in order to better compare them all. Upon comparison, there were a few noticeable differences between them. In the new DTM, there was a large gorge which did not exist in the source maps (figure 3.8), and some hills were shaped differently than in the source maps (figure 3.9). The gorge was shown to be in the western foothills of the mountain. The location of the supposed gorge was checked on available satellite imagery, but only the small river channel shown in the source maps was visible. Upon conferring with Andreas Hemp, the gorge was deemed an error.



Figure 3.8 Erroneous gorge appearing in the new DTM

The differently-shaped hills in question are shaped identically to those on the source maps in two dimensions, but the discrepancy lies in the third dimension. That is, the contour lines would have been shaped the same, but the height values were different. For example, a small caldera in the source maps is a ring shaped hill with a depression in the middle. In the new DTM however, there is a ring shaped hill, but instead of having a full depression within the ring, the land apparently rises again and continues to become a round topped hill as seen in figure 3.9. My theory as to the hill discrepancies is that this DTM was created using the “Topo to Raster” tool (this new DTM also shows a telltale stair-stepped pattern), and whoever created the DTM used incorrect height values for some of the contour lines. In the case of the caldera, they likely overlooked the fact that the contour line values should be decreasing within the caldera.

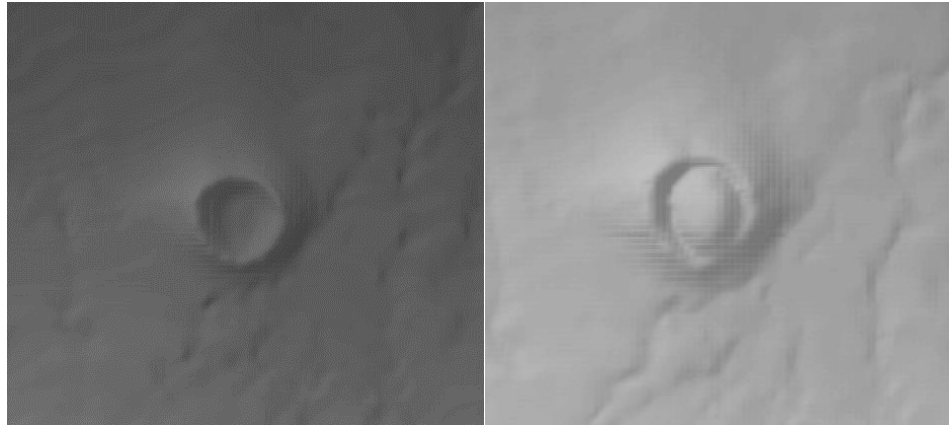


Figure 3.9 Detail of a caldera using the source maps' height values (left) and the new DTM's height values (right).

In any case, this new DTM seemed to contain multiple errors. Manfred Buchroithner suggested contacting someone at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt [DLR]) because in the past, someone had helped him fuse multiple DTMs together into one. After a protracted chain of connections, someone ready and able to help was found. They seemed very willing, and did a small bit of preliminary work, but frequent out-of-office periods and long periods between replies suggested an already heavy work load. The minor work performed on the DTMs was not exactly what was expected. It was hoped that a brand new DTM could be created with the multiple inputs, unfortunately, the preliminary work seemed to consist of an intense smoothing of the inconsistent borders (between foot and meter contour lines). This certainly got rid of inconsistency between the foot and meter contours, but the features of the landscape were intensely obscured at all borders. I tried to explain this, and asked if there was anything that could be done to facilitate further work but received no response. With the sample provided being unlike what was desired and having received no responses after multiple weeks, I decided to continue work on the contour layer alone.

The contours created with 20 meter contour interval were adequate for the source maps at a 1:50,000 scale, but as the final map scale was to be 1:100,000, the contour interval must be increased to preserve legibility. Thinking that the interval should be a multiple of the source maps' 20 meters, contours with 40, 60, and 80 meter intervals were created to ascertain their practicality for the final map. It was advised, however, that either 50 or 100 meter intervals be used. This meant that new meter contour lines needed to be created. A 50 meter contour interval was chosen because it is small enough to

display smaller features in the savannah, which would be lost if using a 100 meter interval. After creating the 50 meter interval contours from both the foot and meter DTMs, there still existed the matter of the border disconnect between foot and meter rasters. The problematic border regions were manually changed in OCAD to connect to their counterpart, accounting for the general landscape of the area (figure 3.10).

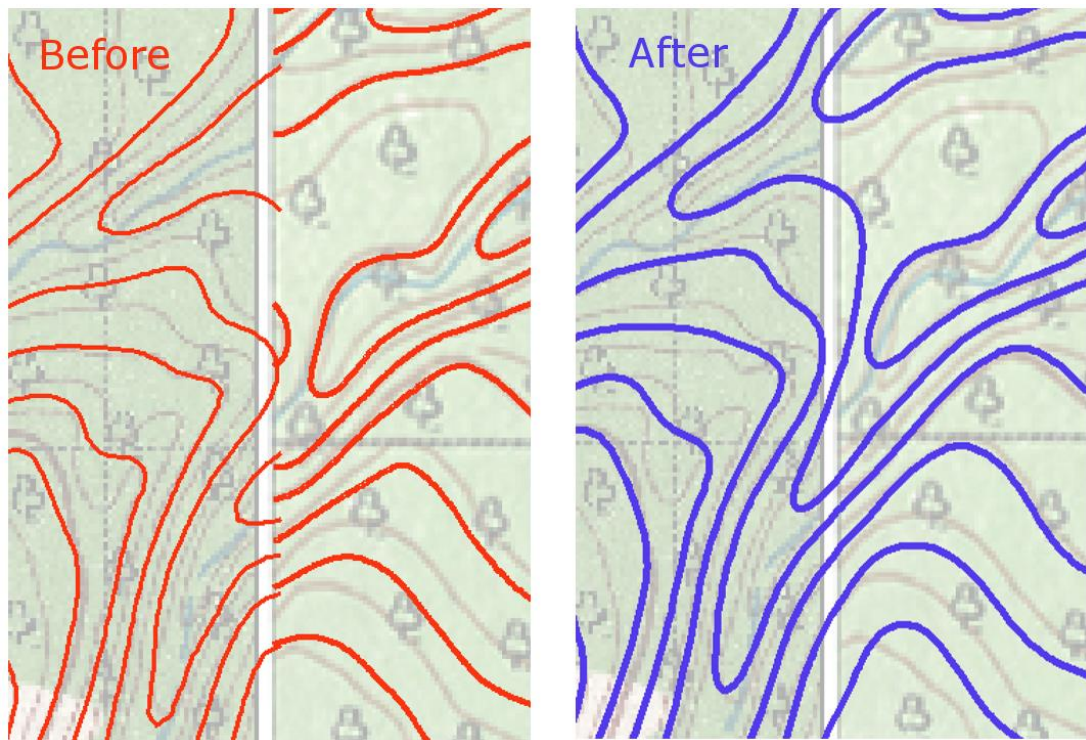


Figure 3.10 Detail from before and after manual connection of contour lines

3.2 Buildings

A distinction is made between different buildings in the source maps; the legends do not explicitly make the difference clear, but there are square and circle symbols on the



Figure 3.11 Detail of the "Moshi" tile (Ordnance Survey, 1990).

source maps. In figure 3.11, you can see a small map excerpt which shows square symbols in the lower portion, and circle symbols in the upper portion. In figures 3.12 and 3.13, one can see the two different legend schemas for buildings. It seems that circle symbols are either residences or non-permanent buildings, and square symbols connote a built-up or more permanent building.

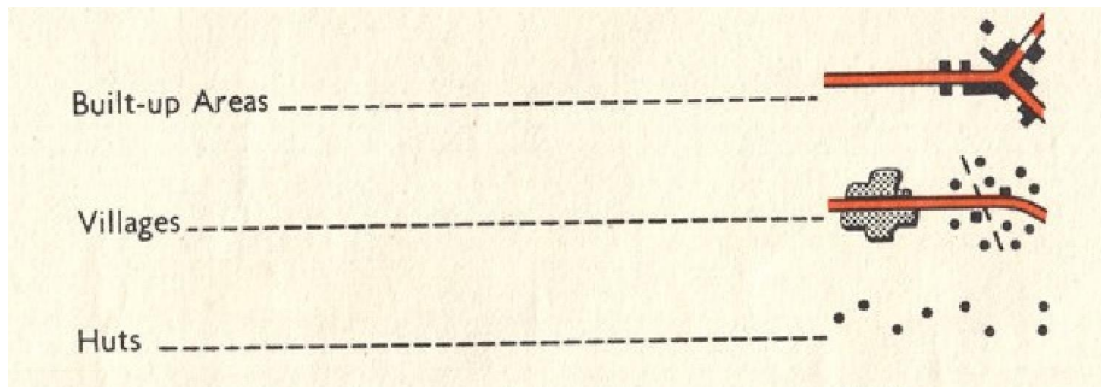


Figure 3.12 Legend excerpt from "Rongai" tile (D.O.S., 1963).

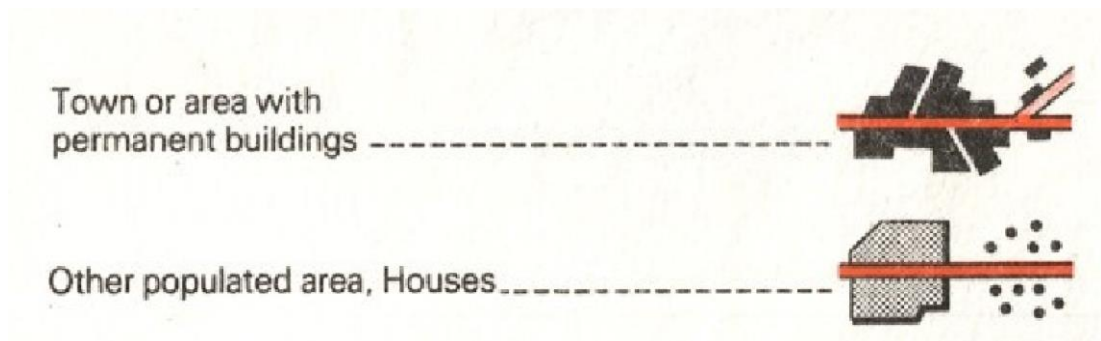


Figure 3.13 Legend excerpt from "Rombo" tile (Ordnance Survey, 1991).

In any case, the distinction between building types is not necessary for the final map, so the two building types have been merged. The dramatic population increase since the source maps were created makes an update necessary. Population density has risen and villages and towns have grown as population increased. Some places that were depicted as empty savannah in the source maps are now the location of sizeable villages. Conversely, certain areas shown in the source maps to contain buildings have been vacated and the buildings removed.

3.2.1 Building Digitization

First the 49,911 buildings (both square and circle symbols) in the source maps were digitized as a foundation for further edits and updates. Under advisement from Andreas Hemp, when updating the building layer, points were to be placed in order to replicate the general distribution of buildings but not necessarily for each and every building. In the higher density towns and villages, creating a point per building would be

unnecessarily tedious for our purposes (if not impossible with the available satellite data), so an overall impression of populated and unpopulated areas was the goal.

Where building density is high and point-per-building digitization becomes infeasible (i.e. points overlap), the points were manually generalized as they were digitized (i.e. points were placed within the dense area so they would not overlap). Due to this manual generalization, it was necessary to keep the same scale throughout the digitization, or else the resulting building point shapefile would not have a consistent resolution (i.e. maximum density). Because no scale is evident in the satellite imagery, digitization must be performed with consistent variables. The grid present in the source maps was overlaid on top of satellite imagery as a zoom guide; digitization was performed always with the width of two grid cells visible on the same monitor (even a smaller or larger monitor would skew the resolution). A specific symbol shape and size was used for the entire process; if the cue to generalize was overlapping symbols, a smaller symbol would mean higher resolution. If the product was to be a true density map of the buildings, such manual generalization would be inappropriate. However, the goal in digitizing the building layer was to give a general idea of populated areas, so it would be of no use to create thousands of extra points which could not possibly be shown in the scale of the final map.

The quality of the satellite imagery varied, so the ease of detection of buildings varied. There are almost certainly locations in which some buildings avoided detection, but as the goal was to merely provide an overall impression of populated or unpopulated areas, a problem would exist only if there were multiple undetected buildings in an area devoid of digitized symbols. After deleting many buildings that no longer exist and adding many more that have been created since the source maps were published, the building layer contained 75,821 points. At the scale of the final map (1:100,000), all of the digitized buildings were not able to be symbolized. Even with the manual generalization already performed, the point density was still generally much too high. In high density areas, every other layer was obfuscated by building points. Even with a small point symbol, the building layer was a messy conglomeration of points. Some further generalization was necessary.

3.2.2 Processing of the Building Shapefile

There were three operations utilized to generalize the points into something usable via selection/elimination. The tools can be sorted into two categories: the first is spatial (deletion by location), the second is quantitative (deletion of a portion). Two spatial generalization tools were used: the first of these deals with conflicts with other layers (ArcMap's "Select by Location"), and the other deals with conflicts within the building layer itself (ArcMap's "Delete Identical" tool). The quantitative operation deals with thinning the database somewhat so other layers are not obfuscated (i.e. deletion of every n -th row in the database).

3.2.2.1 Select by Location

The "Select by Location" tool was used to select building points within a given distance to certain other layers. The distance was chosen within which there would be graphical conflicts (i.e. buildings overlapping roads or rivers), and the selected building points were then discarded. It was briefly thought that the building layer could be placed underneath the other layers in order to retain the building points yet divert the focus to the roads and rivers. Unfortunately, this did not work well visually with the smaller lines of the minor roads and rivers. Even with the larger line features, the buildings protruding from underneath the roads do not add much information and their deletion gives a cleaner appearance to the lines. Through experimentation, it was found that deleting those buildings within 30 meters of paved roads, and 25 meters of major roads, minor roads, and rivers resulted in an acceptable output. Theoretically, if there were single strips of buildings along those roads, deleting buildings that overlap the roads would be problematic. However, wherever there was an abundance of buildings which were deleted because of their close proximity to roads, there were plenty of buildings a little further from the road (which were not deleted) to preserve the general impression of building presence.

3.2.2.2 Delete Identical

The second spatial tool utilized was the "Delete Identical" tool. Although the tool's name suggests that it deals only with identical features, the "XY tolerance" parameter makes it possible to delete features within a given XY tolerance from one another on the basis of identical attributes. In this case, points within the XY tolerance are deleted on the basis of

their “shape” (i.e. the existence of a point within the tolerance is enough to warrant deletion). Setting the tolerance at 75 meters provided an output with no overlapping building points at the desired scale and size of building symbol. The sheer number of building points seemed too great, so I experimented with the “delete identical” tool to thin the points with larger and larger XY tolerances. Although a higher tolerance decreased the number of building points in as desired, the density variation within the building point layer was completely destroyed. In figure 3.14, one can see a theoretical example of how the “delete identical” tool affects density variation. In short, the point density in towns and villages became nearly the same as sparsely populated savannah fields. To counter this misrepresentation, a process was devised to delete points with roughly the same density variation as the entire building point layer. This is the quantitative operation.

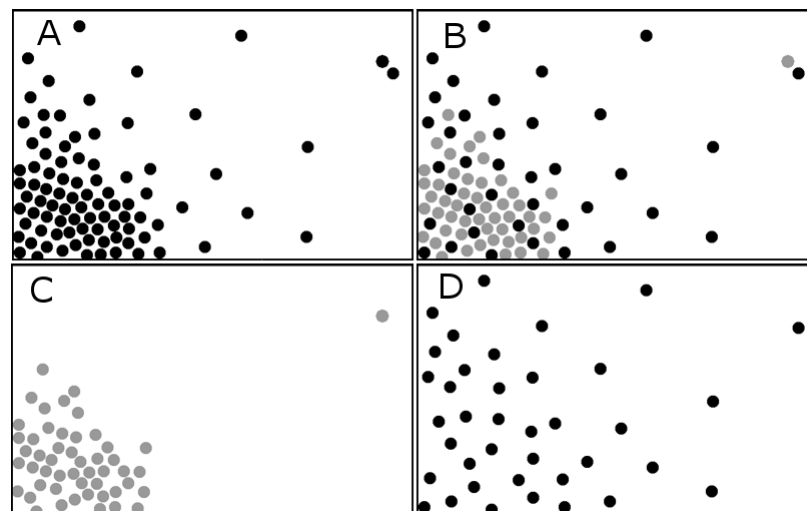


Figure 3.14 Theoretical situation showing the “Delete Identical” tool’s effect on density variation.

If the tool is used on a sample point layer (A), points within a given tolerance are deleted (grey symbols in B). These points for the most part come only from high density areas (C) and the result is a loss of density variation (D).

3.2.2.3 Quantitative operation

The quantitative operation is the selection and deletion of points based on their database row. Database rows are created sequentially as points are digitized, so deleting every n -th row deletes every n -th digitized building point. Using the “Select By Attributes” tool, one can make use of a sequential numeric database field such as a unique identifier

(OBJECTID, FID, OID, etc.) to select a portion of the database, which could then be discarded or kept as a new shapefile (discarding the unselected portion). Using the SQL formula: `"SELECT * FROM [the building layer] WHERE MOD('OBJECTID', 2)=0"` will select every second database entry (changing the "2" to a "3" will select every third, "4" every fourth, and so on). Theoretically, if there were not a regular placement of building points, deleting every n th database row could change the distribution of points so that the density variation is altered or artificial clusters are created. For example, if points are digitized alternating between left and right halves of an area, as shown in figure 3.15, deleting every second database row would delete all the points in one half but none in the other. Because the building points were digitized systematically (in transects from north to south and vice versa) and not haphazardly, this process thins the database and preserves density variation without introducing false cluster patterns as in figure 3.15.

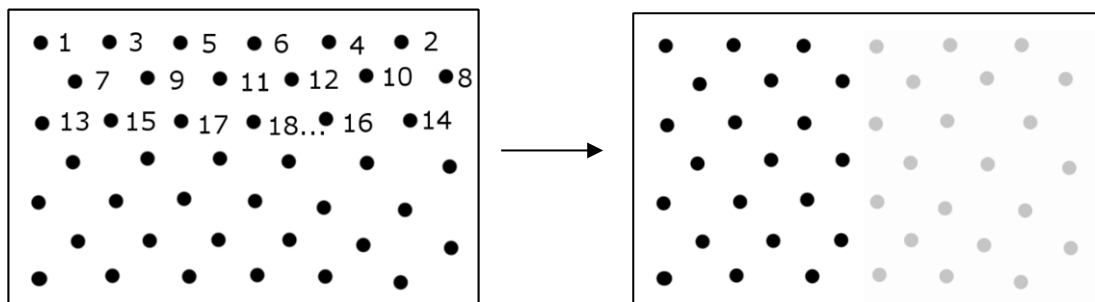


Figure 3.15 Theoretical example before and after quantitative operation. Numbers designate the order of digitization. When every other database row (i.e. digitized point) is deleted (gray dots on the right), false patterns can emerge.

Deletion of $1/4$, $1/3$, $1/2$, $2/3$, and $3/4$ of the building points were tested. This operation worked well to thin the database but cannot solely produce a suitable output. For example, deleting every third point does little to resolve graphical conflicts in dense areas, but deleting a majority of the points makes it seem as though nobody lives outside of towns and villages. Therefore, both spatial and quantitative methods would be used in conjunction.

The spatial tools should be used after the quantitative operation to help preserve density variation (figure 3.15). The order of spatial tools can make a difference as well (figure 3.16). If "Delete Identical" were used before "Select by Location" (blue arrows in figure 3.16), it is possible that some building points would be deleted in favor of other

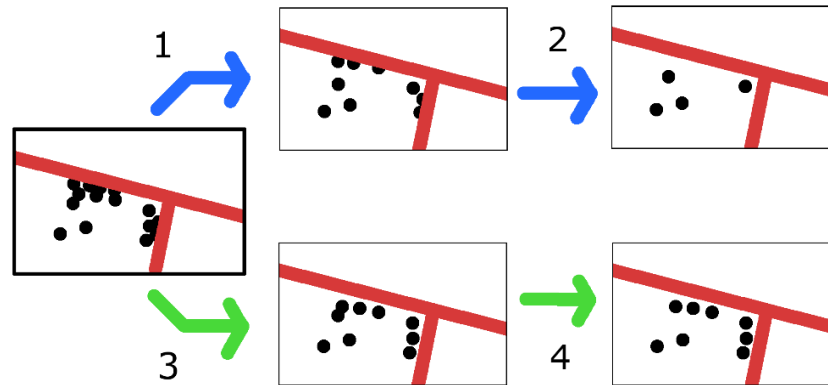


Figure 3.16 Different orders of spatial operations. Blue arrows show "Delete Identical" performed first, green arrows show "Select by Location" performed first.

building points overlapping a road (step 1). Those points would in turn be deleted when using "Select by Location" to delete points overlapping roads and rivers (step 2). However, if "Select by Location" were used first (green arrows), the points overlapping roads would be deleted (step 3) and then "Delete Identical" can deal with any further graphical conflicts. This way, buildings near roads can be preserved as much as possible. The order of operations, then, should be thus: quantitative operation, "Select by Location", "Delete Identical". However, after some consideration of this final output, it was advised that an alternate be created. The alternate was to contain polygons (to be mentioned in more detail later) rather than the dense point-filled villages. Without the need to cull some points within the dense village clusters, the quantitative operation was deemed unnecessary. Therefore, "Select by Location" was performed with respect to the roads, rivers, and also village polygons. Building points were deleted within 75 meters of the village polygons to leave a slight buffer between single building points and village polygons. The "Delete Identical" tool was then used with a 75 meter tolerance to produce the final building layer.

3.3 Town/Village Polygons

It was decided that polygons be used for towns and villages rather than the building points, because the high density of building points in those areas obfuscated other layers. Due to Andreas Hemp's experience and knowledge of the Kilimanjaro region, he created a shapefile with polygons of the important villages to be represented as polygons in the final map. The only processing needed was to smooth the polygons. They were smoothed with a 250 Meter tolerance and will be used in the final map.

3.4 Roads

Roads were initially digitized from the source topographic maps. The location and status of roads were confirmed (or edited) during the field work in Tanzania. Using a GPS device loaded with the source maps, the digitized road network was compared to reality while traveling along various roadways. A waypoint was created in the GPS device when any discrepancies were noticed, and a note taken to detail the type of discrepancy. Eventually, the day's track (where we had driven) and waypoints (discrepancies) were imported into the computer. The digitized road network was then edited using the waypoints as guides as to what edits were necessary. Due to the number of roads to be depicted in the final map, driving along every single road would have taken much longer than the duration of field work in Tanzania. Therefore, roads that could not be checked in person were confirmed or edited as needed with help from available satellite imagery.

The source maps contained various categories of roads including "All Weather Road - Bound Surface", "All Weather Road - Loose Surface", "Dry Weather Road", "Main Track (Motorable)", "Other Track and Footpath". The final map takes this schema and tweaks it slightly; certain classes have been merged and titles changed, but the overall categorization is similar. The categories used are "Minor Road (4x4 Required)", "Major Road (4x4 Recommended)", and "Paved Road". In the mapped area, there are relatively few paved roads and their category is obvious. The distinction between "Minor Road" and "Major Road", however, is less obvious. Certain roads could easily be placed in one category or the other, but in any doubt, Andreas Hemp made the decision in which category a road was to be placed.

3.5 Hiking Trails

Initial digitization came primarily from the "Kilimanjaro" tile (D.O.S. 1964b), but as it is over 50 years old, numerous edits were expected and indeed necessary. Due to the unfortunately long waiting time between applying for a permit to enter the national park and receiving the permit, there was no chance to personally gather data concerning the trails within the park. Since the "Kilimanjaro" tile was created, many tracks depicted have been closed to the public and certain routes have been cemented as official. Absent on the "Kilimanjaro" tile were many of the non-summit hiking trails (such as circuits), or trails to the lower peaks of Mawenzi and Shira. Over the years, Andreas Hemp has manually

drawn in existing trails to his paper copy of the “Kilimanjaro” topographic sheet. With his help, many relevant trails were added to the scant few trails already digitized. The trails were then compared to other tourist maps, and trails that were not already present in the digitized trail network were added (of which there were few).

3.6 Rivers

The rivers were digitized using the source maps. The source maps had two classes of flowing water: “watercourse” and “indefinite”. It was chosen to use one class of river for the map because of the difficulty in determining whether a river had become more or less “indefinite” (i.e. whether a river had changed categories) in the recent decades. During field work, rivers could not be checked as freely as could the roads. Rivers could not be followed up- and down- stream as easily as roads could be driven on, and in fact, there was often no “river” to speak of. Much of the year, many of the rivers depicted in the map are nothing more than dry creek beds or trenches, filled only during periods of heavy rain. Because fields and depressions seen during field work may have been destined to become ponds and streams during the long rainy season, the existence of streams could often be neither confirmed nor denied simply because of the time of year. Since field work was little help in confirming the accuracy of the rivers layer, another tool able to be utilized was satellite imagery.

One might hope for satellite imagery during the rainy season when riverbeds are full, but with the rainy season comes cloud cover which often makes satellite imagery useless. As such, the majority of available imagery comes from periods with little to no rain. Detection of permanent rivers in the savannah is possible; sometimes a glint might be seen reflected off flowing water, or using imagery with high resolution one might be able to see the water itself tinting the riverbed. Often however, they are detected indirectly through the impact made to their environment, such as the presence of eroded gorges or the serpentine patterns of riparian vegetation. The smaller the stream, the less impact it has on its environment. Small seasonal streams might exist on the available satellite imagery only as dry depressions or small trenches nearly impossible to identify as a stream bed. Therefore, the smaller a stream is, the more difficult it is to identify. Thus, it is infeasible to confirm or deny the existence of many of the streams in the savannah. Unfortunately, on the mountain itself, it is practically impossible to detect rivers due to widespread tree

cover. With the difficulties of surveying rivers in person and the limited feasibility of detection by satellite imagery, only two small measures were undertaken to edit the rivers layer. First, cursory scans of the satellite imagery were made and the rivers were changed only if substantial deviations to the digitized rivers layer were found (no dramatic changes could be confidently identified). Second, the digitized rivers layer was scanned to find any suspect river courses (e.g. where a river runs towards another but ends meters before joining as a tributary), the satellite imagery was consulted when one was found, and edits made if necessary. Otherwise, all river data digitized from the source maps were to be retained and assumed to be correct.

3.7 Springs

Springs were digitized from the source maps. They were generally in areas difficult or impossible to check. Some were in the national park, and many were across the border in Kenya (both inaccessible during the field work). The springs are too small to be visible with the satellite images available. Therefore, I was not able to confirm the location of the springs, so the locations of springs come solely from the source maps. Boreholes, cattle dips, water holes and wells were digitized from the source map, but deemed insignificant and therefore not to be included in the final map.

3.8 Bodies of Water

Lakes and reservoirs were digitized from the source maps. They are present on the map submitted alongside this thesis, but their final status is still uncertain. Many of the digitized lakes and reservoirs are quite small. To depict them on the final map at scale, they should be less than a millimeter in length. This means a decision has to be made whether to enlarge these lakes for display on the final map – as with *Kilimanjaro* (Ordnance Survey, 1989) – or to leave them out. If the small reservoirs are deleted, it must then be decided whether the corresponding dams are important enough to be symbolized in the final map. There are dams on rivers, which should likely be included, but some dams and reservoirs are some distance away from river paths. Whether they should be included in the final map has yet to be determined. Nevertheless, there are multiple large lakes, reservoirs and important dams which will certainly be included in the final map.

3.9 Vegetation

My vegetation base layer was created from multiple sources. The main source was a vegetation map supplied by Andreas Hemp (Hemp, 2006). This map covered roughly 75% of the final map coverage, and contained overlaid graphic elements including contour lines, village polygons, village labels, roads, rivers, national park boundary, etc. (figure 3.17). Because the overlaid graphic elements were not required, it was necessary to extract only the basemap vegetation zones from the map. Manual digitization would have been needlessly time consuming because there were hundreds or thousands of separate vegetation patches and further processing would still need to be performed before cartographic use.

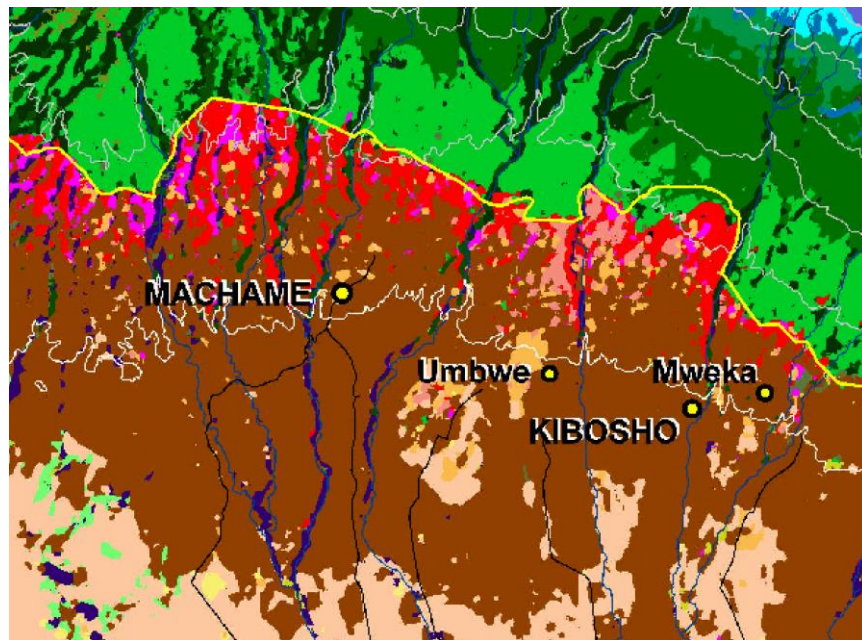


Figure 3.17 Detail of vegetation map showing graphic overlays.

3.9.1 Classification Tools

The first attempts at extraction consisted of using the unsupervised and supervised classification tools included in ArcMap. The unsupervised classification was completely unusable; there were myriad classes, with no observable pattern to the classification (one class contained pixels from multiple different vegetation categories). The supervised classification was more productive but ultimately unsuccessful for the same reasons. There were more than 20 classes in the vegetation map to account for, and some of the classes consisted of very subtle color differences (figure 3.18). The tools consistently mistook similarly colored classes for each other. This vegetation map image was a lossy file format (JPG). Therefore, throughout the areas of supposedly consistent vegetation, there were many different pixel colors; all similar, but not identical. As can be seen in figure 3.19, what should have been two neatly defined color zones actually contained many different pixel colors (i.e. many more than the two that should be present). Even when using the colored legend boxes as training samples, the resulting classification was rife with errors (figure 3.20).

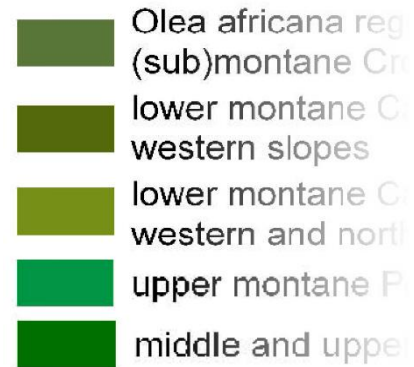


Figure 3.18 Example of similar colors in the vegetation map



Figure 3.19 Close-up of the vegetation JPG with lossy pixels evident.



Figure 3.20 Erroneous classification caused by lossy pixels.

The borders of individual vegetation zones were especially error prone. Large homogenous areas were usually classified together into one class, but a different class was sometimes given to every single pixel within a few pixel widths of the border.

Expecting that all vegetation zones under a given size could somehow be deleted, it was briefly considered to further process the output of the supervised classification tool into a usable product. The myriad single-cell vegetation zones (or zones under a certain size) could be deleted as long as the inner portions of each larger vegetation zone were correctly classified (resulting in a single large patch). There were two problems however: the interior of large vegetation zones was not always classified into one single category and some of the erroneous features were quite large. The classification sometimes resulted in very thin (less than 10 pixels' width) erroneous classes, which appeared at the border of entire vegetation zones. Depending on the size of the zone, the area of the erroneous border class might be quite sizeable. One would have to find and delete each of the erroneous border classes, which means checking hundreds of vegetation patches for an erroneous border class. No path forward could be found with the lossy vegetation map and the output of the classification tools.

After hearing of the problems encountered and after some searching through hard drives, Andreas Hemp found two more images of the vegetation map, both of them lossless TIF files. The first one included hillshading as well as the overlaid graphic elements, and the other contained the graphic elements but no hillshading and was not georeferenced. Hillshading was incompatible with the classification tools for a similar reason that the JPG was unusable; hillshading introduces different colored pixels (intentionally in this case), which the tools confuse with other classes. A cursory test confirmed that there were insurmountable problems with any output of the classification tools with the hillshaded vegetation map.

3.9.2 Extraction by Color

After the problems with the supervised classification tool, it came to mind to try some image manipulation techniques. The TIF without hillshading was imported into the program GIMP (GNU Image Manipulation Program) to try to extract the regions by color. Using the legend as the "official" color for each vegetation type, all pixels with that precise CMYK color were selected. Each vegetation class was exported as their own TIF files and imported into ArcMap. This procedure worked well. Each vegetation type was effectively able to be isolated. The one downside is that it left the resulting image with many holes where certain off-colored pixels existed, as well as any other overlain data

such as roads. The holes from the overlain graphic elements were unavoidable and would be dealt with when the vegetation data was altogether further processed. With Andreas Hemp's guidance, certain vegetation classes were merged together (certain subclasses of vegetation were not necessary for the final map). Then the individual images were merged into one image (with a database field to preserve the vegetation classes). Finally, this single image had to be georeferenced. As the map had few features other than vegetation, it was difficult to accurately place control points to georeference the image to the source maps. Luckily, having another georeferenced vegetation map made it simple to match points from this TIF vegetation map to the georeferenced JPG vegetation map.

3.9.3 Second Vegetation Source

My second source was data from a yet-unpublished paper of Andreas Hemp's and a colleague of his, Pekka Hurskainen. It was in the form of a georeferenced TIF raster image. The classes included in the data were much more detailed than necessary for the purpose of the final map. With Andreas' guidance, classes were either deleted or merged with others. This resulted in a second source with holes where there were once irrelevant classes. The two sources overlapped somewhat, but where there was overlap, this second data source was used. This second data source is current data as opposed to the other decade old data. This new vegetation data, appended to the other data, covered another roughly 10% of the map. Now there was an issue: roughly 85% of the map was covered by vegetation polygons, but there was still another 15% with no vegetation data. It would be unacceptable to create a map with partial vegetation data, but there was no other known source of vegetation to cover the remaining 15%. The only option seemed to be to create the vegetation polygons. Andreas Hemp would create the remaining 15% of the vegetation polygons necessary to cover the extent of the final map. As this would be a time-consuming task, the vegetation polygons from the two sources were further processed to deal with the holes in the vegetation layers. Final processing would only happen with 100% vegetation coverage, but I wanted to know exactly how to process the vegetation as soon as it was received.

3.9.4 Processing the Vegetation Polygons

From each of the sources, there are vegetation patches simply too small for the scale of the final map scale (1:100,000). To generalize the vegetation data, it was converted back and forth between raster and vector data to take advantage of operations able to be performed on each. While in raster form, the “expand” tool in ArcGIS can be used to expand each vegetation zone by a certain number of pixels. This allows it to expand into the holes in the data. After expanding into a portion of the holes, it is easily converted back to vector data. The smallest vegetation zones can easily be accessed due to a “shape area” database row and then easily deleted. Converting back into raster format, the zones are expanded into the new holes created by deleting the smallest patches. This process can be repeated back-and-forth until enough of the smallest patches are deleted to make the vegetation layer adequate for the final scale.

Deletion was done in small steps, going back and forth between deleting the smallest polygons (vector) and expanding into the resulting holes (raster), because if all vegetation zones below the eventual size threshold were deleted in one step and the remaining vegetation zones expanded into the resulting holes, certain artefacts could become apparent. The vegetation zones surrounding the hole would expand until they meet another vegetation zone. Theoretically, the polygons would meet along the topological skeleton of the hole to be expanded into (figure 3.21). Topological skeletons seem to mostly consist of more or less straight lines, so any hole would be filled with polygons that meet at straight lines. The larger the hole to be expanded into, the larger the skeleton-shaped border. If deletion and expansion are performed instead in small amounts at a time, the skeleton pattern is less apparent (many small skeleton patterns rather than one large one). Deleting and expanding in such a piece-wise manner does not necessarily make the data any more correct, but it is merely an attempt to give it a more natural look.

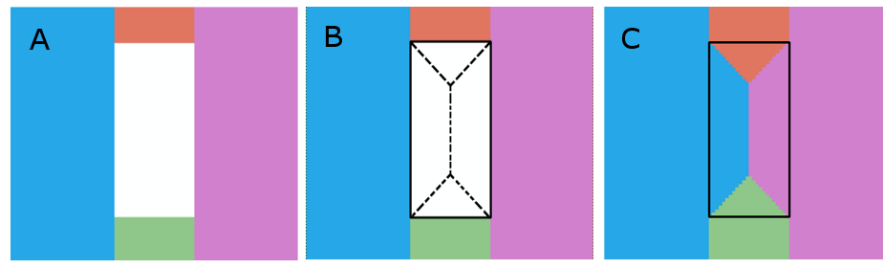


Figure 3.21 Theoretical example showing the expand tool and its relation to topological skeletons.

A: a hole surrounded by four polygons. B: hole border and topological skeleton (dashed line) highlighted. C: After expansion, the polygons meet at the location of the former hole's topological skeleton.

There are drawbacks of performing such a system of delete and expand; deletion based on size alone could delete important vegetation zones such as vegetation along rivers. Many patches of vegetation along rivers are classified as "riverine vegetation" and many are classified as "marsh vegetation". If these patches are small enough, they might be deleted altogether during a delete step and surrounding vegetation zones (e.g. savannah or agriculture) would expand to fill the hole. Riparian vegetation is an important vegetation type to preserve and therefore, a more selective deletion should be performed. Instead of deleting simply by size, one can use the "select by attributes" tool in ArcGIS to selectively delete patches under a certain size based on their vegetation type (i.e. preserve the riparian vegetation types).

Unfortunately, due to time constraints, the remaining 15% of vegetation was not able to be created before this thesis was to be submitted. The remaining 10% of the vegetation data must still be completed, and the vegetation data processed altogether before use in the final map.

3.10 Swamps

Swamps were digitized from the source maps and confirmed with satellite imagery. In the source maps, the majority of swamps fall under the category "seasonal swamp". Unfortunately, as with rivers, these swamps depend on rainfall. Without imagery from the rainy season, swamps might never be spotted as easily as they otherwise would be. As seen during field work, dry swamps look different than the surrounding savannah. The vegetation is different, and the color of the soil is sometimes different as well, (possibly due a buildup of salts and minerals from repeated evaporation). Using satellite imagery,

seasonal swamps can often be identified and confirmed by the presence of different vegetation. Many of the seasonal swamps depicted in the source maps now show obvious agricultural or residential land-use patterns. Presumably, the swamp no longer exists. The presence of many of the swamps, though, is difficult to confirm or deny. There are often neither signs of swamp, nor changed land use (such as agriculture). It is impossible to tell whether the swamp exists but can't be seen in the dry-season satellite imagery, or if there is simply no swamp in that location. It was advised that further work on the swamp layer be delayed until the vegetation data was complete, and the marsh/swamp vegetation zones be used as clues as to which swamps still exist, should be edited, or deleted altogether. Because the vegetation data wasn't created by the time of this thesis' submission, no further work was performed on the swamp layer.

3.11 Rock and glacier drawings

Andreas Hemp created the rock and glacier drawings included in the map. After some image manipulation, the drawings were georeferenced and placed in the map. These drawings are not yet final versions. The final versions of the drawings will be completed in the weeks to come.

3.12 Park Boundary and Half-Mile Forestry Strip

There is no park boundary shown on any of the source maps but even if there were, it would need to be updated. The montane forest on Mt. Kilimanjaro was protected as a forest reserve in 1921, but not until 1973 was Mt. Kilimanjaro declared a national park (UNESCO, n.d). Even so, only the mountain above the 2,700 meter contour and six forest corridors along the hiking trails were considered national park. In September 2005, the Kilimanjaro Forest Reserve was merged with the Kilimanjaro National Park Authority (KINAPA), and most forest reserve lands were absorbed into the national park. The majority of the map tiles were created before the national park existed. In those tiles that were made after the creation of the national park, vegetation change and the abrupt absence of settlements are the only clues as to the location of the park boundary (or what was at the time the forest reserve boundary).

There is a large roughly half-mile wide strip of land on the eastern and southern edges of the national park known as the half-mile forestry strip (HMFS) (figure 3.22). These lands were set aside in 1941 to be managed by the Chagga council for the purpose of cheap wood production (Kivumbi & Newmark, 1995). Ownership and land management of the HMFS has changed multiple times since then (district councils' commercial wood production; central government's concentration on soil and water conservation, etc.[*ibid.*]), and the ownership of the HMFS is currently being debated between KINAPA and the local villages.

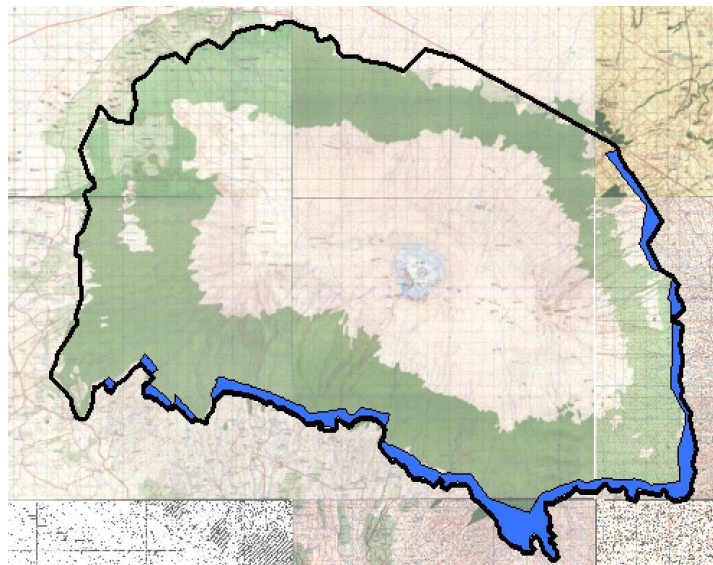


Figure 3.22 HMFS shown (blue) within the boundary of the former forest reserve lands.

Multiple different polygon shapefiles were used as sources for the park boundary and HMFS. The first shapefile depicted the forest reserve lands in 1972 in the "Arc 1960" datum. The other shapefile depicted the national park with its current boundaries (minus HMFS), though shifted many meters away and overly simplified (what should be smooth curves are instead angular). To avoid confusion, these boundary files will be referred to by their file type (e.g. "national park raster", "forest reserve shapefile", or the generic "layer"), and the real-life boundaries will be referred to as "national park boundary" and "forest reserve boundary".

3.12.1 Transformations Applied

Although the metadata showed that the national park shapefile was supposedly in the correct datum (Arc 1960), there was certainly some positional error. After converting the

polygons to line features for a better view, some common datum transformations were applied to the national park shapefile. The assumption was that the unknown transformation was simply a difference in datum or projection incurred through mistaken use of ArcMap's "Define Projection" and "Project" tools. Unfortunately, none of the chosen transformations resulted in an accurate boundary.

3.12.2 Partial Manual Georeference

Without a perfect fit found for the national park shapefile, it was decided to georeference the national park layer, but use sections of the forest reserve shapefile wherever possible. The national park shapefile was converted to a raster image and manually georeferenced to line up with the forest reserve shapefile. The forest reserve boundary is not identical to today's national park boundary, but enough boundary is the same to confidently place control points on the two layers (see black colored line in figure 3.23). This placed the national park raster in the correct location, but its over-simplification meant it was not suitable for the final map. A new shapefile was created from parts of each boundary. The national park raster was converted back to a shapefile and both the national park shapefile and the forest reserve shapefile were split where they deviated from each other. The difference between the two boundaries can be seen in figure 3.23. The identical portions of the two boundaries are shown in black and the deviations shown in color (former forest reserve in blue, national park in red). A new boundary was created piece-wise from both shapefiles using the forest reserve boundary wherever possible (black portions of the boundary in figure 3.23), and the national park boundary where necessary (red portions).

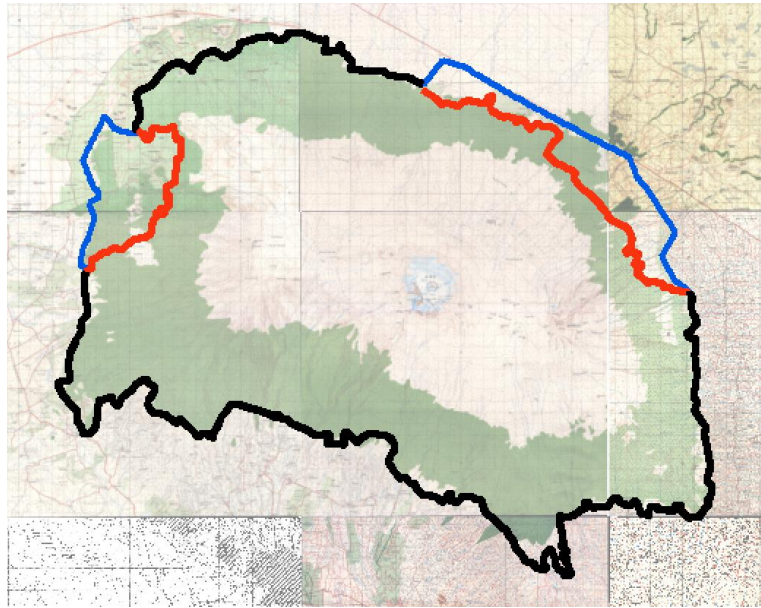


Figure 3.23 Diagram of the former forest reserve boundary (blue) and the current national park boundary (red). Shared boundary shown in black.

Unfortunately, upon further inspection of the forest reserve boundary, Andreas Hemp found that it did not precisely conform to the location of the boundary that he knew to exist at certain locations. Any georeferencing based on the imprecise forest reserve shapefile would therefore itself be imprecise (as would this new boundary sourced mainly from the forest reserve shapefile).

3.12.3 Manual Georeference of Boundary

The last resort was to forgo using the forest reserve shapefile as a template, and manually georeference the boundary around the entirety of the park. The national park shapefile was the closest we had to an accurate border, so it was converted to a raster image for use as a template for manipulation. The raster line was then manually georeferenced with around 175 reference points determined by Andreas Hemp. A spline transformation was used to make the boundary line adhere to Andreas Hemp's control points. In the end, a passable boundary line was created. The control points were placed according to knowledge and experience, but also educated guess. Without a reliable boundary line to use as a guide, this was the best shapefile obtainable.

3.12.4 Correct Boundary

Later, after conversing with a colleague, Andreas Hemp was able to obtain a different shapefile of the updated park boundary in the “WGS 84” datum. After a quick conversion to our “Arc 1960” datum, it was placed accurately, and was an obvious replacement to our georeferenced boundary line. Also included was a shapefile of the original HMFS. Part of the original HMFS to the northeast of the mountain is outside of the current national park boundary (figure 3.25). As with the rest of the HMFS, this portion was once the outer edge of the forest reserve, but the inlying forest reserve land was one of two large areas which operated as commercial forest plantations (orange in figure 3.24) and not eventually merged with the national park. The HMFS was clipped to the border of the national park and is to be used in the final map.

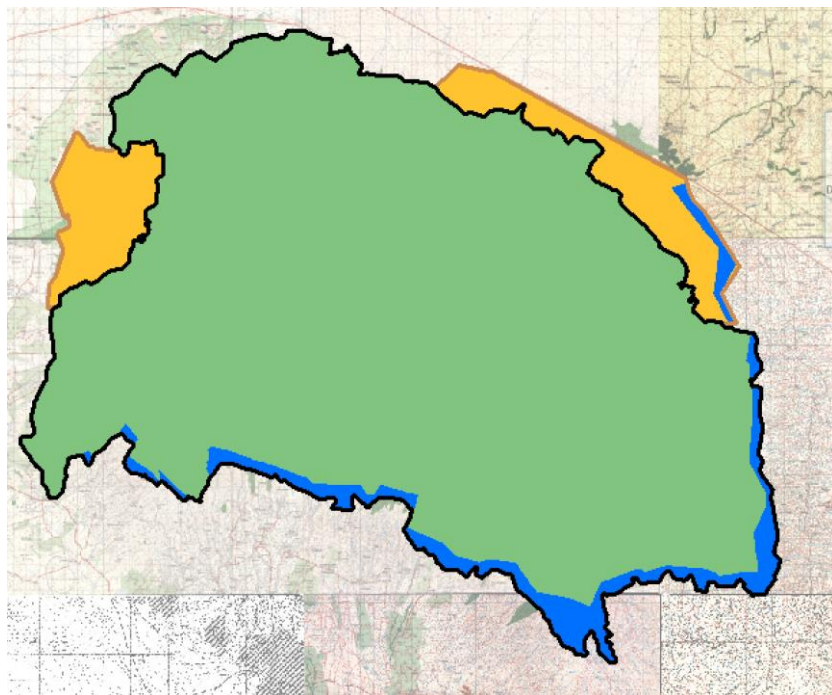


Figure 3.24 Diagram showing the HMFS (blue) within the national park (green) and the commercial forest plantations not merged with the national park (orange).

3.13 Points of Interest

As this map could be used by tourists, it was suggested that points of interest be included in the final map such as waterfalls, hot springs, important cultural sites, etc. A local tour

guide was contacted regarding possible locations to be included on the map. Unfortunately, as my field work came to an end, there was little to no time to confer with him and create a tourist destination layer. Theoretically, points could be created through email correspondence, but without someone to point to a specific location, the difficulty of placing points would be compounded greatly. It was decided that Andreas Hemp would have to meet with the tour guide and create the layer with his help at some point in the future. Unfortunately, that meeting did not occur by the submission date of this thesis.

3.14 Airports

Since the "Sanya Chini" tile (D.O.S., 1969) was created, the Kilimanjaro International Airport (KIA) was created. It lies between the towns of Arusha and Moshi, and is likely the entry point into Tanzania for most international guests to the Kilimanjaro region. Recent satellite imagery was used to digitize the airport's airfield and certain unreachable roads. The Moshi Airport, located within Moshi itself, was digitized from the source maps and with the help of satellite imagery.

3.15 Powerlines

Only the largest powerlines in the region were digitized (those on the largest stanchions transmitting over 60kV). Powerline locations were ascertained through personal observations, Andreas Hemp's knowledge, and use of available satellite imagery. Known powerlines were located on available satellite imagery through the detection of stanchions, and the path of the powerlines was pieced together by scanning for further stanchions. For the most part, the locations of stanchions were logical spots for the continuation of the powerlines, but in certain situations, further personal observations were necessary because either no further stanchions could be located, or the location seemed strange because it did not follow the general pattern of powerlines continuing straight from the stanchion, or at gentle angles.

3.16 Railroads

Railroads in the map area were built around 100 years ago and are no longer used. There are plans to restart rail service, but significant reconstruction will no doubt first be necessary. Although the rail lines are more or less useless, the rails still exist and are

therefore useful to facilitate orientation. Because no changes have been made to the rail network since they were created, the railroads were taken directly from the source maps.

3.17 Quarries

A couple quarries were located and digitized with the help of Andreas Hemp. The rest were located by scanning available satellite imagery for the entire map area. In certain locations with many quarries near each other, each individual quarry was digitized. This created a quarry layer that must still be generalized due to clusters of quarries too dense for the scale of the final map (1:100,000).

3.18 Symbols

As a start of the cartographic design, certain symbols have been created for the final map. (WC, water point, picnic area, helipad, etc.) These symbols are only prototype symbols, every part of them are still open for editing when performing final cartographic design. It is possible, however, that the symbols present on the map submitted with this thesis will be the symbols that appear on the final map.

4 Further Work

This map could not be completed within the timeframe allotted for a master's thesis. Many of the layers required lengthy digitization or processing; often, weeks or months were spent doing one single task throughout every single day (e.g. digitizing contour lines, scanning satellite imagery for roads, digitizing building points, etc). Between the lengthy processing, problems with the data, and lack of available data sources, progress on the final map was steady but disappointingly slow. Several layers must still be finalized before use in the final map. Vegetation data, bodies of water, rock drawings, tourist destinations and swamps all need to be processed to some extent (or created altogether) before cartographic use. Then, the lengthy cartographic design process can begin. With all of the layers present, colors, patterns, symbols, shapes, and sizes need to be chosen for every feature to best suit the map. Outside of cartographic design, simple layout design is needed to create and arrange the different map elements. The legend must be created once the symbols for each feature are finalized, and the further necessary map elements (north arrow, metadata, scale,

etc) must be created and placed. The submission of this thesis does not signal the end of work on this map of Mt. Kilimanjaro and the surrounding region. Work will continue as time allows.

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