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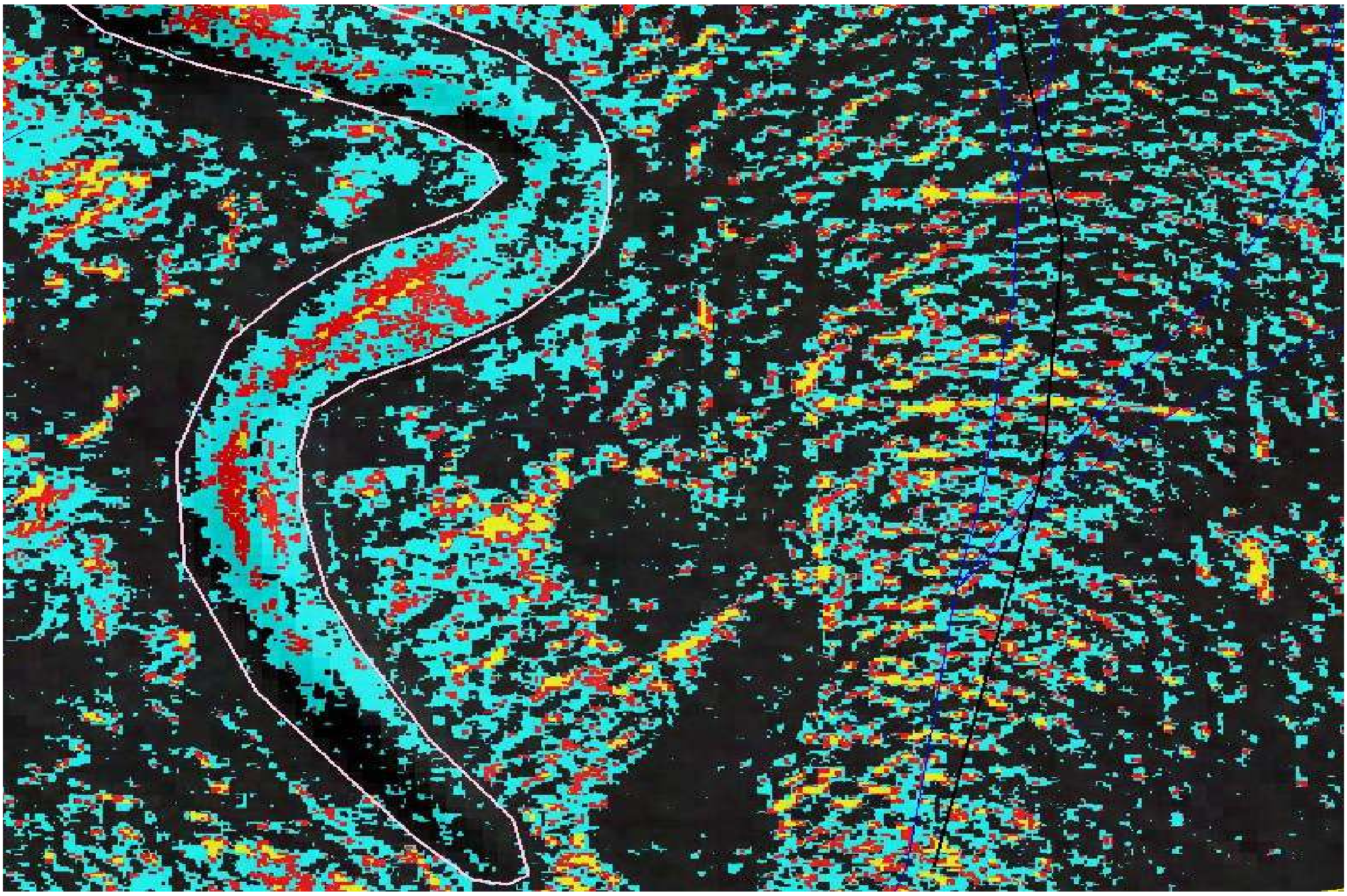
Tarascon, 4th July 2013

Project Ref: *Ref.: Consultancy Report NMSU-USGS Subcontract No. Q01581 for the project*
Groundwater Exploration and Assessment in the Eastern Lowlands and associated Highlands of the Ogaden Basin Area, Eastern Ethiopia

Executive Summary

This is the final report for the USAID-USGS-NMSU project for Groundwater Exploration and Assessment in the Eastern Lowlands and associated Highlands of the Ogaden Basin Area, Eastern Ethiopia.This USAID-funded project aims to help the Ethiopian Government and NGOs working in the water sector to increase their borehole drilling success.

FINAL TECHNICAL REPORT



USGS science for a changing world — USAID FROM THE AMERICAN PEOPLE — RTI — Water for everyone, everywhere watex

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I. EXECUTIVE SUMMARY

In the context of emergency, field insecurity and urgency, conventional methods of mapping groundwater in the greater Horn of Africa region have largely been limited in addressing recent famine and drought, yielding results too fragmented, and impracticable for achieving meaningful sustainable responses. In this context, UNESCO has adopted the WATEX© System approach developed by its partner Radar Technologies International (RTI) to achieve comprehensive, rapid, large-scale hydrogeological investigations to improve the effectiveness of drought mitigation efforts in the region.

This system integrates remote sensing (hyper frequencies and optic) with geophysical and conventional hydrogeological assessment techniques and geographic information systems to map and assess alluvial, fractures and deep aquifers for a wide range of contexts, including conflict, emergency and early recovery situations.

During the course of this investigation of a 41 000 km² has been added in the southern continuation of the 16,323 km² zone of the Upper Fafen-Jerer River system in the Somali Region of eastern Ethiopia, the WATEX© System has mapped all shallow alluvial groundwater, conductive fractures and deep aquifer structures. In addition to water resources, this study mapped the geological formations, structure, soils and recharge, enabling a full assessment of hydrogeology of the survey area. Hydrogeology has been assessed in terms of its precise location, potential storage capacity and recharge.

A major finding of this survey is the discovery and assessment of a deep seated aquifer structure, which was undocumented in existing literature or scientific knowledge. The East Karamara aquifer is located on the eastern flanks of the Karamara Mountain Rage, situated 3 km southeast of Jijiga town. It is buried from 50 to 700 m below the surface along the Jerer Valley, is 1 to 35 km wide and 200 km long. The structure comprises highly permeable karstified Hamanlei limestone and Adigrat sandstone. It is partially confined by impermeable aquicludes of the Karamara basaltic range to the west, the uplifted basement to the east, and sealed by Uarandab shale formations above. Groundwater flows through the aquifer in an indicative 143° SE direction, with a high probability of artesian conditions in the southern half of the aquifer. The structure continues on the project extension to the South West, near Birkot, along the Fafen valley down to the great gypsum barrier which represents a major discontinuity in the hydrogeologic system of the survey area.

The estimate of the storage capacity of this structure aquifer is under evaluation by the USGS but it geometry extending to 200 km long and an average of 15 km width might reveal the major aquifer of this eastern part of Ogaden.

The validity of the model will continue to be strengthened as more boreholes are drilled with the survey maps and tools. The uncertainties and limitations presented herein, particularly those dependent upon solid rainfall and evapotranspiration data, will be further refined with the use of aquifer well logs and additional hydrogeological modeling.

The maps and tools resulting from this study, including the new information about shallow alluvial groundwater, perched paleo-rivers and the large Karamara aquifer, significantly raises the prospect for improving the livelihoods of the nearly 1 million people living in this water-scarce area, most of who live in poverty and have limited access to basic services and clean water.

With proven productive boreholes in the aquifer zone, the WATEX© groundwater target maps have great potential to improve the efficiency of borehole drilling from 25% to up to 77% proven with the present wells drilled by IRC. We expect to increase soon this rate of success over 80%.

On a scientific level, the detection of the Karamara aquifer in a region where most known sedimentary aquifers are uplifted tabular plateaus opens the prospect to detect other similar structures in the Horn of Africa during the expected Phase II.

II. INTRODUCTION

This report has been prepared by Radar Technologies International (RTI), further referred to as "RTI" or the "Consultant", in compliance with the ***Subcontract No. Q01581 for the project*** **Groundwater Exploration and Assessment in the Eastern Lowlands and associated Highlands of the Ogaden Basin Area, Eastern Ethiopia signed the 19th of April 2013**
The study mainly focuses on the assessment of the groundwater potential and its quality.

RTI has been contracted by NMSU to provide highly technical services of developing a database of hydrogeological information derived from advanced remote-sensing information of the Eastern Higlands of Ogaden and Jerer Valleys of the Somali Region in Ethiopia.
In addition to the database, RTI shall deliver specialized hydrogeological analysis, technical advice for project planning, and assistance in building capacities of beneficiaries in database management.

RTI is applying its proprietary technological approach called the WATEX© System, which enables the integration of remote-sensing (radar, optical, geophysical) and conventional data into a comprehensive observation and assessment. The WATEX© survey was focused on the area prioritized by the Government of Ethiopia, i.e. a 41 000 km^2 swath of the Lower Fafen Valley within the larger Juba–Shebelle Basin (See 1.4 below for a map of study area). This area defines the geographic scope of the services to being provided by RTI.

A. Scope of work

As per the contract, RTI is providing the following services:

1. Groundwater resources database (GIS)

RTI is developing a GIS database of hydrogeological resources which will be delivered to USAID-USGS before the end of July 2013. The database will compile the results of implementing the WATEX© System.

2. Thematic digital maps

RTI has developed a package of thematic, high-quality maps for USAID-USGS, including a hydrogeological map, soil map and aquifer recharge map. Other maps such as geological maps will be developed since they are a prerequisite for the afore-mentioned maps.

3. Groundwater Exploration Navigation Systems (GENS)

RTI will also develop and deliver to USAID-USGS two (2) units of the Groundwater Exploration Navigation System (GENS) by the end of June 2013. The GENS will be a practical tool that will allow field technicians and well drillers to easily navigate and locate groundwater by enabling field access to maps and coordinates that lead to high potential water sites, resulting in higher accuracy locating potential water sites than using maps. The GENS must enable beneficiaries to save time and resources and avoid long delays and costly un-productive well-drilling.

4. Drilling handbook

RTI will also develop and deliver a "Drilling Handbook" document for well drillers and groundwater field technicians. Tailored to the specific study area, the main purpose of the Handbook will be to guide groundwater experts on best zones for groundwater productivity and recharge in the study area. Users of the Handbook should be able to drill new productive wells more rapidly and minimize the loss of time and resources associated with drilling unproductive wells. RTI will deliver to USGS-USAID 4× hard copies and electronic copies of the Handbook by the beginning of July 2013.

5. Analysis and technical advice

Finally, RTI will provide USAID-USGS scientific analysis of the results of work performed, including expert advice and recommendations on the potential for improving groundwater management in the specific study area. Such analysis will entail drafting of technical reports, such as the present consultancy report and the final technical report.

B. Background

1. USAID-USGS Initiative in the Horn of Africa

USAID-USGS launched a regional scientific initiative that aims to combat climate change in water-scarce areas of Africa by identifying emergency and sustainable water supplies and delivering measures to mitigate against long-term drought and famine. The initiative is funded by USAID.

2. The Challenge

Most countries in the Horn of Africa region have arid and semi-arid climates. In 2011, the region experienced the worst drought in 60 years in the Horn of Africa. As a result, many pastoral zones have dried up, and millions of Somalis, Kenyans and Ethiopians have faced severe shortages of drinking water and food, requiring an urgent response. Those living in refugee camps have been particularly vulnerable. Measures to mitigate against future drought and to prevent water-related conflict are greatly needed.

Water scarcity is exacerbated by the lack of understanding of groundwater in the Horn of Africa. Most data are incomplete, fragmented or outdated, and scientists in the area lack the tools to assess groundwater to rapidly improve water supplies. Furthermore, actors in the region lack the policies and skills necessary peace.

3. The Opportunity

There is a need to develop groundwater as a means to meet emergency and long-term needs, and in a way that promotes sustainability. New advanced technologies now exist, such as the WATEX System™ developed by Radar Technologies International (RTI), which can provide rapid solutions to regional and local challenges. This initiative also provides an opportunity to mobilize existing partnerships to deliver a rapid, sustainable impact. Ultimately, the challenge is to respond to the crisis and make a lasting difference to peoples' lives.

4. What are the goals of this initiative?

USAID-USGS assesses the availability of groundwater resources of target areas and determines which resources can be utilized safely for emergency and long-term development situations. The initiative also strengthens the drought preparedness of local, national and regional actors by building the capacity to sustainably manage groundwater resources. The ultimate goal is to build the resilience of populations vulnerable to drought and famine.

5. Expected outcomes (2013-2014)

1. Identifying and mapping regional groundwater resources for emergency situations and long-term development.
2. Developing Groundwater Management Tools to Combat Drought.
3. Building skills and capacities for managing groundwater for drought and conflict mitigation.

The priority area has been selected on the North-Eastern part of Somali Region of Ethiopia

1. Increase access to water for thousands of vulnerable populations
2. Precise understanding of where safe groundwater resources exist and how much can be used for emergency and long-term development needs.
3. Sustainable skills in groundwater assessment and management built.

III. STUDY AREA, TOPOGRAPHIC AND CLIMATIC CONTEXT

A. Geographic location

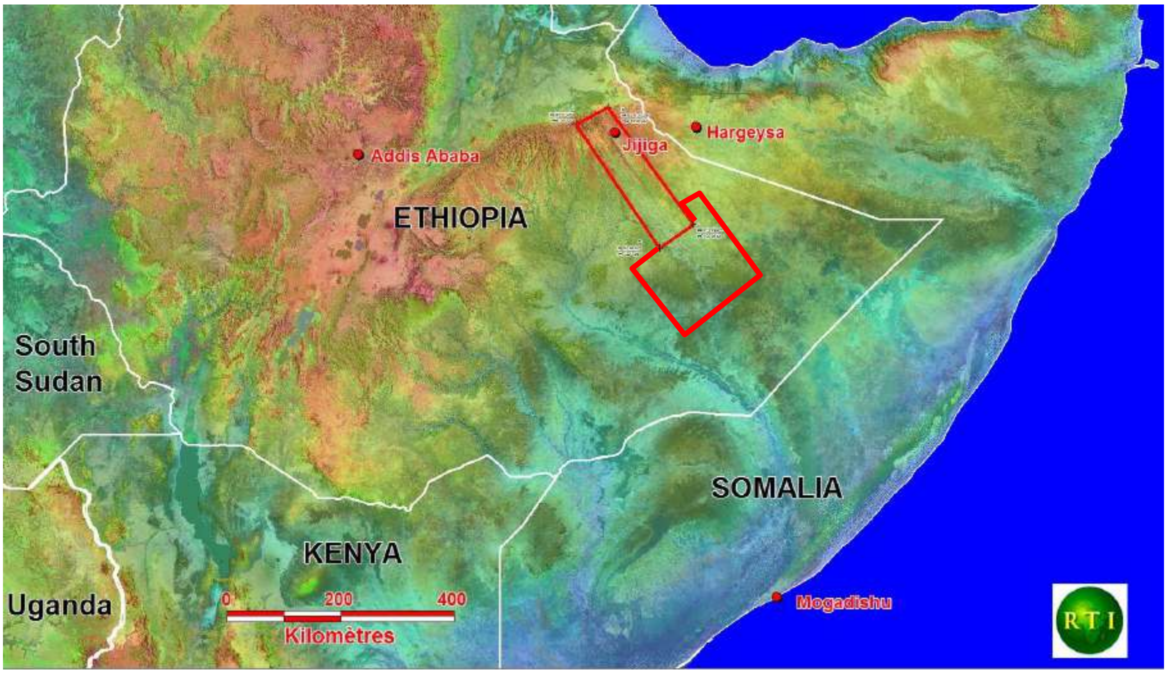

Figure.1- The survey is an area (red box) located in the eastern highlands of Ethiopia, in Somali Region, close to the border of Somaliland, on the southern part of the Afar depression.

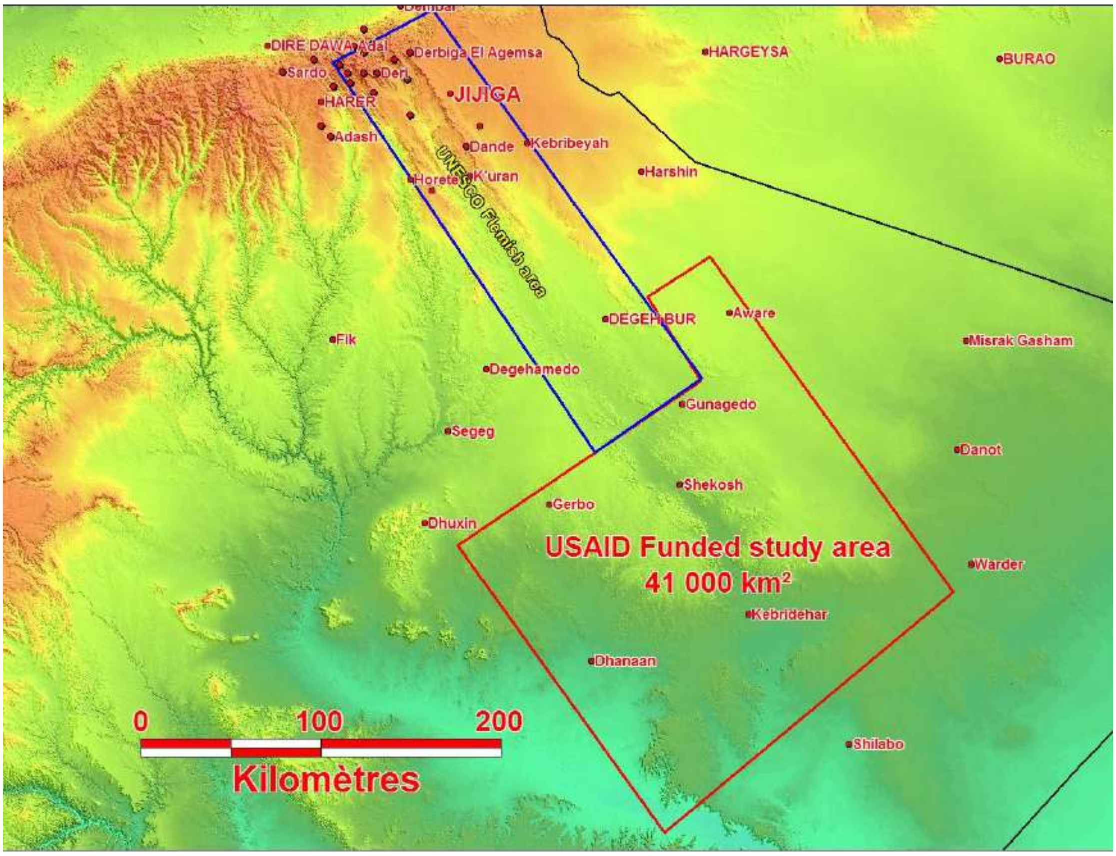

Figure. 2 - Study area (red polygon) shown on topographic overview of Ethiopia extracted from shaded SRTM elevation model.

The project area is located in the Jijiga, Dhegahbur and Korahe zones of the Somali National Regional State. Jijiga town which is the capital of Somali National Regional State is situated southeast of Addis Ababa at about 630kms asphalt road running from Addis Ababa through Harer to Jijiga. The project area starts near Chinaksen town, which is located at about 35km northwest of Jijiga, the regional capital, and extends down to about more than 400km down to Shilabo on the Shebelle River, in the Southeast direction (fig 2).

Fafem and Jerer river basins and their eastern adjacent areas are elongated areas NW-SE direction of about 250km length and the proposed study area is covering a surface area of 16, 323 km² annotated by the red polygon as shown Fig.1 and 2 This survey area is dominated by the narrow Karamara range which stretches all along the NW-SE direction separating the Jerer Valley in the East and the Fafem Valley in the West.

Topography

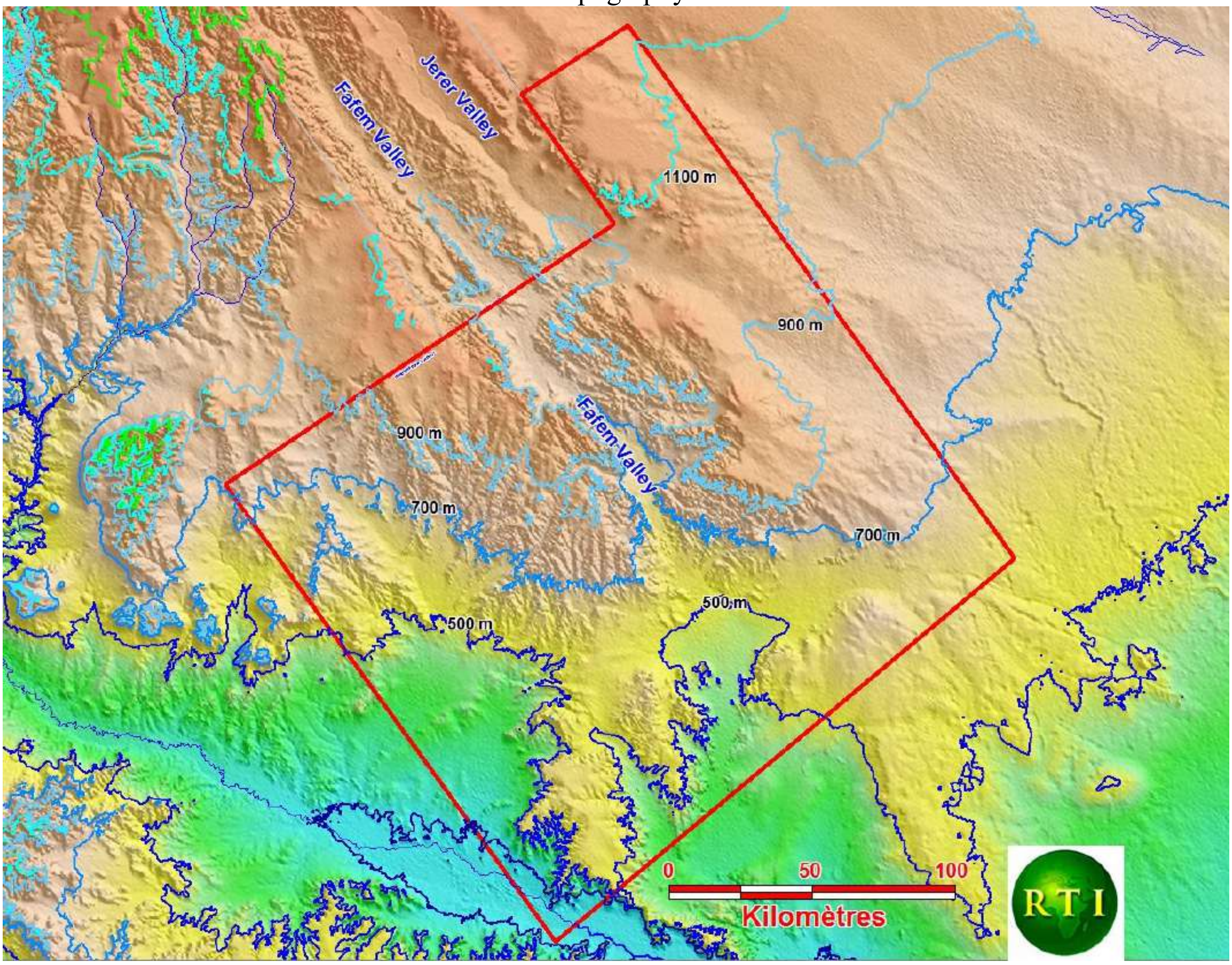

Figure. 3 - Colour coded SRTM image: the high altitude are coded in orange and lower altitude in blue. The red polygon identifies the study area. Notice the two major watersheds, the Fafem in the West and the Jerer in the East, flowing from an altitude of 2500 m to 500 m.

B. Climatic and pluviometric context

Assessment of the rainfall conditions of the Fafem-Jerer and Wabi Shebele River Basin

The Wabi Shebele river basin is characterized by bimodal type rainfall pattern.

1. The rainy seasons of July-August and September in the upper Wabi Shebele and Jijiga area

The north western and eastern part of the Wabi Shebele basin (around Kofele, Adaba, Deder, Harar and Jijiga) receive most of **their rainfall during July, August and September** associated with the north ward passage of the ITCZ (Inter-Tropical Convergence Zone). From September to November, the ITCZ moves back to southward direction, causing a rapid end to the rainy season during September/October. By December and January the ITCZ moves further southwards into Kenya.

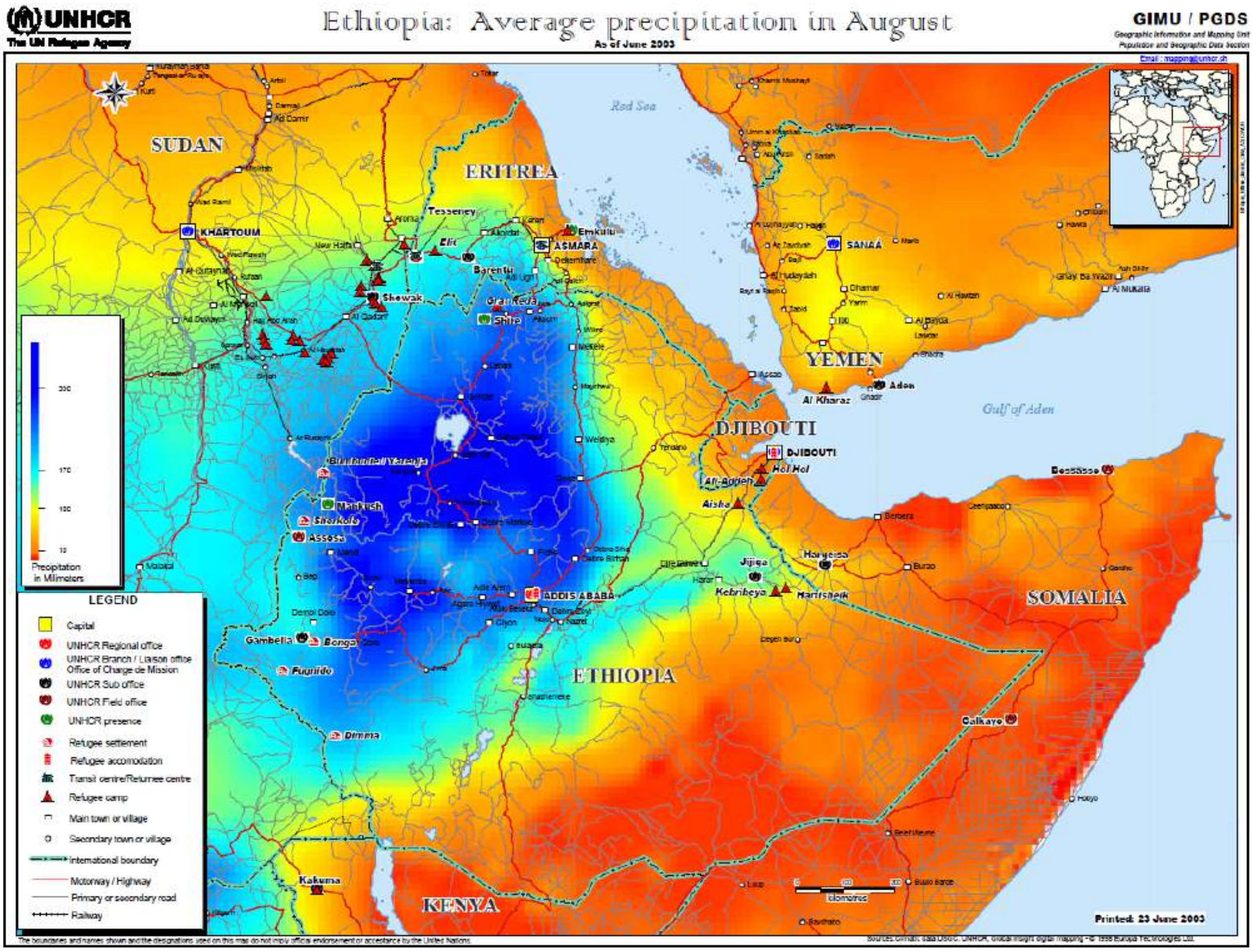

Figure 4 - Average precipitations during the wet season in August. Sources: Climatic data: USGC. UNHCR, Global Insight digital mapping

2. The rainy seasons of March-May and October-November in the South Eastern Part of the Wabi Shebele

From about in **mid-March to May (Belg season)** the pressure system changes to Warm, moist and unstable air from the Indian Ocean moves in from the east and converges with stable continental air mass from the Sahara high pressure cells.

Distinctly, **the south-eastern part** of the low lying areas of the Wabi Shebele basin that is east of 42o and south of 8o (Around Degehabur, Gode, Kebridehare, and Kelafo) receive **no rainfall in July and August**. It rather **has two rainfall seasons**. The first season is **from March to May, and the second season is from October to November**. The March to May rains is caused by moisture from Indian

Ocean, while the October – November rains may be associated to the retreat of the ITCZ in southward direction.

3. The dry season of January

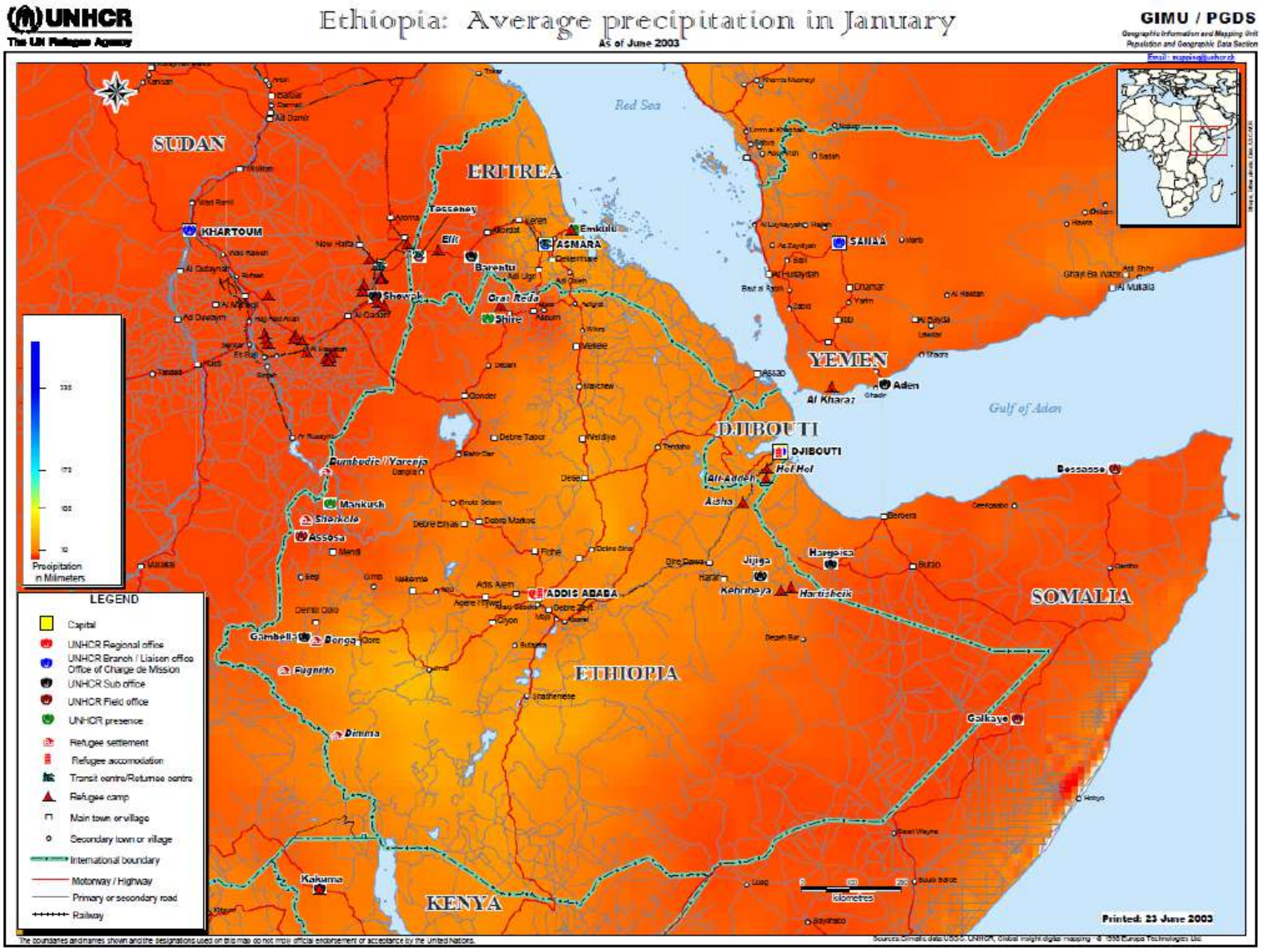

Figure 5 - Average precipitations during the dry season in January. Sources: Climatic data: USGC. UNHCR, Global Insight digital mapping

These maps are showing that the Jijiga area is extremely dry in January with less than 10 mm of rain and less than 100 mm for all Ethiopia.

C. Rainfalls map of the survey area

According to these results, RTI has adapted a new rainfall map tailored to the survey area based on altimetry isolines and integrating annual rainfalls data from the Ministry of Agriculture (see map below). In fact, the altitude is a major factor in determining the precipitation levels. RTI has drawn the lines to indicate the altitudinal zones thanks to measurements taken every 200m on SRTM and attributed a value of average annual precipitation.

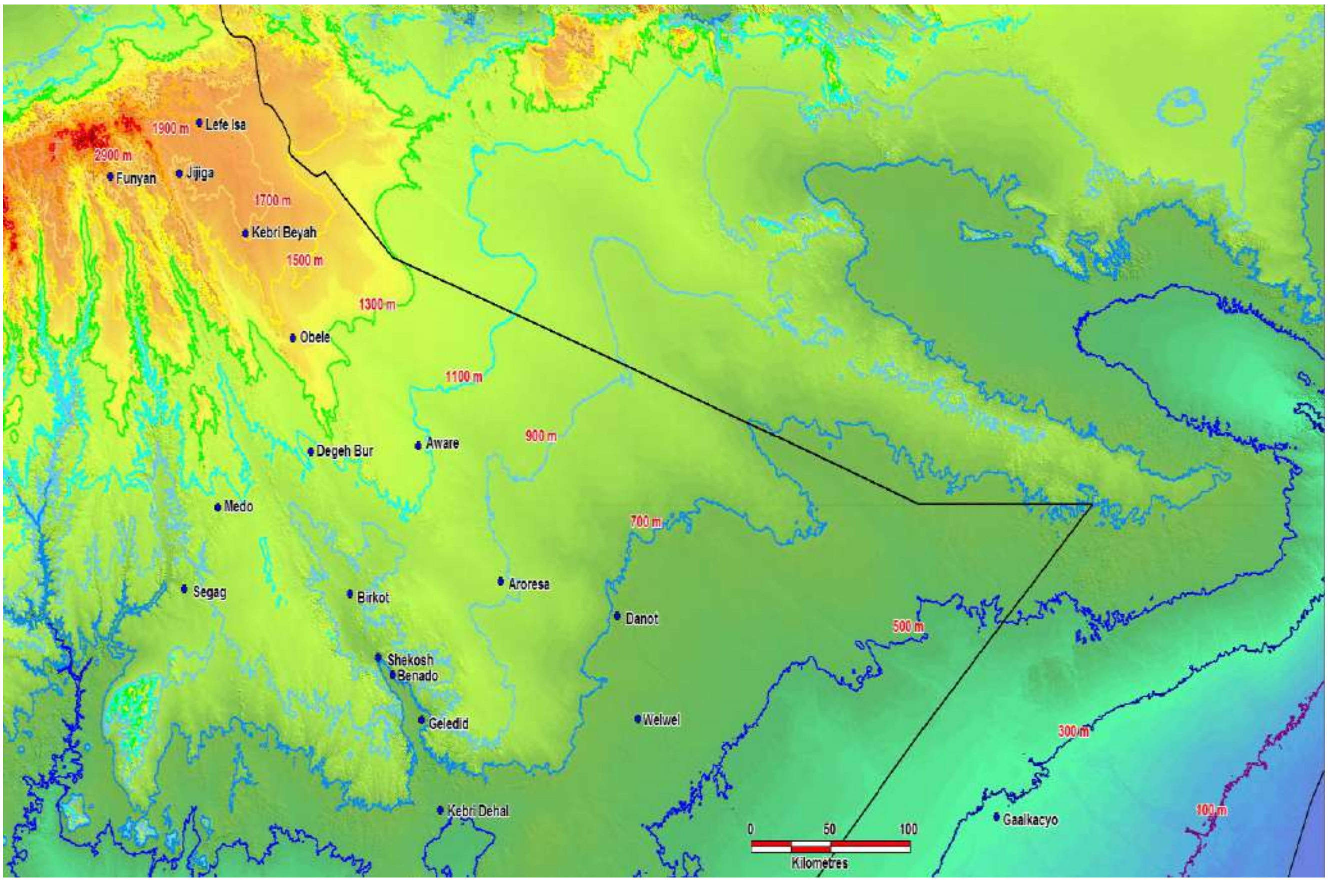

Figure 6 - Study area showing elevation lines every 200 m

For Jijiga located at 1700 m, RTI has considered an average mean value of 570 mm/an.

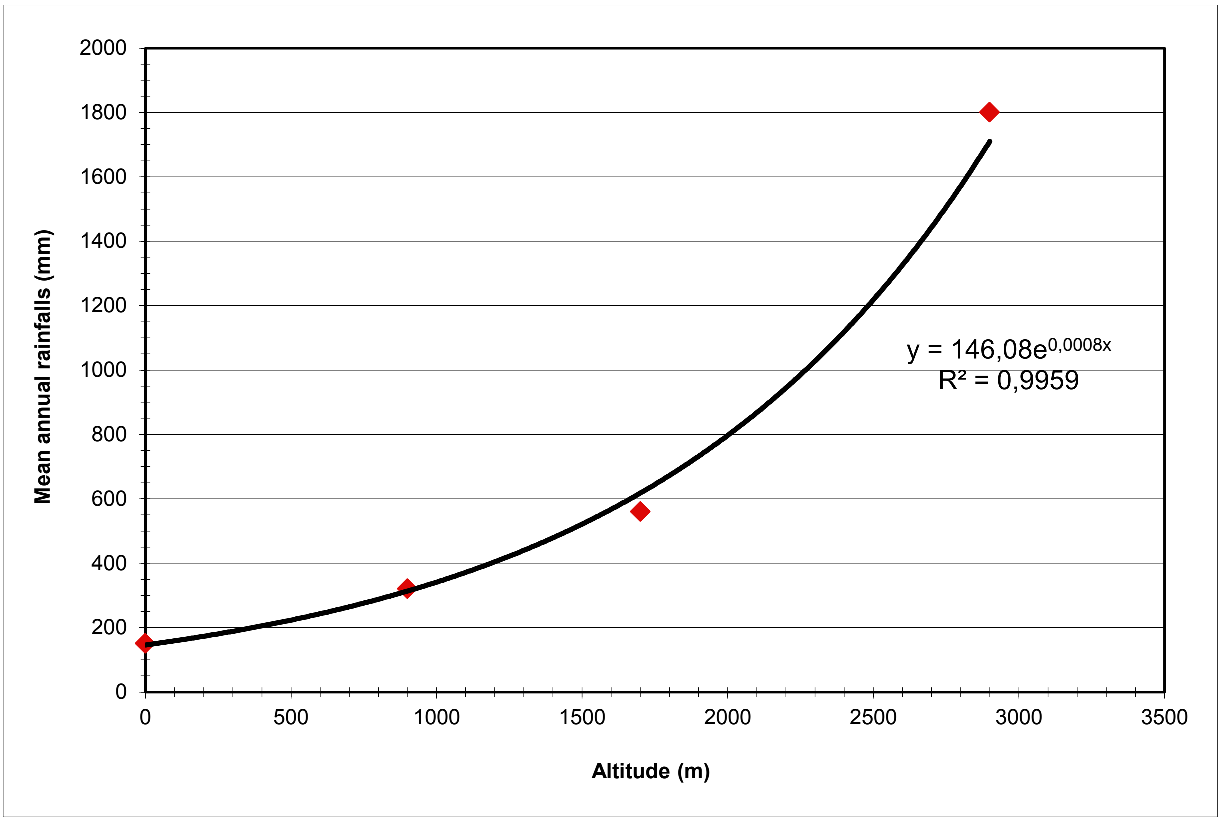

Figure 7 – Regression curve needed to interpolate rainfalls value between sampled points.

- <u>The upper most part of the basin</u> is dominated by the highland climate type (Dega). This climatic zone is characterized by an altitude above 2,300 masl, mean annual temperature less than 16°C, and mean annual rainfall lies between 900 and 1800 mm. The Arsi, Bale and Cherecher mountain ranges are included in this zone (consisting of about 15% of the basin).

- The second zone is characterized by weina dega climate with altitude between 1,000 – 2,300 masl, mean annual temperature varies between 16 – 20°C, and mean annual rainfall lies between 500 mm and 900 mm. Undulating escarpments characterize the topography. It covers about 25 % of the basin area and lies above the junction of Ramis river with Wabi Shebele river. Surroundings of Jijiga and Harar are also located in this zone.
- The last zone is desert type, and arid condition increases as one travels from Centre of the basin to the frontier with Somalia. It covers about 60 % of the basin area. The altitude decreases from 900 to 200 masl, mean annual temperature could reach 38C, and mean annual rainfall ranges between 150 and 500 mm. The Gode irrigation scheme is located in this zone.
- For altitudes lower than 100 m, RTI has selected the lowest value of 150 mm/year, as referred in the report (p41). For an elevation of 900 m, we have selected a value of 320 mm/year corresponding to the southern limit, in Birkot.

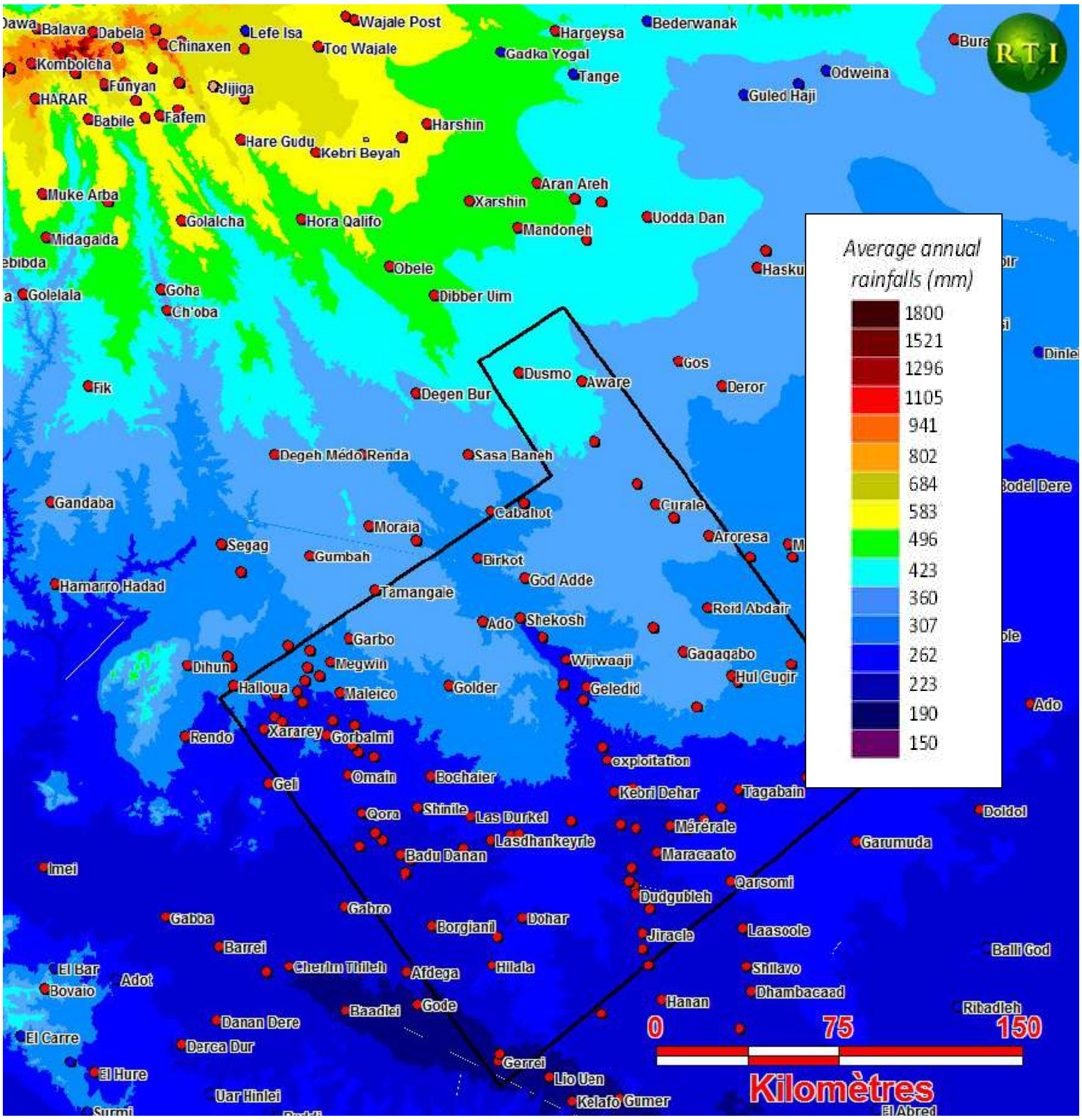

Figure 8 – Resulting synthetic annual rainfalls map generated by RTI

Most of the water feeding the survey area is harvested by the Fafem and Jerer watershed on the highlands of Eastern Ogaden. **<u>The survey area is very dry.</u>**

IV. DATA COLLECTION

A. LANDSAT

A collection of remotely sensed images and ancillary data were used for this study. 44 Landsat 7 images were processed using the 7 channels to extract complete 4 derived products assembled into mosaics of the Horn of Africa:

- Landsat (7,4,2) and Landsat (3,2,1)
- NDVI mosaic for vegetation Index
- Sultan processed mosaic to enhance lithological/chemical signatures

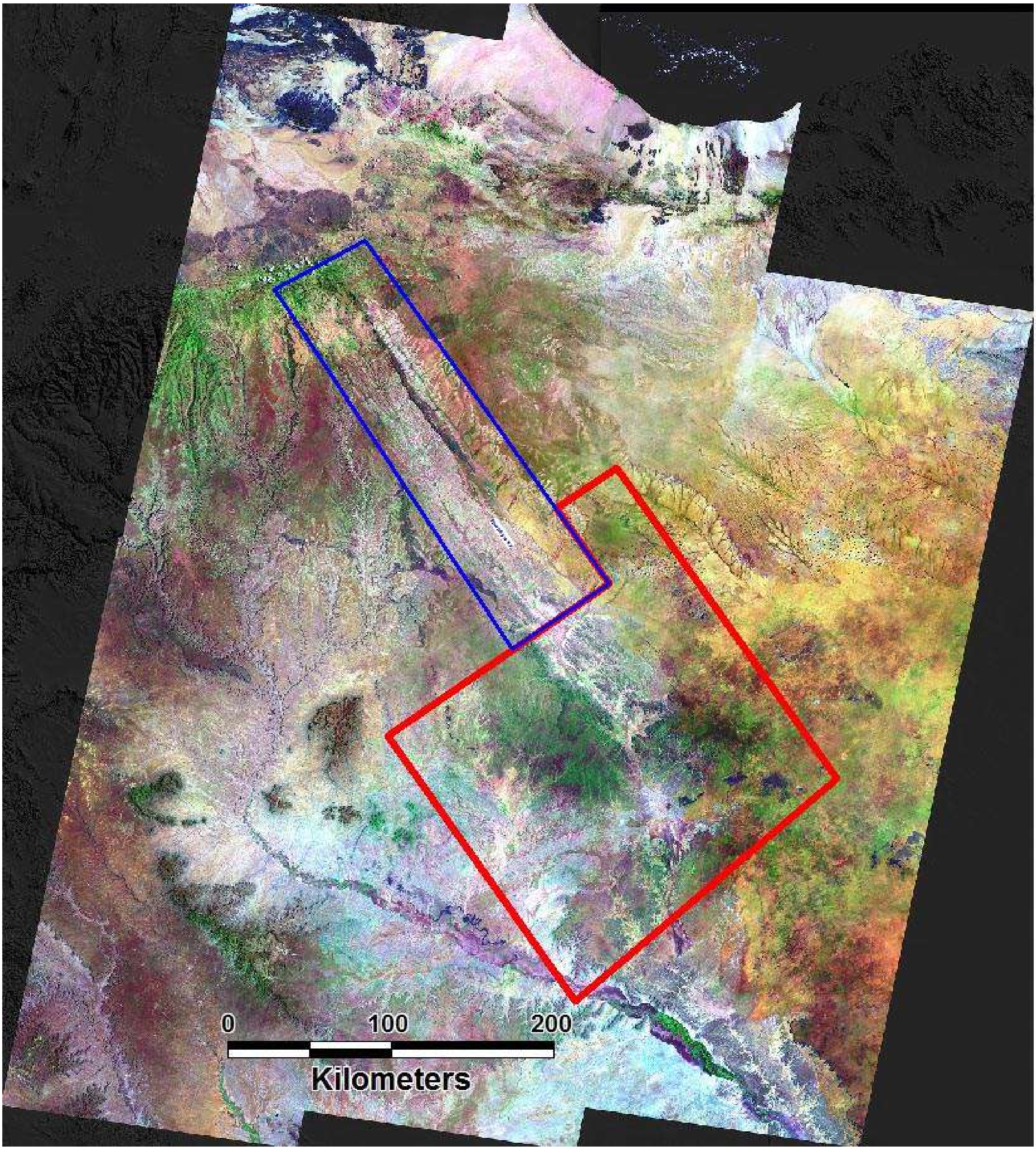

Figure 9 -Landsat 7.4.2 generated by RTI

B. SRTM (Shuttle Radar Topographic Mission) and derived products

The 2003 release of the Shuttle Radar Topographic Mission (SRTM) global terrain model provides slope and elevation data of unprecedented quality compared to other topographic information of the region. This terrain model with pixel size of 90 m (5 m, 90% vertical accuracy) is providing accurate access to geomorphologic models with slope maps which are used to determine watershed boundaries.

The SRTM images have been assembled into a single mosaic in order to extract topographic isolines and slopes over an extended surface over the survey area, in order to sustain a broad structural interpretation. SRTM for the study area has been processed and assembled.

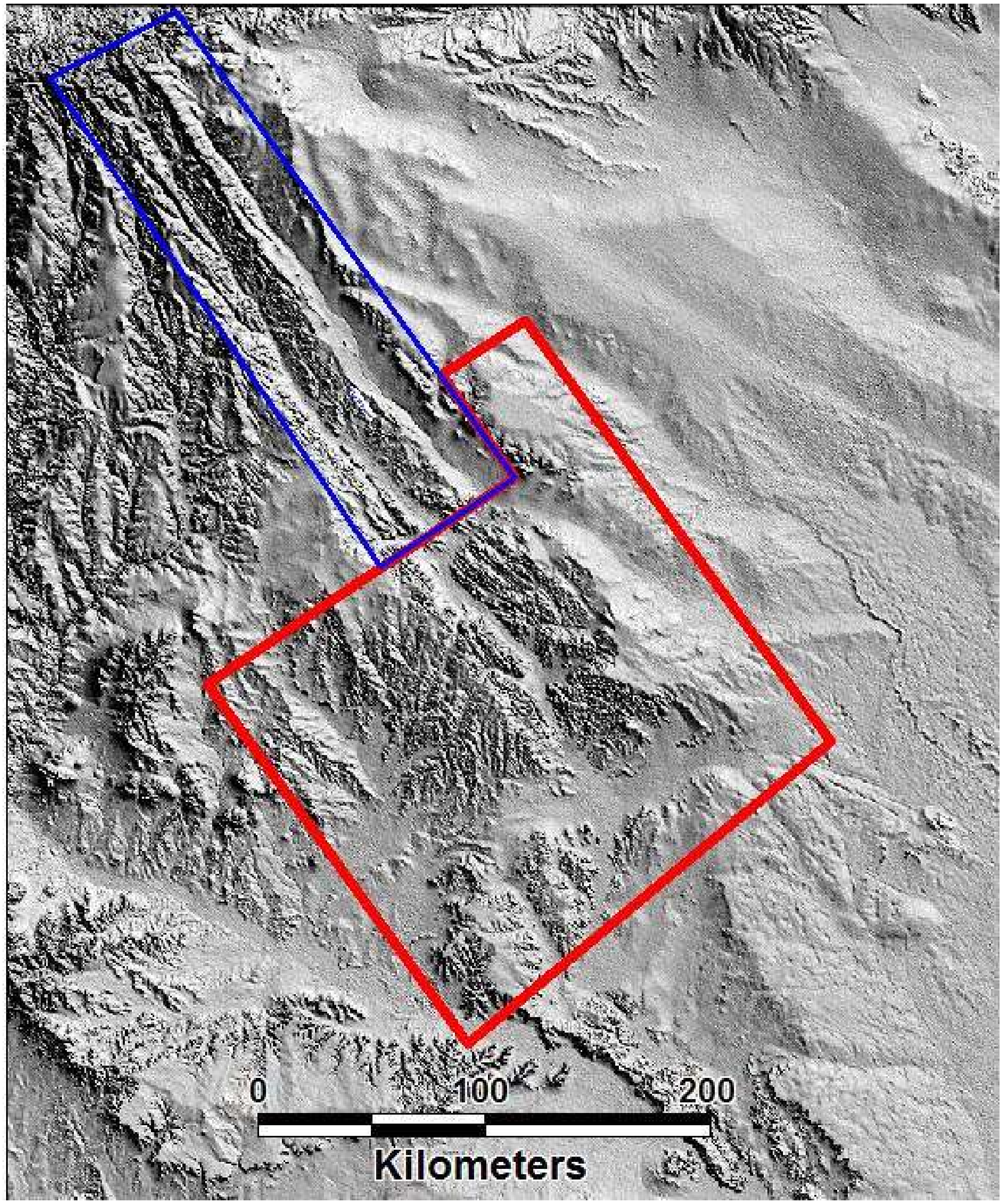

Figure 10- Shuttle Radar Topographic Mission shaded image of the survey area.

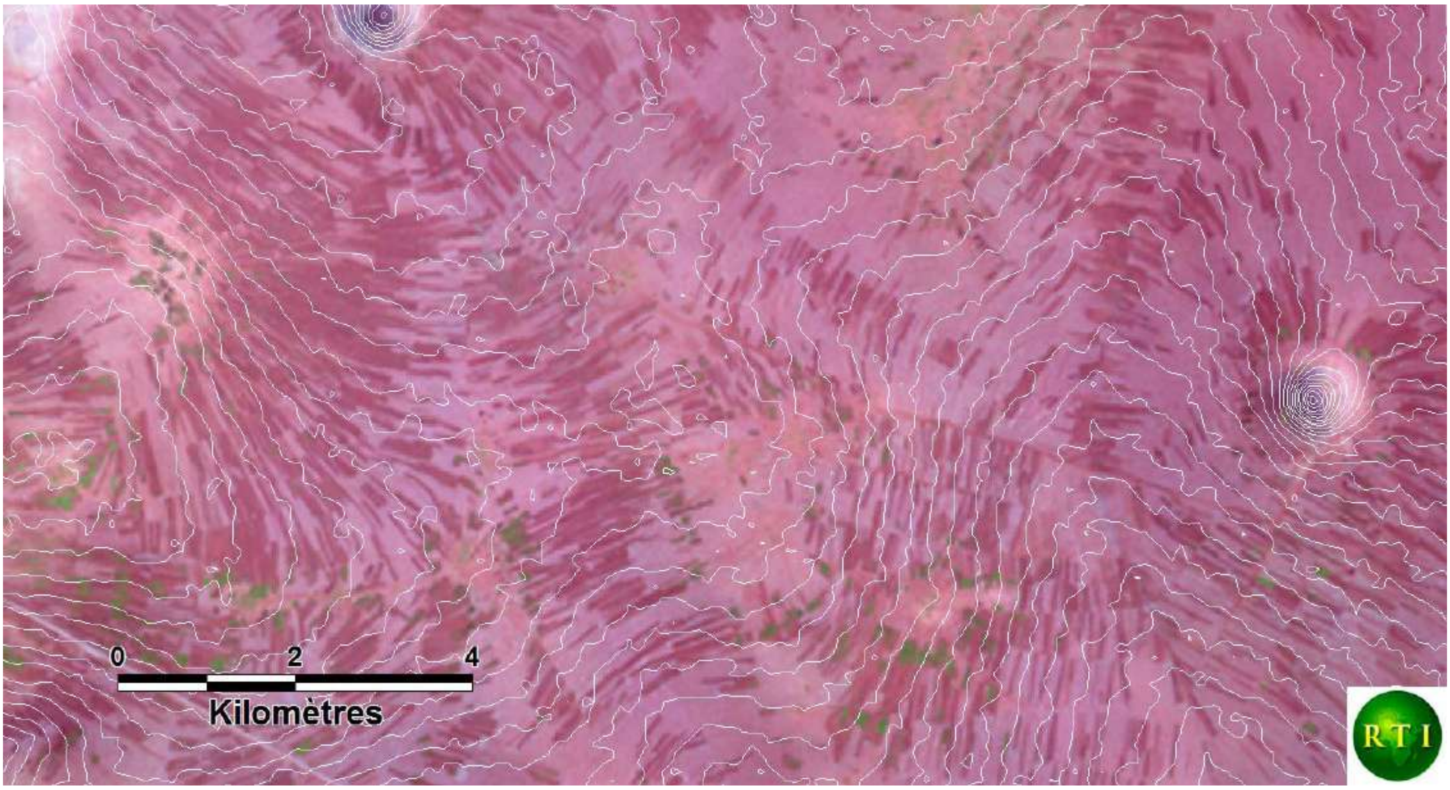

Figure 11- Topographic isolines every 5 m on the Jijiga agricultural area. Notice that the shape of the cultivated areas is adopting the topographic contours.

Slope map derived from SRTM

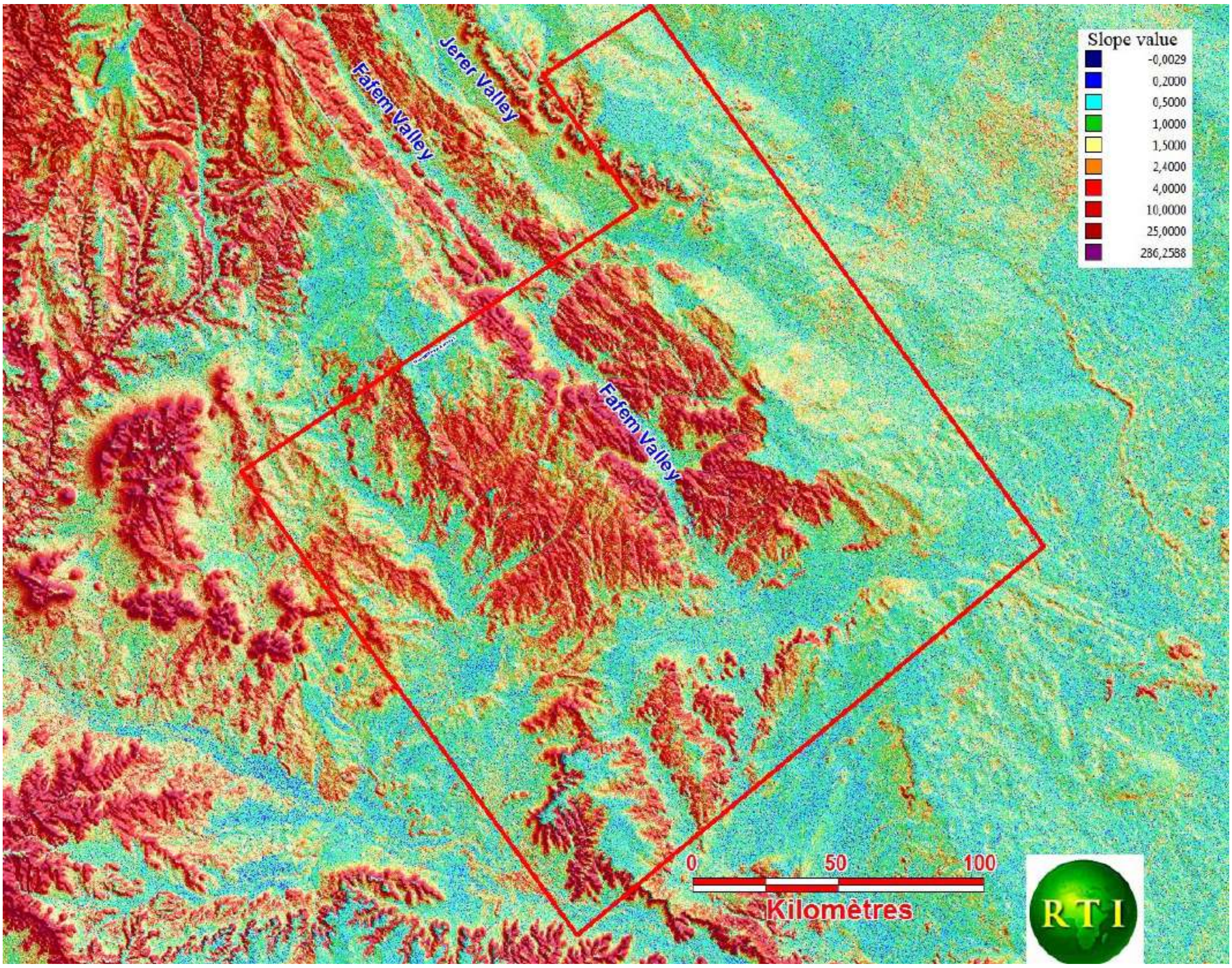

Figure 12 - Slopes map derived from SRTM.

Slopes are derived from the SRTM data remain steep (red) with deeply incised and high relief features, characterized by rugged and coarse topography and deeply cut valleys, are observed at upper part of Fafem and head of Jerer Rivers while piedmont lands and valleys extend to the East and south-East towards Somalia below an altitude of 1000 m (blue).

Beside the Jijiga agricultural plain in the North East, the most important areas for future developments on the survey area are the lower valleys of the Fafem and the Jerer rivers and their tributaries.

C. Radar Imagery

Acquisition and processing of 3 layers of 46 ortho-rectified multi-frequency and multi-seasons radar mosaics have been used in order to build the WATEX image of the whole survey area.

1-RADARSAT-SAR, C band, Pixel size 25 m, Resolution 50m, acquisition angle 31°-39°, Polarity V-V, 12 images were acquired in March 2009. Ortho-rectification based on SRTM data.

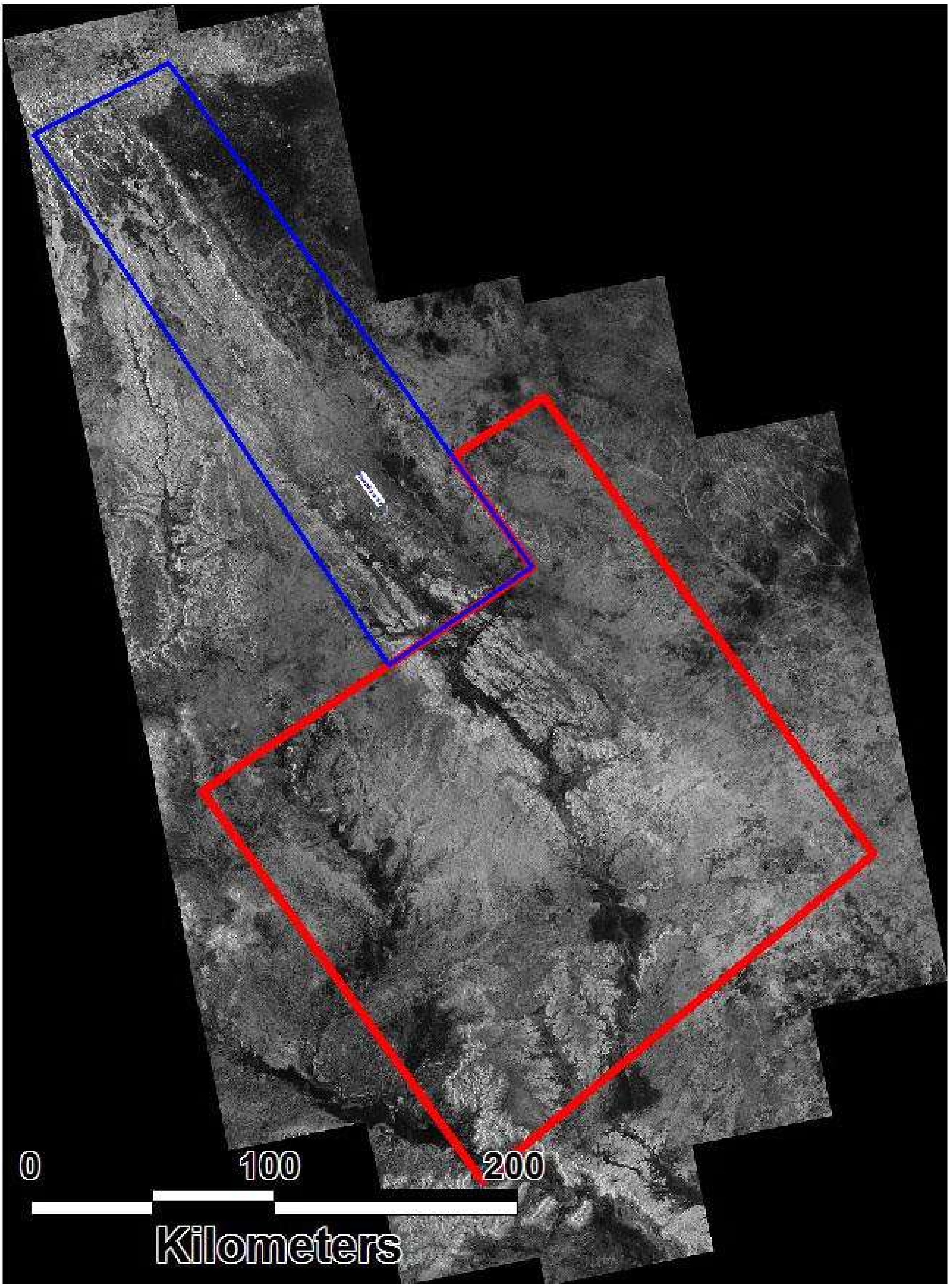

Figure 13 - RADARSAT mosaic acquired in single polarity in March 2009 over the survey area.

2-PALSAR SAR, L band, Pixel size 6.25 m, Resolution 12m, acquisition angle 31°, Double Polarity H-H, H-V, 12 radar images were acquired during the dry seasons of May-June 2008.

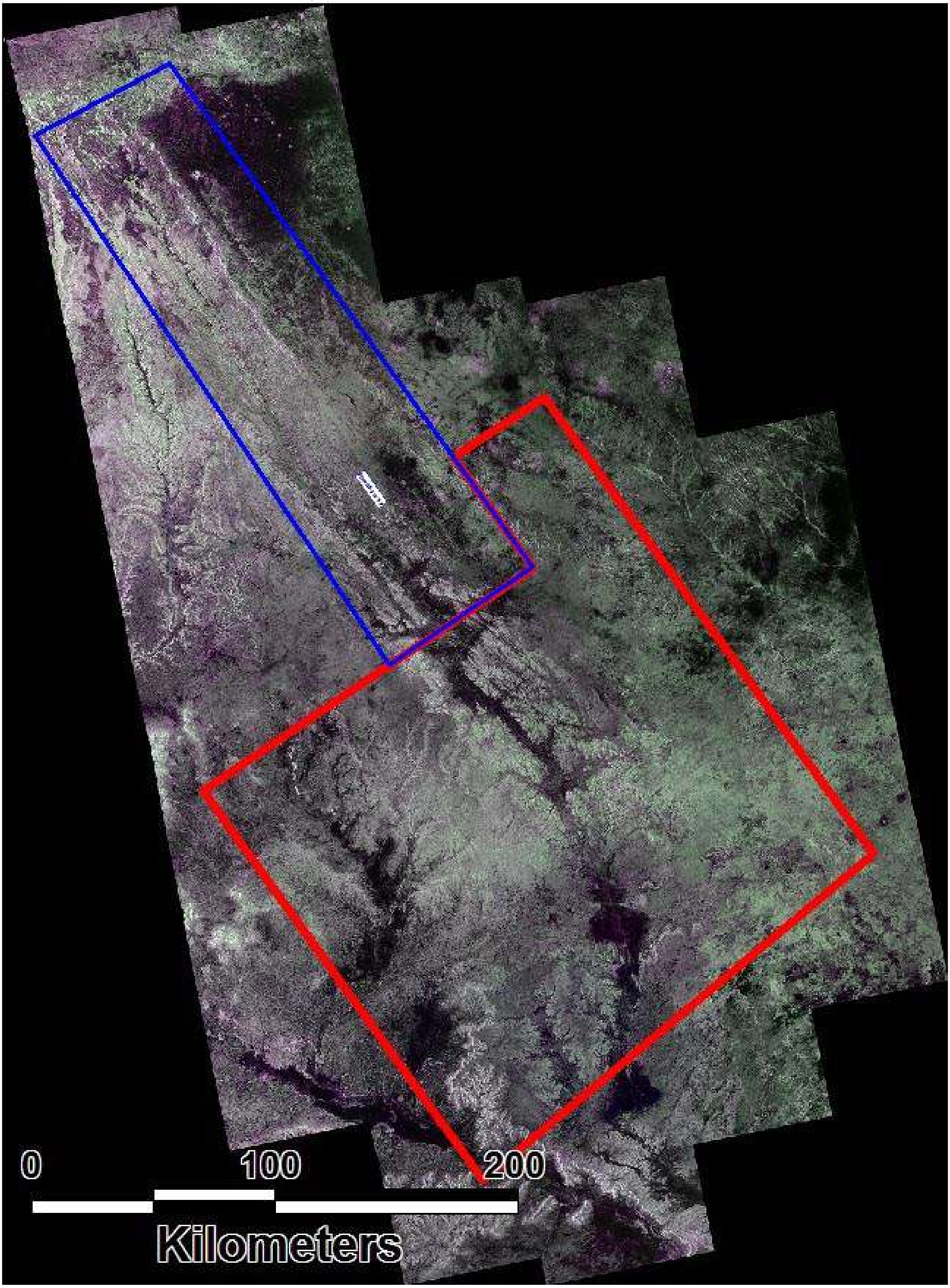

Figure 14 - PALSAR Mosaic of May June 2008 acquired during another dry season in multi-polarity over the survey area.

D. GIS data integration

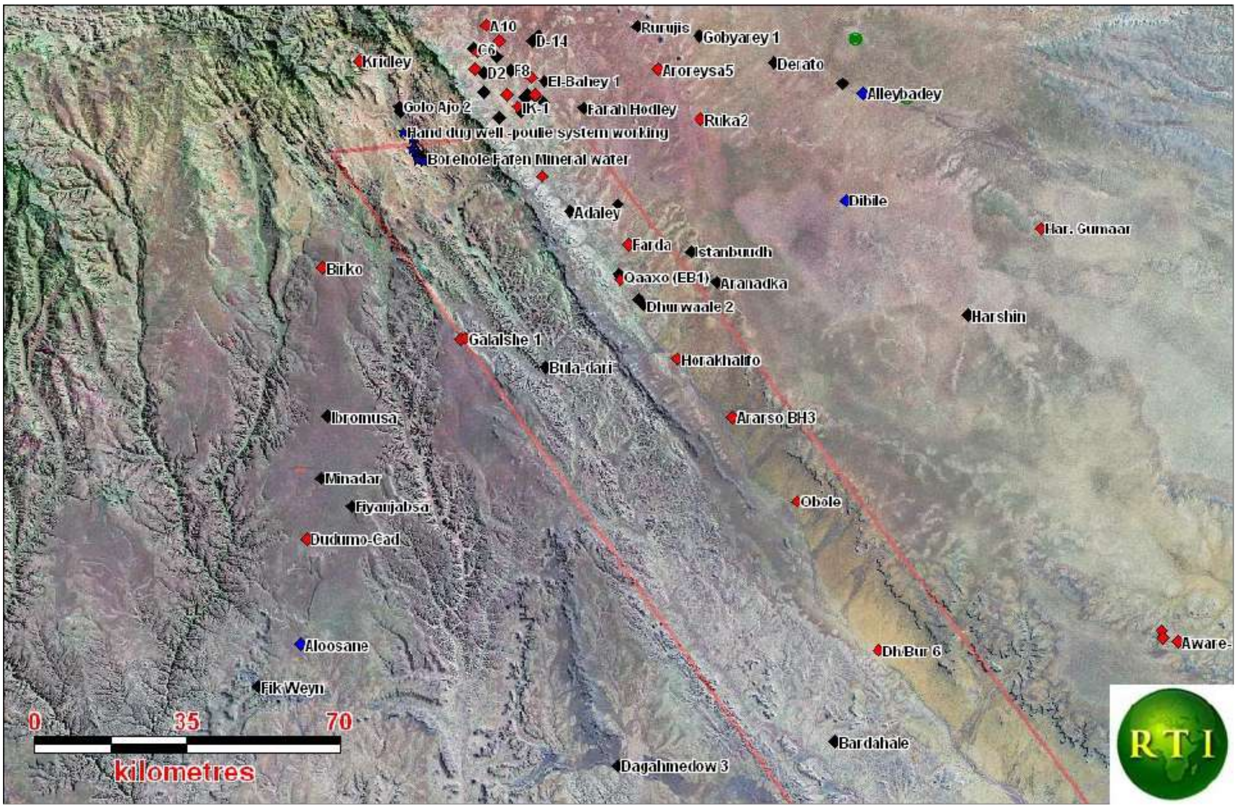

Figure 15- Landsat image showing location of the wells drilled in the Fafem-Jerer Valley project recorded from existing reports and converted into GIS points.

RTI has processed and integrated all remote sensing data and ancillary data. All data collected thus far have been converted into the same geographic units, Geodetic, WGS 1984. So far, a substantial amount of attention has been given to water wells location and their attributes (depth, yield, static and dynamic level). All such data (provided in excel sheet format) have been converted into MapInfo points (GIS format).

RTI has also integrated additional data provided by UNESCO and from the Ministry of Agriculture in Addis Ababa for the Jerer-Fafem Valleys. The attention of the survey data integration has been focused on well/borehole data and oil boreholes within and near the survey area.

As data is integrated and processed, RTI has built the GIS database. Hardware structure and software platforms are also under development. The hardware is a high-capacity, secure, mobile and compatible with PC/laptops and servers. The software (MapInfo) allows users to browse, manipulate, analyze and add additional layers of data to meet specific management and assessment needs.

RTI is taking a multi-layered approach to constructing the GIS database structure in which the data are organized in categories. The purpose of multilayer integrated platform is to produce hydrogeological maps (that may be hard copies or web maps) that enable various areas to be distinguished according to their hydrological feature in relation to the geology. They indicate, on a topographic base, such items as the extent of the principal groundwater bodies, the scarcity of groundwater elsewhere, the known or possible occurrence of artesian basins, areas of saline groundwater and the portability of groundwater. They also show, according to scale, information of a local character, such as the location of boreholes, wells and other works, contours of the potentiometric surface, the direction of groundwater flow, and variations in water quality.

E. Geologic map

1. Geology of the study area

The geological map of Ethiopia (scale 1:2,000,000), first compiled by Kazmin (1972) and then revised by Tefera et al. (1996), constitutes an excellent reference material to have general lithological distributions and structural setup of the country. As large parts of the map were covered by interpretations of aerial photographs and satellite imageries, modifications and updates based on recent geological mappings being carried out by the GSE and research findings are very essential. The map broadly categorizes the geology of the country into Precambrian basement rocks and Phanerozoic cover rocks, which include Late Paleozoic and Mesozoic sedimentary successions and Cenozoic volcanic and sedimentary rocks. Hence, according to Kazmin (1972, 1975) and Tefera et.al (1996) the south-eastern part of Ethiopia is mainly underlain by Mesozoic and Tertiary sedimentary rock successions with sporadic occurrences of Tertiary volcanic rocks and Precambrian basement rocks at the north-eastern and south-western margins of the Ogaden Basin.

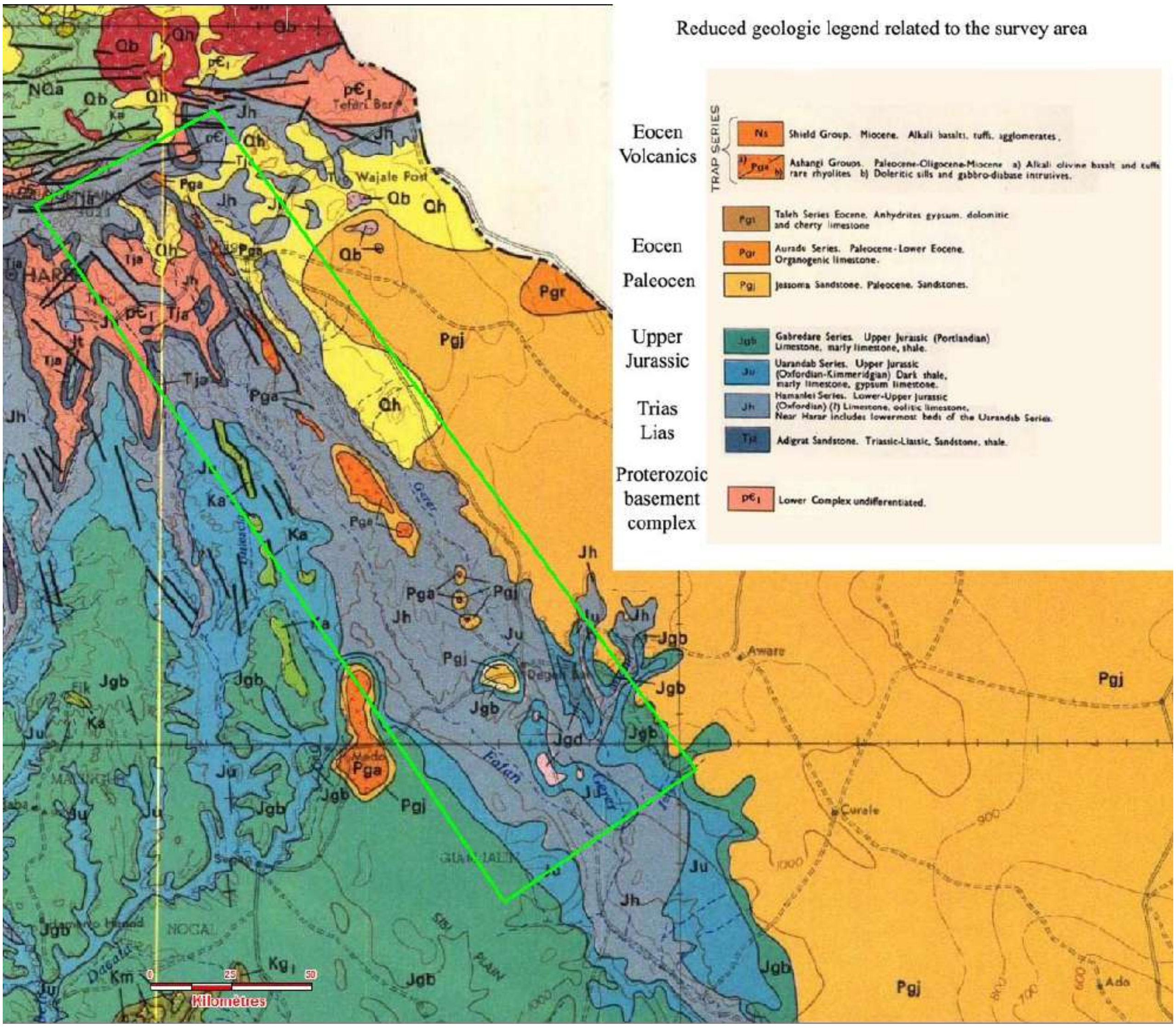

Figure 16 - Part of the Geological map of Ethiopia 1:2,000,000 compiled by V.Kazmin

The north-western to south-western half of the project area is mainly covered by Mesozoic sedimentary rocks, namely the Adigrat sandstone, Hamanlei limestone and shale, Uarandab marl and shaly limestone, Tertiary volcanics (Ashange basalts) and Quaternary alluvial deposits.

Moreover, the Precambrian basement rocks grouped as Archean Alghe Group consisting biotite and hornblende gneisses, granulite and migmatites with para-gneisses are restricted to north-western part of the project area in the upper Fafem valley.

The Jerer-east part of the project area is almost entirely underlain by Jessoma sandstone and minor Auradu limestone, which have Late Paleocene to Early Eocene ages.

Our reinterpretation has been confined to the boundaries of the Proterozoic basement outcropping in the northern part of the survey area, to the Lias to Upper Jurassic formations and Early Eocene, including Eocene volcanic formations.

Notice on this map the reduced amount of fractures.

2. General Geologic context

Precambrian granite and metamorphic rocks dominate the basement rocks of Northern Somalia and southern "Bur" basements. Then the present sea-margins of Somalia began developing in Permo-Carboniferous Time as rift and pull-apart basins formed, and these basins evolved intermittently over 150 million years until seafloor spreading commenced in the Late Jurassic.

At the initiation of seafloor spreading between West Gondwana [Africa] and East Gondwana [Madagascar, Seychelles, Greater India, Australia and Antarctica] at about 165 Ma, sediment facies changed throughout the basins from dominantly continental to marine. Volcanism and normal faulting occurred at the same time. Thermal subsidence and mechanical (sediment) loading dominated margin evolution following margin breakup, and seafloor spreading ceased in the Western Somali Basin in Neocomian /Aptian Time. Vigorous ocean currents along the East African margin probably commenced in Mid-cretaceous Time, and widespread regional volcanism occurred in the late Cretaceous.

By the close of the Middle Jurassic, oceanic crust separated Eastern Africa from Madagascar-Seychelles, and the respective shorelines began to subside, leading to Middle Jurassic-Early Cretaceous marine transgression. The Middle Cretaceous was a period of alternating transgression and regression phases. Late Cretaceous-Early Cretaceous transgression followed. The Early Oligocene was a quiet period of gentle regression marked by the absence of Oligocene sediments in some areas. Late Oligocene-Miocene transgression with accompanying tectonic movement followed. Subsequent regression established the present-day coastlines.

In the south and East of the survey area, the Precambrian basement rocks occur at the base of the Late Paleozoic to Early Mesozoic Karoo sediments overlain by Jurassic and Tertiary sedimentary rock successions. The Mesozoic sedimentary rocks, in the Ogaden Basin comprise Adigrat sandstone (form top of Karoo sediments), Hamanlei limestone; Uarandab marl and shaly limestone; Gabredarre limestone with shaly and gypsiferous rocks; Korahe main gypsum formation; Mustahil marly limestones; Ferfer shale, dolomite and anhydrite; Belet Uen limestone with some sandstone and shale; and Amba Aradom sandstone which were deposited from Early – Late Jurassic to Cretaceous periods (e.g., Tefera et al. 1996). Sedimentary rock distribution in Ogaden Basin, i.e. eastward gradation of carbonates and evaporites into basinal shale (e.g., Purcell, 1981) suggest deepening of the depositional basin geometry in Ogaden. Earlier Purcell (1976) described uplift and subsidence of the eastern and western Ogaden, respectively, along the Marda Fault Zone, which is generally presumed to dip due northeast with local opposite dipping faults. Furthermore, Tertiary sedimentary rocks: Jessoma sandstone; Auradu limestone; Taleh anhydrite, gypsum, dolomite and clay; Karkar limestone with intercalation of marl were deposited in eastern portion of the Ogaden Basin, mainly to the east of Marda Fault zone.

These sedimentary successions are generally absent in other parts of Ethiopia. Apart from the sediments sporadic Tertiary volcanic rocks Ashange basalt (Tefera et al. 1996) occur overlying both the Mesozoic and Tertiary sedimentary rocks. Superficial sedimentary deposits, alluvial deposits in the major river valleys, colluvial deposits at the base of the ridges, and alluvial sediments on the plateaus/plains are not uncommon.

V. GEOLOGICAL INTERPRETATION

We had to revise and modify the existing geologic map of the survey area before undertaking this survey, because of a certain number of inaccurate indications as shown in the examples below.

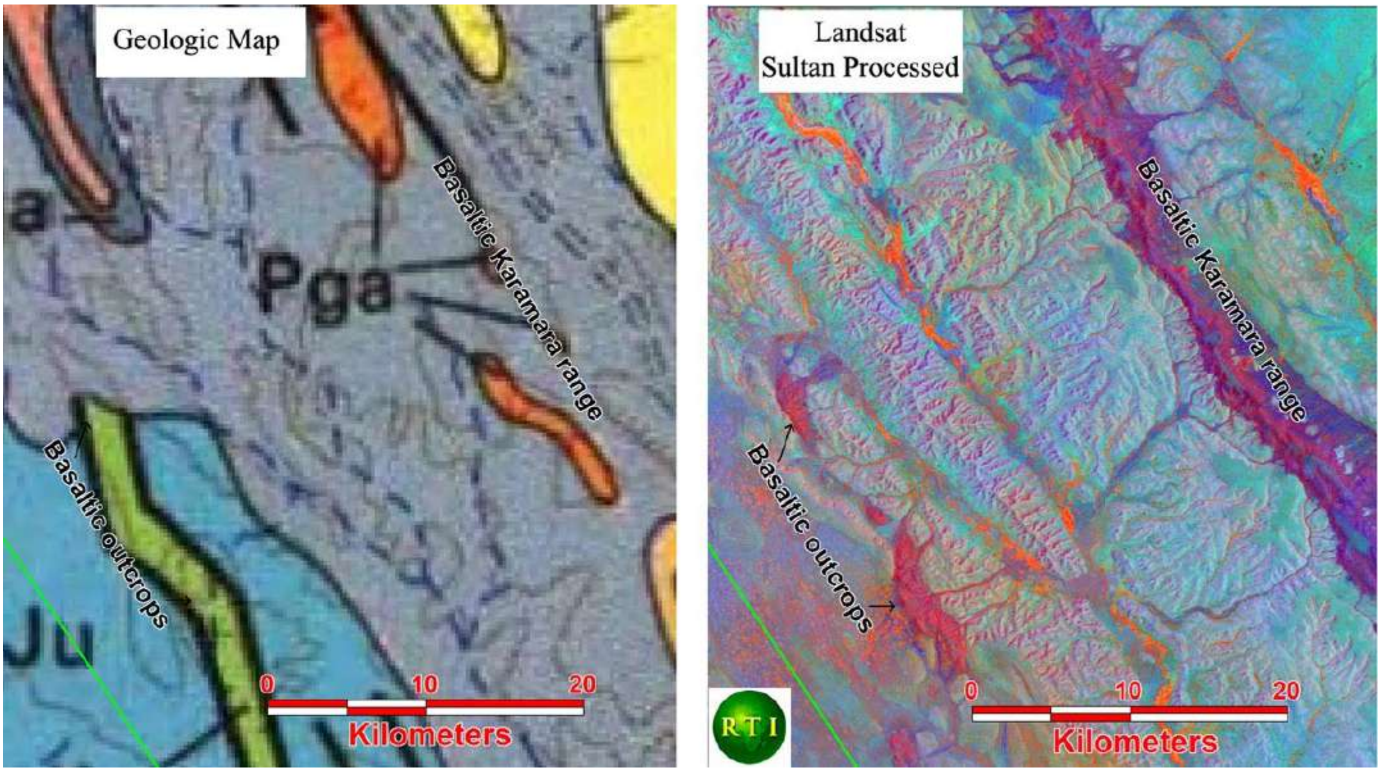

Figure 17- The Middle Western part of the survey area on the geological map (left) shows a discontinuous volcanic range along the Karamara range. On the opposite, the Sultan Processed Landsat image on the right, enhancing lithological contrasts, shows this range as a continuous purple belt (Basaltic volcanics).

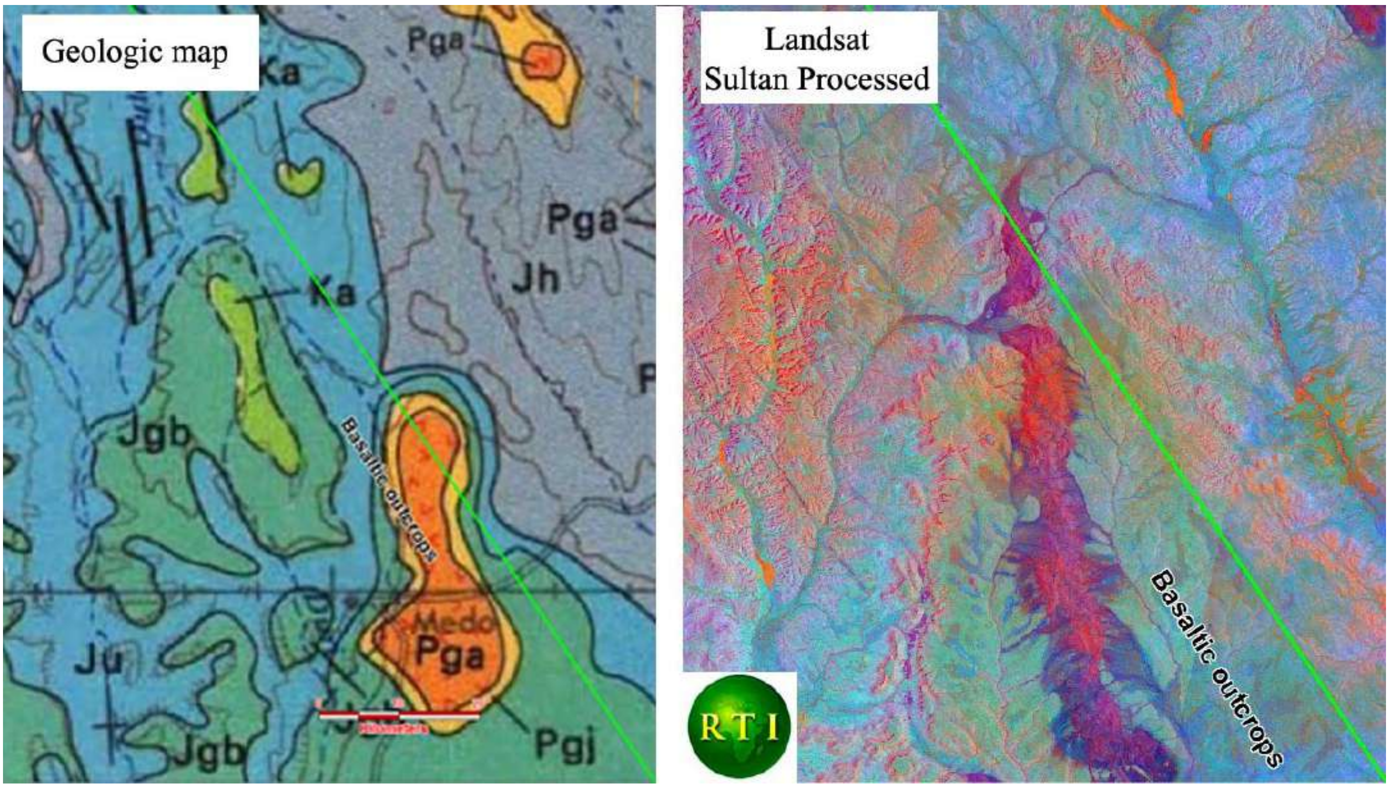

Figure 18 - The lower Western part of the survey area on the geological map (left) shows volcanic formations which differ in size, shape and place on the Sultan Processed Landsat image (right).

A. Tectono-stratigraphic evolution of Somali Region

Most of the formational names used in the geologic classification of Ethiopia and Somalia were established by the previous geologists who assigned the name of the nearest town to the type of each formation.

According to the geological and hydrogeological maps of Ethiopia and oil exploration works cited by IHS Petroconsultants, in Somali region, the following stratigraphic units were used for the new geologic mapping.

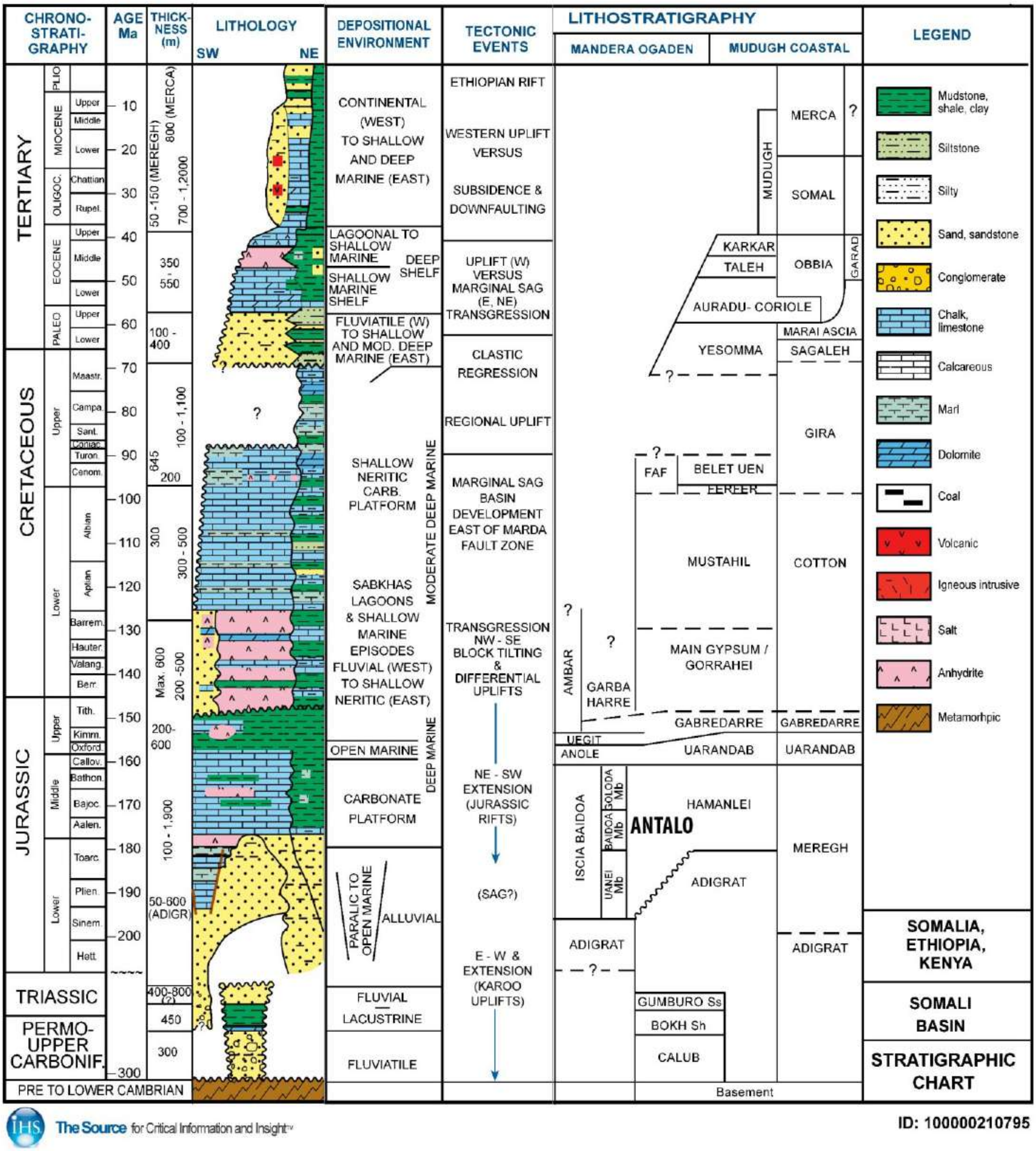

Figure 19 - Lithostratigraphy and lithology of Mandera Ogaden and Mudugh Basins (IHS)

B. Lithological descriptions and radiometry

1. Introduction

After processing Landsat images of the whole area, using the 7 channels to enhance radiometric lithological contrasts, a field trip in Jijiga and the Upper Fafem Valley was organized from the 12 to the 14th of November 2011, on request of UNESCO and of the Ethiopian Government and some field observations were used to sustain the present geologic interpretation.

Radiometric information combined to field sampling were useful to determine lithological boundaries and the relations between the uplifted Proterozoic basement impacting the Jurassic Adigrat and Hamanlei formations, generating the intrusive fissural Neogen volcanic formations of the Karamara range affecting the Jessoma sandstones deposits.

These combined observations appeared to be the keys of the new geologic and structural elements controlling the whole hydro geologic processes of this survey area.

2. The Basement Complex

High-grade metamorphic rocks of Precambrian origin outcrop along the road on the western flank of the Karamara range, West of Jijiga. They include granitic ortho-gneisses, quartzo-feldspathic and biotite gneisses, meta-gabbros, amphibolites and amphibole gneisses all along the road from the Bridge across Fafem River to Harar, along the Jijiga-Harar asphalt road.

Figure 20 - Metamorphic formations injected by quartz veins along the road from Jijiga to Harar on the flanks of the Upper Fafem Valley (42°37'24" E, 9°15'22" N) . ©RTI 16 July 2012.

Figure 21- Migmatites along the road from Jijiga to Harar : (42°38'33" E 9°17'28" N) . ©RTI

3. Alluvial deposits on the basement Complex.

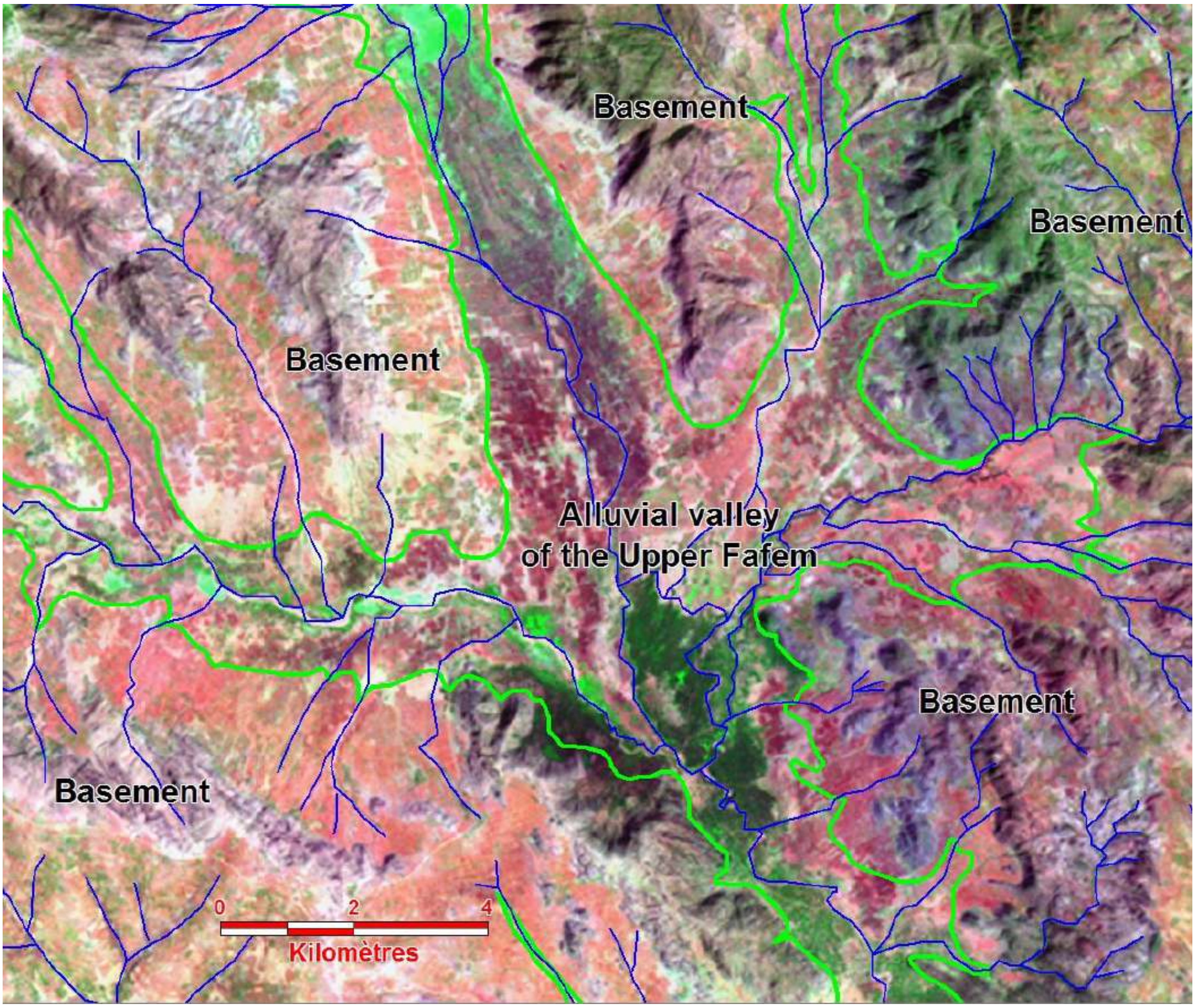

Figure 22- Alluvial valleys of the Upper Fafem river overlying the basement complex.

The basement complex is an aquiclude conveying rainfalls along the thalwegs infilled with alluvium resulting from the weathered basement erosion.

The wadi alluvial deposits represent a surface of 17,600 km² or almost 13% of the total study area and play a major role in superficial groundwater distribution.

They are found at the beds and along the banks of seasonal streams draining the study area. They are particularly broad and their alluvium composed of loose aggregates representing the upstream geologic formations through which the wadi runs.

Their alluviums are predominantly enriched by the eroded basement components rich in silica, by Adigrat sandstones and by the Hamanlei shales and carbonates.

The alluvial deposits of the upper Fafem provide the main soils for agriculture (see attachment 1) and host aquifers down to an average of 50 m in the deepest areas with good productivities due to the rich content in quartz grains resulting from the erosion of the Adigrat sandstones and weathered silica rich basement.

4. Lower Jurassic - Adigrat Sandstones Formation (Aalenian to Callovian)

They represent the basal sands deposited during the Jurassic marine transgression. This transgression is related to the break-up of India and Madagascar from Somalia.

The basal sandstones in Somali Region are present throughout East Africa, and were named by W. T. Blanford in 1870.

They consist of fine to coarse-grained, varicolored quartzitic, micaceous, cross-bedded, un-fossiliferous sandstones, locally grading upward into sandy Limestones with a commonly poorly cemented, but locally quartzitic, unfossiliferous. It is a massive and well sorted sandstone forming cliffs with an average thickness of about 800 m in Mekelle area.

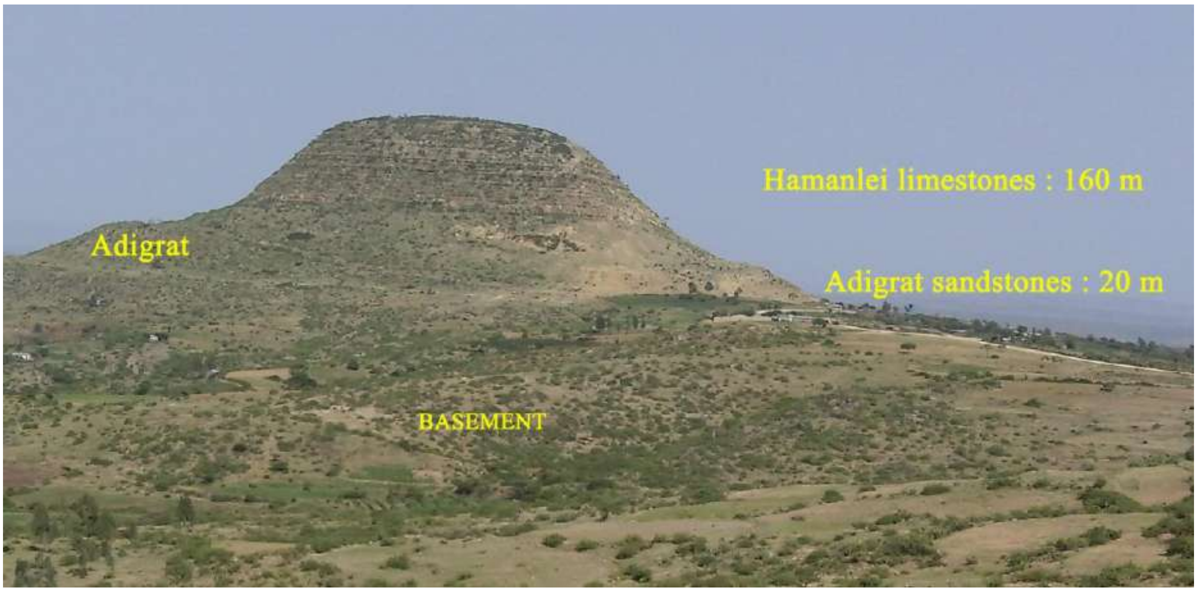

Figure 23 - Photography of the Adigrat sandstones covered by Hamanlei limestones (steeper slopes) North West of the survey area (coordinates 42°422710 E 9°334790 N). ©RTI 16 July 2012.

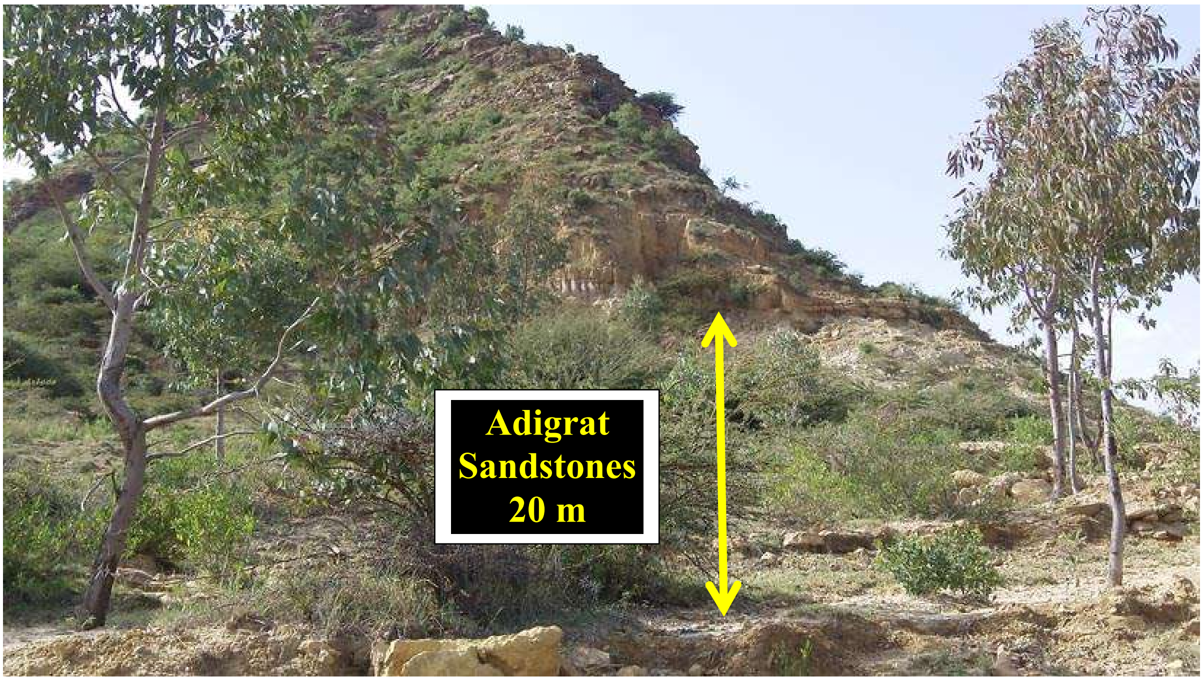

Figure 24 - Zoomed photography of the Adigrat sandstones of Fig.25 in the Upper Fafem valley. Adigrat sandstones which are only 20 m thick lay on the basement, along the track from Bombas to Funyan. ©RTI 16 July 2012.

The base of the Adigrat formation may be non-marine which passes up into marine sandstones before passing up into shallow marine carbonates of the overlying Hamanlei Formation.

The non-marine basal part of the Adigrat Formation is poorly dated;

The Adigrat Formation is often well cemented suggesting a significant risk on reservoir quality, although some porous zones can be considered as the main aquifer reservoir of the upper Fafem and Jerer Valleys.

In the survey area, the average thickness of the Adigrat sandstones might reach 250 m.

The Adigrat Formation is likely to infill remnant topography in the upper Fafem and Jerer valleys, and obscures the basement which is itself weathered in the depressions as observed with the WATEX imagery next chapters.

A shale interval marks the transition between the Adigrat and Hamanlei Formations.

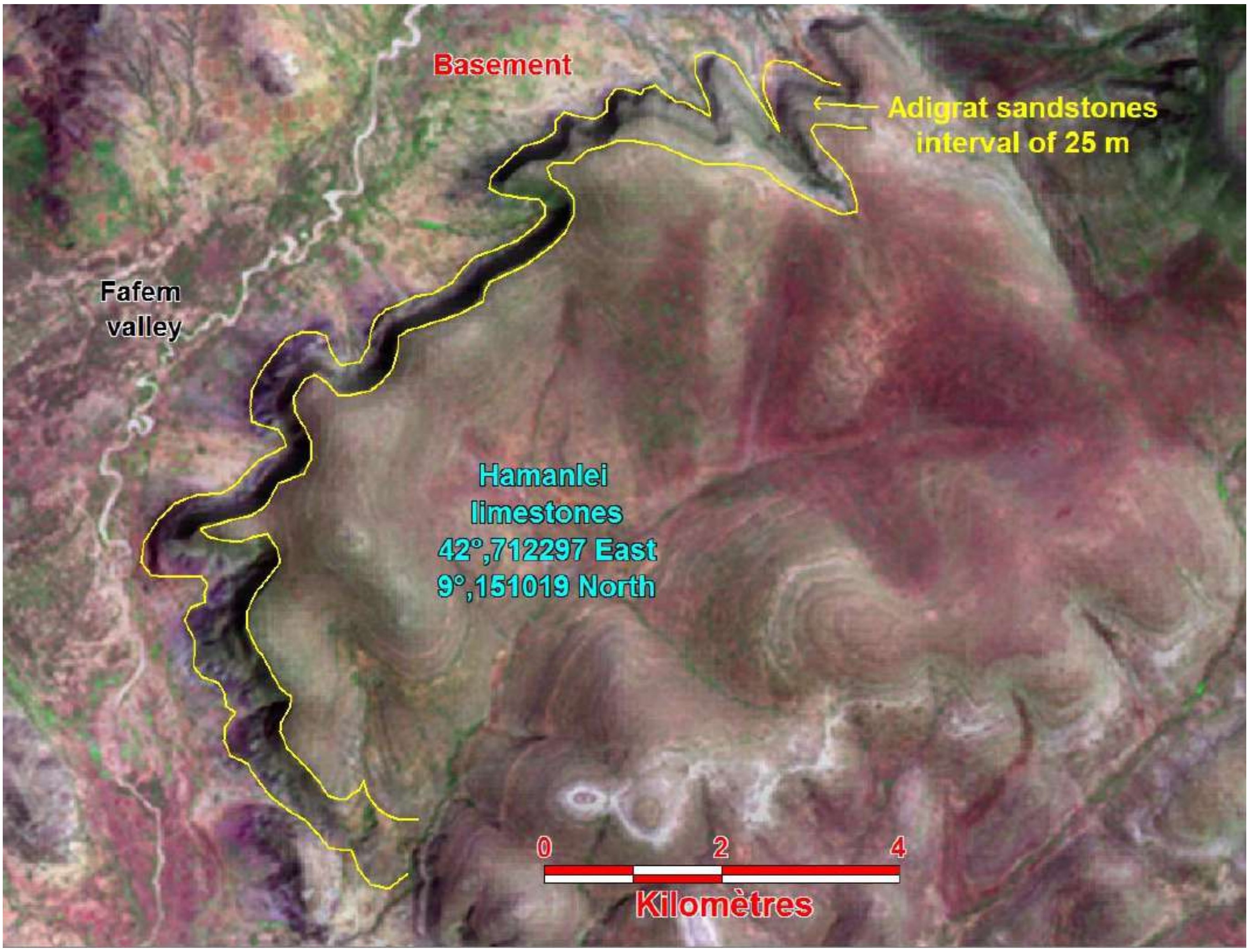

Figure 25- Landsat (7,4,2) processed of the Adigrat basal Sandstones, in the Upper Fafem valley. Adigrat sandstones which lay directly on the basement in the Upper Fafem Valley are topped by the cliff forming Lower Hamanlei formations.

These Adigrat formations overlying the basement aquiclude represent good aquifers and recharge zone when exposed to rainfalls in the upper part of the survey area.

They are not very favorable for agriculture unless irrigated or close to the water table stored below.

5. Early - Middle Jurassic Aalenian to Callovian - The Hamanlei formations

Named from the village of Hamanlei in Ethiopia where it is described as white to buff, well-bedded, mainly oolithic and fossiliferous limestone, were first named by Blanford (1870) and later described in detail by Mohr (1963), Beyth (1971), Kazmin (1972 & 1978), Merla et al. (1973) and Merla (1979).

They are typically developed in the Mekelle area, with 750 meters of thick sequence deposit of fossiliferous yellow marl and limestone.

The succession thickens to 1420 meters in the Danakil Alps, where it consists of thinly bedded, pale fossiliferous limestones.

The Hamanlei Formations are divided into three stratigraphic intervals, Lower, Middle and Upper Hamanlei.

The Abbay beds (Middle Jurassic) correspond to the lower sequence consists of 257 m of barren land alternating gypsum, limestone, dolomitic limestone, sandstone and shale.

The Limestone sequence (Upper Jurassic) of Middle Hamanlei is the most massive with a thickness which might reach 750 m. This sequence consists predominantly of barren fossiliferous yellow limestone containing thin beds of marl and calcareous shale, and occasionally arenaceous bands near the top.

The Hamanlei limestones in Jijiga area along the Jerer and Fafem rivers reach an average thickness which never exceeds 250 m.

Near Jijiga, because of the presence of the Marda fault shear zone, Hamanlei limestones are subject to kartification which represent excellent aquifers and recharge zone when exposed to rainfalls.

Figure 26 - Lower Hamanlei formation along the Jerer valley south of Jijiga. Notice the centimetric marl layers between white compact limestone beds (43°0583 E, 9°0289 N). ©Picture RTI 18 July 2012.

Figure 27 - Lower Hamanlei formation along the Jerer valley south of Jijiga. Notice the centimetric marl at the base of the karsted limestone bed (43°0583 E, 9°0289 N). ©Picture RTI 18 July 2012

Figure 28 - Cliffs forming Lower Hamanlei formation North of Jijiga. (42°57300 E,9°5158 N). Notice the vegetation between the limestone beds indicating groundwater circulation. These formations are well preserved thanks to the Oligocene basalts cover. ©RTI. Picture.

6. Callovian – Kimmeridgian - Uarandab Formation

The Callovian - Kimmeridgian interval is a time of shale open marine facies deposition across much of Ethiopia and Somalia.

Uarandab formation which is a semi-regional shale horizon is named by the village of Uarandab in Ethiopia, where this formation is composed of 55 m of gray, brown, and greenish gypsum-bearing shale intercalated with gray argillaceous limestone in the middle part, and similar shale in the lower 15 m. Fossils are common with abundant Belemnites and ammonites.

This formation outcrops in large area of Fik zone such as Segag and Gasangas areas.

The formation is also present in most of the oil wells in Somali Region of Ethiopia and there it is mostly shale with a maximum thickness of 300 m.

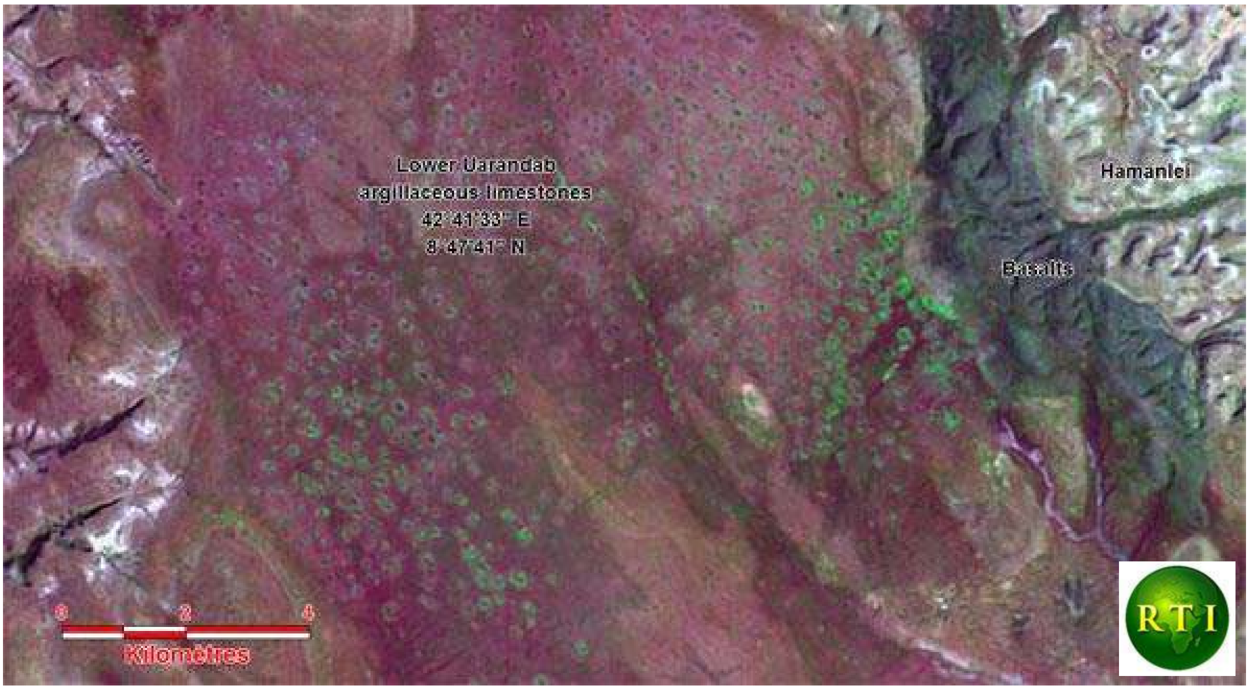

Figure 29 - Landsat (7,4,2) processed of the Lower Uarandab formations. The clay rich limestones are more favorable to agriculture than the barren Hamanlei formations. Notice the dotted surface of sinkholes resulting from the kastification of the underlying Hamanlei formations.

Figure 30 - High resolution optic image showing the agricultural zone on the Uarandab formations punctured by sink holes above the karsted Hamanlei formations.

Figure 31 - Uarandab marly formations along the Jerer Valley, near Qaaxo wells (43°00371 E, 8°9861 N). Thickness of   17 m. ©Picture Casey Walther-18 July 2012.

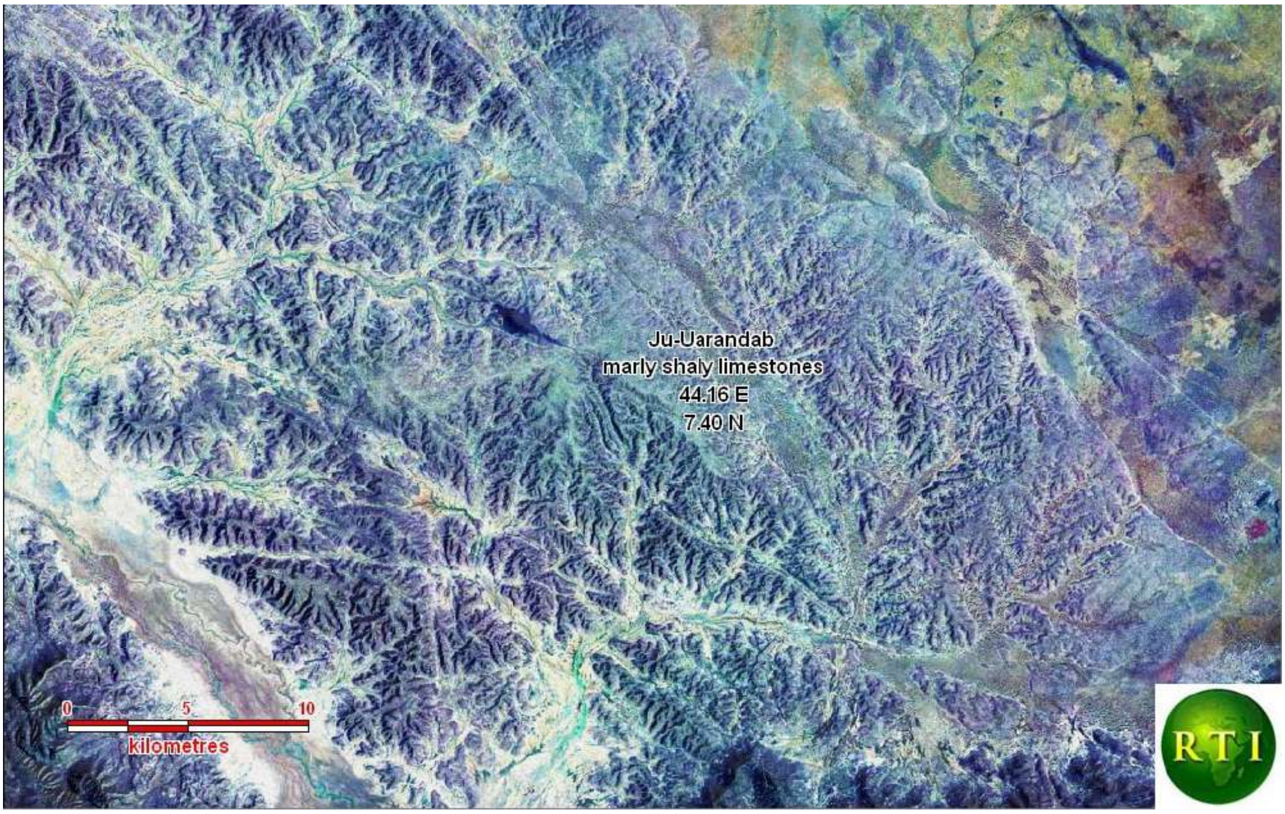

Figure 32 - Landsat image (7,4,2) showing the Upper marly gypsum bearing shales of the Uarandab formations in Somali Region, South West of Jijiga.

<u>The Uarandab formations are a main aquiclude sealing Hamanlei aquifers. Beside the lower Uarandab carbonated formation, the upper marly gypsum formation is not favorable for agriculture.</u>

7. End of Jurassic (Portlandian) - Gabredare Formation (Portlandian)

Gabredarre comes from the town of Kabredarre in Korahe Zone. It is described as dark shale and marly and gypsiferous limestone.

The upper 40 m are fossiliferous.

They are underlain by 20 m of thin-bedded alternating Oolithic and marly limestone with gypsum bearing shales, overlying 30 m of earthy ocher-colored limestones, and finally 60 m of gypsum.

Below the gypsum is 130 of finely crystalline, yellowish, partly oolithic limestone grading downward into 40 m of yellowish and gray marl containing flattened ammonite impressions.

A maximum thickness of 629 m was present in the Gumburo oil well where the Gabredarre is a limestone with shale members. The oolithic limestones could offer some opportunities for aquifers.

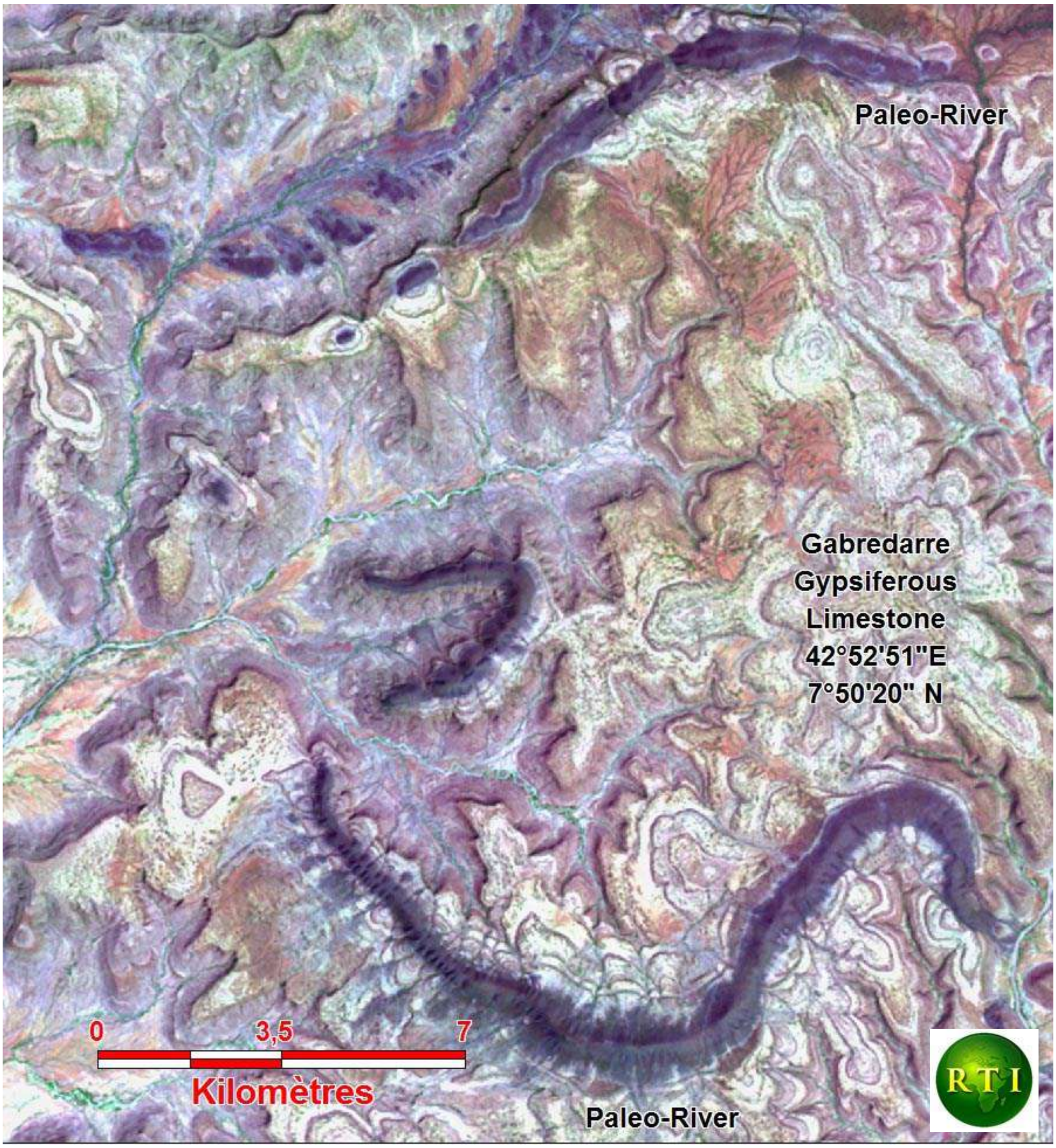

Figure 33 - Landsat image (7,4,2) showing the Gabredare limestones on the South west of the survey area. These formations have a very specific radiometric and shape signature.

Notice the meanders of a paleo-river infilled with basalts resulting from an eroded basaltic shield cover during the global uplift of Ogaden in the Late Cretaceous. Below the basalts meanders lie the original paleo-river alluvial sediments which might host confined aquifers sealed by the basaltic cap.

8. Cenomanian-Senonian - Belet Uen Formation

This series consists of creamy to light grey limestones from neritic to locally reefal origin, with intercalations of greenish grey glauconitic shales and green or brown sandstones, over a thickness from 87 to 232 m.

This formation which is outcropping near the village of Beletwein in southern Somalia is composed of 145 m of mainly limestone.

In descending order, it consists of:

- 35 m of alternating white and yellowish bearing limestone, shale, and sandstone with some gypsum beds passing upward into the Jessoma sandstone;
- 25 m of similar limestone with some shale;
- 15 m of siliceous limestone;
- 20 m of alternating brown, calcareous, locally quartzitic sandstone and arenaceous limestone; and 28 m of pseudo-nodular Limestone with abundant mollusks and echinoids with two Orbitolina zones at the top;
- 11 m of compact fine-grained whitish limestone in beds 0.2 to 1.0 m thick;
- 3.5 m of brown calcareous sandstone abundantly fossiliferous; and at the base
- 7.5 m of alternating gypsum and cream to buff fossiliferous limestone.

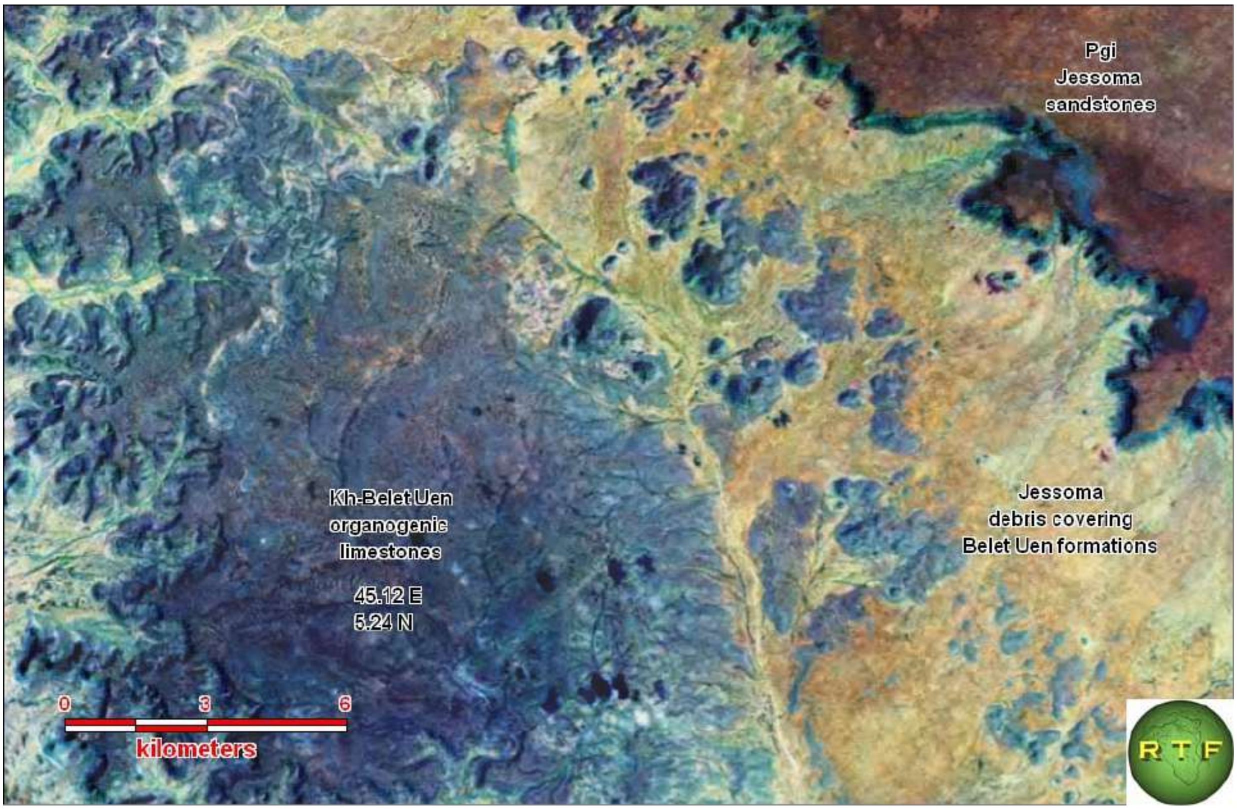

Figure 34 - Landsat image (7,4,2) showing Kh-Belet Uen organogenic limestones which could be misinterpreted as Km-Mustahil Limestones due to the deep-blue color. They are overlaid on the East by the brown Pgi-Jessoma sandstones.

9. Late Maastrichtian – Paleocene - Yesomma Formation (Cretaceous Companion to Thanetian)

This formation is outcropping near the village of Jessoma, East of Buulo Burti, in southern Somalia with a thickness of 300 to 400 meters and overlies the Belet Uen Formation unconformably.

The Jessoma sandstones are composed of red, brown, purple, and yellow sandstones. Cross bedding is common and interpreted to be of fluviatil origin. Loosely cemented fine to very coarse-grained sandstone with local gypsiferous beds at the base, it is unfossiliferous but, from the ages of the rocks beneath and above, it is believed to include deposits of the Turonian and most of the Senonian.

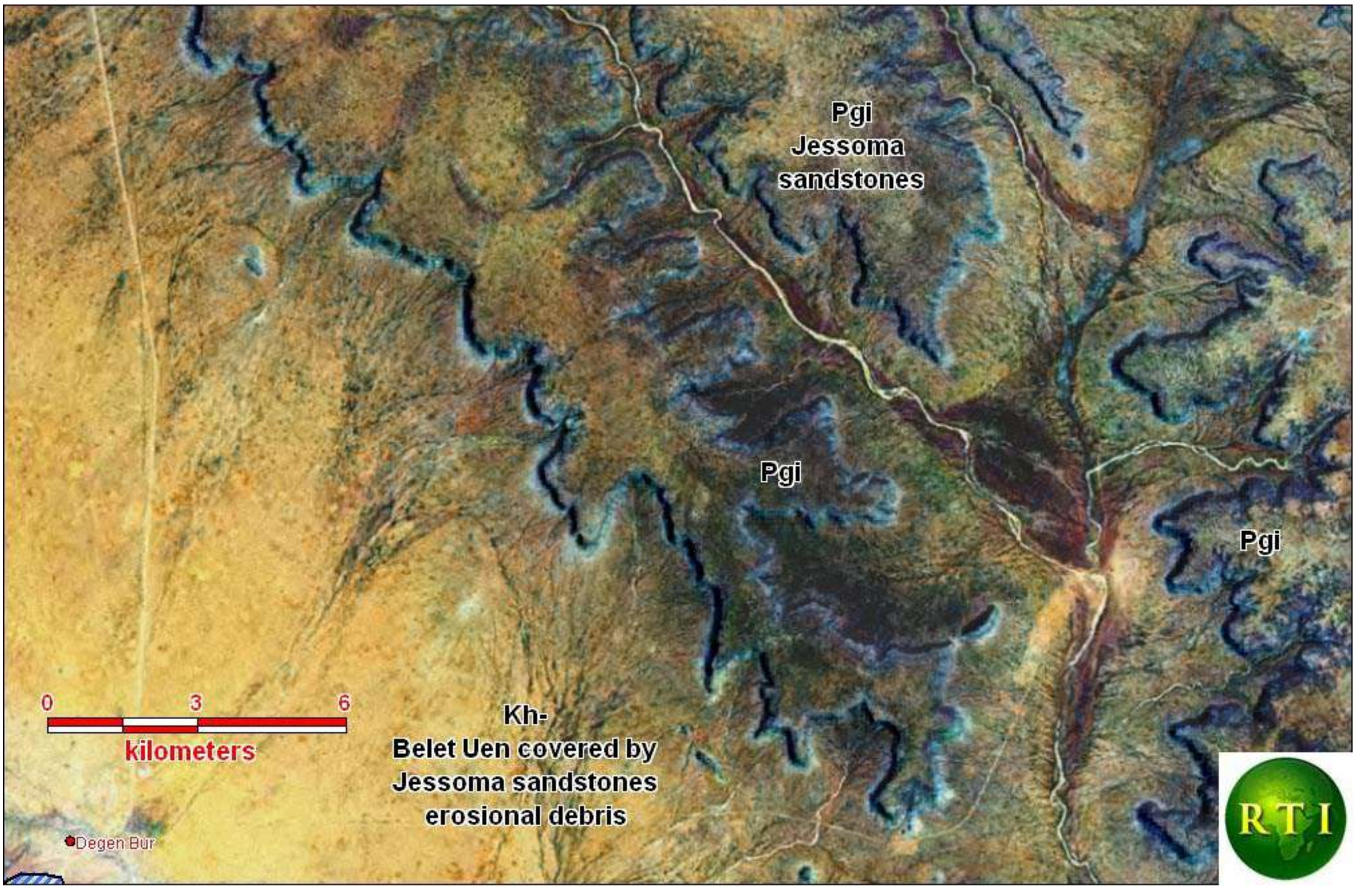

Figure 35 - Landsat image (7,4,2) showing Jessoma sandstones on the South west of the survey area. The Jessoma sandstones form steep cliffs over the Belet Uen formations, north of Deben Bus, along the Jerer Valley, South East of Jijiga, in Somali Region.

Eroded sandstones washed down to the valley of the Shabelli River cover large parts of the underlying Belet Uen Formation not visible on Landsat images in this area.

Jessoma Sandstone formations outcrops lie east of Jijiga all the way down to Warder Zone.

Uncemented sandstone contains subsurface calcareous concretions.

The unconformable contact, however, is seldom seen as the Jesomma sandstone weathers deeply and forms a cover of several meters of loose sand over the first cemented layers.

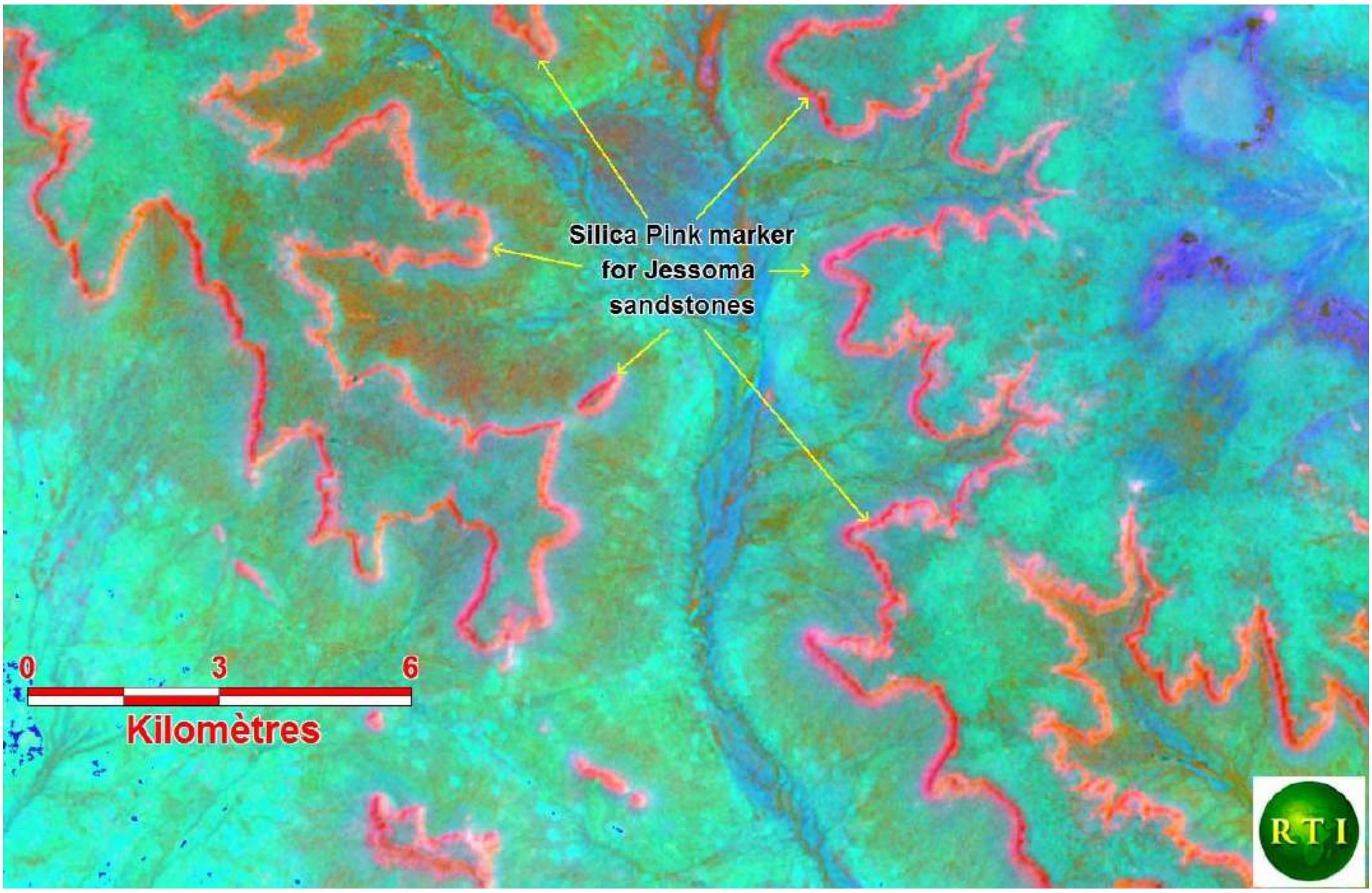

Figure 36 - Same area seen by Sultan Processed Landsat image showing the pink boundary of silica rich Jessoma sandstones formation forming cliffs.

The pink rim enhanced by Sultan Processed image represents the silica rich component of the Jessoma sandstones formation.

This is an important marker to differentiate the Jessoma Sandstones from the underlying Belet Uen or Uarandab underlying formations.

Drilling within the Jessoma sandstones is difficult due to the tendency of loose sand beds to cave into the boreholes. The sands, and also fractured sandstone beds, may contain groundwater of good quality and show high transmissivities in pumping tests (GTZ wells III b and IV, Burco).

<u>The lack of underneath aquiclude remain a question for their value as an aquifer, but these sandstones are one of the major regional inter-granular recharge areas which outcrop on the eastern rim of the survey area.</u>

The Jessoma Formation is typical only in the Sinclair wells in Wader zone and Shilabo district of Korahe Zone. The following Jessoma thicknesses were encountered Sinclair Oil wells in Somali Regional State:

- 430 m of Jessoma sandstone were found in the XF-5 well located close Gorgor village of Gashamo district.
- 396 m of Jessoma in XE-5 located close to Daratole village of Danot district.
- 374 m of Jessoma was found in XEF-1 oil well located close to Koratunje village.

Based on the above illustrated thickness, the Jessoma sandstone thickness increases from east to west and northwest.

<u>These formations do not provide good land for agriculture unless irrigated.</u>

Figure 37 - Top of Jessoma sandstones formation near Obole along the road to Degen Bur: coarse sandstones are cemented by iron oxides (43°5556 E, 8°4439 N). ©Picture RTI 17 July 2012.

Figure 38 - Base of Jessoma sandstones formation near Obole: (43°5556 E, 8°4439 N). Mudstone and siltstones intercalations over base conglomerates Picture RTI 17 July 2012. Such formations could be considered as aquicludes. ©Picture RTI 17 July 2012.

10. Eocene - Auradu Limestone (Tertiary Thanetian to Priabonian)

A transgression at the start of the Eocene, possibly associated with high sea levels during the Ypresian, resulted in the deposition of limestones of the Auradu Formation over the Yesomma Formation.

Outcrops are found in a band extending through the western part of Galgudud region to the coast of the Indian Ocean via Duusa Mareeb and Ceel Dheere.

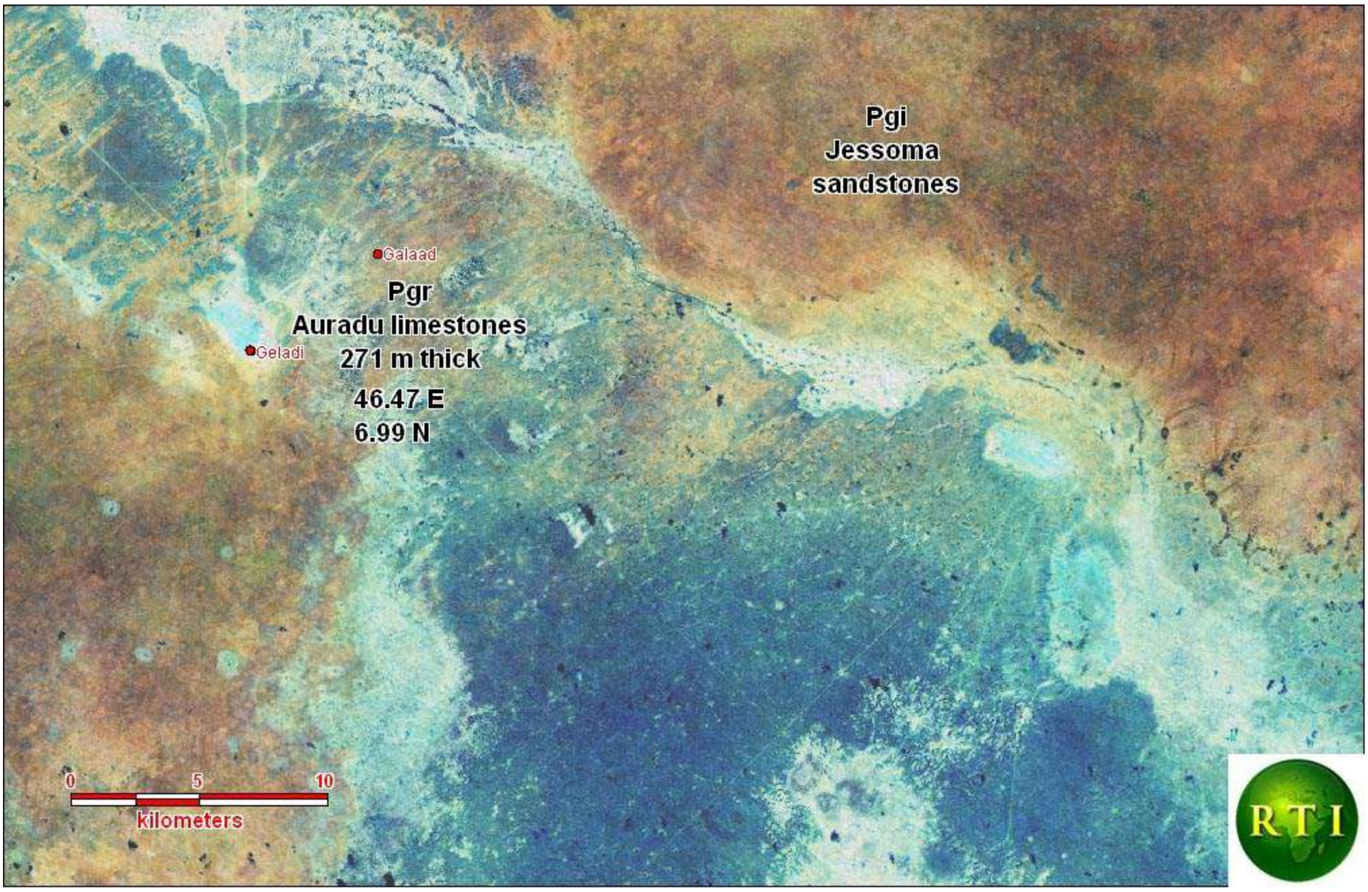

Figure 39 - Landsat image (7,4,2) showing Pgr-Eocene Auradu limestones (blue) near Galaad, over Pgi Jessoma sandstones (brown) and punctuated by karsts or Mudugh beds.

The age of the Auradu limestone in outcrop includes the Paleocene and the Ypresian and part of the Cuisian Stage of lower Eocene as indicated by the presence of shallow-water Foraminifera such as Lockhartias, Sakesarias, Alveolinas, and Nummulites.

Auradu series are finely crystalline, compact, hard, and usually tan to light-brown limestone with local thin gray shales.

The Auradu Limestone reaches a thickness of 400-500 meters in the western parts of the area and up to 2,000 meters at the Indian Ocean.

Outcrops may show some karstification.

The limestone beds are commonly fractured and offer a good potential for groundwater storage and yield. Wells in the Auradu limestones produce good quality water and frequently in large quantities.

If overlain by impervious layers, artesian groundwater is found such as in the southeast near Duusa Mareeb. Flowing artesian drilled wells exist in the Ceel Bur area.

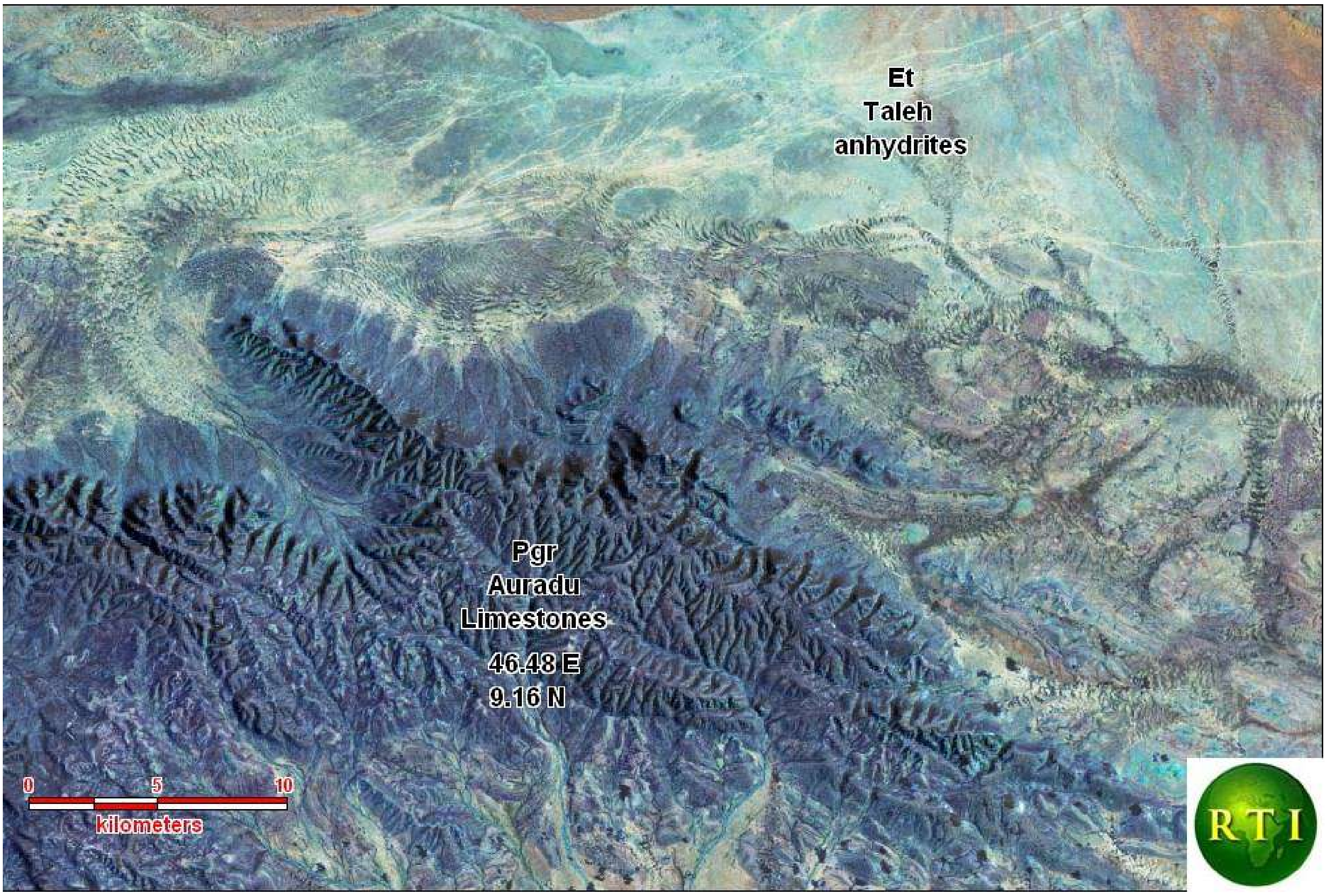

Figure 40 - Landsat image (7,4,2) showing another overview of the Pgr-Eocene Auradu limestones (blue) covered by Taleh anhydrites and gypsum formations (light blue) in North Somalia.

In Somali Region of Ethiopia, the Auradu limestone outcrops eastern part of Warder Zone and the Sinclair wells in Warder Zone, has penetrated a maximum thickness of 399 m of Auradu limestone was found in the XE-3A well located Close to Bokh town.

Barren land covers these formations which are obviously not prone to agriculture.

11. Tertiary Volcanic formations-Tv Basalts

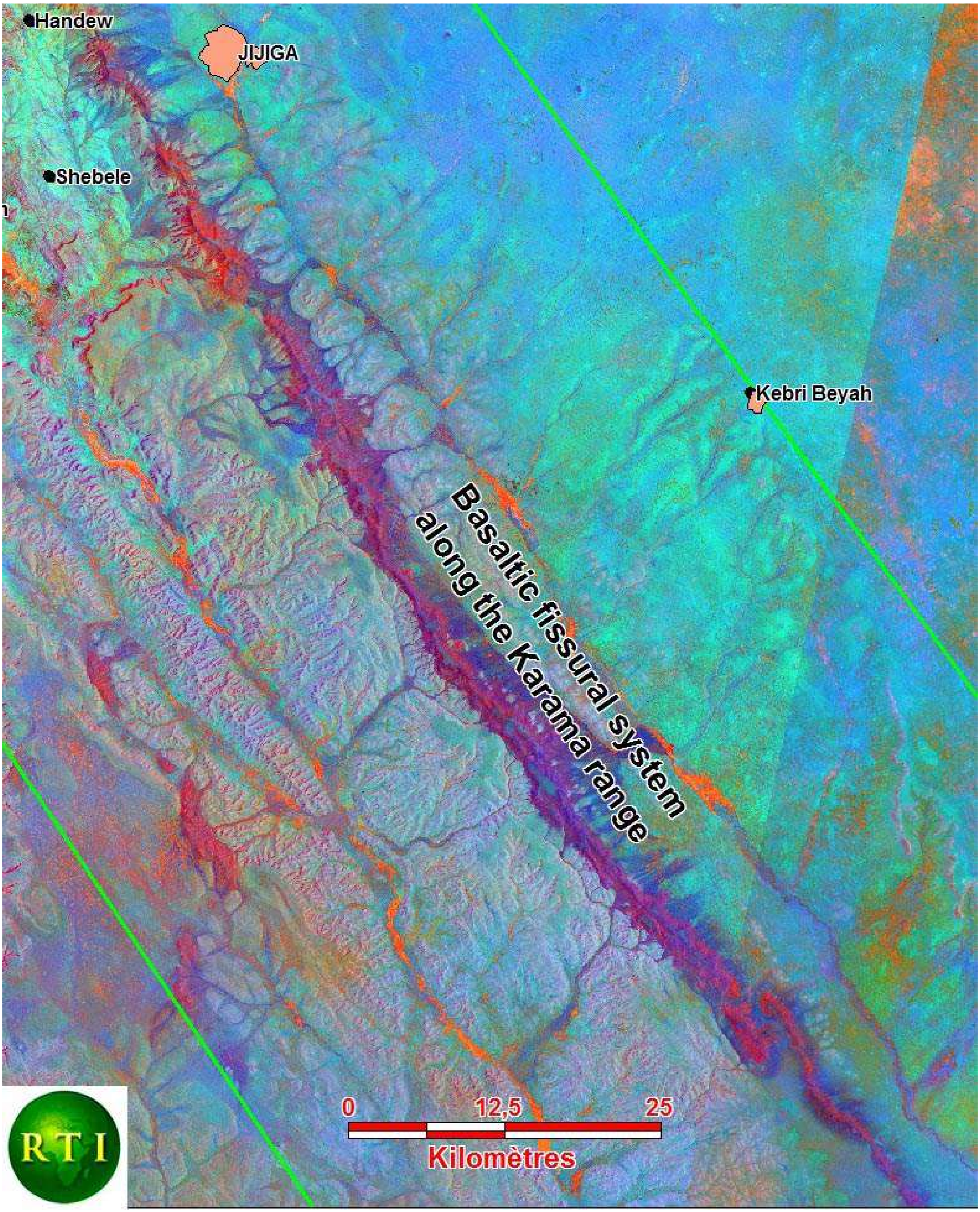

Figure 41 - Landsat Sultan Processed image showing in deep blue-purple the fissural basalts system oriented N 160° as a backbone across the survey area.

When carefully analyzed, this fissural system is not continuous but appears "en echelons" with dislocated shear distensive patterns which will be commented in detail in the next structural chapter. This elongated system is outcropping along a visible trend of 130 km, but most likely longer as suggested 250 km in the south by other elongated basaltic segments.

This fissural basaltic system, of tertiary period, reveals one of the major structural trend of the survey area called the Marda Fault System first reported by Purcell in 1976.

Figure 42 - Picture of the basaltic ridge separating the Jijiga Plain from the Upper Fafem Valley, showing along the road from Jijiga to Shebele, interlayered basalts (locally called Jima Volcanics) and volcanic tuffs. The Adigrat sandstones and located below the basalts. ©Picture RTI

Basalts are frequently encountered in deep drilled wells northeast of the Shabelli River.

These basalts may serve as aquifers where they are fractured or scoriaceous, and as confining layers where they are dense and impermeable.

Artesian water has been struck when deepening boreholes through basalts in some areas.

Recent boreholes undertaken by GTZ encountered olivine basalts as a sill in Auradu limestone near Dhuusa Mareeb and Ceel Bur. the basalt sill near Dhuusa Mareeb is impervious.

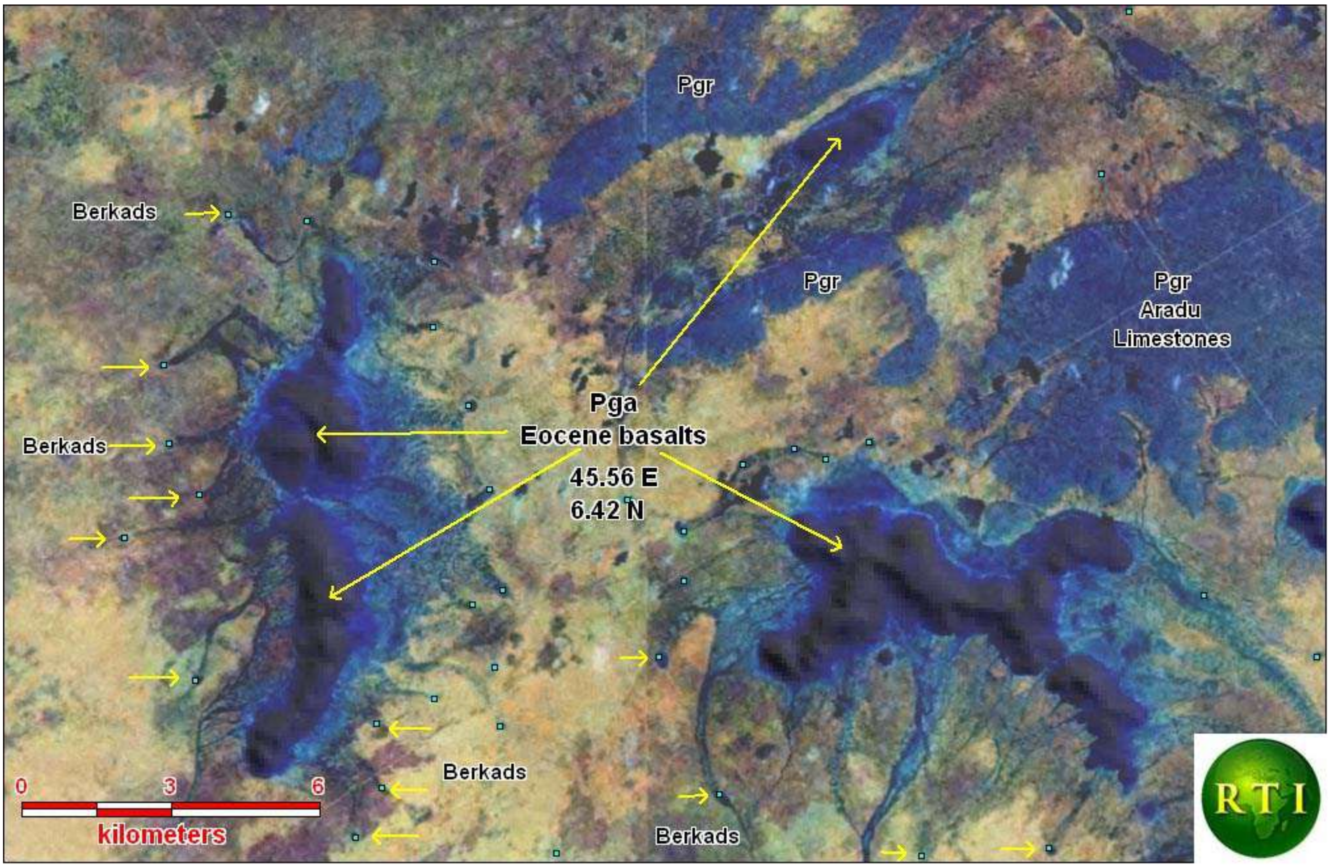

Figure 43 - Landsat image (7,4,2) showing Pga-Eocen basalts hills protruding through Auradu limestones. Rainfalls are harvested with berkads all around these intrusive basaltic bodies.

Figure 44 - Google high resolution optic image showing berkads all around these intrusive basaltic bodies (See attached geographic coordinates).

12. Oligocene plateau basalts

Figure 45 - Aerial photography of the Adigrat sandstones (agricultural area) covered by Hamanlei limestones (steep slopes) and capped by Oligocene basaltic plateau (flat top), North of the survey area (coordinates 42°20’10” E 9°27’46” N). ©RTI picture 12 November

These Oligocene basaltic sheet covers have protected the underlying Cliff forming Hamanlei limestones formations from erosion during the uplifting phase of Ethiopia.

Such basaltic plateaus occur in the north of the survey area, just close to the rift margin, north of Jijiga.

13. Basalts sealing perched Paleo-river beds

Basalts which outcrop near Segag need further investigation to determine their potential as aquifers, as they correspond to paleo river beds filled by basaltic lavas, and eroded after uplifting.

Alluvial deposits of these perched rivers could be sealed below and would store and convey important freshwater quantities.

These basalt flows are indicated on all geologic maps but with location errors of 18 km.

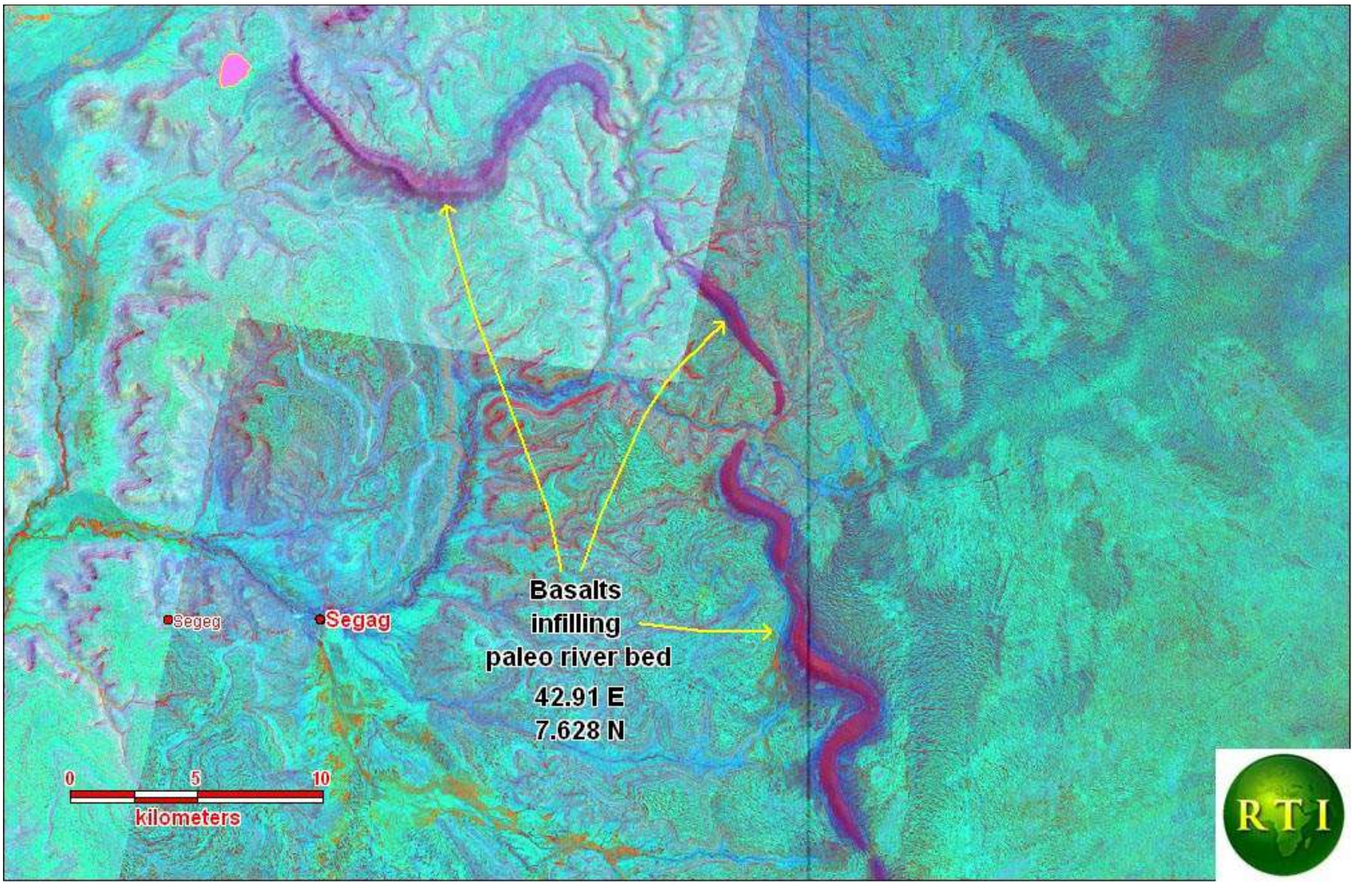

Figure 46 - Landsat image Sultan Processed showing the radiometric signature of the basic lava flow.

Some segments of these paleo-rivers which extend continuously along 20 km over a width of 500 m, might store important quantities of freshwater in the well preserved alluvial deposits (if not metasomatized by the overlying basalts).

From a simple approximation, such individual segments of aquifers might have preserved some 10 m thick alluvial deposits with a porosity of 10%;

In such a case, these individual aquifers could host 10 million cubic meters of recoverable fresh water.

It will be worth drilling underneath.

C. Derived Geologic Map

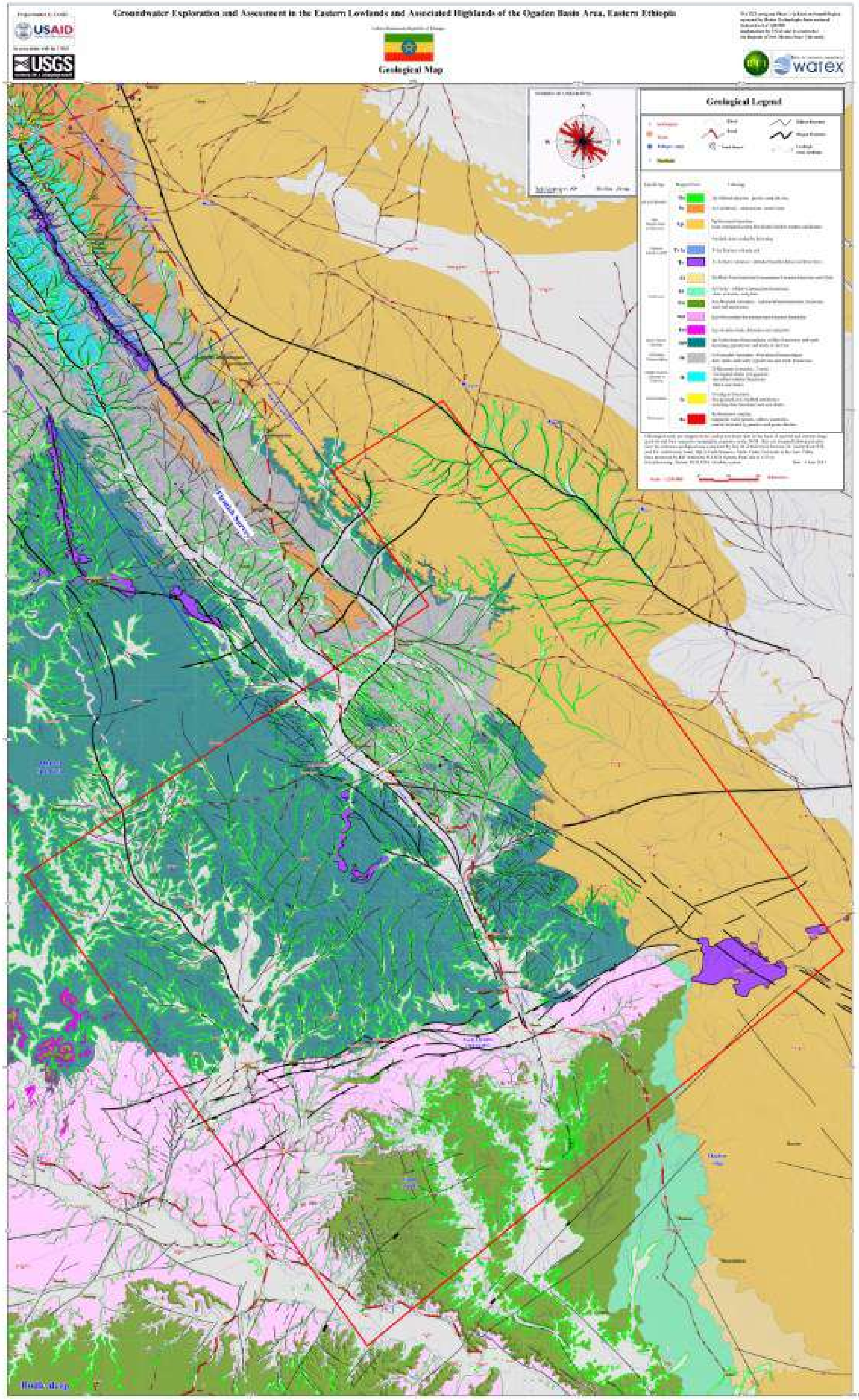

Figure 47 - New geologic map resulting from the radiometric analysis.

This new interpreted geologic map based on Landsat radiometry analysis, which takes into account, when not contradicted by imagery analysis, the former geologic denominations and boundaries, is the base of the ground water analysis process. It is delivered as paper print and .jpg format at 200 000 scale.

VI. GEOMORPHOLOGIC AND STRUCTURAL INTERPRETATION

A. General context

1. Uplift and fracturing

Uplift and fracturing occurred in northeast Africa beginning from the Late Cretaceous resulting in regression of the Mesozoic Sea and deposition of Cretaceous to Tertiary sedimentary rocks in the eastern Ogaden Basin (Jessoma sandstones and Auradu limestones), eruption of voluminous flood basalts and subsequent volcanism forming the Ethiopian highland plateaus (such as the Jima basaltic magmas injected along the Karamara range in early Eocene), and development of the East African rift systems including the Main Ethiopian rift, the Gulf of Aden and the Red Sea rift. Such tectono-volcanic events accompanied by intense fracturation along the shear-distensive corridor of the Marda fault system, uplifts led to major consequences on erosion and sedimentation dynamics.

2. Geomorphological analysis

The Marda Fault Zone first reported by Purcell (1976), has attracted all our attention as it is a major structure affecting the survey area along a trend oriented Northwest-Southeast from the north-eastern Ogaden for about 900 km across the Belet Uen area in Somalia (e.g., Geleta, 1998).

The Marda Fault Zone is a major continental structure that down-warped the eastern Ogaden (e.g., Purcell, 1979 and 1981) coastal Somalia changing the pattern of sedimentation and also marks apparently the boundary between the Mesozoic and Tertiary sedimentary deposits in the Ogaden Basin (e.g., Kazmin, 1972; Tefera et al. 1996). Marda is presumed to be a Precambrian structure later reactivated during Tertiary periods

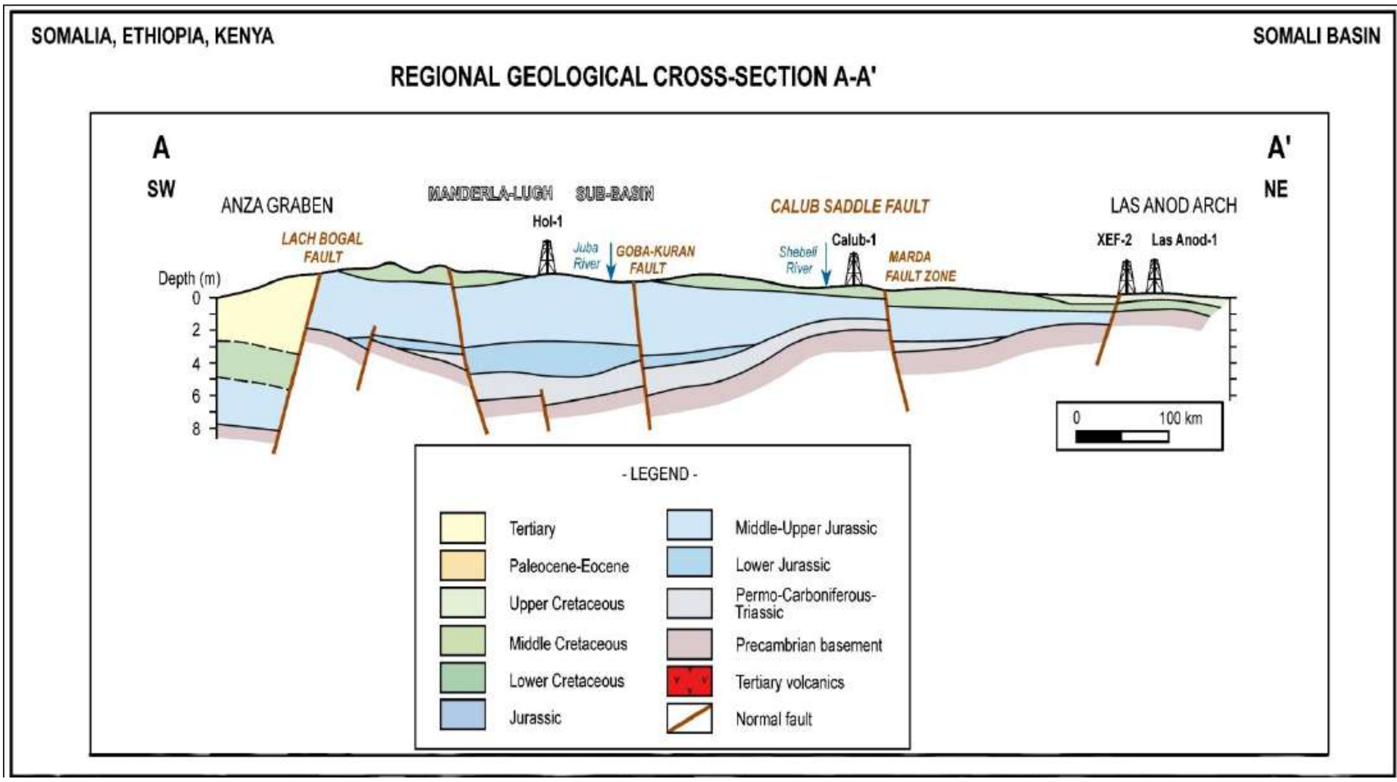

Figure 48 - This IHS cross section clearly indicates in the southern part outside of the survey area, the Marda fault corridor between the oil wells of Calub-1, and XEF-2, Las Anod.

The Marda Fault corridor which is playing a major role for surface water drainage and recharge of deeper aquifers has never been properly studied because it is too shallow for oil exploration and too deep for traditional hydrogeology surveys, that is why it has been carefully studied in this report.

B. Fractures analysis

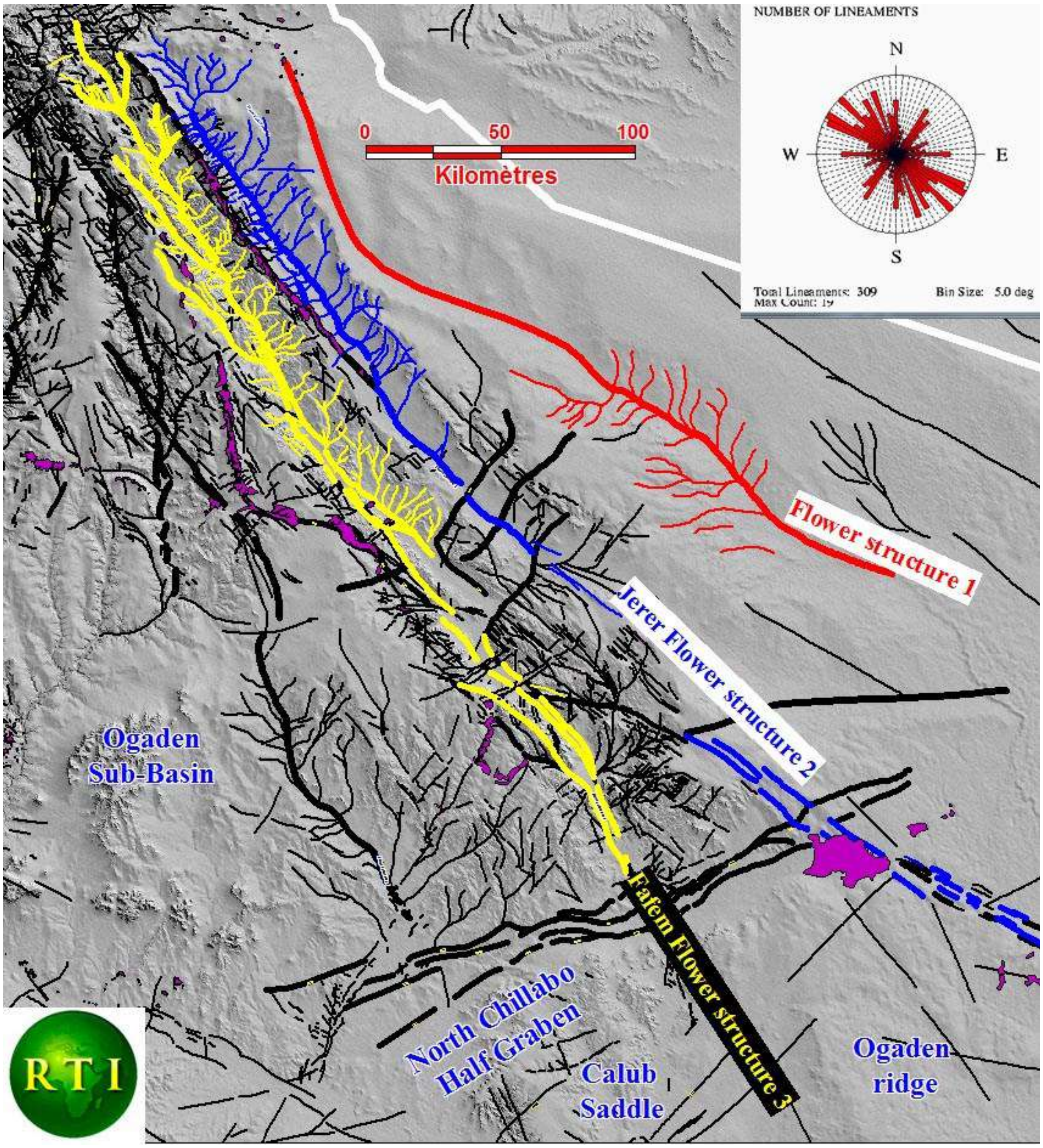

Figure 49 - SRTM color coded image with detailed fracture patterns on the survey area (red polygon).

Among thousands of fractures extracted from radar imagery, the SRTM and the slope map, the main fractures have been selected to illustrate the structural type which is affecting the whole area.

It appears that the major N 140°-160° pattern of elongated fractures known as the Marda fault system, is the result of three major shear structures called "Flower structures" described in red, blue and yellow.

They control each a distinctive watershed playing a major role in groundwater circulation from the

the flower structure n°1 in red controls the Uardere watershed.

The flower structure n°2 in blue controls Jerer watershed.

The flower structure n°3 in yellow controls the Fafem watershed.

The Jerer and Fafem watersheds are separated by the elongated basaltic dyke of the Karamara range (purple color) which operates as an aquiclude in the hydrogeological process, with a tight separation between the groundwater harvested by the Jerer and the Fafem watersheds.

After a course of almost 200 km, these two watersheds are dislocated by N 45° to N 60° major fractures which drain the groundwater flows along the southern part of the Fafem.

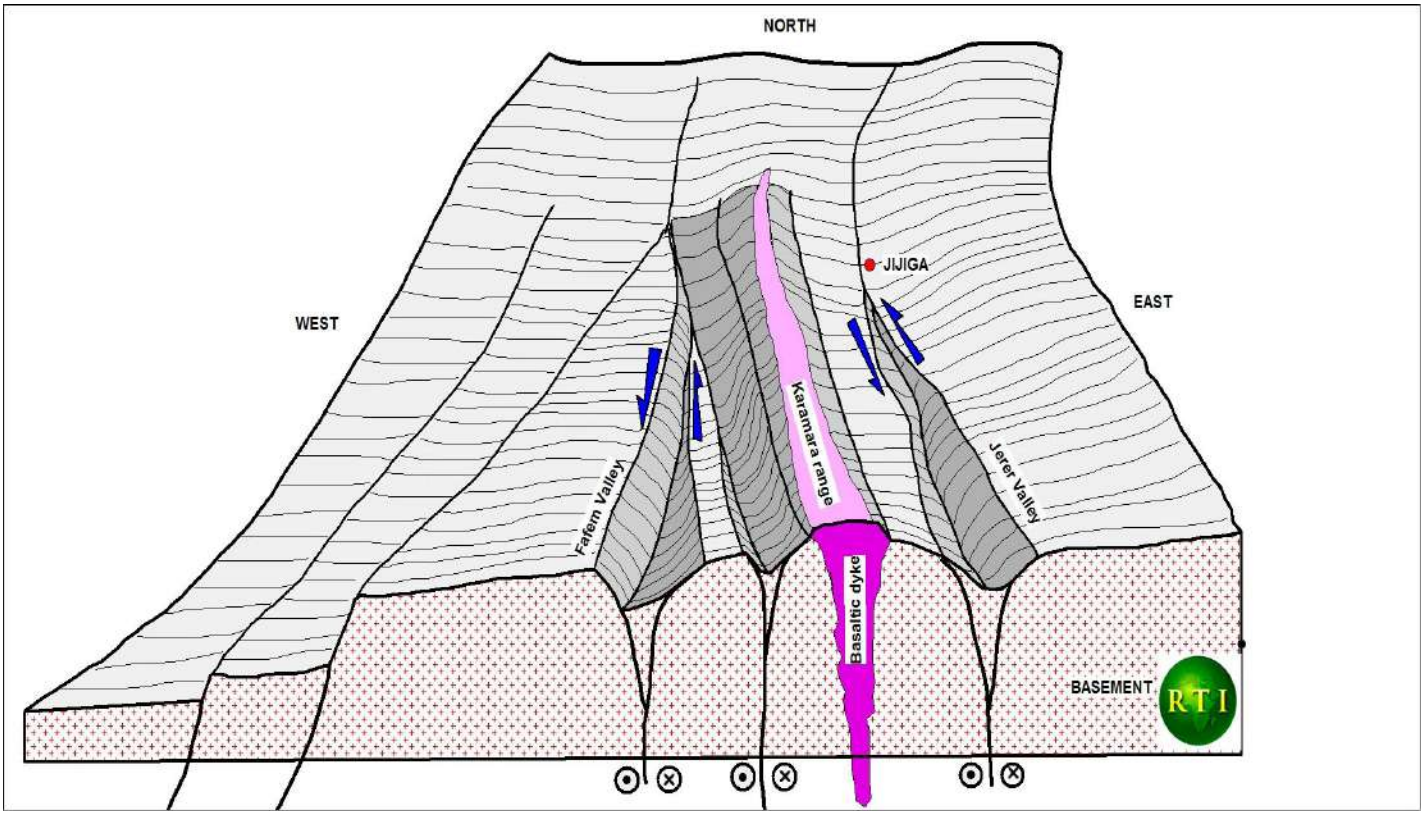

Figure 50- 3D structural model of the Fafem and Jerer valleys.

The three major N140°-160° patterns of elongated sinistral shear fractures known as the Marda fault system, are the result of three major shear structures called "Flower structures" which control each a distinctive watershed playing a major role in groundwater circulation from the harvesting area of the highlands in the north, to the low plains of Ogaden in the south.
This diagram illustrates in 3D the flower structure n°2 which controls Jerer watershed and the flower structure n°3 which controls the Fafem watershed.
The Jerer and Fafem watershed are separated by the elongated basaltic dyke of the Karamara range (purple color) which operates as an aquiclude in the hydrogeological process, with a tight separation between the groundwater harvested by the Jerer and the Fafem watersheds.
As such Marda Fault system appears to generate major prospective areas for groundwater assessment.

Gravimetry map and basement depth

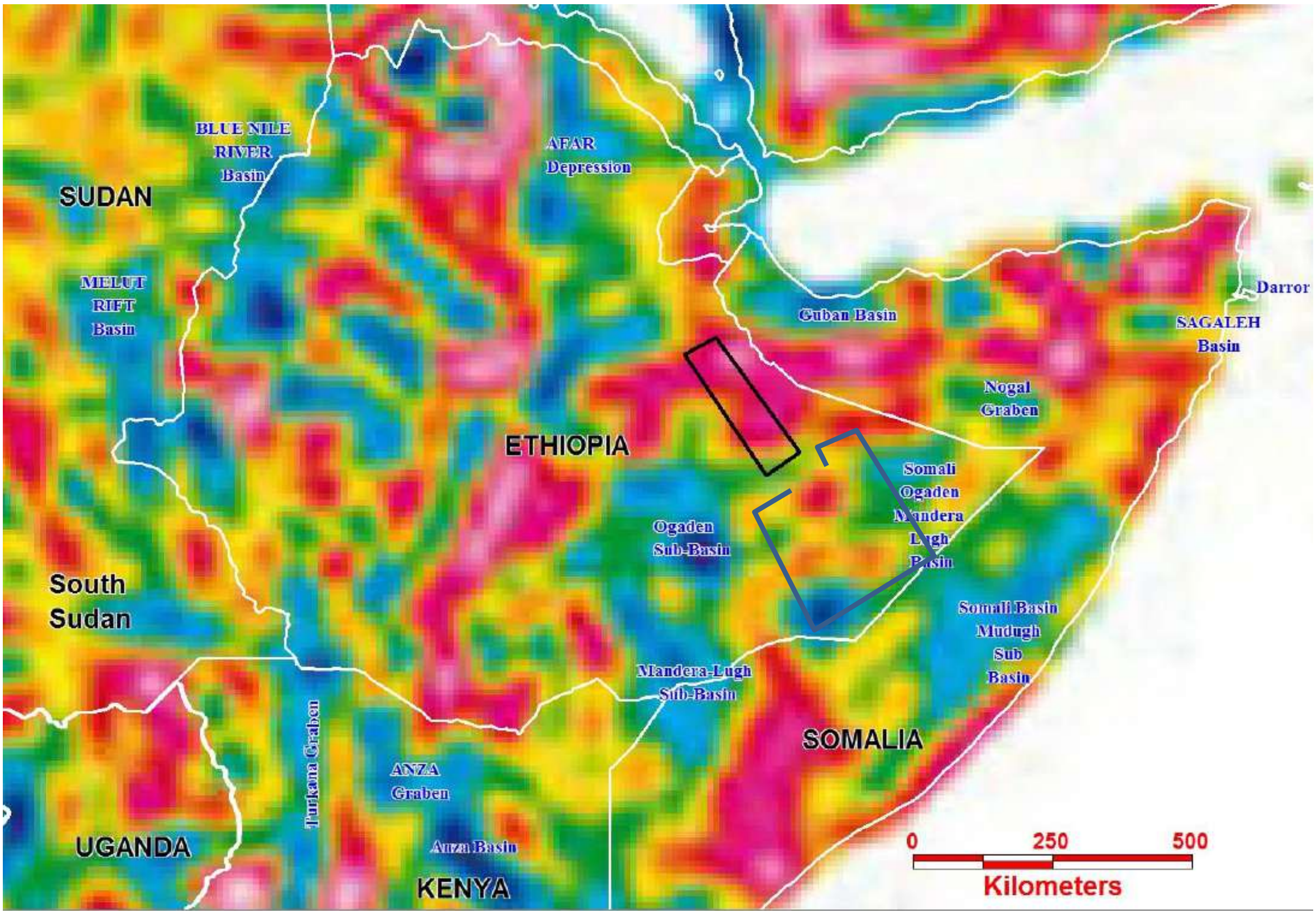

Figure 51 - High-Pass filtered Gravity anomaly map of Africa showing outcropping or shallow basement in red and sedimentary basins in blue. The main oil exploration basins are marked with blue letters. The survey area is located in the black polygon, in a red zone

This map has been extracted from the report "A crustal thickness map of Africa derived from a global gravity field model using Euler deconvolution" published the 1st of July 2011 by Getachew E. Tedla[12], M. van der Meijde[1] A. A. Nyblade[2,3] and F. D. van der Meer[1].

In this case, Crustal thickness was computed from the free-air gravity anomaly EIGEN-GL04C, which was developed from 30 months of GRACE Level 1B data covering the period from 2003 February to 2005 July and surface gravity data from seven different sources (Christoph *et al.* 2008, Fig. 1A).

The satellite orbits were used to incorporate lower spherical harmonics up to 150◦ in to the model, and the remaining higher degrees (i.e. 150◦–360◦) were computed from terrestrial gravity data.

In general, regions that are associated with large sedimentary basins tend to have thinner crust whereas ancient orogenic belts appear to have somewhat thicker crust.

Gravity highs (in red) are associated with higher density igneous and metamorphic rocks and gravity lows (in blue) with lower density sedimentary rocks.

The USAID-USGS Phase 1 area is overlying a deeper basement than on the Flemish survey area.

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[2] *Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA*

[3] *School of Geosciences, The University of the Witwatersrand, Johannesburg, South Africa.*

VII. HYDROLOGY

A. Drainage systems

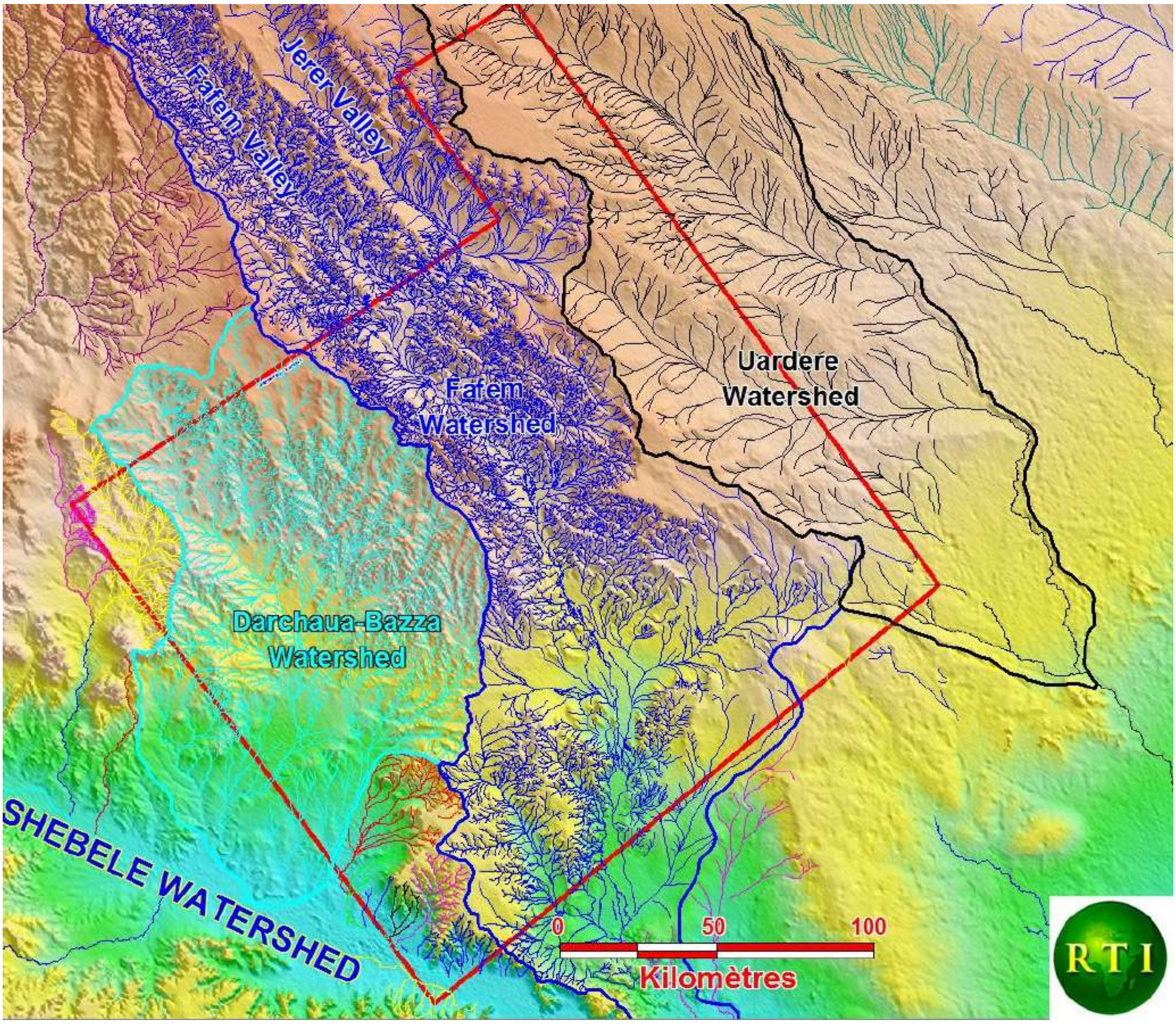


Figure 52 - Drainage system of the Fafen river (deep blue).

The Fafen watershed covers a surface of 39 400 km² and extends far beyond the limits of the survey area. It hardly flows during the rainy season and its lower course is not accurately drawn on topographic maps.
The Darchaua-Bazza watershed covers a surface of 14 540 km² over Jessoma sandstones and flows to the Shebele. It is mainly an endoreic drainage system never mapped on any topographic maps.
Its main role is to recharge possible deeper aquifers thanks to rainfalls harvested in its northern part in the highlands of the Somali region of Ethiopia.

The Uardere watershed covers a surface of 25 460 km². This watershed does not host any active river; it is rather a drainage system which does not exist on any map.

Among these 3 watersheds covering the survey area, the Fafem provides most of the groundwater thanks to underground water circulation.

B. Watershed hydrogeological characteristics

Slopes

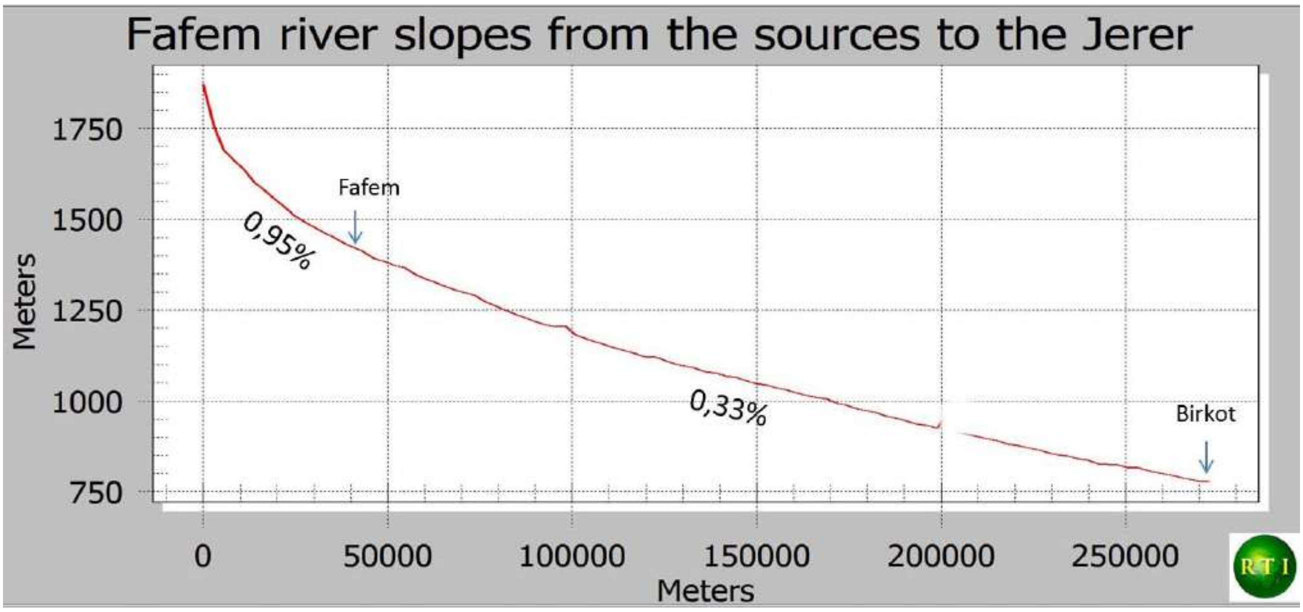


Figure 53 - Slope analysis of the Fafem river course from the source to Birkot.

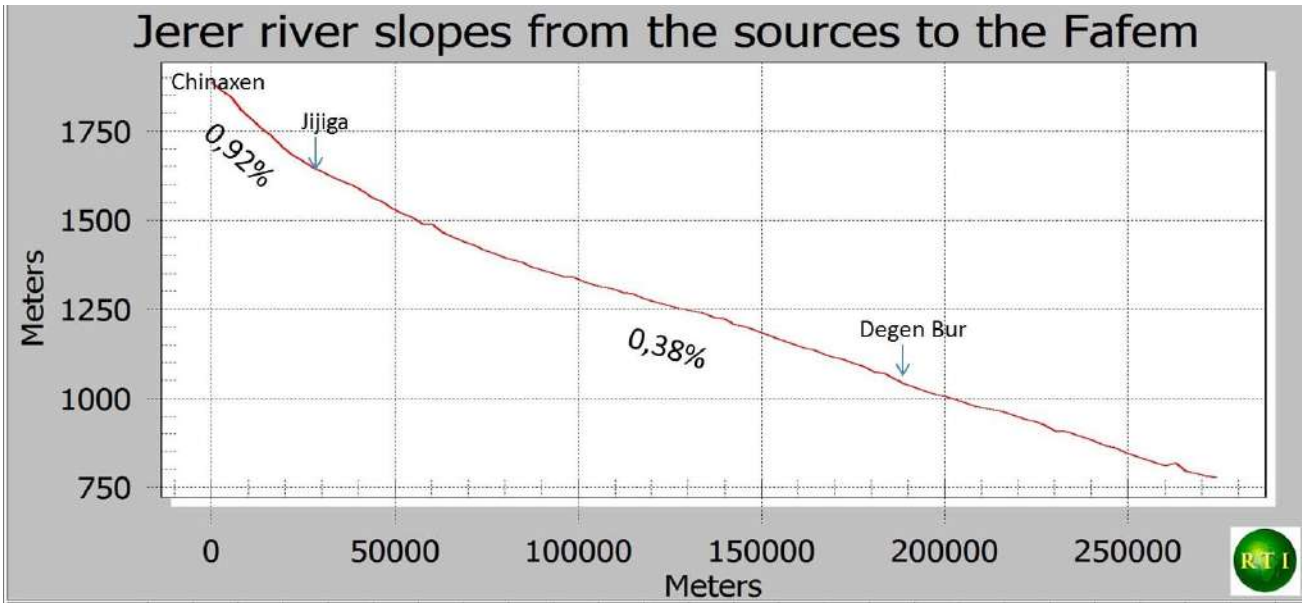


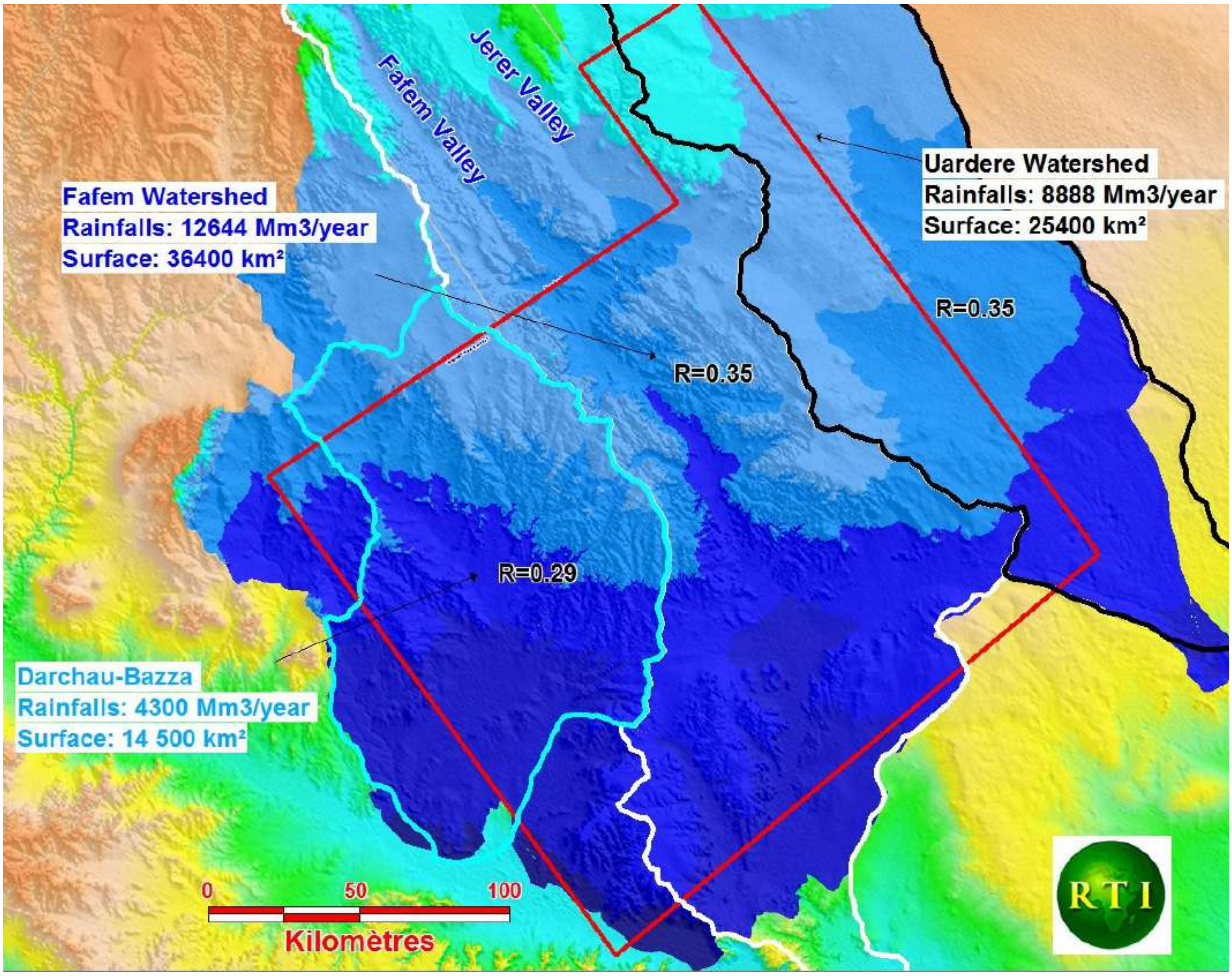
Figure 54 - Slope analysis of the Jerer river course from the source to Birkot.

The slopes of the Jerer river are more regular but steeper (Break of steep slopes of 0.92% to 0.38% in Jijiga) than the slopes of the Fafem river which are more irregular (Break of the steep slopes of 0.95% to 0.33% in Fafem).

As a consequence, more alluvial potential is expected in near the break-off slope south of Fafem village than near the break-off slope south of Jijiga.

In both cases, we can expect well sorted alluvial deposits because of comparable slopes lower than 0.5%, which imply good aquifer conductivities on both river alluvial aquifers.

C. Estimations of harvested rainfalls quantities



Fafem watershed

Ratio Rainfalls/Surface of 0.35 with a surface of 36 400 km² receives an annual amount of 12.6 Billion m^3 mainly harvested in the North, outside the survey area.

Uardere Watershed

Ratio Rainfalls/Surface of 0.35 equal to the Fafem watershed, with a surface of 25 400 km² receives an annual amount of 8.8 Billion m^3 mainly harvested in the North, outside the survey area.

Darchau-Bazza Watershed

Ratio Rainfalls/Surface of 0.29, with a surface of 14 500 km² receives an annual amount of 4.3 Billion m^3.

THE RAINFALL/SURFACE RATIO (indicates rainfalls efficiency on a watershed)

Watershed	Surface in Km²	Rainfalls in Million M3/Year	Ratio R/S
TOTAL FAFEM	36 400	12 644	0,347
TOTAL UARDERE	25 400	8 888	0,350
TOTAL Darchau-Bazza	14 500	4 300	0,297

The Fafem watershed is harvesting 12.6 billion m^3 water/year for a surface of 36 400 km². The rainfalls/surface ratio of the Fafen watershed is averaging 0.35.

The Uardere watershed is harvesting 8.88 billion m^3 water/year for a surface of 25 400 km².
The rainfalls/surface ratio of the Uardere watershed is also 0.35.

Both of them have the most efficient upstream watershed which plays a major role in aquifers replenishment.

The Darchau-Bazza watershed is harvesting 4.3 billion m^3 water/year for a surface of 14 500 km².

We can expect favourable recharge conditions from the highlands for Fafem watershed through the Adigrat sandstones and the Jessoma limestones, and for Uardere watershed through the Jessoma sandstones and insignificant contribution to aquifers replenishment by Darchau-Bazza watershed.

D. Recharge areas and the recharge map

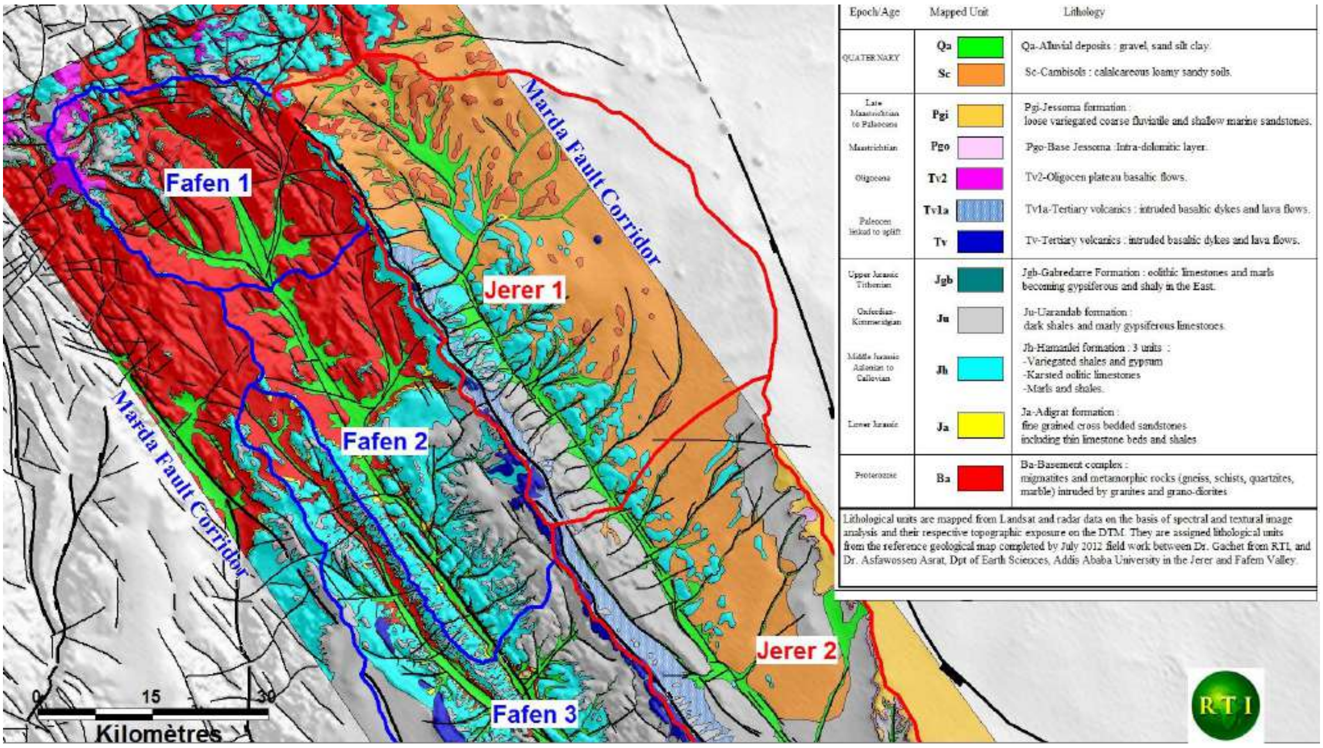


Figure 55 - Sub-watershed divisions overlying the geologic map.

As formerly shown, the Fafen watershed is harvesting 3 billion m^3 water/year and the Jerer watershed 4.1 billion m^3/year. Their respective rainfalls/surface ratio averaging 0.40 is almost comparable.

Both of them have the most efficient upstream sub-watershed if we consider their rainfalls/surface ratios:

- Ratio for Upper Fafem 1 Sub-watershed = 0.64, twice more than Fafem 5 = 0.31
- Ratio for Upper Jerer 1Sub-watershed = 0.55, less than twice Jerer 4 = 0.31

This can be explained by the rainfalls quantity falling in the highlands and the sharp decrease of rainfalls downstream to the Somali border.

In such a context, we can expect favorable recharge conditions from the highlands for both watersheds.

1. Recharge of the Fafem watershed aquifers.

According to the geologic map, both watersheds overlie the basement aquiclude (red) the Adigrat sandstones (yellow intergranular recharge zone), the intensively fractured and slightly karsted Hamanlei formations and the alluvial formations.

The Jessoma sandstones can also play an important role in recharging the aquifer but they appear on the eastern margin of the survey area with East dipping layers, that is why they have not been considered in this study.

Runoff could be rapidly absorbed by the alluvial sediments, the Adigrat sandstones and the Hamanlei karsted limestones.

These formations can harvest drain and store the most important water quantities falling on the highlands. The Fafem valley drains 3 billion m^3/year (see Fafem tables) and the Upper Fafem (Fafem 1) at least 1/3 of the total water quantities harvested on the complete watershed.

Most of this water quantity (after removing evapo-transpiration) could be stored within the Adigrat-Hamanlei (averaging a cumulated thickness of 250 m in this area) and conveyed downward to the South-East along the Marda Fault system, under the overlying Uarandab formations.

The fractures of the Marda fault system can accelerate vertically and laterally the surface water absorption and transit and most likely seep to the surface all along the transfer zones.

Nevertheless, beside the alluvial deposits, there are no structures along the Fafem valley, as explained later, to store substantial groundwater quantities in these formations.

2. Recharge of the Jerer watershed aquifers.

Along the Jerer valley, the most efficient sub-watershed, according to the former analysis, are:

- Jerer 1 (ratio of 0.55)
- Jerer 2 (ratio of 0.43)

These two units can harvest drain and store 2 billion m^3/year (see Jerer 1and 2 tables) or at least 50% of the 4.1 billion m^3 harvested on the complete Jerer watershed.

In such a favorable geologic and structural context, most of the rainfalls quantities on the highlands, upstream the Jerer watershed, are immediately swallowed by fractures and absorbed horizontally and vertically by the Adigrat sandstones and the Hamanlei karsted limestones and conveyed underground, limitating the evapo-transpiration subs traction.

Such a scenario repeated for million years can contribute to the storage of very important freshwater quantities available downstream, within the main Adigrat and Hamanlei aquifers.

As a result, the Jerer river hardly flows even during the rainy season.

Figure 56 - Jerer dry river bed in July, during the rainy season, downstream the Qaaxo wells: where have gone the 2 billion m^3/year? RTI picture 18 July 2012.

<u>Our main question is: where has all this harvested water gone?</u>

The WATEX process will allow us to answer to such a question.

3. The Recharge map

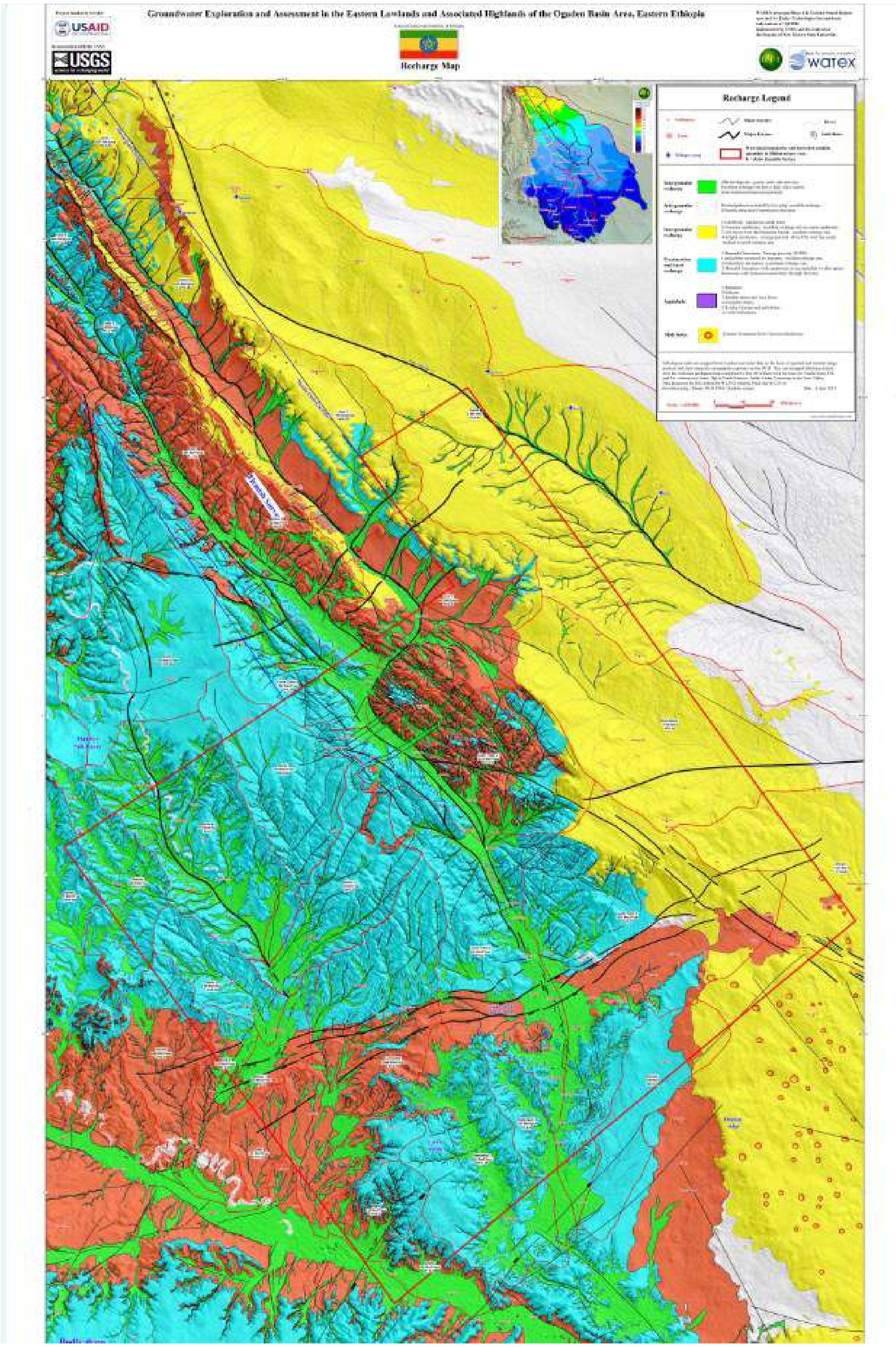


Figure 57 - Recharge map extracted from the geologic and structural map

This recharge map is showing a good intergranular recharge potential (Yellow Jessoma sandstones) and karsted limestones (blue).
The aquicludes are coded in orange (Uarandab shales and basalts).
The resulting Recharge Map has been edited at a scale of 200 000 and distributed electronically.

VIII. THE WATEX © PROCESS

A. WATEX is a Geo-Scanner designed to detect buried aquifers

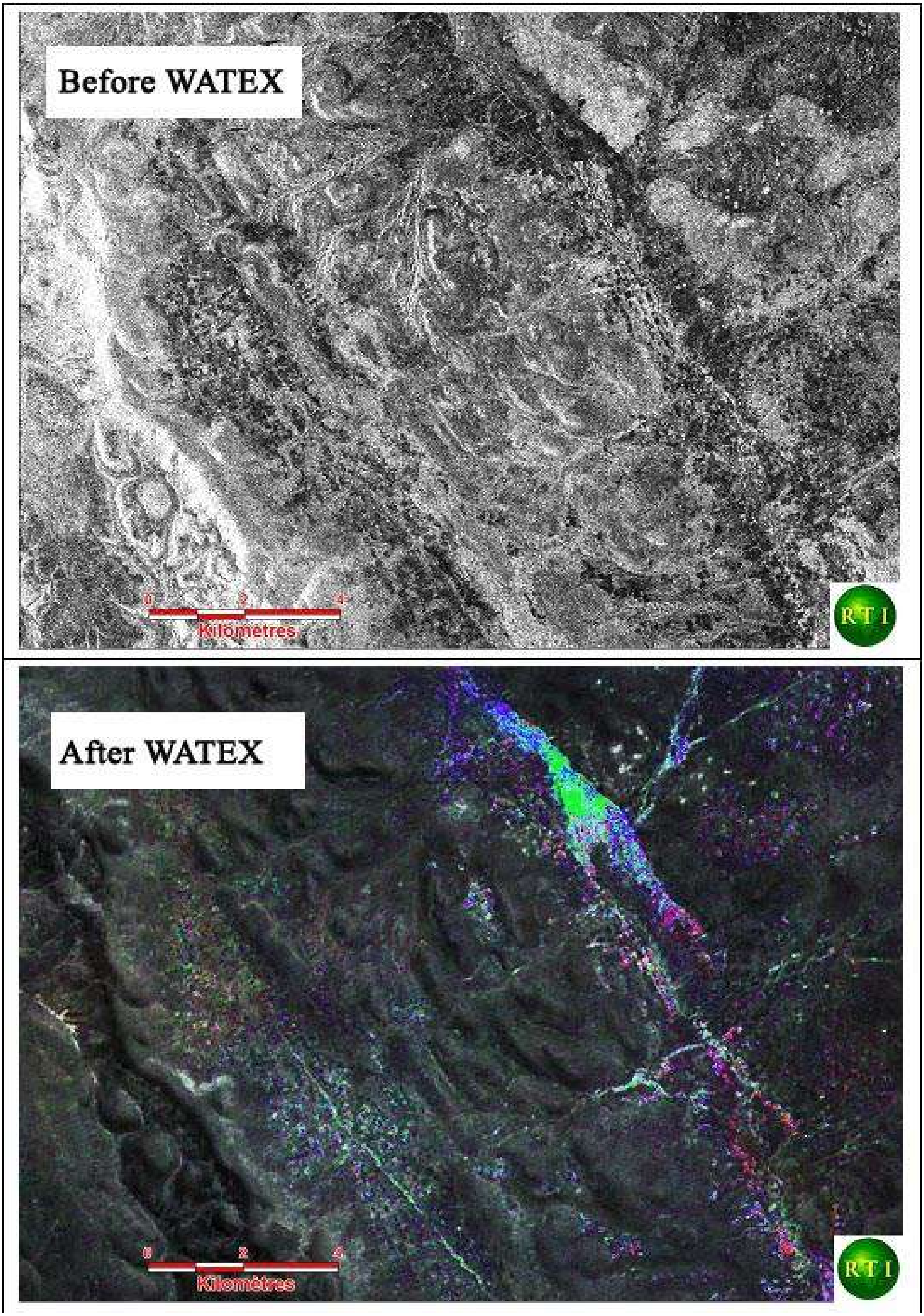


Figure 58 - Radar and WATEX© image from January 2010, over Jerer valley.

The radar based WATEX© system has been applied worldwide since 2004 for groundwater exploration.

The WATEX process reveals buried moisture as bright areas.

The image of the Jerer River reveals black areas which are totally dry on the first 20 meters.

Bright lines indicate leaking fractures which reveal the existence of a much deeper leaking aquifer.

Bright surfaces along the Jerer course indicate alluvial aquifers which appear to be discontinuous (green areas on the WATEX© image).

WATEX processing automatically enhance the most subtle moisture features which will lead to identify potential ground water drilling sites with high confidence over huge areas, far below the limits of radar penetration. Such indicators must be linked to a geomorphologic and structural detailed survey to be properly interpreted.

B. WATEX© methodology

The methodology employed for this project can be defined in few phases.

The early phase of analysis involves mapping features which directly (or indirectly) affect the likelihood of finding large, renewable reservoirs such as the geologic context the weathering processes, vegetation cover, watershed boundaries, slopes, and river profiles to estimate energy level of transportation along wadi (i.e. riverbed) courses. All these features which can determine accretion or erosion impacts upon reservoir thickness and productivity have already been exposed in the former chapters.

1. Size and shape of the WATEX bright anomaly

For alluvial aquifers, the assessment of the size of the radar anomaly is an indicator of the water storage volume. An aquifer with a sustainable production to support a community of 20,000 persons during a year implies the need to find a buried reservoir with an overall productivity of nearly100,000 m^3/year. Assuming permeable rocks with porosity of 10%, this is equivalent to a wadi reservoir of about 2,000 m long and 60 m wide, assuming a reservoir thickness of 7.5 m at an average depth of 10 to 15 m from the surface. Accordingly, only radar anomalies covering a minimum surface of 12 hectares (2,000 m x 60 m) must be considered in order to meet the above project goal.

At this stage of the WATEX © process, it is almost impossible to know if anomalies are associated with buried reservoirs (versus surface moisture linked to clay or silts deposits), and more analysis is required.

2. Amount of upstream watershed drainage

Since each potentially suitable target must also be fed by an upstream watershed capable of supplying at least 1 million m^3/year of water to the reservoir, (The watershed surface area and average annual rainfall are used to estimate total yearly catchment, which is then corrected for evaporation, erratic runoff, and other water losses).

3. Geology of the aquifer

Alluvial aquifer potential depends on the nature of their sediments since their origin determine the alluvial aquifers ability to reliably absorb and store sufficient water volumes. It is necessary to discriminate between “reservoir feeders” vs “reservoir poisoners”. For example, basaltic rock types can create excessive clay and colloids which will reduce reservoir porosity and permeability, and are called “reservoir poisoners”. Alternatively, “reservoir feeders” such as quartzite and sandstone can produce gravels that are ideal for sustaining large volumes of quality water storage.

Intergranular and karsted aquifers quality depends on their geologic origin structural history and diagenetic conditions through time.

Thus, carefully mapping and understanding geological context is crucial.

4. Major fault structures

A linear river system controlled by graben-like structures is more likely to be old enough (several thousand years to million years) to contain thick and multi-layered reservoirs, particularly if it sits downstream a well rain fed area.

5. Slopes and dips.

For alluvial aquifers, the optimum riverbed slope is between 0.1% to 0.4% in order to ensure sufficient vertical recharge of alluvial aquifers within wadi courses. (Very gentle slope or flat would result in a silt accumulation, compromising its ability to store sufficient water reserves.

Too steep slope might result in a reservoir prone to erosion of gravel bed that is essential for recharge during the rainy season.

In the case of the Jerer and Fafem rivers, we have already confirmed an average slope of 0.33% to 0.38% which confirms their great interest regarding their alluvial aquifers all along their course.

The slope and the dip of intergranular and karsted aquifers will also control the recharge and transit time of the groundwater flows.

Once the five parameters listed above are satisfied, it is then possible to detect and make an overall assessment of the most promising alluvial aquifers.

In order for these areas to be suitable for people settlements, RTI considers the implications of settlement near areas of existing cattle ranching, crop farming, and indigenous settlement.

Sites that are close to roads, agricultural land and wood fuel sources are prioritized.

Environmental impact studies are essential for sustainability.

Aquifers with high suitability are then examined to ensure close proximity to a suitable platform, since we recommends that new settlements be within 500 meters of at least one water point (The Sphere Project 2004).

6. Conductive fractures

Some fractures appear on the WATEX© images with a white and bright tonality, which means that they are conducting groundwater.
Such fractures, in a sedimentary environment, are important indicators of deeper aquifers, but can be targeted by drillers to access shallow groundwater. Nevertheless, these fractures should lead to deeper and more prolific aquifers in specific geologic and structural context.

IX. AQUIFERS DETECTION OVER THE SURVEY AREA

A. Weathered basement

Early tertiary-late Eocene uplift of Ethiopia has erased, almost everywhere, the weathered zone of the basement whenever exposed.

In the Upper Fafem valley, we can expect such aquifers only in basement depressions, close to Adigrat base sandstones.

Such weathered basement aquifers can reach a thickness of 40 m maximum with good yields if the nature of the basement is acid (rich in quartz) and less productive if the basement is basic.

Signature of such aquifers is well identified on WATEX images.

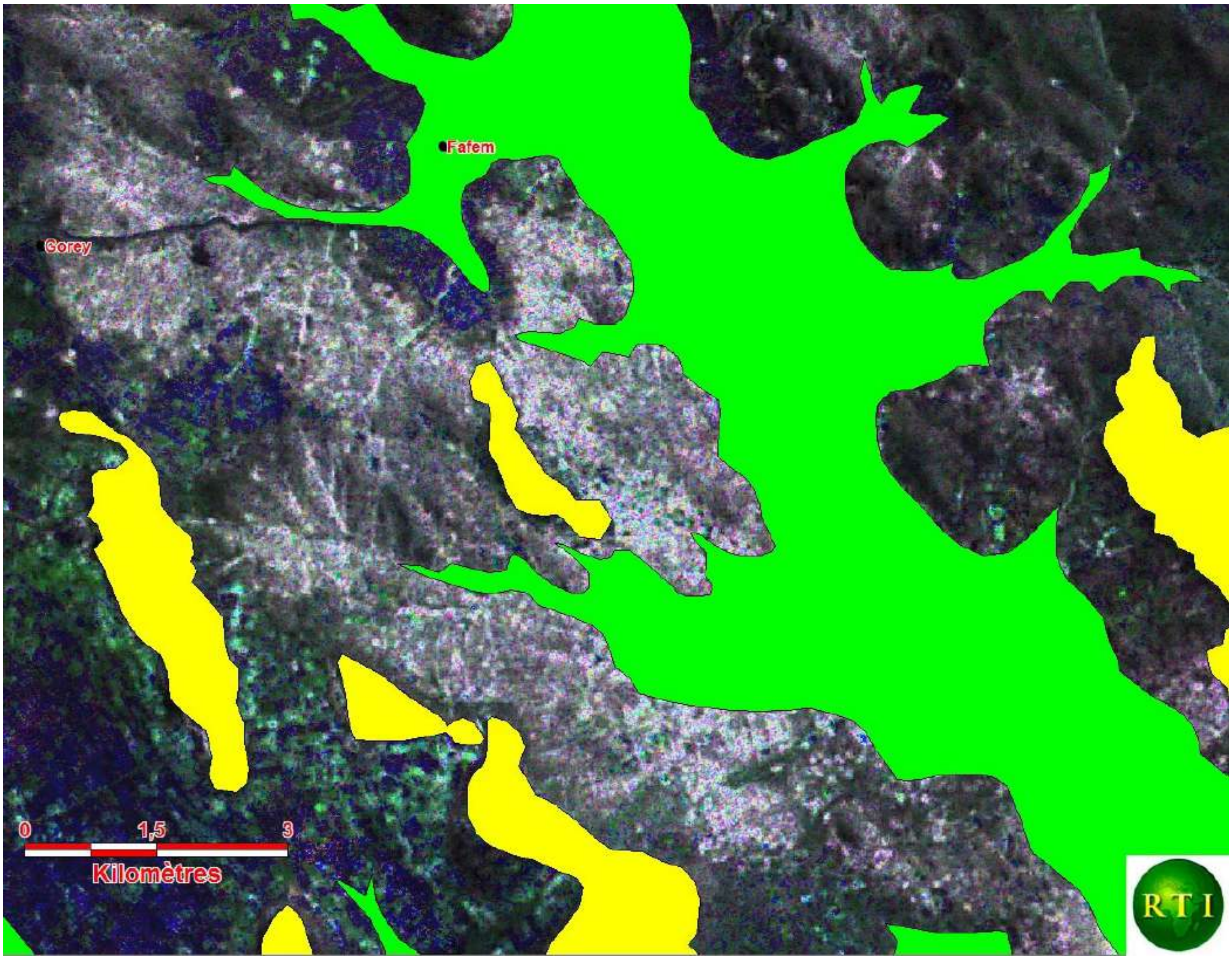


Figure 59 - this WATEX © image south of Fafem village, shows alluvial deposits (green) , Adigrat sandstones (yellow) and bright zones which reflect the existence of residual moisture in the weathered basement.

These bright areas represent shallow potential aquifers but cannot sustain important yield if not connected to a river system fed by rainfalls.

Nevertheless, such aquifers are marginal and can only be used to supply fresh drinking water for small communities.

B. Alluvial aquifers

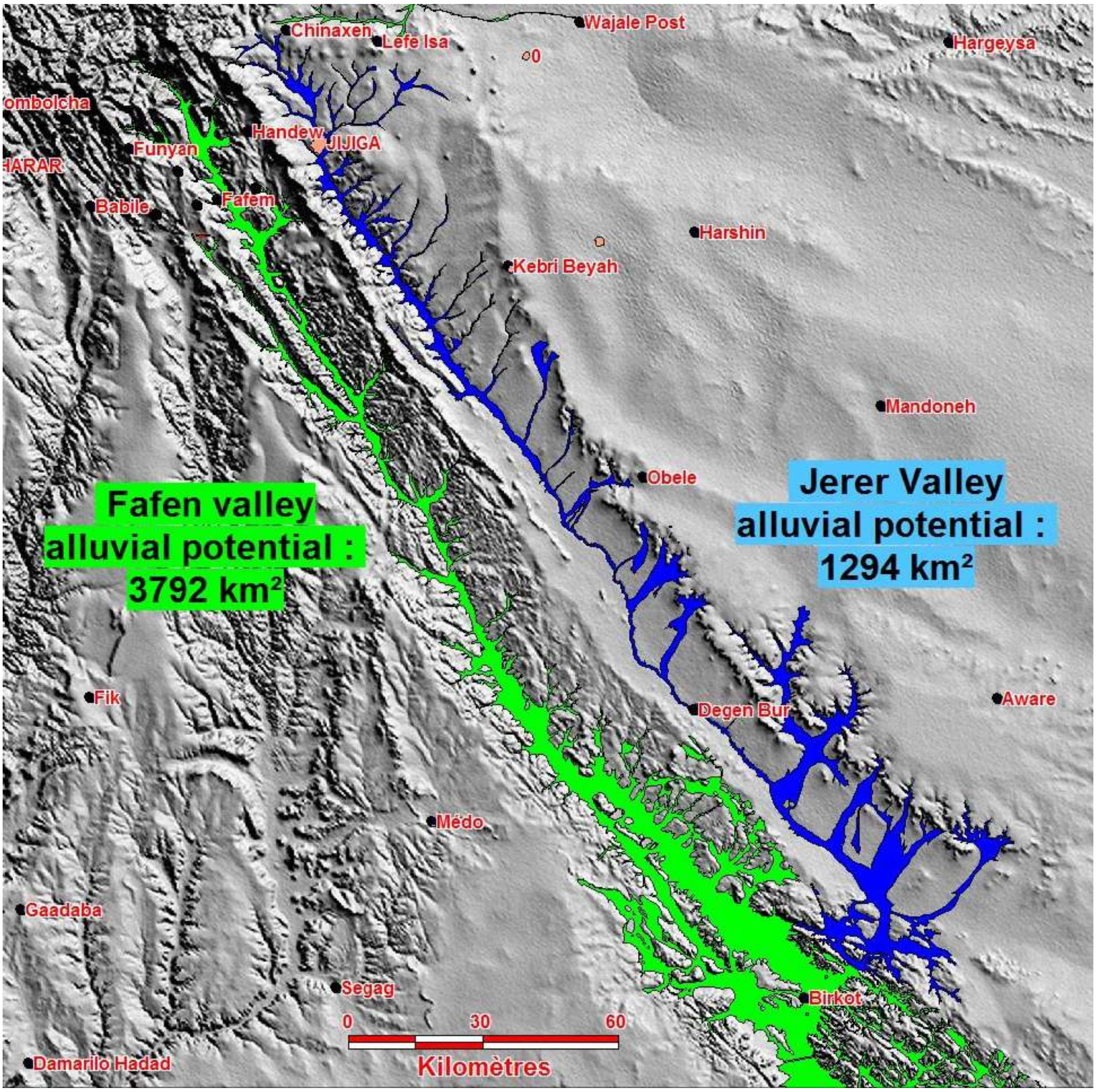


Figure 60 - Alluvial potential of the Jerer and Fafem rivers.

The Fafem alluvial potential is almost 3 times bigger than the Jerer.

Alluvial deposits of this area represent good soils for agriculture because they result both of the weathering of all the minerals from the basement enriched by Hamanlei carbonated sediments and the Uarandab marls and clays.

These two rivers cannot be perennial, because most of their water is quickly captured by fractures and absorbed by karsted limestones of the Hamanlei formations, especially along the Jerer valley.

This is the reason why the groundwater potential of these two rivers is heterogeneous and fragmented as revealed by the WATEX © images (Fig.62).

Moreover, these aquifers can be replenished by the normal course of the river by vertical recharge, but also by deep seated fractures with artesian water coming from the Adigrat and Hamanlei formations, especially along the lower course of the two rivers.

The WATEX © process can determine, within the boundaries of the alluvial deposits, where are the most prolific alluvial aquifers.

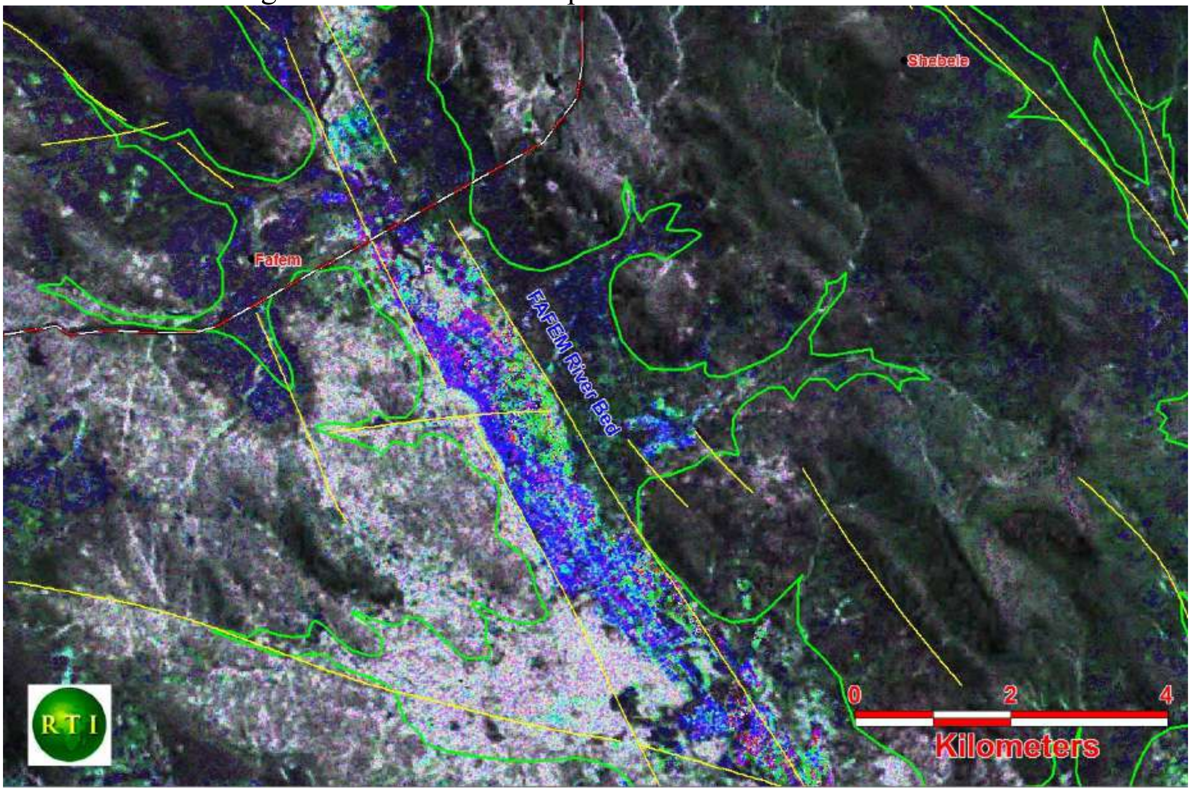


Figure 61 - WATEX© Processed image showing the course of the Fafem river south of the main bridge crossing the river south of Fafem village.

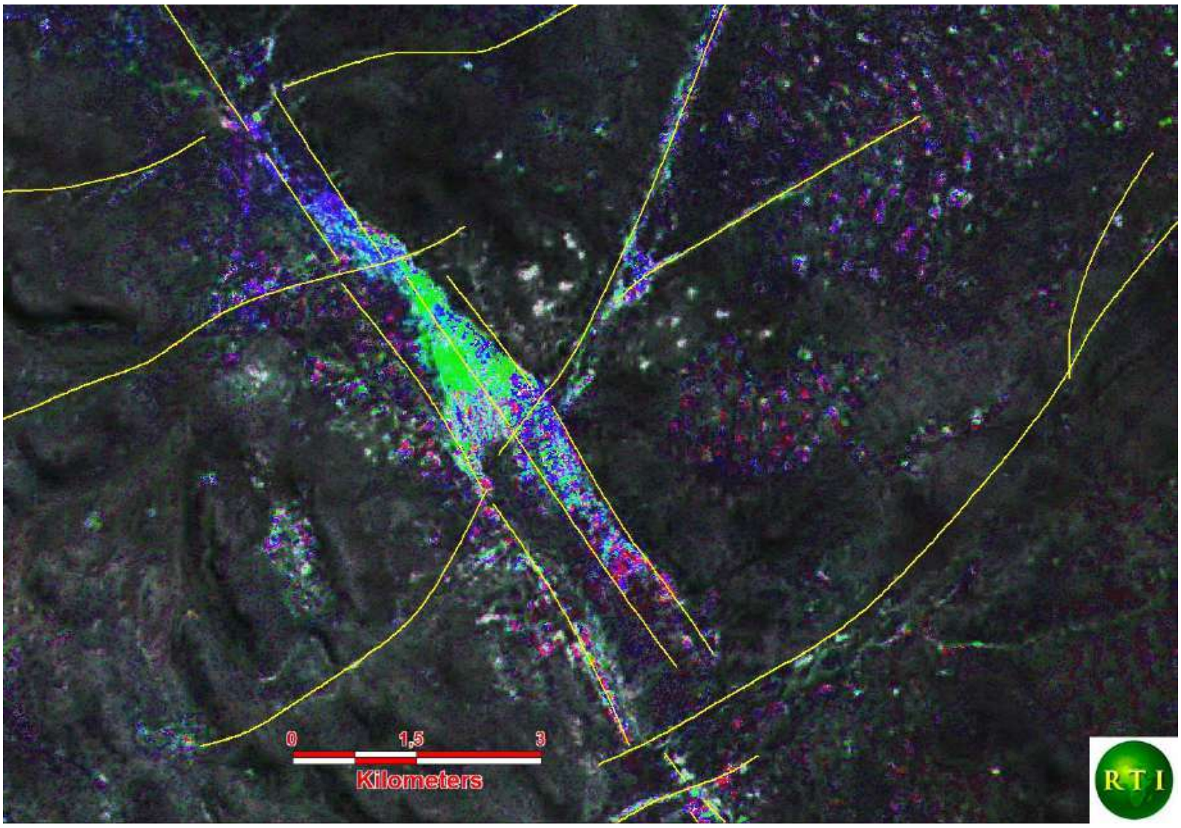


Figure 62 - WATEX© image Processed image showing the course of the Jerer river south of Jijiga with bright isolated alluvial aquifer prolonged by N160° bright fractures.

The blue response of alluvial deposits along the Fafem and Jerer rivers bordered by fractures, several kilometers long confirm the important aquifer potential of these alluvial targets with bright anomalies.

4-Major fault structures tell us that:

A linear river system controlled by graben-like structures is more likely to be old enough (several thousand years to million years) to contain thick and multi-layered alluvial aquifers, particularly if it sits downstream a well rain fed area.

Moreover, when such rivers are connected upstream to a broad watershed fed by substantial rainfalls quantities in a favorable geologic context, with slopes higher than 2/1000, we can expect broad alluvial aquifers with good productivity even along river segments with poor radar response (dark), it means that an aquifer lays below 20 meters.

Nevertheless, along the Jerer valley, there is a predominant factor: the alluvial aquifer is fed by deeper aquifers (Adigrat and Hamanlei formations in this case) transferring artesian freshwater from below through deep seated fractures of the Marda Fault system.

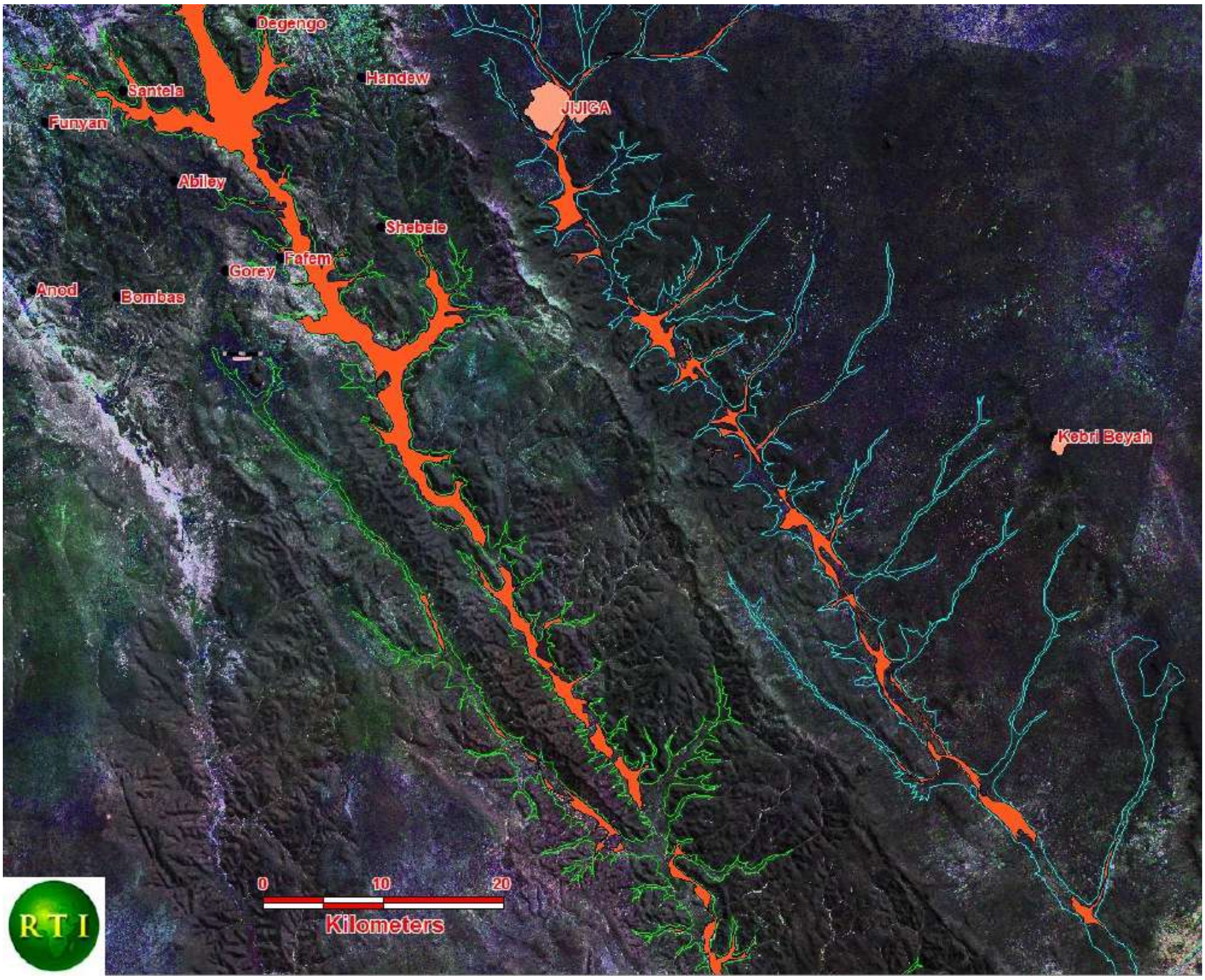


Figure 63 - Interpreted WATEX© image indicating High Alluvial Groundwater Potential of the Jerer and Fafem aquifers (orange polygons).

This image is showing that the High Alluvial Groundwater Potential is fragmented along the Jerer and the Fafem rivers.

The high potential alluvial aquifers cover only 9% of the total alluvial surface with a surface of 460 km².

With an assumption of average thickness of 5 m cumulated aquifer and a porosity of 10%, these aquifers have a storage capacity of 230 million m^3 which represents only 3% the 7 billion m^3 of water harvested annually by the two watershed.

These figures suggest that most of the water is captured downstream by fractures and stored underground.

C. Adigrat sandstones aquifers

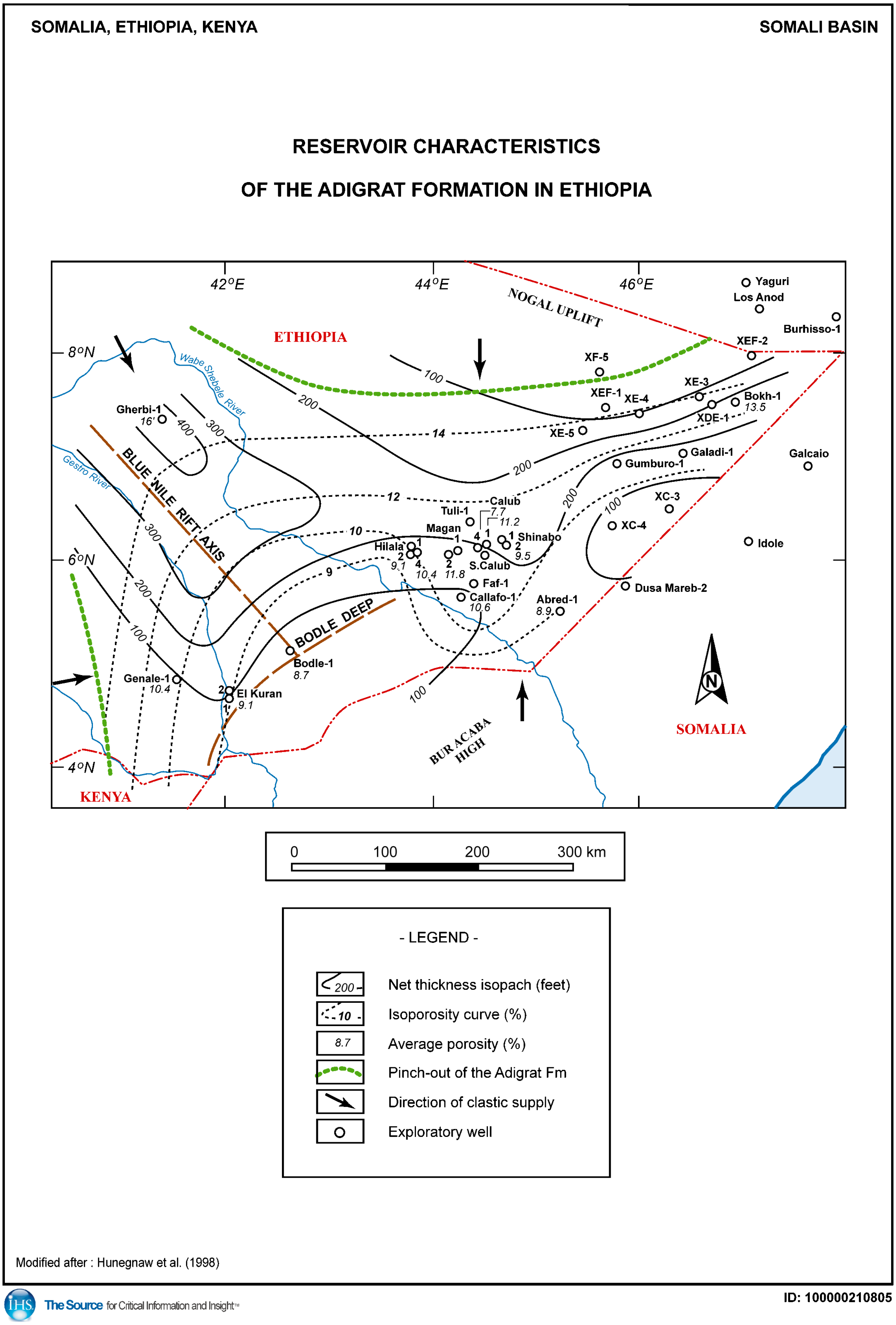


Figure 64 - Adigrat aquifers specificities in Ethiopia-Somali Region from HIS-Robertson 1998

According to IHS reports based on oil exploration and drilling results, the Adigrat sandstones can be potential reservoir in the East Somali - Ogaden - Mandera Lugh basin.

In **El Cabobe-1 well,** fine to very fine grained sands have log derived porosities of 5-20%.

In **Garad Mare-1 well**, the Adigrat Formation consists of very fine grained, carbonate cemented sandstones and siltstones with very low porosity and permeability interbedded with marls and dolomites. The interval can be up to 500 ft (150m) in neighboring areas (Harms and Brady, 1989).

Oolithes present in **Bulo Burti-1 and Garad Mare-1** indicate that they may be in close proximity to a shoal bank with better original reservoir properties.

According to the oil wells in Ogaden, the average expected thickness is 200 m, but in the Fafem valley, outcropping formations reach an average of 25 to 30 m only with an estimated porosity of 14% with well sorted quartz grains in the sandstones.

This means that if well exposed to rainfalls, an Adigrat sandstone block of 1km², with a cumulated storage unit of 10 m (less than 50% of the lithological column) and a porosity of 14% can store 1.4 million m^3 of water, or a volume of 1.4 m^3 /m^2.

This capacity can be increased if the Adigrat formations are well exposed to fractures which improve the recharge process and enlarge rock porosity and conductivity, which is the case in the Marda shear fault system environment.

In any case, the recharge capacity is linked to rainfalls quantities, but the cumulative process working years after years is most likely creating huge opportunities downstream.

D. Hamanlei fractured and karsted aquifers

According to HIS and to BEICIP report of 1998, the overlying carbonates of the Hamanlei have good reservoir in the Lower and Middle Formations.

1. Lower Hamanlei

Figure 65 - Outcropping Lower Hamanlei formations along the Jerer valley south of Jijiga (43°0583 E, 9°0289 N) showing karsted and fractured fossiliferous limestones: most likely reefal facies on the margin of a tilted block © RTI 18 July 2012.

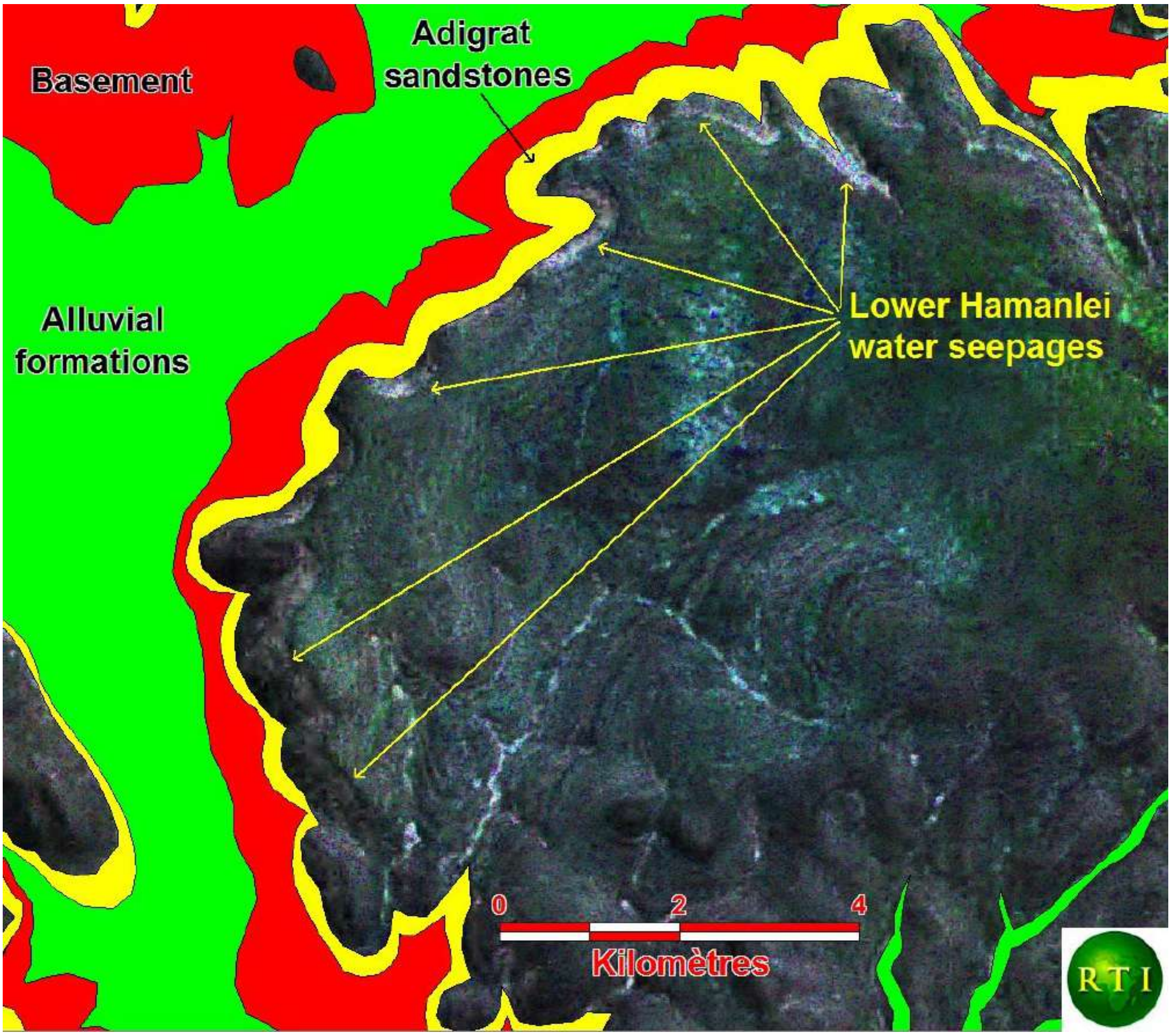


Figure 66 - WATEX© image of lower Hamanlei formation, on the Western part of the Karamara range, near the Fafem valley (42°44'47" E, 9°09'37" N). This explicit image is showing indications of water seepages on the rim of the Hamanlei formations in contact with Adigrat sandstones indicating the groundwater conductive potential of the Lower Hamanlei limestones.

2. Middle Hamanlei reservoirs (early/Middle Jurassic)

The reservoirs are composed of two main lithologies.

- -Grainstone/packstone have good porosities (15-20%), cementation may result in poor conductivities, except in fractured zones.
- -Dolomite has porosities ranging from 11 to 26% and permeabilities from 5 to 60 mD.

Most likely, meteoric water has enhanced carbonate reservoir characteristics in fractured areas of the Lower and Middle Hamanlei formations along the Marda fault corridor.

In the survey area, the Hamanlei formations thickness could average 250 m.

One cannot expect important karstified limestones, because of general low rainfalls over Ethiopia since Miocene (aridification of East Africa) and the fact that CO2 solubility is generally low in meteoritic waters in tropical areas due to high temperatures.

Porosity and permeability (conductivity) should be expected from the structural context of the Marda shear corridor involving brecciated limestones and mylonites.

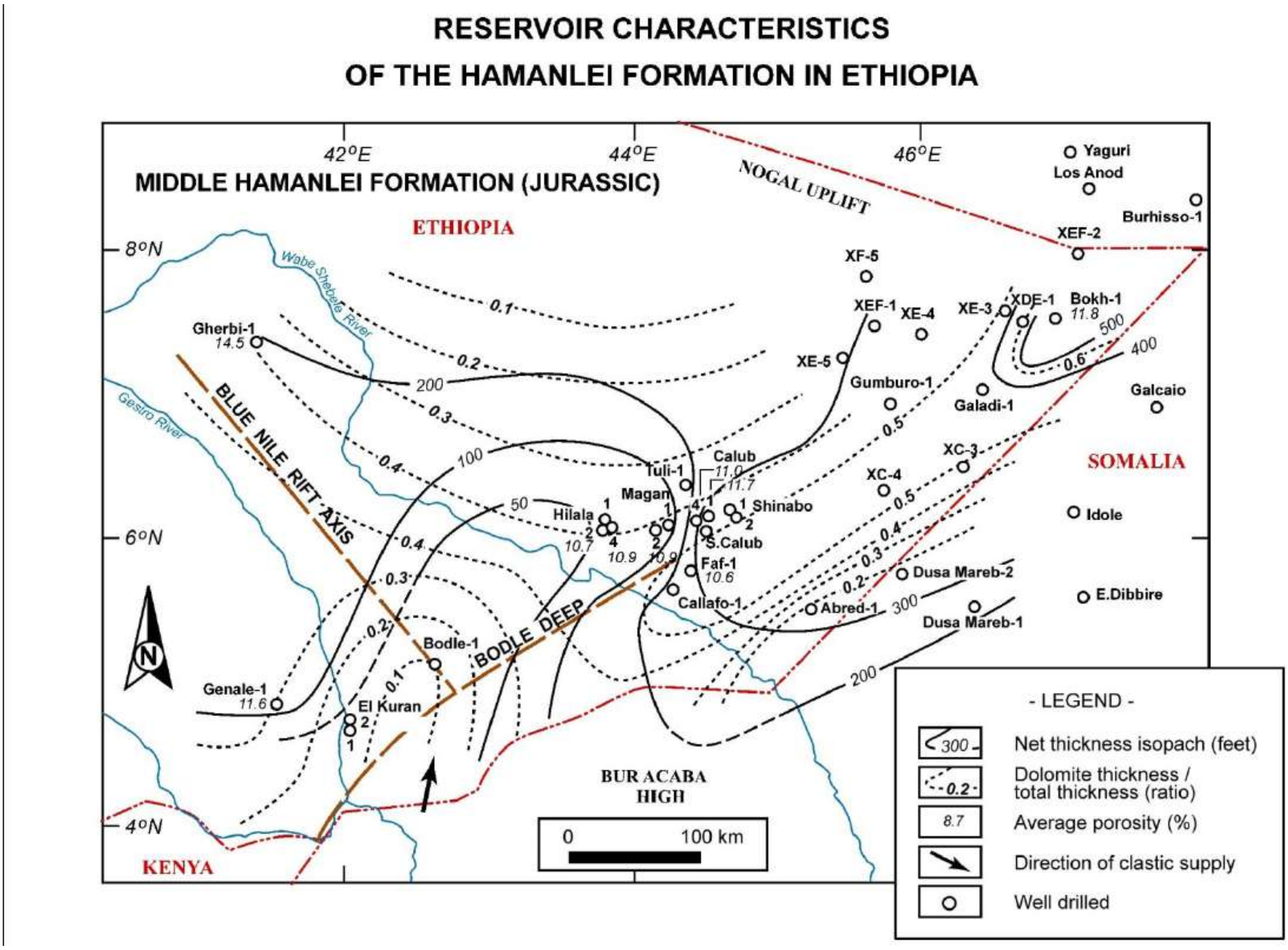


Figure 67 - Hamanlei aquifers specificities in Ethiopia-Somali Region from IHS-Robertson 1998

This means nevertheless that if well exposed to rainfalls, the best Lower Hamanlei reservoirs of 1km², with a cumulated storage unit of 80 m (among the lithological column of 200 m) and a porosity of 18% can store 18 million m^3 of water, or a volume of 14 m^3 /m^2, almost 10 times more than the Adigrat sandstones.

This capacity can be considerably increased if the formations are well exposed to fractures and karstifications which will improve the recharge process and enlarge rock porosity and conductivity, which is expected in the Marda shear fault system environment.

As these formations are well sealed by Uarandab formations, drilling such aquifers might result into artesian wells in structural traps downstream the Jerer and Fafem watershed.

E. Conductive fractures and their WATEX© response

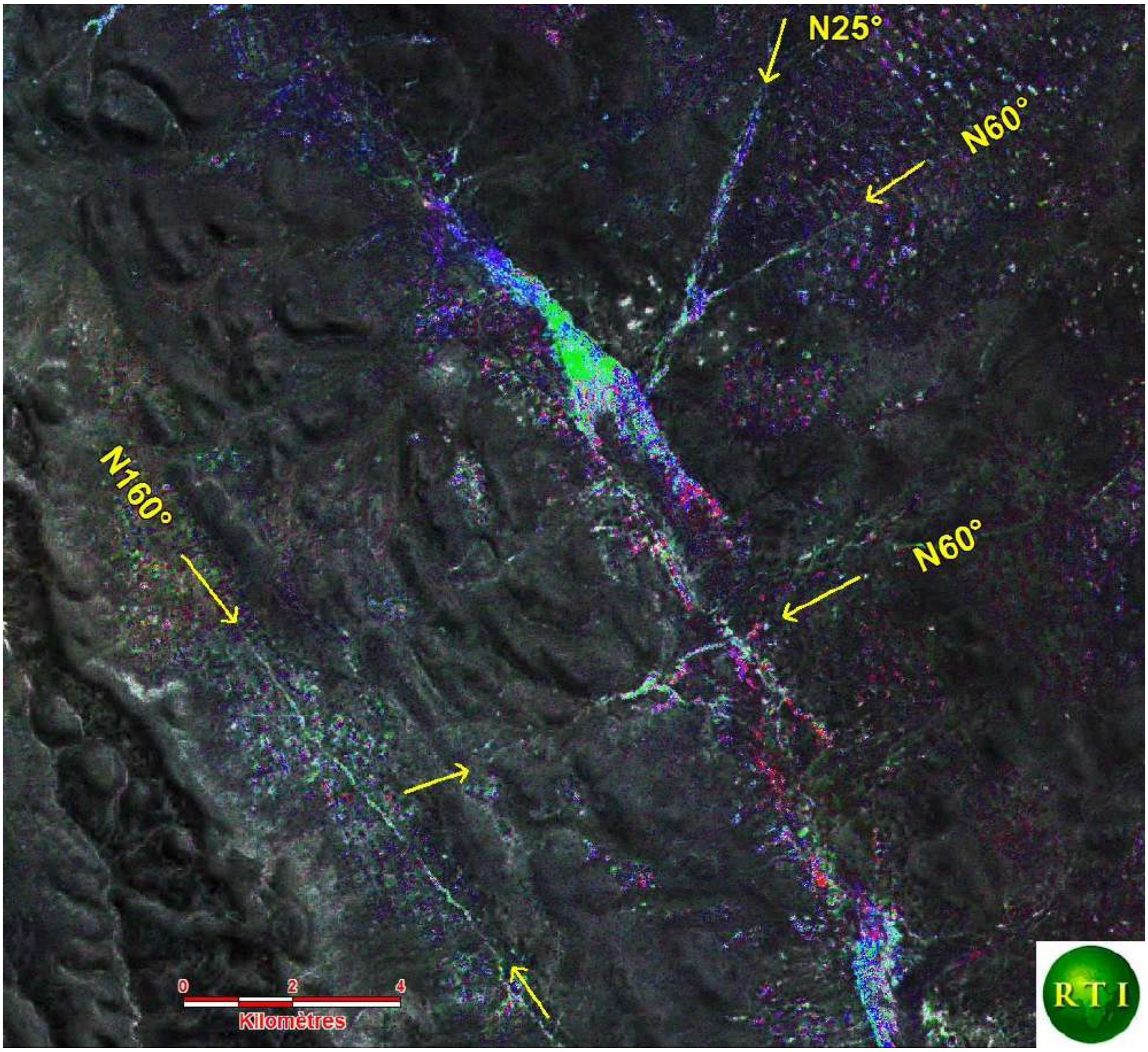


Figure 68 - Leaking fracture along the Jerer valley adjacent to Kebri Beyah : this WATEX© image shows 3 major structural directions enhanced by the effects of their leakage along N160° parallel to the Marda fault system and complementary N60° and N25° fracture systems.

Such leaking fractures reveal the existence deeper aquifers confirmed by the geologic model and expressed by the geologic cross sections.

A shallow well through these fractures will access freshwater almost from the surface, but drilling deeper should provide access to huge quantities of clean fresh water, in a sustainable, from the Hamanlei and Adigrat aquifer (more than 300 to 400 m deep)

Nevertheless, such fractures can be drilled and provide continuous access to freshwater in economic conditions, because shallower access to water supplied by deeper geologic formations.

The structural rosace illustrates the meaning of the concept of "conductive fractures" along the Jerer valley adjacent to **Kebri Beyah** well detected by the WATEX© image.

The concrete expression of the Marda fault system and is represented by N45° and N 130° to 160° structural directions.

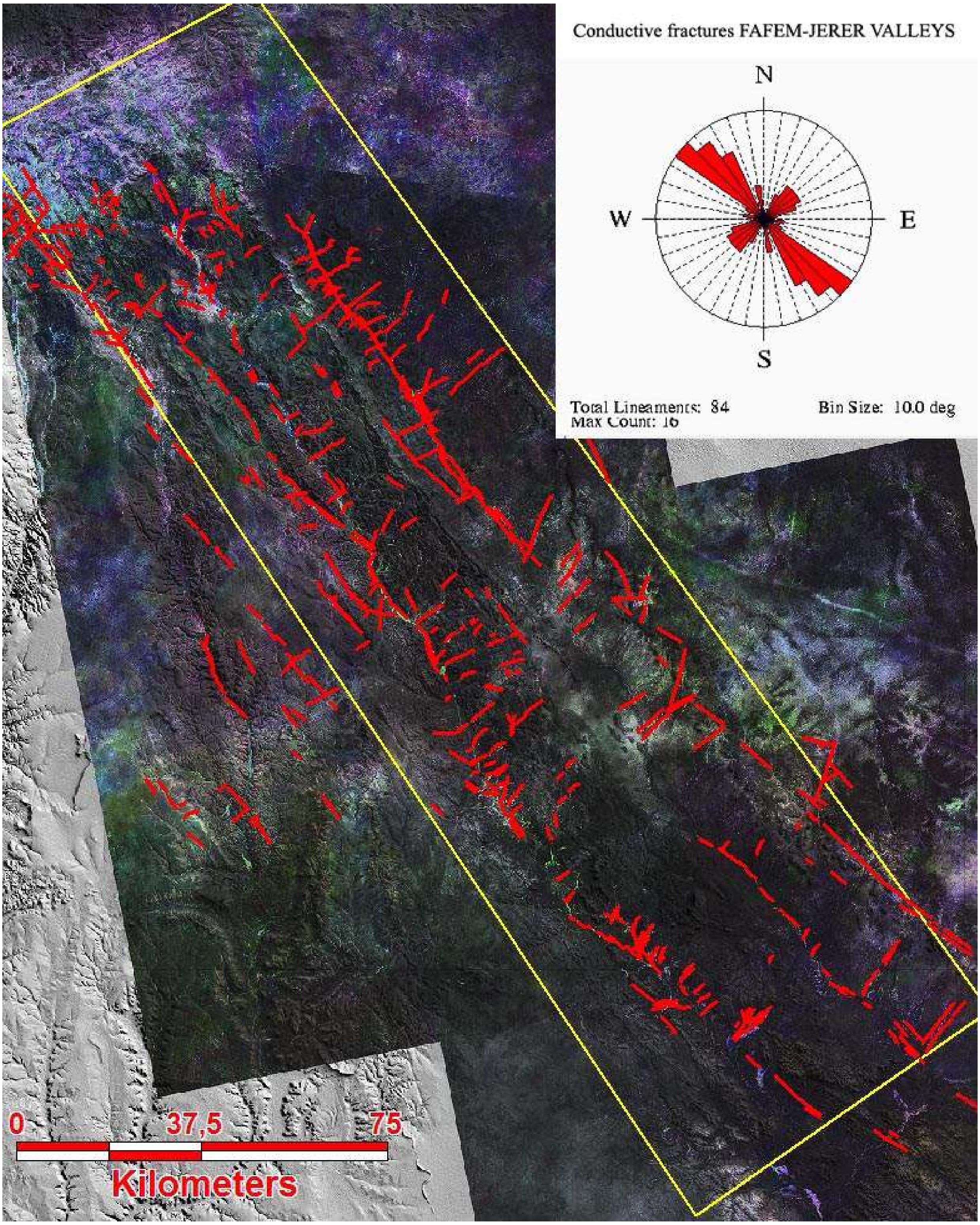


Figure 69 - Conductive fractures extracted from the WATEX© image.

These fractures which convey groundwater to the surface can be drilled with shallow wells and can be considered as water targets.

Nevertheless, they also indicate the presence of deeper aquifers in a specific geologic and geomorphologic context and should indicate where to drill deep wells in order to access the main source of leakages which must be, along the Jerer Valley, the Hamanlei karsted limestones and the Adigrat sandstones.

<u>N45° to N60° conductive fractures should be more prolific than N160° fractures because better oriented to be opened by the shear motion of the Marda shear corridor oriented N160.</u>

F. Structural traps: discovery of the East Karamara Aquifer (EKA)

Several cross sections have been located across the new geologic map to determine the magnitude of structural thrusts and prove the existence of the East Karamara Aquifer (EKA) resulting from the effects of the late Cretaceous, early Eocene uplift all along the Marda shear-distensive corridor.

These E-W cross sections are tied to existing water boreholes.

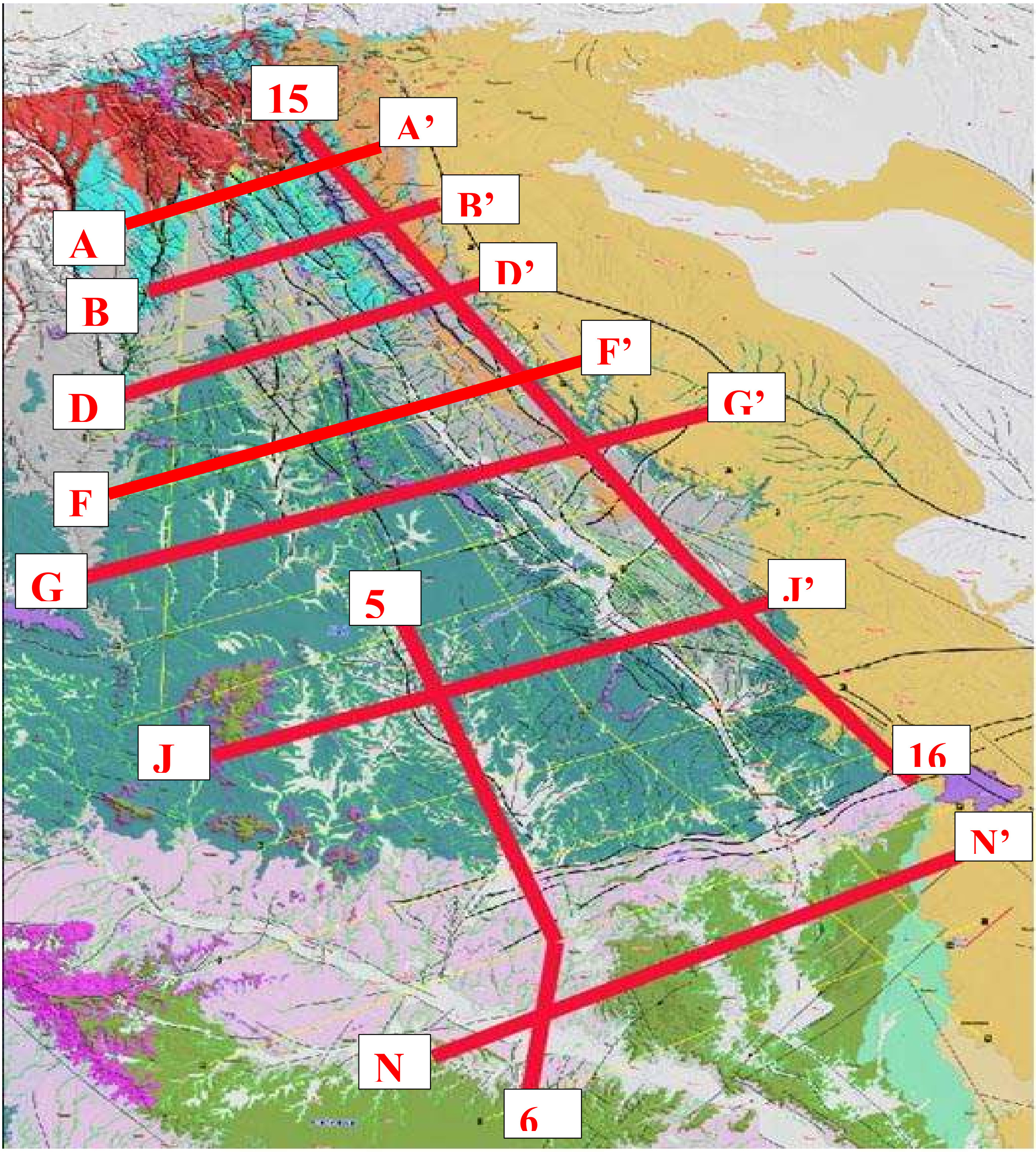


Figure 70 – Location of the geologic cross sections.

1. F.1-IRC Gerasley Borehole on cross section AA'

During our visit on the site, the 31st of January 2013, the drilling rig had reached a depth of 136 m before breaking down, after crossing 8 m of black shales.
This borehole has finally reached a depth of 138 m in the basement.

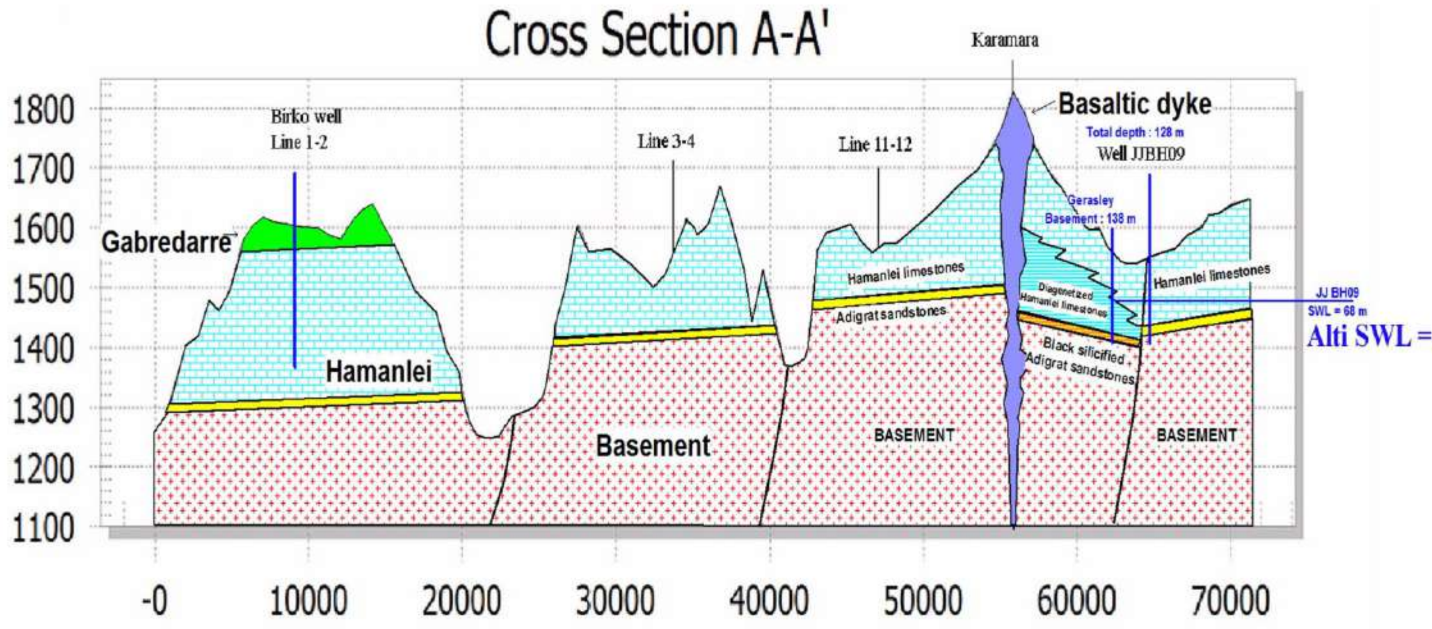


Figure 71 - New geological cross section of Garasley borehole.

The boreholes cuttings reveal that the Adigrat sandstones and Hamanlei limestones have been deeply diagenised by the presence of the Karamara volcanic activities as shown in the cuttings which revealed basaltic occurences.
This intrusion of volcanic effects within the stratigraphy of the aquifer is a strong warning but does not change the structural pattern of the East Karamara structure, but affects the geometry of groundwater target map which appears to be thinner in the north and wider in the south as shown Fig 3.

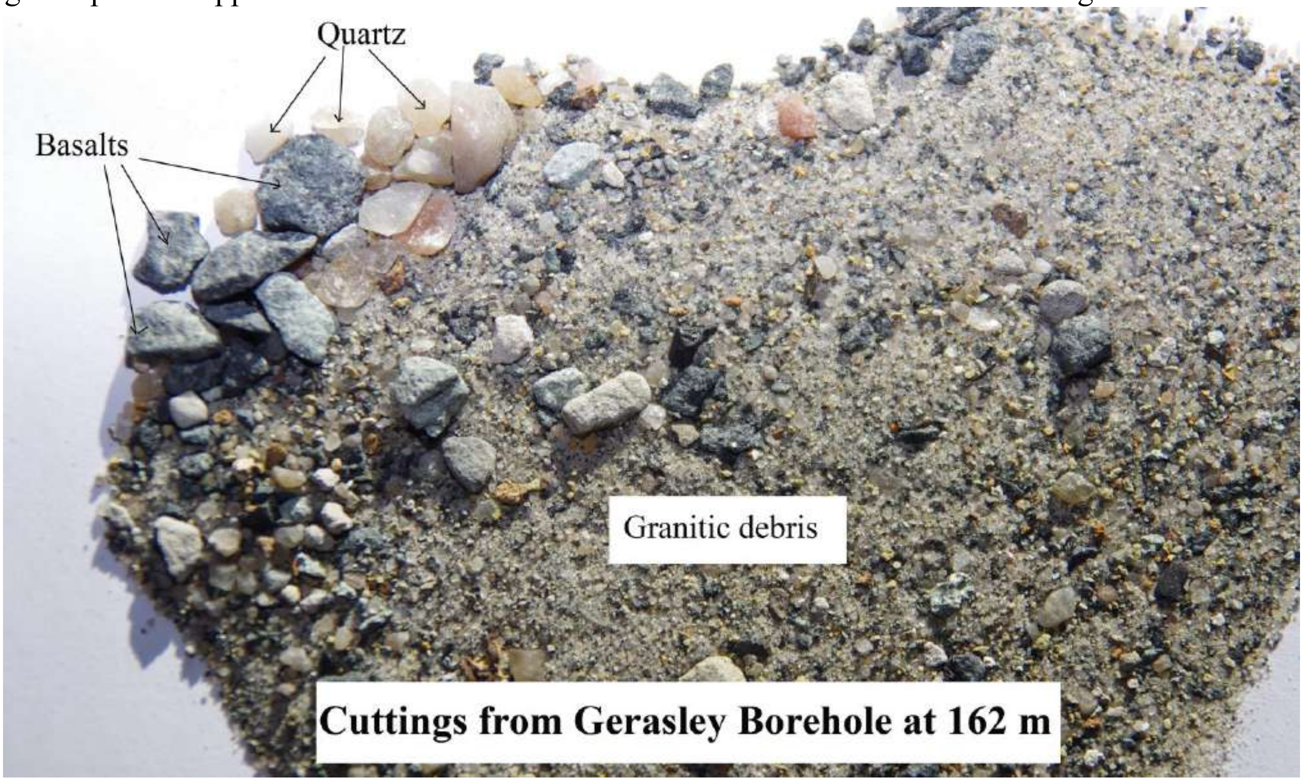


Figure 72 - Cuttings from Garalsey borehole at a depth of 162 m showing occurrences of basaltic intrusions in the basement.

2. F.2- Garbile Borehole on cross section BB'

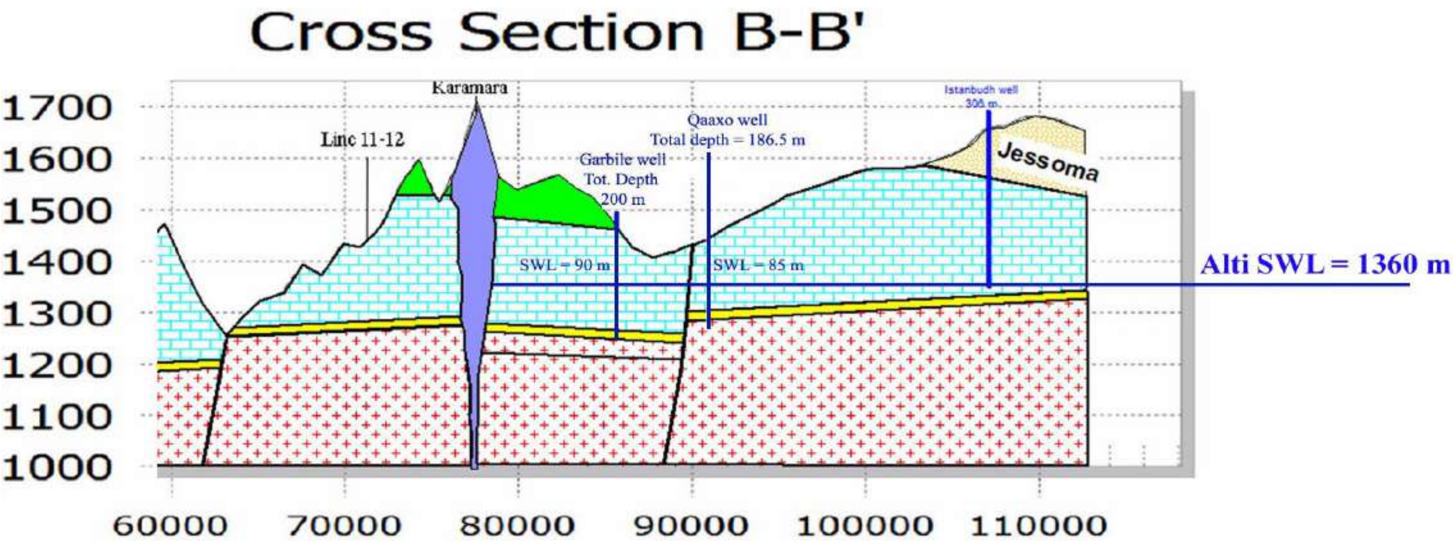


Figure 73 - Cross section BB' is showing the existence of a low compartment in Garbile borehole (Graben) which has reached the basement at a depth of 200 m, compared to the Qaaxo borehole which has reached the basement at 170 m, the fault has a minimal thrust of 30 m.

The main question which remains to be solved is the dip of the basement between Qaaxo and Istanbuth boreholes in the East of the structure.

Measurements of dipping limestone layers along the Qaaxo River, East of Qaaxo borehole, indicate a dipping angle of 4° to 6° oriented to N 225°.

These angles determine the lateral extension of the aquifer between the Karamara and the East, with a SWL at 1360 m.

3. F.3- IRC Ararso Borehole on cross section DD'

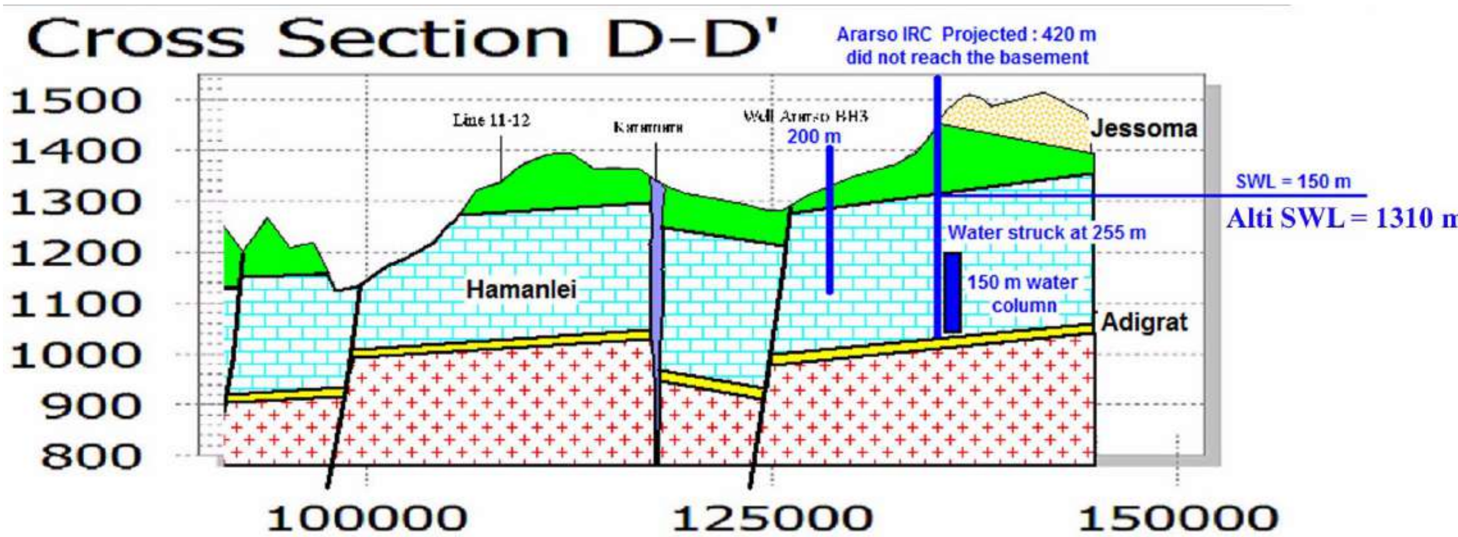


Figure 74 - Cross section DD' is clearly showing the water column of 150 m within the Hamanlei limestones within the East Karamara structure. The borehole did not reach the Adigrat sandstones.

The thickness of the water column confirms that the Karamara basalts act like a waterproof dam (lateral aquiclude) and that the East Karamara Aquifer is confined between this Karamara dyke and the overlying Uarandab shales.
The dip of the basement below Ararso borehole is maintained to 6° and determines the aquifer extension to the East, with a SWL reaching 1310 m.

4. F.4- IRC Degen bur Borehole on cross section FF'

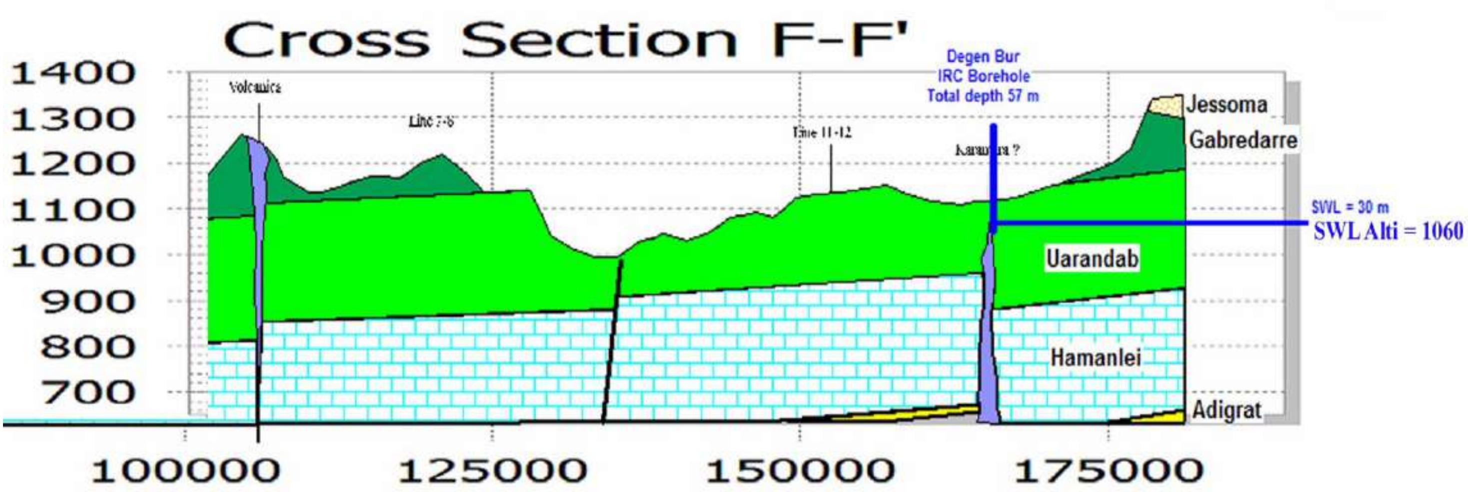


Figure 75 - Cross section FF' is showing Borehole of Degen Bur which has reached the water table at 30 m and reached the top of the Karamara dyke at 57 m.

Such data confirm that the East Karamara Aquifer confined between this Karamara dyke and the overlying Uarandab shales is almost reaching the surface thanks to the intrusive Karamara dyke. This borehole if localized 100 m east of the dyke would have reached a thicker artesian water column after crossing 200 m of Uarandab shales.
Notice the SWL at 1060 m.

5. F.5- on cross section GG'

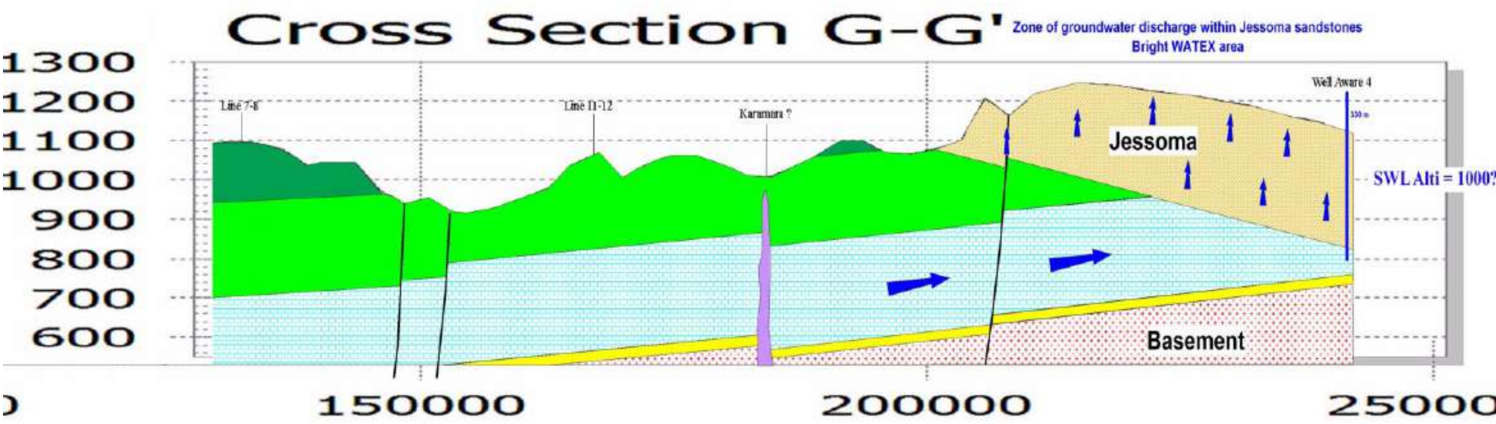


Figure 76 - Cross section GG' is showing the contact between the Jessoma sandstones and the Hamanlei limestones through the unconformity.

This explains the discharge indications on the WATEX image as shown below.

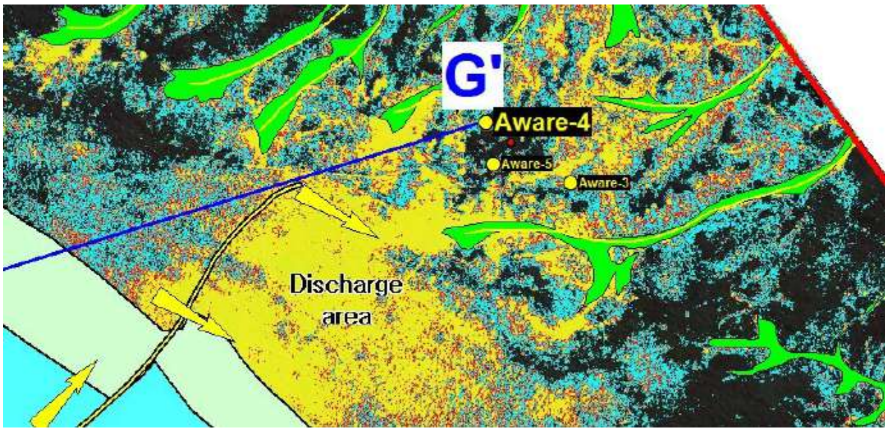
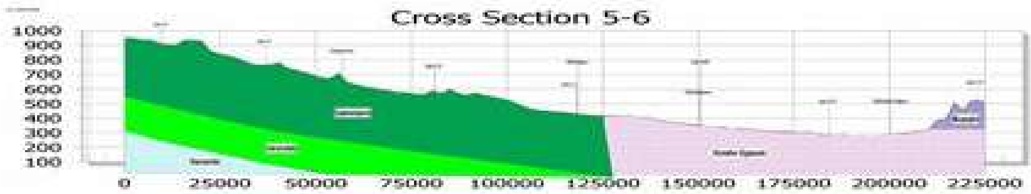
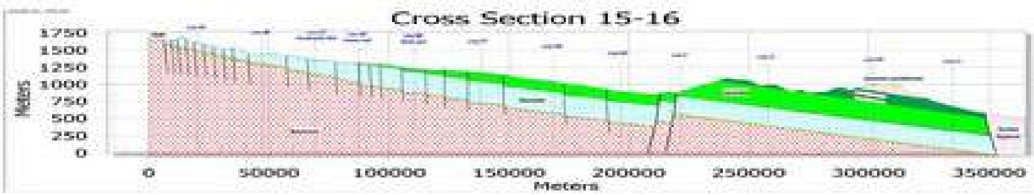


Figure 77 - WATEX image showing a yellow discharge area along the eastern end of line GG' indicating that the Karamara East Aquifer structure could be broader than initially mapped.



Cross section 5-6 shows that the Jurassic geological layers dipping regularly to the South are interrupted by a major fracture opening a Hemigraben structure filled by Korahe Gypsum (Pink) around 125 km from Point 5.
This major fracture sealed by gypsum interrupts the groundwater flowing southward within the Gabredarre formations.



Cross section 15-16 shows that the Jurassic geological layers dipping regularly to the South are interrupted by a horst, around 200 km south of point 15.
The same major fracture as on cross section 5-6, opening a Hemigraben filled by Korahe Gypsum (Pink) is reached 350 km south of Point 15, almost at the end of the cross section.

Figure 78 - NS cross sections

The EW cross sections are showing that the East Karamara Aquifer structure (EKA) has been already drilled along a trend of 150 km from the suburbs of Jijiga to Degen Bur.

The eastern dip of the basement measured near Qaaxo on the overlying Hamanlei limestones should be confirmed in the south by more boreholes to determine the exact eastern extension of this aquifer which remains confined in the West by the Karamara basaltic range.

On the western part of the Karamara range, there is no equivalent structural aquifer, because of lack of existing confining lateral barrier on a basin dipping to the South-East.

As the Jessoma sandstones overly the Jurassic Hamanlei formations over a late Cretaceous unconformity, there is a possibility of recharge and discharge of the EKA structure as revealed by the cross section GG' and the discharge indications of the WATEX image.

The NS cross section have revealed the existence of a major hemi-graben filled by Korahe Evaporites which contribute to sealing the aquifers upstream.

Phase II would allow to reveal the direction of the deep water flows and the extension of such a process with possible extended aquifers within the Jessoma sandstones in the south to the Ethiopia-Somali border.

X. THE WATEX TARGET MAP

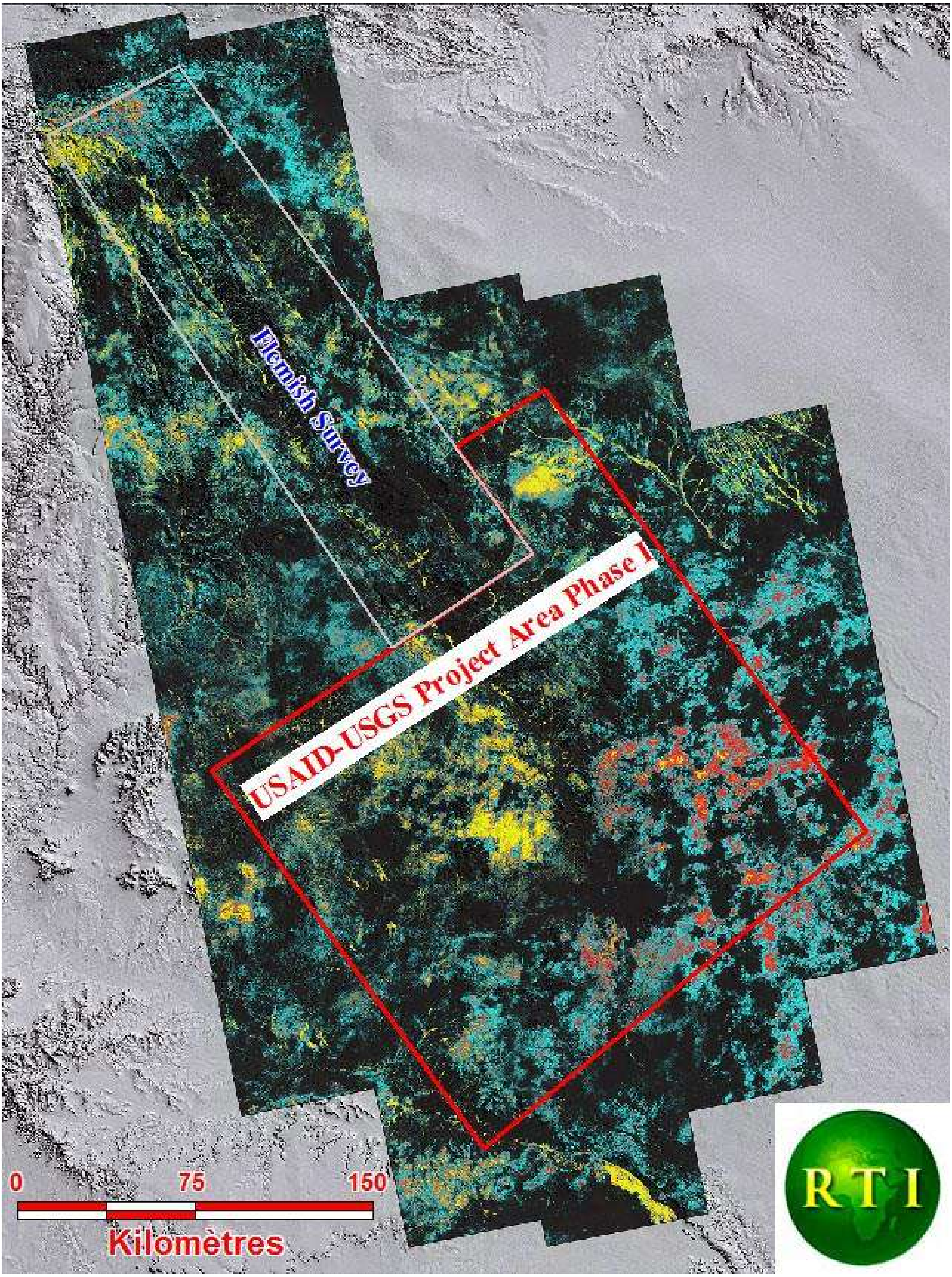


Figure 79 - The WATEX target Map over the survey areas

A. <u>Presentation of the Groundwater aquifers</u>

According to these rules, the whole WATEX © image has been processed and interpreted in order to classify the groundwater potential of the whole study area, with the highest probabilities to find aquifers.

As a result of this analysis, we can synthesize all the former results by the Groundwater Target Map.

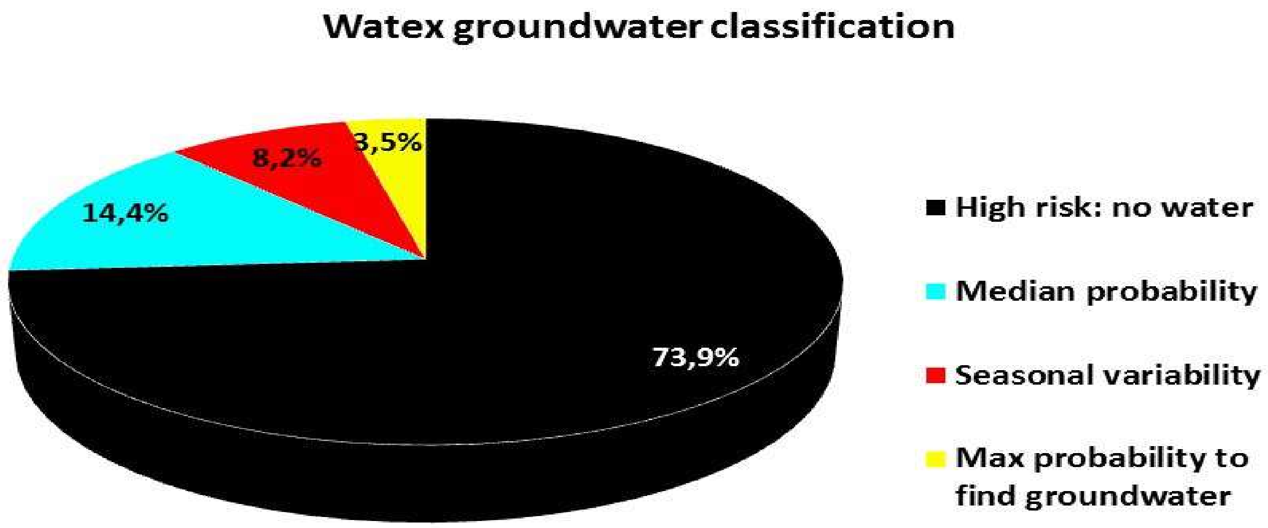
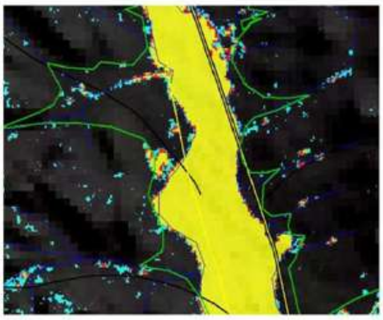


Figure 80 - WATEX groundwater classification in terms of probability.

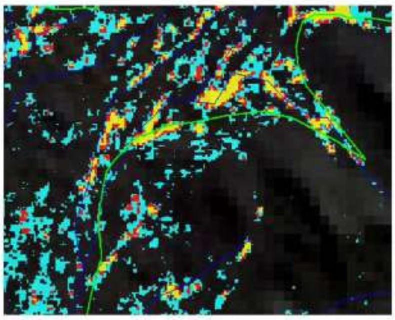
- The black background predominates on the WATEX processed image, which confirms that **<u>74% of the survey area is extremely dry</u>**, with low chances to reach shallow aquifers (from 0 to 80 m).

- The yellow colors cover only 3.5% of the survey area and show High Probability of shallow aquifers within alluvial sediments (alluvial aquifers from 0 to 80 m) or indicate discharge zones.

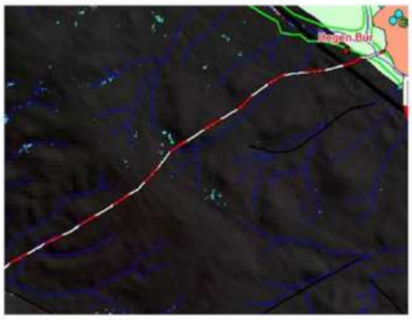
- The blue and red colors represent areas of superficial moisture, the red with seasonal variations. Such superficial moisture result most likely from discharges of deeper aquifers, as almost no rainfalls can maintain all the year superficial moisture in such an arid environment.



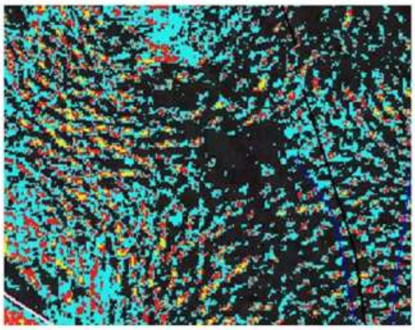
High Probability to reach alluvial aquifer



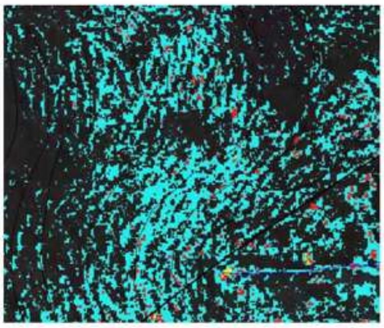
Medium Probability to reach alluvial aquifer



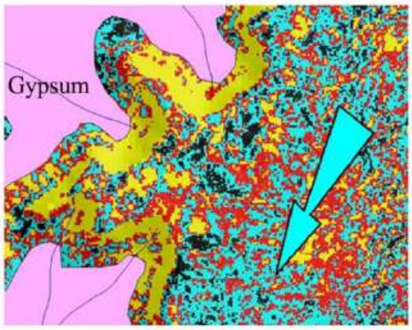
Dry area : no aquifer from o to 80 m



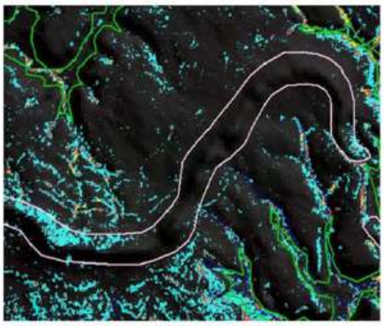
High Probability to find sand dunes aquifer



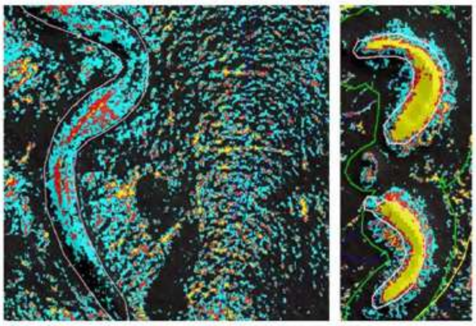
Medium to low probability sand dune aquifer



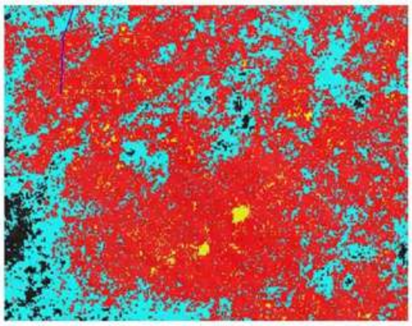
Yellow : groundwater discharge
from Mustahil layer



Dry perched river sealed
by basaltic sheet



Medium Probability (left) to high (Right) to find
groundwater in perched aquifer under basaltic seal



Moisture over Jessoma sandstones

Fig. 86. WATEX images offering a various pattern of aquifer structures

B. Deep aquifers revealed by the WATEX© process at the junction of the two surveys

The main asset of this survey is the discovery of the **East Karamara Aquifer (EKA).**

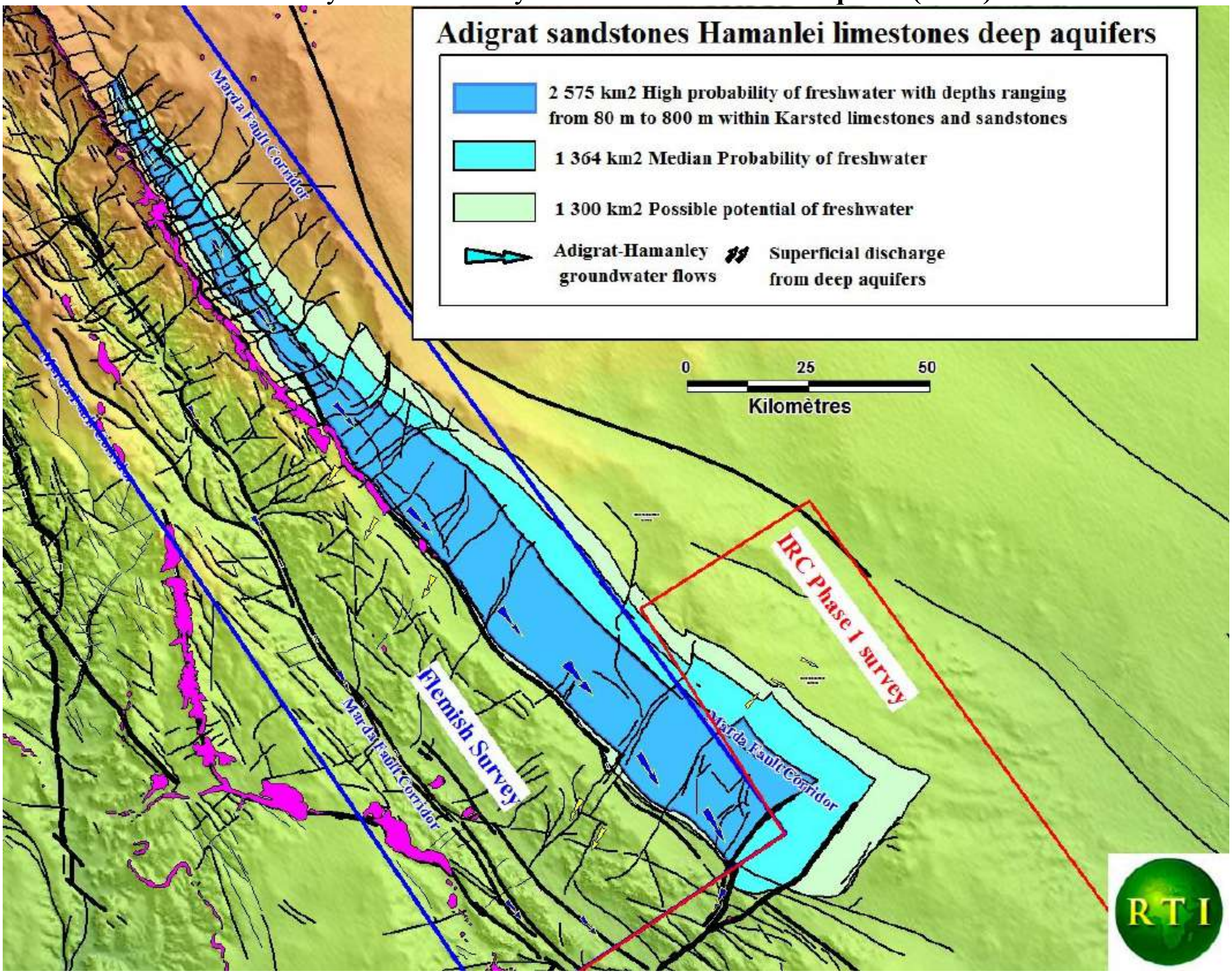


Figure 81 - Illustration of the possible model of the East Karamara Aquifer.

The WATEX © process sustained by structural and geologic observations in the field confirm the extension of this structure along a distance of 200 km (opened to the South East) and a width of 5 to 7 km, and sealed by the Uarandab shales.

As far as the Karamara basaltic range is continuous and represents a tight aquiclude, this aquifer should be confined within the graben and the basement should be reached between a depth of 150 m in the north to a depth of 450 m in the southern part of the survey area.

Within the Marda structural corridor structuring this graben, we can expect an increased permeability thanks to shear open fracturing in spite of poor karstification as seen on the field near Qaaxo well.

In this context, we can define 3 different storage capacity zones within and near the Eastern Graben:

1. **The High probability area (over 85%)** to find freshwater covers a surface of 2 575 km².
2. **The Median probability area (from 50% to 85%)** to find freshwater covers 1 364 km².
3. **The possible potential extension of this structural aquifer (less than 50%)** covers a residual surface of 1 300 km².

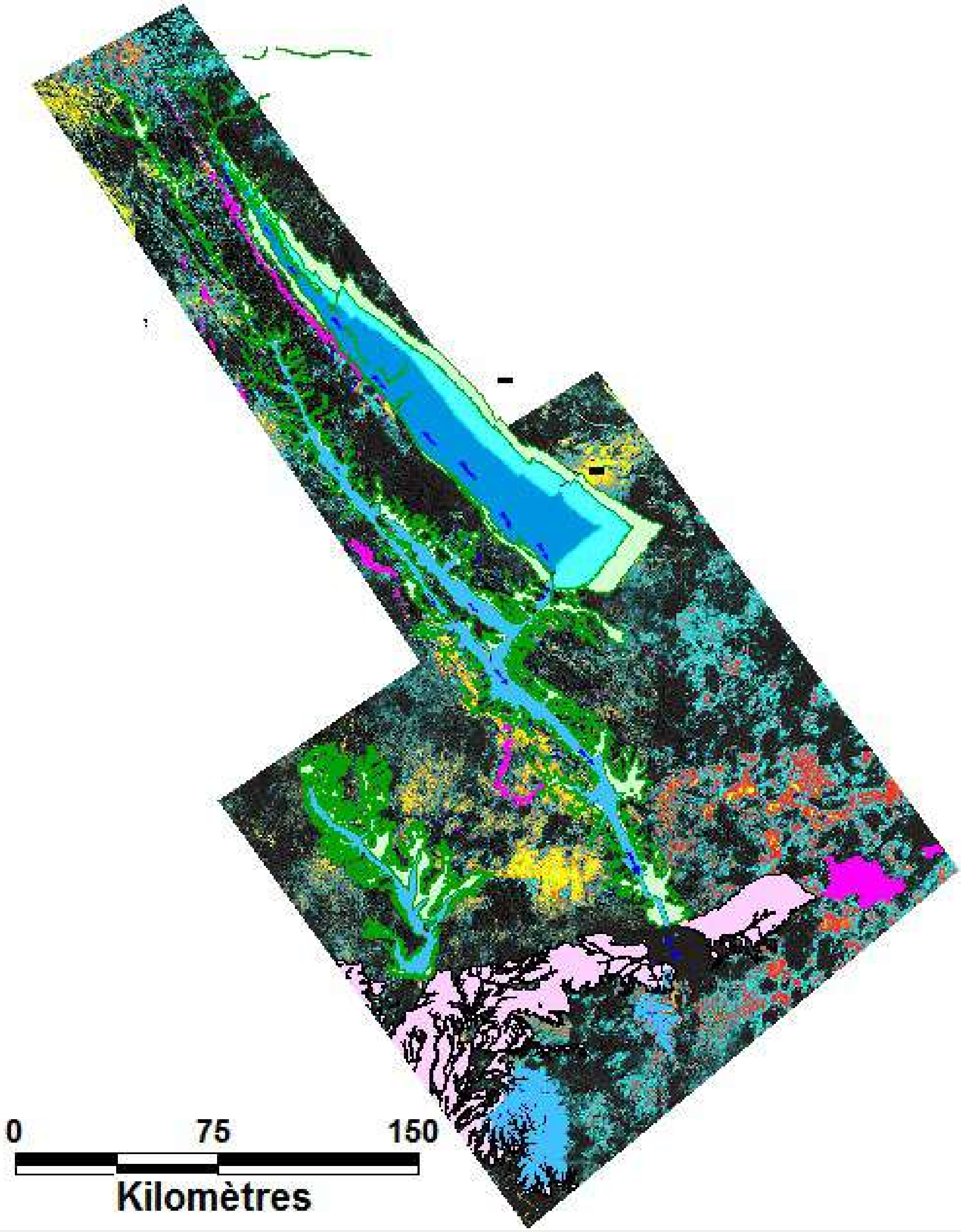


Figure 82 - Simplified Water Target Map

CONCLUSION:
This deep structure which starts south of Jijiga with a narrow neck of 2.5 km wide and 100 m deep ends up 230 km in the south with a broad bottom of 35 km wide and 700 m deep.
This aquifer controlled by the basaltic ridge of the Karamara and sealed by Uarandab shales is permanently flowing along the narrow southern part of the Fafen valley, down to the great gypsum barrier (Pink).

Surface waters continues to progress southward, but deeper groundwater blocked by the gypsum barrier percolates to the South West into the Ogaden Basin or is discharging towards the south west as shown by the yellow patches on the WATEX images

Groundwater potential in sand dunes

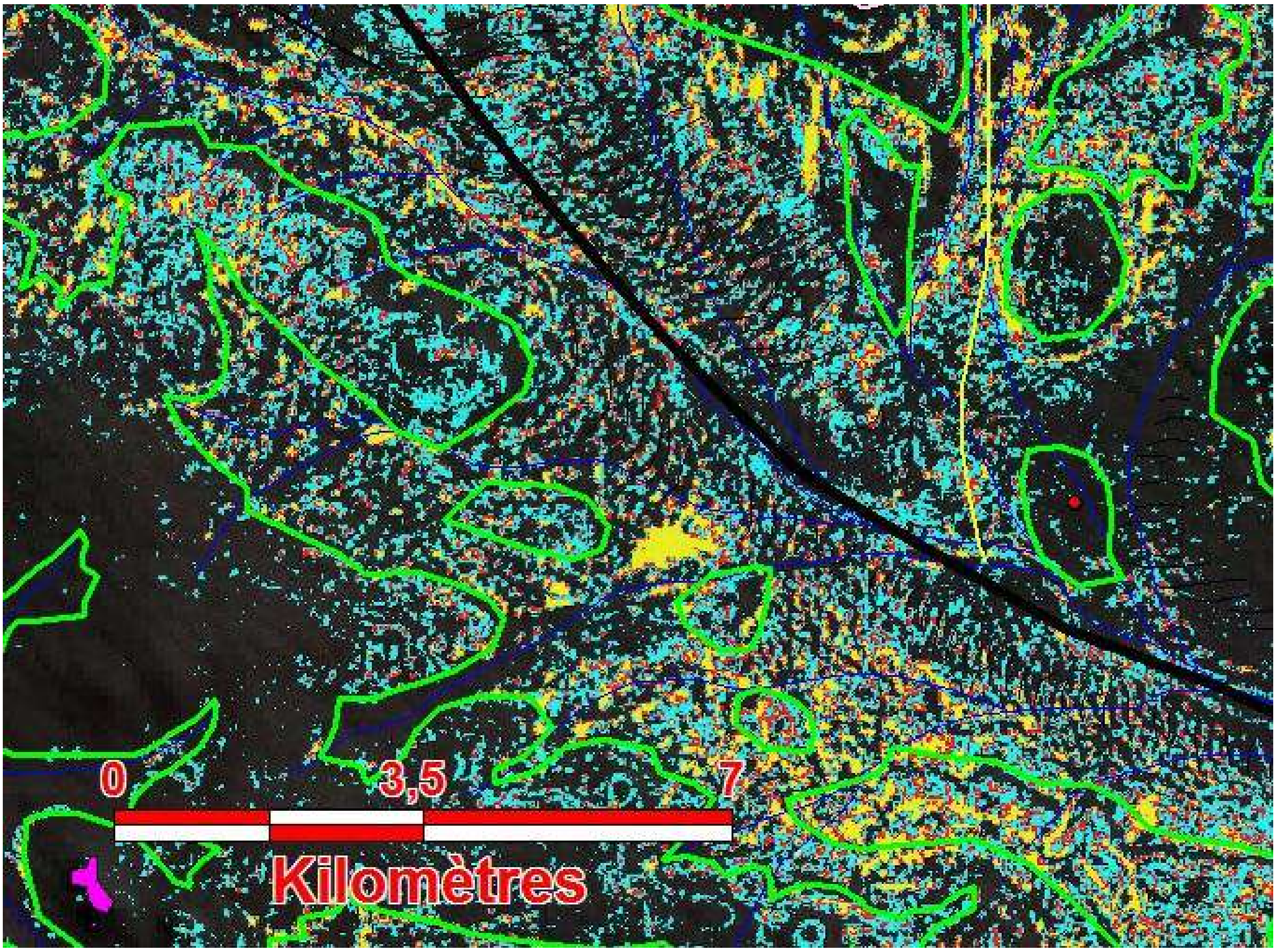
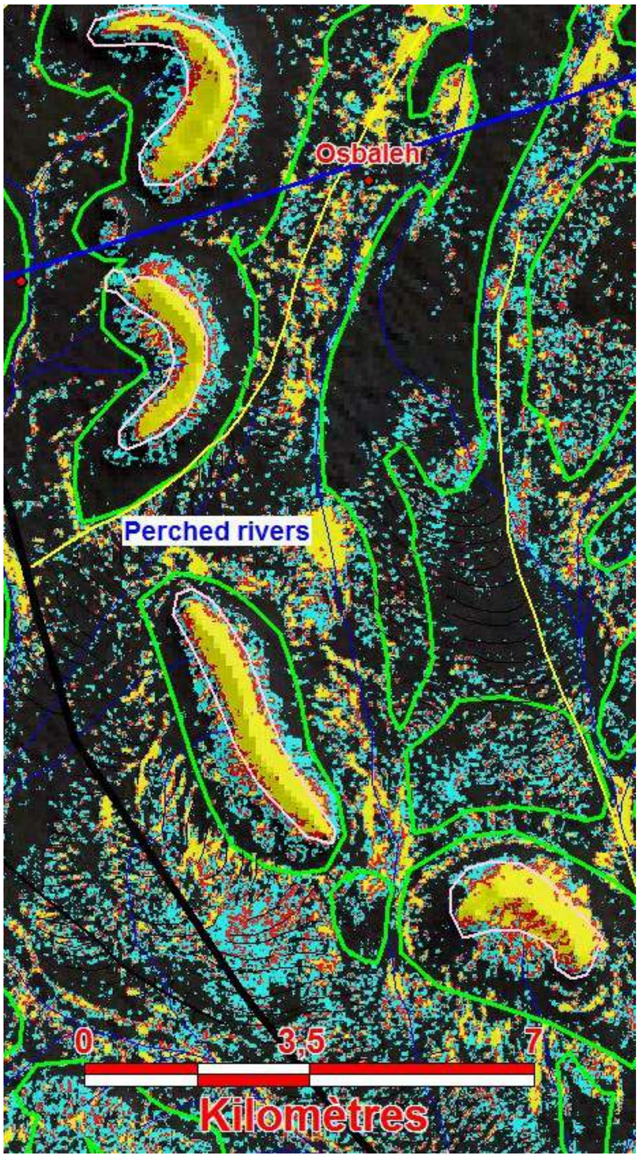


Figure 83 - WATEX image of sand dunes.

The Gabredarre formations in the Denan Woreda are locally covered by sand dunes which can harvest and store groundwater as indicated by the yellow alignments on the WATEX image. They most often lay within paleo-river beds not mentioned in actual maps. They might offer small hand dug aquifers replenished every year by rainfalls for local communities and implement their livelihood. The biggest yellow patches are worth being drilled.

Perched paleo-rivers and their groundwater potential



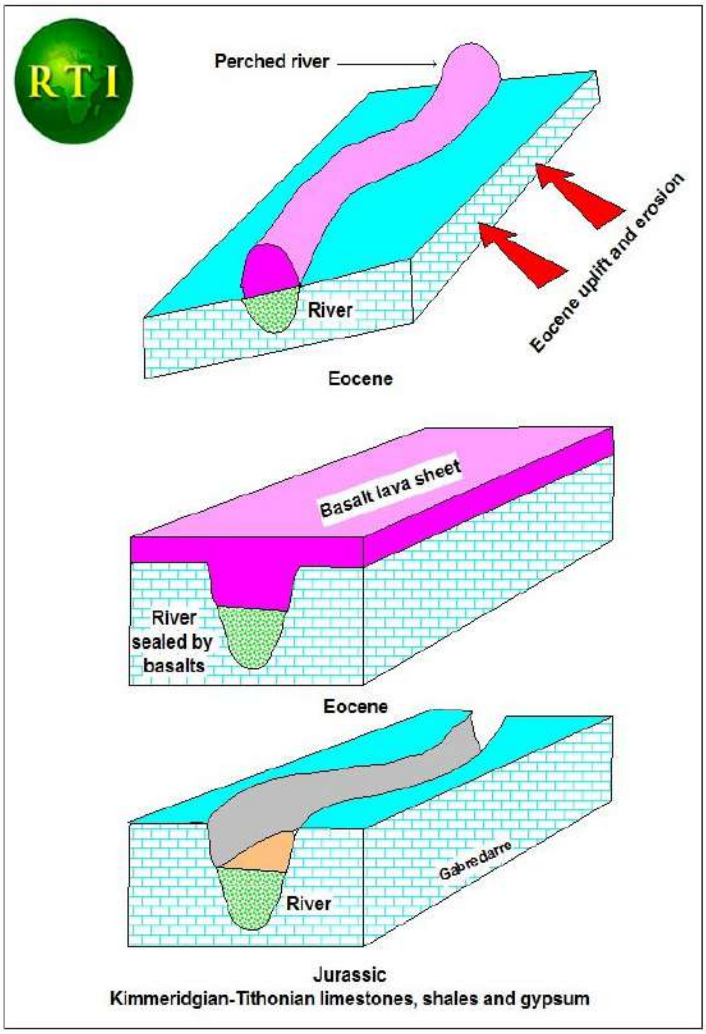


Figure 84 - WATEX image of perched rivers and associated geologic model.

Rivers dug within the Gabredarre formations near Osbaleh in Denan Woreda have been flooded by lava flows. The paleo-sediments sealed by lava have been uplifted and eroded during the Eocene. The results today is the remaining lava plug sealing paleo-sediments of an old river system which can host important water quantities and can be replenishable by intersecting rivers.

Reserves evaluation within a sealed perched river

- Length: **4400 m**
- Width: **570 m**
- Alluvium Thickness: **30 m**
- Surface cross section of the river alluvium: **8550 m²**
- Sediments volume trapped under the lava plug:

37.6 Million m^3

- Sediments porosity **15%**
- **Hosted groundwater volume: 5.64 Million m^3.**

The bright WATEX signature might suggest that these elongated perched rivers have a weathered basaltic seal which is a sign that these structures are full of water.

Groundwater discharges within the Mustahil limestones

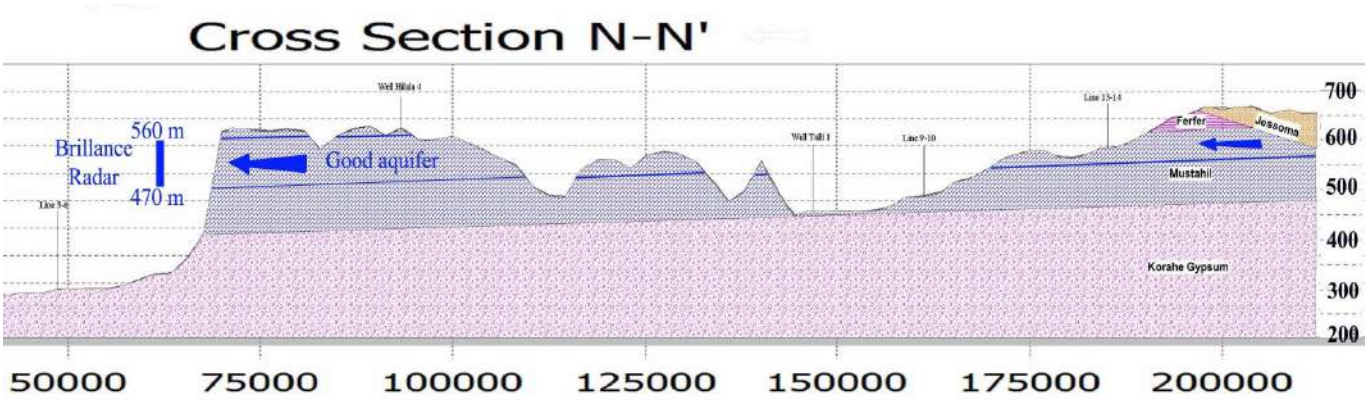


Figure 85- Cross section showing Mustahil limestone formations" floating" over Korahe Gypsum.

This WATEX image is overlying Mustahil limestones formations floating on the Korahe gypsum (pink area), just on the other side of the SW-NE major accident with a thrust of several hundred meters.
All the hydrogeological process of the northern part of the survey is interrupted by the major SW-NE accident.
The aquifers of the Mustahil formation within the Calub Saddle depend exclusively on the superficial residual flow of the Fafem and on local rainfalls limited to 240 mm/ year.

The surface of the Calub saddle covers 2479 km² on the Western bank of the Fafem river and 1272 km² on the Eastern side and they respectively harvest 595 and 305 Million m^3/year.
If we remove 90% of these quantities from evapotranspiration, the remaining available quantities are reduced to 60 million m^3 in the west and 30 million in the East; it just means that the Calub Saddle is located in a very dry environment.
Nevertheless, the WATEX image shows some possibilities such as bright radar backscattering along the flanks of the cliffs, as shown on the cross-section, indicating potentially good aquifers that we are going to show next page around Hilala.

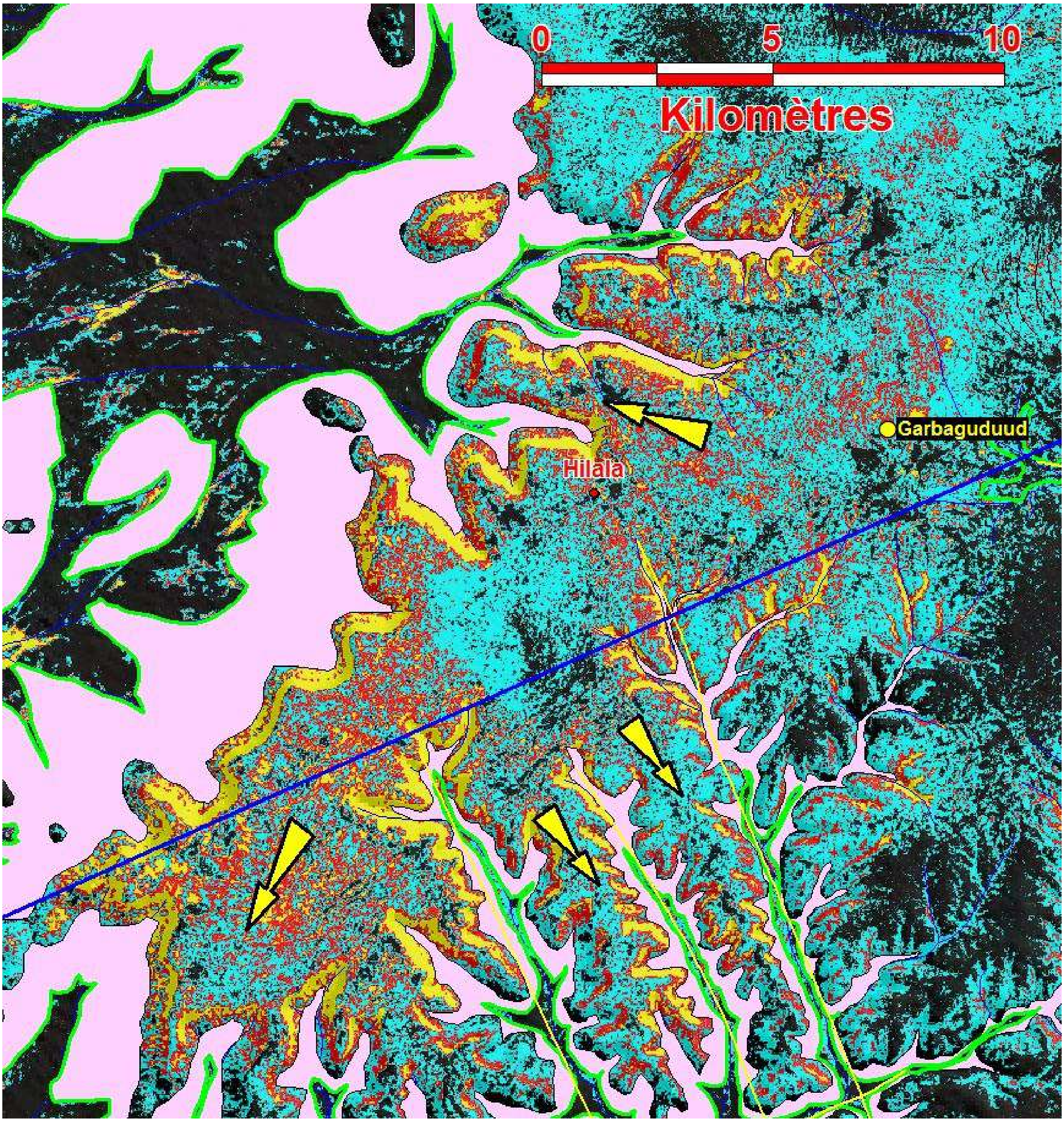


Figure 86 - WATEX image of lateral discharge from Mustahil formations (sandstones-Limestones)

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This WATEX image is overlying Mustahil limestones formations floating on the Korahe gypsum (pink area), just on the Western side of the Fafem River which harvests 595 Million m^3/year.

If we remove 90% of these quantities from evapotranspiration, the remaining available quantities are reduced to 60 million m^3 which are stored thanks to the good recharge capacity of the Mustahil limestones.

Due to the SW dip of the Mustahil formations, the aquifer is discharging on the South Eastern flanks of the cliffs which is translated by a continuous yellow bright WATEX ribbon.

Yellow arrows indicate the direction of the underground water flows.

(See cross section of line N-N')

From the width of the discharge, we can measure an aquifer thickness of 90 m.

Conclusion: on the eastern part of the survey area, Mustahil formations can be drilled at least down to 200 m with important probabilities to reach an aquifer with a water column of 90 m. Nevertheless, the sustainability is vulnerable because of very low rainfalls.

CONCLUSION.

WATEX© survey has detected and confirmed the existence of a deep aquifer structure which stretches over almost 200 km from NW to SE along the Eastern part of the Karamara range, and if its aquifer potential needs to be refined by more well data, we can consider that it has been already tested on its margins by the US Army well JJ889, 5 km south of Jijiga, the JIJIGA wells 15 km south of Jijiga, the 7 QAAXO wells 43 km south of Jijiga, within the Garbile well, 46 km south of Jijiga, the Ararso and Dhikhirley well 100 km south of Jijiga, and Degen Bur wells, 150 km south of Jijiga, providing a pattern of reliable data on its lithological characteristics and transmissivities.

Moreover, this East Karamara Aquifer (EKA) laterally confined by the Karamara range, is most likely extending over a broader surface to the East, thanks to a synthetic basement structure dipping Westward towards the center of the Ogaden Basin

Such a configuration related to the Marda Shear corridor, would increase the importance of the recoverable freshwater reserves which have been recharged since several million years.

Moreover, this survey has revealed the continuation of the Groundwater flows of the East Karamara structure into the narrow bed of the Fafem river, south of Birkot, down to a major gypsum barrier, before it vanishes into the deep Ogaden Basin.

Several other small aquifers have been revealed, each of them might contribute to small communities in a sustainable way.

The resulting Aquifer WATEX© Map has been edited at a scale of 200 000 distributed electronically and installed within the GENS, the RTI Navigation system.

Henceforth, drillers since the preliminary results of July 2013 know where to drill with maximum efficiency and success.

FINDINGS AND RECOMMENDATIONS

The survey area, too shallow for oil exploration companies and too deep for traditional hydrogeological studies has revealed several important assets, thanks to the use of new technologies.

After a long process of reconsideration of the geologic and structural map, of the rainfalls map, the WATEX© process has revealed the East Karamara Aquifer, buried between a depth of 50 to 450 m along the Jerer Valley, over a distance of 200 km opened to the South East and 5 to 20 km width.

The groundwater capacity of this aquifer is under close evaluation by the USGS.

This aquifer will offer a major economic asset for the region if its depletion does not go beyond the annual recharge to be defined by ac curate modeling.

The WATEX© process has also detected the continuation of the East Karamara water flow in the south, through the structural controlled Fafen river course, blocked in the south by a great gypsum barrier.

The overall analysis must be completed by important ancillary data such as Seismic sections in the southern part of the survey area, which will give the "architecture" of the basement and deeper geology and structures (>200m depth).

-High-resolution gravity data for greater precision of deep geological modeling. The source of gravimetric data has already been identified.

-Datation of groundwater produced by existing wells would help to secure data on the replenishment rate.

All the results and maps edited at 200 000 scale have been loaded in the GENS (RTI Navigation system) have been delivered with the drilling handbook to the drillers and exploration geologists in charge of the development of this area. Henceforth, IRC drillers through a USAID program have already started to drill since last December 2012 using the present results with maximum efficiency and success.

The detection of the Karamara aquifer in a region where most known sedimentary aquifers are uplifted tabular plateaus opens the prospect to detect other graben structures in the Horn of Africa. Despite this important finding, further study of the Karamara aquifer, such as modeling its full extent by the USGS will be critical achieving a more complete assessment.

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2nd August 2013