Master Thesis

Institute of Applied Geosciences

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Impact of geological structures on rock mass characterization ,Giba reservior, NW Mekelle,Ethiopia

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Contents

Abstract

Water shortage continues to be a serious problem in Tigray, northern region of Ethiopia, especially in the regional capital called Mekelle. To mitigate the current water supply problems, the Tigray Mines and Energy Bureau have recently embarked a major water supply project called the Giba dam water supply project. The study area covers approximately 40 km^2 to the north east of Mekelle. This study focused on fractures assessment of the Giba dam reservoir, to show possible relationships between the lineament and known geological structures and to help identify structural features that may impact hydraulic parameters of the Giba Dam, and rock mass characterization at the proposed Giba dam reservoir. Analysis were carried out using remote sensing analysis, digital elevation model (DEM) analysis , field studies and existing borehole data ,in-situ tests ,laboratory results and maps.

From the different method analysis, four dominant normal faulting and strike slip faulting movements are obtained. These are the WNW-ESE, NNE-SSW, NW-SE, NE-SE trending sets are described and analyzed in detail. Normal faults and extension fractures are more porous than the strike slip faults. The rock mass characterization of the reservoir area was made based on field data and existing laboratory results. Analysis of permeability and rock mass strength and RQD was carried out of the dam axis and reservoir area. The permeability results of the dam site and the reservoir area in the rock units is medium to high. The cross sections available from the dam axis show that foundation rocks are sedimentary rocks consisted of marly limestone and shale intercalated with gypsum veins. Finally rock mass classification has been performed according to RMR systems. Since the area is affected by fracture network this influences the rock mass quality at the dam foundation and the reservoir area. These normal fault and different joint systems also significantly affect the permeability of the rock units at the dam foundation.

1. Introduction

1.1. Background

A dam is an artificial barrier usually constructed across a stream channel to impound surface water for different purposes such as domestic water supply, irrigation, and hydropower. An adequate assessment of geologic and geotechnical conditions is imperative for a safe dam design and construction under question. The Giba dam is one of the options proposed for the Mekelle water supply. Most Dams in Mekelle are constructed of the earth fill. The design of the Giba dam is under process. Over 50 percent of all dam failures within the Mekelle drainage basin can be linked to geologic and geotechnical problems referring to previous studies (Co-SAERT 2002). The geological and geotechnical problems range from foundation defects caused by inadequate investigations to internal erosion through the embankment. Each dam site may have its own unique set of geologic and geotechnical challenges. Similarly, the design requirements are different for dams of different size, purpose and hazard potential classification.

Dam projects that lack the benefit of geologic input are likely to cost more than necessary, function below their expected optimum or fail all together .Thus, the intention of conducting an engineering geological and geotechnical mapping is to help in selecting a technically feasable, cost effective dam or site and insure the longer span of the life of the Giba dam structure (Fig 1).

The main objective of this study is to develop a preliminary geological model of the project area, study in detail the Mekelle fault and its associated structures and also characterize the rock mass of the reservoir area. Detailed lithological description of the Mekelle fault, structural mapping, and engineering geological mapping was important to get the necessary data used in different analytical methods. In addition, the analysis of the topography is done by constructing Digital Elevation Models (DEM) and remote sensing analysis in order to determine the structural gain of the area through lineament analysis with photogrammetric methods (ShapeMetrix3D) to obtain structural data (i.e. joint set).

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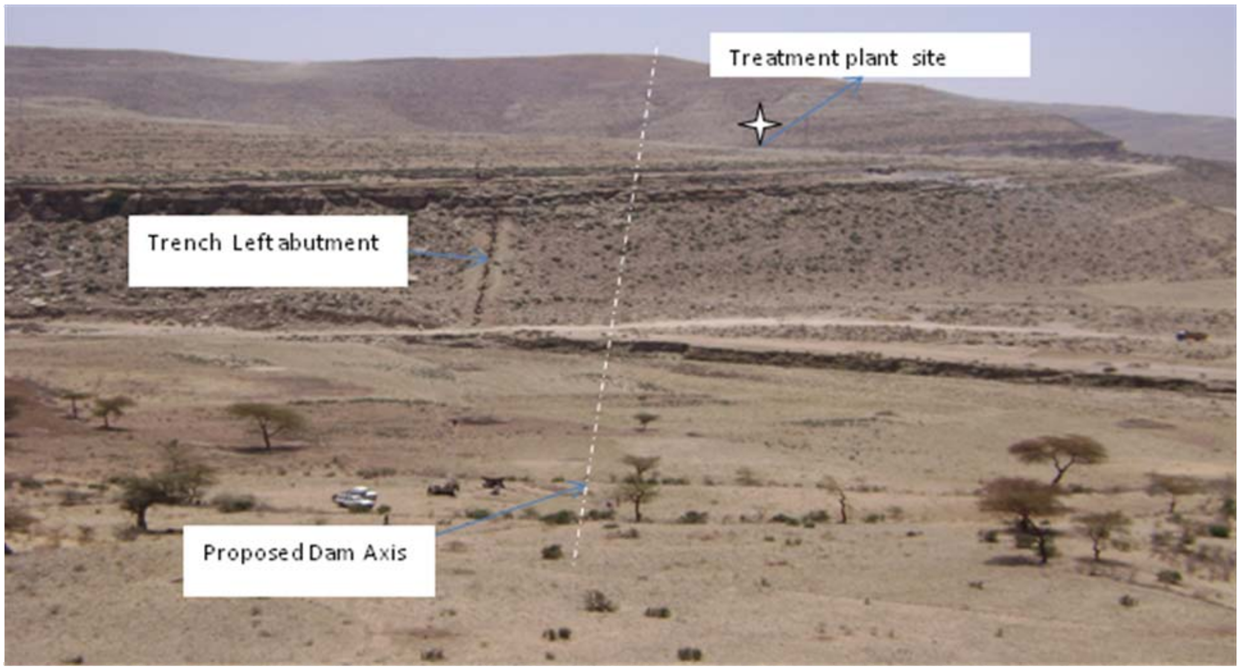

Fig. 1: Partial view of reservoir site and left abutment dam axis

1.2 .Problem statement

Water shortage remains a serious problem in the region of the town Mekelle in the northern region of Ethiopia. For the last 10 years water demand increased resulting in an alarming situation due to rapid population growth and infrastructural development. Accordingly, the Tigray Mines and Energy Bureau have recently embarked on a major water supply project, the Giba dam water supply project, to alleviate the current water supply problems of the town and surroundings.

Accordingly, to ameliorate this problem, the Bureau of Tigray Water Resource started a project in the year 2000 at a site five kilometers away from the town by digging 11 wells. However, five of them resulted in no yield while the remaining six are supplying less than their intended capacity (they were supposed and expected to supply for 20 years) (Mekelle Water Supply Service Office 2004/05 report). To this end, the project implementing body, Tigray Water Resource Bureau, identified an option and concluded in 2008 that, reliable water supply for the town could be supplied from the *Giba* dam.

Considerations of past and present geological conditions are crucial for site selection of any engineering work and environmental activity. The need of engineering geological involvements in the area is increasing from time to time since its commencement. An Engineering geologist is needed to develop a geological model of one given site with a consideration of geological material and rock mass properties as well as geological processes (Knill, 2003). The geotechnical behaviour of the ground could vary from one site to the other due to the geological conditions/processes in the past and present. So, those processes should be well understood in order to avoid any unpredicted risk. Due to severe problems of water supply to Mekelle, Tigray Water Resource Bureau proposed the Giba dam across the Elala River. As previous studies (Co-SAERT 2002) show, more than 20 micro and small dams were constructed within the Mekelle drainage basin. But most of them failed for various reasons, in addition to poor knowledge and consideration of the past and present geological conditions of the proposed sites.

The geological conditions of the 65km long Mekelle fault and its associated structures, the Mesozoic sediments (limestone, shale, sandstone, dolomite, and gypsum) and intrusion of dolerite dykes play a major role in the water tightness of the Giba reservoir and dam foundations. Even though the Mekelle fault passes 2.5 km away from the dam axis in north east direction, the associated and local/minor structures cross cut the Giba reservoir more than one time.

A preliminary development of the geological model of the study area, the characterization of the Mekelle fault and its associated structures to minimize/reduce unexpected risk from the past and present geological conditions as well as basic information for further studies and related engineering works is necessary. Therefore, this study envisages with the objective to develop a preliminary geological model of the project area, in particular focusing on fault zones and their associated structures and characterization of the rock mass of the reservoir area.

1.3 .Location of the Giba dam project

The Giba Dam is located in Tigray regional state (northern part of Ethiopia), about 20km from Mekelle town along the Mekelle –Hagreselam main road (Fig. 2). The geographic location has the coordinates 540000 to 548000 east and 1507250 m north. The Giba reservoir area is part of the Ethiopia central plateau just to the west of Afar rift valley, located about 800 km north of Addis Abeba (the capital city of Ethiopia).

The proposed Giba Dam will be built on the river Giba in a branch of the Giba basin which is a tributary to the Tekeze River. Located 25 km north east of Mekelle in the north of Addis Abeba.

The mapping covered the area between the junction of Agulae with the Giba River and the area north east of the sandstone quarry at Chin Feres Mariam and along the Mekelle Fault. The mapping extended close to the dam northwest of the cement factory and to the junction of the Mekelle-Wukro and Hagere Sellam roads.

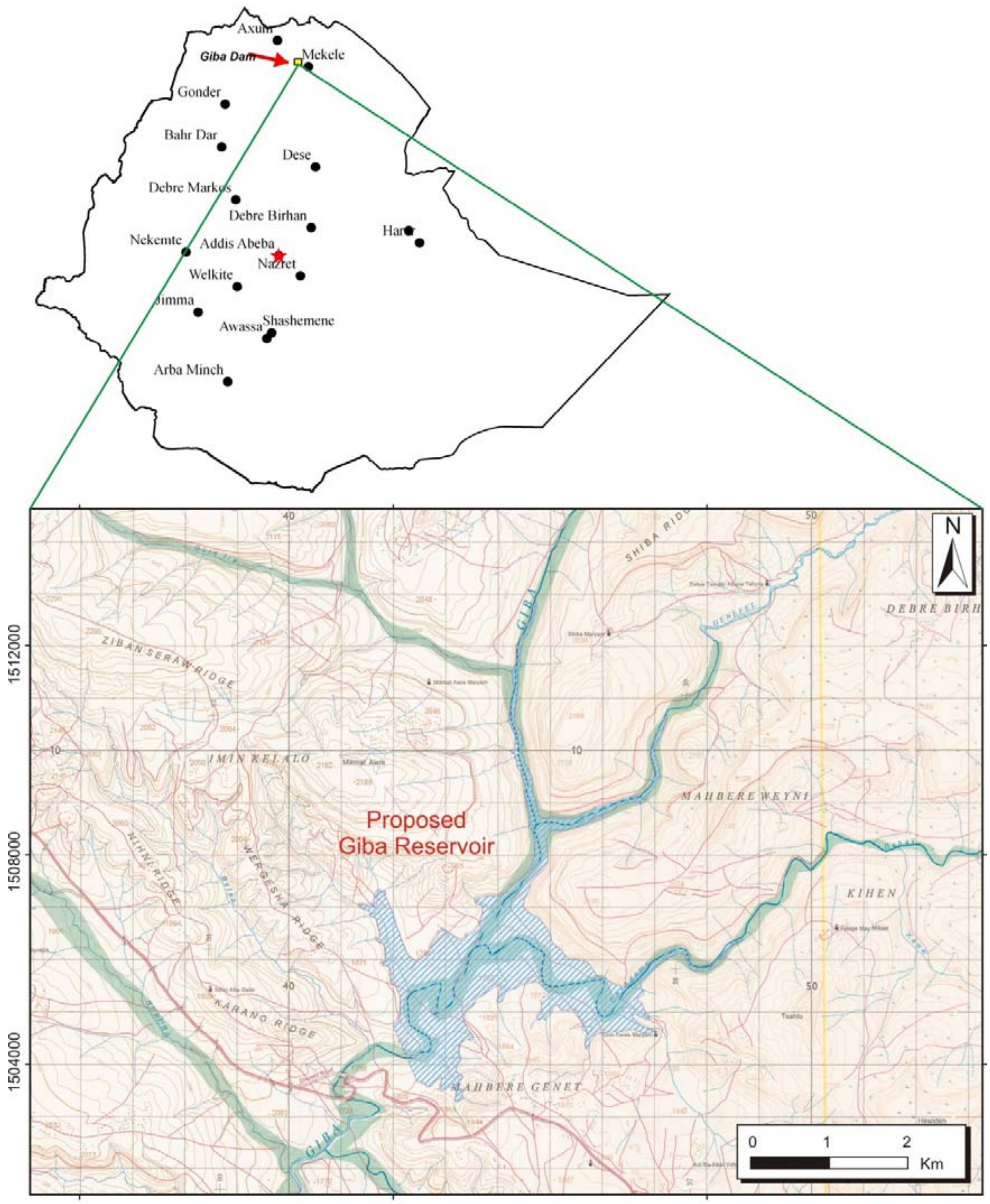

Fig. 2: Locational map of the Giba reservoir from the topographic Map of Ethiopia showing the enhanced reservoir area outlined by blue marks.

2. Basics

2.1 .Geological overview

2.1.1. Sedimentary basin of Mekelle outlier (Regional geology)

The first recorded geological work in the northern regions of Ethiopia was started by Blanford (1870). Since then several scholars have been attempting to study the geology of the northern part of the country including the Mekelle outlier (Fig. 3). The evolution of the sedimentary basin in Tigray (Mekele Outlier) began in either the Ordovician or Carboniferous and probably ended in lower Cretaceous before the eruption of the Trap Volcanics (Beyth 1971).

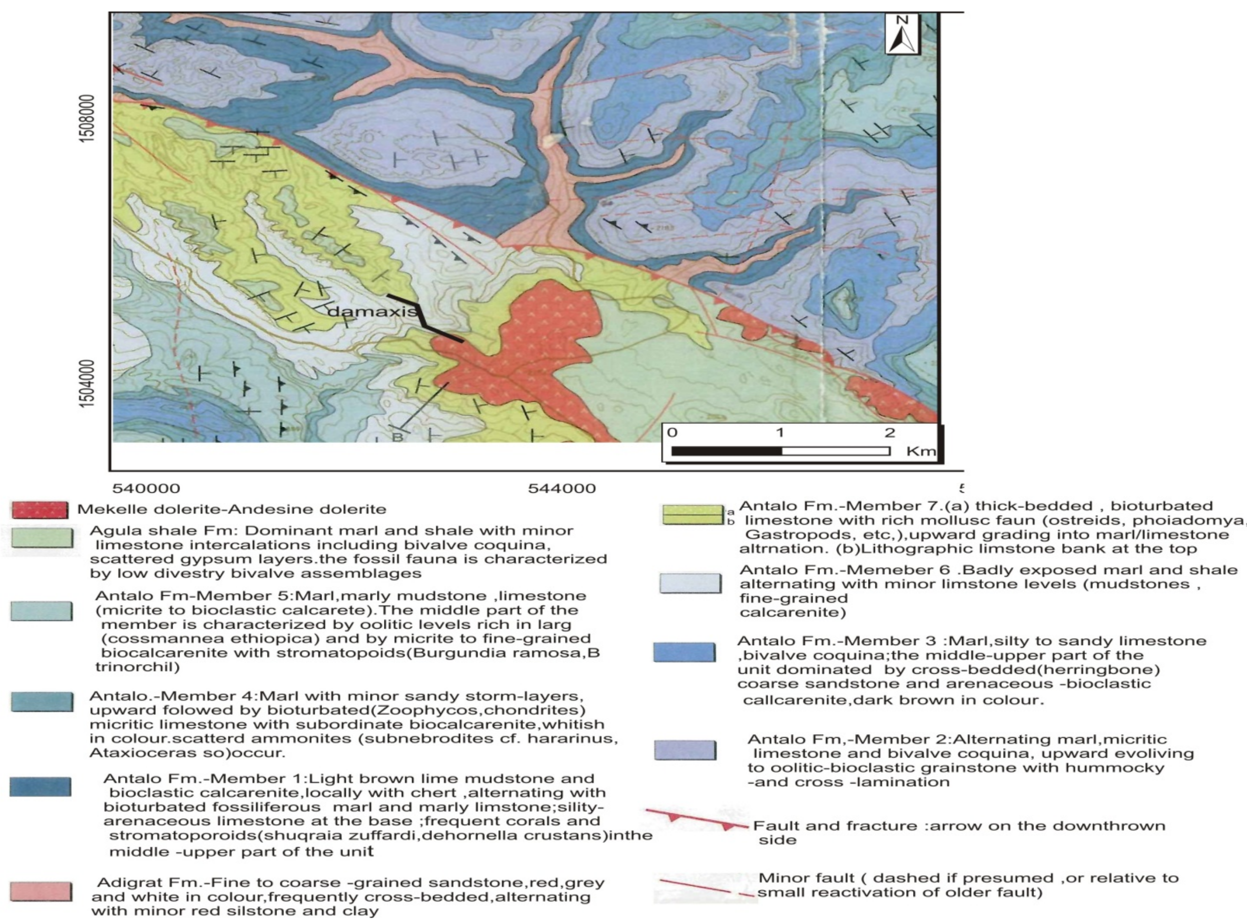

Fig. 3: Regional geological map (Geological map of Mekelle outlier, by Russo et al, 1995-1996).

The Mekelle outlier is composed of Precambrian Metasediments and Metavolcanics at the lower most part, followed by Enticho Sandstone and Edaga Arbi Tillites. The Enticho Sandstone and Edaga Arbi Tillites in turn are overlain by an assemblage of Jurassic continental clastics and marine sediments with a transitional facies between the continental clastics and the marine sediments. All the geological sequences mentioned above are cross cut by a young sub-volcanic dolerite body, especially along the Mekelle Fault in close proximity to Mekelle Town and the Aynalem well field all the way to Chelekot, along the way to Samre and around Debri.

The general regional stratigraphy of the Outlier can be summarized as follows from bottom to top (Beyth, 1972).

Edaga Arbi Glacial Deposits and Enticho Sandstone:

This unit consists of tillite and conglomeratic sandstone. The Edaga Arbi glacial formation is composed of dark- gray tillite at the base, then massive silt stone and shale, overlain by red and green shale, while the Enticho Sandstone formation is composed of white, calcareous, coarse - grained sandstone containing lenses of silt, conglomerate with sub-rounded to well-rounded pebbles, cobbles and boulders. Scattered erratics, mainly granite and gneiss, are very common.

Adigrat Sandstone: This unit consists mainly of friable, medium grained, well-rounded and well-sorted sandstone. The unit is cross-bedded and arranged in beds or layers and separated by red ferruginous siltstone or laterite beds at the top. It is a steep cliff forming gentle slopes at places at its bases. In places, it is yellow to red sandstone, fine to medium grained inter-bedded with variegated siltstone and clay (Beyth, 1971).

Antalo Limestone: The lower part of Antalo Limestone in the central part of the Mekele outlier is composed of well-bedded (up to 3 meters thick), yellow to white, finely crystalline limestone with few quartz grains which form a steep cliff on top of the Adigrat

Sandstone. Above this steep cliff the unit is composed of gently terraced slopes of yellow marl and coquina. Covered by yellow with few brown to black sandy limestone. This layer is overlain by a yellow coquina and white limestone. The limestone displays karst features, solution channels, and caves with secondary calcite. A white, finely crystalline limestone interbedded with yellow marl and sandy coquina overlays the karstified limestone and forms cliffs and gently terraced slopes. The upper most part of the unit is very well bedded, white, finely crystalline limestone with fossils and yellow marl inter-bedded with coquina containing silicified lenses. The limestone forms a distinct cliff. In general the Antalo Limestone is a non-dolomitic intercalation of limestone and marl (Levitte, 1970).

Agula shale: This unit is mainly observed north of Mekele, in the vicinity of Mekele and Antalo village. North of Mekele the unit is composed of finely laminated black shale, marlstone, and limestone containing gypsum. Near Mekele this unit contains some sandstone extensively intruded by Mekele Dolerite. This unit is more calcareous in the northern part of the Mekele outlier, and more silty and sandy in the south, near Antalo village. The Agula Shale covers only the eastern part of the Mekele Outlier in the central area of the sedimentary basin. The lower part of the Agula Shale is composed of gray shale containing limestone and the uppermost part is composed almost entirely of variegated shale, alternating from brown to purple and gray to green (Levitte, 1970). Agula Shale is the uppermost unit in the limestone sequence; it is overlain by the Amba Aradam Sandstone.

Amba Aradam Formation: It is silty and clayey in the northern part of the Outlier and conglomeratic in the southern part. Most of the sequence is lateritized. It is composed mainly of siltstone, sandstone and argillite and varies considerably in thickness at several localities in the vicinities of Mekele and Abi Adi. The rock is hard and contains many pebbles of quartz up to 4 cm in diameter. In places the quartz pebbles become concentrated enough to be called conglomerate (Levitte, 1970). The distribution of this unit is mainly restricted within Mekele Outlier and an age of Lower Cretaceous is given by Beyth (1971).

Mekele Dolerite: The area around Mekele, including the present study area, is penetrated by many basaltic intrusions most of which are sills from 0.5 - 30 meters wide, though dykes and small stocks are also common (Levitte, 1970). The rocks are black, fine to medium grained and hard. Exposures are jointed vertically and horizontally and the blocks thus formed are weathered by exfoliation. Except the Amba Aradam Formation the whole section is intruded and the most preferred section is Agula Shale, which is very soft and has less cover than similar soft formations in deeper sections (Levitte, 1970). It is exposed within Mekele Outlier and in the escarpment of the Mekelle fault. An age of Tertiary is given by Beyth (1971).

According to Bossellini *et al* (1997), the stratigraphy of Mekele Outlier consists of a Lower Sandstone unit i.e. Adigrat Sandstone (Triassic – Middle Jurassic in age), an intermediate, largely carbonate unit, Antalo Limestone (Oxfordian - Kimmeridgian), and an upper sandstone unit, Amba Aradam Formation (probably of Early Cretaceous age). Flood Basalt's of Tertiary age unconformably overlie the sedimentary rocks and in places are intruded by a network of dolerite sills and dykes.

Structures

Four sub parallel fault systems exist across the Mekelle Outlier and are designated from north to south as the Wukro, Mekele, Chelekwot and Fuicea Mariam (Mai-Nebri) fault belts as shown below (Fig. 4). They are normal faults with steeply dipping fault planes and probably active after the deposition of the Agula shale and before the Amba Aradam formation. The first three faults dip southward with a moderate to steep angle. The Mekele Outlier is therefore composed of three big tilted blocks (Beyth, 1971). Along these fault lines asymmetrical synclines were formed, dipping about 70 to NE and 200 to SW, and plunging southeast. Mainly Agula shale is exposed along the syncline axis. According to Beyth (1971), the main movement along these faults was probably post Agula shale, but Amba Aradam formation is not affected by these faults. These fault lines are used as fissure for the Mekele Dolerite dyke intrusions.

The longest of these faults within this system in the area is the Mekelle fault, which passes north of town and running several kilometers along its strike with considerable vertical displacement and dips about 70° to SWS. The vertical displacement of these fault systems is not prominent and difficult to measure due to absence of marker beds. Faulting brings the lower most formation of the Antalo Group against its upper most formation, near the town Mekelle, which means a throw off at least 400 meters (Levitte 1970).

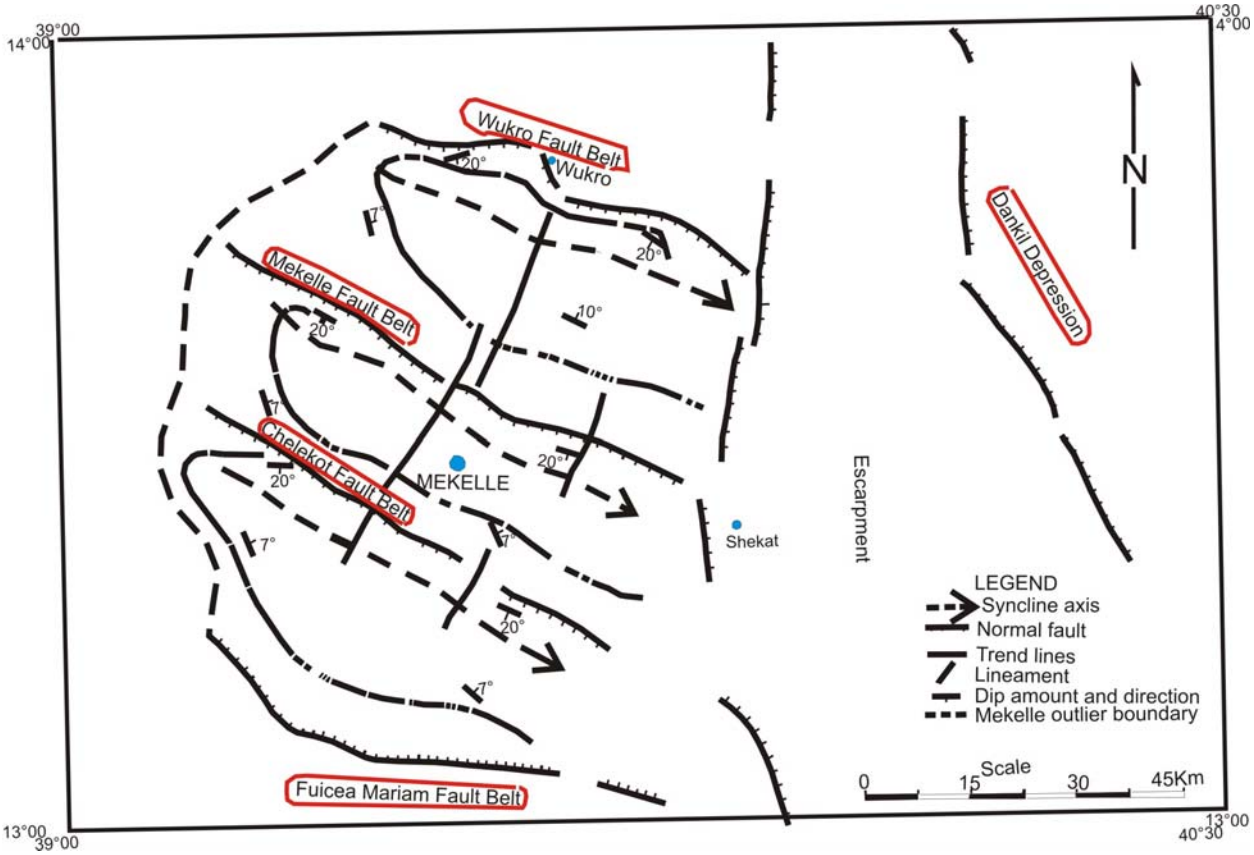

Fig. 4: Structural sketched map, Mekelle Outlier (modified after Beyth, 1971)

The Mekelle fault system passes through the upper part of the Giba dam reservoir just about 2-2.5 kilometers north east of the dam axis. It has a total estimated length of 65 kilometers and Mekelle Dolerite intruded along it.

2.1.2. Detailed geological overview of the Giba dam reservoir and its surrounding area

The geology of the reservoir is discussed in several papers (Gebrihans, 2007), Russo et al.1996). In the year of 2001 a detailed geological map of the Giba reservoir was made in scale of 1:10,000 by Efrem. Starting from this the following modifications were made with the lithological mapping description of the area especially near of the Mekelle fault because the major structures are important for understanding the basin development based on field observations (Fig. 5).

The Giba catchment is located in the western part of north Mekelle. It is floored by the Antalo formation and Adigrat sandstone. The main rock formations which outcrop in the larger part of the study area are shale- limestone intercalations, limestone, and igneous rocks, mainly the Mekelle dolerite, which intruded into the Mesozoic sedimentary rocks. The shale _limestone intercalation is the upper most part of the Antalo group. It is composed of shale, marl and limestone intercalations which rarely contain thin layers of gypsum (Yehdego, 2003).

The main lithologic units are recent sediments (alluvial and colluvial/talus deposits), dolerite, travertine, and shale intercalated with thin beds of limestone, crystalline black limestone, karstified limestone, marl-shale intercalated with thin layer of limestone, and Adigrat sandstone. In areas where dolerite intrusions are found, the beds were tilted from its horizontal layering. The dominant sedimentary rock unit outcropping in the study area underlying the shale and limestone intercalation is the limestone unit.

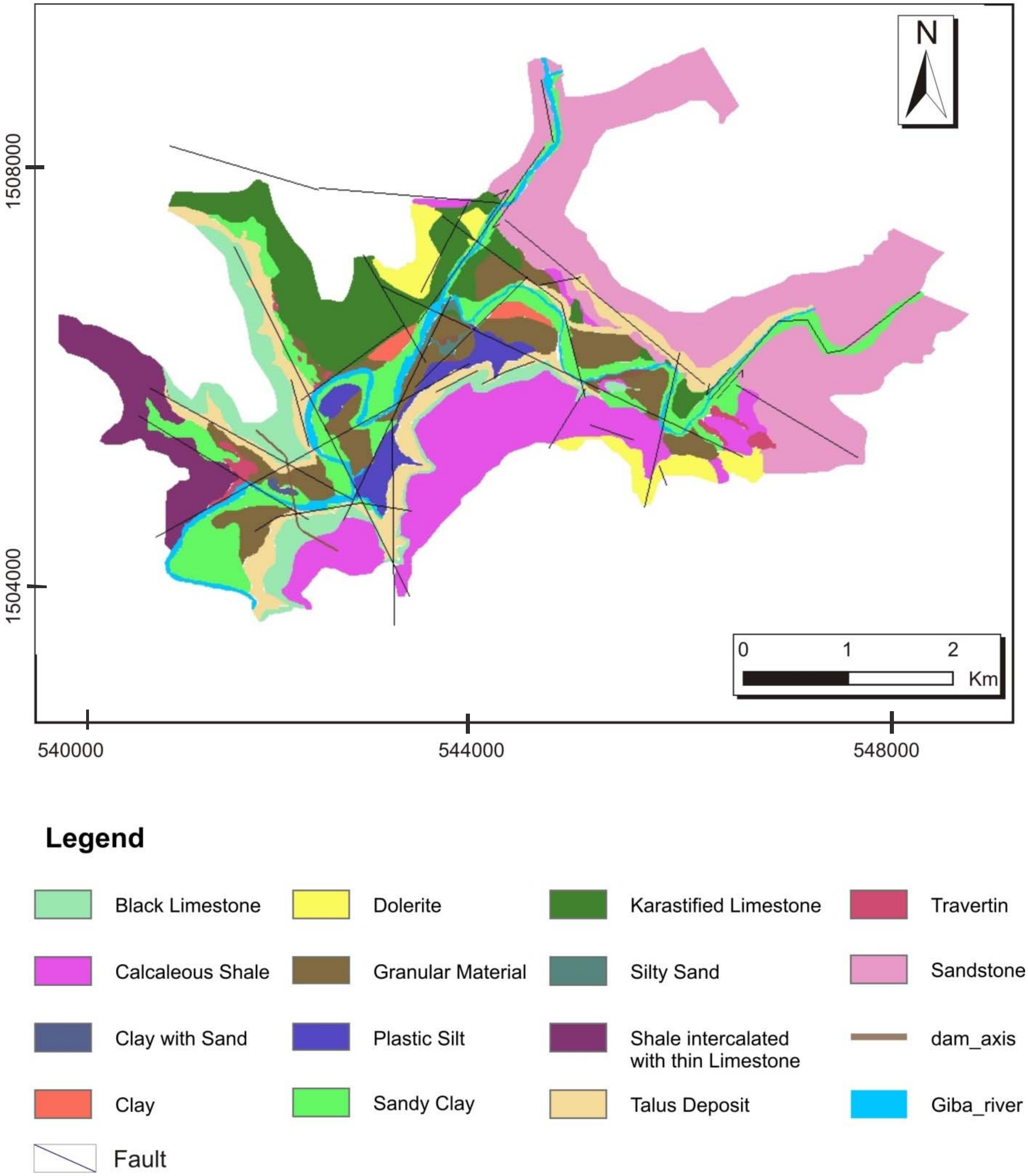

Fig.5: Lithological map and its lineaments in the area of the Giba dam reservoir (modified after Gebrehanis 2007).

Alluvial (recent sediments)

The alluvial soil types are dominantly found at the lower valley floor along the Giba River and its tributaries. These are composed of coarse and fine grained river deposits. The coarser materials are formed by being transported within the reservoir area. In places, these coarse materials are cemented by calcite precipitates while the fine deposits are forming the flat topography of the reservoir area.

Talus/Colluvial Deposits

These deposits are limited to the feet of the limestone cliffs. These are composed of boulders of different rock types. These deposits are generally poorly sorted or erratic in nature. The materials mainly cover the gentle to moderate slopes of the dam site and reservoir area following the limestone cliff and the alluvial plain.

Dolerite

Ridge forming dolerite dykes and sills are commonly outcropped in the south and south east of the reservoir while the phonolitic exposure is found at the northern rim of the reservoir. They are also found in the eastern side and north, up to Mekelle fault of the Giba reservoir. In many places it is proved that it has cut the sedimentary succession from below.

The dolerite outcrop is dark greenish, fine to medium grained, crystalline, forming dykes and sill networks that intruded boulders or cross-cut the sedimentary succession. They are highly weathered, jointed and show spheroidal weathering. The core of the weathered body contains hard, relatively fresh dolerite rock (Fig. 6). WNW-ESE aligned faults and NNE-SSW aligned fractures are identified in this area mainly bounded by the Mekelle fault in the north.

Fig. 6: Dolerite showing spheroidal weathering with a fresh core at the center.

Travertine/Tuff dams

Travertines are widely exposed and were observed along the main Giba river and its tributaries and along fault zones. They are good indicators for the humid conditions that existed in the area in the past few thousand years. According to Moeyersons (2005), environmental deterioration in the basin started around 3000 BP due to forest recession. This forest recession is thought to be not climate driven but due to human activities in the area (Moeyersons, 2005). Among the exposures of travertine deposits three localities are important: near Chin feres–Maraiam church, upstream of the dam axis at a contact between karstified limestone/talus and downstream side of the dam axis (right side of the main River) (Fig.7). Most of the outcrops of travertine are along fault zones. It is highly weathered, whitish in color, soft and with frequent voids or cavities.

Fig. 7: Travertine along the dam axis.

Shale intercalated with thin beds of limestone

This rock unit was found on the downstream part of the dam site. This unit is dominated by the shale layer with thin beds of limestone and marl. Its color varies from light yellowish to greenish gray, fine grained, shows fissility and some fractures (Fig.8).

The unit shows a cyclic nature of the inter-beds and is commonly observed along gentle slopes due to its low resistance to weathering as compared to the cliff forming bedded limestone. The shale layers are characterized by their fissility and thinly bedded or laminated nature.

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Fig. 8: shale with thin beds of limestone.

Black limestone

These limestone units are exposed above the talus covered geological unit. It is widely spread in the southwestern and eastern periphery of the reservoir, extends around the left and right abutments of the dam axis, and continues towards the reservoir. The upper most part is dark gray to black in color, finely crystalline, fractured with parallel and cross-bedding types and compacted. In the sections, the lower part is dark gray, thinly bedded and at the very bottom part intercalated with marl and shale while at the top part black and thick bedded towards the foot of the cliff dark, dark-brownish, massive with thin beds of fossiliferous and oolitic limestone are observed. The bedding planes are more or less horizontal although it shows dipping at some localities due to the faulting related tilting.

Highly jointed limestone that is affected by three dominant joint sets. The dominant joint sets are with strike of 120°, 65°, 160° and dip vertical to sub –vertical. The cliff forming limestone in most of the area is exposed above the reservoir water reach except in few places. The reservoir water level might reach the bottom of the cliff forming limestone just northeast of the proposed dam axis.

Karistified Limestone

This unit is wide-spread in the north-western part of the reservoir area and is not cliff forming. It rather lies flat on the surface forming gentle slope landforms (Fig. 9). It is bounded in the north by the Adigrat sandstone and in the south by gentle slope forming landforms overlain by steep cliff forming limestone units. The southern boundary is marked by a stream draining to the east. The stream valley is underlain by stream sediments, travertine and bedrock at certain places. The bedrocks exposed in the stream bed show gentle to steep dip. Close to the junction of the stream with the Giba River, the karstic limestone is bounded by gravel with boulder size rocks. It is light gray coloured, crystalline, with interconnected voids or cavities with rough and sharp edged surfaces and networks of joints. Moreover, this unit is highly faulted and tilted, having bedding with a dip of 15°and orientation of 265°.

Fig. 9: Karstified limestone exposed on the west side of the reservoir.

Marl-shale with thin layer of limestone

This unit is mainly exposed on the southern part of the study area along the road to Mekelle and near Chenferes area. It is light yellowish, greenish gray, dark, friable, moderately to highly weathered. The thickness of this bed varies from 0.2 to 2m. The marl is mostly yellowish with few beds of brown-yellow to black coquina and sandy limestone. The bed thickness is variable. The limestone layer is finely crystalline, black to yellow in color containing some fossils. In places intercalations of massive and friable mudstone are also observed in this unit.

Adigrat sandstone

This lithostratigraphic unit of the Adigrat sandstone unit is exposed in the northern periphery of the reservoir area. This rock unit is restricted in only two localities, at the foot of the northern cliff (along the main Suluh River or north Giba and along the north side of Agual River) just at the northern periphery of the reservoir area (Fig.10). The sandstone outcrops in these areas are overlain by limestone and its vertical thickness and underlying unit is difficult to determine from field observations.

It is found throughout much of the Mekelle fault and is particularly distinctive along the north of the Agulae River course and along the main Suluh River or northern Giba River valley. It is characterized by fine to medium grained sandstone with some cross-bedding structures and is poorly cemented. The sandstone in the area is overlain by limestone.

This formation varies in texture and color. In the northeast of the confluence of Agulae River with Giba River, the sandstone is medium to coarse grained, very friable, with variegated color (whitish, yellowish, light reddish and dark reddish where iron rich). In the north western part of the reservoir area, it is cliff forming (block forming jointed deposits), commonly exposed as hard massive beds, well cemented by calcite, jointed (block forming), with brown color. The calcareous units of Adigirat sandstone are formed close to the contact with the Antalo limestone. The lower sandstone units are fractured.

Some of the fractured sandstones are cemented by vein forming calcite .Macroscopically with the aid of hand lens feldspar, quartz and dark iron rich oxides are the principal minerals observed in this rock unit. It is restricted in only two localities, one at the foot of the northern area. There are three dominant joint sets in the area with strike of 330°, 290°, and a north _south trending set.

Fig.10: Adigrat Sandstone (from photo collection) on the western part Subuh River.

3. Methodology

3.1. Morphology analysis

In the process of lineament recognition a morphological analysis is very important. To determine the geometrical relations of structural discontinuities at the surface, remotely sensed observations and DEM were used in the present study, which are a first step in analyzing and interpreting their tectonic significance. Both methods use image analysis and digital elevation model for structural analysis.

It has to be emphasized that space image and topographic analysis is used as a first and generally nonexclusive tool for tectonic interpretation, to be completed with field analysis.

A recognition of the main morphological features related to the tectonic activity in the region was obtained from an analysis of topographic maps (scale 1:50,000), aerial photographs (scale 1:50,000) and free satellite images.

3.1.2. Lineament mapping

The region was previously mapped by A. Russo et al (Geological map of Mekelle outlier, 1995-1996) and recently by Gebrehanis (2007). Based on these maps observations and modifications were made with the remote sensed scenes. For the observations aerial photographs with a scale 1:50,000 and free images that cover the project area were used in order to identify lineaments and other geological structures (e.g. variation in lithology, fabric intensity, faults, fractures). Images were georeferenced and displayed on computer–aided data processing software in a GIS environment. Lineaments were detected by hand. Afterwards lineaments were refined using digital terrain model (DTM) analysis and compared to pre/existing geological maps of the Giba dam reservoir (Gebrehanis 2007).

3.1.3. Digital Terrain Models

The analysis of the topography was done by constructing Digital Elevation Models (DEM) .The term DEM refers to a model of a featureless surface that contains only {*x, y*, and z *axes*} coordinates without accompanying attributes. It can represent any continually varying surface, both real and conceptual. For geological surfaces, *x* and *y* axes are generally the geographic coordinates. The *z* can be elevation above sea-level, but also geochemical concentrations, geophysical information such as magnetic susceptibility or gravity anomalies, etc.

Source data for the construction of DEM were digitized topographic maps of Northern Mekelle in a scale of 1.50,000 with contour intervals of 20 meters in altitude. The combination of topography and the elevation data and generating a grid (raster) of regularly spaced elevation points by filling empty spacing between the fixed points creates a DEM. There exists a wide variety of interpolation methods. In this case Kriging (TIN) was used for generating a DEM surface constructed for the investigation of the area.

With the use of the DEM, structures in the reservoir area were analyzed. Sedimentation features could be recognized as well as lineaments. Observing and mapping potentially active structures, generally lineaments and identifying them as active faults demands an additional discriminating factor. In this study, this is provided by additional information obtained from aerial photographs, satellite images and structural field investigations.

3.2. Field mapping

The study area was mapped at a scale of 1:10,000. Based on this some modifications were made to the previous geological maps. The following methods and approaches are used to accomplish this geological mapping of the Giba dam project. The bases for mapping include preliminary information from the existing map at the scale of 1:50,000 (prepared by the Ethiopian Mapping Agency) and scale of 1:10,000 (prepared by TAHAL consulting engineers, 2008) and a geological map of Mekelle outlier at a scale of 1:100,000 (Russo et al., 1996).

Field investigations were carried out in the Giba Dam reservoir in the key areas of interest that was identified during aerial photograph analysis. A number of field sites (traverses) were used during the mapping. Site one was the Mekelle fault both on the Agulae and Subuh Rivers. Site two and three were located at the right and left abutment of the dam axis and on the reservoir area. During field work, fault and fracture systems were mapped and the following structural data were collected for structural analysis:

- Fault orientation.
- Detailed outcrop studies along the Mekelle fault.
- Detailed discontinuity description and documentation.
- Lithological description modification.
- Engineering description of rocks at the reservoir.
- Mapping of faults, joints, bedding within the areas.
- Identification of microstructures of fault kinematics such as slickensides and striation.

All field data were geospatially located using Global Positioning Systems (GPS) way point collection, and were subsequently stored in a computer data base linked to Geographic Information System (GIS) based maps.

3.3. Field based structural analysis

Detailed discontinuity description and measurements were carried out at 19 different locations. Joints, slickensides, fault planes, and strike orientations of faults were measured.

For all the types of fault kinematic data visualization, processing, and analysis, the computer software Tectonics FP by Reiter (2003) has been used. Additionally the joints are plotted as scatter plots. Rose diagrams were used for the documentation of the strike of the joints and the fault orientations.

3.4. Photogrammetric derived structural analysis

In addition to the discontinuity analysis in the field, photogrammetric methods were used to map the structures. Stereoscopic pair images taken in the field were converted to a 3D model using commercial computer assisted shapeMterix^{3D} (Gaich et al, 2006) software. From these visible geometries features of discontinuity orientations and its spacing were taken.

3D IMAGE/MODEL

Shape matrix^{3D} (Gaich et al, 2006) is a recent software package to create surface with three- dimensional images. A standard calibrated digital camera was used by software from 3G software and measurement to obtain the stereographic image pairs. Two defined locations are needed for taking a stereoscopic pair image to acquire three dimensioned images as shown in Fig. 11. Two reference poles were placed during photo shooting with a short distance apart in front of the slope facing straight towards the camera. Then the orientation between the references poles is measured which in other word is the strike of the slope face. Three series of photographs were taken from the left abutment, from the reservoir area and from the sand stone from the quarry site of the cement factory. The two images taken were transferred to the computer and processed to a 3D image using shapeMetrix3D software using the SMX Reconstructor software (SMX User Manual, 2006)**.**

The right and the left image of the rock face was modified and adding information about the used camera, the reconstruction area and the image, the offset has to be defined.

By repeating the procedure as shown in Fig .11 (two image points turn into one 3D surface point) for a dense grid of 3D measuring points which are connected then to a 3D model ,the soft ware package calculates the 3D image . This 3D model overlain by one of the pictures leads to a 3D image. Incorrect surface measurements at the border regions can be rectify by the "SurfaceTrimmer". Then establish a relationship to a superior co-ordinate system. With the software component "Referencer" the surveyed reference elements are used to transform the 3D image and the measurements into this co-ordinate system (SMX User Manual, 2006).

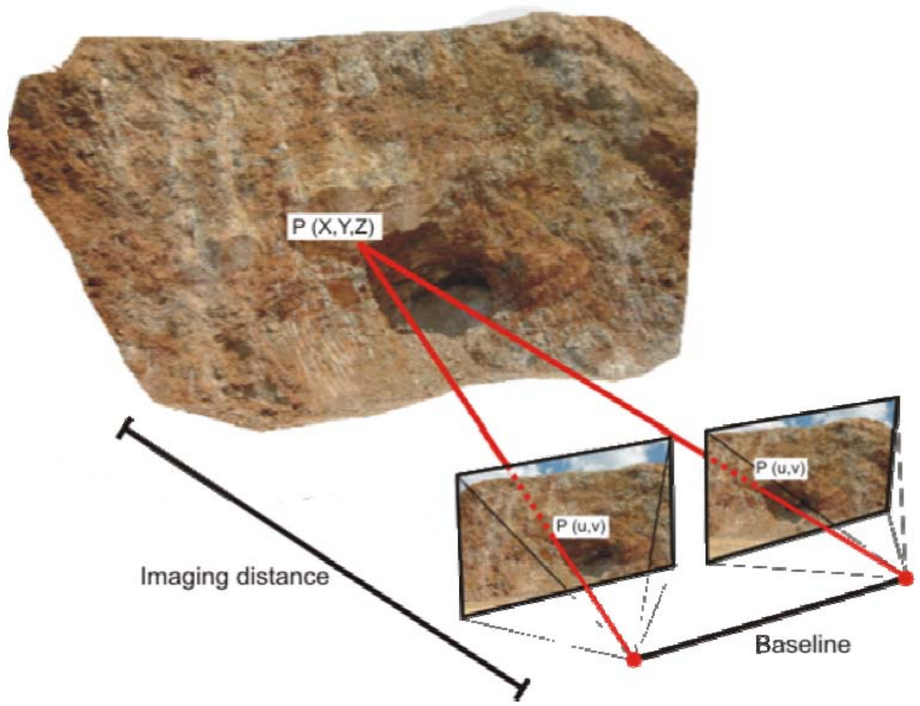

Fig. 11: Stereoscopic image pair: two corresponding image points P (u, v) turn into one three dimensional object point P(X, Y, and Z) (modified after Gaich et al., 2006).

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The software component "Analyst" is used to visualize and asses the generated 3D image. Shape matrix^{3D} is used for the analysis of 3D images showing rock faces in a wide range of scale (e.g. for tunnel faces, slopes, quarries, constructions like dams). Shape-MetriX3D "Analyst" is used for different tools with respect to geological/geotechnical assessment. Such as orientation of discontinuity surfaces (dip/dip directions), orientation of discontinuity traces (dip and dip directions), spacing (mean normal) in joints, spatial variation of discontinuity sets, volume, area and length.

Furthermore the measured structural data can be grouped into different structure sets. These sets can be displayed in stereogram with the associated statistics. After analyzing the 3D image the data can be exported into different formats for using it in other software packages (SMX User Manual, 2006).

3.5. Rock Mass Classification Scheme

In order to make accurate appraisal of the characteristics of the rock mass of the Giba dam reservoir, field investigation (such as detailed discontinuity description and measurement, spacing, aperture), and engineering geological description of the project and shape matrix images was made. In addition laboratory test results and borehole logs which were taken from the different sites of the reservoir area conducted by Addis Geosystem plc (2007, 2008) were also used for the classification system. Existing engineering geological mapping (prepared by TAHAL consulting engineers, 2008) at a scale of 1:10,000 and existing geological maps were used.

The following data were used for rock mass characterization of the dam site:

- Borehole logs from 22 drills with a total depth of 1330m which were bored at the Dam site, reservoir, spill way, stilling basin and construction site conducted by Addis Geosystem plc, (2007, 2008).
- Samples both of rock and soil were collected for laboratory index and engineering property tests conducted by Addis Geosystem plc, (2007, 2008)..
- In-situ tests in boreholes (Packer and percolation test and SPT) by Addis Geosystem plc, (2007, and 2008).
- Excavation of 22 test pits with a total depth of 119.12m and in-situ testing in test pits (DCP, falling head permeability) by Addis Geosystem plc, (2007, 2008).

- Excavation of trenches and collection of samples from boreholes, test pits for construction materials were carried out by Addis Geosystem plc (2007, 2008).
- Detailed discontinuity description.
- Detailed discontinuity measurement of spacing, aperture, field engineering geological description of the project and,
- Shape matrix images were collected in the field.

From the drillings, RQD, permeability and rock strength results along the Dam axis and the reservoir area were taken. By combining the borehole data, laboratory results and field data analysis, an interpretation was done. Data processing and analysis, producing cross sections from the drilling log information was made.
To characterize the rock mass of the Giba dam reservoir two well established rock mass classifications were used the Rock Quality Designation (RQD, Deere, 1967) and Rock Mass Rating (RMR) Bieniawski 1973, 1989).

3.5.1. Rock Quality Designation (RQD)

Rock Quality Designation was introduced by D.U. Deere (1964) as an index to assess rock quality. The RQD is defined as the percentage of core recovery; it is indirectly based on the number of fractures and the amount of softening in the rock mass that is observed from the drill cores. RQD represents percentage obtained by dividing the summed lengths of all core pieces equal or greater than 100 mm by the total core length (Johnson and DeGraff, 1988). It doesn't account for the strength of the rock or mechanical and other geometrical properties of the joints. Therefore, RQD partially reflects the rock mass quality (Fig.12).

The method is widely used as a standard parameter in drill core logging to identify low quality rock zones. RQD is to be used as an index of rock quality where problematic rock mass that is highly weathered, soft, fractured, sheared and jointed, occurs. It is counted in complement to the rock mass (Deer D.U. and Deere D.W., 1988). In simple words the RQD measures the percentage of "good" rock recovered from an interval of a borehole. There are two methods to measure RQD, the direct method (where core logs are available) and the indirect method (where no core logs are available). The procedure for measuring RQD directly is illustrated in Fig. 12. The recommended procedure of measuring the core length is to measure it along the centerline. Core breaks caused by the drilling process should be fitted and not accounted for. In this study the direct method (core logs available) was used from the cores of 22 boreholes drilled by Addis Geosystem (2007, 2008).

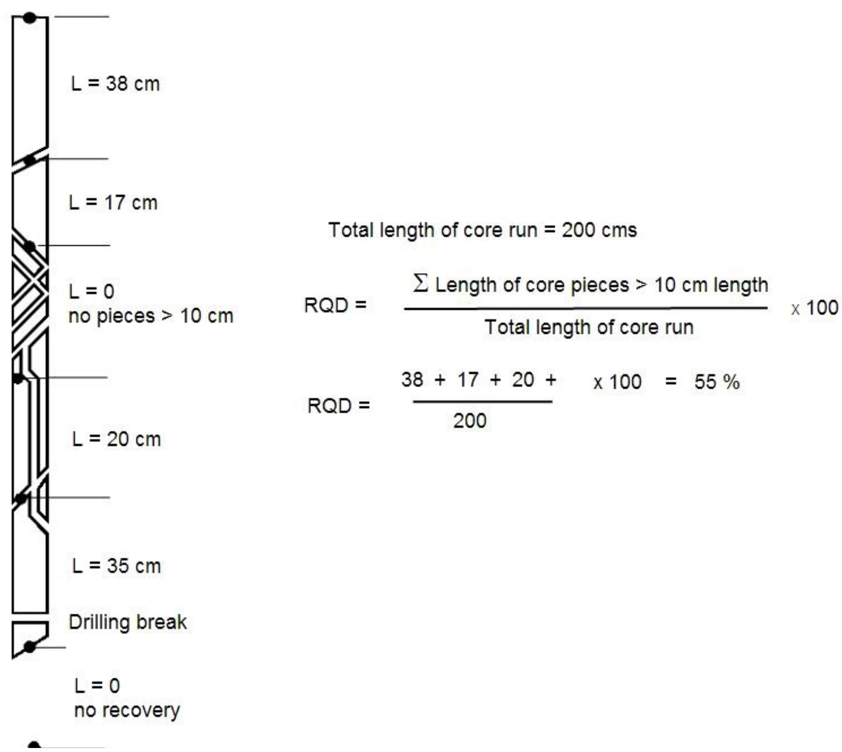

Fig. 12: Procedure for measurement and calculation of *RQD* (After Deere, 1989).

The relationship between the numerical value of the RQD and the engineering quality of the rock mass as proposed by Deere (1968) is given in Table 1.

RQD (%)	Rock Quality
< 25	Very poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

Table 1: Correlation between RQD and rock mass quality (Deere, 1968)

3.5.2. Rock mass rating (RMR)

Bieniawski (1972-1973) introduced a geomechanics classification also known as Rock Mass Rating, at the South African Council of Scientific and Industrial Research (CSIR). The rating system was based on Bieniawski`s experience on shallow tunnels in sedimentary rocks. The classification was modified several times in 1979, 1983, 1986 and 1989, as more case history are available.

When applying this classification system, one divides the rock mass into a number of structural regions that classifies each region separately. The RMR system uses the following six parameters, whose ratings are added to obtain a total RMR-value (Geomechanics classifications):

i. Uniaxial compressive strength of intact rock material;
ii. Rock quality designation (RQD);
iii. Joint or discontinuity spacing;
iv. Joint condition;
v. Ground water conditions and
vi. Joint orientation.

The first 5 parameters (1 to 5) represent the basic parameters (RMR basic) in the classification system. Parameter 6 is treated separately because the influence of discontinuity orientations depends up on the engineering applications.

$$\text{RMR= RMR basic +adjustment for joint orientation}$$

$$\text{RMR basic} = \sum parameters \ \text{(I+ ii+ iii+ IV+ V +Vi)}$$

From the six parameters for Rock Mass Rating the uniaxial compressive strength of intact rock material and the Rock quality designation were used from the laboratory results and borehole logs conducted by the project. The discontinuity spacing, joint condition and ground water conditions were collected during field studies and analyzed for the result. Based on all this information the RMR (Rock Mass Rating) of the Dam reservoir was made.

4. Result

4.1. Faults and fracture characterization

The dam site is characterized by several fracture sets**.** Based on the remote sensing analysis (Fig. 15), on the specificity of the morphology (Fig. 12, DEM), and the detailed geological map produced in the area (Fig, 5) and geomorphologic evidence of the river course, with development of slip stria on the fault surfaces (slickenlines) used as criteria, the possible faults in the area were identified and classified. In addition faults were mapped where distinct offsets have been identified in the field; often indirect topographic evidence (from geomorphologic investigations and morphological evidence of the river course) was also used as criteria to identify the possible faults in the area. Most of the faults seen in the remote sensing interpretation were also identified in the field.

Based on the methods outlined above, faults of the present study were classified in two systems of faults:

- Normal faults
- Strike-slip faults (dextral or sinistral).

In this study the classification of faults and fractures into systems was based on the orientation of the structures (i.e. trend of lineament or strike of plane).

4.2. Digital elevation model of Giba reservoir

As tectonic deformation modifies the relief of the affected region, topography gives a first and essential indication of the distribution and arrangement of morphological structures within a studied region. Three-dimensional visualization is therefore crucial to the study of structural geology. The visualization of a three-dimensional structure from two-dimensional maps is greatly completed by topographic relief.

To visualize the lineaments at the dam site, contour lines of 20m were generated from the topographic map of northern Mekelle from 1.50,000 scale (digitized manually out of North Mekelle 1: 50,000) to make the DEM of the dam reservoir area. Using the DEM structures in the reservoir area the Mekelle fault and other local faults in the reservoir area were analysed and visualized as shown in Fig. 13. Sedimentation features could be recognized as lineaments from this DEM as well. Observing and mapping potentially active structures, generally lineaments and identifying them as active faults demands an additional discriminating factor. In this study, this is provided by additional information obtained from areal, satellite image and structural field investigations.

The large scale 3D images derived from topographic maps proved to be very useful in combination with satellite images to envision and highlight large scale structures recognized by photo –geology and field observations. Presentation of structural terrain features by draping a satellite and aerial photo image over a DEM was used for analyzing and presentation purposes. A combination of the elevation models from topography and field observations led to a digital terrain model of the area, which was used as a basis for analysis and presentation of results.

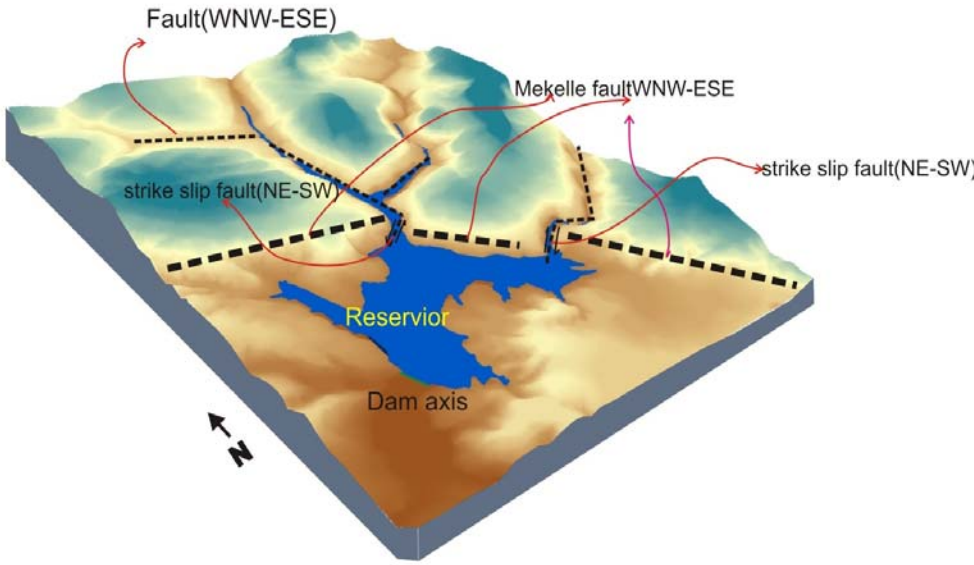

Fig.13: Digital Elevation Model (DEM) from 20 meter contour interval

4.3. Remote sensing data Interpretation (lineament analysis)

Information derived from remote sensing data at proper scale of the investigated features is the first and essential tool for constructing structural geological models and guides the choice of fieldwork location. The key purpose is to extrapolate remote sensing responses into meaningful models useful for kinematic and dynamic analysis.

The structural features of the Giba reservoir have been discussed by Gebrihans (2007), Asmelash (2008), Gebremedihin (2008), Efrem (2009), and Russo et al. (1996). Here, the following approach in the fault assessment establishing a general 3D model of the Dam reservoir is discussed. Analysis of aerial photographs and satellite images was applied to the whole study area of the Giba reservoir to identify lineaments and other geological structures (e.g. faults, fractures) (Fig.14). All the faults or lineaments found in the reservoir area are determined on the basis of morphological lineaments.

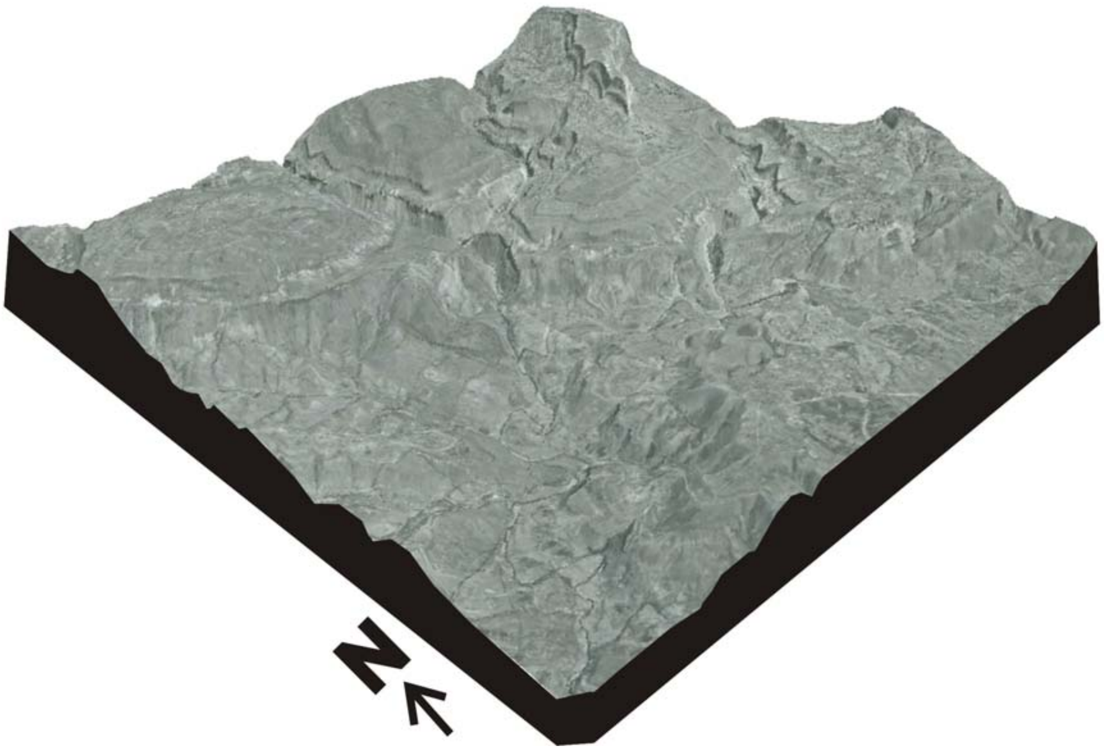

Fig.14: Digital elevation model from an aerial photograph from a reservoir area in a scale of 1.50,000.

Based on aerial photographs and free satellite images at 1.50,000 scales, a total of 20 lineaments were identified. Lineaments derived from both aerial and free satellite photographs have been grouped into systems based on their orientation. Four main lineament systems (NNE-SSW; ENE-WSW; NW-SE; and NE-SW) were identified (Fig, 15).

System 1 lineaments (black, Fig, 14) are oriented WNW-ESE (trend ~270-290 or~090-120°). These systems are most pronounced in the northeast of the dam axis, and the same lineament directions were encountered in the central part of the basin (along Augulae and Suluh River junction).

System 2 structures (red, Fig, 15) consist of NNW-SSE to NNE-SSW (~ 350-30° trend), are spreading parallel to the dam axis along the left and right abutments. This system has a trend similar to the fault that passes in the center of the reservoir.

System 3 lineaments (yellow, Fig, 15) are oriented NW-SE (trend ~40-60°). these are less dominant in the area, and these lineaments are passing along the dam axis.

System 4 the prominent lineaments (green, Fig. 15) are oriented NE-SW (trend ~40-60°). This system appears to be mostly localized in the center of the dam axis and on two specific areas along the Mekelle fault, north-east of the dam axis and also distributed on the center of the reservoir area. The first of these lies in the Agulae River and the second is located west of the Agulae River along the Suluh River. These two lineaments show dextral and sinistral strike slip in the north east of the dam axis and displace the Mekelle fault. The faults zones are closely spaced (20-30m), and strike slip separations (spacing between them increases from approximately 20-30m) of up to 30 m were observed. The valleys that distinguish this system are generally 10-30 m wide and have a curved trend.

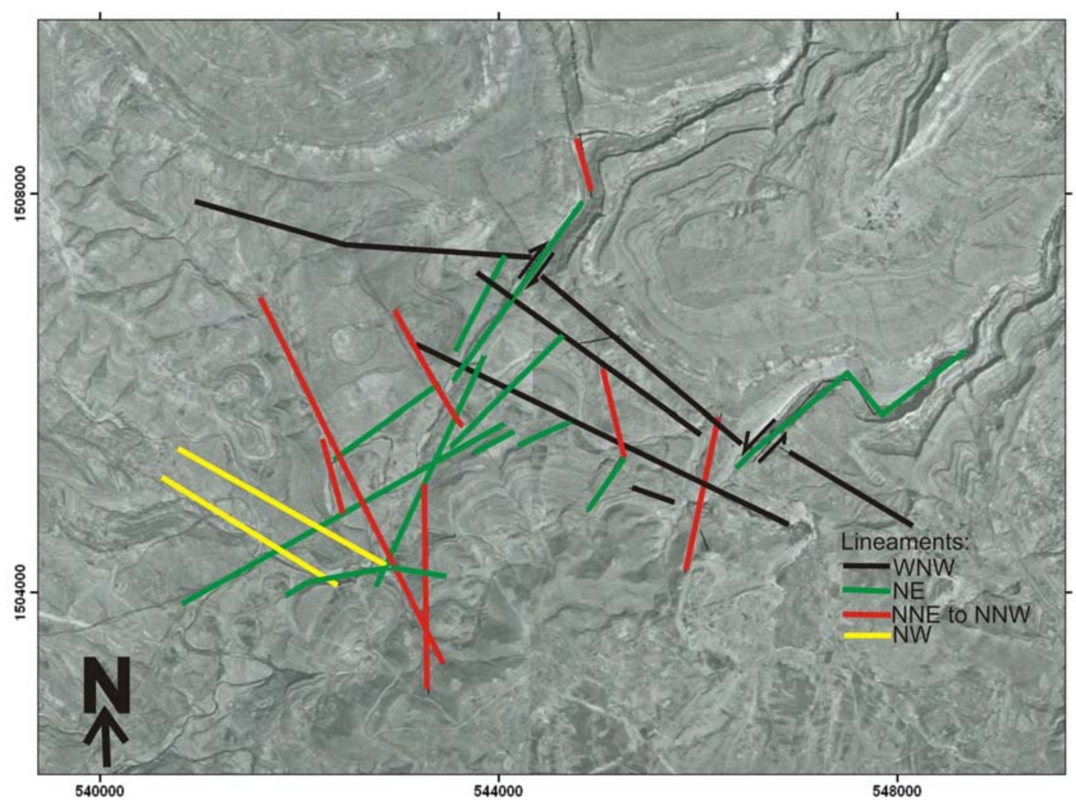

Fig. 15: Aerial photograph interpretation from remote images at 1.50,000 scale of the Giba reservoir.

4.4. Structures identified in the study area

General structural analysis

After a regional reconnaissance from each field camp, detailed structural analysis was carried out. Four key areas were chosen for detailed fracture and fault analysis in the field (Fig. 16), based on their structural interest accessibility. The first objective of the field work was identification of the lineaments picked from the aerial photographs (DEM). In most cases field observations proved that the lineaments correspond to major fault structures, many of which are weathered out to leave gorges and river valleys. The second objective of the field work was the Mekelle fault and its characteristics and also the left and the right abutment of Dam axis and the reservoir area was also investigated of the field study.

Based on the above statements, the fractures identified from field observations will be described and analyzed. Structures identified and mapped in the field are faults, bedding, joints, and slickensides.

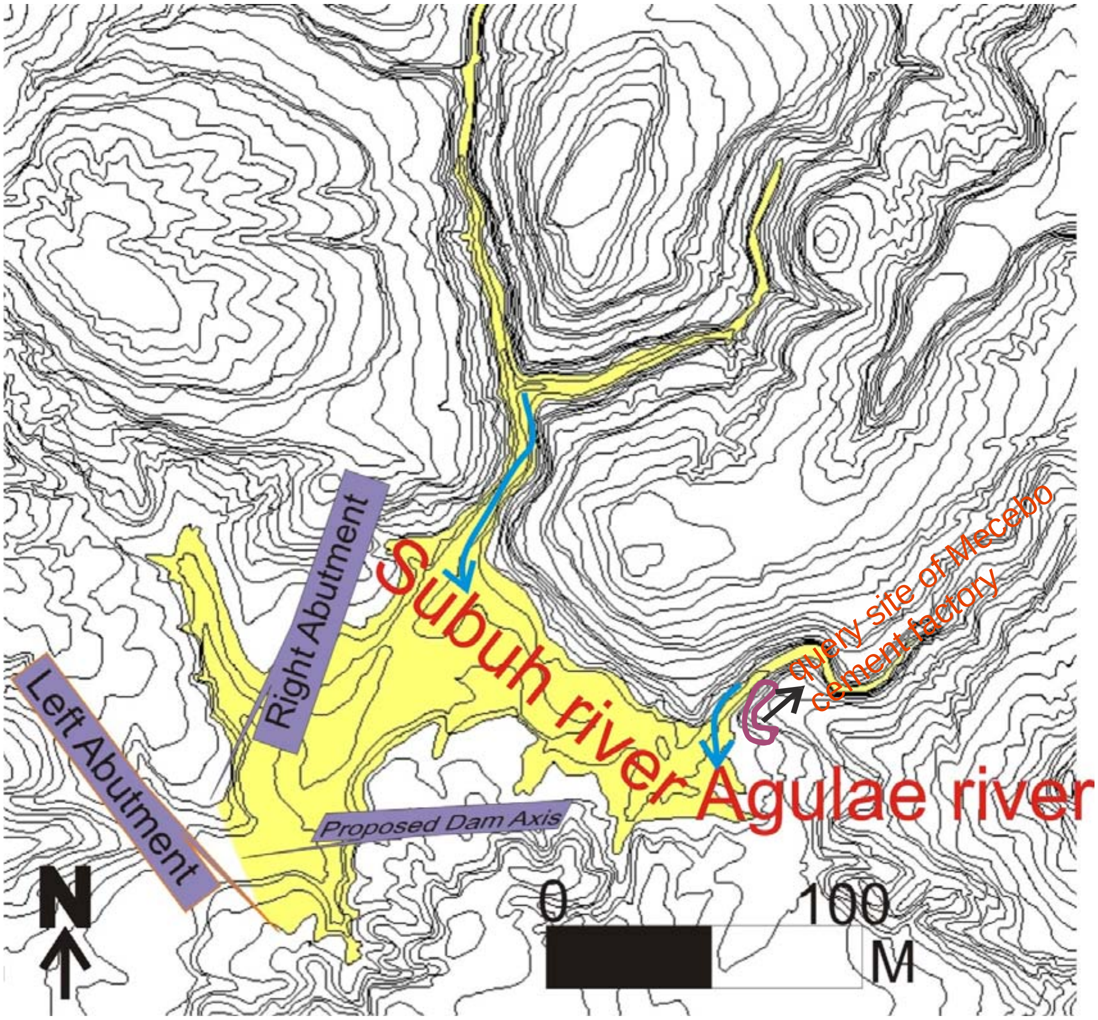

Fig.16. locations where the field data were collected

4.4.1. Structural analysis

In the study sector of the Giba dam reservoir quantitative data on structural discontinuity characteristics were acquired and analysed. During the field study, however it was not easy to get much data from the area due to covering by colluvial deposits and highly disturbed rock mass. Structural discontinuity characteristics from 19 different areas were collected and analyzed from the reservoir area and also across the major faults. (refer to Fig. 16). Most of the fractures were observed left and right from dam axis, along the Suluh and Agulae River and the reservoir area.

For each observation, the distribution of the different discontinuity sets, recognized on the basis of orientation data, is independently analyzed by means of sphere projection plots. This analysis allows one to identify the accuracy of correlation between each discontinuity set and to the major and local fault around the reservoir.

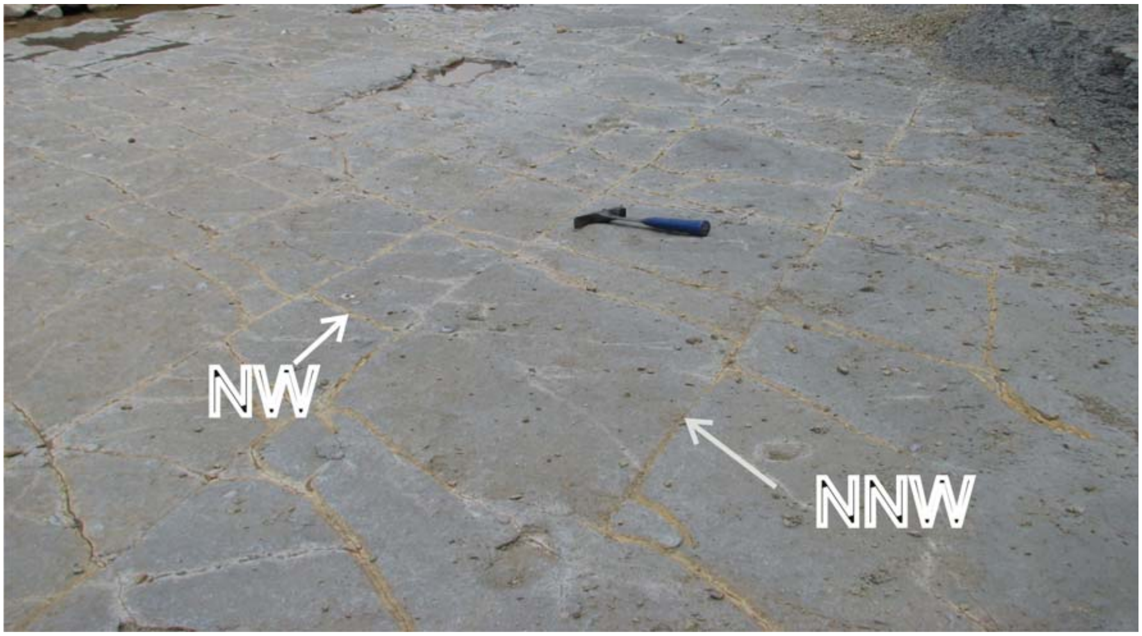

Fig. 17: NW and NNW trending fractures on the center of the reservoir .The hammer is 40 cm long for scale

Based on the data collected in the field and sphere projection plots (Fig. 19) and additional shape matrix software analysis, the area is characterized by the occurrence of four dominant orientations of joints and other rarely occurring shear fractures. Most of the joints in the reservoir area are open joints and at some places especially in the sandstone unit fault zone of Mekelle fault veins filled with mm of clay fault gauge and calcite cement were observed. The joints observed on the field terminate on the rock.

These are, NNW to NNE (350-0 strike) (~N-S), NE-SW (240 strike), WNW-ESE (290 strike), and NW-SE (315 strike). Three joints from the dominant set are located just to the right and left abutment of the dam axis, being the ~N-S , NE-SW and the WNW-ESE ones .Three sets with strike orientation NW_SE, WNW –ESE, and ~N-S are dominant nearby the Mekelle faults(Fig. 17).

Generally the Mekelle fault is associated with dominant parallel extension fractures of strike orientation of WNW-ESE and conjugate fractures form at acute angle with strike orientation of N-S. These are almost normal to the Mekelle fault. The N-S joint and the WNW –ESE both form blocks accessible for toppling failure. This acute angle between the extension fractures and the fault plane is a unique indicator of the sense of shear along the fault, and it points in the direction of relative motion of the block containing the fractures.

Along the central part of the reservoir area the dominant joint sets are the ~N-S and the NE-SW striking ones. On the Agulae river quarry site of Mesebo cement factory the dominant joint sets are NW-SE and WNW –ESE (Fig.18).
From the rose diagram distribution shown in (Fig .19) the NE-SW are the most dominant joint sets. The NW-SE (290 strike) are the second dominant joint sets in the area, followed by WNW-ESE joints and the N-S orientations fourthly.

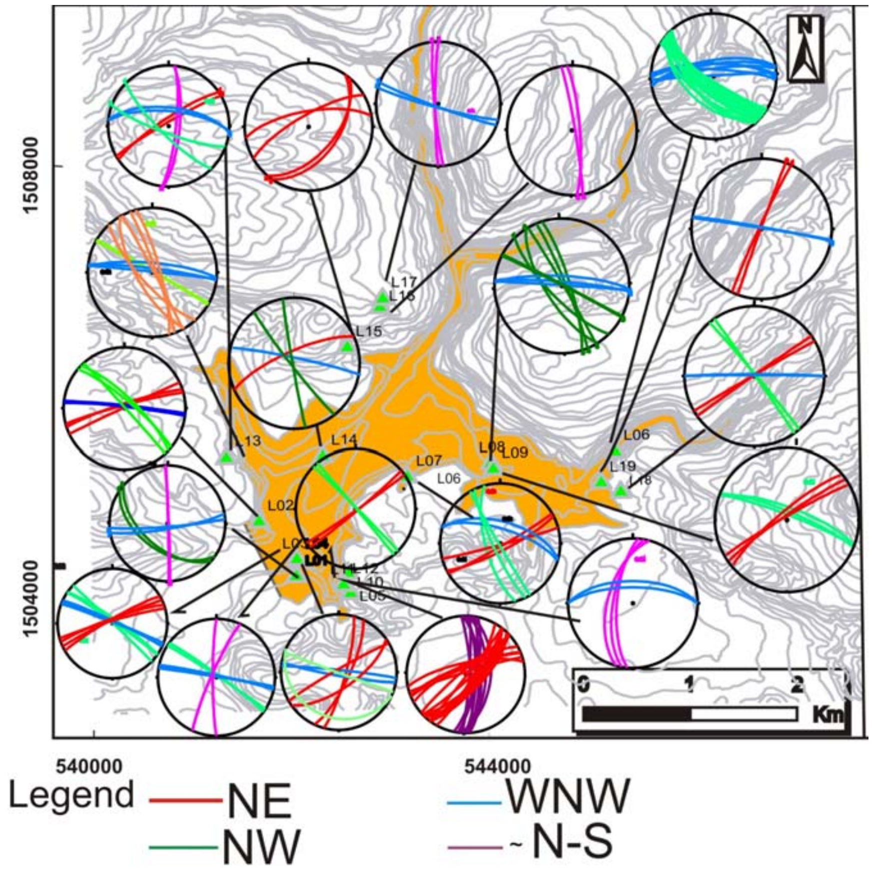

Fig.18: Stereographic projections of the orientation of fractures and distribution on the Giba dam reservoir from 19 different locations. Opening fractures and suggesting extension directions varied from NE-SW to NW-SE .

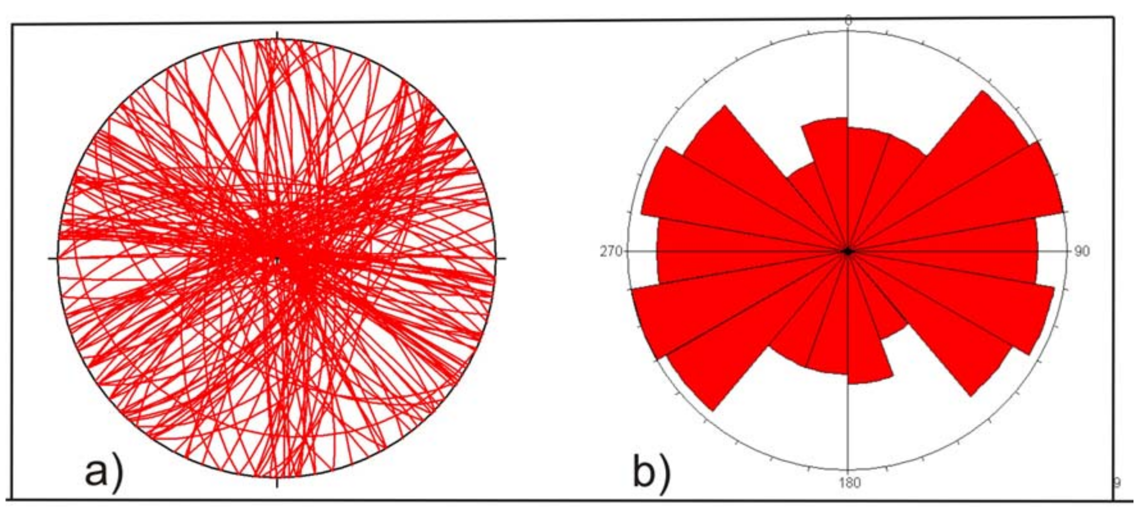

Fig19. Steoreonet sphere projection (a) and Joint strike distribution as rose diagram (b) of joints sets in the Giba dam reservoir.

Bedding

The bedding plane orientation of the Giba reservoir shows consistencies throughout the region. Based on the field measurements, the bedding planes are almost horizontal except in few areas, which are locally faulted and are steeply inclined towards southeast. The dominant orientations from field measurements and shape matrix results show 020/26. The bedding thickness varies from place to place from 0.15 cm -2 m (Fig.20).

Fig. 20: Yellow color limestone with almost horizontal bedding.

4.4.2. Fault mapping

A total of 15 fault sets was observed and described in the field exhibiting from small displacements at centimeter scale to millimeter scale. Among these are fault orientations of WNW-ESE (system 1, black in the Fig. 22). These include the Mekelle fault and other local faults. This system can be traced about 2.5 km away from the dam axis in north -east direction and previous investigations indicated that it continues up to 65 km along its strike with considerable vertical displacement and dips about 70° to SWS (Beyth,1972). The Mekelle fault seems to have a vertical displacement. As indicated from aerial photo interpretations and field observations the Mekelle fault is not one trace line but has several faults that are parallel and tilted between the Agulae and

Subuh River. Due to the strike slip faults along the Mekelle fault blocks were tilted by as shown in the Fig. 21.

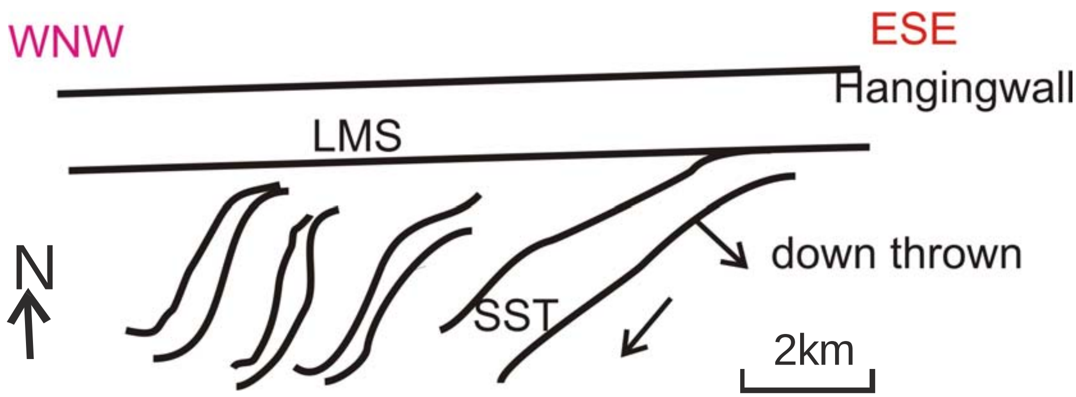

Fig. 21: field sketch of Mekelle fault movement with its rotated blocks between the Agulae and Subuh River LMS –limestone, SST-sandstone

Various fault orientations with dominant NE-SW strike directions (system4, green in Fig. 22) were also identified and this fault set is normal to the Mekelle fault. This includes the strike slip fault found along the cross cutting of the Mekelle fault. A set of NNE-SSW –oriented faults (system 3, red Fig. 22) also appears parallel to the Dam axis. Fault systems corresponding to lineament system 2 are fault sets located along the dam axis. These are the NW-SE trending faults with an average fault plane of 013/70E. Minor faults were also observed in the south of the dam axis, in the reservoir area these structures are shorter and more discontinuous (Fig. 23).

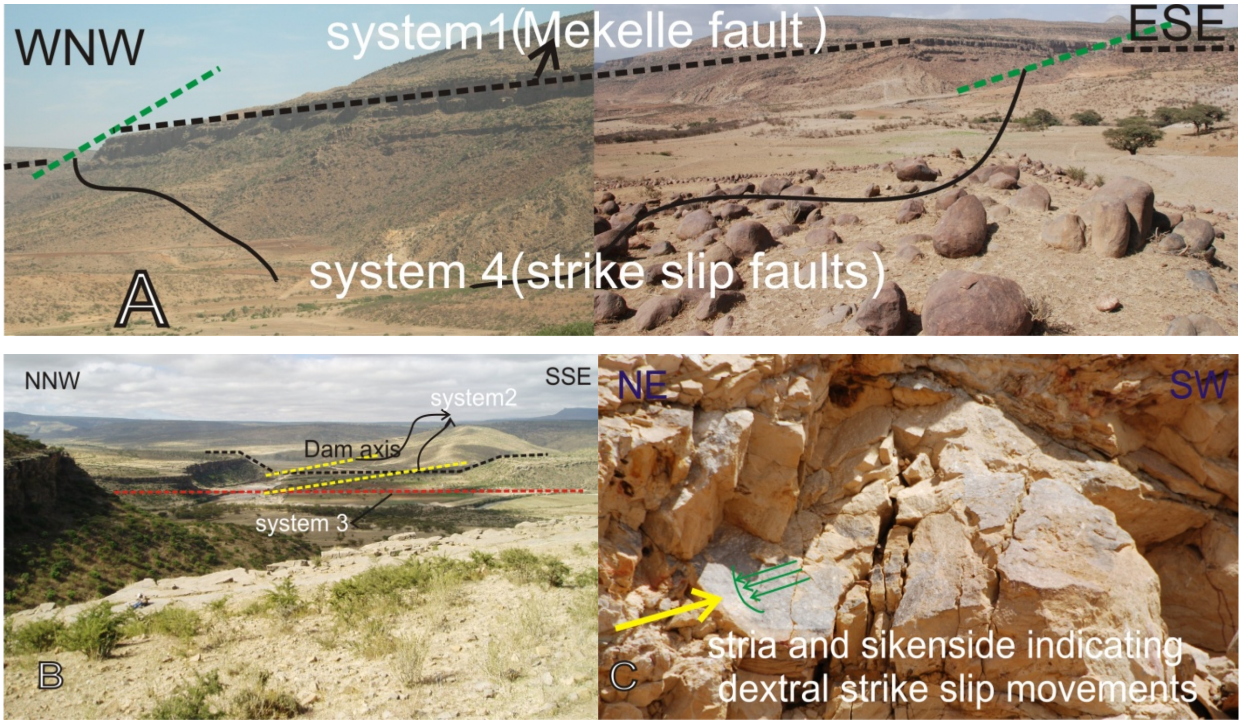

Fig. .22. Field identification of faults. A) the Mekelle fault with black color (system1) and two major gorges/valleys trending NE –SW along the Mekelle fault with green color (system4). b) red (system3) and yellow color (system2) show the NNW and NW trending faults respectively C) Fault kinematics exposed within the NE-SW trending stream bed dextral strike –slip slickenside and striations were found on the Messebo quarry site.

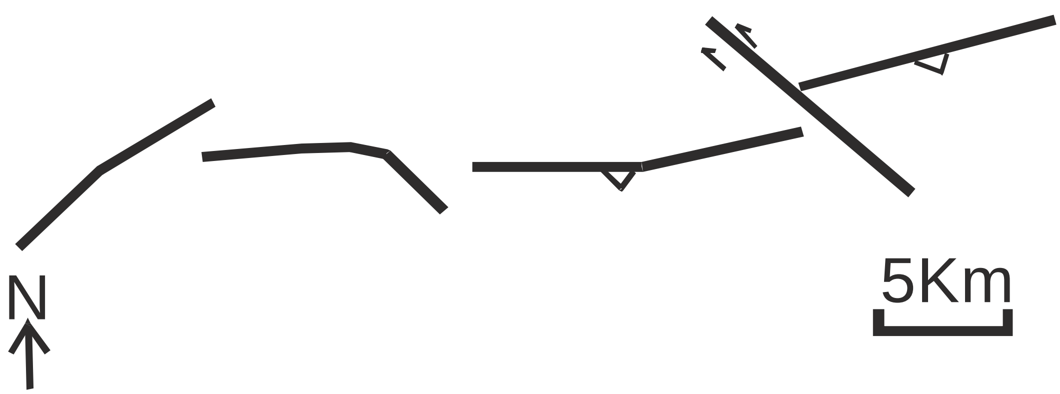

Fig23. Sketch of faults in the reservoir area (in the center of the reservoir which is almost west of the dam axis)

4.5. Strike slip faults

Although fault systems show dominantly normal fault movements, both field evidence from slickensides and aerial photograph or free satellite image data indicate that strike-slip faults occur in the area.

Though various studies conducted by Beyth (1972), Gebrihans (2007), Asmelash (2008), Gebremedihin (2008), Efrem (2009), and Russo et al. (1999) and geological maps in a scale of 1:10,000, 1:100,000 from this region these faults were not mapped as strike slip faults before. The recognition of strike slip faults was prominent on the aerial photograph interpretations, field observations, DEM and the modified geological map produced from the area and also from indirect topographic evidence. These strike slip faults are found along the north east of the dam axis on the two river valleys of Agulae and Subuh River cross cutting the Mekelle fault.

The strike-slip displacement was concluded from different types of evidence at various scales. With regard to fault kinematics strike slip faults inferred from aerial photographs (Fig.15) and DEM (see Fig. 13) produced from the area show NE-SW trending were observed with the WNW-ESE trending Mekelle fault. On the other hand, an overall prevalence of left lateral displacement is supported by different lines of evidence (slickenside at quarry of cement factory).

In the field no clear evidences were found for main strike slip fault movements due to high weathering and erosion in the area in addition to the nature of the rock mass. Apart from these, clear striations and slickenside on a few fracture planes were identified and analyzed along the quarry site of the cement factory on the Agulae River of the Mekelle fault. The slickensides recognized along the WNW-ESE trending Mekelle fault on the quary site of Mesebo cement factory principally record strike slip faults movements, overprinting an earlier, much less evident sinstral strike slip displacement. The strike of slickensides was mainly NE-SW (as shown Fig. 24 below) with 70° dip and a dip direction of 115°. The striation shows an orientation of 212/05. Striations on the slickensided surface trend of NE –SW, parallel to the strike of the fault.

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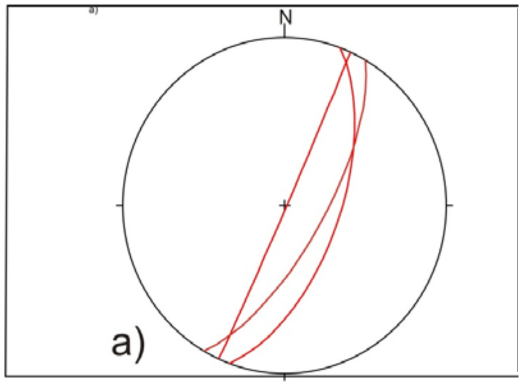

Fig.24a. Lambert projection slicken sides (great circles) with NE-SW strike direction.

The second evidence for the strike slip fault was also found in the field from Shogalu River around the Agulae River, which shows the exposure of small faults along the river outcrop, where limestone joints filled with quartz are cut by faults which offset the veins in a left –lateral sense as shown in Fig. 25.

Fig. 25: Small strikes slip faults exposed on the river outcrop in the Shegalu River, on the Giba Dam reservoir. Limestone joints filled with quartz are cut by the faults which offset the veins in a left-lateral sense.

The third evidence for the strike slip faults observed in the field is block rotations. These rotational blocks bounded by sets of parallel strike slip faults have been identified around the Mekelle fault. Block rotations may be the response of being caught between two independent strike slip faults as illustrated in Fig. 26.

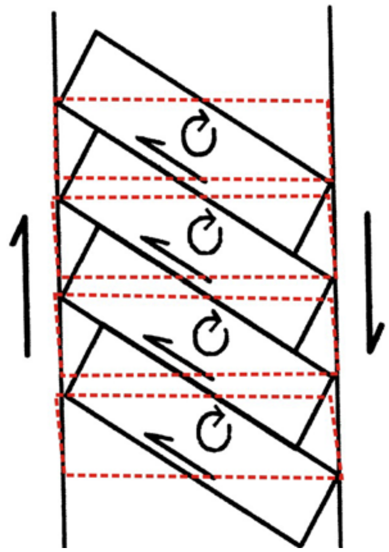

Fig. 26**:** Model illustrating systems of strike slip faults and block rotations under simple shear. The blocks are separated by antithetic faults.

The rotations are especially well visible along Mekelle fault where the sandstones exposed in between the two rivers of Suluh and Agulae. The rotations change systematically as shown in the sketch (in Fig. 26).The blocks rotate the most when they are captured between the two independent strike slip faults during their oblique displacement. The left-lateral slip is a manifestation of the right-lateral shear within the region and clock wise rotation of the blocks between the left lateral faults. The Agulae river is marked by the left lateral while the Suluh river is marked by right lateral fault.

This strike slip displacement with subsequent block rotations induced local zones of contraction and extension. The strike orientation of the rotated blocks from field observations were NW-SE (110/285) (Fig. 27).These rotations are about 40°+ -50° from the Mekelle fault, documented from the field measurement along the Mekelle fault (Fig.

28). These blocks are rotated also with the same direction to the striations found on the quarry site.

Fig. 27: Hinge showing axis of rotation of blocks along the Mekelle fault.

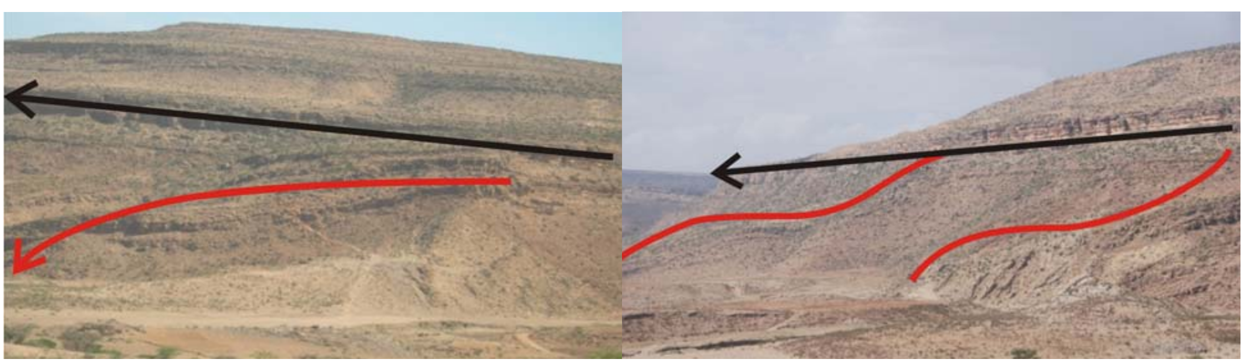

Fig 28**:** Rotated blocks along the Mekelle fault with red color; the black color indicates the orientation of the Mekelle fault.

5. Interpretation and discussion of fractures

The use of three different methods to assess the structures associated with Mekelle fault across the reservoir area allowed to obtain a good picture of the general structure of area. The three methods for structure identification are generally well correlated. Most of the lineaments found from the aerial photos, free satellite image, DEM and field mappings are generally similar. In this part the major findings of the thesis are presented, namely answers to the research questions concerning the structure associated to the Mekelle fault and structural relations in the reservoir.

An integration of remote sensing in structural modeling combined with structural geology and field observations is presented. Furthermore, an overall summary of each of the fault systems identified through remote sensing (i.e. lineament mapping from aerial photos, DEM produced) and field studies the possible interpretations and implications of these observations is presented.

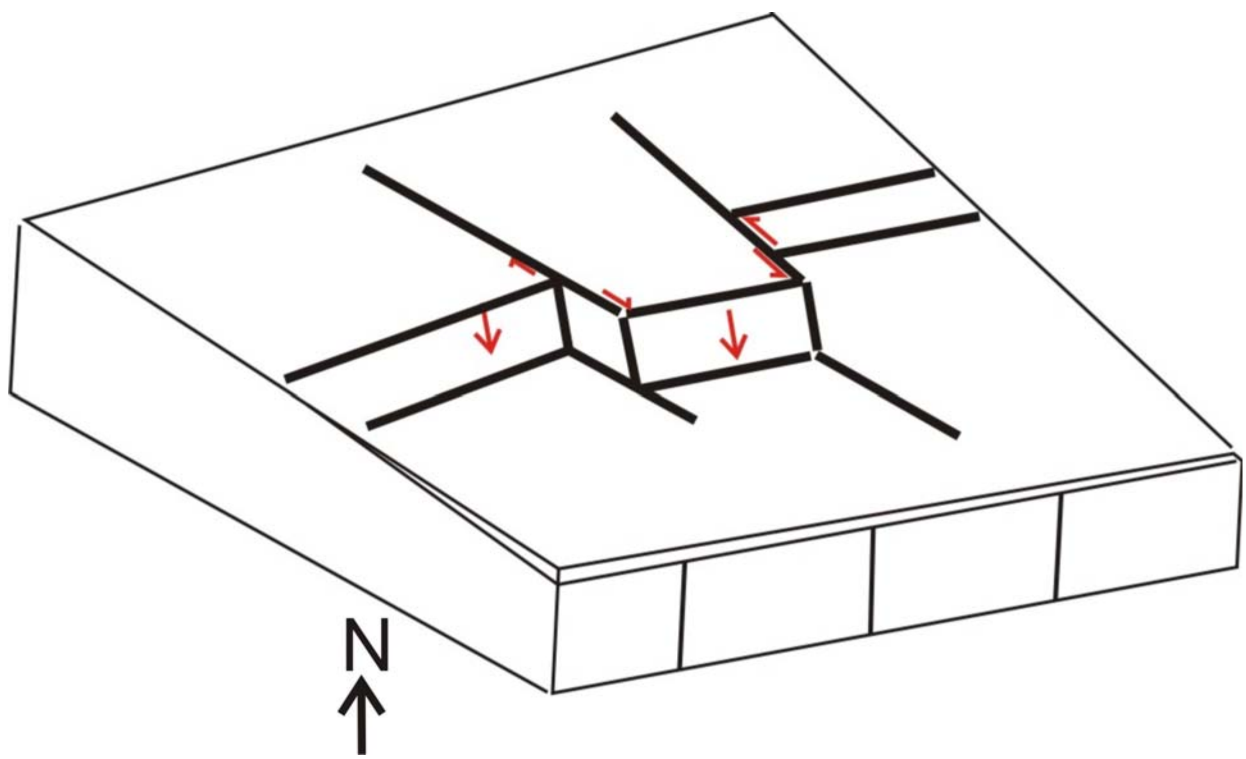

Fig . 29: Model illustrating the Mekelle fault zone and fault displacements.

The dam site, reservoir area and its surroundings is highly affected by major and minor fractures (faults and joints). In addition also sedimentary structures (bedding) affect the structure of the site. Characterization of the architecture of the construction site in a faulted reservoir provides the basis for interpreting the bulk permeability anisotropy in the reservoir, an important step in optimizing well placement.

Associated with the Mekelle fault are two sets of strike slip faults (left-lateral and right-lateral) along the main fault plane (Fig. 29). The geological structures (faults, joints, tension and shear, fractures and lithologic contacts) play an important role for the leakage in the reservoir area. An overall summary of each of the fault systems identified through remote sensing (i.e. lineament mapping) and field studies is presented and they can also be described according to their displacement (see Table 2).

Table2. Main characteristics for each fault system identified from remote sensing and outcrop studies.

Lineament system	Orientation	Sense of movement	Comments
System 1	WNW–ESE	• Normal fault	
System 2	NE–SW	• Dextral strike-slip • sinstral strike-slip • Normal fault	
System 3	NNW–SSE	• Normal fault	
System 4	NW–SE	• Normal fault	

From the analysis by different methods, four dominant fracture sets show dominantly normal faulting and (dextral and sinstral) strike sip fault movements (Table2). In the reservoir area these can be discriminated into WNW-ESE, NNE-SSW, and NE-SW and NW-SE strike directions, respectively. Sedimentary structures of solution voids, karst features, horizontal and inclined bedding planes and cross bedding of low angle in the sedimentary rock units are also very common. Faults of insignificant displacement and length are also common.

Among the dominant fracture sets in the area are those with WNW orientations. These include the Mekelle fault and fractures with similar strike orientations that are also found in the junction Agulae and Suluh and also around the periphery of the Dam reservoir. Though the Mekelle fault passes 2.5 km NE of the dam axis, the associated structures in the reservoir area may play a major rule in the leakage assessment.

The second fracture set in the study area is the NE-SW striking. These NE-SW fractures are dominant in quantity and extent. This includes the two strike slip faults localized in the northeast of the dam axis cross cutting of the WNW-ESE trending Mekelle fault. Strike slip faults combined with normal faulting also provide a reasonable account for the frequent north east branching of fracture zones in the Giba dam reservoir. This pattern broadly extends over the center of the dam axis and on the center and peripheries of the reservoir of this study area. The strike slip faults are younger than the Mekelle fault.

The third dominant fracture set in the area is the NNW-SSE to NNE-SSW striking ones. Among them are the faults striking parallel to the dam axis. They are also distributed in the center of the reservoir. NNW-SSE fractures are conjugate fractures to the Mekelle fault. The Mekelle fault and its conjugate fractures in the reservoir area play a major role in the leakage effect and the dam safety and will increase the permeability in the reservoir area.

The fourth detected fracture set is aligned NW-SE. Among these are the fractures that are parallel to the dam axis.

The other major structures which affect the strength or quality of rock mass are joints. Joints of various orientations (strikes) have been detected. Dominant orientations vary from WNW–ESE through to NE–SW. Accordingly features with orientation of WNW-

ESE are the same strike orientation as the Mekelle fault. Most of the joints are extensional fractures.

From the above analysis the normal faults and extensional fractures have to be considered for the risk assessment of the dam than the strike slip faults. And the faults in the reservoir are connected to each other this network fractures may increase the permeability of the dam reservoir.

5.1. Rock mass classification

Engineering geological properties of rock masses during the feasibility study and preliminary design stages of a project are very important. When very little detailed information is available on the rock mass, its stress and hydrologic characteristics, the use of a rock mass classification scheme can be of considered benefit in order to determine probable problems and necessary precautions to be taken prior to construction. Rock mass classification schemes can be used to build up a picture of the composition and characteristics of a rock mass to provide initial estimates of support requirements, and of the strength and deformation properties of the rock mass.

The most important goal in the characterisation of rock masses is to provide the engineer with qualitative and quantitative data to describe their structure and assess their mechanical and hydraulic properties at a scale commensurate with the volume of rock affected by the structures (AFTES, 2001).

In order to make an accurate appraisal of the characteristics of the rock mass, an initial site investigation of the geology was made (Gebrehanis, 2007). From the information gained from site investigation, a drilling pattern was developed in 2007 by Adis Geosystem, which considered estimated permeability and allowed leakage the dam. The dam and its associated concrete structures are mainly founded on limestone and shale. These are affected by high jointing and faulting especially near the surface. This study explains rock mass type of engineering geological assessment for safe design of the proposed Giba Dam.

The area was engineering geologically mapped in large scale (1:10000) and some laboratory tests and preliminary subsurface boring or drilling was also performed. Small scale engineering geological classification was made before but the assessment lacked laboratory data and subsurface boring.

The results of the investigation obtained from drill holes, Lugeon test data, and point load tests were combined with field data collected for rock mass classifications. Based on the field activities, and manual tests and other geological and engineering geological field observations, and the existing data of laboratory results, descriptions and classifications of soils and rocks for engineering purposes have been made.

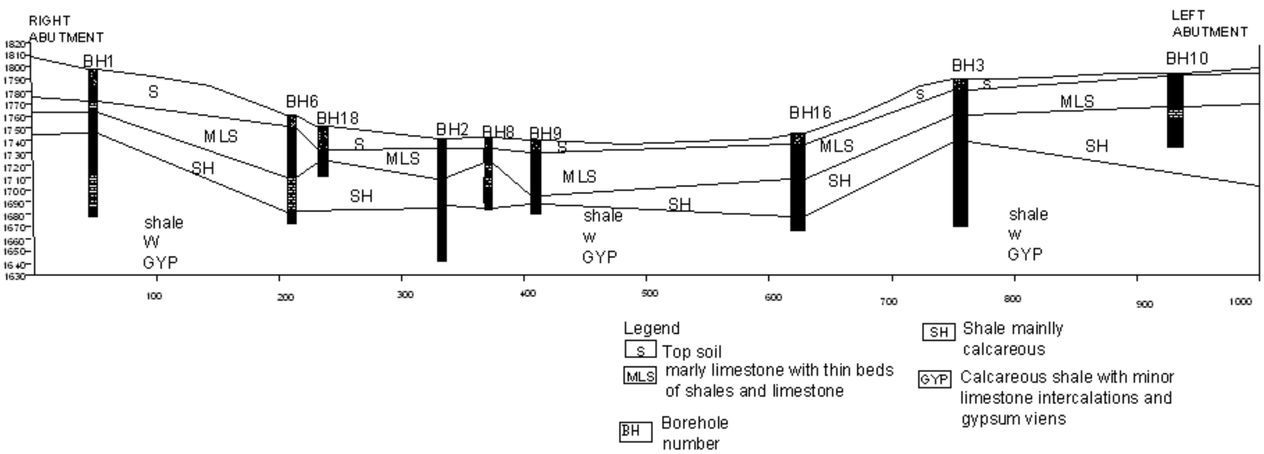

Fig. 30:.Geological cross- section of dam axis

5.2. The geology of the study area

Geological factors are among the most important factors in designing and constructing a dam. Of the various natural factors that influence the design of dams, none are more important than the geological ones. Not only do they control the character of formations, but they also govern the material available for construction.

The detailed geological description including mapping was illustrated in part two. In this section the engineering geological description of the dam site is presented. The dam site is situated in an area underlain by quaternary deposits and rock units of Ordovician to lower Cretaceous (Mesozoic sediments and Tertiary sediments) that consist of the following formations.

From the cross section available (FIG. 30) on the dam axis which was made from drill logs, the dam axis foundation is underlain by marly limestone and then very thick shale (mostly compact, calcarious and karstified) and this unit is underlain by shale dominated by jointed thinly bedded layers of limestone and gypsum layers.

5.2.1. Quaternary deposits

The Quaternary deposits found in the area are composed of alluvial, Talus/colliuval materials. The alluvials are composed of silty / clayey or sandy soils, granular soils (active river channel deposits) and locally cemented granular soils (old river channel deposits). Silty clays, clays and sandy soils occupy the plain areas and flood plain of the main rivers and tributaries. The granular soils cover along the river channel of Giba and Agulae. The maximum thickness of the Quaternary alluvium in the river valley below the dam axis is 12m obtained from drillings (Addis Geosystems Co.PLC, 2008)**.** The talus/ colluvial deposits covers the gentle to steep slope forming land around the alluvial deposits mostly following the cliff forming limestone.

Table3. Summary of laboratory index test results of soil samples from test pits of the dam site (Addis Geosystems Co.plc, 2008)

Test pit No	elevation (m.a.s.l)	location	Depth (m)	Typical name
TP-01	1752	Ra	5.7	Clayey sand
TP-2	1752	Rv	6.5	coarse clay with sand _slit gravel
TP-3	1760	-	6.60	Clayey sand
TP-4	1764	La	6.40	Clayey sand
TP-5	1754	Ra	7.40	coarse clay with sand
TP-7	1762	d/s dx	7.40	Salty sand
TP-8	1754	La	6.80	Sandy lean clay

Ra…….Right abutment, RV…..River valley, La……..left abutment, d/s dx…….downstream of the dam axis

The laboratory results of the test pits (Addis Geosystems Co.PLC, 2008) as shown in tables 3 and 4 (8 at the dam axis and 10 in the reservoir area) show that the main soil types are silty sand, sandy fine clay, coarse clay with sand –silty gravel, clayey gravel, clayey sand. From the permeability test results made by Addis Geosystems Co.PLC, (2008) (table 4) the sandy to gravel soils are expected to be highly permeable.

Table. 4. Summary of laboratory index test results of soil samples and falling head permeability test results of test pits excavated from the reservoir area (Addis Geosystems Co.plc, 2008)

Test pit No	elevation (m.a.s.l)	location	Depth (m)	Average K-value(cm/sec)	Typical name
TP-9	1764	Ra	1.50	2.210E-04	Silty sand
TP-10	1765	Rv	1.50	4.130E-04	Sandy fine clay (CL)
TP-13	1777	Ra	1.20	9.500E-04	Sility sand (SM)
TP-12	1761	La	5	2.636E-06	Gravel sand
TP-13	1777	Ra	4.7	1.800E-04	Sility sand (SM)
TP-14	1777	Ra	0.5	2.500E-04	Sility sand (SM)
TP-14	1771	La	1.5	8.000E-04	Silty clay –sandy fine clay
TP-14	1771	La	3.40	9.500E-04	Silty clay –sandy lean clay
TP-15	1771	d/s dx	1.00	2.630E-0	Silty clay –sandy lean clay
TP-15	1773	d/s dx	3.00	8.000E-04	Coarse clay(CH)
TP-16	1773	d/s dx	0.70	5.000E-04	Sandy fine clay (cl)
TP-17	1775	La	3.50	2.636E-05	coarse clay with sand(CH)
TP-17	1765	La	5	1.740E-03	coarse clay with sand(CH)

Ra…….Right abutment, RV…..River valley, La……..left abutment, d/s dx…….downstream of the dam axis

5.2.2. Dolerite / phonolite

These rocks show variations in jointing and weathering. Compositional variations are also expected between outcrops in the northern part and southern and south -eastern part. It is greenish gray and dark in color (light gray in phonolite), medium to coarse grained and grains are irregular in form, with angular edges and rough to smooth surfaces. Their engineering properties are expected to be equal but weathering is more intensive in the dolerite (showing its potential as embankment material) than in the phonolite fracturing /jointing (closely spaced) generally equally affected both rocks types. Minor vesicles (voids) and moderately to highly weathered, differential (spheriodal) weathering in dolerite is typical even though directional weathering along joints and faults are present.

The strength, which is a necessary engineering parameter for design and construction, is moderately strong from visual observations as no drill hole is conducted in the dolerite and Schmidt hammer tests in similar units do exist. It frequently occurs as dykes and sills. NNE and WNW striking vertical joints with close to medium spaced rock mass (0.5 to 10 cm) are dominant in this unit. Aperture of the joints is moderately wide at times filled with clay and calcite (in the south and south east outcrops). No moisture is observed along joints. This engineering geological unit is less important with respect to foundation of dam site and reservoir water tightness. Experiences in this area indicate that no water leakage is expected. The dyke’s surfaces are impermeable and structures are annealed.

5.2.3. Limestone

Generally light gray and black colors are typical for this rock type. Crystalline, well bedded and fresh to slightly weathered rocks are found at the dam site. The material strength from the laboratory tests of the existing unconfined compression tests (Addis Geosystems Co.PLC, 2008) for rock samples taken from drilling shows 26.489 MPa the

Schmidt hammer test values range on average from 17 to 225 MPa. It is affected by two fault systems (WNW and NNE trending faults) (see Fig. 5). Due to the bedding and intensity of fracture this rock significantly affects the rock mass behavior.

<u>Black color limestone</u> -This unit is formed in the upper part of Antalo limestone formation and consists of black colored, fine grained jointed /fractured and at few places closely jointed and horizontal bedding planes with smooth to rough surfaces and slightly partially discolored limestone. Most of the joints are open and some joints are completely filled with clay and calcite cement. The dominant joint sets in the black limestone from the shape matrix results (Fig. 32) and joint analysis from field observations shown in Fig. 16 are ~N-S, NE-SW and WNW-ESE .The joint end with the rock. The ~N-S with WNW-ESE forms block that may show toppling failure.

Joint spacing from shape matrix analysis range from 1.61, 1.35 to 0.30m for ~N-S, NE- and WNW- sets respectively (Fig. 31). The horizontal bedding with spacing of 25cm was found from the shape matrix results. As well these rocks due to intensity of fracture and bedding are permeable to semi- permeable.

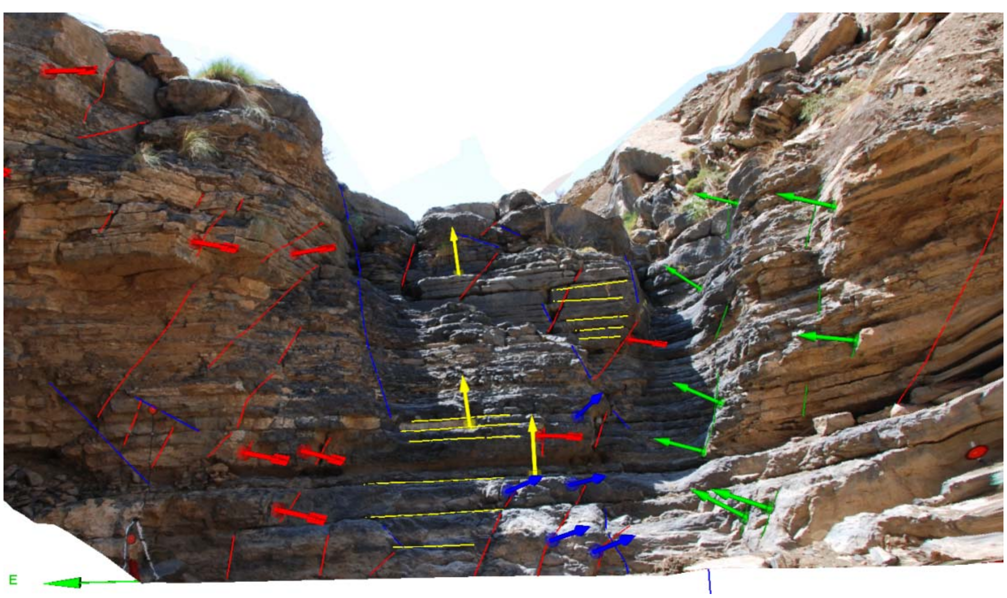

Fig31: Shape Metrix 3d structural analysis and 3D model of the black limestone found on the reservoir area.

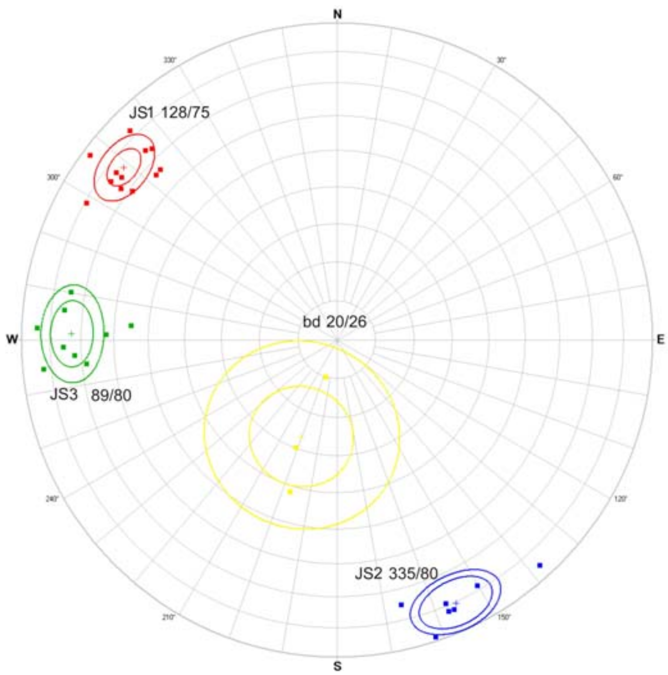

Fig 32: Lambert projection with structural data of different discontinuity sets.

Light gray colored limestone **-**This lower part of the Antalo limestone formation is exposed in large parts of the dam site and part of the reservoir area. They are exposed in large parts of the right and left abutment and usually overlain by colluvial material. They are light gray to gray coloured. Fine crystalline limestones of this unit form the lower part of the limestone formation. The limestone spacing was much denser than in the black limestone. It is highly fractured and jointed at the first and becomes less jointed in the lower section. The thickness of this unit is ~20m as documented from drillings.

The joints are slightly weathered and rough, opened up to 15 cm and partially filled with clay. Three dominant joint sets were observed from field analyses and shape matrix results (Fig. 34).. These are WNW, NE and NW striking with joint spacing ranges from 1-3 meters. The joints end with the rock mass.

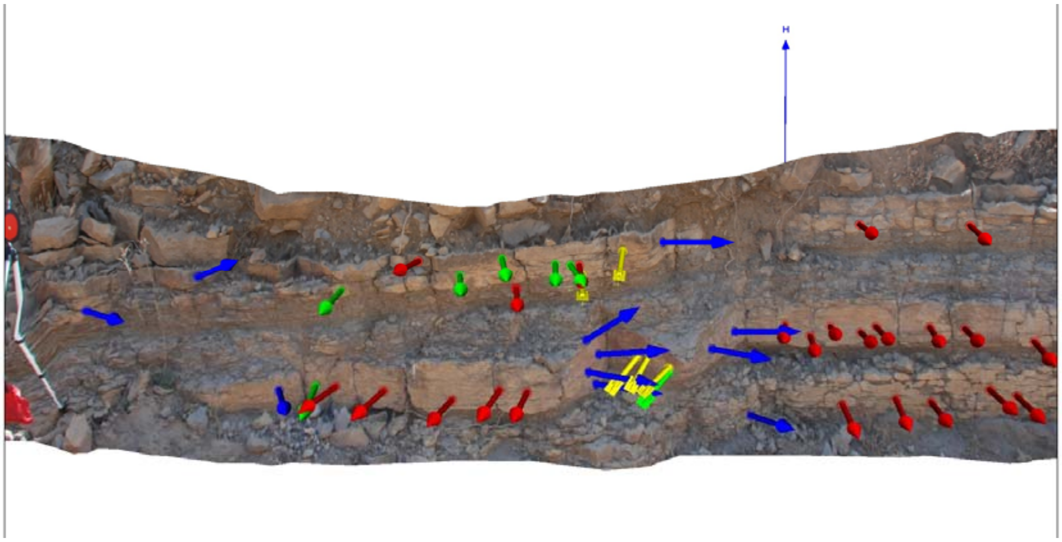

Fig33: Shape Metrix [3d] structural analysis and 3D model of the gray coloured limestone found on the left dam axis of reservoir area.

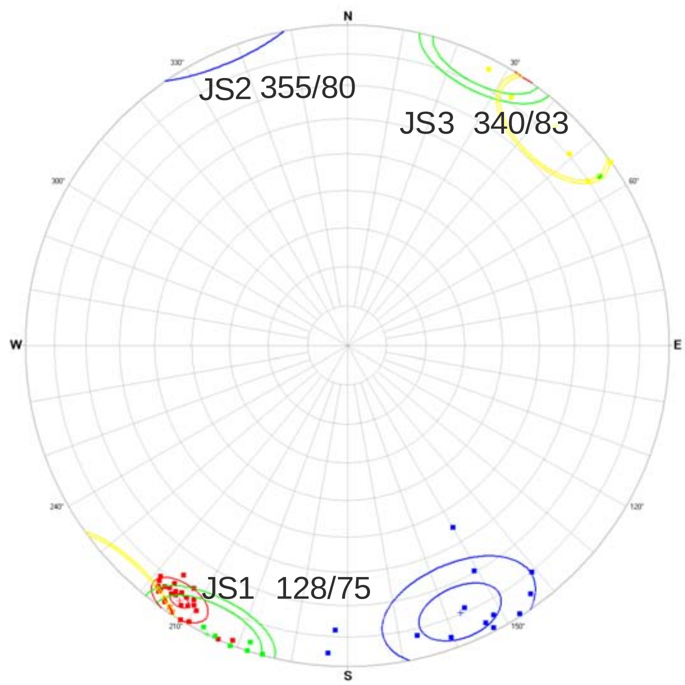

Fig 34: Lambert projection with structural data of different discontinuity sets.

5.2.4. Shale intercalated with thin beds of limestone

This unit is dominantly characterized by its intercalation feature and its weathering degree. It outcrops in the downstream part of the dam site. The shale layers are thicker than the limestone layers. The limestone layers are jointed (vertical and horizontal joints), slightly weathered, generally sub-horizontal and minor voids are also observed. The shale layers are weak, moderately to highly weathered, show some fissility on fresh outcrops, and are impervious. Such engineering geological units are generally unstable with respect to excavation and loose strength up on exposure to air. To be used as construction material detailed geotechnical investigation is required to determine its properties and vertical and lateral variations to estimate its quantity and quality.

5.2.5. Sand stone

This sand stone forms the lower part of the Adigrat sandstone formation. This unit consists of reddish and light yellowish coloured, medium to coarse grained, slight to moderate and in some places highly weathered sandstone that underlies the limestone unit. The grains show irregular form, angular edges and rough to smooth surfaces. Intact rock compressive strength on unconfined compression tests and Schmidt hammer tests (Mesebo cement factory 2000) range from 13.5 to 58 MPa, but the strength of the sandstone outcropping in the project area seems to be weaker due to weathering and lack of cementing material. It was obtained in the south- east to north-west of the dam site.

The thickness of this unit is not measured, but it is estimated to be about 35-40 m. From the shape matrix results and from field measurements the three dominant joint sets are NW-SE as set 1, WNW-ESE as set 2, and horizontal bedding and a slickenside 282/80 was found on the quarry site of Mesebo cement factory founded on the area (Fig. 36). The general dip of the joints in the field was almost vertical to sub vertical. The joint spacing from the field observations were 1-3 m .The shape matrix results show that the joint spacing of set 1 ranges from 0.64 to 5.83 m and from 0.61 to 3.60m for set 2(Fig. 35)..

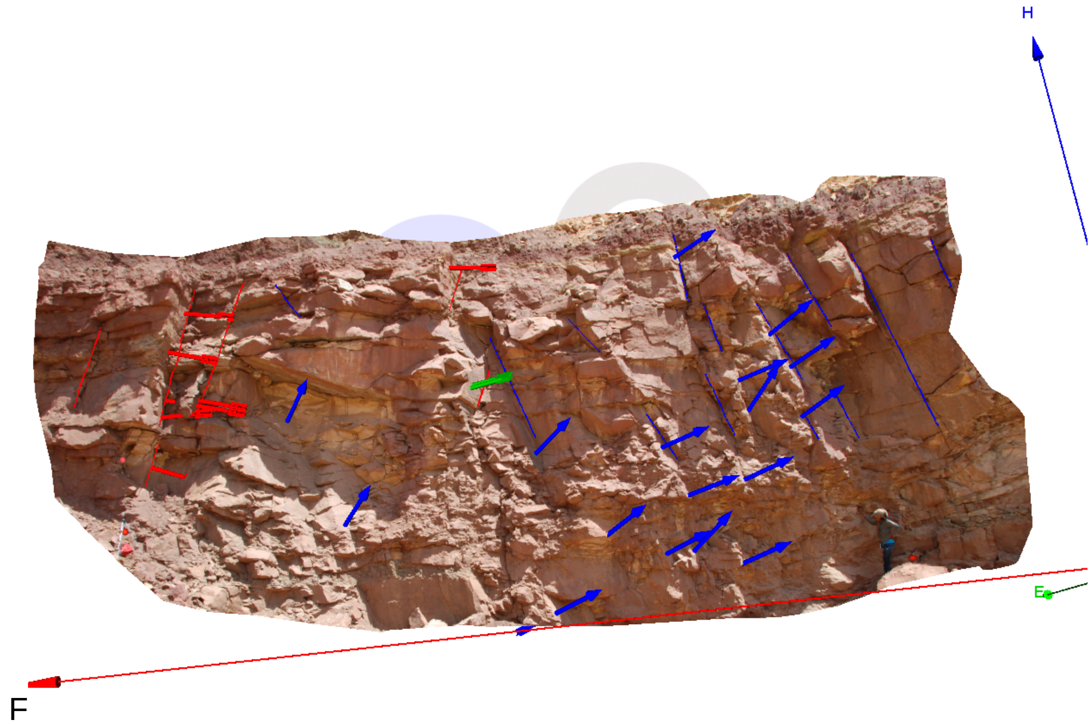

Fig. 35: shape Metrix [3d] structural analysis and 3D model of sand stone from query site of Mesebo cement factory.

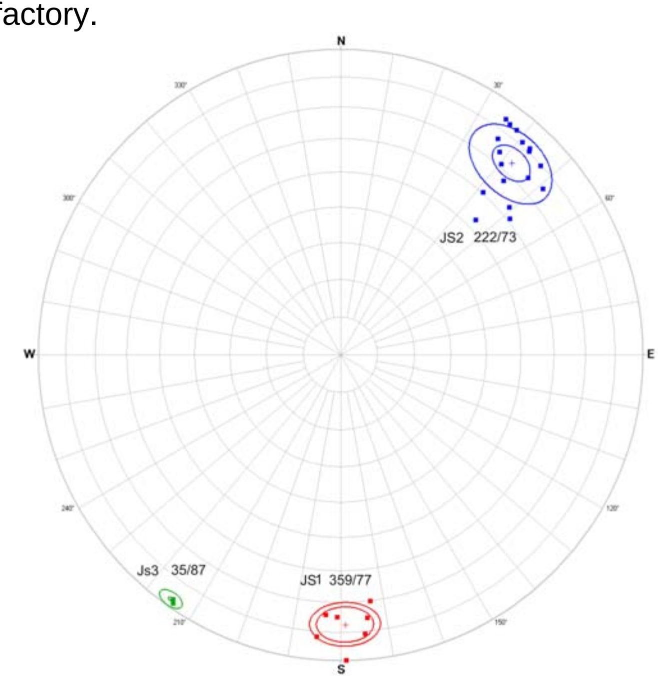

Fig. 36: Lambert projection with structural data of different discontinuity sets of the sand stone from query site of Mesebo cement factory.

6. Rock mass quality

Rock mass quality is among the most important geological factors for the design and construction of a dam project. It is important to make accurate rock mass quality classifications to evaluate the properties of rock masses and rock engineering geological properties at the dam site, and also to decide the rock masses around the dam and determine appropriate excavation depth of the dam foundation.

Table 6. Geotechnical parameters of the dam site from drilling results (Addis Geosystems Co.plc, 2008).

Borehole Number	Elevation (m.a.s.l)	location	Depth (M)	RQD (%)			Permeability (Lugeon)		
				Minimum	Maximum	Average	minimum	Maximum	Average
B1	1808	Ra	120.3	0	100	63	0	33	9.4
B2	1752	Rv	100	0	100	65	0	9.5	5.3
B3	1800	La	120.2	0	100	24.5	0.4	58	19.56
B6	1771	Ra	88.67	0	100	42 .3	0	38.3	11.84
B8	1753	u/s dx	60	0	100	58	-	-	8.9
B9	1750	d/s dx	58.53	0	100	66.8	-	-	44.9
B10	1805	La	55.72	0	100	34.9	33.8	53.7	43.75
B16	1756	La	79.40	20	100	73.57	18.5	30.9	24.7
B18	1761	u/s dx	40.86	30	90	74.85	1.1	18.1	9.6

Ra…….Right abutment, RV…..River valley, La……..left abutment, u/S dx ……..Upstream of the dam axis, d/s dx…….downstream of the dam axis

In this paper evaluation and classification of rock mass quality that was gained from the drilling result from the project is presented. Rock quality designation (RQD) values from different areas of the dam site, reservoir area and tunnel dam axis were taken from drilling results and average values are summarized and presented in table 6 and 7. According to the RQD values (tables 6 and 7), the quality of the rocks in the right abutment is better than in the left abutment. Very poor to poor rock mass was found in the left abutment while in the right poor and fair rock mass was found. Good to fair quality of the rock mass was found in the reservoir area. Fair quality of rock mass is found in the upstream and downstream side of the dam axis and the river bed.

7. Permeability

Permeability is an important factor in designing a dam and its foundation. It is important to evaluate the permeability of the dam foundation to estimate the seepage and will decide the appropriate grouting range. Permeability is controlled by the quality of the rock mass, the availability of the jointing systems, fault zones, the shears, and fissures. Therefore the prediction of permeability distribution for material of the dam body and foundation is one of the critical aspects of the dam project. Different methods such as Lugeon tests, pumping tests, and falling head were used in the investigation of the dam (Addis Geosystems Co.PLC, 2008).

A total of 75 permeability tests were carried out during the studies (48 tests in the dam axis, 18 in the reservoir area, and 1 in the stilling basin, 2 in spill way, and 6 in the tunnel dam axis) at different locations in the project area. Using the data obtained from the project (Addis Geosystems Co.PLC, 2008) the results of permeability tests on rock units are shown in table 6 and 7. The permeability in the rock units was measured in Lugeon scale (0-3 Lugeon impervious, 3-10 Lugeon low permeability, 10-30 Lugeon medium permeability, 30-60 Lugeon high permeability, and greater than 60 Lugeon means very high permeability).

The permeability of the right abutment is low to medium and the permeability results of the left abutment show medium to high permeability. The permeability upstream of the dam axis ranges from low to medium while the permeability downstream of the dam axis show high and in the river valley low permeability. Permeability results from the reservoir area range from medium to high. Generally permeability results of the dam site and reservoir area in the rock units that underlie the dam basin and foundation is medium to high. This high permeability especially along the left abutment and the reservoir area is one of main geological engineering problems of the Giba dam.

Therefore, improving the rock units is recommended for reduction of seepage flow through the foundation.

Table 7. Geotechnical parameters of the reservoir area and tunnel axis boreholes (Addis Geosystems Co.plc, 2008).

Borehole Number	Elevation (m.a.s.l)	location	Depth (M)	RQD (%)			Permeability (Lugeon)		
				Minimum	Maximum	Average	minimum	Maximum	Average
B7	1812	Ta	90.43	0	100	58.3	27.9	65.5	49.71
B 12	1765	Re	40.57	10	100	49.5	25.7	33.5	29.6
B13	1780	Re	40.67	0	90	76	-	8.8	8.8
B14	1783	Re	40.67	40	100	71.7	5.9	54.7	30.3
B17	1766	Re	40	0	100	-	17.8	25.3	21.5
B20	1780	Re	49.80	0	100	-	37.1	68.7	54.67
B21	1794	Re	90.39	0	100	-	1.3	41.2	11.2

Ta…….Tunnel axis, Re…….reservoir area

8. Strength of rocks

The estimation of rock mass strength is becoming important to reduce stability problems that occur in dam foundation. The strength of the rock material is included as a classification parameter in the majority of rock mass classification systems. Strength and deformation properties of a rock mass are much governed by the existence of joints. On the other hand, the mechanical properties of a rock mass are also related to the quality of the rock mass. In general, a rock mass of good quality (strong rock, few joints and good joint surface quality) will have a higher strength and high deformation modules than that of a poor rock mass. A number of uniaxial compressive strength tests have been conducted under the foundation of the dam. The results of previous data on unconfined compression test are shown in table 8.

Table 8.the results of previous data on unconfined compression test (Addis Geosystems Co.PLC, 2008).

Rock unit	Minimum (Mpa)	Maximum (mpa)
Dolerite	90	110
Sand stone	13.5	58
Shale	12	20
Limestone	17	164

9. Rock mass Rating

According to Bieniawski (1973, 1989) rock mass rating of the dam site was performed. Rock mass rating of the dam site and its reservoir area of different rocks are performed as shown in table9 below. According to the RMR values, the rock units are classified in the range of very good quality (class I) to poor quality (class IV).The RMR value determined for worst conditions is 34. Accordingly, the shale is placed in the weak rock (IV) group. In contrast the maximum rating RMR value is 84. Thus, the dolerite is placed in the very good rock and the limestone is placed in good rock (II) while the sand stone is placed in medium rock (III) group.

Table9. RMR classification of the dam site rock units.

Parameters(rating)	Rock types			
	Dolerite	Shale	Limestone	Sand
Rock Quality Designation (%)	20	8	13	8
Spacing of discontinuities	20	15	15	15
Condition of discontinuities	24	6	22	15
Groundwater conditions	10	10	7	10
Strength of intact rock	12	2	7	7
Direction of strike and dip of joints	-2	-7	-2	-2
Total	84	34	62	53
Class/description	I	IV	II	III

II/G- good rock quality, III/fair rock quality, I-very good rock, IV-weak rock quality

10. Conclusions and recommendations

Based on this study the following conclusions and recommendations are made.

The dominant rocks in the area are composed of the Mekele dolerite, Antalo limestone Adigrat sandstone, travertine and shale intercalated with thin beds of limestone. The dam area is generally covered by highly jointed an weathered/fractured limestone at the right and left abutments, alluvial deposits, residual soil and loose sandy clays and weathered colluvial materials in the central and sloppy parts of the dam axis. The dolerite rocks found in the reservoir area are used as a barrier.

The dam area is characterized by several lineaments as shown on the geological map of the dam reservoir (Fig. 5) and lineament map produced from aerial photographs (Fig.15) which was used in correlating the DEM map (Fig.13). The integrated aerial photo interpretations with DEM have identified most probable structures in the area are in good agreement with the lineaments mapped on the surface and geological cross.

According to the interpretations proved from aerial photo from 1:50,000 scale maps, DEM and field study show a number of N-S, WNW-ESE, NW-SE, NE-SW trending structures. Among these are the WNW-ESE striking Mekelle fault and the NE-SW dextral and sinstral striking faults identified both on the Suluh and Agulae river. These displaced the Mekelle fault and tend to rotate the blocks found between the two strike slip faults. The Mekelle fault with WNW-ESE orientation is older than the two strike slip faults.

According to the available cross section on the dam axis which was made from drill logs, the dam axis is underlain by marly limestone and then very thick shale (mostly compact, calcarious and karstified) and this unit is underlain by shale dominated by jointed thinly bedded layers of limestone and gypsum layers.

Rock mass characterization by the reservoir area was done by using the existing drilling logs, laboratory data and field studies. From this soils include mixtures of silty sand, sandy fine clay, coarse clay with sand –silty gravel, clayey gravel, and clayey sand. Similarly, the dominant rock units include closely spaced jointed dolerite, shale intercalated with thin beds of limestone, bedded limestone and sandstone.

Permeability or hydraulic conductivity result of the dam site are grouped into low to high permeability. Therefore, improving the rock especially with high permeability at the left abutment and the reservoir area units is recommended for reduction of seepage flow through the foundation. According to the RQD values quality of the rocks in the right abutment is better than in the left abutment. The rock mass rating available from the dam site ranges from very good rock to weak rock quality.

Though various borehole logs were conducted from dam site, reservoir, spill way, stilling basin and construction site but as the Mekelle fault is within the reservoir area detailed subsurface investigations with drilling boreholes, in-situ and laboratory testing should be recommended around Mekelle fault.

Since the area is affected by fracture network this influences the rock mass quality at the dam foundation and the reservoir area, especially on the left abutment and the east of the dam axis around the Mekelle fault. These fault and different joint systems also significantly affect the permeability of the rock units at the dam foundation. Therefore, improving the weak rock units, appropriate grouting and supporting the dam foundation is highly recommended.

Well studies of sedimentation problems or hazard assessment and possible remedial measures to leakage/seepage problems of the Giba dam reservoir should also be recommended.

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12. Appendix

Location		Sets	Orientation (Mean Dir/Dip)	Aperture (cm)		Persistency (m)		Filling Material
Northing	Easting			Min	Max	Min	Max	
		Set One	200/89	0.3	0.4	0.3	2	soil
		Set Two	115/75	0.2	0.5	0.5	4	clay
		Set Three	145/67	2	3			
542800	1503040	Set four (bedding)	20/88	2	3	0.8	1.5	filled with clay
		Set One	35/87	1	2			Open joint
		Set Two	340/83	0.2	0.8			Open joint
		Set Three	22/87					open joint
542660	1504000	Set four bedding	011/12					
		Set One	44/76					
		Set Two	335/89					
542184	1504805	Set Three	7,/88	0.1	20	1	3	open
		Set One	36/86					
		Set Two	294/83	0.1	0.3			
542666	1504247	Set Three	10,/87	5,	10,			old open joint completely filled
		Set One	42/88					
543360	1503739	Set Two	315/80					
		Set One	153/80			0.6	3	open joint
		Set Two	240/88	3,	4,			
544125	1505423	bedding	15/80			1	2	open joint
		Set One	22/80			0.4	2	open joint
545245	1505514	Set Two	330/80					
		Set One	0/70					
543334	1504033	Set Two	275/70					
		Set One	30/88					
		Set Two	240/70	2,	4,			
		Set Three	7,/85	3-,8				
543274	1503861	Set Four	70/85					
		Set One	87/88		6-.8	0.5	5	
		Set Two	220/55	3,	5			filled with clay
543372	1507318	Set Three	170/82			1	3	open joint
		Set One	6,/65					clay/ open
		Set Two	225/78	1,	4,			
		Set Three	326/80					
546897	1505149	Set Four	95/75			0.5	3	
		Set One	12,/86	5,	7,			
		Set Two	260/88					
546644	1505290	Set Three	336/75					
		Set One	330/75					
540781	1504554	Set Two	125/50			1	3	
542292	1504722	Set One	270/86					

		Set Two	200/86					
		Set One	325/89			3	4	filled with clay
		Set Two	0/90			1	4	
542987	1504102	Set Three	50/90	3,	4,			
		Set One	10,/90	2,	6,			
542320	1503210	Set Two	295/90					
		Set One	140/87					
543149	1506302	Set Two	45/90					
		Set One	135/70			0.7	3	
542144	1503582	Set Twol	55/80					
		Set One	105/88	0.3	0.8	1	3	light weathered material
543034	1503582	Set Two	175/86	0.5	1,	2,	3	
		Set One	330/80			1	3	
		Set Two	355/70			2	4	
545926	1504781	Set Three	55/85	0.1	0.3			filled with calcite cement
		Set Two	135/70			0.5	4	soil
		Set One	55/80			1	2	