Aquifers developed on basement rocks of Ethiopia: their genesis, properties and classification

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This is to certify that the thesis prepared by Gaddissa Deyassa Daddi entitled: ***Aquifers developed on basement rocks of Ethiopia: their genesis, properties and classification*** and submitted in fulfilment of the Degree of Doctor of Philosophy in Earth sciences (Hydrogeology) complies with the regulations of the university and meet the accepted standard with respect to originality and quality.

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ABSTRACT

Aquifers developed on basement rocks of Ethiopia: their genesis, properties and classification

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Addis Ababa University, 2015

The basement rocks of Ethiopia were traditionally described as a system of regional aquiclude. This attribution ignores regional differences in aquifer properties, structure and functioning. In contrast, this work presents how the interactions of evolutionary and modern geological processes determine aquifer development and hydrogeological characteristics of the basement terrain of Ethiopia. It specifically addresses the role of geomorphic history (deep weathering and stripping) in affecting aquifer genesis and their control on vertical and spatial heterogeneity. In addition, the study provides field evidences for existing literature based weathering-stripping model previously developed for the country. Detailed examination of geological, hydrological and hydrogeological evidences enabled the understanding of the causes of regional variation in aquifer properties. The aquifers exhibit noticeable regional differences. Thus, conceptual hydrogeological model depicting three coherent categories of aquifers are developed: (a) in western basement terrain, aquifer is relatively extensive in the thick weathered mantle over fractured bedrocks of low to high-grade metamorphic rocks. High groundwater storage but low hydraulic conductivity characterizes this aquifer. (b) in the northern, groundwater occurs in fractures and discontinuities in bedrocks toward the surface and tectonically induced relatively deeper fracture zones. These aquifers have high hydraulic permeability but low storage capacity. (c) in the Borena lowlands of southern basement region, groundwater occurs in wadi beds, fractures, and preferentially weathered mantles. The orientations of wadi beds follow regional fractures, which control groundwater flow regime and enhance preferential weathering of bedrocks. Aquifers are of intermediate type with regard to hydraulic properties. The variations in low-flow indices and shapes of flow duration curves of streams manifest contrast in bulk storage capacity and hydraulic conductivity of catchments in the three basement regions. This contrast has been used as evidences for characterization of aquifers.The implication of these regional differences on groundwater exploration and exploitation has been the subject of this study.

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LIST OF ACRONYMS

AAU	Addis Ababa University
ANS	Arabian Nubian Shield
a.s.l	above sea level
BFI	Base Flow Index
EAO	East African Orogeny
EIGS	Ethiopian Institute of Geological Surveys
GSE	Geological Surveys of Ethiopia
MB	Mozambique Belt
MDBF	Mean daily base flow
NNE	North-North- East
N-S	North-South
SMDBF	Specific mean daily base flow
SSE	South-South-East
SSW	South-South-West
UNESCO	United Nations Educational, Scientific, and Cultural Organization
WHO	World Health Organization
WMO	World Metrological Organization

CHAPTER 1: INTRODUCTION

1.1 Background

Crystalline basement rocks occur in tropical region of sub- Saharan Africa, India, South America and Australia (Wright, 1992). They occupy 40% of the land area of Sub-Saharan Africa and 220 million people live in rural areas underlain by crystalline basement rocks (MacDonald et al., 2000). Aquifers developed from basement rocks occur in tropical regions and in sub-Saharan Africa. Some estimates show that only some 30% of the rural populations of sub-Saharan Africa have access to a clean potable water supply of minimum quantity (Wright, 1992). The bulk of the shortfall will have to be met by groundwater derived from basement aquifers (Wright, 1992).

Aquifers of basement rocks occur within the weathered residual overburden (the regolith) and the fractured bedrock (UNESCO, 1984; Acworth, 1987; Wright, 1992; Chilton and Foster, 1995). Regolith develops over the bedrock by process of deep weathering. The thickness of weathered mantle and the corresponding aquifer properties depend on a complex combination of controlling factors that include bedrock characteristics, climate (past and present), age of land surface; relief and other site specific factors (UNESCO, 1984; Acworth, 1987; Wright, 1992; Jones, 1985). Thus, the vertical heterogeneity of aquifer properties depend on the type of regolith lithology (i.e. mainly texture and thickness) (Acworth, 1987; Chilton and Foster, 1995). Several researches from Africa, (Foster, 1984; Acworth, 1987; Taylor and Howard, 1998, 2000; Edet and Okereke, 2005) and from India (Dewandel et al., 2006) emphasize that the hydrogeological characteristics (mainly hydraulic conductivity and storage) of the weathered mantle and the underlying bedrock derive primarily from the geomorphic processes of deep weathering and stripping.

These authors highlight the significance of tracing the geomorphic evolution of weathered land surfaces over basement rocks. They emphasize that identifying the dominant geomorphic process operating on surfaces, is of vital importance to comprehend the hydrogeological characteristics of basement rocks.

In Ethiopia, about 23% of the land area is occupied by Precambrian basement terrain; more than 10 million people reside in the basement terrain of the country. This population depend on groundwater from basement rock complexes for domestic and irrigation use.

However, model explaining the hydrogeological set up and genesis of basement aquifers is lacking. Some works (e.g. EIGS, 1988; Cherenet, 1993; EIGS, 1996) and many unpublished regional hydrogeological studies (GSE, 2002; Belete et al., 2003; GSE, 2003;Belete et al., 2004; Alamirew et al., 2005) consider the Precambrian basement terrains of the country as regional aquiclude or very poor aquifers regardless of their spatial differences in terms of groundwater occurrence and potential. Nevertheless, Kebede, (2013) has recently proposed a literature-based model depicting the cyclic evolution of weathering surfaces over the basement bedrocks of the country. However, linkage between geomorphic processes and the hydrogeology of the crystalline basement terrains of the country remains unresolved.

1.2 Rationale of the research

Basement aquifers are distinctive in that their occurrence and characteristics are largely a consequence of the interaction of weathering processes related to recharge and groundwater through flow and stripping. Close relationship exists therefore, between the present-day condition (amount and distribution) of meteoric water (i.e. hydrological and hydrogeological characteristics) and contemporaneous geomorphic processes operating on basement terrains.

Significant spatial variations exist in sets of interacting factors, which include bedrock geology, climate, and topography. These spatial variations lead to heterogeneity in rates of geomorphic processes (deep weathering and stripping) in different regions. Consequently, considerable heterogeneity exists in the hydrogeology of deeply weathered land surfaces (Chilton and Smith-Carington, 1984; Houston and Lewis, 1988; Howard et al*.,* 1992; McFarlane et al., 1992).

Despite the significant spatial heterogeneity, the existing premises in Ethiopia, however, consider the Precambrian basement terrains of the country as a regional aquiclude or very poor aquifers regardless of their spatial differences in terms of groundwater occurrence and potential. As such, the linkage between geomorphic processes and the hydrogeology of the crystalline basement terrains of the country remains unresolved.

Therefore, a comprehensive approach that integrates geology, hydrology (rainfall amount and distribution), and geomorphic processes (deep weathering and stripping) becomes milestone in describing aquifer in basement regions of the country. This improves the understanding on basement hydrogeology of Ethiopia which will be of vital importance in planning, development and management of groundwater resources in basement terrain.

1.3 Problem statement

The genesis of aquifers on Precambrian basement rocks of Ethiopia is not well understood, nor was it research focus so far. This is because of incomplete understanding of hydrogeology of basement aquifers of the country. As such, it implies that the existing knowledge and the reality are in disparity; while basement aquifers are still the sources of water for drinking, domestic, and irrigation uses for rural and urban population. Consequently, it remained that fundamental link that elucidates relationship among geology, hydrology, geomorphic processes (weathering and stripping), and aquifer properties is lacking.

1.4 Research objectives

1.4.1 General objective

The general objective of the research is to develop conceptual hydrogeological model (framework) of aquifers developed on basement rocks of Ethiopia by establishing linkage among geomorphic processes (deep weathering and stripping), hydrology, and aquifer properties.

1.4.2 Specific objectives

The specific objectives of the research include:

- Verification of the reliability of previously developed literature-based weathering-stripping model by using definite field evidences.
- Investigation of variations in aquifer parameters (storage capacities and hydraulic conductivities) and examine any relationship that may exist among operating geomorphic processes (deep weathering and stripping), regolith thickness, and aquifer parameters in type catchments of basement regions.
- Investigate any relationship that may exist between low-flow indices (base flow indices, specific mean daily base flows, recession slopes), shapes of flow duration curves and relative thickness of weathered mantle in type catchments of basement regions.
- Infer hydraulic properties (hydraulic conductivity and storage capacity) from variations in low-flow indices and use the results to study descriptive variables of hydrogeological indicators in basement terrains.

1.5 Methods and materials

The literature-based genetic model previously developed for the evolution of weathered land surfaces over basement terrains of the country, was tested against two sources of evidences: Climatic and geological evidences, and field–based geological evidences.

The first set of evidences is derived from climatic conditions and associated geologic and geomorphic activities occurred in chronologic order. It involves evaluation and investigation of evidences exhibiting the prevailed climatic conditions and geologic phenomenon in particular geologic time and the corresponding geomorphic processes (deep weathering and stripping) that had operated since the Late-Palaeozoic. These mainly include Permo-Carboniferous glaciations, warm and wet Jurassic climate, the Cenozoic plume induced uplift, the late-Miocene eruptions of shield volcanoes, and their effects. The evidences for corresponding geomorphic processes are substantiated by field facts observed during extensive fieldwork to the basement regions. These include stratigraphic relationships and contacts, erosional landforms, exhumed deep weathering surfaces, duricrusts and inselbergs,

The second set of evidences is generated from field studies and descriptions of weathered mantle-bedrock profiles and a thorough review of lithologic-logs of wells drilled in basement terrains in the three regions. 364 lithologic-logs (of which 228 with pumping test data) of wells drilled in basement terrain have been collected from database of respective Regional Water Resources Bureaus and Water Works Construction Enterprises. Data lacking geographic locations and those with incomplete records are discarded. The data have been plotted on geological map of each region to check its reliability with respect to lithology and data with inconsistent lithologic descriptions has been discarded. The lithologic logs are then re-interpreted in terms of weathered mantle-bedrock profiles and the depths to bedrock are estimated.

The field investigation on other hand, involves close observation of variation in thicknesses and vertical heterogeneity of weathered mantle-bedrock profiles among the three basement regions through long traverses in extensive field campaigns. This is followed by selecting representative study sites (type catchments) for detailed examinations of the lithology and textural variation of weathered mantle and subsequent hydrological (rainfall and base flow) and hydrogeological (storage and hydraulic conductivity) investigations. The type catchments are: Worei in the northern, Uwa in the western and Alona-Kefera in the southern basement regions. 86 weathering profiles are described in the three basement regions over different bedrock lithologies.

These weathered mantle-bedrock profiles are grouped based on lithologic similarities in each region and the study sites. 12 profiles in Worei, 16 in Uwa and 10 in Alona- kefera catchments are depicted. Descriptions of these weathering profiles addressing textural, thickness and lithological variations within profiles in each region over different bedrock lithologies are performed. The result from these descriptions is synthesized to establish weathered mantle-bedrock profiles corresponding to each basement region. This was followed by comparisons of thicknesses and vertical heterogeneity of weathered mantle among the three study sites and with the "typical" weathering profile developed for equatorial region. This enabled the complete understanding of the cyclical dominance of geomorphic processes (i.e. regionalization of geomorphic processes) in each basement region of Ethiopia. The complete analysis and integration of all these evidences help conceptualize the contrasts in weathering mantle-bedrock profiles thereby addressing regionalization and rate of geomorphic processes operating in each basement region.

The hydrogeological characteristics of the three basement regions are addressed by comparing aquifer properties mainly (storage capacity and hydraulic conductivity) and investigation of responses of aquifers to pumping. The pumping test data of the same wells indicated above are used to investigate the hydraulic characteristics of basement aquifers in each region. Pumping test data with short duration(less than 12 h) are rejected and the results from constant- discharge analysis are used. Diagnostic plots (Bourdet et al., 1983; Bourdet et al. 1989) of simultaneous plots of drawdown as a function of time in log-log and semi-log scale helped in analysing the aquifer responses. This facilitated the identification of appropriate conceptual model in the three basement regions. Analytical pumping test solutions that best match to drawdown responses are fitted to identify types of aquifers. The analysis of matches between each solution and recorded drawdown was done iteratively using AQTESOLV software (Duffield, 2007).The aquifer types obtained from this analysis are compared with the weathered mantle-bedrock profiles developed for the three basement regions.

Analysis of low-flow regimes of streams in selected watersheds (catchments) was used as an alternative method to corroborate the relative contrasts in aquifer storage capacities and hydraulic conductivities obtained from pumping test analysis.

The method involves analyzing time series of daily flows to produce summary of information that describe the low-flow regime of the gauged streams in the three basement regions.

These include low-flow indices and flow duration curves. The low-flow indices include base flow indices, specific mean daily base flows, and slopes of recession segments. Hydrograph separation and extraction of base flow indices was made by Time Series Analysis module of River Analysis Package developed by (Marsh et al., 2003). The flow duration curves of the same streams, derived from the complete time series of recorded river flows, have been constructed according to the steps described in (WMO, 2008). Consequently, comparisons of the values of low-flow indices(base flow indices, specific base flow indices and recession slopes) and shapes of the duration curves from the five catchments of the three regions are made to study descriptive variables of hydrogeological indicators (i.e. thickness of weathered overburden). The contrasts in low-flow indices and shapes of the lower segments of flow duration curves are related with thickness of regolith mantles to infer storage capacity and hydraulic conductivity of catchments in each region.

Therefore, evidences from the genetic model, field evidences, and operating climatic conditions from the late Cenozoic to present converge to assert regionalization of geomorphic processes over the basement terrain. Thus, linkage between geomorphic processes and hydrogeology of basement terrain is established and generalized categories of aquifers are developed.

1.6 Physical description of the study regions

1.6.1 Distribution of basement terrain of Ethiopia

The geology of Ethiopia in general is composed of Precambrian crystalline basement rocks that are sequentially overlain by Palaeozoic to Mesozoic sedimentary rocks and at the top by Cenozoic volcanic (EIGS, 1996).

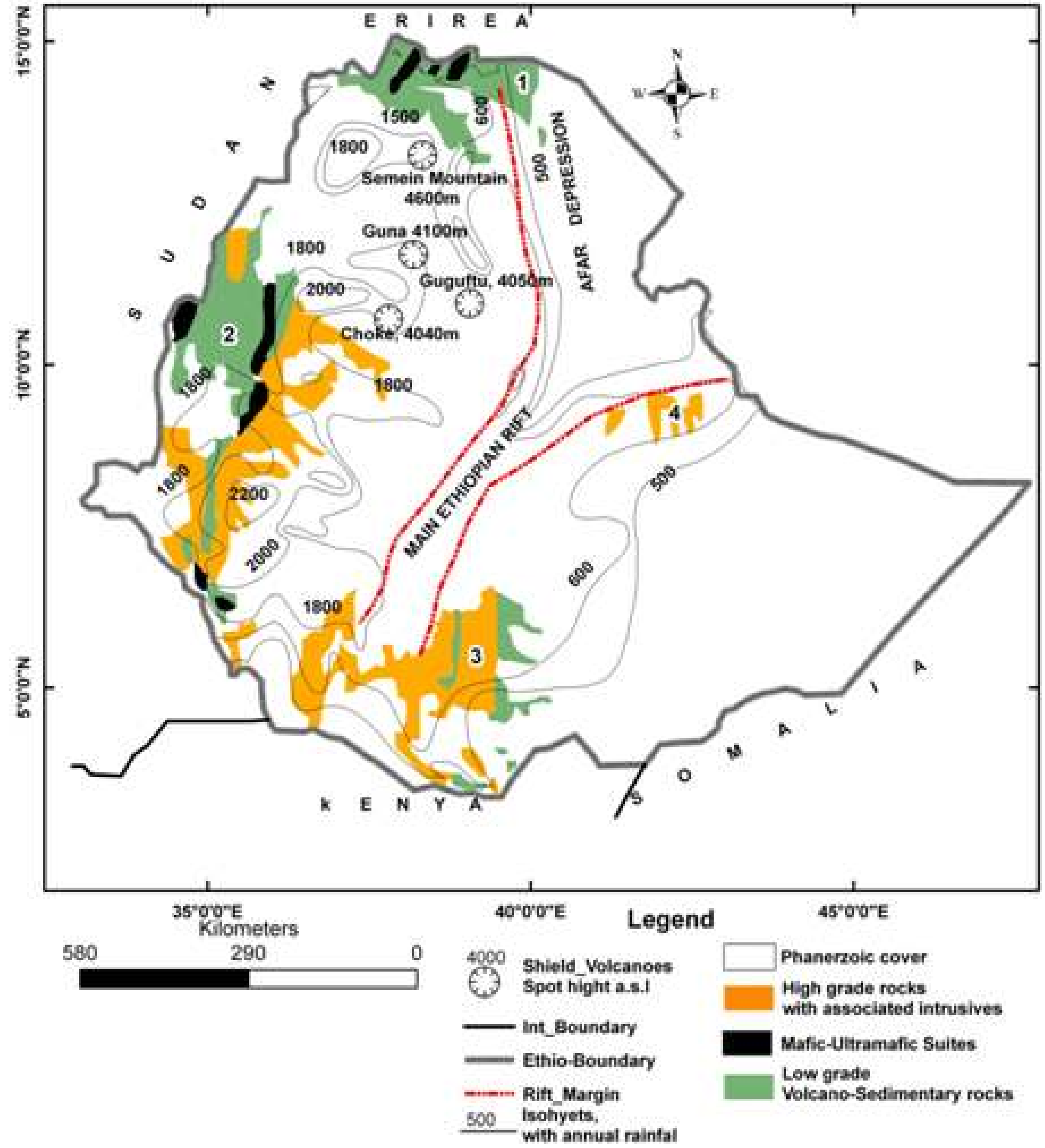


Figure 1) Distribution of Precambrian basement terrain of Ethiopia (simplified from EIGS, 1996). Numbers (1, 2, 3, and 4) show the locations of exposures of basement rocks in North, West, South and East. The map also depicts the distribution of annual rainfall. Locations of centres of late Cenozoic shield volcanoes with elevations are also indicated.

In some localities (e.g. in western and southern basement regions), where the Palaeozoic and Mesozoic sediments are missing, Tertiary to late Miocene volcanic rocks directly overlay the basement rocks. The Precambrian basement rocks of Ethiopia are exposed in five parts of the country: North, South, West, Southwest, and East (fig.1). The Precambrian terrain of Ethiopia is considered to comprise the rocks in the Arabian- Nubian- Shield (ANS) and the Mozambique Belt (MB), which are parts of East African Orogeny (EAO) (Kroner, 2005, Yiehunei and Fekadu, 2007). The EAO marks the formation of a vast tract of juvenile Neo-proterozoic continental crust, and where East and West Gondwana joined (Stern, 2002; Johnson and Baraki, 2003; Stern et al., 2004; Kroner, 2005; Philip et al., 2008).The ANS is distinguished from the Mozambique Belt by its dominantly juvenile nature, relatively low grade of metamorphism, and abundance of island-arc rocks and ophiolites (Avigad et al., 2006; Kroner, 2005). The MB essentially consists of medium- to high-grade gneisses and voluminous granitites (Kroner, 2005). The crystalline Precambrian basement rocks of Ethiopia in general, consist of low-grade to high grade metamorphic rocks that are intruded by syn- and post-tectonic granites and granodiorites (EIGS, 1996). Kazmin et al., (1978) have divided the Precambrian basement of Ethiopia in to upper, middle, and lower complexes based on the grade of metamorphism.

1.6.2 Description of bedrock geology of basement regions

The northern basement terrain

The geologic framework of the northern basement terrain is highlighted from four 1:250,000 map sheets: Mekele (Arkin et al., 1971), Adi Arkay (Hailu, 1972 unpublished), Adigrat (Garland, 1980), and Axum (Tadesse, 1999). The Geological Survey of Ethiopia/Ministry of Mines produces these geologic map sheets.

The northern crystalline basement consists of low-grade metamorphic rocks that are intruded by diorite, granodiorites and granites (Beyth, 1972; Garland, 1980; Tadesse et al., 1999). The low grade (green schist facies to locally amphibole) facies (Asrat, 2001) rocks belonging to Upper Complex (considered in age of early Proterozoic), have a very thick succession of magnificent exposures in the north (fig.2) (EIGS, 1996; Alene et al., 2006; Bussert, 2010).

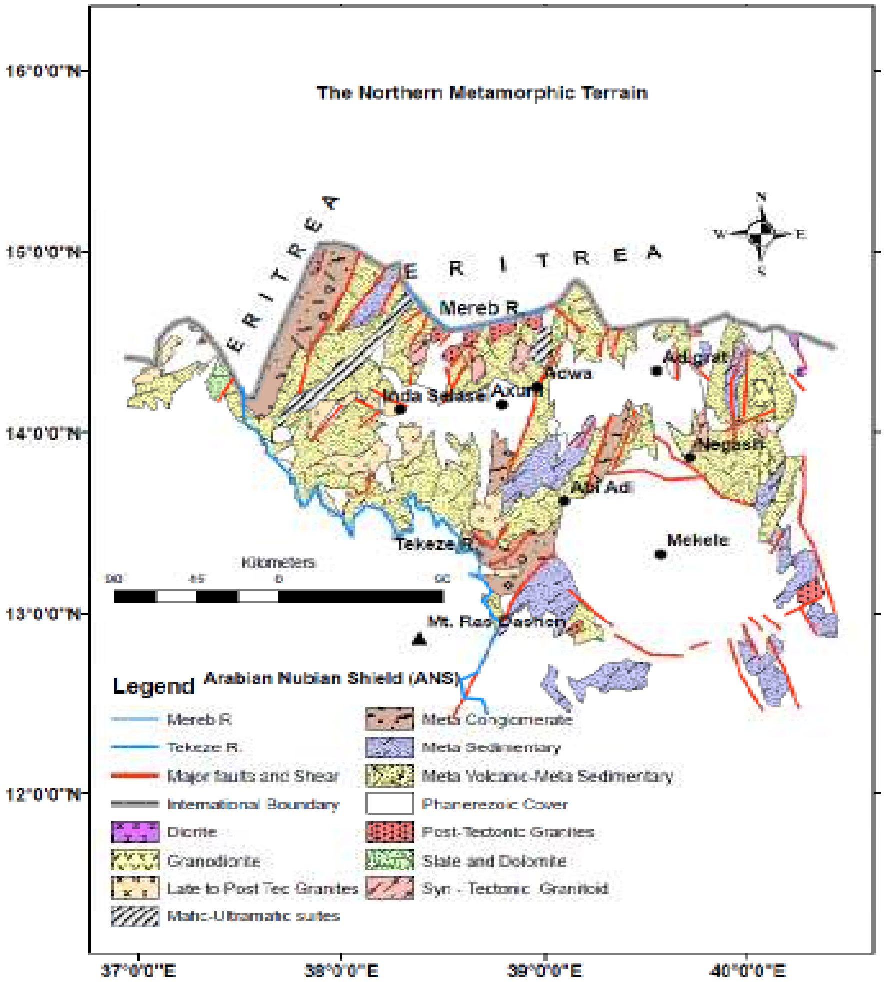


Figure 2) The Northern Metamorphic Terrain of Ethiopia (modified After Taddese, 1999; GSE, 1996 and Asrat et al., 2001)

The rocks are composed of assemblages of mafic-ultramafic suites, meta-volcanic, meta-sandstone, and meta-conglomerates. The metamorphic rocks are composed of an older island arc meta-volcanic sequence, the Tsaliet Group, and a younger meta-sediment sequence, which is termed the Tambien Group (Beyth, 1972; Garland, 1980). The Tambien Group consists of interbedded carbonates and siliciclastic sediments, locally capped by glaciogenic diamictites of "Sturtian" age (Alene et al., 2006; Bussert, 2010).

The Western basement terrain

The western Ethiopian Precambrian shield comprises a low-grade volcano-sedimentary assemblages and high grade ortho- and Para-gneisses and forms the southern extension of the Arabian-Nubian-Shield that forms the northern-half of the East African Orogen (Kebede et al., 2003)(fig. 3).

The low-grade volcano-sedimentary sequence, with its characteristic linear belts of dismembered mafic-ultramafic bodies, variably interpreted as remnants of ophiolite sequence (Berhe, 1990; Abdelsalam and Stern, 1996). Plutonic rocks with gabbroic-granitic compositions commonly intrude within the low-grade belt and at the boundary with the high-grade gneissic terrain (Alemu and Abebe, 2007; Kebede and Koeberl, 2003). The lower complex comprises various gneisses and migmtites, mainly of granitic composition. The rock consists of mainly of biotite and amphibole-bearing gneisses, quartzo-feldspathic granitic gneisses (EIGS, 1996; Asrat et al., 2001) (fig.3).

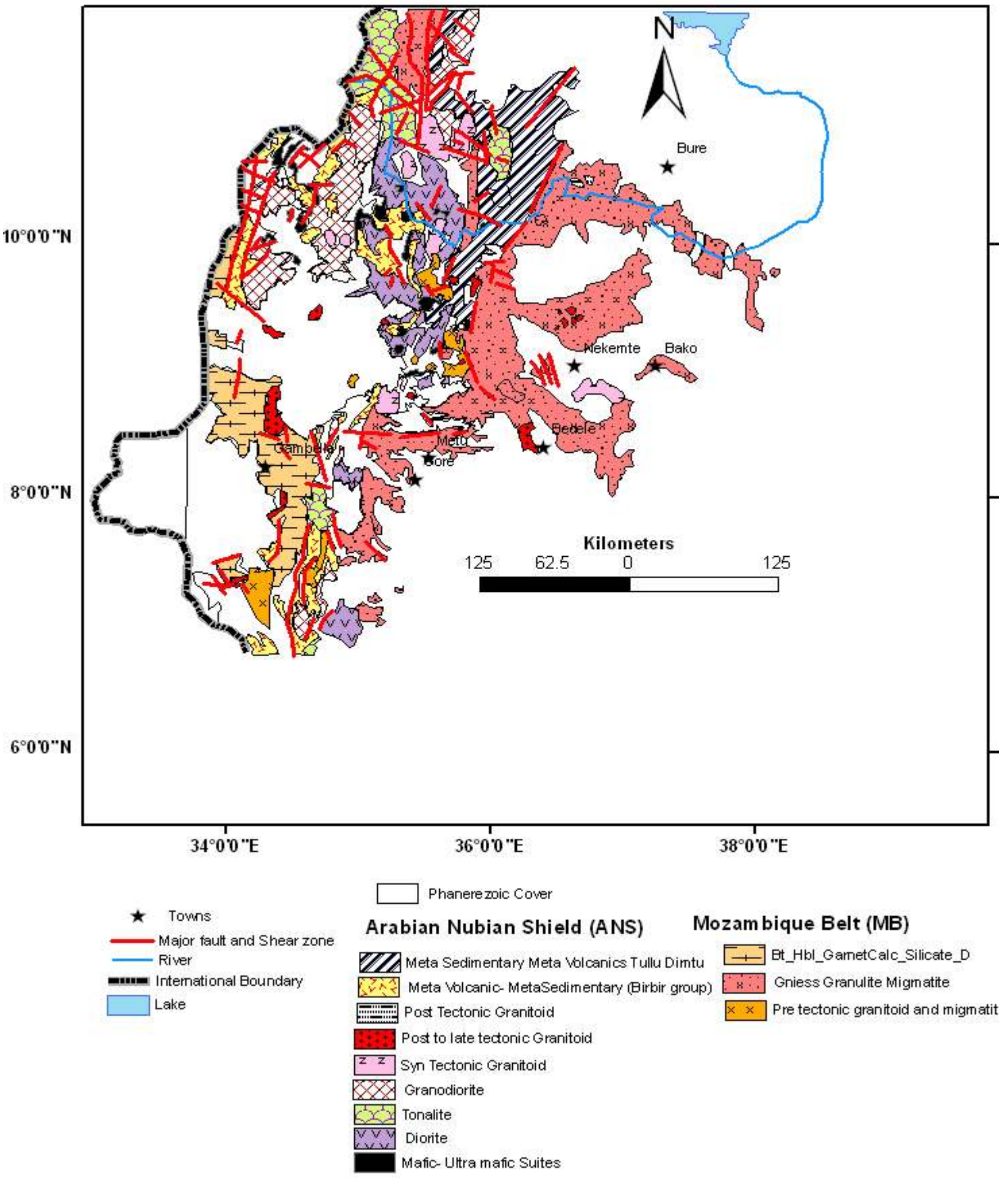


Figure 3) The basement terrain of western Ethiopia (After: Taddese Alemu and Tsegaye Abebe, 2007; Asrat et al., 2001; GSE, 1996)

The south western and southern basement terrain

The metamorphic terrain exposed in the southwestern are classified as lower complex; which is believed to be the northward extension of the Mozambique Belt (Kazmin, 1978; EIGS, 1996).

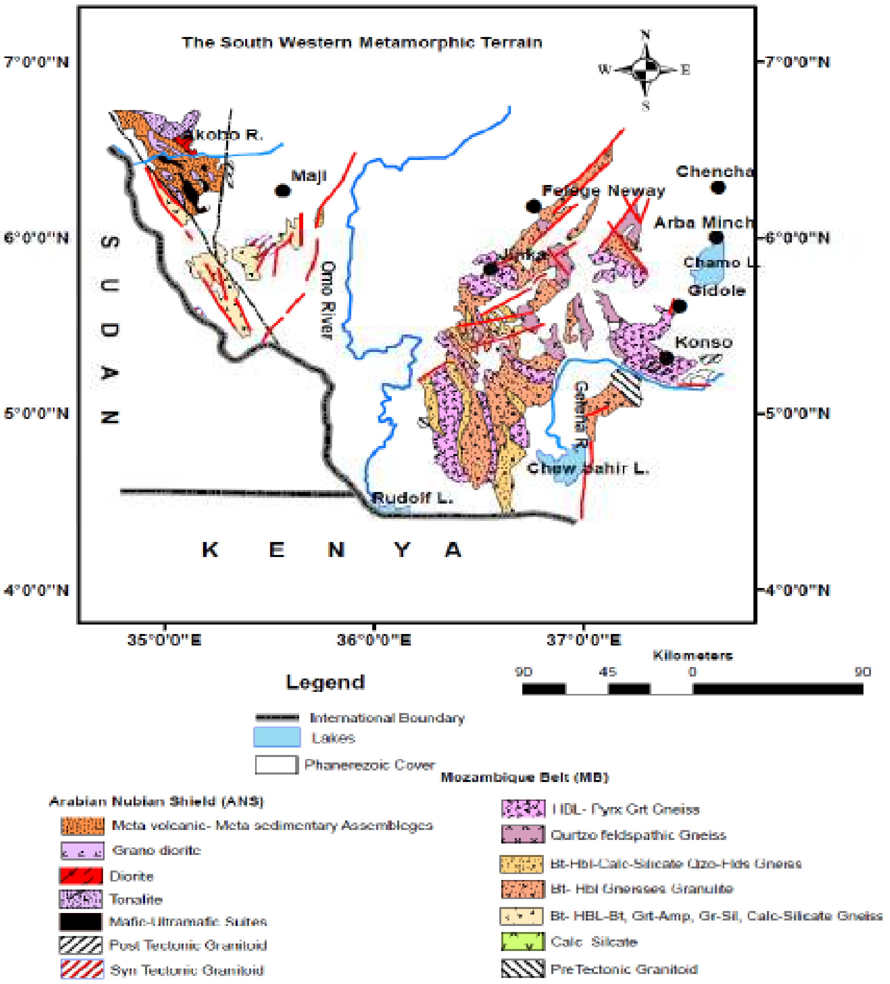


Figure 4) South western basement terrain of Ethiopia (After: Asrat et al., 2001, Davidson, 1983; GSE, 1996)

The rock consists of mainly high grade biotite and amphibole-bearing gneisses, quartzo - feldspathic granitic gneisses intruded by granitoids; mafic ultra-mafic suites, low grade meta-sedimentary assemblages which are intruded by intrusive(fig.4) (diorite, granodiorite and granitoids) (EIGS, 1996; Asrat et al., 2001).The metamorphic terrain exposed in southern region of Ethiopia consists of high grade gneisses and migmatites with subordinate quartzo feldspathic gneisses, calc-silicate rocks and amphibolites which are classified as lower complex (Kazmin, 1972).

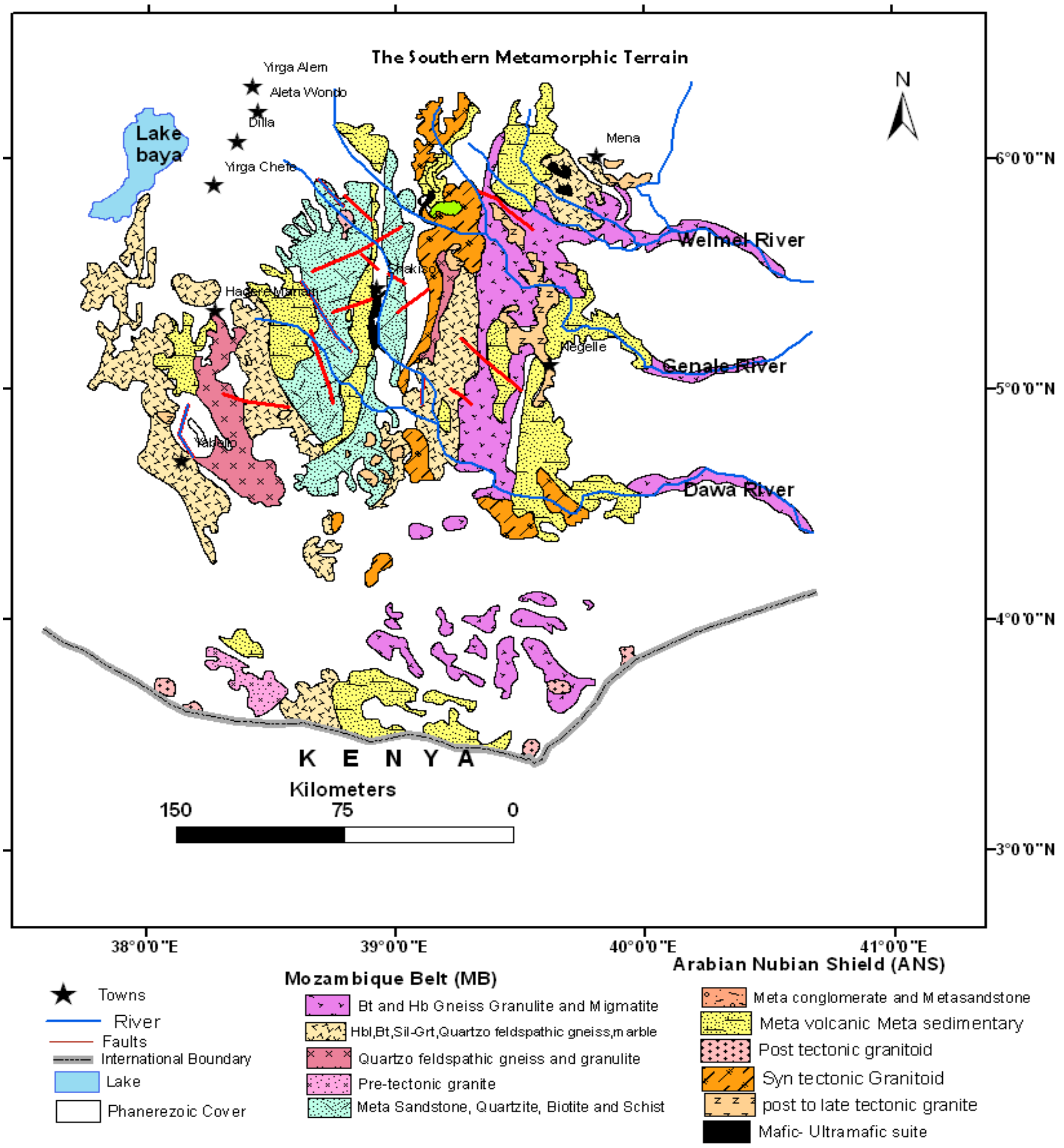


Figure 5) The basement terrain exposed in southern Ethiopia (modified after: Asrat et al., 2001; Yihunie et al., 2008; GSE, 1996)

The main lithological units recognized in southern basement of Ethiopia include ortho amphibolites. These are intercalated with minor quartzo-feldspathic rocks and quartz schist; dismembered bodies of mafic and ultramafic intrusive interpreted as ophiolite; and syn- to late tectonic granitoids metamorphosed in the upper green schist- to middle amphibolites facies (Yihunie, 2002). The upper complex rocks also occur, in the southern region include the Adola group and Kadjimiti beds (Alene et al., 2006) (Fig.5).

The eastern basement terrain

Rocks containing gneisses and migmatites with subordinate quartzo-feldspathic gneisses, amphibolites, and schists dominate the eastern basement region of Ethiopia. They are classified as the lower complex (Teklay, Kroner and Mezger, 1998).

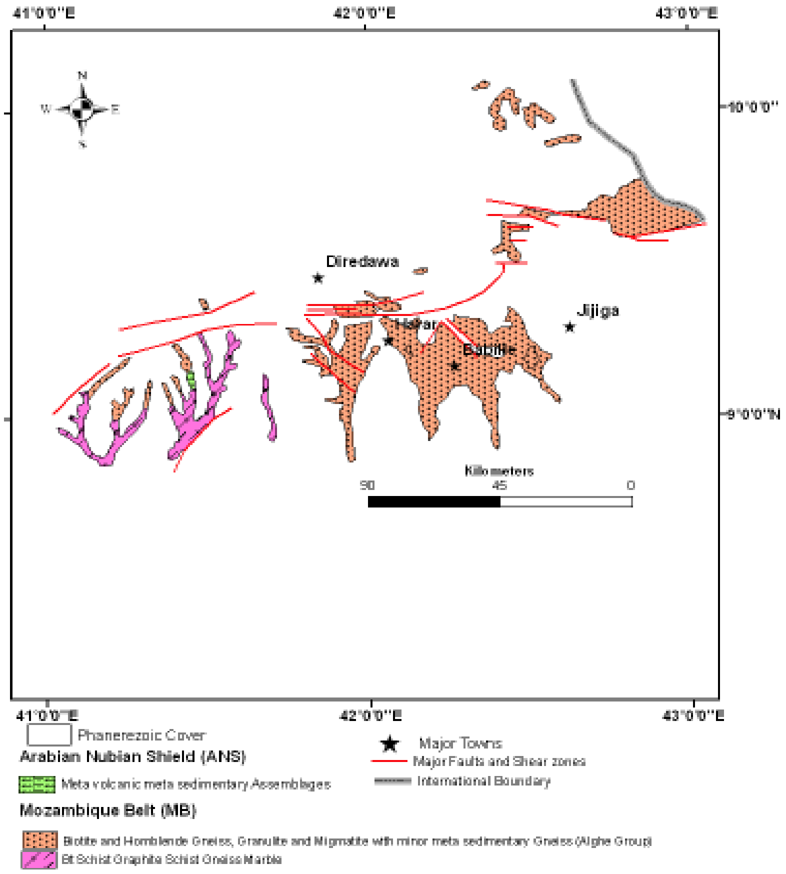


Figure 6) The metamorphic terrain in Eastern region (modified from Asrat et al., 2001; GSE, 1996)

The middle unit, also known as the Boye group, consists of biotite and quartz muscovite schists, meta-arkoses, quartzite, marbles, meta-pelites, are reported(Teklay et al., 1998).

1.7 Organization of the thesis

This thesis is presented as a series of inter-related chapters addressing the research objectives. It is organized in six chapters that follow the sequences of tasks outlined. A concise review of existing thought is presented as background information in the first chapter. Research rationale, problem statement, and objectives of the research are outlined respectively in this chapter. Methods to achieve the objective of the research and physical description of the basement terrain are also included in this chapter. Chapter 2 presents the climatic and geological evidences.It addresses the evaluation and investigation of evidences exhibiting the prevailed climatic conditions and geologic phenomenon in particular geologic time and the corresponding geomorphic processes (deep weathering and stripping) that had operated since the Late-Palaeozoic. Chapter 3 presents field evidences which are generated from data obtained from type catchments in each basement region and from extensive field campaigns in the basement regions. The theme of these two consecutive chapters specifically aims at addressing the specific objective-1 indicated above. Chapter 4 discusses the linkage between the geomorphic processes and hydraulic properties of the basement terrain. It thus establishes a geomorphic framework for hydrogeology of basement aquifers of the country. Implications of basement aquifer classification on groundwater exploration and development are discussed in chapter 5. Chapter 6 presents concluding discussion, which summarizes and integrates elements of geomorphic processes, hydrology, and hydrogeology. It also forwarded issues requiring further research activities.

CHAPTER 2: CLIMATIC AND GEOLOGICAL EVIDENCES FOR EVOLUTION OF BASEMENT LANDSCAPES OF ETHIOPIA BY DEEP WEATHERING AND STRIPPING PROCESSES

2.1 Introduction

2.1.1 The process of deep weathering and stripping

Weathering is the breakdown of rocks by mechanical disintegration and chemical decomposition by physical, chemical, and biological processes at or near the surface of the Earth (Ollier, 1959; Selby, 1993; Whalley and Warke, 2005). Physical or mechanical weathering occurs when volumetric expansion and related alteration of stresses lead to failure and disintegration of the rock. Erosional unloading, freezing of water and freeze-thaw effects as well as thermal fatigue due to repeated heating and cooling are major activities that cause physical weathering. Chemical weathering on the other hand, involves a number of chemical reactions acting between rock minerals and water upon many different types of rocks. These chemical reactions decompose primary minerals and rocks and transfer the products to other phases such as soil water and clays (Drever, 1997). The major chemical reactions involve in rock decomposition include solution, hydration, oxidation, reduction, carbonation, and hydrolysis. These chemical reactions take place under optimum range of climatic conditions. Deep weathering is the term normally used to describe the process by which a more or less thick mantle of altered rock is formed by in situ weathering (Ollier, 1959). It involves the occurrence and accumulation of insitu altered mantle of thickness tens or even a hundred meters. In this case, the products of weathering have remained in situ for long stable period (10^6–10^7a) (Fairbridge and Finkl, 1980). It implies that during this time rates of weathering must have exceeded rates of erosion. These circumstances lead to the formation of deep weathering profiles. Deep weathering is often referred to as tropical weathering and has often been used as an indicator of former humid tropical climate conditions (Pain and Ollier, 1996; Ollier and Pain, 1996). Denudation is defined as the overall degradation and levelling of continental landmasses (Ahnert, 1970, 1996; Smithson et al., 2008). It includes all processes that lower the relief at the surface of the Earth. It acts physically or chemically. Physical denudation or (mechanical denudation) (Meybeck, 1987), corresponds to the removal of solid particles from the land surface (stripping). It is achieved by different exogenic processes, including mass wasting and erosion by wind, running water, waves and glaciers.

Chemical denudation (or chemical erosion) is defined as net dissolved mineral mass loss in solution from watersheds and continents, with associated transport via groundwater and rivers to the oceans (Drever, 1997). It is therefore a result of deep weathering. Wayland, (1934) and Willis, (1936) conclude that denudation is effected not only mechanically, but must also occur in solution (chemically), from the movement of infiltrating water as groundwater.

2.1.2 Factors affecting the processes of deep weathering and stripping

Weathering is a complicated process; many different factors affect the dominant type of process as well as the weathering rate. The most important factors are climate and bedrock composition. Climate is a leading factor in determining weathering. Temperature is a climatic factor that affects the reaction rate. Bland and Rolls, 1998 suggests that a rise in temperature by 10°C rises the reaction rate by a factor of two. Water plays an important role in most weathering processes. In chemical weathering, the most important function of water circulating within the rock mass is to prevent equilibrium in weathering solutions to be attained (Thomas, 1994). Therefore, chemical reactions need water to occur; water is also crucial to many mechanical weathering processes. The storage and movement of water in the regolith is a highly influential factor in determining weathering rates.

Louis Peltier, (1950) contends that rates of chemical and mechanical weathering are guided by temperature and rainfall conditions (fig.7).

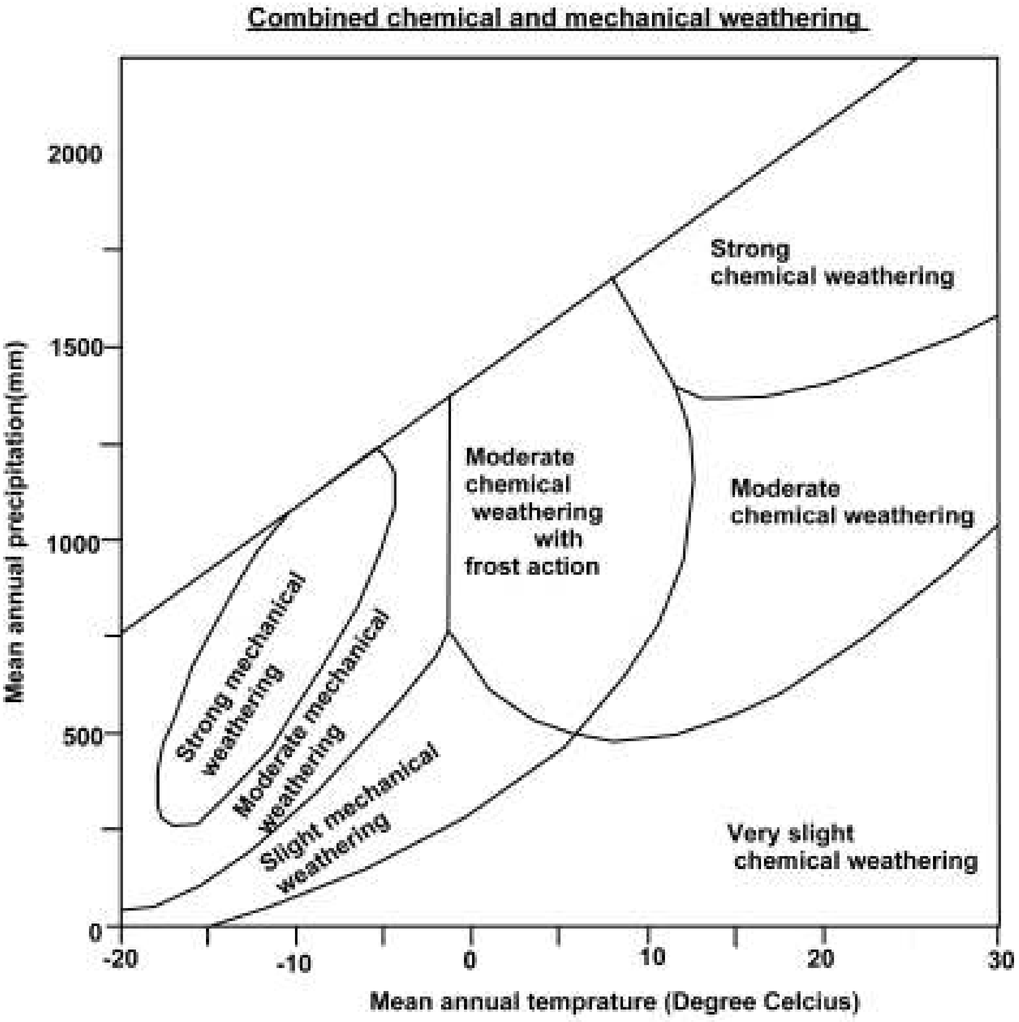


Figure 7) Relation of chemical and mechanical weathering rates to temperature and rainfall. Adapted from Peltier, (1950)

The intensity of chemical weathering depends on the availability of moisture and high air temperatures (fig.7). It is intense in wet and warm regions. However, it is minimal in dry regions, where water is scarce; and in cold regions, where temperatures are low and water is frozen for much the year (fig.7). As a result, thicker weathered mantle developed in humid-equatorial region than temperate and arid regions (fig.8) - the collective effects of higher mean annual precipitation and higher mean annual minimum temperatures. This can be envisaged from the relationship between the present climatic zonation and weathering thickness (Strakhov, 1967) (fig.8).

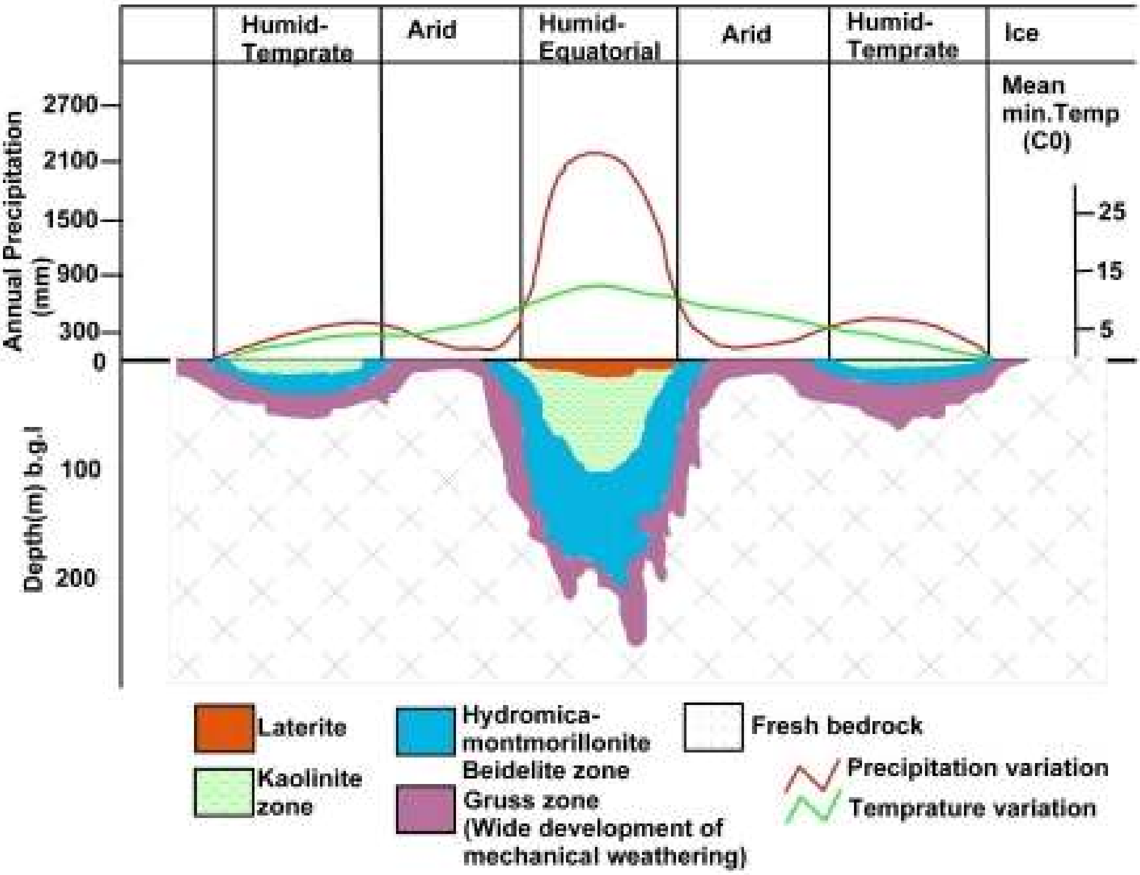


Figure 8) The relationship between depth of weathering profile and global climatic zonation in present times. (Adapted from Strakhov, 1967).

The mineralogical composition and lithologic texture of the bedrock also play important roles in the development of the weathered layer. Commonly thick regolith develops over coarse-grained salic rocks such as granites; granodiorites, and ortho-gneisses. Thick quartz-rich dominate the basal (top of the bedrock) part of the profile of salic rocks. On mafic bedrocks such as diorites, gabbros, diabases and dolerites, thick weathered mantle may developed but the base of the mantle tend to be clayey (UNESCO, 1984). On some metamorphic rocks of stable mineral composition such as slates, phyllites and argillaceous schists, weathered layers may be thin or absent, even when these rocks underlie extensive peneplains in climates otherwise favourable for deep weathering (UNESCO, 1984).Other environmental factors for the formation of deeply weathered regolith mantles include long tectonically stable period, moderate relief, and humid tropical climate. Formation of deep regolith requires long tectonically quiet (several million years) to develop (Nahon and Tardy, 1992). Tectonically active environments promote instability and hence enhance erosion of weathered mantle. For a deep regolith to form, the rate of chemical weathering and downward progress of the weathering front must exceed the rate of erosion. Hence, moderate relief is required that is sufficient for the occurrence of drainage to allow leaching of the products of chemical weathering. Wayland,(1934) and Willis,(1936) deduced that surfaces of low relief favour vertical rather than horizontal movement of meteoric water (in the vadose zone) so that weathering of rock necessarily occurred in situ. Significantly, high relief (i.e. uplifting) promotes mechanical denudation/stripping.

2.2 Landscape evolution by processes of deep weathering and stripping: previous studies

Landscapes evolve in response to external forces, such as tectonics and climate, which influence surface processes of stripping/denudation and weathering. In terrains where Pleistocene glaciations and aeolian are nonexistent, landscapes are dominantly transformed by the action of meteoric water (Taylor, 1998). Portion of water from rainfall infiltrates into the subsurface (ultimately as recharge) favouring deep weathering. Deep weathering involves the removal of materials in solution (chemical denudation) Wayland (1934) and Willis (1936) by the movement of infiltrating water as groundwater. Landscape evolution by process of deep weathering is accentuated by many authors,(e.g. Budel,1957, the theory of ‘double-planation’;Ollier,1959, ‘etchplanation’;Thomas,1960, ‘etch plain’; Twidale,1991, ‘the two-stages of landform’) in the weathering environments. However deep weathering as the process of landscape evolution was not included in the previous theories of landscape evolution e.g. Back wasting-Pedimentation theory of Penck, 1924 and King, 1962; and down wasting of Davis, (1899). Running water over the land surface accelerates mass movement and erosion of weathered mantle (stripping) causing change in landscape. The processes of deep weathering and stripping act contemporaneously with different rates of operation. The recent versions of stability-instability models take account of regolith formation and tectonics. A wider interpretation of these models considers (stability and instability) the result of a ‘cratonic regime’ (Fairbridge and Finkl, 1980). The longer period of (perhaps 10^7–10^8y) landscape stability involves advanced weathering. Alternatively, the period of instability enhance erosion of regolith. The development of key landforms (duricrust-capped plateaux, inselbergs, tors, core boulders and core stones) in weathered landscapes are commonly associated with an alternate cycles of deep weathering and stripping(Linton, 1955; Ollier, 1959;Büdel, 1982; Thomas, 1965; McFarlane, 1991;Tiwadle, 1981; Nahon and Tardy, 1992). It has also been suggested that these landforms are relicts that show deeply weathering process is followed by stripping (Pain and Ollier, 1996; Ollier and Pain, 1996). The work of Taylor, (1998) in Uganda clearly demonstrated the evolution of landscape through cycles of deep weathering and stripping which are tectonically controlled. Tectonic uplift is shown to induce episodes of stripping while tectonic quiescence is required for subsequent deep weathering. It is thought that climate (mainly rainfall and temperature) governs the rate at which these geomorphic processes operate, by controlling the input of meteoric water to the land surface (i.e. warm humid versus arid conditions).

2.2.1 Cyclic deep weathering and stripping history

The cyclic deep weathering-stripping model of Kebede, (2013) has, recently depicted the development of weathered land surfaces over the Ethiopian basement terrain. Here, only a brief summary of the model is presented. Nonetheless, more emphasize is given to data from field evidences and literature to test the reliability of each stage of the model and the dependability of the whole model. The model can be summarized in to four major stages of weathering-stripping processes, which were fashioned by phases of glaciations, tectonic quiescence, and optimal climate and uplifting:

The first stage involved complete stripping of Precambrian surfaces of Ethiopia by late Carboniferous-Permian glaciations. The second stage was the development of thick regolith cover during the Cretaceous period. The third stage involved mainly the stripping of the deeply weathered mantle following the Cenozoic uplifting of Ethiopia (Afar dome).This phase instigated the regionalization of geomorphic processes. The fourth stage is operating from late Miocene to present, and involves the regionalization of complex and contemporaneous weathering and erosion processes following the rainfall amount and distribution caused by Late Cenozoic uplift (mainly shield volcanoes).

2.3 Climatic and geological evidences for cycles of deep weathering and stripping

2.3.1 The extent and erosional landforms of Permo-Carboniferous glaciations: implication to stripping

Exposures of lithified, poorly sorted terrigenous glacial sediments are found in different parts of the Tigrai region in northern Ethiopia. The occurrence of glacial sediments in this region was first identified by (Dow et al., 1971). Dow et al., (1971) provided detailed lithological descriptions of these sediments and recognized as tillites. These glacial sediments consist of continental glaciogenic sediments, predominantly dark clay- and siltstones, which often contain dispersed pebbles or boulders (Bussert and Schrank, 2007). Stratigraphically, these sediments are situated between the overlaying Mesozoic sandstone and the underlying late Proterozoic, low-grade basement rocks (fig.9) of the Arabian Nubian Shield (ANS).

Figure 9) A representative outcrop showing the stratigraphy of the Paleozoic, Mesozoic sediments, and Precambrian basement rocks. (Photo taken near the Edaga Arbi town, Tigray region, northern Ethiopia)

The recent study on Palaeomagnetism properties of Paleozoic sediments in Tigray region (northern Ethiopia) Kidane et al., (2013) showed that the glacial sediments in the north of Ethiopia are compatible in age with Dwyka group sediments, which were formed during the Karoo Ice ages (South Africa) (Hambrey& Harland 1981; Deynoux et al., 1994; Rubidge, 2005). He concluded that the late Carboniferous Dwyka land ice sheet had probably extended more than 1000 km further north (including northern Ethiopia) than previously known. (Le Heron et al., 2009) also report the presence of glaciated regions in the neighborhood of northern Ethiopia during the late Carboniferous to early Permian period.

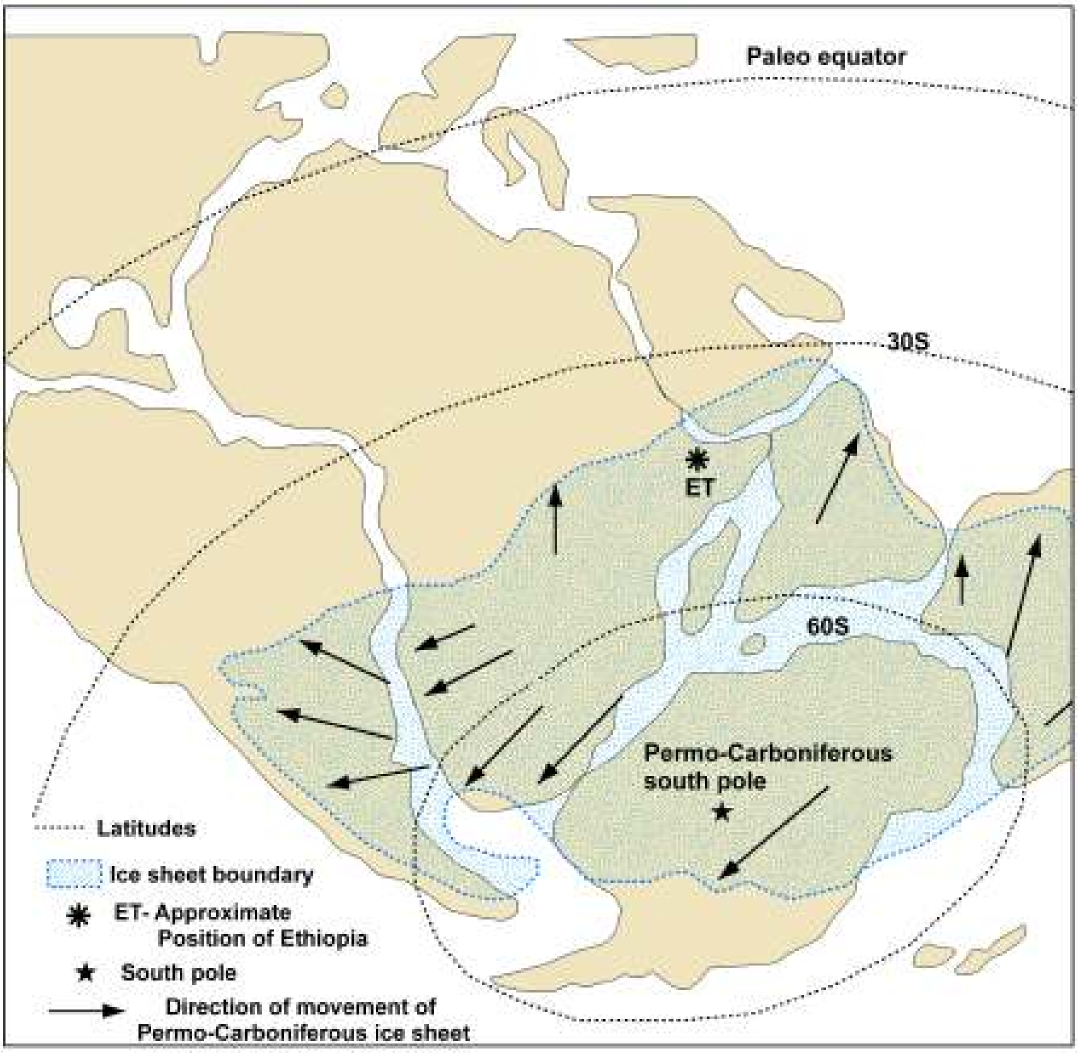


Figure 10) Paleo geographic map of the continents during the late Carboniferous and early Permian epochs showing the inferred distribution and direction of movement of continental ice sheet
Source:http://www.britannica.com/EBchecked/media/92057/ accessed on 17/03/2013

In some paleogegraphic reconstruction (e.g. Scotese, 1994) it is depicted that Ethiopia was positioned south of paleo equator in low to medium latitude (roughly about 35^0-50^0 S) (fig.10) where it was covered by extensive ice sheet that possibly flowing in north east in to Arabian plate.

This is a view in agreement with the work of Bussert,(2010) who proposed a northward directed palaeo-ice flow direction based on the analysis of palaeo landforms(wedge striae, crescentic gouges, lunate fractures and roche moutonnées) of glacial erosion in northern Ethiopia.

The occurrence of these erosional landforms suggest that their formation is attributed to mechanical erosion/stripping that had significantly reduced the relief of the landscape over the surface of Proterozoic basement rocks.

Coltorti et al., (2007) described the landscape on basement rocks of northern Ethiopia as exhumed planation surfaces because of intense erosion. He contends that the erosion was so intense that it was able to planate the northern Ethiopian basement landscape to altitude not too far from sea level.

Elsewhere, Tadesse and Melaku, (1998) have reported the occurrence of glaciogenic sediments and their erosional landforms on basement rocks of Negele area (southern basement). They have indicated that these rocks are comparable with the late Paleozoic glacial sediments in northern Ethiopia described by Dow et al., (1971).

Furthermore, Hunegnaw et al.,(1998) also reported the occurrences of Permian pre-rift sandstones and conglomerates of glacial to fluviatile origin in the Ogaden basin (eastern basement region).

In the Blue Nile gorge (western basement region), (Jepsen and Athearn, 1964), reported the occurrence of pre-Adigrat sediments filling the N-S oriented channels formed within Precambrian basement rocks.

It is also observed in the field that the pre-Adigrat sandstone directly overlays the completely stripped surfaces of the Precambrian basement rocks in the Anger graben, western basement region (fig.11).

Figure 11) Field photo showing an outcrop where the pre- Adigrat sandstone directly overlies the stripped surface of the Precambrian basement rock. Note that no weathering mantle detected along the contact zone. Photo was taken in Western basement terrain, Harkumbe locality about 60km north of Nekemte town.

This is well-preserved field evidence indicating that the late Palaeozoic continental ice sheet had at least affected some part of western Ethiopia and had resulted in complete removal of weathering mantle from the top of bedrock.

The general insinuation is that the advancing Permo-Carboniferous glaciations had instigated complete stripping that significantly lowered the relief of the entire region. The same surface is common elsewhere in east Africa (e.g. Uganda) (Taylor and Howard, 1998). Thus, this paleo surface is presumed the first erosional surface in the geomorphic landscape evolution models of Uganda (Taylor and Howard, 1998) and Ethiopia (Kebede, 2013).

2.3.2 Warm and wet climatic conditions in the Jurassic to middle Cretaceous period: implication to deep weathering

Deglaciation at the end of the Palaeozoic is associated with the northward migration of Gondwanaland to lower latitudes (tropic-sub tropic regions), (fig.12) (Caputo and Crowell, 1985).

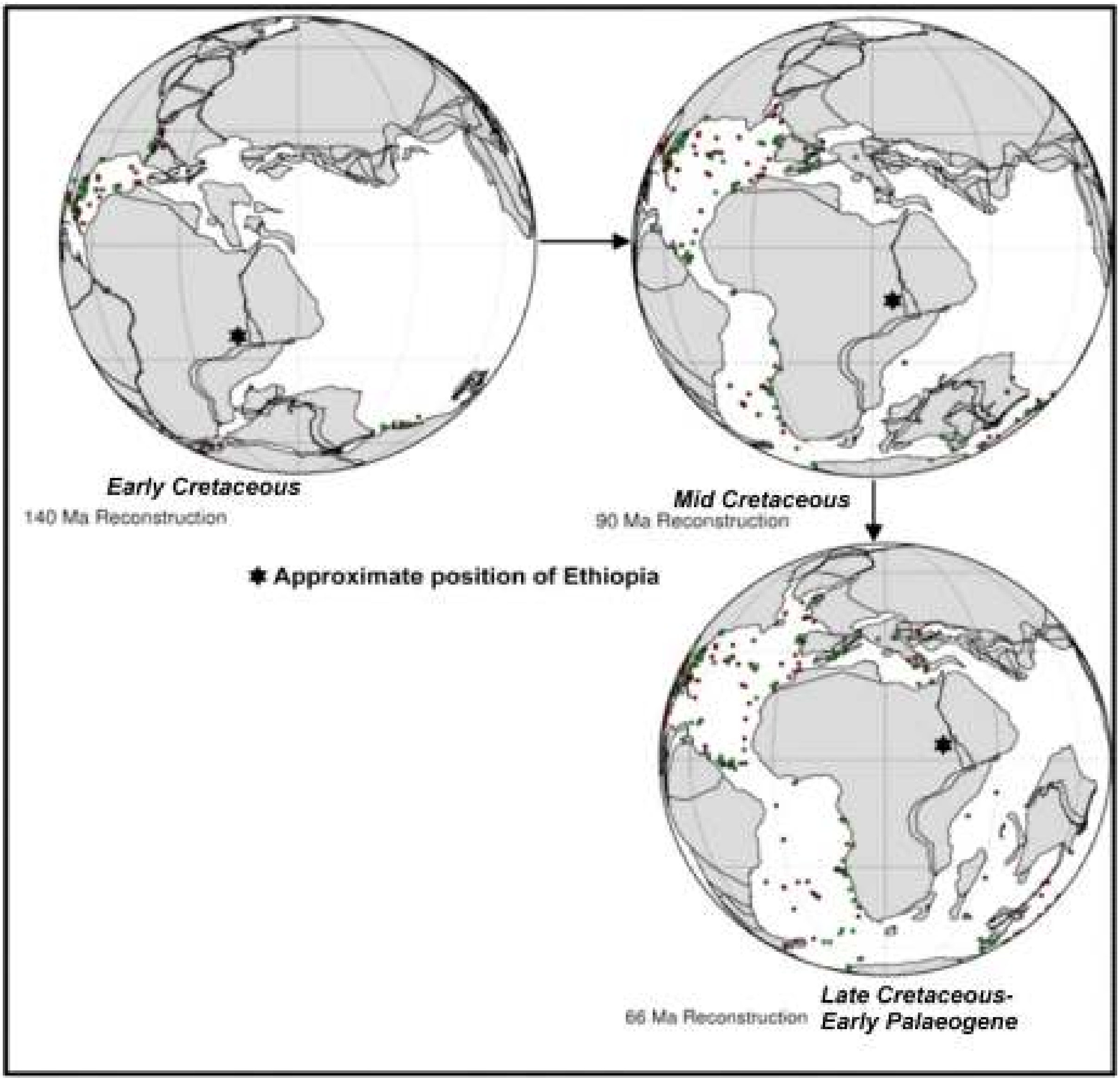


Figure 12) Plate tectonic reconstructions of Gondwana land from early Cretaceous to late Cretaceous-early Palaeogene time

Source :(www.odsn.de/odsn/services/paleomap/paleomap.html)

Furthermore, the other prevalent scenario was the significant rise in atmospheric CO_2 content during Jurassic-mid Cretaceous. The mid-Cretaceous record provides abundant evidence of humid continental climates and reduced areas of continental aridity (Fawcett and Barron, 1998). This interval was a time when continental ice sheets were absent on the Earth: it was a “hothouse” Earth (Burke and Gunnel, 2008).

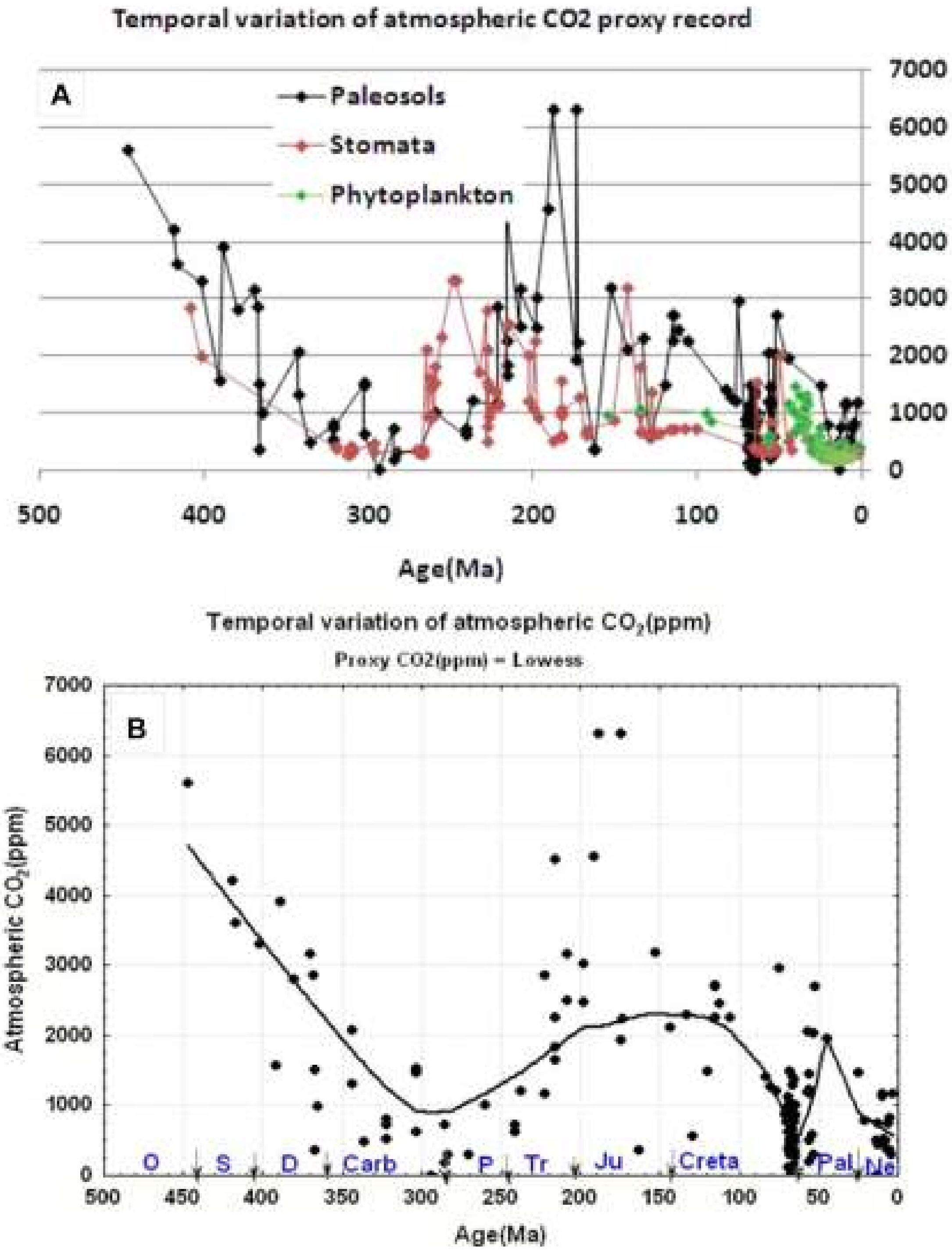


Figure 13) A) Plot of atmospheric CO_2 concentration records from three major proxies: Paleosol, stomata and phytoplankton. B) Atmospheric CO_2 concentration records of proxies: paleosol and stomata; the bold dark line is lowess smoothing fit to provide a clearer picture of the overall shape between CO_2 and age. Proxy data source: compilation of Royer, (2006)

This is in agreement with proxy elevated atmospheric CO_2 levels in paleosols, density of stomata in fossil tree leaves and phytoplankton as it is compiled by (Royer,2006)(fig.13).

Based on these proxy indicators, the CO_2 content was extremely high (reaching perhaps above 3000 ppm) (fig.13) for the Jurassic and the early to middle Cretaceous. It was many times larger than today.

Such elevated CO_2 levels in these long time scales were thought to be fed by volcanic eruptions along the rifting areas (Ruddiman, 1997).What so ever the case, those conditions of very high CO_2 content in the atmosphere would have enhanced the magnitude of the greenhouse effect during that period, compared to present conditions.

Frakes, (1979) stated that, between the middle Triassic and the middle Cretaceous, climates were characterized by mean annual temperatures possibly as much as 10ºC higher than today at the global scale.

Thus, higher temperatures forced higher evaporation rates, increasing the water content of the atmosphere and the global greenhouse effect, and therefore, a much higher precipitation rate over the continents, under very warm climates. These conditions in the parts of Africa and elsewhere, which lay in the humid tropics during the Cretaceous, would have been highly favourable to deep weathering. Thus, extremely intense weathering processes would have been developed generating very thick weathering mantles. Many authors (Radwanski and Oilier,1959; Ollier,1959;1960; McFarlane et al., 1992; Ollier, 1993) east Africa, (Thomas, 1965; 1966; Thomas and Thorpe, 1985) west Africa (Partridge and Maud, 1987) southern Africa (Schaefer et al., 1995), South America (Dewandel, 2006) India (Mabbutt, 1965; Fairbridge and Finkl, 1980)Australia, have reported the presence of thick weathering profiles produced by deep weathering of Precambrian rocks in many areas of Gondwanaland.

In Ethiopia, the development of thick regolith mantle favoured by tectonic quiescence and optimum climatic condition in late Jurassic is discussed by Kebede, (2013), and considered as the second stage in his landscape evolution model.

Thus, the late Mesozoic landscape of Ethiopia consisted of deeply weathered mantle produced by the in situ alteration of Precambrian basement bedrocks primarily from the Jurassic to mid-Cretaceous.

Where exhumed or uncapped by latter terrains, this surface is identified by key landforms such as duricust capped plateaux, inselbergs and core boulders. Thick weathering profiles exposed by road cut, slope cut and stream cut are good sites to observe the weathering-bedrock profiles. The presence of core stones and undisturbed quartz veins in the weathering profile (fig.14B) helps in distinguishing the insitu alteration of the weathered mantle.

The development of thick weathering profile requires long tectonically stable period. It therefore, indicates that significantly thick regolith observed today must have been developed by optimum climatic conditions during prolonged tectonically quiet period. However, the present-day thickness varies from place to place depending on the operating geomorphic processes and other local factors.

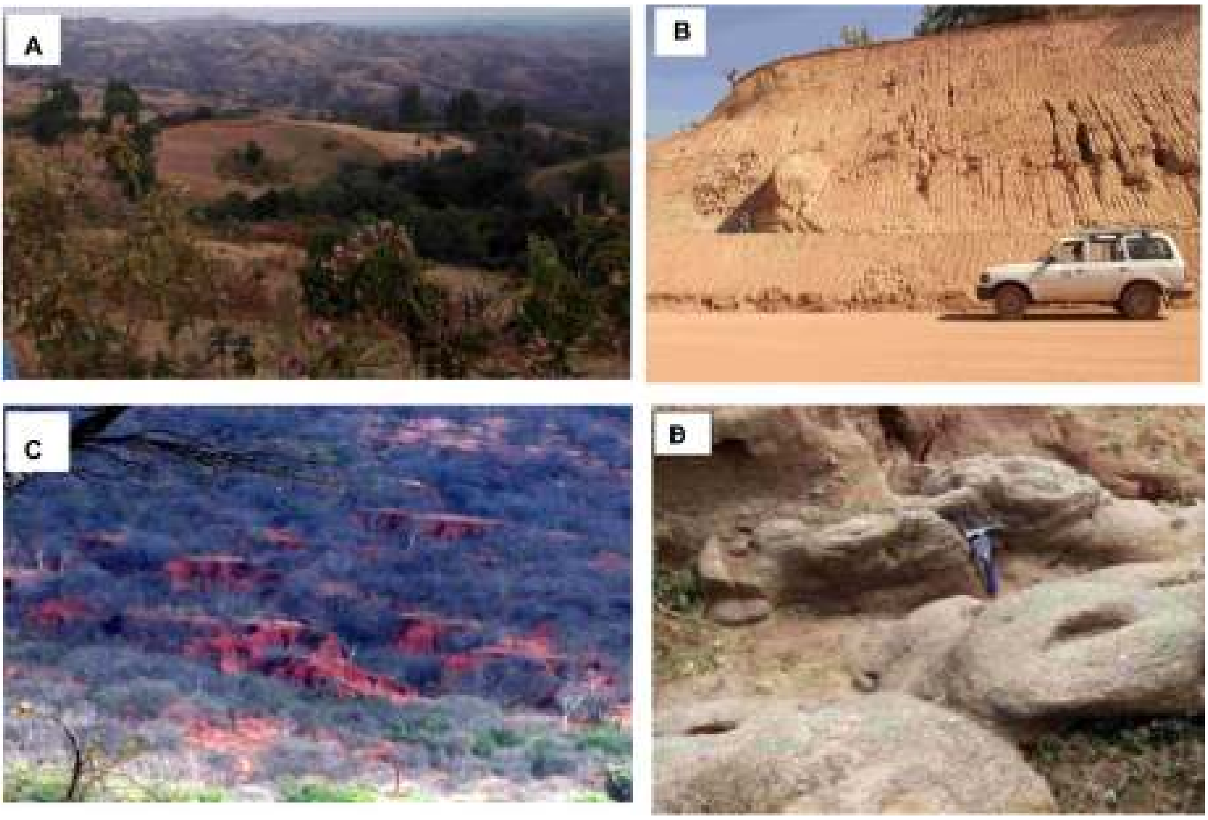


Figure 14) Surfaces over the basement rocks of Ethiopia A) Landscape view of part of Uwa catchment, western basement region; note absence of deep incision to expose bedrocks. B) Thick deeply weathered profile with core boulders in it; a newly exposed road cut near Daleti locality, western basement region. C) Exposure of remnants of weathered mantle, in interfluves of Borena lowland. D) Core stones and “grooves” formed by differential weathering manifesting weathering.

This surface is well preserved in western Ethiopia than any other part in the country (fig. 14 A, B). In the northern part of Ethiopia, the weathered mantle is totally stripped by the Cenozoic erosion process (fig 14D). In the Borena lowlands, this weathered mantle is preserved under the basalt of late Cenozoic, in some localities it is exhumed in interfluves areas (fig. 14C).

2.3.3 The Cenozoic magmatic plume induced uplift (Afar dome): the cause of stripping

Non-orogenic crustal uplift had occurred in Ethiopia by impingement of a mantle plume head. This regional basement uplift had resulted in the formation of Afar dome (Sengor, 2001; Pik, et al., 2003) (fig.15). The higher relief due to the uplifting instigated fluvial erosion (fig.15). Burke, (1996) suggested that erosion started as the Afar dome started to rise and before the eruption of the Ethiopian traps began. He intended that the absence of lateritic cover over the African surface over a roughly circular area of ≈1000km diameter centred on the Afar dome is attributed to this erosion process.

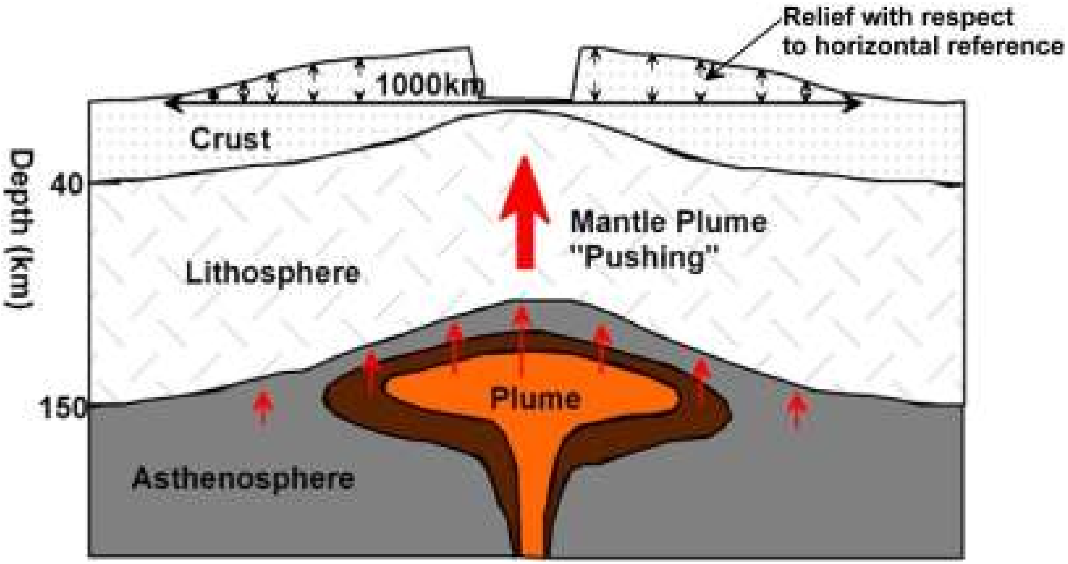


Figure 15) Uplift model predicting large-scale uplifted dome provoked by mantle plume impingement on continental lithosphere; note that the relief is higher towards the centre of the dome (eg.Ethiopian Plateau) adapted from Wichura, et al., (2011)

The absence of laterite in a wider region is due to topographic swell that lead to stripping of the deeply weathered surface on an upward surface (Burke and Gunnel, 2008). Abdelsalam and Ismail, (2012) indicated that the eruption of 30Ma volcanic rocks was on a peneplain surface, as indicated by the relatively flat base of the volcanic pile extending for hundreds of kilometres. Merla and Minucci, (1938) had also reported the earlier Ethiopian landscape as having been an area of low relief surface. They intend that the low relief was a product of pre-volcanic erosion perhaps in Eocene times, which could have been interpreted to be a result of stripping. It could be envisaged that in many areas of northern Ethiopia, the lateritic cover has been completely removed by erosion.

However, in several locations including the western extreme of northern Ethiopia, the flood basalt eruption that followed the domal uplifting protected further erosion of laterites (weathered surface) as it is noticed from lithological logs of water wells. Consequently, in several localities of Ethiopia now laterites mark the contact between the basement and the flood basalts sequences. Pik et al.,(2003), indicated by plotting the contacts(basal levels) between flood basalt and the basement rocks, that the total surface uplift lies significantly above sea level westward (400m-500m in the Sudanese plain) and reaches a maximum elevation of ≈2000m towards the eastern border of the plateau(nearer to center of the dome) (fig.16). This shows that the western and the southern basement regions would far from the centre of the uplift attaining relatively lower relief.

Thus, the stripping would have been a slower process in western and southern region as compared to the northern region. Consequently, the process of stripping was not able to induce complete removal (i.e. low relief) of late Cretaceous deep weathering mantle from the western and southern regions. As a result, surfaces of remnants of weathered mantle is observed occupying relatively higher elevations (as high as 2000m above sea level) and deep incision is not common (fig.14A) in the western region. In the Borena lowlands (southern basement terrain), the slow process of denudation could be evidenced by the presence of swarm of inselbergs dotting the extensive low relief areas (plains) and remnants of preserved weathering mantle in interfluves capped by duricrusts(dominantly calcrete and fericrette). Preserved paleo-weathering mantles are observed in areas rapidly capped by Cenozoic volcanics. This is evident from borehole litholgic log penetrating into the basement rocks overlain by younger basalts (discussed in chapter three).

Davidson and Rex,(1980) and Davidson,(1983) had also reported the presence of a basal unit of red lateritic grit below the 45 Ma basalts of the Omo River valley in southern Ethiopia, as well as beneath other younger basalts (≈30 Ma) elsewhere in that region. The laterite was interpreted as capping a low-relief pre rift surface onto which the basalts were emplaced. Thus, the Afar plume impingement has instigated the process of stripping which had operated at various rates in different regions.

2.3.4 The late Cenozoic uplift and its influence on moisture-bearing air circulation: implication to variations in rainfall amount and regionalization of geomorphic processes thereof

The present day high topography of north-western plateau of Ethiopia is the result of thick lava pile and the uplift occurred in the past 30Ma through the combined effects of the rise of Afar mantle plume and rift-flank flexuring of the Afar depression and main Ethiopian Rift (Pik et al, 2003; Gani and Abdeselam, 2007).

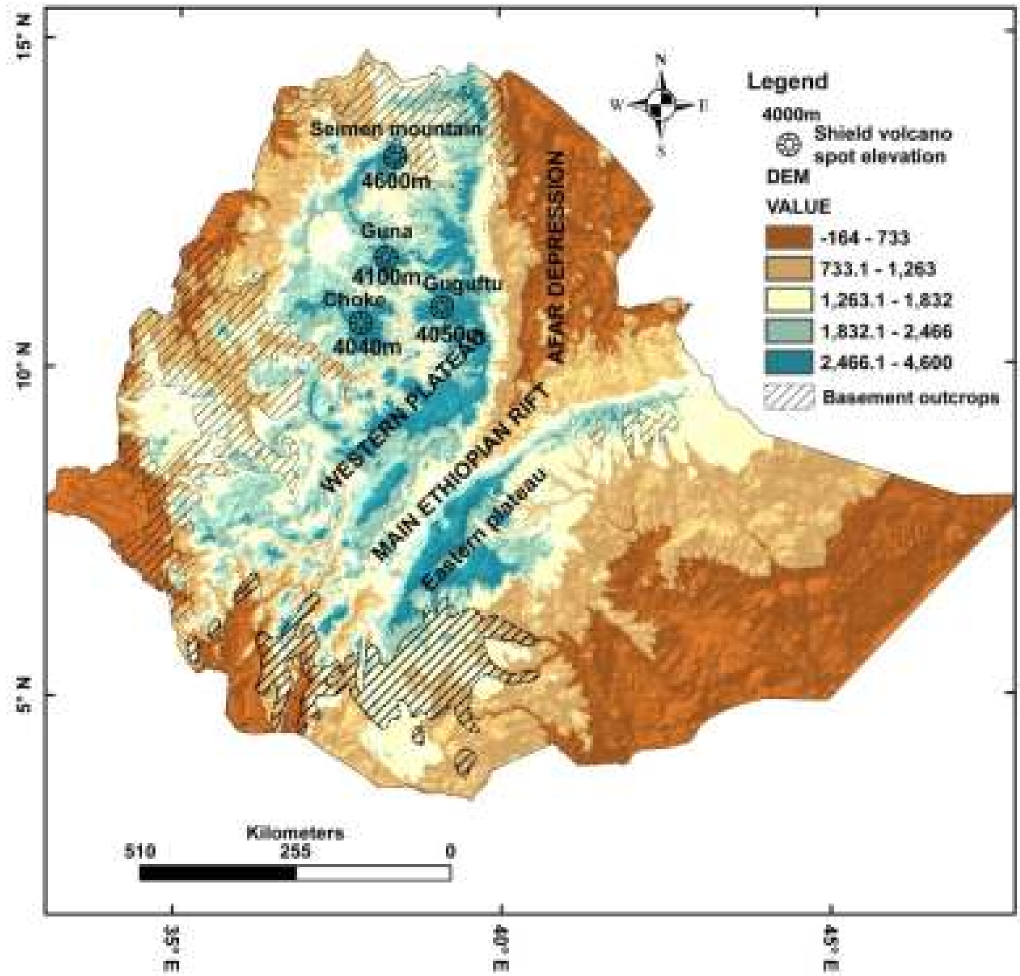


Figure 16) Distribution and extent of basement outcrops in Ethiopia, elevation variations and locations of the main shield volcanoes are also indicated.

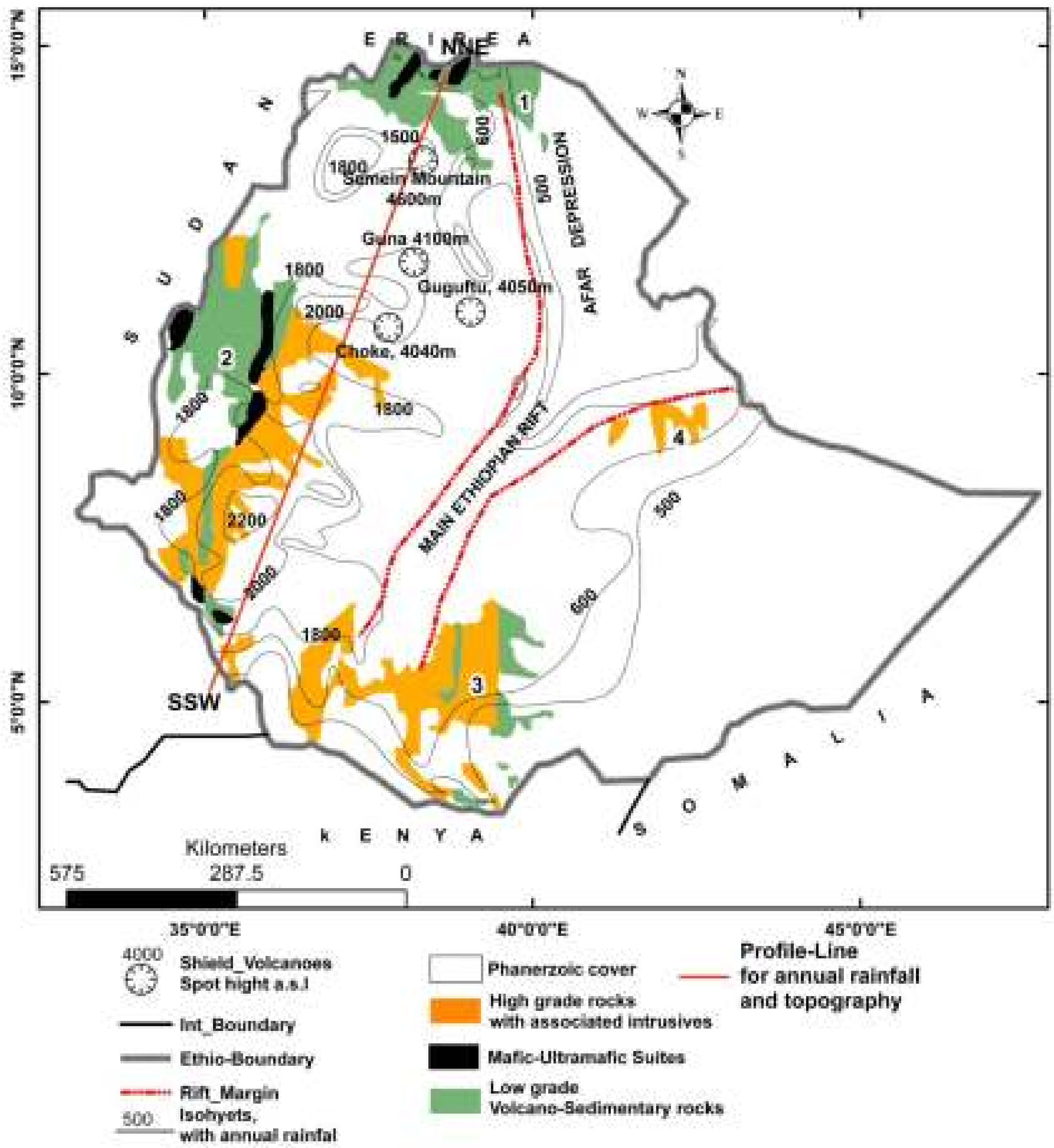
Above the plateau, parts of the highest reliefs are formed by subsequent, less voluminous, shield volcanoes (fig.16). These prominent shield volcanoes(e.g. Choke, the Semen Mountain, Guna and Guguftu)(fig.16) over the north western part of the Ethiopian plateau further rise the altitude of the plateau well over 4000m a.s.l (fig.17) forming an efficient orographic barrier to moisture-bearing winds from Indian and Atlantic oceans and Congo basin.

This controls the distribution and amount of rainfall in the country (fig.17) thereby influencing the geomorphic processes regime and environmental conditions (Sepulchre et al. 2006; Wichura et al., 2010a).

Consequently, the northern region is isolated from heavy and prolonged rains and remained rain shadow region (fig.17). The annual rainfall ranges from 500mm to 700mm (fig.17). The western region of the country however, remains under heavy and prolonged rainfall that ranges from 1800mm to 2200mm (fig.17).

The Borena lowland receives annual rainfall that ranges from 500mm to 600mm (fig.17); arid to semi arid conditions have been active in this region.

Therefore, the variation in rainfall amount and distribution over different lithologies cause the regionalization of geomorphic process regime that gave rise to variations in rates of weathering- erosion processes over the Precambrian and Phanerzoicdrocks.



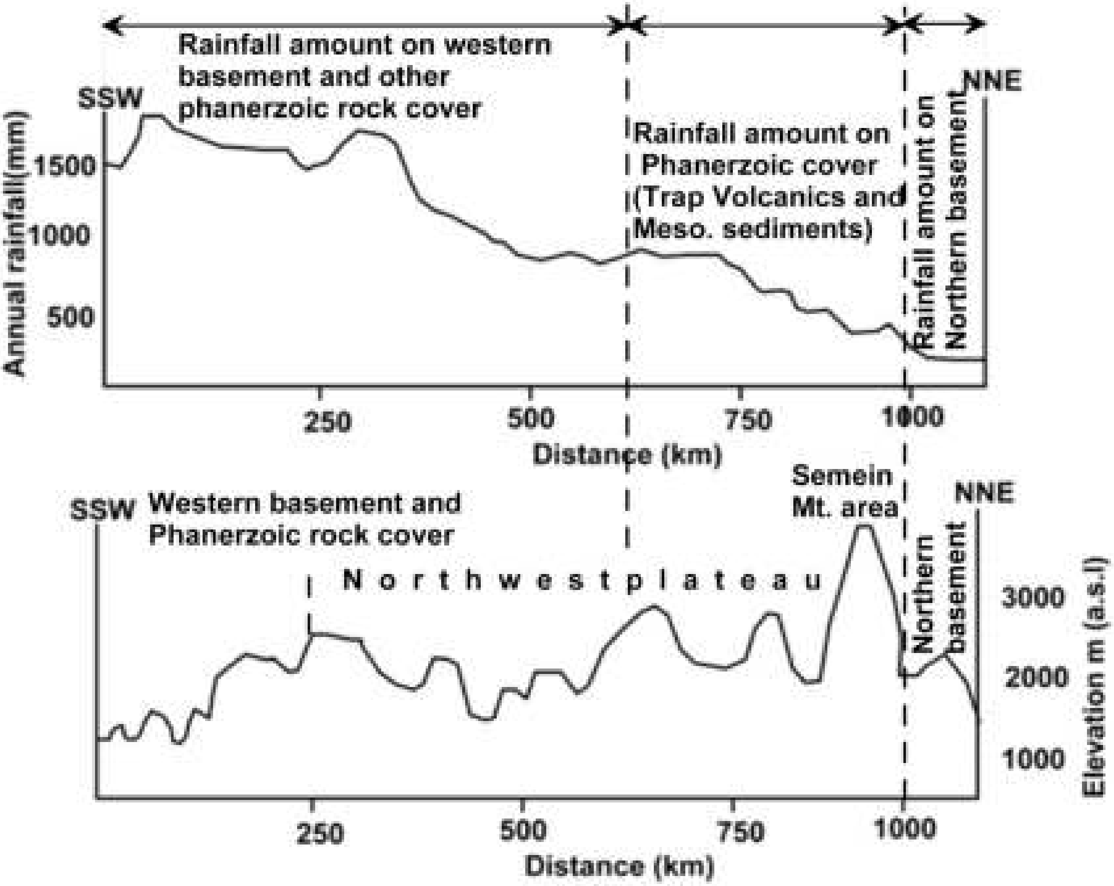


Figure 17) Locations of the main shield volcanoes and distribution of annual rainfall amount over the basement rocks (top). B) Cross section depicting the variation of annual rainfall amount from SSW to NNE (bottom) (indicating the general decrement of annual rainfall from SSW to NNE) and cross section indicating the topographic variation from SSE to NNE (bottom).

CHAPTER 3: FIELD-BASED GEOLOGICAL EVIDENCES AND THE RESULTING GENERALIZED WEATHERED MANTLE-BEDROCK PROFILES

3.1 Introduction

Much of the evidences are generated from field investigation, which is corroborated by data obtained from lithologic logs. Field evidences such as variation in regolith thicknesses and contacts between the tertiary volcanic and weathered surfaces over the basement rocks are generated.

Close observation to road, stream, and slope cut along selected traverses (in the three basement region) enabled the description of weathering profiles (thicknesses and vertical heterogeneity in texture) on each lithologic type in each region. Weathered mantle-bedrock profiles are described in the three regions along selected traverses and in the type study sites.

There are many schemes of descriptions of weathering profiles (e.g. Geological Society of London, 1990; Sueoka, 1988; Ollier and Galloway, 1990; McFarlane, 1992; Nahon and Tardy, 1992). These descriptions are often subjective and are applied inconsistently (Taylor, 1999). In the current work, description of weathering profile is made based on textural and lithological variations within weathered profiles to avoid inconsistent application. Lithologic logs from wells drilled in basement terrain have been collected from data base of respective Regional Water Resources Bureaus and Water Works Construction Enterprises. Data lacking geographic locations and those with incomplete records are discarded. The data have been plotted on geological map of each region to check its reliability with respect to lithology and substantiated by field evidences obtained from cut of road, river, slope and quarry sites. Data with inconsistent lithologic descriptions has been discarded. The lithologic logs are then re-interpreted in terms of weathering-fracture bedrock profiles and the depths to bed rock are estimated. To enhance the understanding of regional variation in geomorphic processes, detailed studies have been carried out in (representative) study sites. Evidences from the regional observations are corroborated in to data obtained from the three representative catchments.

3.2 The type study sites

3.2.1 Worei catchment

The Worei catchment is located in the northern basement terrain west of the western flank of the Ethiopian rift. It covers an area of about 920km^2. Bedrock geology underlying the catchment has been systematically mapped in Axum, Adigrat, Adi arkey, and Mekele sheets.

Low grade metamorphic rocks of slate, phylites, black limestone and meta-volcanics dominantly cover the area (fig.18). Glaciogenic sediments (tillites) are found overlying these rocks. Adigrat sandstone further overlies these rocks and the Cenozoic basalt and pyroclastic material found on top of the other units occupying the northern tip of the catchment (fig.18).

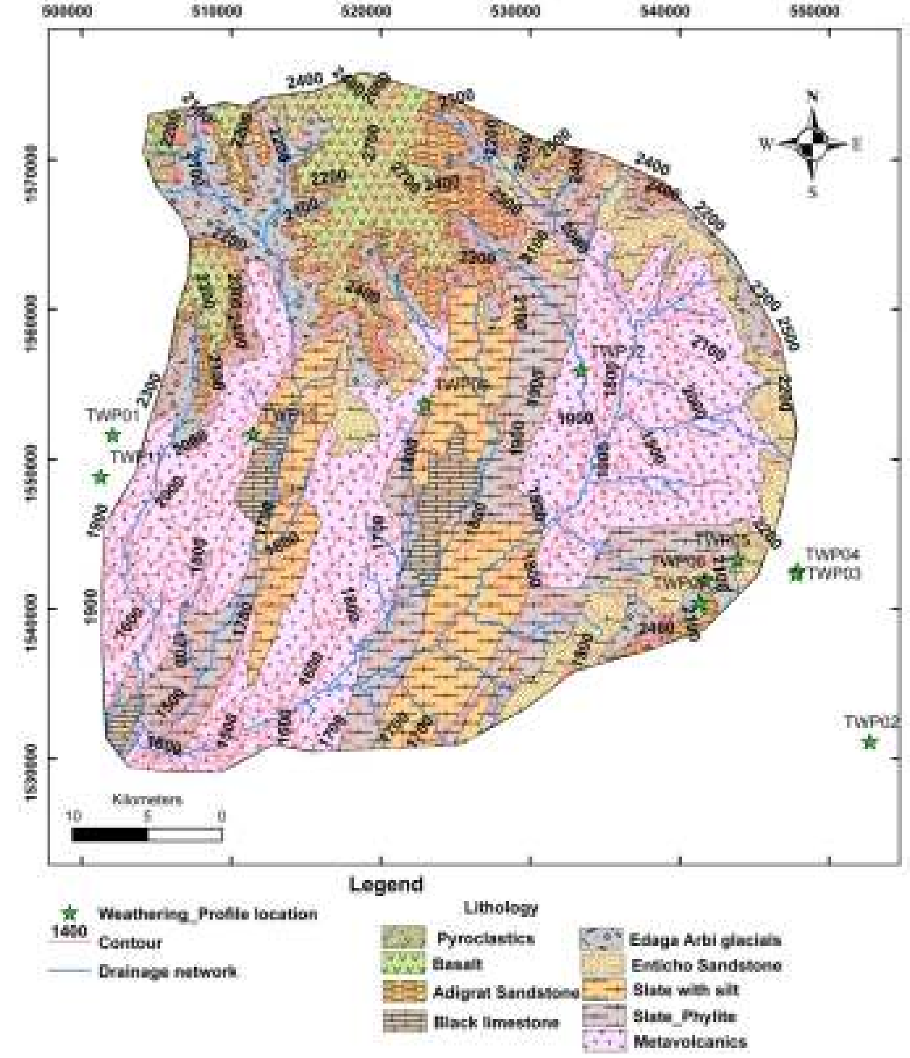


Figure 18) Geological map of the Worei catchment with overlays of contour and drainage network. (Digitized from Adigrat sheet (EIGS, 1977); Axum sheet, (GSE, 1999); Mekele sheet, (GSE, 1971) and Adi arkey sheet (GSE, 2000). Locations of weathering profiles are indicated by green filled stars which are described in section 3.3.

Annual rainfall varies between 600mm to 700mm. The catchment has high relief slopping from 2800 m.a.s.l in the north to about 1400 m a.s.l in the south (fig.18). Taking the two points the relief is about 1400m a.s.l. This gives an area surface gradient of about 30m/km. Because of this relatively higher relief the catchment is deeply incised.

It is drained by Worei stream and its tributaries. Data from the River gauge station at Maikenetal (Station No.121005) also indicates that runoff following the summer rain (June, July, and August) reaches up to 300m^3/sec. This indicates that erosional processes are intense enough to strip the surface of its loose (weathered) mantle.

3.2.2 Uwa catchment

Uwa catchment is situated in the western basement terrain. It covers an area of 1920km^2. Unlike the Worei catchment, this region is underlain by a variety of high-grade (gneisses, schists) rocks. It includes meta-sediments and undifferentiated group of metamorphic rocks (mélanges). Precambrian acidic to basic rocks, which include granites, grano-diorites and gabbros, intrude the bedrocks (fig.19).

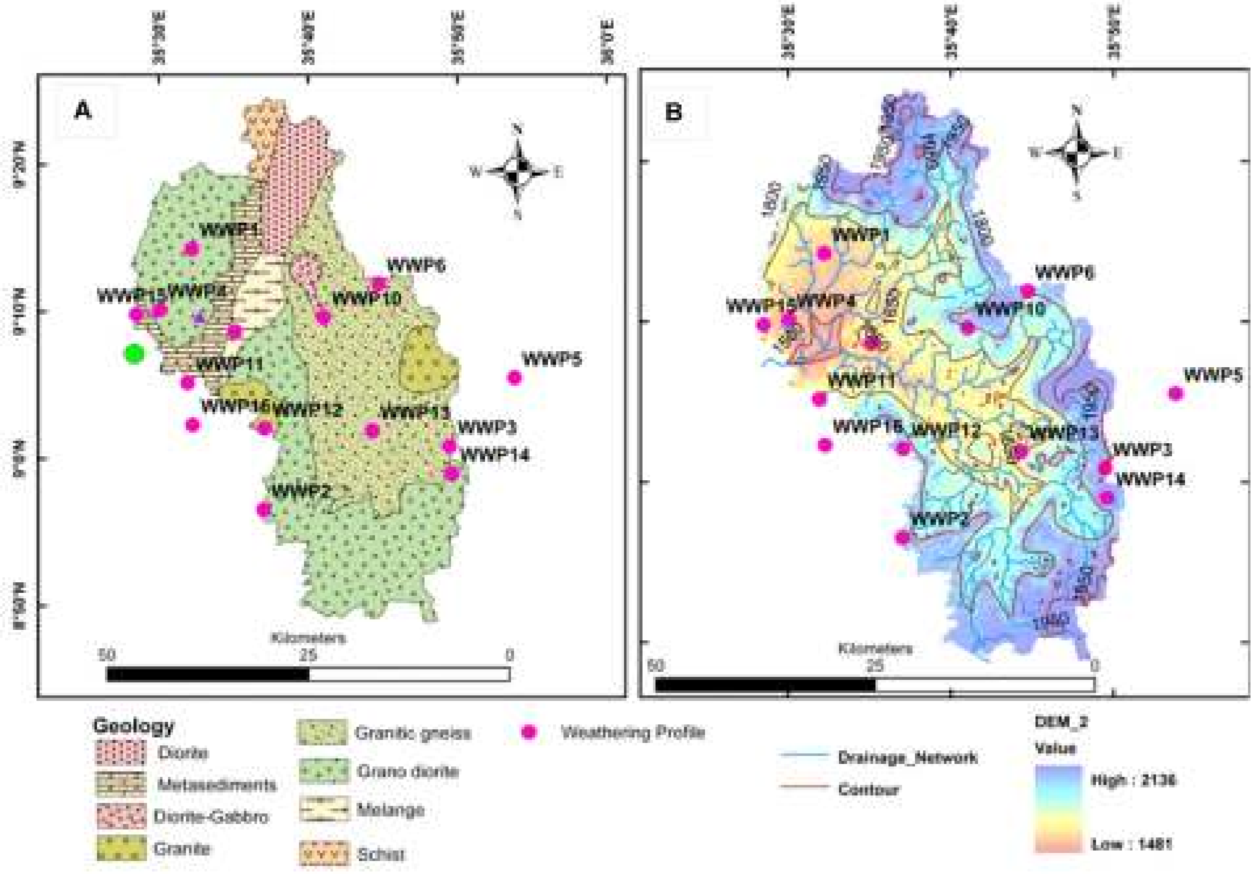


Figure 19) A) Geological map of the Uwa catchment with overlay of points (pink filled dots) indicating locations of weathering profiles which are described in the text of section3.3. (Geological map is digitized from Gimbi sheet (GSE, 2001) and Gore sheet (EIGS, 1987). B) An overlay of topographic map (derived from DEM of Ethiopia) and drainage network.

The catchment exhibits a rolling topography and drops over 600 m from the northern boundary(2140m a.s.l) to the south eastern terminus(1480m a.s.l) (fig.19). This gives the surface gradient to be low (about 15m/km). Despite this relief, the catchment is not deeply incised.

Drainage channels emanate from two trends NE-SW and SE-NW and drain in to Birbir River. Peak runoff during summer (Jun, July, and August) is about $50m^3$/sec (gauging station 101009) which is very low (≈1/6) compared to Worei catchment. Annual precipitation ranges from 1900-2200mm. The condition of high amount of rainfall and low runoff implies that the rainfall is buffered by thick regolith in the catchment. Consequently, erosion is less intense to cause complete removal of the weathered mantle.

3.2.3 The Alona-Kefera catchment

This catchment is sub catchment of Dawa basin and is situated in southern basement region. Basement rocks of different types of gneisses, schists, and granites dominate the catchment with very patchy basalt exposures at the northern terminus. Extensive alluvial deposits, which are derived from gneisses and granite bedrocks and inselbergs, dominate the low relief of the area (fig. 20).The area is characterized by rolling topography that generally decreases from NW to SE direction; higher elevations are in the northern terminus. The central and southeastern parts are characterized by low-lying topography (fig. 20). The Alona, Tilo-kolba, and Kukubi plains are worth mentioning among extensive plain in the area. The streams draining the type catchments are all the tributaries of Dawa River. These streams are flowing within basement terrain. Valleys are commonly broad and thick alluvial sediments are accumulated in valleys.

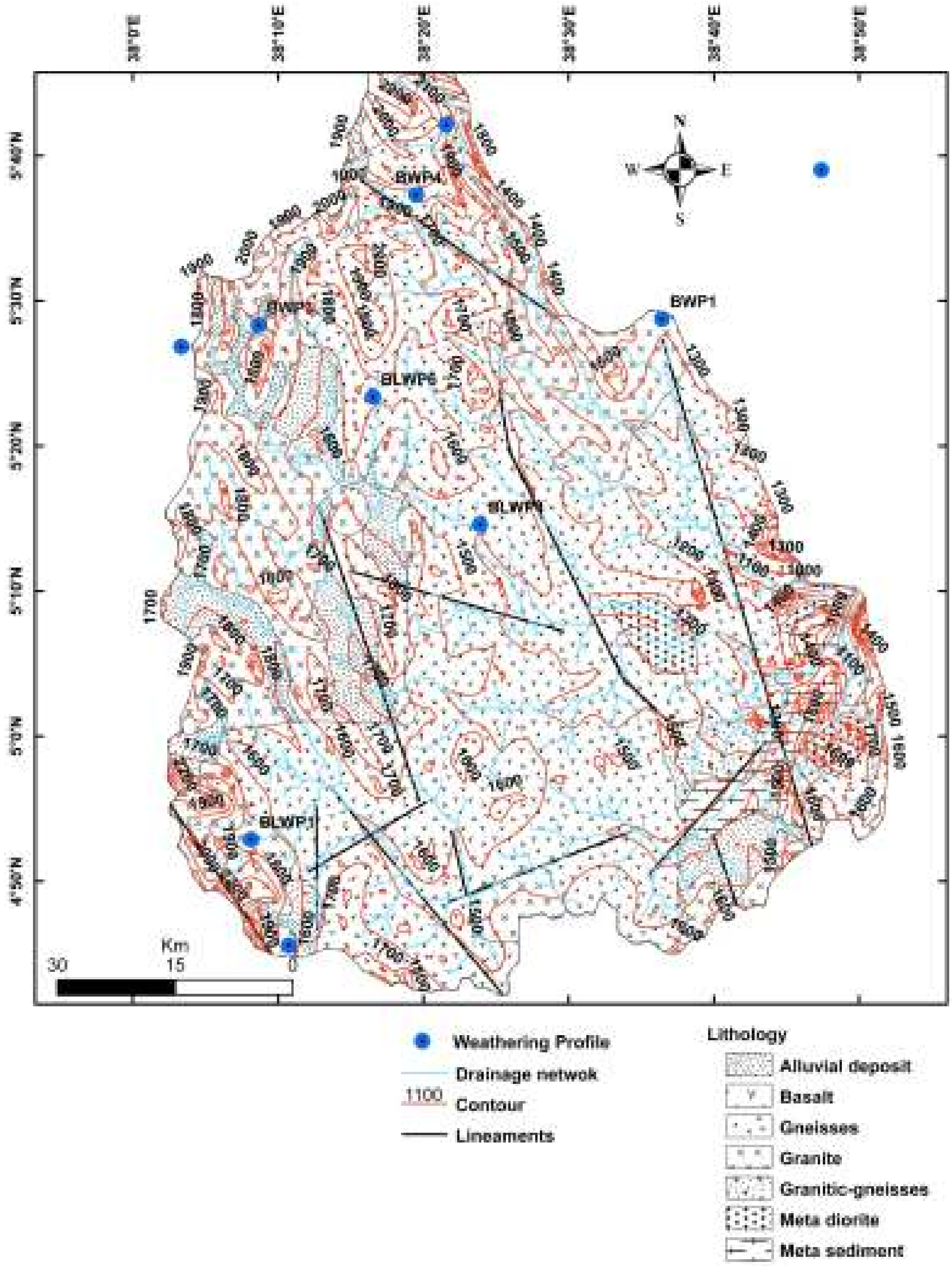


Figure 20) Geological map of the Alona-Kefera sub catchment with overlay of points (blue filled dots) indicating locations of weathering profiles, contour lines indicating topographic variations and drainage networks. (Geological map is digitized from Yabello sheet (GSE, 2004) and Hagere mariyam sheet (GSE, 1997).

The effect of differential weathering is apparent in the plains where resistant granites and gneisses form swarm of inselbergs dotting the plain. The presence of inselbergs could indicate that weathering was followed by stripping process. Duricrusts (fericrette and calcrete) ubiquitously found in the extensive plains. Erosion resistant materials mainly quartz and feldspar mineral fragments dominate the top of gently sloping interfluves areas. Annual rainfall varies from 500mm to 700 mm. The Borena lowland generally exhibits semi arid to arid climate.

3.3 Investigation of weathered mantle-bedrock profiles in type study sites and the surrounding areas

3.3.1The Worei catchment

For the northern, basement region 41 weathering profiles are described and analyzed but 12 are shown in the figure (fig.21). From all the profiles and lithologic logs, depth to bedrock (regolith) mantle is estimated (fig. 21). Figure21 depicts a marked similarity among the profiles in the Worei catchment and the surrounding.

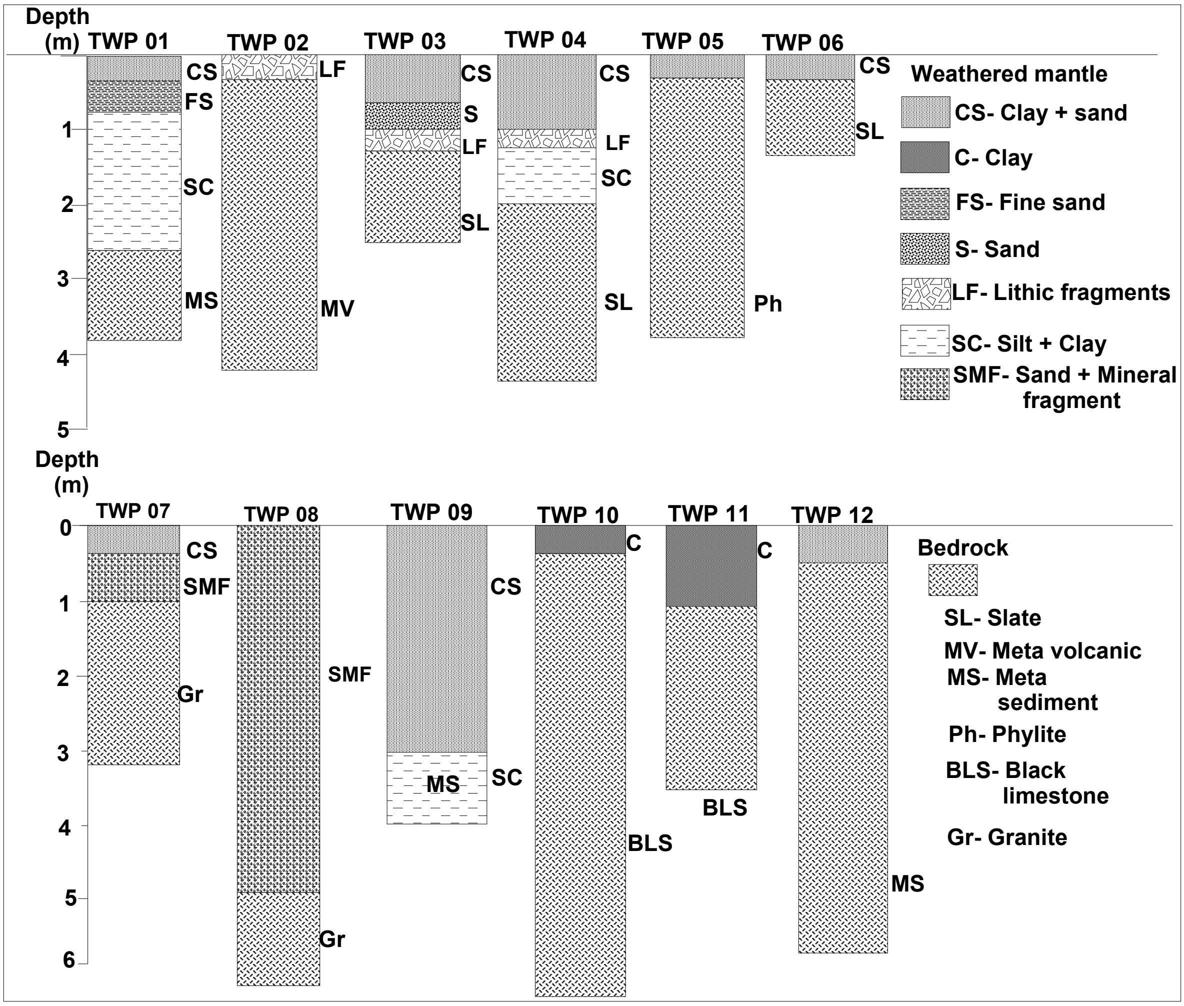


Figure 21) Weathering-bedrock profiles for the Worei catchment and the surrounding area.

The majority of the profiles are capped by clay and fine sand detritus mix with thickness ranging from 0.2 to about 3 meters. In some profiles (TWP5, TWP6, TWP12) this is directly underlain by fractured bed rocks while silt to clay detritus mantle of thickness 0.5 to1meter underlie the remaining profiles. Ferricrete or laterite is generally absent or very thin if present in all the profiles.

Figure 22) Field photos showing exposures where weathered mantle is almost nil: A) Meta volcanic; B) Slate bedrock capped with very thin soil cover; C) Eroded granite exposed at lowland around Rama locality. D) Stripping of the pre-weathered material often reveals boulders; granite boulders exposed on the way to Rama

In general, in the type catchment and the northern basement region at large, the result of field observations on exposures of road cut and the interpretation of lithologic logs show the depth to fresh bed rock below 10m with mean value only about 2m (fig.23).

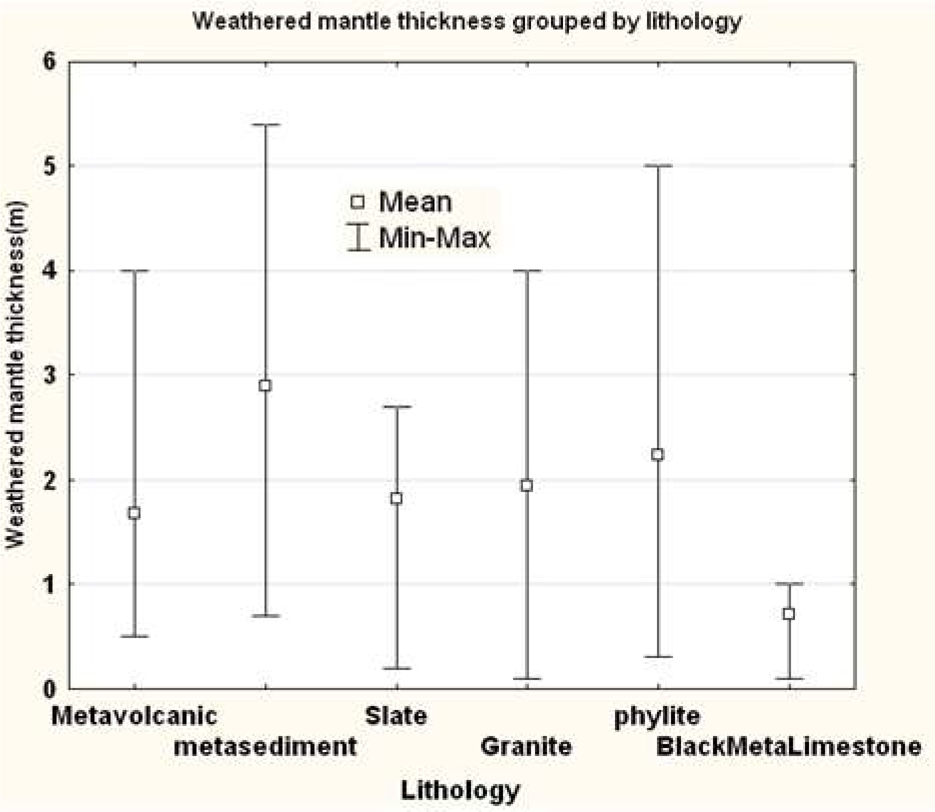


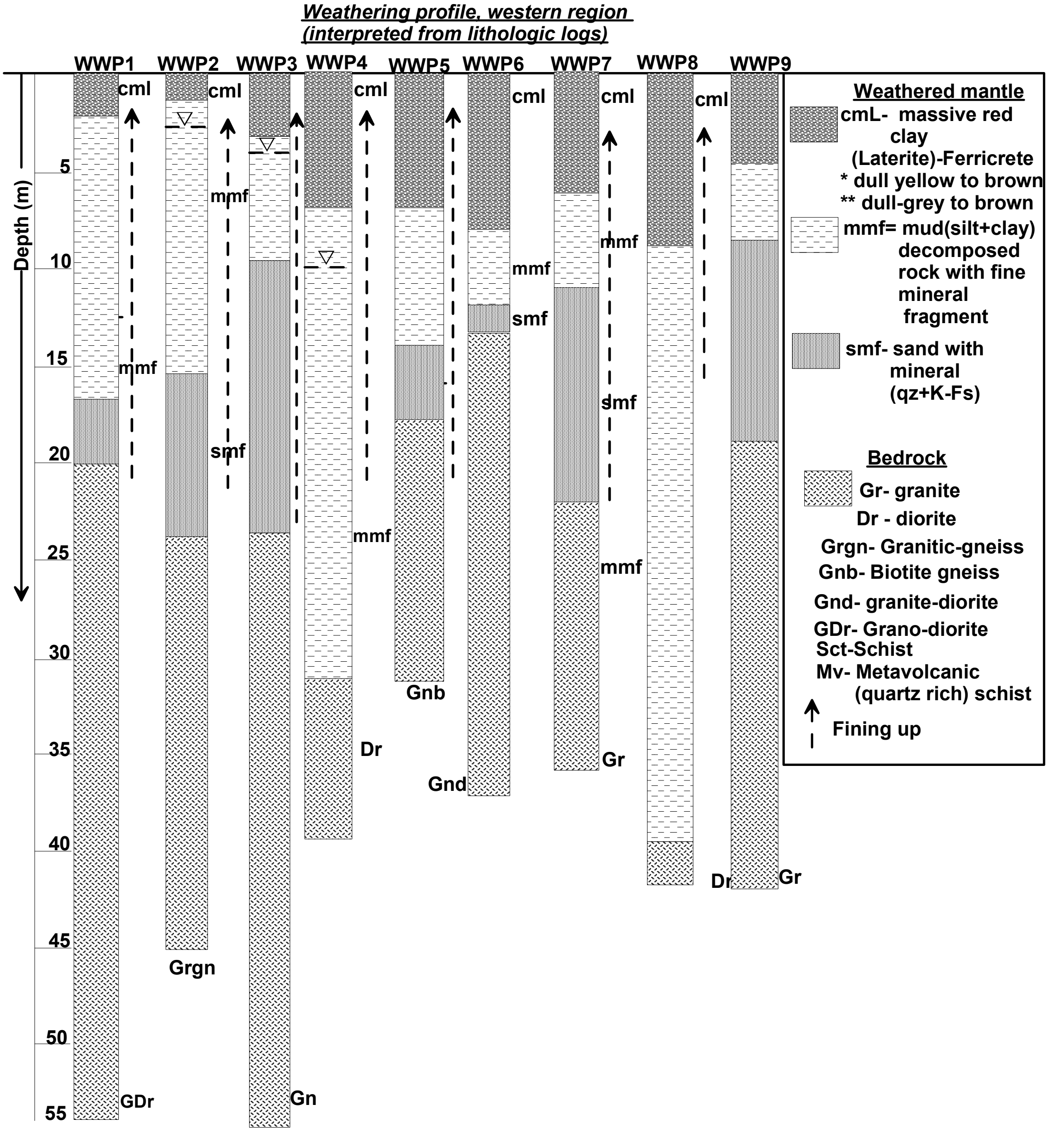
Figure 23) Variations of weathered mantle thickness with lithology in the northern basement region.

Relatively thinner weathering mantle observed over the bedrocks of slates, meta-volcanics, and black meta-limestone. While a comparatively thicker mean weathered mantle observed on granites, meta-sediments, and phylites bedrocks. The stratigraphy of these profiles significantly deviate from the "classical" weathered profile of (Wright, 1992) in that the saproilte is missing or very thin if present and ferricrete (laterite) is absent.

These "truncated" profiles indicate that stripping (erosion) is operating at faster rate than weathering processes in this region. This is attributed to high surface gradient(high relief) which enhances erosion than weathering, and low annual rainfall amount and rocks(slates and phylites) of stable minerals (dominantly quartz and K-feldspar) which hold back the development of deeply weathered mantle.

3.3.2 The Uwa catchment

The description of weathering profiles in the Uwa catchment and the surrounding area is portrayed in figure 24.The figure depicts marked similarity among the profiles in this region. Each profile has consistent textural change up the profile (fining upward) and commonly capped by massive laterite interpreted to be ferricrete.



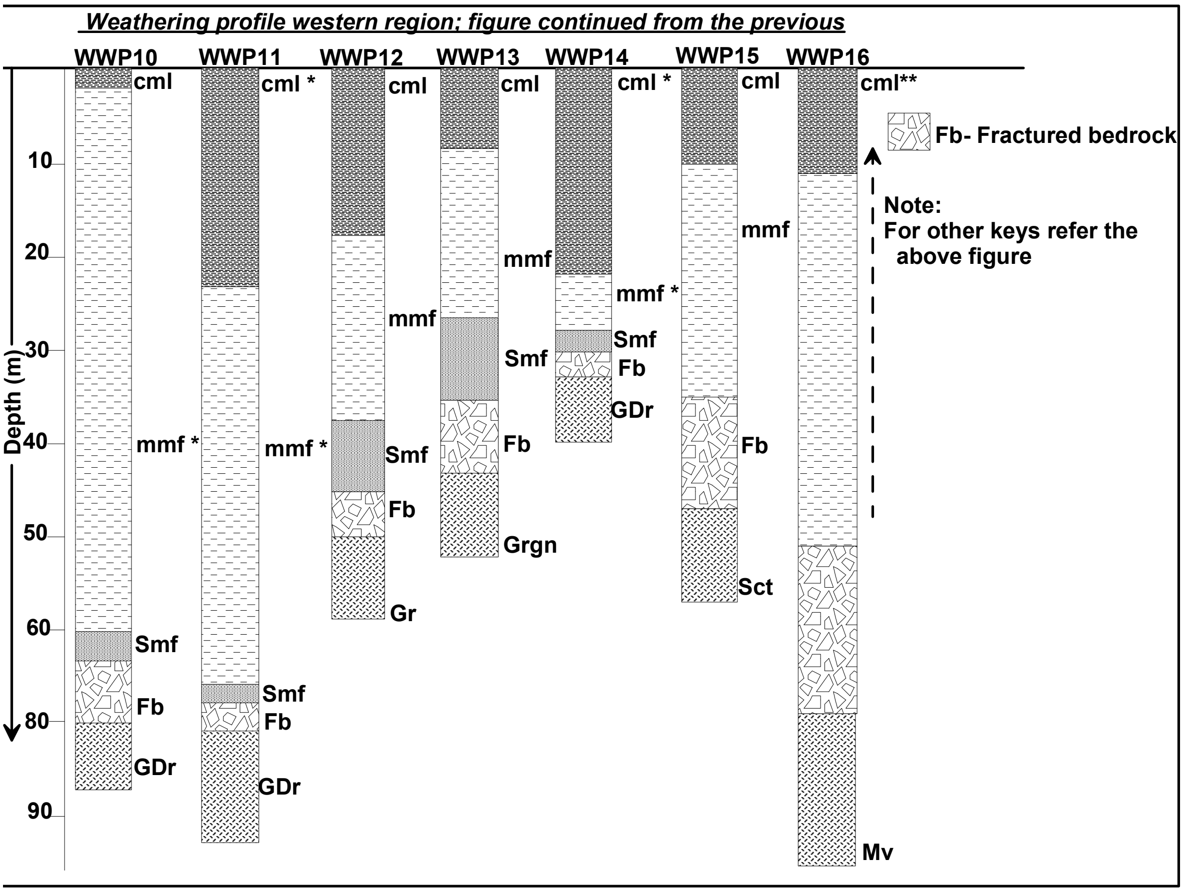


Figure 24) Weathering mantle-bedrock profile descriptions for Uwa catchment and the western region

The thickness of this zone varies between 2 and 10 metres. However, exceptionally thick (>10m) massive clay has capped profiles WWP11, WWP14 and WWP16.The colour of these zones varies from light yellowish-through dull grey to brown.

The absence of red colour from these profiles can be attributed to the continuous leaching of iron pertaining to longevity of deeply weathered mantle.

This is underlain by thick sequence of massive mix of silt and clay with fine mineral fragments, which is the result of completely decomposed rock. This zone is relatively thicker in diorite (e.g.WWP4 and WWP8) and grano-diorite lithologies (e.g.WWP10 and WWP11). This zone is commonly underlain by the zone of sand sized quartz and K-feldspar mineral fragments. Thick quartz-rich zone dominates the basal part of the profile in gneiss and granites lithologies (e.g.WWP2, WWP3, WWP7, WWP9, WWP12, WWP13) but this zone is thin or absent in diorite and grano-diorite(e.g.WWP4,WWP6, WWP8, WWP11).

At the base of each profile is bedrock of different lithologies. The top part of these bedrocks is commonly fractured and slightly weathered and gets into fresh rock with depth.

In this region, the depth to fresh bedrock generally varies from about 10m to about 90m on different lithologies (fig.25). Thicker weathered mantle generally develops over mafic bedrocks (diorite-gabbroic and meta-gabbroic) (fig.25) indicating the role of lithologic variation on weathering mantle development. On gneissic bedrocks, thickness ranges from 25m to 65m, on diorite-gabbroic bedrocks it ranges from 15m to about 90m; on schist, it varies from10m to 70m and on granite 25m to 50m.

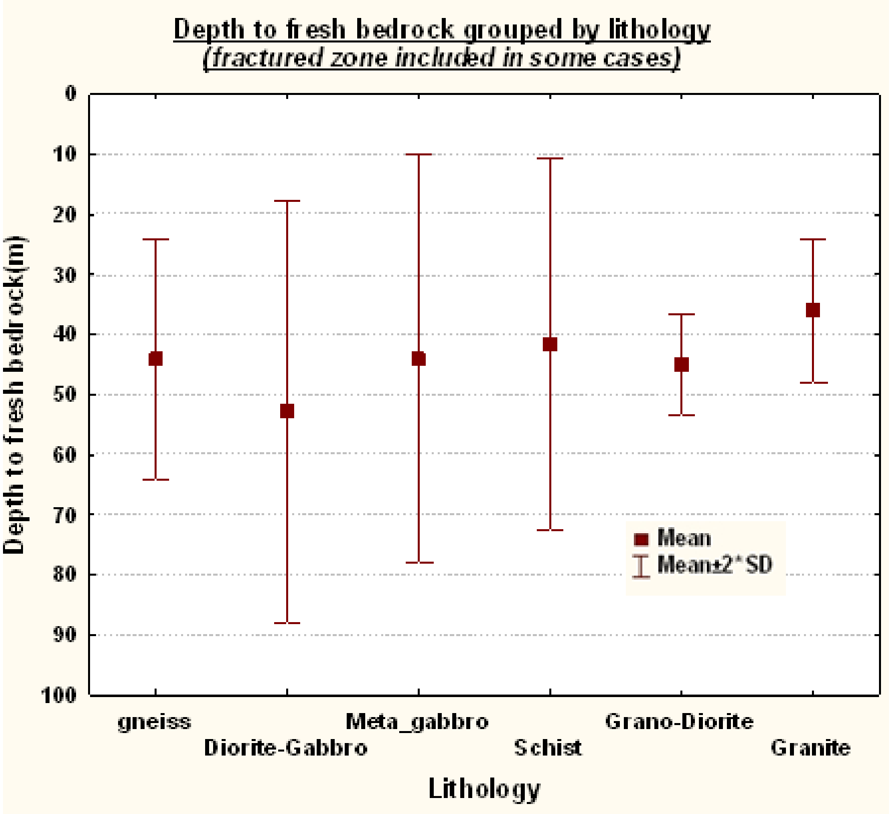


Figure 25) Relationship between weathered mantle thickness (depth to fresh bedrock) and lithology in the Uwa catchment and the surrounding areas

The weathered-bedrock profiles in this region generally mimic those profiles of Wright, 1992, UNESCO, 1984 and Nahon and Tardy, 1992 proposed for tropical environment. The control of bedrock lithologies on weathering development is reflected by absence and presence of some horizons from the profiles and variations of thicknesses of weathered mantle over different bedrock lithologies. Thick quartz-rich zone is found over the acidic bedrock (gneiss and granites) (fig.26C, D). This zone is totally missing in mafic rocks (e.g. biotitic schist) (fig.26A) where the weathered mantle directly grades to fresh bedrock. This can be attributed to relatively higher concentration of unstable minerals relative to quartz: (e.g. Plagioclase= 30%, Biotite=24%, Hornblende= 20%, Quartz=14%, Epidote=12%) (fig.26B) which is subjected to complete dissolution.

Figure 26) Field photos of weathering profiles over different lithologies and thin section. A) An outcrop of weathering-bedrock profile of Biotite-plagioclase schist exposed in a quarry site about 15km East of Gimbi town at a locality called *Ehud Gebeya.* Note that the sandy horizon is missing from the basal part of the profile and the contact between the weathered mantle and fresh bedrock is sharp indicating that the sap rock is also negligible. B) Thin section from the biotite-plagioclase schist C) Sandy detritus at the base of a profile over gneissic bedrock exposed at a new road cut at a locality called *Inango* about 20km west of Gimbi town. E) Zoomed view of the sandy horizon indicted as E in D

Evidences from field observations and borehole lithologic logs reveal that thick younger weathered mantle derived from insitu alteration of late Cenozoic volcanic rocks (dominantly basalts), overlay on top of preserved weathered mantle of basement rocks in some localities. In lithological logs of some water wells, thin horizon of boulders with clay mix marks the transition zone between the preserved weathered mantle and the basalt sequences (fig.27).

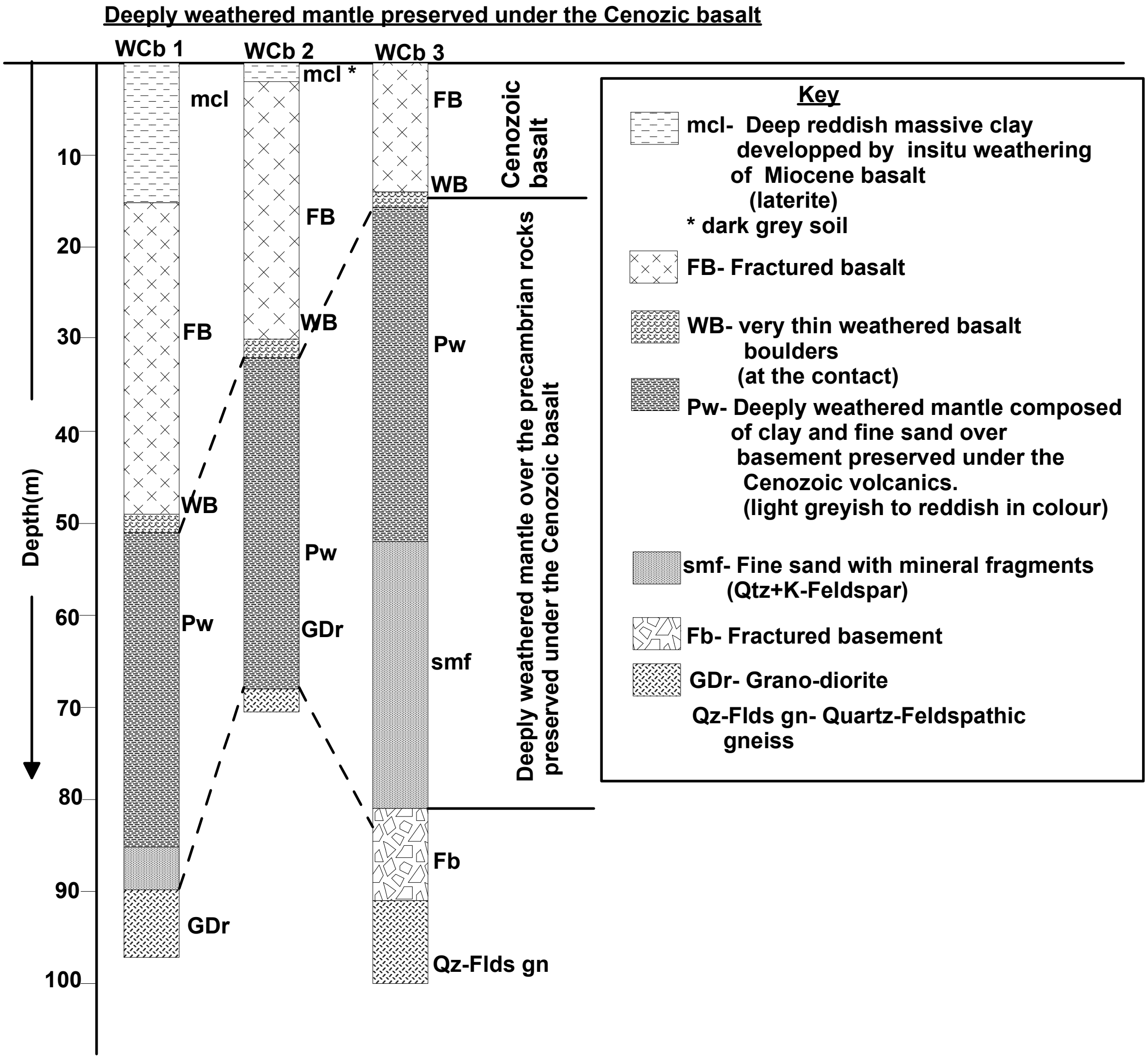


Figure 27) Profiles depicting preserved deeply weathered mantle of basement rocks of late Mesozoic (mid-Cretaceous) under the younger weathering mantles of basalt

In the field, the contact between the weathered basalt and the weathered basement is noticeable mainly by colour variation and mineral fragments. The overlying younger weathered mantle is deeply weathered to deep reddish massive laterites with no observed detritus mineral fragments in it (fig.27). Unlike the overlying recent weathering mantle (derived from basalt), the preserved Mesozoic deeply weathered mantle is pinkish to brownish in colour owing to the prolonged leaching of iron (fig.27). Furthermore, weathering resistant angular quartz fragments are observed in the collapsed mantle (fig.27B).

A) Location:
UTM 36P 812064mE
989309mN
Deep reddish weathered from basalt on top.
Underlying is collapsed paleo-weathered mantle.
Note the colour difference

B) Another contact at location:
UTM 37P 188414mE
998640mN
Paleo weathered surface underlying basalt boulder.
Angular mineral fragments indicate the absence of sub aerial rewoking processes

C) Contact at location:
UTM 37P 226971mE
1026094mN
24km north of Nekemte town

Figure 28) Outcrops indicating the contact between the young weathered mantle derived from late-Miocene basalt and the underlying older (remnants) of deep weathered mantle (Mesozoic) of basement rocks. A) Contact noticed by variation of colour deep red younger weathered mantle, pinkish collapsed remnants of paleo-weathered surface. B) Paleo weathered surface underlying the young basalt boulders; the presence of angular quartz grains indicate the absence of sub aerial reworking processes. C) Basalt boulders overlying the paleo weathered mantle (24km from north of Nekemte town)

The presence of angular detritus mineral fragments manifests absence of reworking by sub-aerial transport processes. The weathering of the overlying basalt indicates that deep weathering is still active in the region.

3.3.3. The Alona-Kefera catchment

In the lowlands of Borena including the Alona-Kefera catchment, two types of loose material mantle are observed. Alluvial deposits are found dominantly in extensive topographically low-lying areas and valleys. They are dominantly sand with minor sand-clay mix at the upper most part. The sand horizon is coarser at the basal part of the profile and is mainly derived from gneiss and granite bedrocks and inselberg ranges.

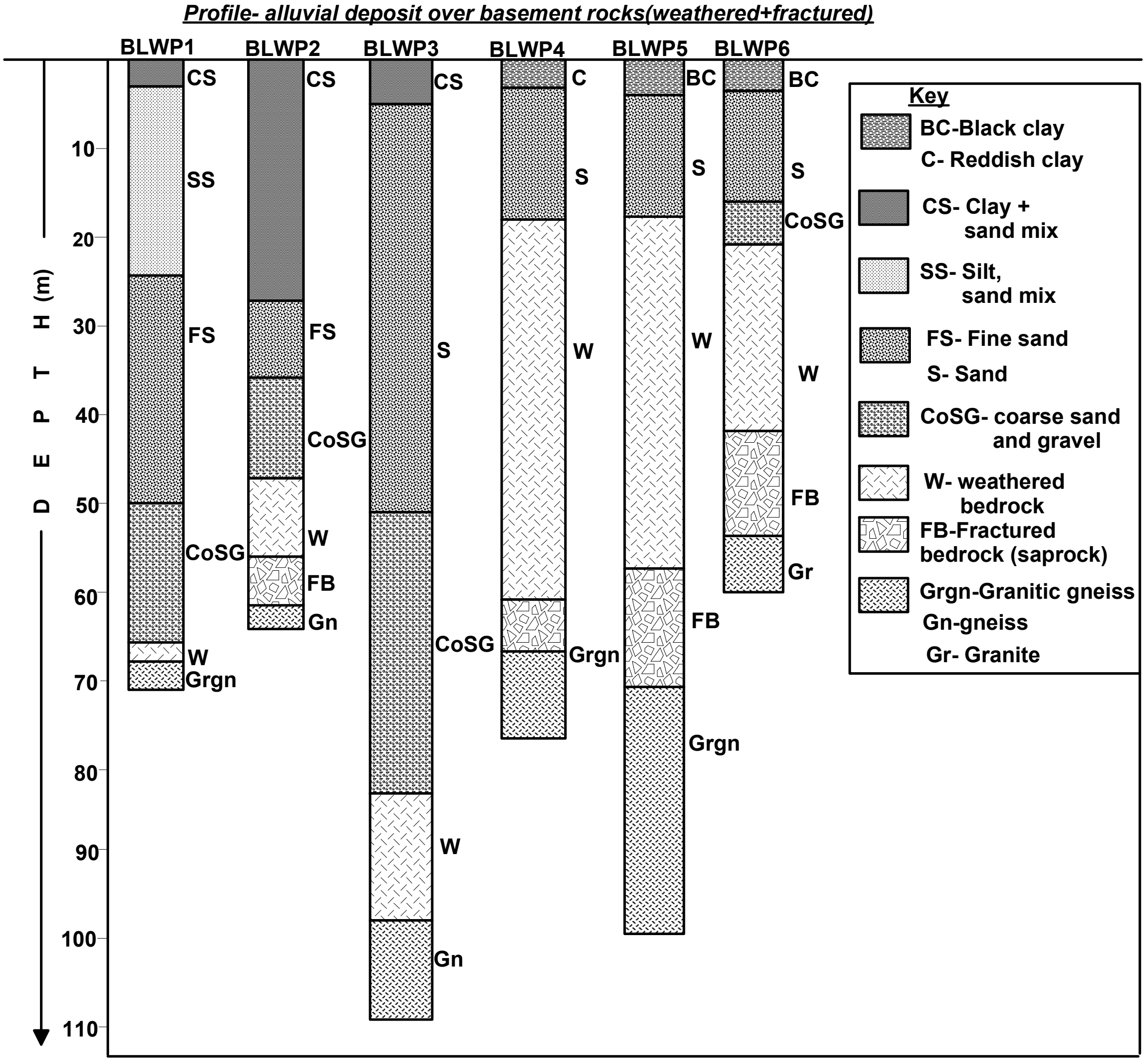


Figure 29) Profiles depicting alluvial deposits over weathered and fractured basement rocks

The thickness of this deposit exceptionally reaches up to 60m as it is noticed in lithologic logs of some wells (e.g.BLWP1 fig.28). In some topographically low areas, the profiles are capped by black clay soil that is underlain by coarse sand and lithic fragments (fig.28 BLWP4, BLWP5, BLWP6) usually about 20m thick.

Alluvial deposit in the low-lying areas generally overlay weathered or fractured bedrocks (fig.28). The topographic depressions are commonly broad and several kilometres long which is interpreted to be manifestations of zones of regional fractures. The presence of weathered mantle beneath the alluvial deposit signifies a systematic linkage between fracture orientations and regolith development (i.e. preferential weathering of bedrocks favoured by movement of water through fractures).

Gently sloping areas and interfluves are commonly covered by ubiquitously distributed weathering residua of angular quartz, feldspar, and lithic fragments with variable proportion (fig.29C). This zone mantles consistent weathering profiles over different bedrocks (fig.30; BWP1).

Figure 30) Field photos taken from different localities in Borena lowlands depicting: A) Ferruginous duricrust (ferricrete) hardened up on exposure to drying because of elevated temperature; ubiquitously distributed over the lowland of Borena. B) Massive iron crust (laterite) underlying the sandy residua. C) Quartz-rich sandy residua on interfluves

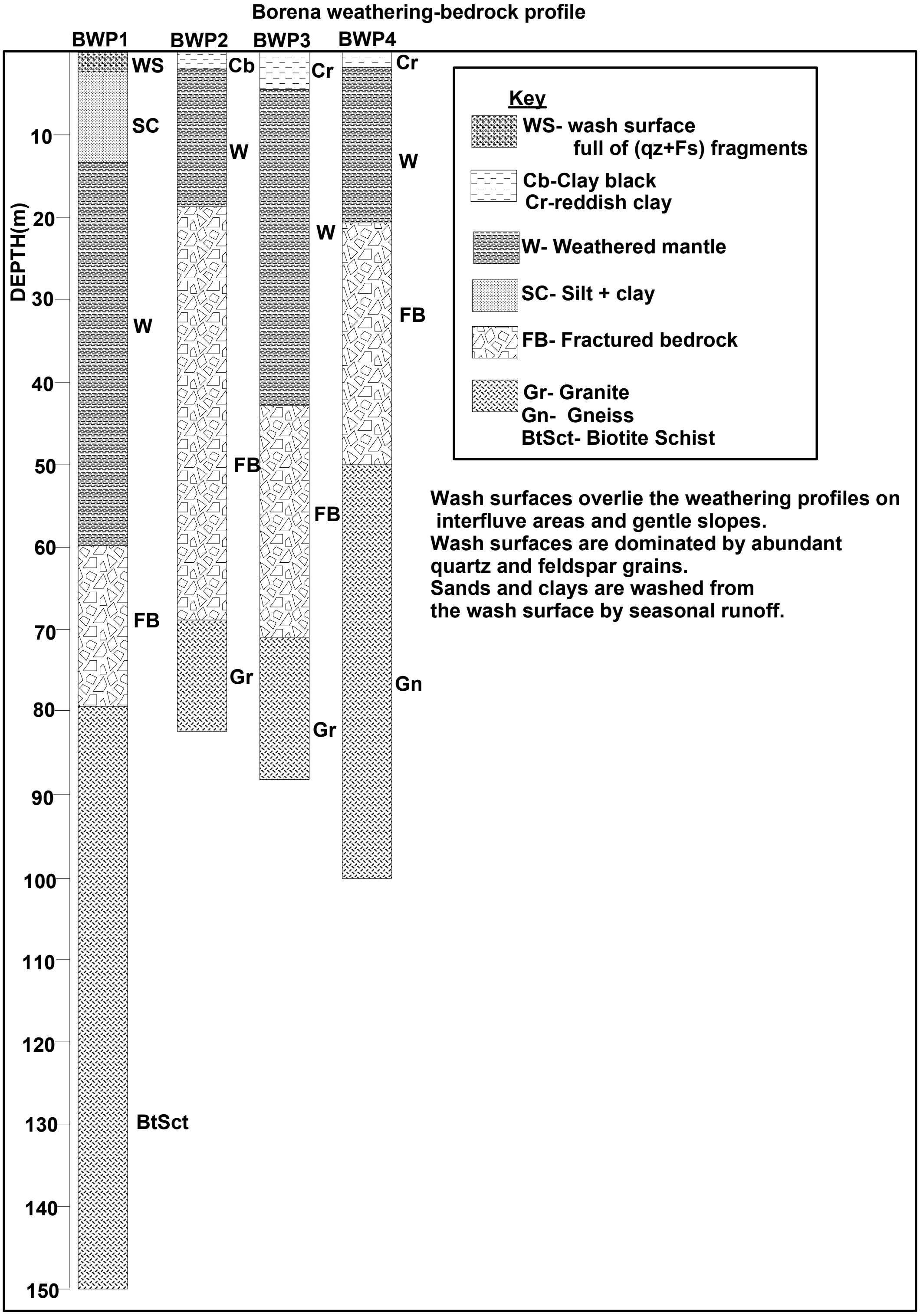


Figure 31) Weathering profiles depicting interfluves of Borena lowlands

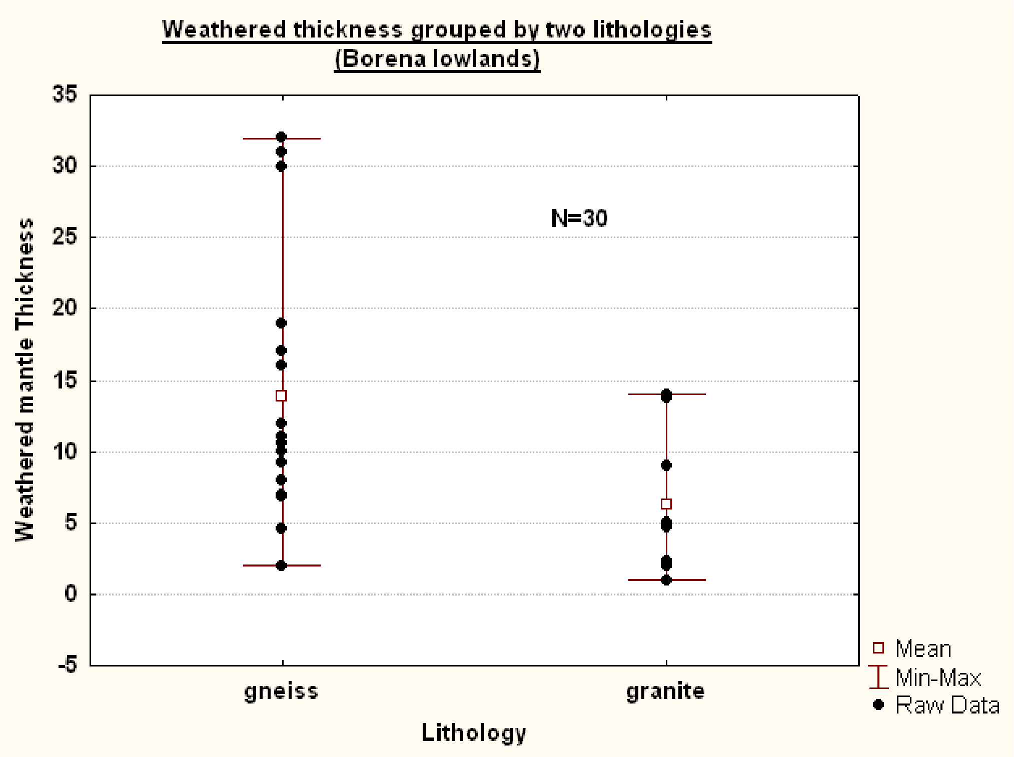


Figure 32) Weathering thickness grouped by lithology for weathering profiles on interfluves in Borena lowlands

The thickness of weathering mantle rarely exceeds 20m on gneissic bedrocks where as in granites well below 15metres (fig.31)

These consistent profiles could be preserved paleo-weathered (possibly Mesozoic deep weathering) mantle on high slope (hill side) areas. These weathering profiles are well preserved under the late Cenozoic basalt cover escaping the Cenozoic stripping (fig.31). The contact between the basalt and the weathered mantle is marked by laterites.

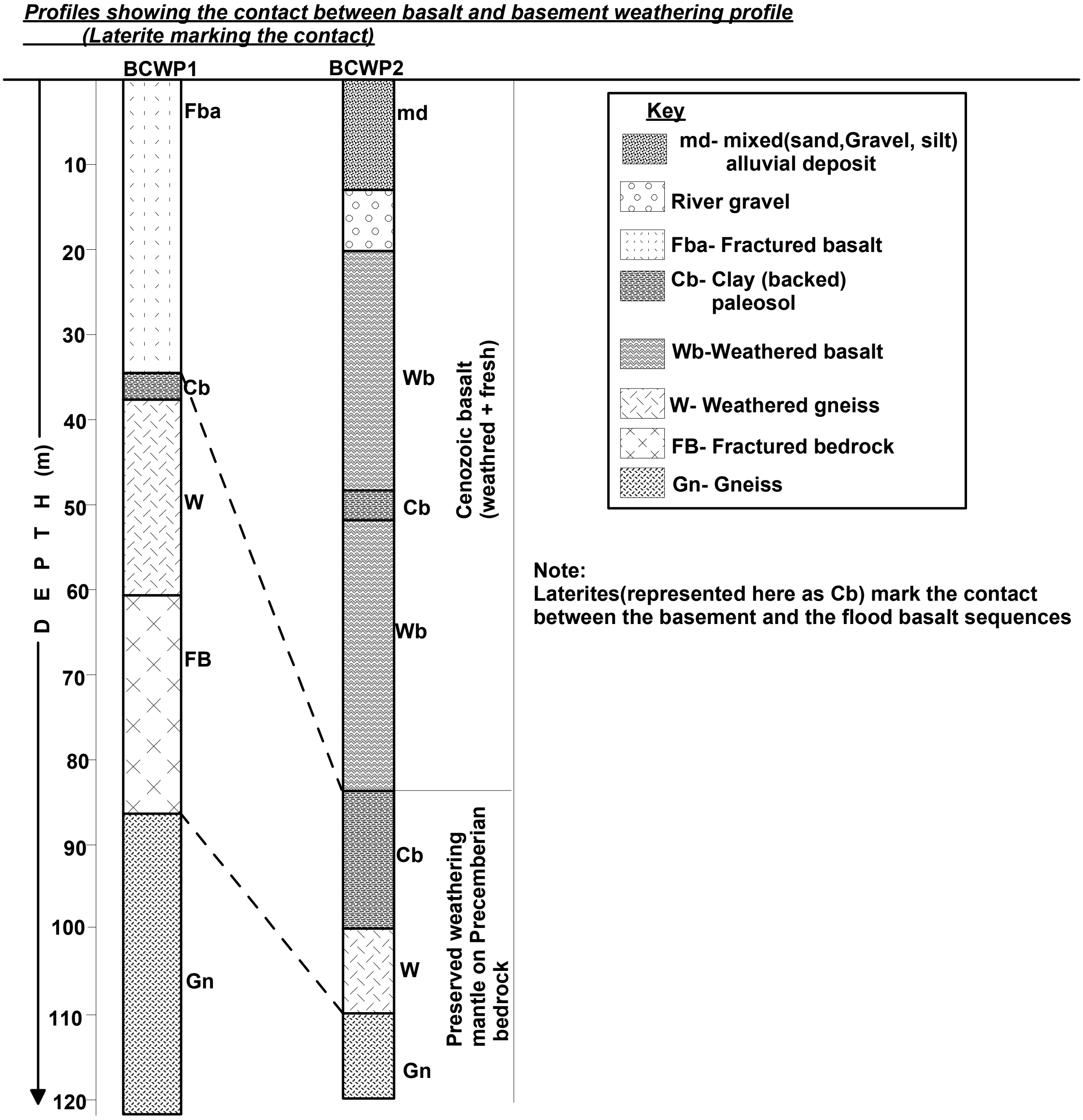


Figure 33) Profiles depicting preserved deeply weathered mantle of basement rocks under the younger weathering mantles of basalt. Note that laterites mark the contact between the basement and the basalt.

The presence of basal unit of red lateritic grit below the basalts of the Omo River valley in southern Ethiopia and elsewhere in this region is reported by (Davidson, 1983). The laterite was interpreted as capping a low-relief pre rift surface onto which the basalts were emplaced over the late Mesozoic deep weathering.

3.4 Variation in weathering-bedrock profiles

The disparity noted in profiles among the three study sites and the three regions at large, reflect contrasting landscape histories in the three regions.

The “truncated” profiles and generally thin regolith mantle over the bedrocks in the northern basement region and the absence of well-developed laterites cover from the top of the profiles indicate that stripping is the dominant geomorphic processes in this region. This is attributed to a drop in base level due to the uplift in the late Cenozoic that had developed high surface gradient. Higher topographic gradient supports erosion than weathering and results in deep incision. Furthermore, low annual rainfall amount and abundant rocks (slates and phylites) of stable minerals (dominantly quartz and K-feldspar) are other factors that limit the development of deeply weathered mantle. As a result, stripping (mechanical denudation) is operating at faster rate than deep weathering in the northern basement region.

In contrast, thick weathering profiles with consistent weathering lithology in the Uwa catchment (and elsewhere in areas unaffected by structural deformation in this region) indicate that these profiles are relatively unaffected by stripping process. Instead, it is envisaged that weathering could be the dominant geomorphic process in this region. Despite high mean annual rainfall amount that ranges from 1800mm to 2200mm, deep incision is lacking in streams (e.g. basement bedrocks are rarely exposed) mainly because of low relief of the area. Furthermore, topographically low relief landscapes favor vertical rather than horizontal movement of meteoric water in the vadose zone as Wayland, (1934) and Willis, (1936) dictate it.

Consequently, the very humid and warm climatic conditions facilitate fast operation of deep weathering than stripping over the western basement bedrocks. This has resulted in the development of thick weathered mantle over gneisses and mafic-ultra-mafic bedrocks, diorites and gabbros intrusive bodies.

The variation in regolith thicknesses over lithologies of different bedrocks under the effect of the same climatic factors (e.g. rainfall amount and temperature) in this region can be attributed to the variation in mineral composition of different lithologies. The development of thick weathered mantle over younger basalt (fig.33, 34) is key evidence manifesting that weathering is operating at faster rate than stripping.

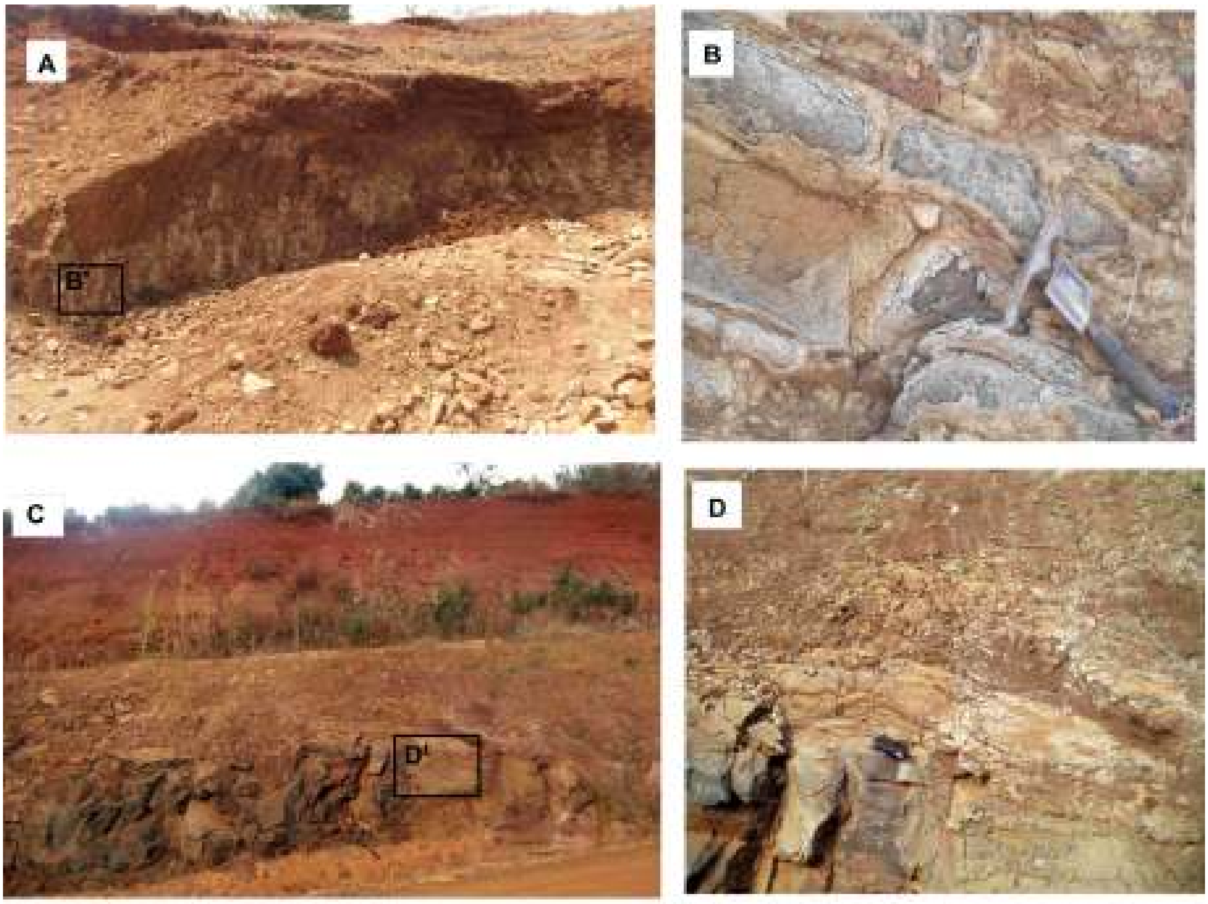


Figure 34) Weathering profile over younger basalt exposed in road cut and quarry: Basalt exposed at a quarry site near Bako locality. B) Zoomed view B' in A, showing preferential (differential) weathering along joints. C) Thick insitu weathered mantle along a newly road cut on the way to Begi town. D) Zoomed view of D' in C showing the weathering front and basalt bed rock

In the Uwa catchment, in situ development of the weathered mantle is well demonstrated by vertical differentiation of the weathered mantle that is implied by textural change up the profile. A sandy zone at the basal level of the majority of the profiles (fig.24) indicate the alteration of biotite, plagioclase, and quartz minerals, which are contained in majority of the bedrocks implying that weathering is still active.

Furthermore, the development of ferricrete in situ (by the relative accumulation of iron) and the occurrence and accumulation of thick insitu altered mantle suggest that deep weathering of crystalline bed rock has occurred for a prolonged period (10^6–10^7a) (Fairbridge and Finkl, 1980; Nahon, 1986) of time**.** During this prolonged time, rates of weathering must have exceeded rates of erosion which implies that this region must have been tectonically stable for longer time.

The Alona-Kefera catchment and the Borena lowland as a whole are far from the centre of the domal uplift. This gives the area relatively a low-lying topography. Nevertheless, there is clear evidence for stripping. This is supported by presence of remnants of regolith with reduced thickness (fig. 30, BWP1) capped by wash surfaces (e.g. sandy residua) on relatively gentle slopes (fig.30C). The presence of sandy residua of mainly angular to sub angular quartz and lithic fragments indicate that they are the result of in situ weathering and at the same time indicate that the slow operation of stripping process in this region. The presence of duricrusts (hardened ferricretes) (fig 30A) covering the extensive low-relief area manifest the area is under arid/semi arid conditions. Hardened ferricretes and calcretes facilitate runoff than infiltration, which actually enhances stripping than weathering. The low relief and low amount of annual rainfall in the area led to development of less prominent drainage network that could not trigger deeper incision. Consequently, deeply incised valleys are uncommon and river valleys are commonly broad and are filled by alluvial sediments dominantly composed of sands.

The presence of generally thinner weathered mantle in Borena lowland than in the western region, despite almost similar parent bedrock materials, indicates a reduced influence of deep weathering in this region. This can also confirmed by the prevailing semi arid to arid climatic conditions, which in effect does not favour deep weathering.

The weathering profiles of basement rocks of Ethiopia show both discrepancies and similarities when compared to the “classical” one (Fig.35).

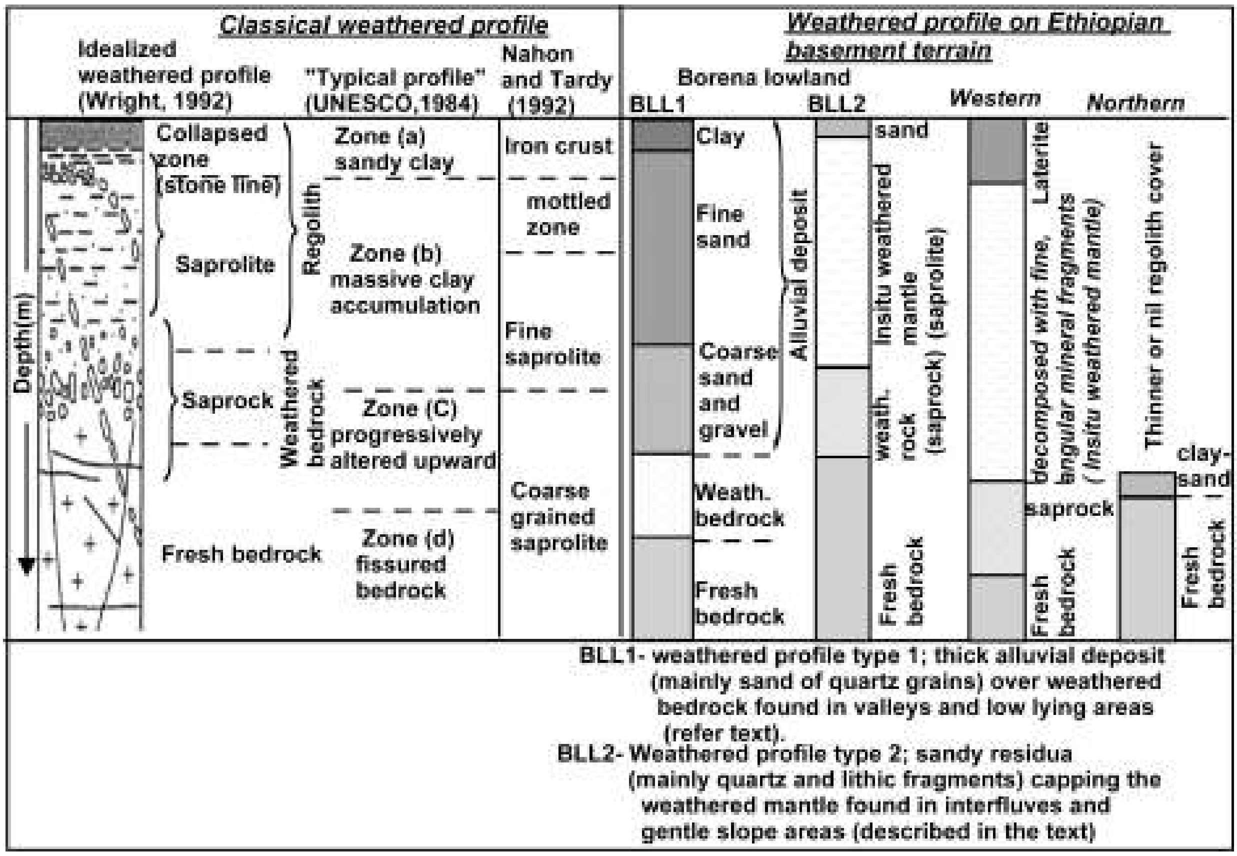


Figure 35) Comparison of classical weathering profiles (Wright, 1992; UNESCO, 1984; Nahon and Tardy, 1992) with weathered profile over Precambrian basement rocks from three regions of Ethiopia

The weathering profiles from the western basement region generally mimic the “classical” weathered profile for tropical climatic setting (fig.35). There is generally consistency of texture between each zone of the profiles. However, the thicknesses of some zones in western basement region show variation implying mineralogical control over weathering process. Moreover, the presence of generally thick regolith thickness in this region implies that the regolith is unaffected by the erosion that has shaped the present topography. Thus, it appears to be the western region is composed of an old weathering profile. Nonetheless, the presence of sand-sized detritus(mainly quartz and feldspar) at the basal of the profiles indicate that alteration of biotite, plagioclase and quartz minerals bedrocks is still active which further deepens the weathering front.

The weathering profiles from Borena lowland differ from the “classic” one primarily by presence of thick sandy alluvial (≈20m or more) deposit on top of weathered rock or fractured bedrock implying an erosion phase. Elsewhere on interfluves and gentle slope areas, the weathered mantle is capped by residua of angular to sub angular detritus of quartz, feldspar and lithic-fragments underlain by massive accumulation of clay manifesting weathering.

The weathered profiles from the northern region considerably deviate from the conventional profile by the presence of thin saprolite indicating a phase of intense erosion (stripping) that had removed the weathered mantle to produce such a truncated profile.

Therefore, the regionalization of geomorphic processes (i.e. variations in rates of deep weathering- stripping processes) over the basement terrains of Ethiopia, is resulted in the production of three contrasting weathering profiles and landscapes corresponding to each region(fig.36) (northern, western and southern-the Borena lowland).

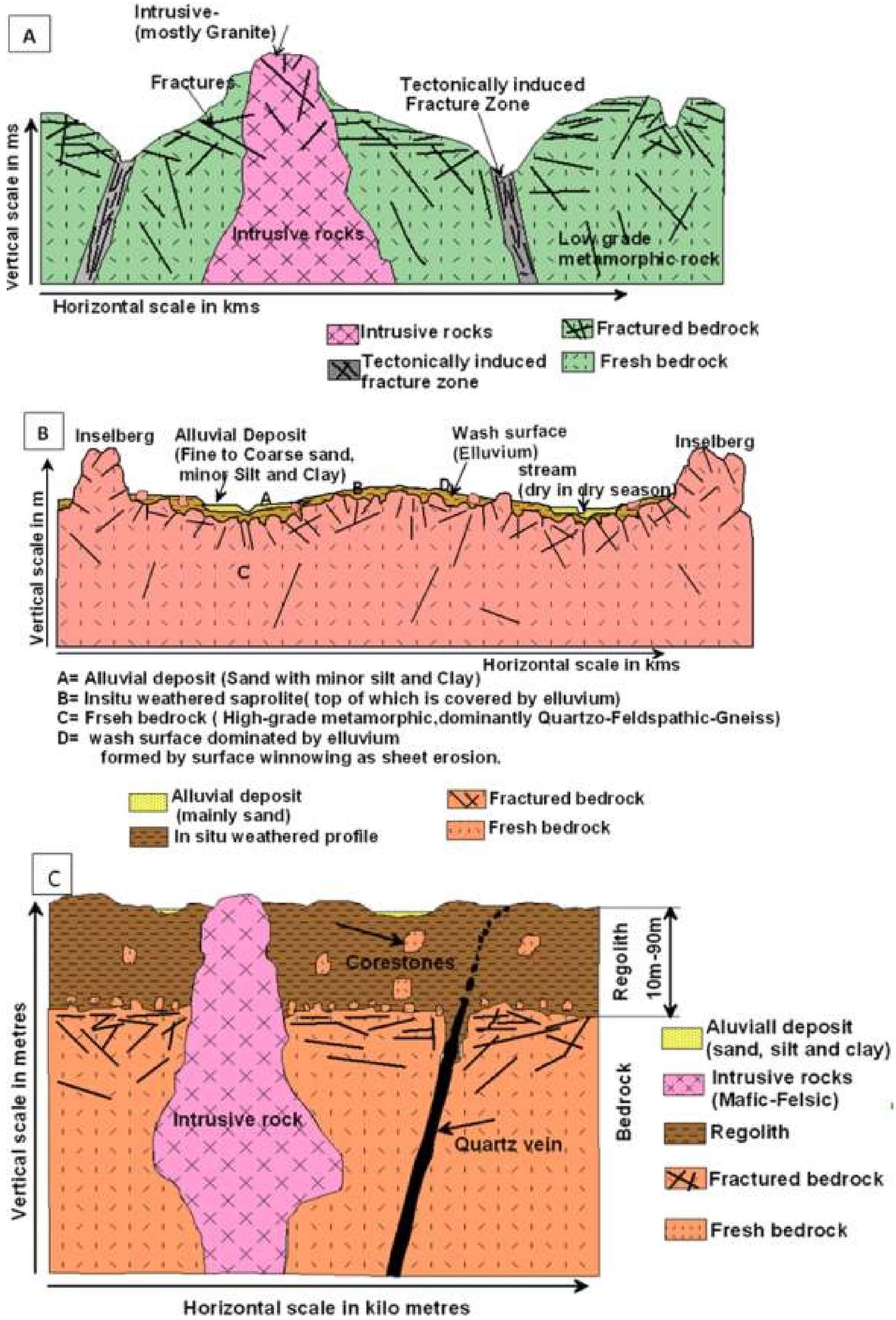


Figure 36) Schematic representations of the regionalized weathering profiles of Precambrian basement rocks; A) The northern basement weathering profile; B) The Borena plain profile with inselbergs; C) The western basement weathering profile; thick and complete weathering profile on interfluves

Thus, the variations and lithologies of the weathering profiles in the entire basement region strongly support the multi phase cycles of landscape evolution. Consequently, this work has presented fundamental field evidences that corroborate cyclic deep weathering-stripping model of landscape evolution. Therefore, it can be deduced that the reliability of the previously developed polycyclic landscape evolution model of Kebede, (2013), is attested by this work.

CHAPTER 4: HYDROGEOLOGY OF BASEMENT TERRAIN OF ETHIOPIA: A GEOMORPHIC FRAMEWORK APPROACH

4.1 Introduction

Crystalline basement rocks occur in tropical regions of Africa, India, South America and Australia (Wright, 1992). Aquifers of basement rocks commonly develop within the weathered residual overburden (the regolith) and the fractured bedrock (Wright, 1992; Acworth, 1987; Chilton and Foster, 1995; UNESCO, 1984). Groundwater transmitting through coarse weathered mantles to the base of weathered profiles and that localized in fractures of bedrocks, provides an important source of potable water supply in many of these regions. Weathered mantles develop over bedrocks by weathering processes. The thickness of weathered mantle and the corresponding aquifer properties depend on a complex combination of controls that include bedrock characteristics, climate (past and present), age of land surfaces; relief and other site specific factors (UNESCO, 1984; Acworth, 1987; Wright, 1992; Jones, 1985). This indicates that hydrogeological characteristics (mainly hydraulic conductivity and storage capacity) of the weathered mantle and the underlying bedrock derive primarily from the geomorphic processes of deep weathering and stripping. The same view was emphasized by many authors (e.g. Foster, 1984; Acworth, 1987; Taylor and Howard, 1998, 2000; Edet and Okereke, 2005; Dewandel et al., 2006). Thus, the vertical heterogeneity of aquifer properties in basement rocks depends on the type of regolith lithology (i.e. texture) (Acworth, 1987; Chilton and Foster, 1995) (fig.37).

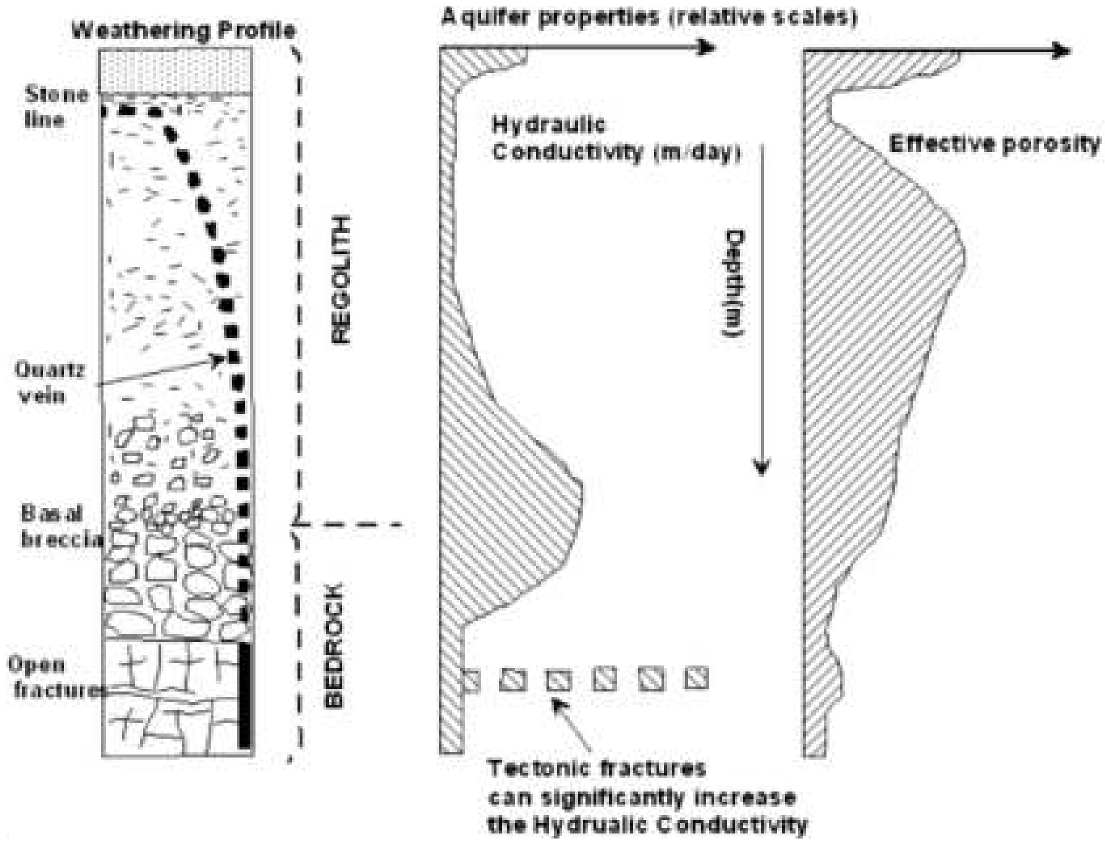


Figure 37) The vertical profiles of hydraulic conductivity, transmissivity and effective porosity for the regolith–fractured bedrock profile (After: Acworth, 1987; Chilton and Foster, 1995)

Therefore, tracing the geomorphic evolution of weathered land surfaces and identifying the dominant geomorphic process operating on those land surfaces provide complete understanding of hydrogeological characteristics of basement rocks. Such holistic approach in understanding the hydrogeological potential of basement aquifer of Ethiopia is lacking. Instead, most previous studies (e.g. Cherenet, (1993); EIGS, (1988, 1996)) and many unpublished regional hydrogeological studies (Alamirew et al., (2005); Belete et al., (2003); Belete et al., (2004); GSE, (2002, 2003) consider the whole basement terrains of the country as regional aquiclude or very poor aquifers. This attribution, in essence, fails to explain regional differences in aquifer properties, structure and functioning. This view disregarded the spatial differences in groundwater occurrence and potential in different regions of basement terrains of the country, which in some cases are promising. The aim of this work therefore is, to establish fundamental linkage among geomorphic processes operating, hydrology, and groundwater occurrence there by setting a geomorphic-framework for comprehending the hydrogeology of basement rocks of Ethiopia.

4.2 Groundwater occurrence

The regionalization of geomorphic processes (i.e. variations in rates of deep weathering-stripping processes) over the basement terrains of Ethiopia has resulted in the production of three contrasting weathering mantle-bedrock profiles and landscapes corresponding to each region (fig.36). Likewise, the comparison of weathering profiles from the basement rocks of Ethiopia show both disparities and similarities with the standard ("classical") weathering profile for tropical region (Wright, 1992; UNESCO, 1984; Nahon and Tardy, 1992) (fig.35). Groundwater occurrence in basement terrain is also found to vary spatially corresponding to the weathering-bedrock profiles resulting from contrasts in geomorphic processes driven by present climate (mainly rainfall).

In western basement region, the weathered mantles show consistent stratigraphy that resemble the "classical" weathering profile (Wright, (1992); UNESCO, (1984); Nahon and Tardy, (1992) discussed above) (fig.35).The weathered mantle is significantly thick reaching locally up to 90m favoured by climatic conditions. The weathered mantle profile commonly show textural change up the profile. Thick silty-clay zone dominates the top part of the profile with high porosity where as the lower part of the profile dominated by relatively coarse-grained material.Variably thick sandy zone mark the basal level of the majority of the profiles indicating higher hydraulic conductivity in this zone. Thus, groundwater flows horizontally in this zone. Water level generally occurs at shallower depth, often less than 10m. The rise of water level beyond water-strike depth in many drilled water wells indicate the confining effect of the fine-dominated mantle (silt-clay-fine sand) (aquitard) at the top of the profile. This effect is pronounced in some localities where the confining layer is relatively thick and dominated by clay material leading to the development of flowing well(fig.38B). Mean annual rainfall ranges from 1800-2200mm in this region. The prevailing wet and warm conditions in this region foster active weathering process leading to the development thick sandy insitu weathered mantle. Deep incision of the weathered mantle is not common albeit the high annual rainfall amount owing to the low surface gradients of weathered surfaces. This has resulted in the development of very gentle convex interfluves landscape over the weathered surfaces leading to the development of regionally extensive aquifer. Thus, much of the rainfall is transmitted through weathered profiles with significantly huge volume of groundwater storage in the weathered mantle at shallower depths (inducing local flow) before its recharge to groundwater reserve.

A) One of the productive hand dug well in weathered mantle. Agulasha locality Western basement region

B) Flowing deep well drilled in weathered mantle; (arrow indicate flowing water) Meeti locality (drilled 1994E.C. and still flowing)

C) Spring discharging from weathered mantle, near Mendi town

Figure 38) Field photos showing hand-dug well and spring tapping weathered mantle. The flowing well indicating the effect of confining layer

This gives comparative advantages by limiting depth of hand-dug wells to shallow depth. Thus digging hand-dug wells remained a common practice in this region, which are abundant in rural area of this region. Abundant springs and seepages are observed in the field. The springs have low discharge values that commonly vary from 0.005 L/s to 0.5 L/s, but rarely go to about 5L/s. The majority of these springs are concentrated at surface elevations between 1500 to 2000m a.s.l at slope side of the landscape where weathered mantle are observed. The low values of groundwater discharge albeit high rainfall amount (1800–2200 mm/ann.) can be attributed to high storage capacity of thick regolith cover.

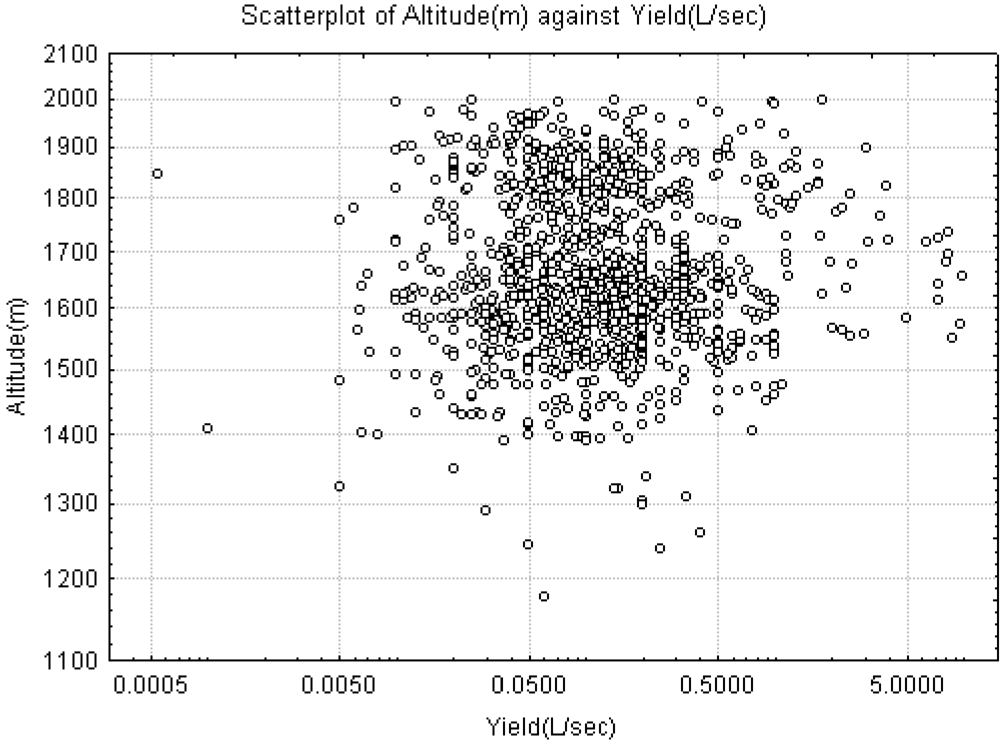


Figure 39) Spring discharge and altitude in the Uwa catchment

Groundwater discharge is by means of abundant springs and sustained base flows in the streams- a consequence of high storage capacity of the thick regoilths in the region. Therefore, groundwater occurrence and movement in this region is in the weathered mantle and the underlying fractured bedrock. However, deep wells extended to the top of bedrocks can tap highly conductive saprock zone. Higher yielding deep wells could be possible because of high storage from the regolith mantle and higher hydraulic conductivity from the underlying saprock (fractured bedrock).

In the worei site and the northern region in general, the weathered mantle-bedrock profiles, deviate from the “classic” profile in that the weathered overburden is very thin or totally missing in some localities. Thus, frequent exposures of fractured bedrocks are common in the region and wells are commonly sited on the fractured bedrocks (fig.40). This is a result of continued stripping effect as consequence of high relief leading to deep incision. Mean annual rainfall that often ranges from 600-700mm is lower as compared to the western basement region. Much of the inflow from rainfall is transmitted through open fractures and surface runoff to deeply incised drainage system to generate high stream flows as derived from stream hydrographs in the region (discussed in section4.4). Direct recharge is little on this surface relative to the deeply weathered surface in the western region. However, significant recharge takes place through tectonically induced fracture zones, and shallow joints and fractures forming localised aquifers (fig.40).

A) Shallow well , near stream
on fractured bedrock (no weathered mantle)
Meta sediment (near Rama town),
northern basement

B) Shallow well , on fracture zone outlined
valley trace (observe very thin soil)
Zongi Tabia

C) Shallow well on jointed bedrock Zongi Tabia;
Northern basement

D) Sub horizontal joints; water discharging
Megebe Tabia; Northern basement

Figure 40) Field photos depicting shallow wells sited on fractured bedrock aquifers

Numerous shallow wells and hand-dug wells tap this shallow-fractured aquifer for community water supply source (fig.40). The occurrence of productive hand-dug wells with shallow depth (often less than 10m, (fig.41) may suggest the presence of fractures at shallow depths below ground surface. The yield from these hand-dug wells is variable and reaches up to 2L/s. Nevertheless, relatively deeper wells are used to tap aquifers in tectonically induced fracture zone. The yield from deep wells is also highly variable ranging from 0.3 to as high as 16L/s indicating considerable heterogeneity in hydrogeological factors.

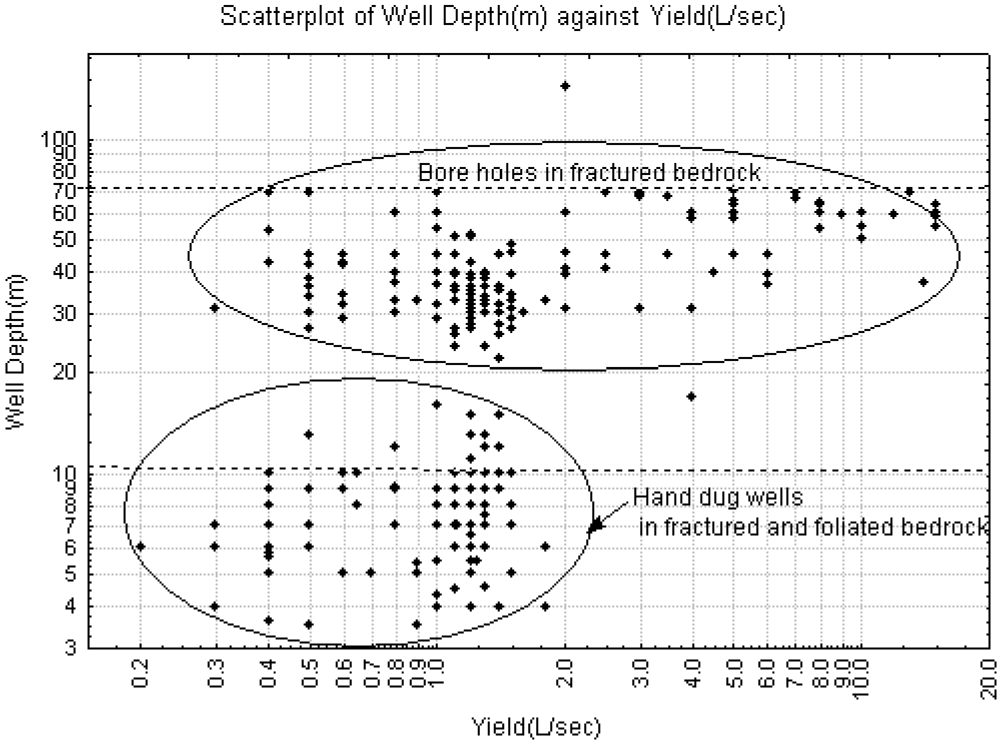


Figure 41) Hand-dug wells and drilled boreholes depth is generally shallower with varying discharge

Therefore, occurrence and movement of groundwater in northern crystalline basement rocks is mainly controlled by fractures and other discontinuities (joints and foliations). For the fact that the occurrences and type of discontinuities (fractures and joints) are spatially variable, the aquifer is of localised extent as compared to the western basement region. Discharge is in the form of highly variable stream flow (due to the high runoff component) along well-incised drainage channels. Base flow is commonly negligible in this region indicating very low groundwater contribution to stream flows.

The weathering profiles from the southern basement region (Borena lowland) differ from the "classic" one primarily by presence of thick sandy alluvial (≈20m or more) deposit on top of weathered rock or fractured bedrock implying an erosion phase. Elsewhere on interfluves and gentle slope areas, the weathered mantle is capped by residua of angular to sub angular detritus of quartz, feldspar, and lithic fragments underlain by massive accumulation of clay manifesting weathering. In low-lying areas, the surface is covered by ubiquitous duricrusts. Thus, the occurrence of groundwater is dictated by this physical make-up (aquifer structure) under the same mean annual rainfall input that generally varies from 400 to 900mm.

The prevalence of duricrusts capping on the extensive plains of Borena lowland are manifestations of intensified evaporation. They facilitate runoff than infiltration. Thus, direct recharge is limited in these areas. The presence of wash surfaces on gently sloping interfluves manifest the operation of erosion under low relief conditions leading to the deposition of sand sized sediments in wide river channels(wadi beds). The wadi beds generally follow regional fractures. These fractures control groundwater flow regime thereby enhancing preferential weathering. The presence of these sediments over the weathered mantle facilitates infiltration into the weathered mantle and fractured bedrocks underneath. This enhances groundwater storage and movement in weathered mantle, alluvial deposits in wadi beds and fractured bedrocks. Elsewhere outside the wadi beds, duricrusts limit vertical recharge and groundwater availability in the bedrocks. Therefore, groundwater occurrence and availability is controlled by interrelated factors (presence of alluvial deposit, fractures and weathered mantle). Groundwater development is commonly by means of traditionally-dug large diameter community wells called locally *Eelas* in rural areas. Most of the *Eelas* are located in wadi beds and fracture traces that are outlined by linear arrangement of vegetation, signifying the presence of a systematic linkage between fracture orientations and the regolith development. Machine-drilled shallow wells are also commonly used to tap water from fractures and weathered mantle.

4.3 Hydraulic conductivities from pumping test data

Analysis of pumping test data from wells in the respective study sites and the three basement regions show significant contrasts in well yields and hydraulic conductivities (Table 1 and fig.42).Generally, higher values of well discharges(mean=5.7L/s)(table 1) and hydraulic conductivities (mean=6.3m/d)(fig.42) are observed for wells from the northern basement region.

Basement region (study site)	**No. of water wells**	**Yield range (L/s)**	**Mean yield (L/s)**
Northern	122	0.4-25	5.7
Western	92	0.5-8	2.8
Southern	100	0.2-3.5	1.5

Table 1) Variations of well yields for wells depth between 50 and 150 m. (Data: from pumping test data in each region in a representative catchment (Bureaus of Water, Mine and Energy of Tigray and Oromiya regions)).

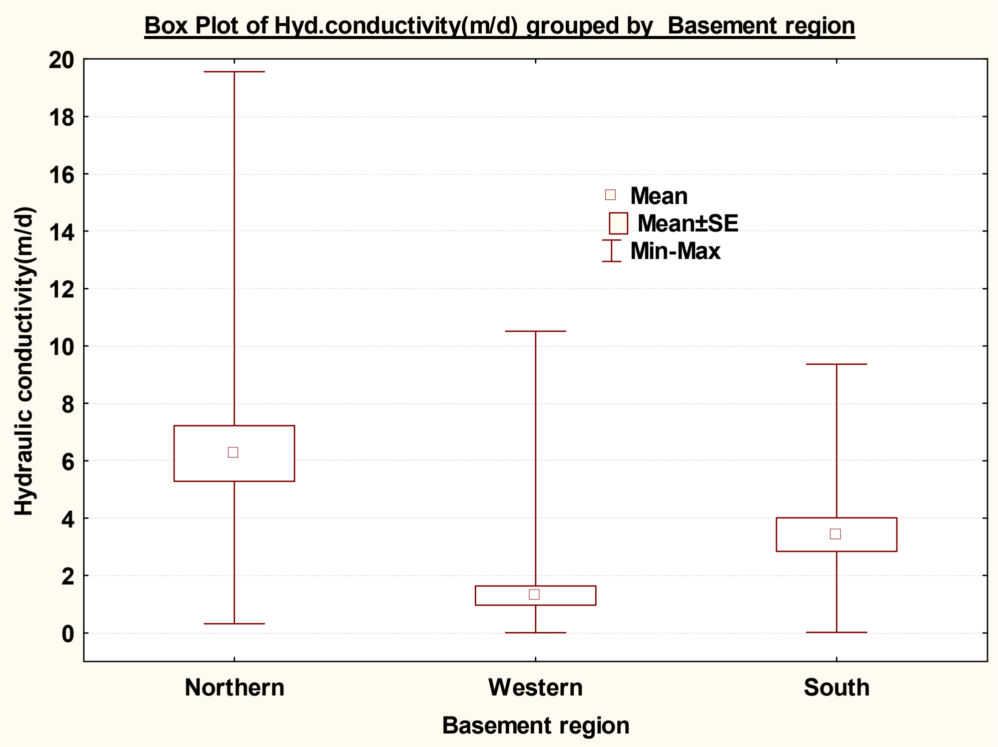


Figure 42) Variation of hydraulic conductivity with the basement region

Well yields from the western basement region show intermediate values. However, they show the lowest hydraulic conductivity values (mean=1.8(m/d) (fig.42) as compared to the other two regions. Those wells from southern region have the least yield (mean=1.5L/s) (table 1) but intermediate values of hydraulic conductivities (mean=.3.7(m/d) (fig.42).

Higher values of well discharges and hydraulic conductivities from the northern basement region can be attributed to the conductive role of fractures, which characterize fractured bedrock aquifers.

In contrast, the lower values of well yields and hydraulic conductivity values in the western basement region demonstrate the role of storage capacity of thick regolith cover mantling bedrocks. Abundant springs and seepages (natural groundwater discharge) are observed in the field. The majority of springs have low discharge values. The low values of groundwater discharge albeit high rainfall amount in this region can be attributed to high storage capacity of thick regolith cover that receive much of the inflow (rainfall), stores and release it slowly to sustain base flows in streams.

4.4 Hydraulic conductivities and storage capacities inferred from low-flow regimes of streams in catchments from the three basement regions

4. 4.1 Introduction

It has been shown (in previous sections) that, in the western basement region where direct recharge hydrology is dominating, the regolith thickness goes to about 90m on different lithologies. In contrast, in the northern region, where stripping results from surface runoff-dominated hydrology, very thin (usually less 10m) weathered mantles cover the bedrocks of different lithologies. In southern basement, the thickness of the weathered mantle rarely exceeds 20m.

Establishing the linkage between the hydrogeology of basement rocks and geomorphic processes, Deyassa et al., (2014) have proposed the classification model of basement aquifers of Ethiopia. The basis of the model was differences in aquifer properties (hydraulic conductivity and storage) which are derived from regionalization of geomorphic processes. The hydraulic conductivity data were obtained from the analysis of pumping test records in each region. However, hydraulic parameters from pumping tests actually represent only point based information than bulk hydraulic parameters of catchments. Furthermore, well drilling to estimate hydraulic parameters is often expensive (Mendoza et al., 2003).

Alternatively, Tallaksen, (1995) outlines the use of low-flow analysis of streams in evaluating the storage-discharge relationships in the knowledge that the low-flows originate from groundwater. Likewise, it has been shown that base flow gives useful estimates of recharge and aquifer parameters such as storage coefficient and transmissivity (Meyboom, 1961; Riggs, 1963; Trainer and Watkins, 1974; Daniel, 1976; Bevans, 1986; Hoos, 1990). Elsewhere(Trainer and Watkins, 1974,1975) suggested that areas with favourable potential groundwater yield, where values for transmissivity and base flow are high, could be delineated by using base flow as an indicator. In addition, (Brutsaert and Nieber, 1977; Moore, 1992; Troch et al., 1993; Eisenlohr et al., 1997; Szilagyi et al., 1998) emphasized that the study of stream recessions provides data on hydrodynamic parameters such as permeability and storage properties of catchments. Furthermore, it is indicated that in unregulated streams, the shape of the lower segment of flow-duration curve is determined chiefly by geologic characteristics of the drainage area (Searcy, 1959). Hence, many authors (e.g. Ayers and Ding, 1967; Peters and Murdoch, 1985; Peters and Driscoll, 1987) suggested that the lower end of the flow duration curve is often used to study the effect of geology (.i.e. the type, thickness, and distribution of surficial materials (including weathered mantle)) on the groundwater flow to the stream. Searcy, (1959) also indicated that flow duration curves could be used to study the hydrogeological characteristics of a drainage basin or to compare the hydrogeological characteristics of one basin with those of another. Also suggested (Peters, 1994), a comparative analysis of these characteristics among basins, yields sound scientific results, particularly if the hydrology for one of the catchments is known.

Thus, the use of low-flow analysis of streams remains a cost-effective alternative strategy that provides more integrative bulk hydraulic properties of catchments. This enables the understanding of dynamics of groundwater discharge (storage capacities and hydraulic conductivities) of catchments that corroborates results obtained from pumping test analysis.

The main objectives of this work are thus: a) to investigate and compare aquifer properties (storage capacities and hydraulic conductivities) of catchments in the three basement regions by using low-flow indices (base flow indices, specific mean daily base flows, recession slopes) and shapes of flow duration curves. b) to investigate any linkage that may exist between the low-flow indices and regolith thicknesses in the catchments of the three regions.

4.4.2 The study sites

Five gauged and unregulated streams (one from northern, three from western and one from southern basement regions) (fig.43) in catchments that represent the hydrological and physiographic variables in corresponding region is selected.

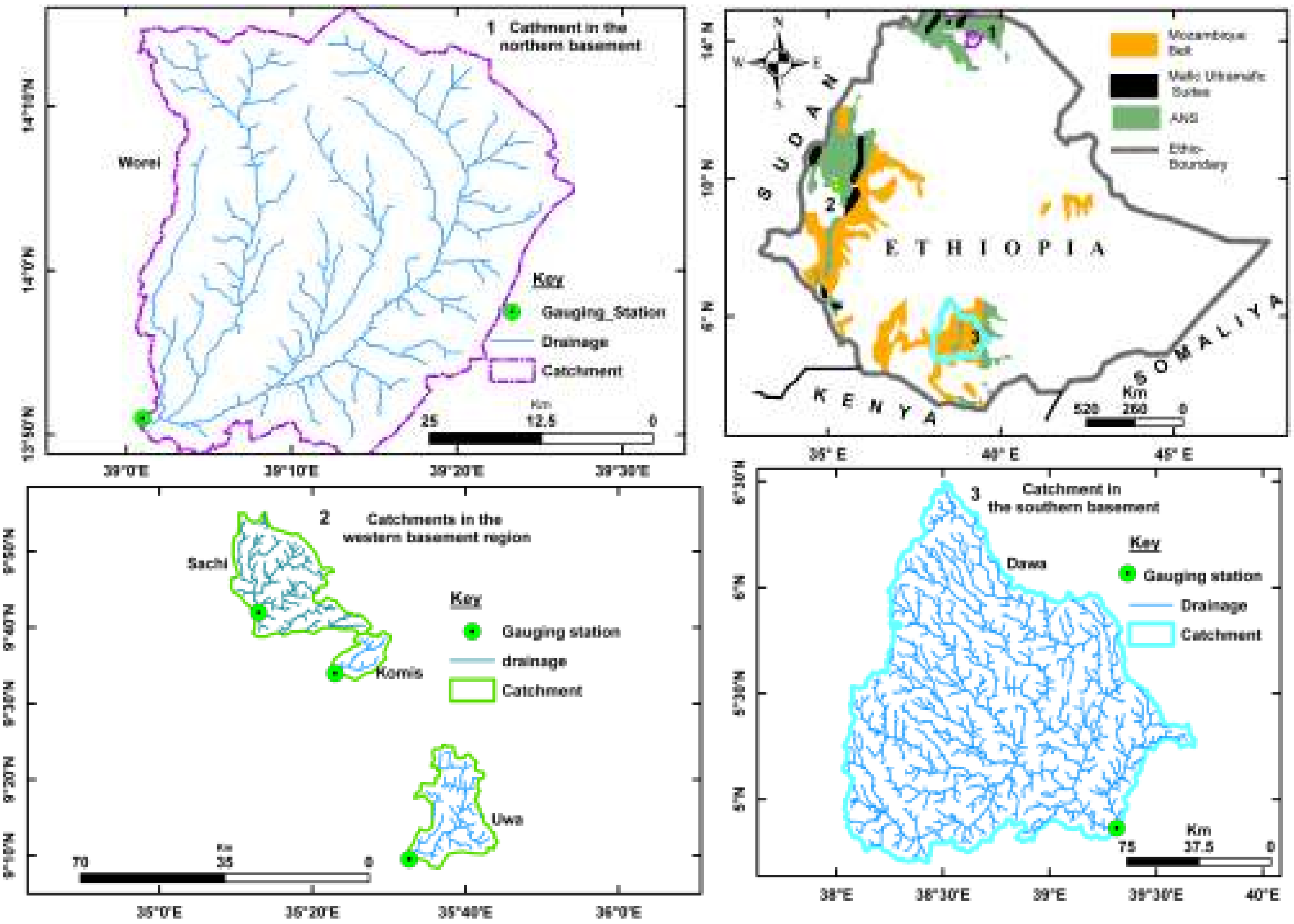


Figure 43) Location of the study sites and streams with gauging station indicated in the three basement regions of Ethiopia

4.4.2.1 Catchment in the northern region

Worei catchment is situated in the northern basement region (fig.43). It is drained by worei stream. Gauging station (Id.no, 121005) for the stream is located at the southwestern terminus is of the stream. Bedrocks of low-grade metamorphic rocks of slate, phylites, black limestone, and meta-volcanics dominantly cover the area (EIGS, 1977; EIGS, 1971).

Annual rainfall in the catchments varies between 600 to 700mm.The highest elevation is in the northern periphery that reaches to about over 2930m a.s.l. The terrain generally slopes from north to south and attains the lowest elevation of 1390m a.s.l at the southwestern terminus. Taking the two points the relief is about 1580m a.s.l. The catchment is deeply incised because of higher relief. This indicates that erosional processes are intense enough to strip the surface of its loose (weathered) mantle. As a result, weathered mantle is generally thin if exists. Depth-to-fresh bedrock is commonly below 10m with mean value less than 2m in the catchment and the northern region at large. This condition indicates the removal of weathered overburden by process of surface water erosion.

4.4.2.2 Catchment in the western basement region

Three representative catchments are selected from the western basement region (fig.43). The catchments are drained by perennial streams called Sachi, Uwa, and Komis. Sachi and Komis drain in to Dabus River, which is the main tributary of Abay (Blue Nile) River in the west. In contrast, Uwa stream flow southward and conveys its water to Birbir River.

Name of stream	**Station Number**	**Catchment Area(Km)^2**	**Relief(m) above sea level**
Sachi	115006	562	982
Uwa	101009	347	606
Komis	115010	112	464

Table 2) Streams and catchments in the western basement region indicating gauging station Id.number, relief and catchment area

Bedrock geology of the study sites are mapped in the geologic map of Gimbi sheet (GSE, 2000) in which Precambrian basement rocks are outlined. Granitic gneiss, meta-sediments, and meta-gabbroic-amphibolites bedrocks underlie Uwa catchment. Foliated, medium-grained diorite-gabbros bedrocks dominate Komis and Sachi catchments.

These catchments are found in the chain (catena) of the Gimbi - Nejo - Mendi highland that stretches from Mendi to Nejo area in NW direction. High and flat terrain (plateau) dominantly occupies this sub region. These streams have gauging stations at their lower reaches (table 2). Annual rainfall amount in these catchments generally varies between 1800 to about 2200mm. The flat and high areas are remnants of thick weathering product that mantle the basement bedrocks. Thick weathering profiles, observed all along the road cut from Gimbi town to Mendi town are excellent exposures (fig.44) to visualize the thickness of the weathered mantle. Valleys are commonly shallow with no deep incision and remain green even in the driest season (fig. 44). Fresh bedrock hardly exposed both in valley bottoms and in valley sides.

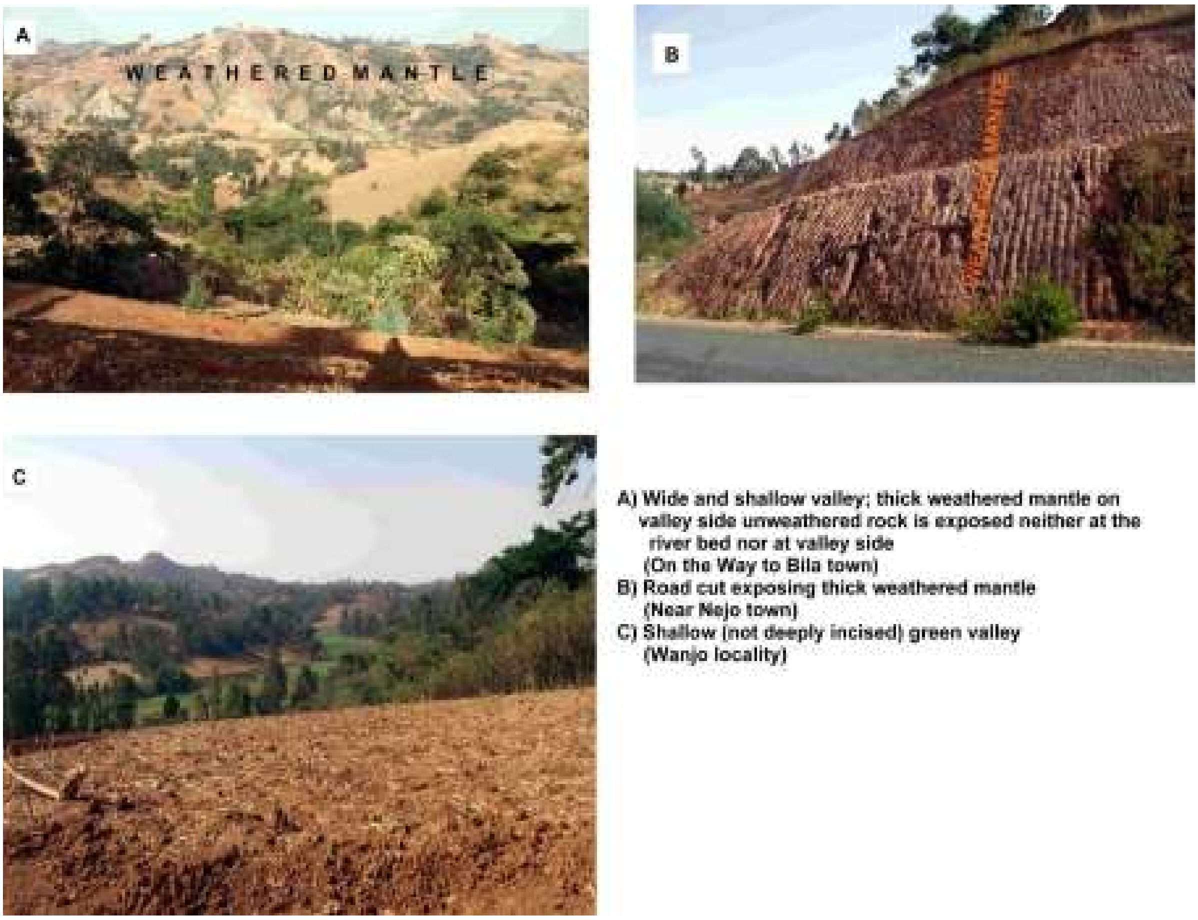


Figure 44) Field photos showing: A) wide and shallow valley with thick weathered mantle in valley sides B) Thick weathered mantle exposed at road cut C) Shallow valley with green bottom manifesting groundwater seepage

4.4.2.3 Catchment in the southern basement region

Dawa is a catchment situated in southern basement region (fig.43).The elevation varies from about 3000m in the north to about 800m a.s.l in the southeast direction. Dawa River drains it with dendritic drainage pattern and has general course in north- southeastern direction. Gauging station (Id.no 071001) is situated at the southeastern terminus of the River. The catchment is underlain by bedrock lithologies of basement complexes that dominantly includes gneisses, schists and intrusive of granites (EIGS, 1996). Very small patches of basalts are found in the northern terminus. Extensive alluvial sand dominated deposits commonly fill topographic depressions in the central and southeastern part of the area. The sources of the sediments are gneisses, granite bedrocks, and inselbergs ubiquitously distributed in the area. Thickness of the alluvial deposit is commonly from 20m to 30m but exceptionally goes up to 60m as it is indicated in lithologic logs of some water wells.

In the interfluves of highland areas, however, weathered overburden covers bedrocks. The thickness of weathered mantle rarely exceeds 20m on gneissic bedrocks where as in granites it is well below 15metres.Mean annual rainfall in the catchment varies between 400 to 900mm.

4.4.3 Methods and theoretical backgrounds

The methods in this study mainly involve analyzing the time series of daily flows to produce summary of information that describe the low-flow regime of the gauged streams in the three basement regions. These include low-flow indices and flow duration curves. The low-flow indices include base flow indices, specific mean daily base flows, and slopes of recession segments. The flow duration curves of the same streams, derived from the complete time series of recorded river flows, are also analyzed to corroborate the low-flow indices. Brief discussion on the use of low-flow indices and flow duration curves in studying descriptive variables of hydrogeological indicator (i.e. Regolith thickness) are also presented. Comparisons of the results of low-flow indices and shapes of the duration curves from the three regions are made. Finally, their implications to storage and hydraulic conductivities of aquifers in each catchment are discussed.

4.4.3.1 Base flow Index (BFI)

BFI is the ratio of base flow to total flow calculated from a hydrograph separation procedure (Institute of Hydrology, 1980; Tallaksen, 1987; Gustard, 1983; Gustard et al., 1992). It was developed in low-flow studies in the United Kingdom for characterizing the hydrological response of catchment soils and geology. Several reviews by many authors (e.g. Hall 1968, Nathan and McMahon, 1990; Tallaksen, 1995; Smakhtin, 2001; WMO, 2008) have presented on the analysis and application of stream hydrograph. Hydrograph separation techniques generally divide the total stream flow in to quick and delayed components. The delayed flow component, referred to as base flow, represents the amount of flow that originates from groundwater. In this work, hydrograph separation of five gauged streams (fig.43) is performed using time series data of daily stream flows (m^3/s) obtained from database of Ministry of Water, Irrigation, and Energy. Whilst, there are many alternative automated separation methods presented in (Nathan and McMahon, 1990), the hydrograph separation was made by Time Series Analysis module of River Analysis Package developed by (Marsh et al., 2003).

It generates an easily automated base flow indices and long-term average daily base flows. The base flows are standardized by dividing by water shade areas to get specific base flows that indicate the volume of water released from a unit area of catchment storage in unit time ($m^3/d/km^2$). The discharge is changed to liter per second per square kilometer ($L/s/km^2$) for comparison purpose. This allows the comparison of the relative storage properties among catchments in the three regions. Furthermore, relation of base flow indices and specific mean daily base flow with weathered mantle thickness is investigated.

4.4.3.2 Recession Curve Analysis

During periods of little or no precipitation, water stored in a catchment gradually depletes. The falling limb of stream hydrograph (fig.45) represents the depletion.

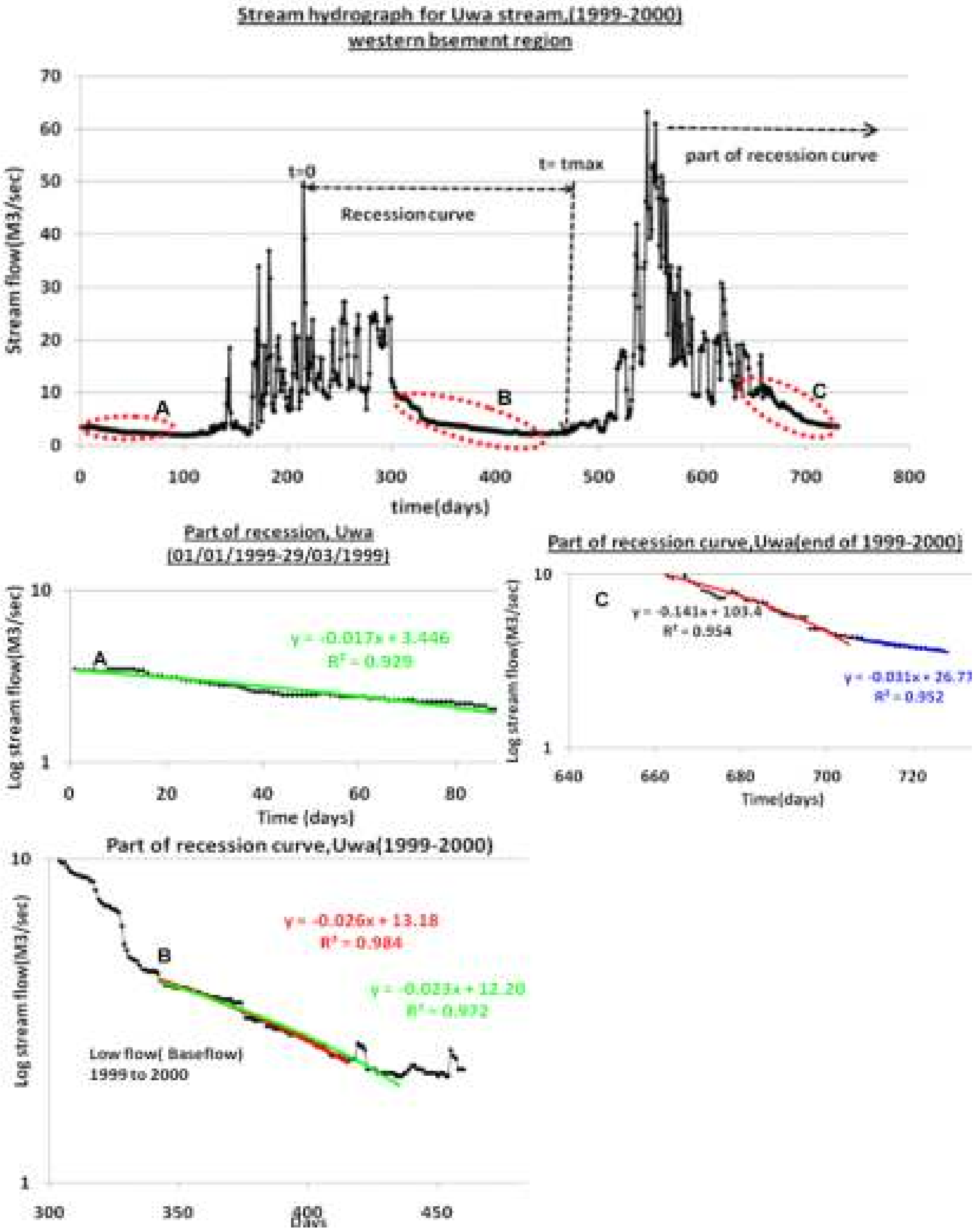


Figure 45) A stream hydrograph showing the recession curve (falling limb) with different individual recession segments (A, B, C) (data from Uwa stream gauge station Id no. 101009, western basement region)

Shape of a falling limb is affected by the hydrodynamic properties of the aquifer, such as hydraulic conductivity and storage coefficient (Brutsaert and Nieber, 1977; Moore, 1992; Eisenlohr et al., 1997). Hall, (1968) and Tallaksen, (1995) presented a comprehensive review of recession analysis. Other authors (e.g. Barnes, 1939; Werner and Sundquist, 1951; Mero, 1964; Shevenell, 1996) proposed that the discharge during the recession period could be represented as sum of N exponential components (eq. 1), which are the function of time.

$$\boldsymbol{Q(t) = \sum_{i=1}^{N} Q_i * e^{-t*\alpha_i}} \qquad \textbf{(1)}$$

Where Q (t) is stream flow at time t>0 (since the beginning of the recession), α_i the slope of the ith component of the recession curve on semi logarithmic scale and Q_i is the initial flow of the ith component.

Accordingly, in this work, the fittings were performed to the individual recession segments on semi-log plots of (Q (m^3/s) on log scale and t (days) linear scale, to extract the individual recession slopes (α_i) (1/d). The early part of the recession part is excluded to avoid the influence of rapid response of flow following a rainfall event.

The slopes of the ith components, (α_is) are extracted after plotting the recession time series data on semi logarithmic scale (fig.45).

4.4.3.3 Flow duration curves

The flow duration curve is a graph of complete time series of stream discharge plotted against exceedance frequency WMO, (2008). Searcy, (1959) had presented the use of flow duration curves in the context of methods and practices in geological surveys. In all cases, the construction of flow duration curves involves ranking the daily discharges and calculation of the frequency of exceedance for each value.

The shape of the flow duration curve is determined by the hydrologic and geologic characteristics of the drainage area. Many authors (e.g. Cross, 1949; Cross and Bernhagen, 1949; Schneider, 1957) showed that the distribution of low-flow is controlled chiefly by the geology of the catchment. They emphasised that the lower end of the flow duration curve is a valuable means for studying the effect of geology on the groundwater flow to streams and or to compare the characteristics of one basin with those of another Searcy, (1959).

It is indicated that curve with a steep slope throughout denotes a highly variable stream whose flow is largely from direct runoff, whereas a curve with a flat slope reveals groundwater storage, in the absence of surface water reservoir in a catchment.

In this work, the flow duration curves of selected stream in the three basement regions have been constructed according to the steps described in (WMO, 2008). This is followed by the comparisons of the shape and the steepness of the lower end of flow duration curves of streams to infer the flow regimes in the catchments from the three basement regions. Hence, a qualitative interpretation on variations of catchment responses is made. Furthermore, discharge values corresponding to the 5% and 95% time of the flow regime are extracted to corroborate the comparison of the shape and steepness of the flow duration curves.

4.4.3 Result

4.4.4.1 Annual Base flow indices and specific mean daily base flows

Base flow indices and specific mean daily base flows are extracted for all the streams under the study following data processing or filtering procedures. The result is provided in table 3.

Gauging Station id.	**Stream name**	**Rec. (yr)**	**Relief (m)**	**Ann. Rainfall (mm)**	**Annual BFI**		**Mean daily base flow(m^3/sec)**		**Specific Mean Daily Base flow (L/s)/km^2**	
					Mean	Std	Mean	Std	Mean	Std
121005	Worei	7	1580	500-700	0.13	0.06	1.4	0.71	0.79	0.15
071001	Dawa	7	2338	400-900	0.42	0.03	7.71	3.38	0.39	0.172
115006	Sachi	12	982	1900-2200	0.66	0.02	8.39	2.02	14.92	3.59
101009	Uwa	13	606	1850-2000	0.69	0.04	4.96	1.52	17.27	5.29
115010	Komis	13	464	1800-2000	0.65	0.08	2.67	1.25	23.81	11.1

Table 3) Summary of relief, mean annual rainfall, the mean and standard deviation of annual base flow, daily base flow and specific mean daily base flow indices

The specific mean daily base flow are the standardized mean daily base flow values, which are divided by water shade areas of the catchments indicating the volume of water released from the catchment storage per unit area of catchment (L/s/km^2). These values allow the comparison of the relative storage properties among catchments in the three regions.

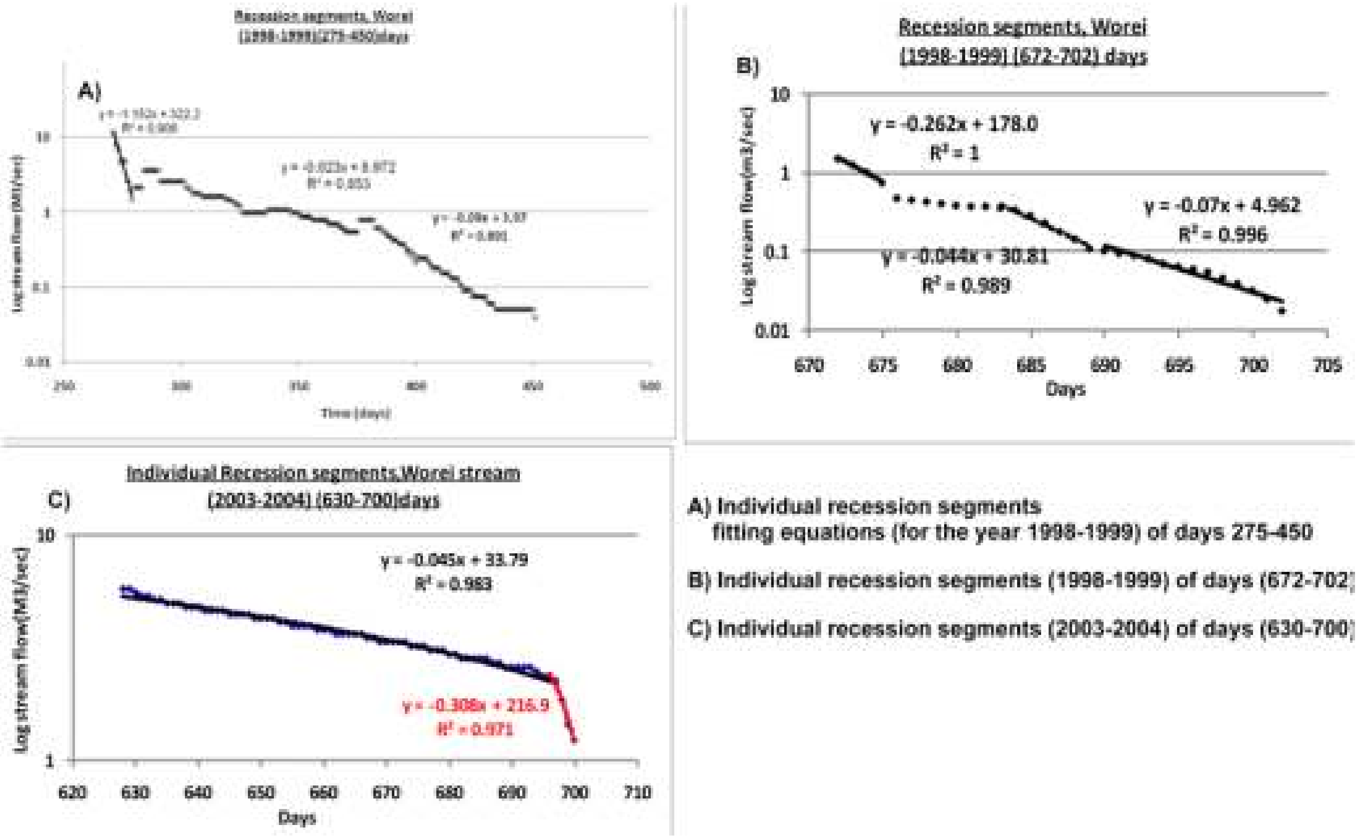
4.4.4.2 Recession slopes (α_i) from individual recession segments

The fitting procedures described in method section were applied to the lower terminus of the recession segments of all the streams under the study (fig.46-50). Figures 46-50 show the parts of fitting models and the individual recession segments. Mean extracted values of recession slopes (α_i) are summarized in table 4; and annex 4 gives the summary of the recession slopes of individual recession slopes (α_i).

A) Mean recession slope (α_i(1/d)) from streams in the northern region			
Gauging Station ID. No.	**Stream name**	**Mean recession slope (α_i)**	**Fitting,R^2**
121005	Worei	0.45	0.926
B) Mean recession slopes (α_i) from streams in the southern region			
Gauging Station ID. No.	**Stream name**	**Mean recession slope (α_i)**	**Fitting, R^2**
071001	Dawa	0.35	0.92
C) Mean recession slopes (α_i) from streams in the western region			
Gauging Station ID. No.	**Stream name**	**Mean recession slope (α_i)**	**fitting, R^2**
115006	Sachi	0.0735	0.925
101009	Uwa	0.0235	0.938
115010	Komis	0.0204	0.970
Mean value		**0.039**	**0.95**

Table 4) Summary of the recession slopes (αi) of the fitting models and fitting errors

The comparison of recession slopes (α_i) (table 3) of streams generally show streams in the western region posses the lowest values (mean α_i=0.03). Those streams draining the northern region have higher values (mean α_i=0.45) and those of streams in the southern region have intermediate α_i-values between the two (mean α_i=0.35) regions (table 4).



A) Individual recession segments
fitting equations (for the year 1998-1999) of days 275-450

B) Individual recession segments (1998-1999) of days (672-702)

C) Individual recession segments (2003-2004) of days (630-700)

Figure 46) Parts of individual recession segments for Worei stream. The late flow regime is fitted with linear model on semi-log plot

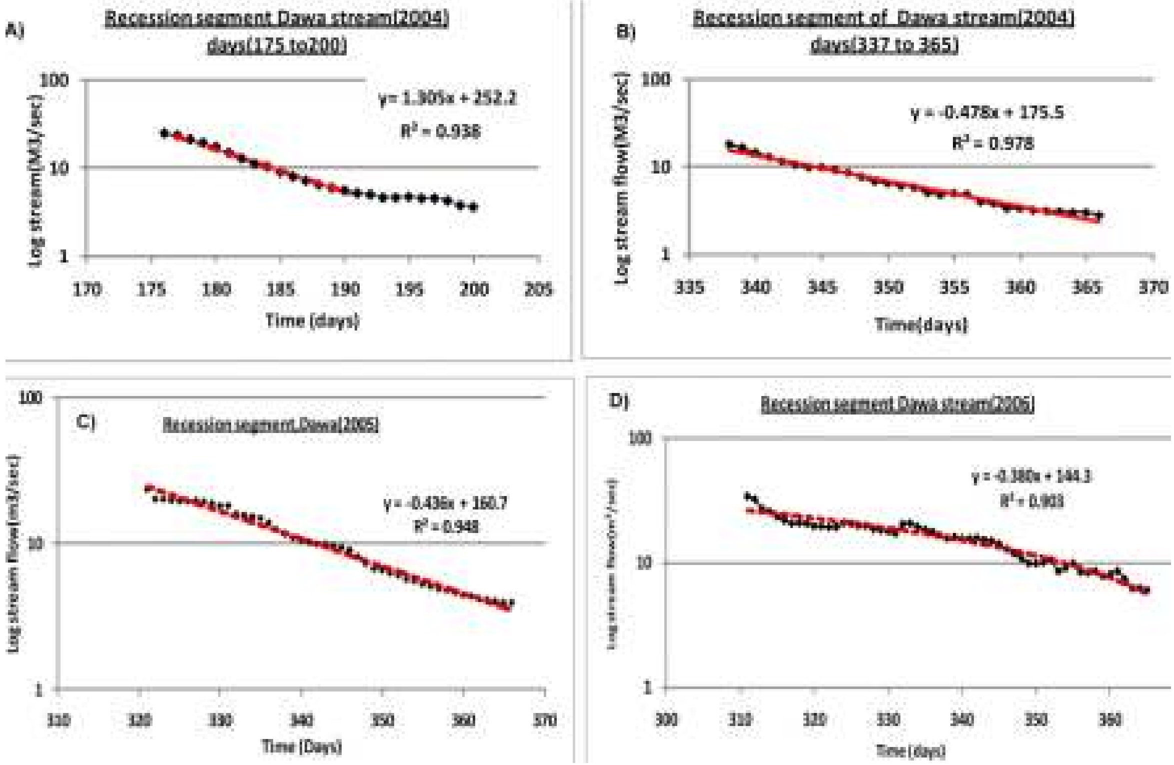


Figure 47) Parts of individual recession segments of Dawa River for late recession with fitting model

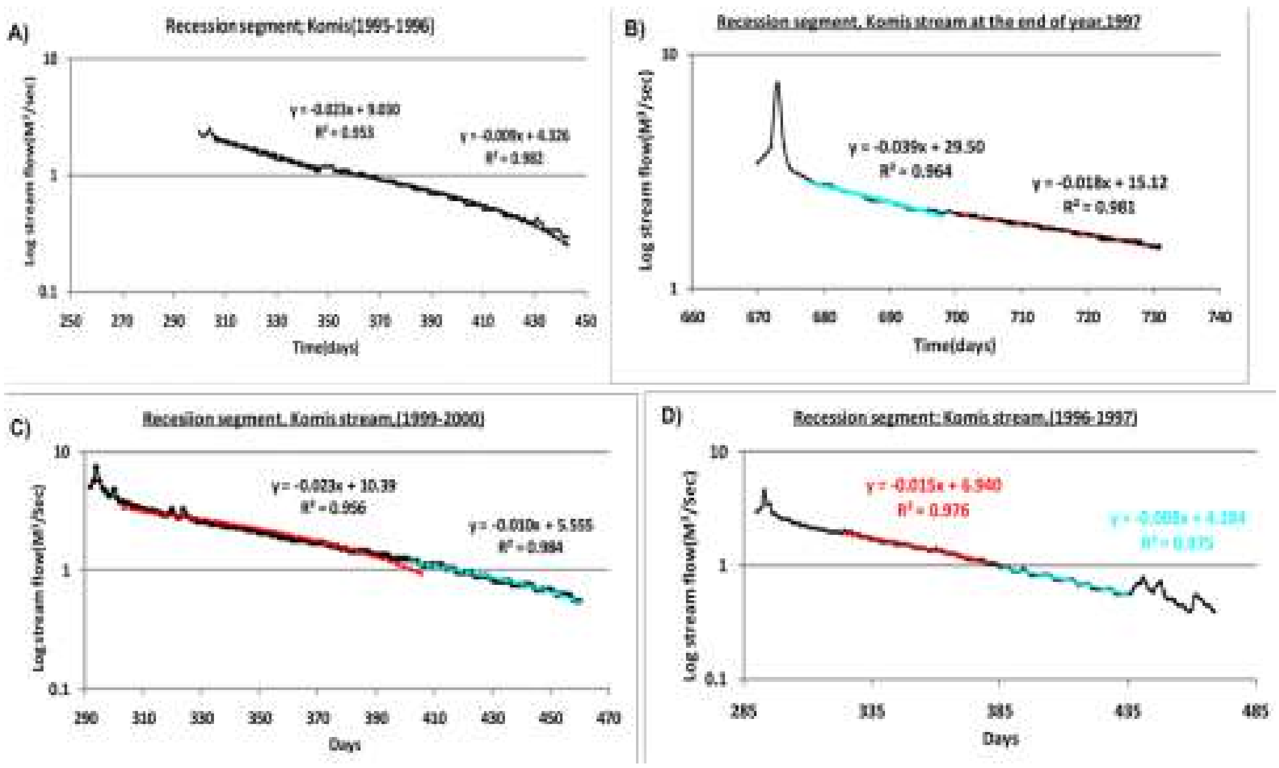


Figure 48) Parts of individual recession segments of Komis stream for late recession period

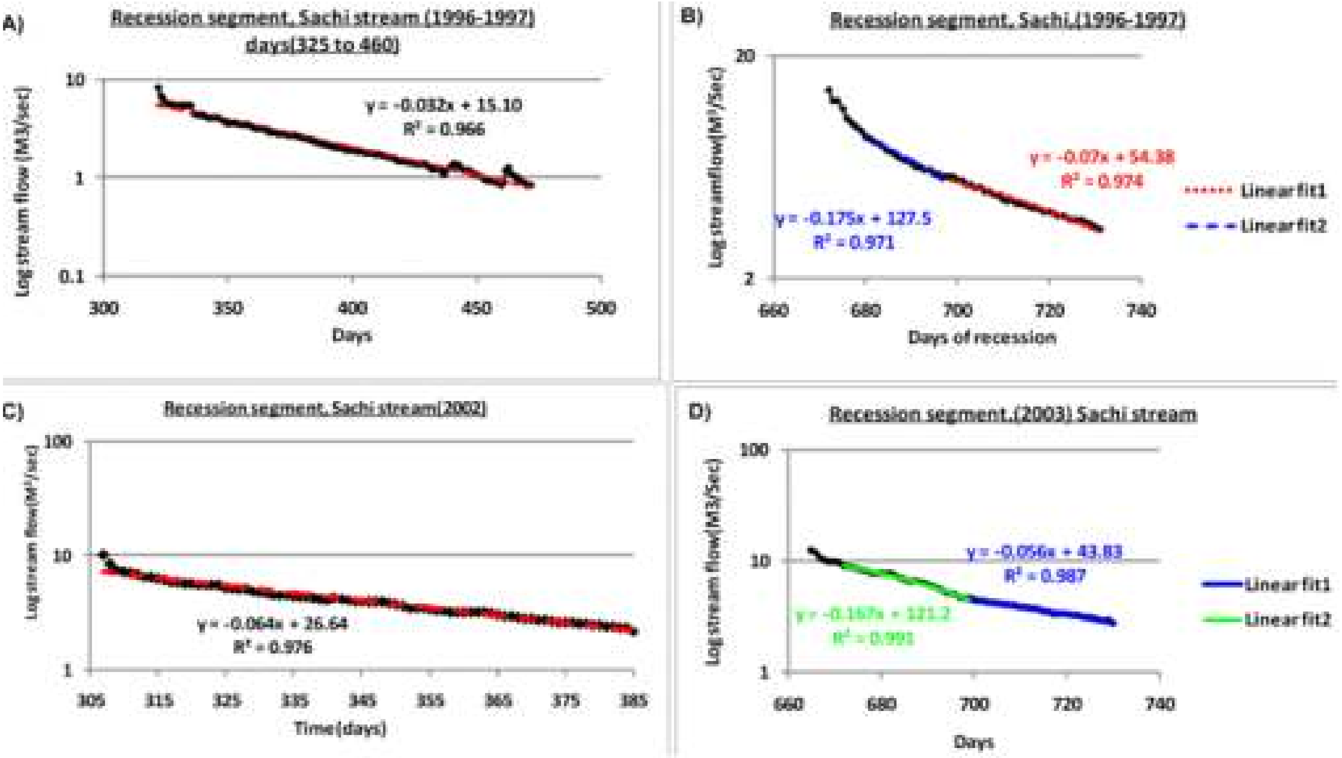


Figure 49) Parts of individual recession segments of Sachi stream for late recession period (with linear fit)

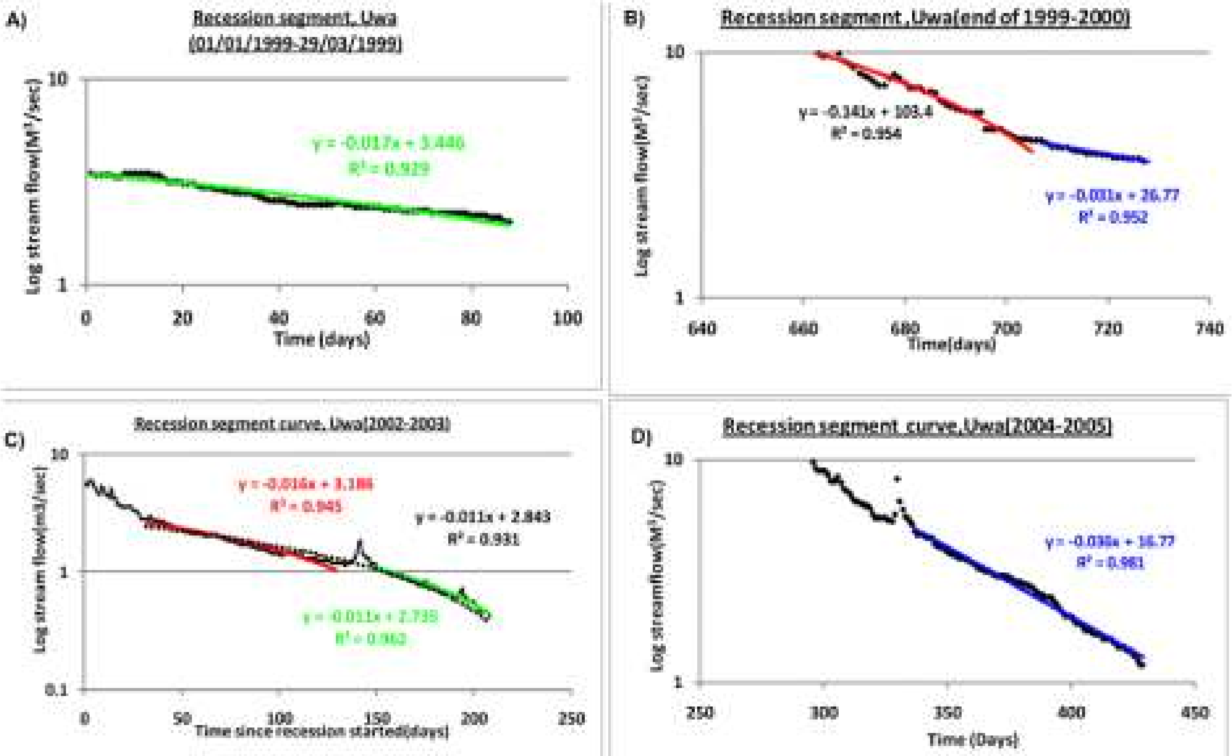


Figure 50) Parts of individual recession segments of Uwa stream for late recession period

4.4.4.3 Flow duration curves

The flow duration curves of selected stream in the three basement regions have been constructed in figure.51.

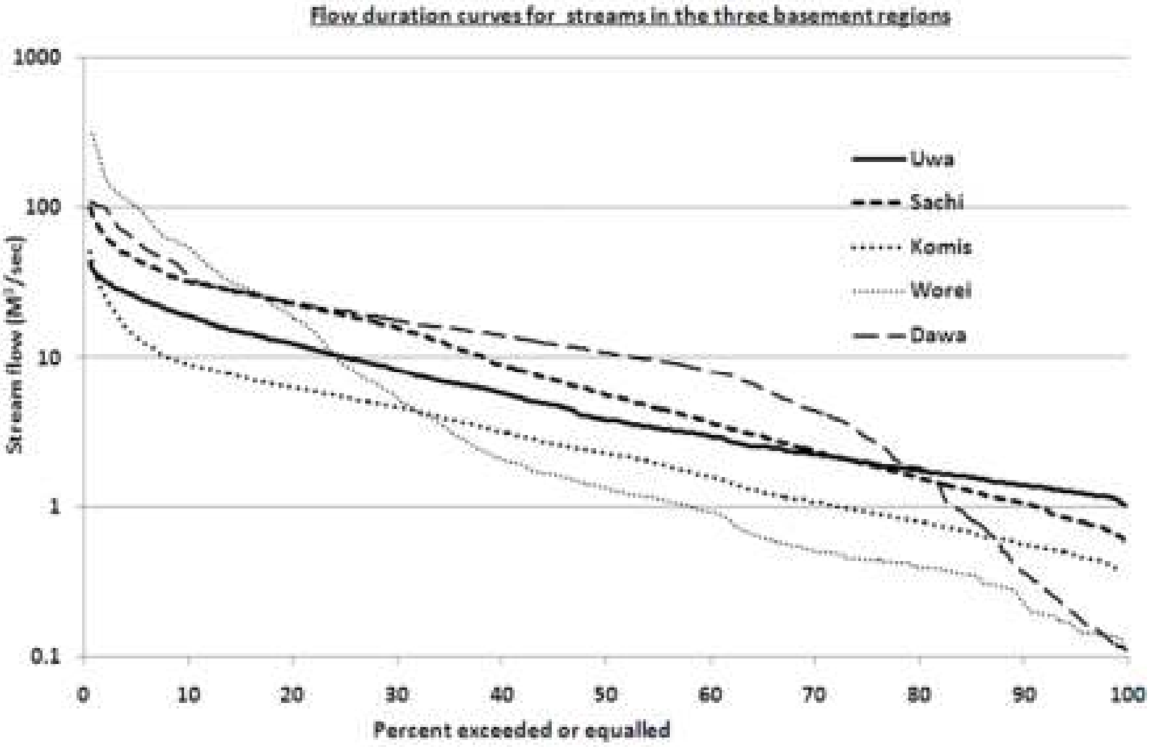


Figure 51) Flow duration curves for all the streams; contrasting shapes indicating variation in flow regimes in the catchments of the three basement regions.

The flow regimes of the low-flows were analyzed by comparisons of the shape and the steepness of the lower segments of flow duration curves of streams under the study (fig.51). The flow duration curve of the stream from the catchment in the northern and southern basement regions generally have steep slopes at their lower segments while those of the western region are relatively flat.

Discharges corresponding to the 5% and 95% exceedance of time are shown in table 4 to corroborate the comparison of the shape and steepness of the flow duration curves. Worei stream has largest value of flow (155m^3/s) for the early time of the flow regimes (5% of the time) but the lowest flow (0.15m^3/s) for 95% of the flow regime (table 5).

Stream	**Gauging station Id No.**	**Mean annual rainfall(mm)**	**Discharge(m^3/s) corresponding to exceedence time**	
			Q_5	**Q_{95}**
Worei	121005	500-700	154.96	0.15
Dawa	071001	400-900	62.46	0.27
Uwa	101009	1850-2000	24.5	1.4
Sachi	115006	1900-2200	57.5	1.1
Komis	115010	1800-2000	15.5	0.52

Table 5) Discharges corresponding to 5 %(Q5) and 95 %(Q95) of the flow regimes with mean annual rainfall ranges to infer hydrologic response of streams

Conversely, the streams in the western region generally have lower flows that range from 15.5 to 57.5m^3/s for the early time of the flow regimes (table 4). Whereas, for the late flow regime (95% of the flow time), the flow ranges from 0.5m^3/s to 1.4m^3/s- the largest low-flows as compared to the streams in the two other regions (table 4). Dawa stream on the other hand, has intermediate flows at both early and late time of flow regimes compared to the other streams in the two regions (table 5).

4.4.5 Discussion

4.4.5.1 Contrasts in hydrological responses reflected in base flow indices and specific mean base flows: implication to storage capacity of the catchments

Worei stream in the northern basement region has the smallest mean values (0.13) of annual base flow index (table 3; fig.52) indicating significantly small contribution of base flow to stream flow. Negligible base flow, as indicated by the smallest base flow index suggests a hydrological regime dominated by surface runoff. The streams draining the catchments in the western basement region on the other hand, have the largest mean values of annual base flow indices (0.63-0.69) (table 3; fig.52). This indicates, base flow comprises a significant component of the total stream flow and so reflects a recharge-dominant, hydrological regime. The Dawa stream draining the southern region has intermediate annual base flow indices (0.35) as compared to the other two regions (table 3; fig.52).

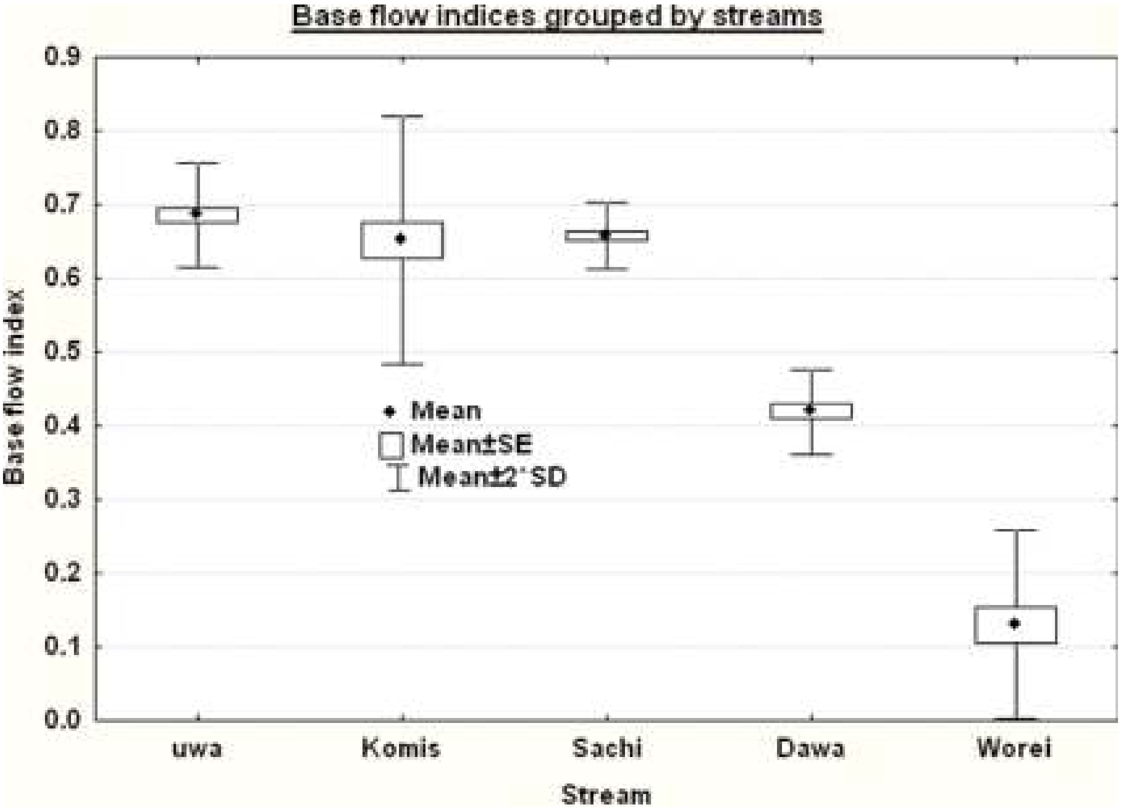


Figure 52) Variations in base flow indices of streams. Uwa, Komis, and Sachi streams show relatively lager values, Worei has the lowest values and Dawa shows intermediate values between the other streams

Similarly, the specific daily base flows of streams draining catchments in the western region possess generally the highest values that range from 14.9 to 23.8 L/s/km^2 (fig.53). This is indicative of voluminous groundwater discharge from storage per unit area of catchments.

In contrast, those draining the catchments in the northern and southern regions have generally lower mean values of specific mean base flows (1.4 and 0.39L/s/km^2) respectively (fig.53) indicating significantly low contribution of groundwater flow to streams.

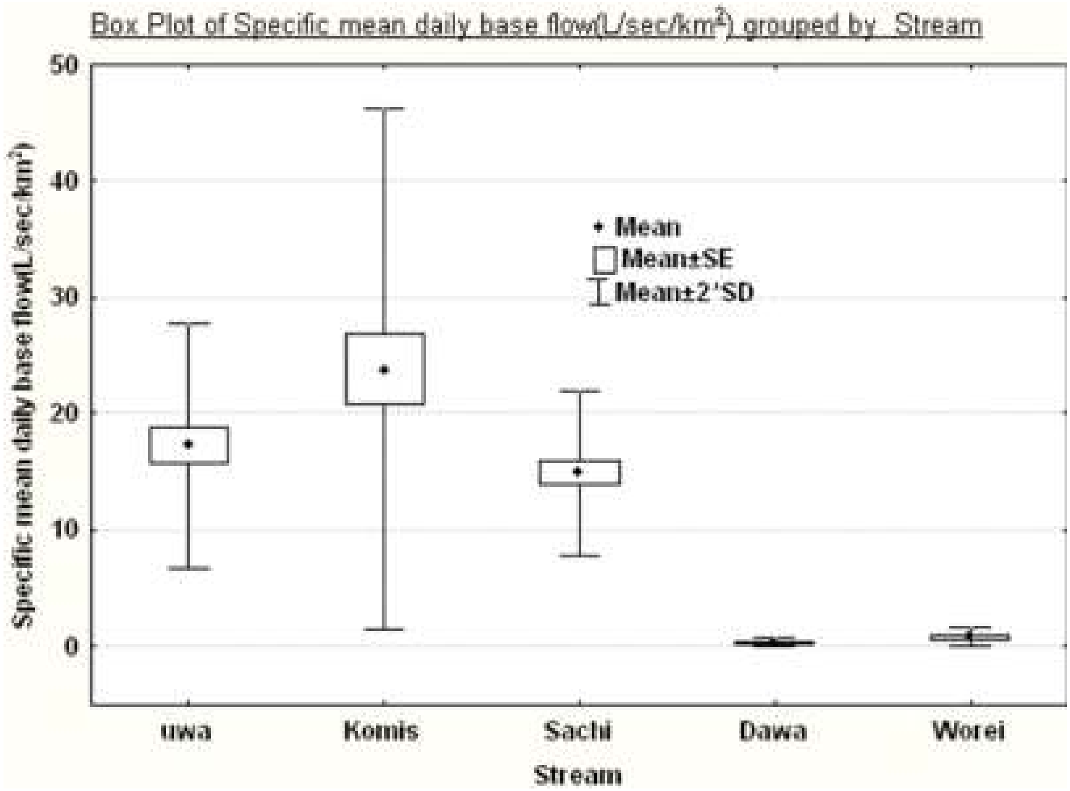


Figure 53) Variations in specific mean daily base flows indicating the volume of groundwater discharged in unit time from unit catchment area. Catchments in the western basement region (Uwa, Komis, and Sachi) contribute significantly higher volume of groundwater and the two other catchments release lower amount

The contrasting hydrological characteristics (i.e. annual base flow indices and specific mean base flows) of streams in the study areas reflect the responses of catchments in the three regions.

The condition of higher volume of discharge, that sustained the base flows in the western streams, reflect high storage capacity of the catchments in this region. This is attributed to thick, deeply weathered overburden (regolith) receiving significant amount of recharge from higher annual rainfall (table5). Furthermore, the condition of low relief surfaces in these catchments favors vertical rather than horizontal movement of meteoric water (in the vadose zone).Thus, erosion was unable to induce removal of weathered mantle. This is exhibited by the presence of wide, shallow (not incised) valleys (fig.44) and hardly exposed fresh bedrock outcrops both in the valley bottoms and in valley sides in these catchments. In addition, valleys commonly remain green even in the driest season (fig.44) suggesting groundwater discharge to streams.

In contrast, the least base flow index and specific mean daily base flow of stream in the northern region indicate higher proportion of surface runoff than base flows in stream discharges.

This implies a hydrological regime dominated by surface runoff. Despite the low mean annual rainfall that ranges from 500-700mm in the catchments, higher runoff is generated because of higher surface gradient. Higher topographic gradient of catchments in this region enhances the rate at which soil water and surface runoff moves down slope, thereby increasing storm water that is flushed to the deeply incised channel networks.

The dominance of runoff over base flow reflects a comparatively low storage capacity, which is expected, in catchments with thinner or stripped weathered overburden.Thus, this catchment does not store significant quantities of water and thus contribute to stream runoff than base flow.

Intermediate values of base flow index and specific mean daily base flow of Dawa stream in the catchment in the southern region, may reflect moderate storage capacity. This condition may be attributed to moderately thick weathered and alluvial deposit reservoir receiving modest amount of annual rainfall (500 to 900mm) to sustain base flow to the streams.

4.4.5.2 Contrasts in recession slopes (α_i) among catchments and their relation to hydraulic conductivities of aquifers

The fitting procedures described were applied to individual recession segments (fig.46-50) of streams under the study. Mean recession slopes (α_i) extracted from fitted models and the summary is presented in table 4.

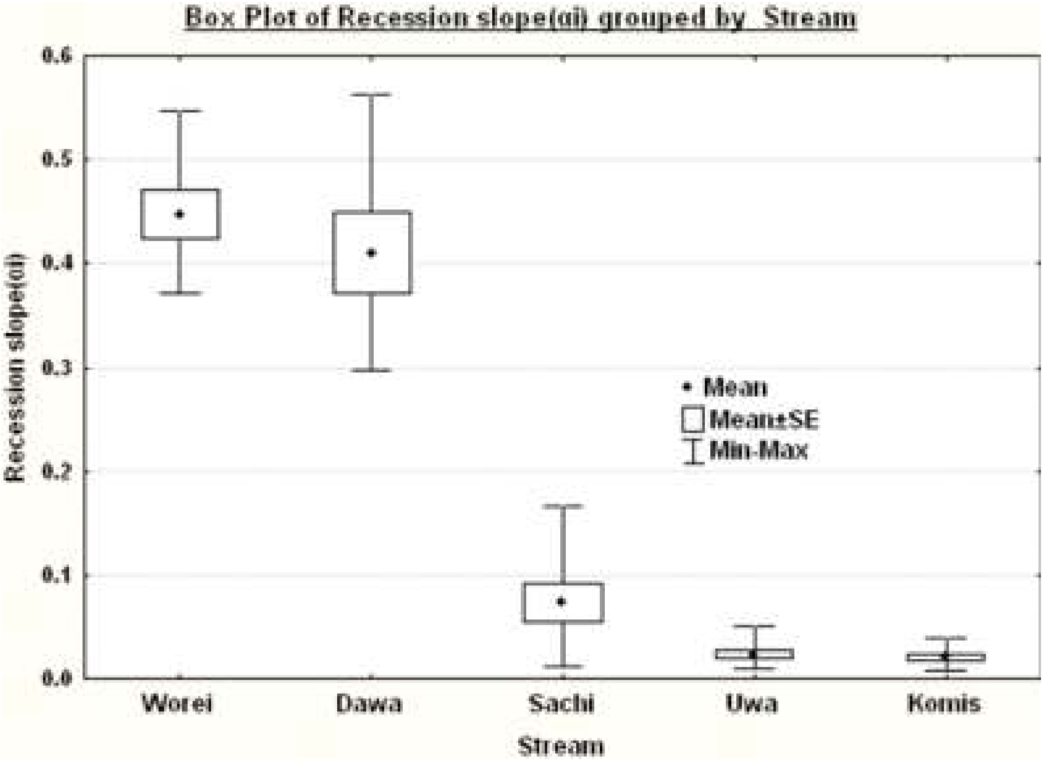


Figure 54) Variation in recession slopes of streams. Streams in the catchments of western (Uwa, Sachi, and Komis) basement generally have lower values whereas; Worei (northern) and Dawa (southern) have relatively higher values of recession slopes

Comparison of the recession slopes (α_i) values for streams draining catchments in the three basement regions show considerable variation (fig.54). Values of recession slopes from recession segments of Worei stream in the northern region and Dawa stream in the southern region are generally larger (table 4, fig.54). In contrast, streams draining the catchments in the western region possess generally the smallest values of recession slopes (table 4; fig.54).

It has been indicated that the value of recession slopes (α), reflect aquifer properties, especially hydraulic conductivity and storage (Ford and Williams, 1989). Larger values of recession slopes (α_i) signify a steep recession, which is indicative of rapid drainage and little storage. Tallaksen, (1995) especially indicated that in the depletion of specific reservoir, the hydraulic conductivity of a reservoir is proportional to recession slope (α_i).

Accordingly, the largest recession slopes, (α_i) of Worei stream draining catchment in the northern basement region (table 4; fig.54) represent rapid depletion of storage indicating higher hydraulic conductivities but lower storage capacity.

In contrast, the smallest values of recession slopes, (α_i) (table 4; fig.54) of streams draining the catchments in the western basement region, reflect slow depletion of storage. This condition is a case of larger storage capacity but smaller hydraulic conductivity of reservoir in these catchments.

4.4.5.3 Contrasts in shapes of the flow duration curves

The shape of the flow duration curves generally reflects the combined effects of physiographic and climate (Cross, 1949; Cross and Bernhagen, 1949; Schneider, 1957). Searcy, (1959) specially, indicated that the distribution of low-flows is dominantly controlled by the geology of catchments. Thus, comparisons of the shape of the lower end of the flow-duration curves are a valuable means for studying the responses of catchments in different regions. Figure 51 depicts the shape of the flow duration curves from streams in catchments in the three basement regions. There are observable contrasts among the shapes and the slopes of the lower segments of the flow duration curves (fig.51). The flow duration curves of the streams from the catchments in the northern and southern basement regions generally have steep slopes at their lower segments (fig.51) indicating high variability of daily flows (table 5). According to Searcy, (1959) and WMO, (2008), this is typical of catchments with little storage and a rapid response to rainfall. This indicates that significant portion of rainfall is flushed in to the incised stream channels increasing quick flow of streams (table 5). The condition of little storage property in the catchments of the northern basement region is attributed to nil or very thin weathered mantle covering the bedrocks (fig.55). In the catchments of the southern region however, the relatively flat type of curves in the upper part tribute to the moderately thick weathered mantle covering this region (fig.51).

In disparity, the streams in the western region possess generally flat types of flow duration curves with very low slopes at their lower segments (fig.51) indicating stream flow with low variability. This is typically a condition of permeable catchment and or one with a strong regularity influence by lake storage or surface water storage (WMO, 2008). However, the absence of lake storage or impound water, lends the thick weathered mantle (Kebede, 2013; Deyassa et al., 2014) to be significant reservoir with ample storage capacity(Mwakalila et al., 2002) that sustain the base flow in the streams.

4.4.5.4 Relation of low-flow indices (metrics) with weathered overburden

The fact that surface water reservoirs (lake or impound water) are absent in the study catchments, renders catchment geology chiefly controls base flow-generating processes (Farvolden, 1963; Smakhtin, 2001; Tague and Grant, 2004; Neff et al., 2005; Bloomfield et al., 2009). Recent studies (Kebede, 2013; Deyassa et al., 2014) showed variations in thicknesses of weathered mantle among the three basement regions in which the catchments under the study are situated. The variations are mainly because of contrasting geomorphic histories in each region (Kebede, 2013; Deyassa et al., 2014).

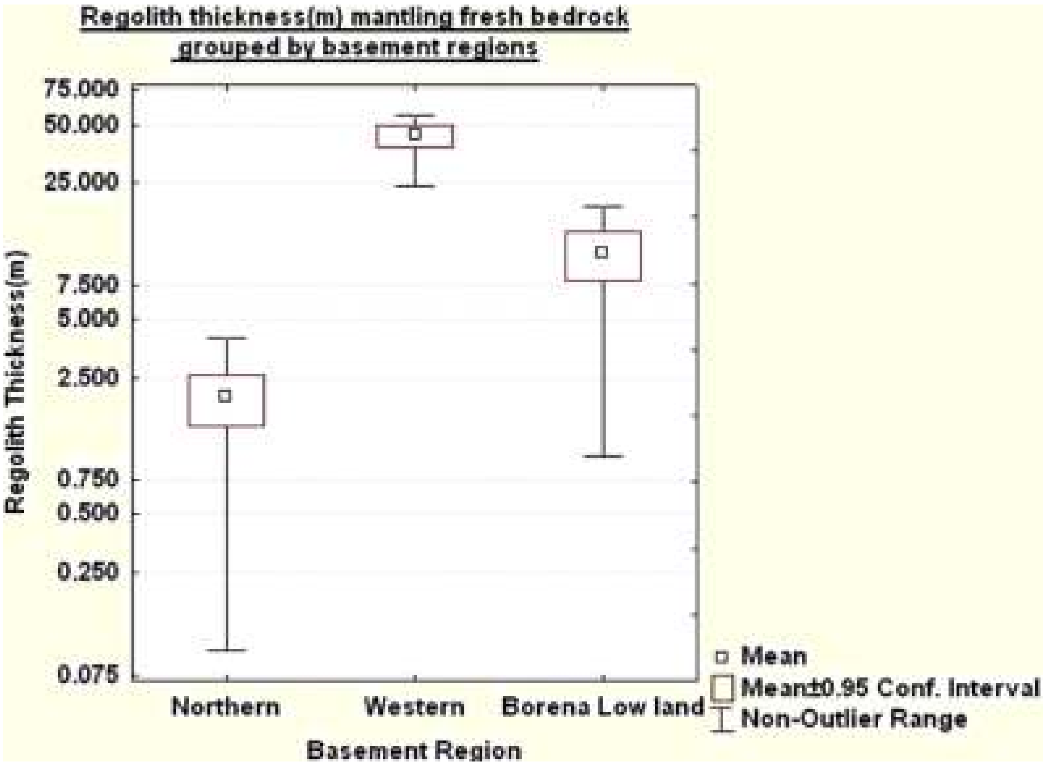


Figure 55) Variation of thickness of weathered mantle in the three basement regions. Thick weathered mantle in the western, thin in the Northern and moderately thick in the southern basement regions (figure from Deyassa et al., 2014).

The studies indicated that thick insitu weathered mantle (mean thickness≈50m) (fig.55) cover the western basement bedrocks. In contrast, in the northern region, the weathered mantle is stripped to negligible thickness (mean thickness≈2m) (fig.55). In the southern (Borena area), the weathered mantle rarely exceeds mean values of about 10m, which is between the two other regions (fig.55).

Correlations among mean regolith thicknesses, mean base flow indices, mean daily base flows and recession slopes demonstrate the controls of thickness of weathered mantle to affect the low-flow regimes of catchments in the three regions (fig.56, 57&58).

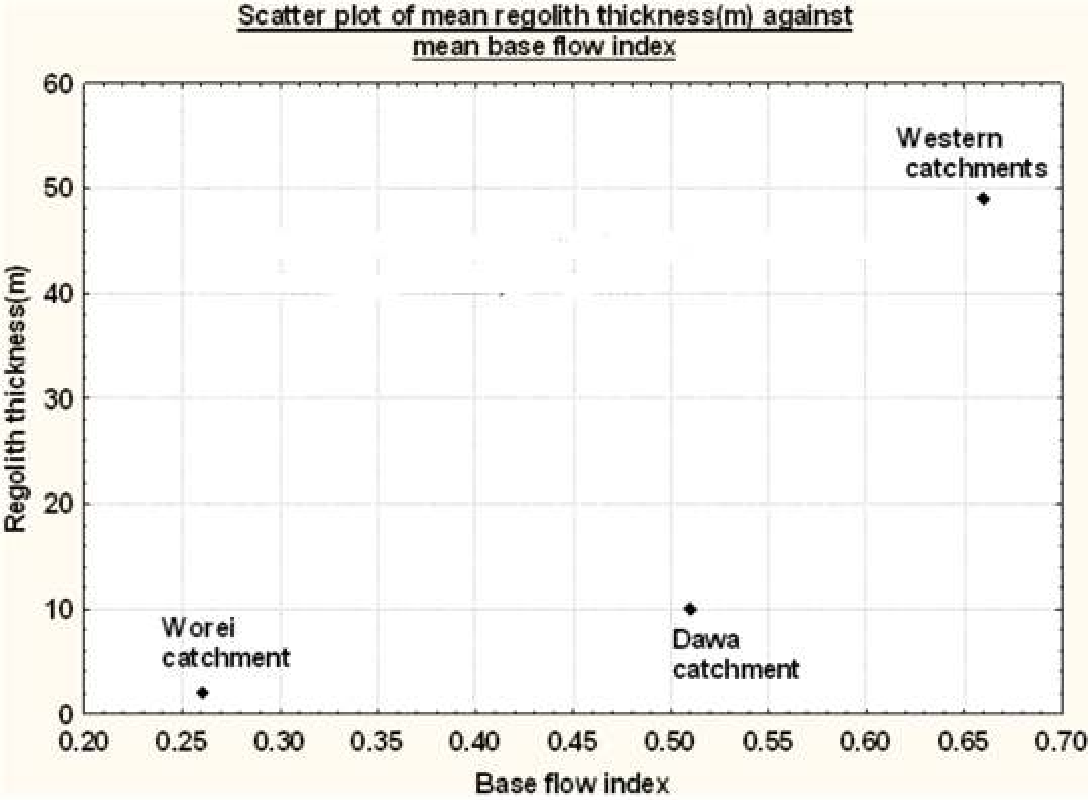


Figure 56) Relation between regolith thickness and base flow index in the catchments of the three regions

Significant positive correlation of mean thicknesses of weathered mantle with base flow indices (fig. 56) and specific mean daily base flows (fig.57) exist among catchments in the three regions. This positive relationship reflects the significance of thick weathered overburden (e.g. saprolite or other regolith), to serve as a more important reservoir that sustain base flows as described by (Smith, 1981; Mwakalila et al., 2002; Witty et al., 2003). This is manifested in the largest values of specific base flows and base flow indices in the western catchments where regolith is the thickest. In contrast, very little specific base flows and base flow indices in the northern catchments indicate the weathered mantle is stripped away to negligibly small thickness.

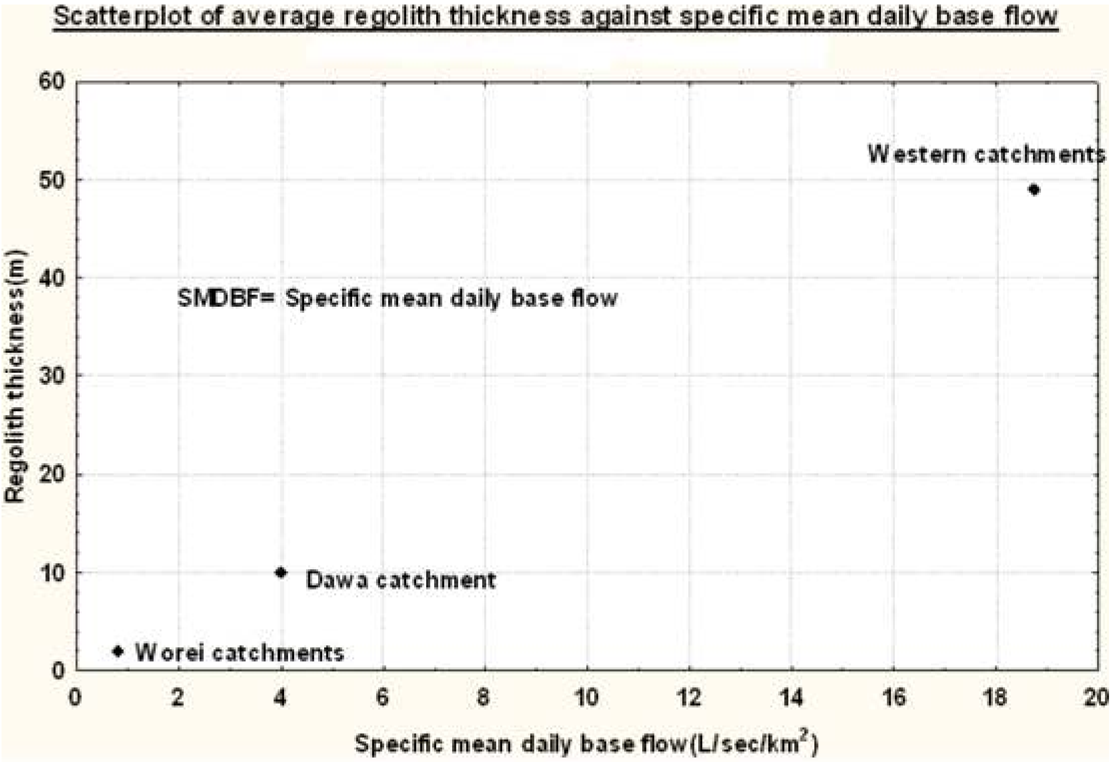


Figure 57) Relation between specific base flows and thickness of weathered mantle in the catchments of the three basement regions

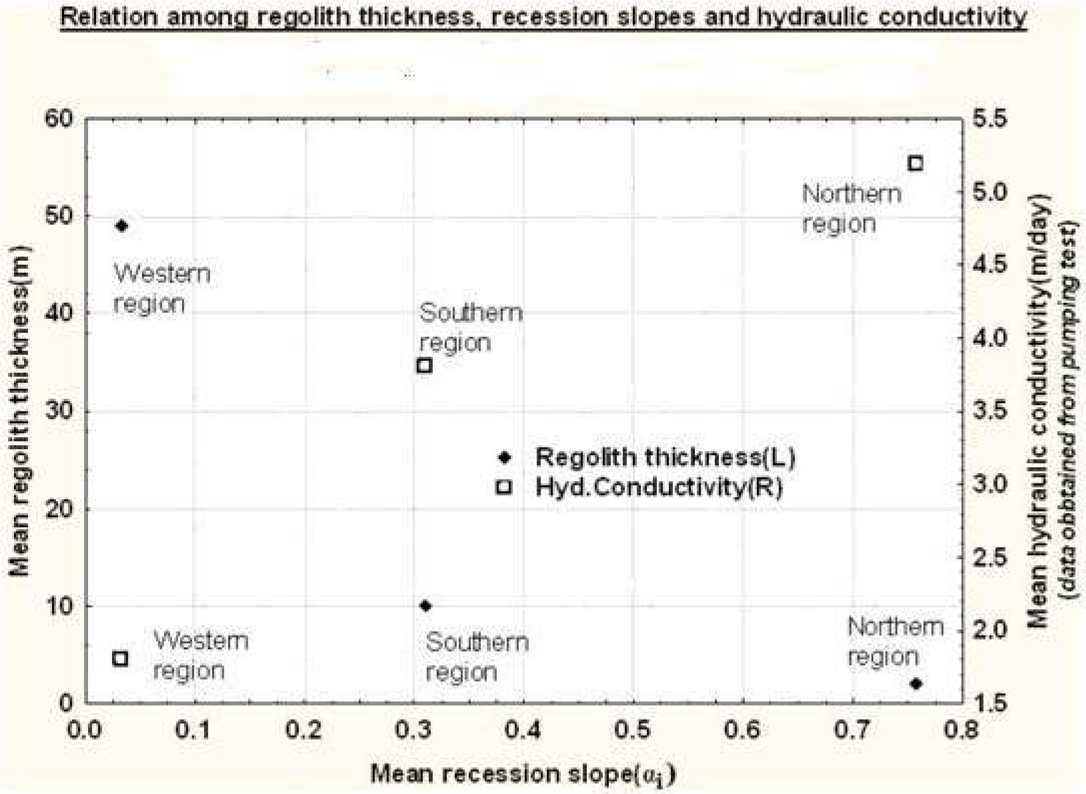


Figure 58) Relation among regolith thickness, recession slopes, and hydraulic conductivity; recession slope is negatively correlated with regolith thickness (left axis), and positively correlated with hydraulic conductivity (right axis).

Furthermore, the relation of thicknesses of weathered mantle with recession slopes (α_i) of individual recession segments gives negative correlation that shows an inverse relationship (fig.58). This signifies that catchments underlain by thick weathered mantle possess lower values of stream recession slopes indicating higher storage capacity (fig.58). This is in agreement with a view described by (UNESCO, 1984; Taylor and Haward, 2000; Dewandel et al., 2006) who emphasized that the weathered mantle provides storage capacity in a composite aquifer system of weathering profile in deeply weathered terrain. This is the situation in the western basement region of Ethiopia, where most of the catchments are characterized by thick weathered mantle because of enhanced deep weathering (Kebede, 2013; Deyassa et al., 2014). The large storage capacity of thick weathered mantle in these catchments is manifested by receiving higher annual inflow as rainfall but discharging it at slower rate as reflected in little values of recession slopes (α_i)(Table 4;fig.54).

Likewise, the largest values of recession slopes, (α_i) of the streams draining catchments in the northern basement region, correlate with smallest mean thickness of weathered overburden (table4; fig.58) in the catchment. This indicates rapid depletion of storage indicating higher hydraulic conductivities but lower storage capacities. In addition, the positive correlation of recession slopes (α_i)with mean hydraulic conductivities (obtained from pumping test in the three regions), (fig.58) also attests rapid depletion of flow indicating very little or nil regolith cover in the northern basement region.

Therefore, the significant variations in specific base flows, base flow indices, and recession slopes can be attributed to contrast in bulk hydraulic properties (storage capacity and hydraulic conductivity) of catchments in the three basement regions. The existence of this variation thus, diverges from the existing premise, which traditionally describes the crystalline basement rocks of Ethiopia as one system of regional aquiclude (EIGS, 1988; Cherenet., 1993).

4.5 Response of basement aquifers to pumping test stresses: implication to identification of aquifer structures

Diagnostic plots (Bourdet et al., 1983; Bourdet et al. 1989) of simultaneous plots of drawdown as a function of time in log-log and semi-log scale help in analysing the aquifer responses. This facilitated the identification of appropriate conceptual model in the three basement regions. Analytical pumping test solutions that best match to drawdown responses are fitted to identify types of aquifers. The analysis of matches between each solution and recorded drawdown was done iteratively using AQTESOLV (Duffield, 2007).The aquifer types obtained from this analysis are compared with the weathered mantle-bedrock profiles developed for the three basement regions.

The analysis of well design from water wells in western basement region revealed that the screen casings are commonly installed towards the bottom of lithologic logs. This depth corresponds to the basal level of the weathered profile just on top of bedrock. This signifies that groundwater is not directly pumped from the weathered mantle assuming that fractured bedrock forms better aquifer. However, the analysis of pumping test data for the majority of the wells showed that drawdown responses are observed to deviate from fractured analytical solutions (models) (fig.59). Leaky aquifer models provide best matches to recorded drawdown data than any other solutions. For example, the drawdown data of Girri well in the Uwa catchment has best fitted to leaky aquifer models (fig.59C) and slightly fitted to unconfined aquifer solutions (fig.59B) but significantly deviates from fractured aquifer solution (fig.59A).The plausible explanation for the reduction of drawdown with time (fig.59C) is that there is contribution of unconfined storage input from aquitard, indicating leakage from the weathered mantle to fractured bedrocks. This corroborates the aquifer structure in this region and the view that weathered-mantle plays the storage role in the composite aquifer system.

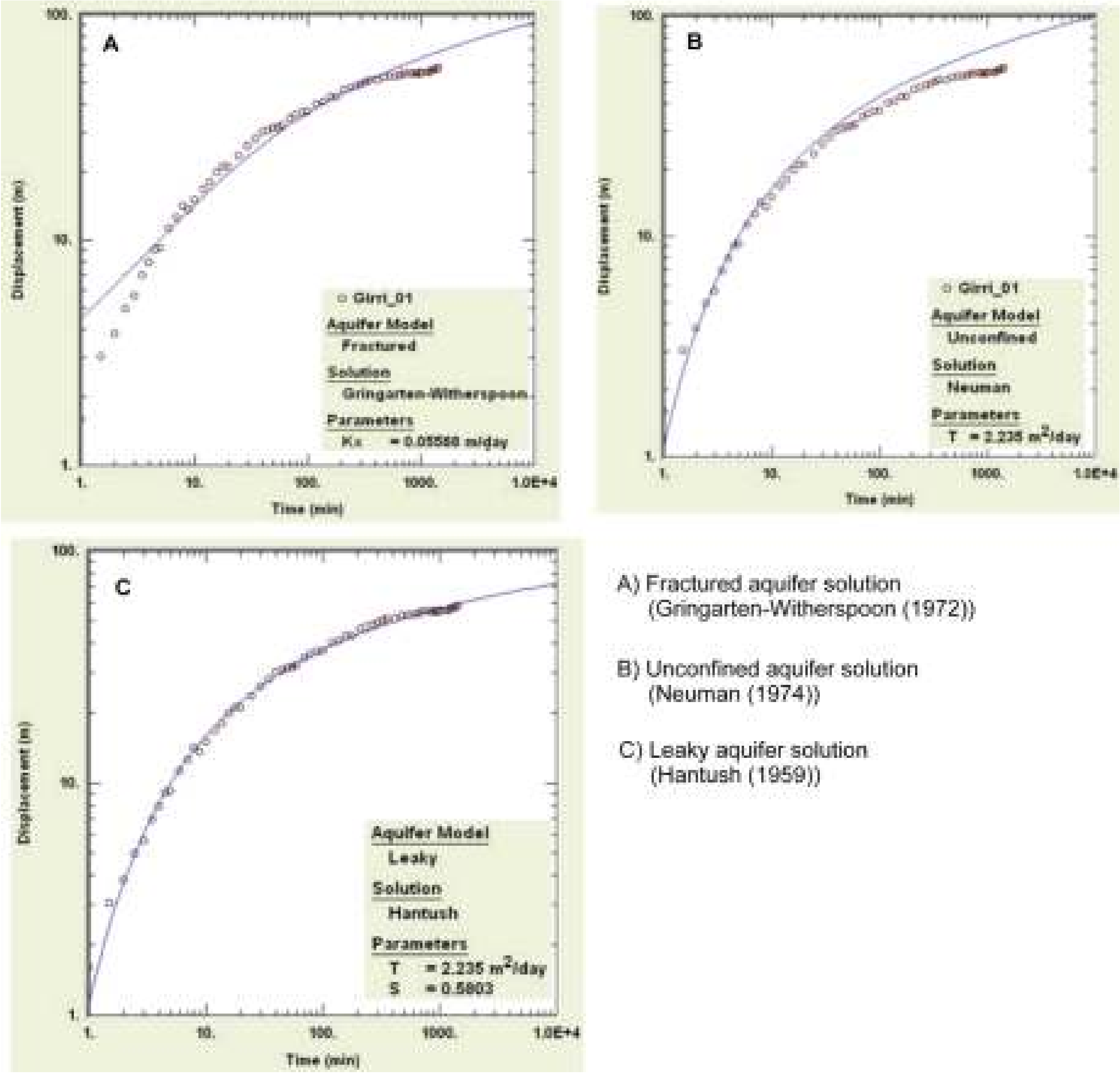


Figure 59) Pumping-test solutions to the drawdown response in the aquifer from western basement with time for borehole (Girri well), in the Uwa catchment. A) Fracture aquifer solution (Gringarten-Witherspoon, 1972). B) Unconfined aquifer solution (Neuman, 1974). C) Leaky aquifer solution (Hantush, 1959).

In the northern basement region, fracture aquifer models provide better matches to recorded drawdown data than any other solutions. For example, the drawdown data of Tsedia well in the Worei catchment (black-limestone) has better fit to fracture aquifer solutions (Moench, 1984; Garingarten-Whitherspoon, (1972) (fig.60 A, B) than confined aquifer solution of Thies, (1935) (fig.60C).

Likewise, a drawdown data from well in the Edaga Hamus area (NBH-5) shows significant deviation from confined aquifer model of Theis, (1935) (fig.60D).

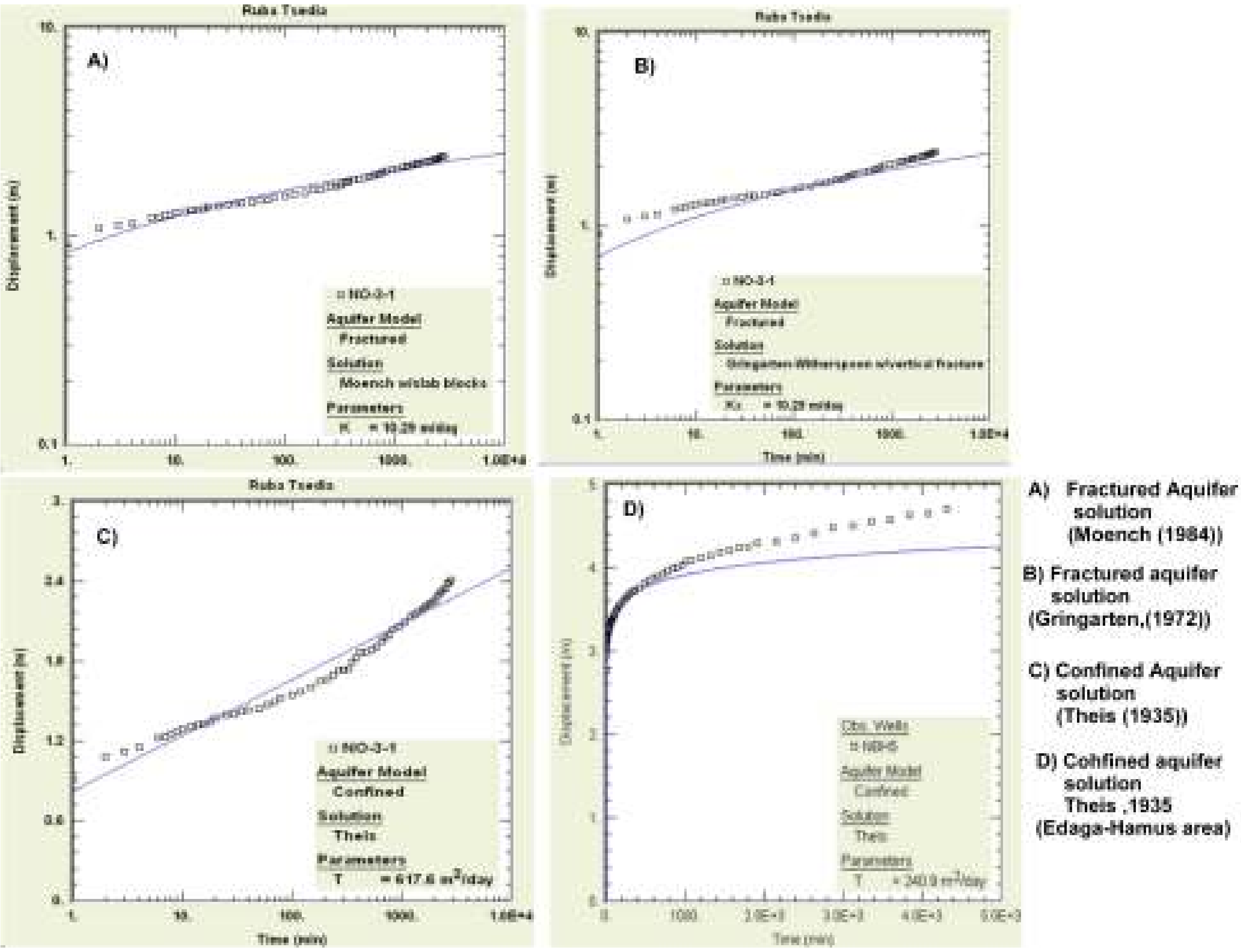
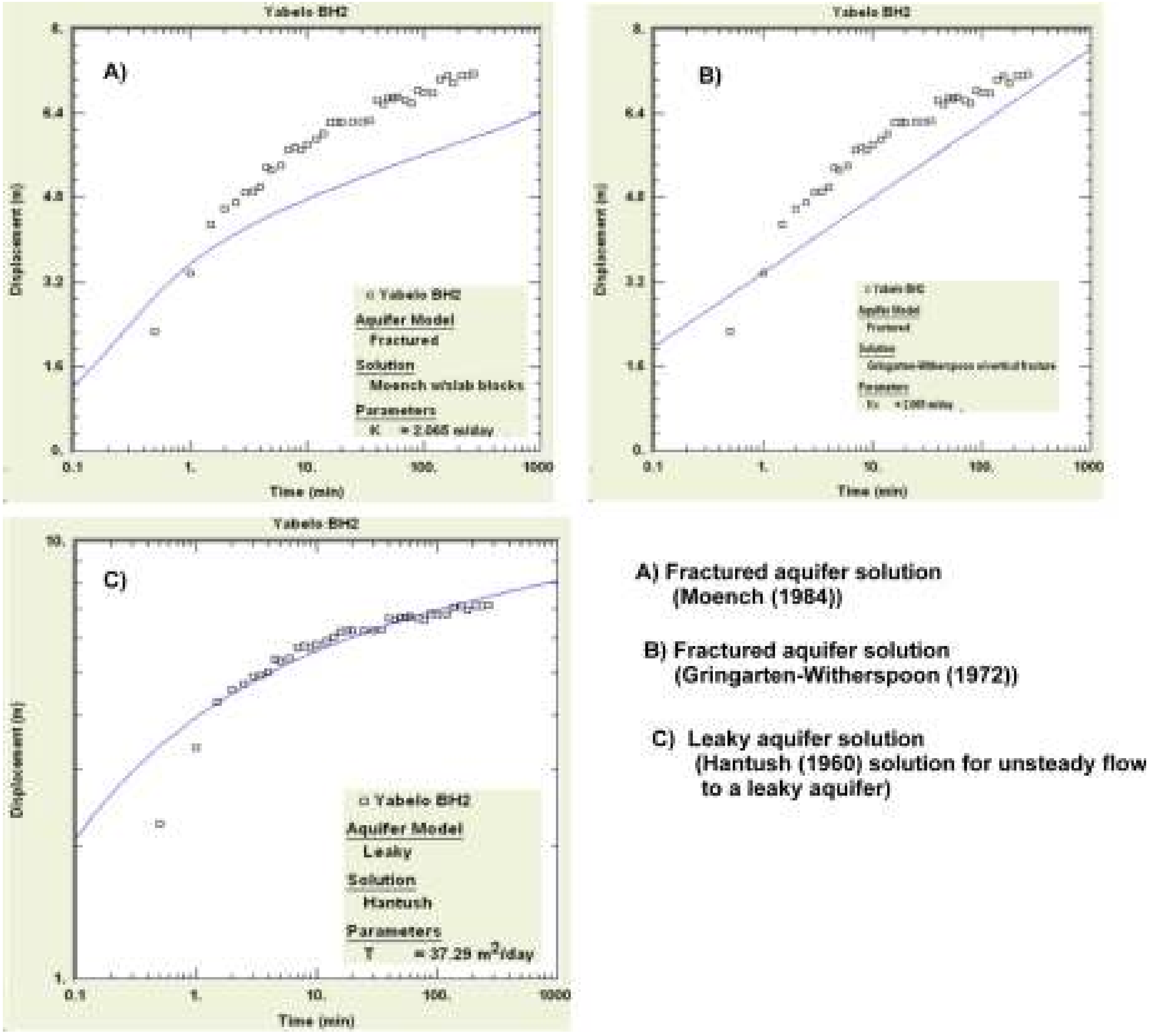


Figure 60) Pumping-test solutions to the drawdown response in the aquifer from Northern basement region with time for borehole Tsedia (NO-3-1) in Worei catchment. A) Fracture aquifer solution (Moench, 1984. B) Fractured aquifer solution (Gringarten-Witherspoon, 1972). C) Confined aquifer solution (Theis, 1935). D) Confined aquifer solution (Theis, 1935), Edaga Hamus area (NBH5).

The deviation of recorded drawdown data from confined aquifer solution because of increased drawdown (fig.60D) indicates the absence of storage supplying the fractured aquifer. This is in agreement with the view that dictates the removal of weathering mantle from the top of fractured bedrocks.

In the southern basement region, the response of aquifers to pumping test was significantly variable. In Yabello and Elgof areas for example the lithologic log reveals 66m and 48m thick silt to sand alluvial deposits over weathered bedrock. In Elgof 02 well, 24m thick fine deposit cover the top part. Screen casings (17m length) are installed at the base of alluvial (medium-coarse sand) of Yabello 2 BH excluding weathered bedrock. In Elogof02 in contrast, 30m screen length was installed at the base of the alluvial deposit and top of the weathered-fractured bedrock. The drawdown response to pumping stress in Yabello BH2 is shown to deviate from fractured models both for Moench, (1984) (fig.61A), and Garingarten-Whitherspoon, (1972) (fig.61) solutions. It however, fits better to leaky aquifer solution of Hantush, (1960) (fig.61C).The relative stabilization of drawdown at late pumping time indicates unsteady flow from the storage of alluvial deposit.



A) Fractured aquifer solution
(Moench (1984))

B) Fractured aquifer solution
(Gringarten-Witherspoon (1972))

C) Leaky aquifer solution
(Hantush (1960) solution for unsteady flow to a leaky aquifer)

Figure 61) Pumping-test solutions to the drawdown response in the aquifer from southern basement with time for borehole (BH2) in Yabello area. A) Fracture aquifer solution (Moench, 1984. B) Fractured aquifer solution (Gringarten-Witherspoon, 1972). C) Leaky aquifer solution (Hantush, 1959).

In Elgof 02, the drawdown response to pumping stress is shown to significantly deviate from unconfined aquifer (Theis, 1935) (fig.62A) and fracture aquifer of Garingarten-Whitherspoon, (1972) (fig.62B) models. However, it better matches to confined aquifer solution of Papadopulos-Cooper (1967) (fig.62C) signifying the confining layer above the alluvial aquifer.

This variation in general indicates that there are different types of aquifers in this basement region as described earlier.

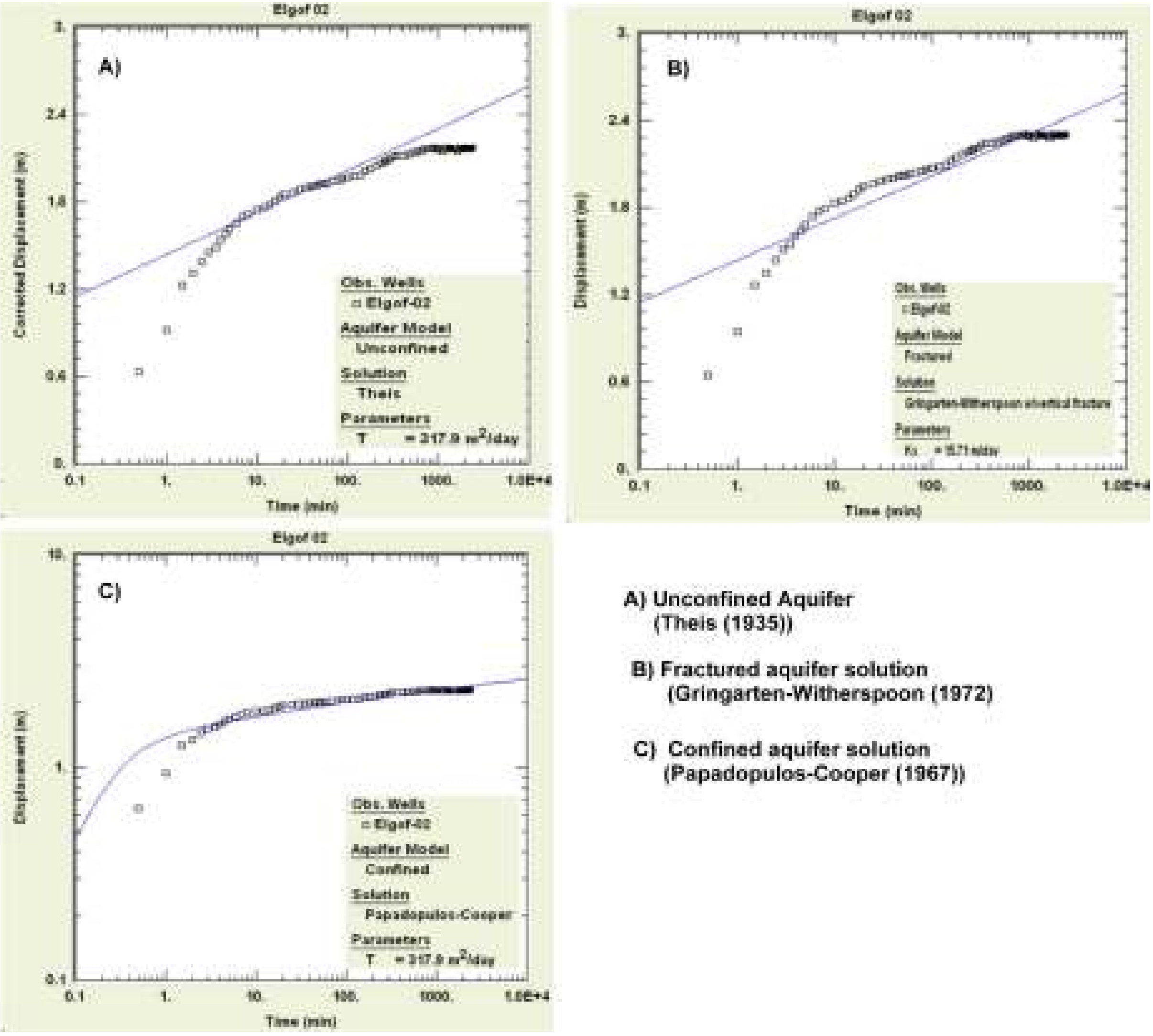


Figure 62) Pumping-test solutions to the drawdown response in the aquifer from southern basement with time for borehole (Elgof 02). A) Unconfined aquifer solution (Theis, 1935). B) Fractured aquifer solution (Gringarten-Witherspoon, 1972). C) Confined aquifer solution (Papadopulos-Cooper (1967)).

4.6 Linkage between geomorphic processes and hydrogeology of basement rocks of Ethiopia

(Published part on Journal of African Earth Sciences 100 (2014) 191–202)

The hydrogeological characteristics of the weathered crystalline rocks are derived from long-term, deep weathering-stripping process (Taylor and Howard, 2000). The geomorphic processes are still active, and the present day climatic conditions (mainly rainfall) continue to drive these processes modifying the already existing landscapes in different rates of operation. This has resulted in the development of contrasting weathered mantle-bedrock profiles in the study sites of the three basement regions (Deyassa et al., 2014) (established in chapter three of this work). This intern has resulted in considerable vertical heterogeneity in aquifer structures and thus varying aquifer properties (hydraulic conductivity and storage capacity). The present rainfall variation over the weathered land surfaces has also intensified the contrast by governing the input flux. Thus, the hydrogeology of basement rocks of Ethiopia differs primarily by their vertical heterogeneity in the aquifer structures and corresponding aquifer properties, and contemporary hydrological processes.

Thus, in the western catchments representing the western basement region, the prevailing wet and warm conditions since Miocene, had been favouring the active and contemporaneous geomorphic processes (with weathering greater than stripping) lead to the development of landscape dominated by gentle convex interfluves of low relief over the thick weathered mantle (Fig.36C). A high annual rainfall received by thick weathered profile enhances contemporary deep weathering. Much of the rainfall flux is transmitted through weathered profile to be added to groundwater reserve (i.e. groundwater recharge). On its percolation in vadose zone, it continues to drive the weathering process. It is likely that the dissociation and disintegration of the existing weathering mantle could result in further increment of the storage capacity of the weathered mantle and an increase in hydraulic conductivity at the basal level of a profile because of the onset of new weathering front. Thus, significant amount of shallow groundwater is stored in the weathering mantle owing to the higher recharge and high storage capacity. Natural groundwater discharge is by means of abundant springs and sustained base flows in the streams, which is a consequence of high storage capacity of the thick weathered mantle in the region. Therefore, groundwater occurrence and movement in this region is in the weathering mantle and the underlying fractured bedrock. The weathered mantle plays the storage role whereas, the basal level of the weathered mantle and the fractured bedrock constitute the conductive role.

In the northern basement region, however, the surface has been subjected to active erosion since late Miocene (Kebede, 2013; Deyassa et al., 2014) that retained the present day landscape features dominated by rugged topography. A regime of ‘‘weathering-limited’’ is prevailing over the low-grade fractured bedrocks owing to the higher relief and low annual rainfall amount. This condition results in the development of thin weathered layer or absent exposing the fractured bedrocks to the surface (Fig. 36A). Hence, much of the inflow from rainfall is transmitted through open fractures and as surface runoff to deeply incised drainage system, generating high stream flows.

Consequently, discharges from catchments in the region are characterized by rapid rise in stream discharges by voluminous contribution from runoff. In contrast, recession flows are negligibly small owing to thin weathered mantle, which is a consequence of lower storage capacity but higher hydraulic conductance. Thus, reduced annual recharge is effected by continued stripping processes in this region. However, significant recharge takes place through tectonically induced fracture zones, foliations, and joints to sustain hand-dug wells and drilled wells in tectonically active zones.

Furthermore, the presence of abundant productive hand-dug wells for water supply and irrigation over the stripped surface, signify the concentration of open fractures towards the bedrock surface indicating that these discontinuities (joints and fractures) are developed from decompression associated with erosional unloading (stripping). This is in agreement with the view of Houston and Lewis, (1988) and Howard et al., (1992) that address the genesis of permeable fractures in basement aquifers.

The southern basement region of Borena lowland has been affected by the prevailing arid conditions as a result of east African aridification (Pierre et al., 2006; Kebede, 2013) since late Miocene. The prevalence of duricrusts (ferrecrete and calcretes) capping the extensive plains of Borena lowlands are manifestations of intensified evaporation. These duricrusts facilitate runoff than infiltration. Thus, direct infiltration is limited because of these capping and the influence of high evaporation loss, which in effect reduce direct recharge. Furthermore, the slow operation of stripping process is exhibited by the prevalence of wash surfaces (fig.30C; fig.36B) over very gentle interfluves. This situation manifests removal of particles (i.e. erosion) under low relief conditions leading to the deposition of sand sized sediments in wide river channels (wadi beds). The alluvial sediments are quartz dominated derived from gneiss bedrocks and inselberg ranges of gneisses and granites. The presence of these sediments over the weathered mantle facilitates infiltration of meteoric water into the weathered mantle and fractured bedrocks underneath thereby enhancing preferential weathering. This signifies the presence of a systematic linkage between fracture orientations and the development of weathered mantle overburden. As a collective consequence, this enhances groundwater storage in alluvial deposit, in weathered mantle and in fractured bedrocks.

4.7 Classification of basement aquifer based on occurrence of groundwater, aquifer structure and hydraulic properties

(Published part on Journal of African Earth Sciences 100 (2014) 191–202)

Regionalization of geomorphic histories, over different lithologies being driven by the late Cenozoic to present climate, leads to significant contrast in groundwater occurrence, aquifer structure and functioning in basement rocks of Ethiopia. It appears that the hydrodynamic properties of these aquifers are mainly related to weathering-stripping processes.

Thus, the following generalized categories of aquifers are proposed based on a large volume of geological, hydrological and hydrogeological evidences for the three basement regions (fig.63):

1. In the western basement region, of deeply weathered surface, the composite profile of weathered mantle-fractured bedrock over low to high-grade bedrocks constitute the aquifer and it is classified as high storage-low conductance type aquifer.
2. In the northern basement region of stripped surface, the weathered mantle is stripped to negligible thickness; groundwater occurs in high-conducting but low-storage fractured low-grade bedrocks.
3. In the Borena lowlands (the southern basement region), the occurrence of groundwater is mostly associated with wadi beds. The occurrence and orientations of wadi beds follow regional fractures. These fractures control groundwater flow regime and enhance preferential weathering of bedrocks. The alluvial sediments (mainly sandy) on top of the sequence serve as infiltration media (and aquifers) to aquifers underneath. The aquifers are of intermediate storage and conductivity. Remnants of weathered mantle are still visible on gentle slopes but contribute little to groundwater flow and storage as they are capped by duricrusts.

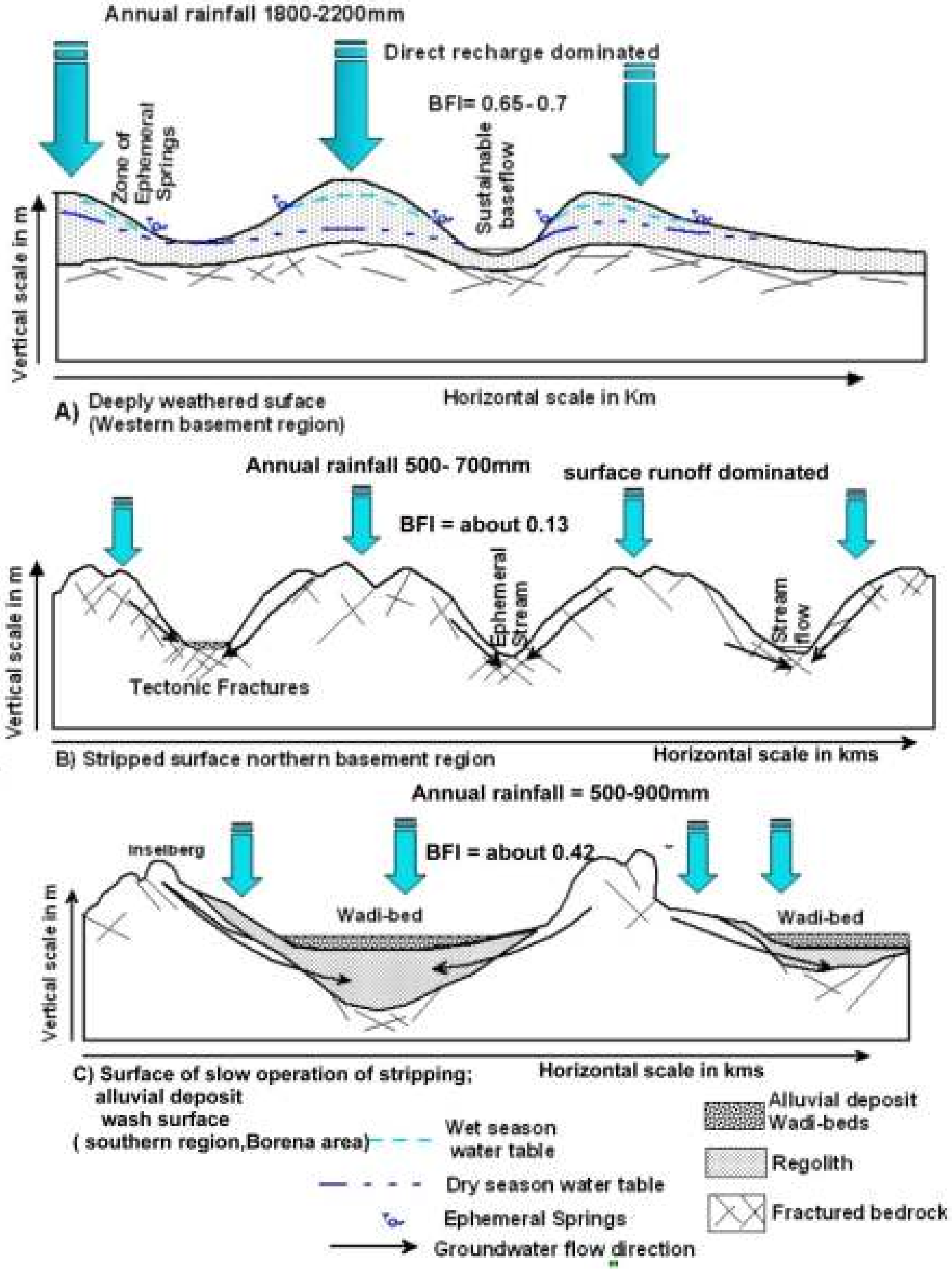


Figure 63) Conceptual model depicting the categories of basement aquifers in three regions of Ethiopia: (A) high storage-low conductive type aquifer on deeply weathered surface of western basement region; (B) low storage-high conductive type aquifer on stripped surface of Northern basement region; (C) Mixed/intermediate type aquifer (groundwater occurrence associated with wadi beds/Alluvial deposits) over regional fractures.

CHAPTER 5: IMPLICATIONS ON GROUNDWATER EXPLORATION AND DEVELOPMENT STRATEGIES

5.1 Introduction

Relationship among hydrology, geomorphic processes, and hydrogeology of basement rocks is demonstrated by this work. It specifically addresses the genesis, regionalization, vertical heterogeneity and functioning of basement aquifers of Ethiopia. The work emphasized that the hydrodynamic properties of these aquifers appear to be mainly related to weathering processes.

In western basement region, where the land surface is being dominated by deep weathering, the aquifer in the weathered mantle is relatively regionally extensive. In contrast, in northern region, where the land surface is being stripped, the occurrence of aquifer is localised. Elsewhere, in Borena lowlands, where stripping is operating at slower rate being limited by low relief, weathering operates variably because of insufficient rainfall. Thus, aquifer development is rather complex. In all the cases, the complete understanding of basement aquifer genesis and their variation in aquifer properties has practical importance on exploration and development of groundwater resources in these aquifers.

Improvements in the understanding of the hydrogeology of basement aquifers of the country thus, provides fundamental tools to the planning and management of groundwater resources which results in optimum use and reduction of development costs. This includes the choice of appropriate methods and technologies for groundwater exploration and development with respect to aquifer types in each region.

Therefore, this chapter forwards some points of consideration in exploration and development of groundwater resources in these aquifers.

5.2 Major points of consideration in groundwater exploration approaches

The regionalization and functioning of basement aquifers demand knowledge of groundwater occurrence and factors controlling groundwater potential in each region. Thus, exploration strategies and methods corresponding to occurrence of ground water in each basement region are summarized in this part.

In the western region where, deeply weathered mantle-bedrock profile constitutes composite aquifer, the exploration strategy should at least involve identifying and mapping of weathered mantle at catchment scale. This enables evaluation of aquifer potentialities from large to small areas. This scale helps in determining useful, cost effective, and appropriate strategies in designing of field surveys (e.g. geophysical investigation).This will maximize the chance of sitting productive wells and well fields for community water supply and even for irrigation water sources. Furthermore, identification of catchments with higher groundwater yield (transmissivity) can be possible by including base flow and specific base flow indices of streams in exploration strategies. Likewise, comparison of the of stream recession slopes also provides relative variations in permeability and storage properties among catchments in this region. In general, the use of low-flow analysis of streams remains a cost-effective alternative strategy that provides more integrative bulk hydraulic properties of catchments. This enables the understanding of dynamics of groundwater discharge (storage capacities and hydraulic conductivities) of catchments that corroborates results obtained from pumping test analysis.

In northern basement regions, where fractured bedrocks form aquifers, hunting and mapping of open fractures and discontinuities are crucial steps in groundwater exploration strategies in this region. This can be done by using geophysical methods (magnetic, resistivity or electromagnetic traverses) whereby most boreholes are sited by 'anomaly hunting'. However, exploration in fractured basement rock should be directed towards finding open fracture zones where permeability is enhanced, rather than blindly following the 'biggest anomaly' principle. This is because there are biggest anomalies also due to mineralization infilling sealing joints (fractures). Fracture zones are primarily structurally controlled. Thus, an understanding of regional tectonics and their structural expressions, densities and orientations are essential in their characterisation. Remote sensing is another method to map linear features. However, linear features are variable in that it may even represent non-geological features. Thus, the use of combined methods followed by field verification is of vital importance.

In the southern basement region, especially in the Borena lowlands, the occurrence of groundwater is complex in that it is associated with wadi beds, which are controlled by regional fractures.

The exploration strategy must therefore involve integration of methods to map wadi beds, deposits of alluvial sediments, and regional fractures. This includes mapping of linear features by using remote sensing methods. The thickness of alluvial sediments and the extents of fracture zones may be resolved by subsequent use of geophysical investigation.

Furthermore, the preferential weathering of bedrocks as a result of infiltration of water from regional fracture can be mapped by spatial differences in thermal characters of rocks.

5.3 Major points of considerations in groundwater accessing methods

Proper exploitation of ground water demands knowledge of groundwater occurrence that mainly includes spatial heterogeneity of aquifer extents, vertical variations in aquifer properties and depth to saturated zone in each region. Comprehending the hydrogeological setup of basement aquifers helps in selecting appropriate and cost-effective groundwater-accessing (utilization) technologies. These include hand-dug wells, drilled wells, non-conventional technologies, and capping springs where groundwater discharges by itself. What is fundamental in basement terrain is therefore, to harmonize the groundwater accessing technologies with local hydrogeology.

In western region, deeply weathered mantle-bedrock profile constitutes composite aquifer, and is relatively regionally extensive with water level relatively at shallower depth. Thus, hand-dug wells can be sited to tap the weathered mantle. Increasing the diameter may help in storing more water. As there are abundant springs in the region, developing these springs will be of advantageous and more economical source for water supply. Drilled wells are also appropriate but the drilling method and depth of drilling require expertise input. The weathered mantle constitutes loose and disintegrated materials that commonly cause collapse. Thus, it is desirable to include suitable drilling methods in a plan of drilling projects. Depth of drilling can be decided based on the demand of water supply and cost of drilling. However, highly permeable zones are towards the base of the weathered mantle-bedrock profiles. Thus, drilling up to this depth will increase well yield. Nevertheless, increasing beyond this depth will not guarantee increment of well yields. In that case planning more shallow wells seems more economical than drilling few deep wells.

In northern basement region, aquifer occurrence is localised in areas where fractures are open and concentrated. Sub- horizontal and open fractures are commonly abundant at the top of the bedrocks mainly due to erosional unloading. Thus, hand-dug wells will be appropriate technologies to tap this aquifer. However, digging by human power may not be possible all the time, thus, controlled (i.e. local scale) blasting (or any other technology that suits) may be appropriate in hard lithologies. Furthermore, tectonically induced water-bearing faults or fractured zones with significantly high hydraulic conductivity may be present at fairly deeper positions. Therefore, shallow or deep drilled boreholes are important to tap such aquifers.

The complexity of mode of groundwater occurrence along with insufficient direct recharge (i.e. semi-arid to arid condition), in southern basement region, especially the lowland areas, imposed its own influence on groundwater accessing technologies. This situation demands the combined use of non-conventional and conventional water accessing schemes. The non-conventional schemes include sand-dams, subsurface-dams connection to floods, improved river bed excavations, and infiltration galleries. These technologies enhance focused (local) recharge and stores considerable volume of groundwater in sand-dominated alluvium in which local groundwater level is raised. As an advantage to use these schemes, the occurrence of acidic rocks (gneiss bedrock and granite inselberg ranges) in this region play important role in supplying quartz-rich sediments to streams. Furthermore, deep incision of streams is lacking because of the low relief in the lowland areas. This condition helps in slow operation of erosion of materials that transport nearly equal grain size (sand-sized) sediments to streams. Consequently, the sediments deposited have commonly higher porosity to store significant volume of groundwater. Thus, water can be tapped from these schemes by the use of hand-dug wells and collector wells fitted with appropriate lifting devices. Conventional schemes include hand-dug wells and machine drilled wells (shallow or deep).Shallow or deep wells can be drilled to tap commonly fractured aquifers. Hand-dug wells could be sited in alluvial deposit and weathered mantle to tap shallow groundwater.

The indigenous practice and knowledge on groundwater development in this region is a traditionally hand-dug large diameter community well called *eelaa. Eelaas* are abundant and the most reliable groundwater exploitation method in all the lowland areas of Borena for domestic use and large number of animals in the region. Another important concern in this region is thus, to focus on improvisation of the design of *eelaas* and water lifting methods.

In general, the harmonization of groundwater occurrence in basement region with appropriate exploration and exploitation methods are summarized in table 5.

Basement region	**Groundwater occurrence**	**Proposed exploration methods**	**Proposed water accessing methods**
Northern	Fractured bedrocks and tectonically induced relatively deeper fracture zones	Hunting and mapping of fractures and discontinuities (densities, orientations)	Dug-wells, shallow wells and deep wells
Southern(lowlands of Borena)	Structurally controlled Wadi-beds(Alluvial deposits), regional and local fracture zones and weathered mantle	Mapping of wadi-beds, alluvial deposits, and regional and local fracture zones. Catchment delineation.	• Non-conventional schemes: sand dams, sub-surface dams and infiltration galleries • Conventional schemes: Hand-dug wells, *Eelaas*, shallow wells and deep wells
Western	Weathered mantle-fractured bedrock profile	• Identifying and mapping of catchments with varying weathered mantle thickness • Using base flow and specific flow indices, recession slopes and flow duration curves in exploration strategies	Capping springs, Large diameter hand-dug wells, Shallow wells, Deep wells that penetrate in to the top part of the bedrock

Table 5) Harmonization of groundwater occurrence in basement regions with appropriate exploration and exploitation methods

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis reports how the interactions of evolutionary and contemporary processes determine the hydrological and hydrogeological characteristics of the basement terrain of Ethiopia. It specifically addresses the role of evolutionary histories of geomorphic processes (deep weathering and stripping) in affecting aquifer development and control on their vertical and spatial heterogeneity. The study also validates the reliability of literature based weathering-stripping model previously developed for the country, by providing definite field-based evidences that advances its dependability.

Thus, conclusions are presented based upon a detailed examination of a large volume of geological, hydrological, and hydrogeological evidences collected during this study, and interpretation of existing data:

Conclusion 1: The regionalization of long-term landscape evolution has resulted in production of contrasting weathering-bedrock profiles over basement terrains of Ethiopia and field evidences validate this

The regionalization of geomorphic processes (i.e. varying rates of weathering and stripping) following the climate variation since late Miocene has resulted in vertical heterogeneity in weathered-fractured bedrock profiles. This has resulted in the production of three contrasting weathering-bedrock profiles and landscapes corresponding to each basement region.

The variations and lithologies of the weathering profiles in the entire basement region strongly support the multi phase cycles of landscape evolution. Consequently, this work has presented fundamental field evidences that attest polycyclic deep weathering-stripping model of landscape evolution is tenable.

Conclusion 2: The hydrogeology of basement terrains of Ethiopia is determined by the interaction of long-term landscape evolution and modern day climate.

Conclusion 2.1: Thus, the fundamental linkage between long-term geomorphic processes (deep weathering and stripping) and hydrogeology of basement terrains has been established

This work has established the linkage between long-term evolutionary development of landscapes, by contemporaneous geomorphic processes (but operating at different rates), and hydrogeologogy of basement rocks of Ethiopia. The regionalization of geomorphic processes, lead to the development of different aquifer structures with contrasting hydraulic and storage properties in each basement region (northern, western and southern (Borena lowland)).

The geomorphic processes are still active, and the present day climatic conditions (mainly rainfall) supplying meteoric water to aquifers and continue to drive these processes modifying the already existing landscapes.

Conclusion 2.2: Groundwater occurrence, aquifer structure, and functioning exhibit important contrast in basement rocks of Ethiopia

In the western region, where weathered mantle is thicker (as a result of deep weathering), and present-day groundwater recharge exceeds surface runoff, aquifer is relatively extensive in the thick weathered-bedrock profile (fig.63A). Much of the rainfall is transmitted through weathered profile to be added to groundwater reserve (as recharge flux). On its percolation in vadose zone, it continues to drive the weathering process by dissociation and disintegration of the existing weathering mantle thereby enhancing the storage capacity of the weathered mantle. Recharge flux is achieved primarily by an aquifer of fine sand in the weathered mantle. At the base of the profile, new weathering front is continuously being set resulting in coarser material of higher hydraulic conductivity.

In contrast, in the northern basement region, where the weathered-mantle is removed partially or completely by prolonged stripping and recharge is largely exceeded by surface runoff, aquifer occurrence is localized (fig.63B). Aquifer occurs in sub-horizontal fractures and discontinuities (developed because of erosional unloading) in bedrocks toward the surface and tectonically induced relatively deeper fracture zones. Moderate recharge is largely facilitated by open fractures.

In disparity from the two, the southern basement region, especially in the Borena lowlands, groundwater occurrence is mainly associated with wadi beds (fig.63C), which are controlled by regional fractures. Aquifers occur in alluvial sediments, fractures and preferentially

weathered mantles. The recharge influx is indirect and localized to stream beds and fracture zones as direct recharge is limited by ubiquitous duricrust covering the lowland areas.
Therefore, the hydrogeological characteristics of the weathered crystalline rocks are derived from long-term, deep weathering- stripping process.
Thus, the hydrogeology of basement rocks of Ethiopia differs primarily by their vertical and spatial heterogeneity in the aquifer structures and hydraulic properties (storage and hydraulic conductivity). The variation is further pronounced by difference in rainfall amount that affect the supply of meteoric water to aquifer.

Consequently, this work has shown that aquifer structure and groundwater occurrence exhibit important contrast in different regions of basement rocks of Ethiopia.

In consequence, generalized conceptual hydrogeological model depicting three categories of aquifers are thus, proposed based on the interpretation of existing data and hydrogeological evidences collected during this study (Fig.63). Additionally, the significant variations in low-flow indices and shapes of flow duration curves manifest contrast in bulk hydraulic properties (storage capacity and hydraulic conductivity) of catchments in the three basement regions. This has also provides corroborating evidences to the conceptual hydrogeological model.

Therefore, this thesis has shown the fundamental linkage between long-term geomorphic processes (deep weathering and stripping) and hydrogeology of basement terrain mediated by meteoric water.

Conclusion 2.3: The new aquifer genesis model overrides the existing simplistic view of aquifer classification of basement rocks of Ethiopia.

The result from this work thus, deviates from the existing premise, which traditionally describes the basement rocks of Ethiopia as a system of regional aquiclude; it establishes coherent relationship between the hydrogeological characteristics of basement terrain and both the long-term evolution of the landscape and contemporary hydrology. It has also presented hydrogeological conceptual model of basement aquifers depicting aquifer categories, groundwater occurrences and functioning.

Conclusion 3: The complete understanding of basement aquifers genesis and their variation in aquifer properties has practical importance on exploration and development of these aquifers.

The harmonization of appropriate exploration and exploitation methods with groundwater occurrences in basement regions are proposed following the complete understanding of basement aquifer genesis and their variation in aquifer properties.

6.2 Recommendations

Basement aquifers are complex systems; thus, further improvements in the understandings of functioning and hydrodynamic properties are of great importance in planning, development and management of groundwater resources in these aquifers. The following issues are recommended for further research needs:

- The effect of lithological differences has not been the subject of this study in detail. The relative importance of regional scale weathering-stripping model versus lithological variations in controlling/affecting regolith thickness (and thereby aquifer properties) needs further investigation.
- Any tool (hydrological, geochemical, isotope, lithological) that help to understand runoff generation and base flow characterization in the three regions could be used to validate the proposed model.
- Appropriate groundwater management strategies that suits basement aquifer in each region needs further investigation. Furthermore, the implication of basement aquifer classification in response to climate change needs to be investigated.
- The results obtained in this work can be used to produce a revised hydrogeological map of basement rocks of Ethiopia.

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APPENDICES

Annex1: Weathered mantle thickness over different bedrock lithologies

Easting	Northing	Regolith thickness(m)	Lithology	Basement Region
552721	1531154	0.5	Metavolcanic	Northern
543884	1543313	2.6	metasediment	Northern
511449	1551698	1.2	Slate	Northern
501258	1548851	2.3	Slate	Northern
543884	1543313	2.7	Slate	Northern
541682	1541929	0.2	Slate	Northern
543205	1540070	9	Alluvial on Granite	Northern
541335	1540445	1.7	Granite	Northern
479111	1583595	1.7	Slate	Northern
533396	1556000	2.2	Slate	Northern
492909	1547913	3.6	Phylite	Northern
493308	1548392	4	Metavolcanic	Northern
494052	1549376	0.2	BlackMetaLimestone	Northern
494325	1549815	1	BlackMetaLimestone	Northern
494670	1550061	0.1	Granite	Northern
494950	1550111	0.1	BlackMetaLimestone	Northern
495211	1550512	0.6	Phylite	Northern
495277	1551160	0.4	Phylite	Northern
495690	1551804	0.6	Phylite	Northern
495930	1551534	0.7	metasediment	Northern
496470	1551975	0.3	Phylite	Northern
495997	1552107	4	Phylite	Northern
496623	1552897	6.5	Phylite	Northern
496562	1543308	2.5	Phylite	Northern
512948	1551992	1	BlackMetaLimestone	Northern
512889	1552056	0.7	BlackMetaLimestone	Northern
513040	1551990	2.6	Phylite	Northern
578251	1539695	3.7	Phylite	Northern
513929	1552313	1	Phylite	Northern
580926	1538004	1.4	Phylite	Northern
513929	1552313	1.5	Phylite	Northern
495143	1550309	5.4	metasediment	Northern
494562	1548810	1	BlackMetaLimestone	Northern
578361	1539596	4	Phylite	Northern
514029	1552214	1	BlackMetaLimestone	Northern
496507	1543128	2.4	Phylite	Northern
580837	153192	2.4	Slate	Northern
579762	1533815	1.6	Metavolcanic	Northern
576617	1542139	0.6	Metavolcanic	Northern
580912	1541023	1.7	Metavolcanic	Northern
580826	1537994	1.7	Metavolcanic	Northern

787828	1022089	54	Gneiss	Western
810584	997593	56	Gneiss	Western
774878	1014424	45	Diorite-Gabbro	Western
818494	1006243	35	Gneiss	Western
784149	1011793	55	Gneiss	Western
801716	1017896	37	Gneiss	Western
687753	1057888	43	Meta_gabbro	Western
687743	1057878	56	Meta_gabbro	Western
772023	1013822	52	Diorite-Gabbro	Western
779047	1000038	40	Gneiss	Western
810871	994191	52	Diorite-Gabbro	Western
801124	999430	53	Schist	Western
787851	999657	75	Diorite-Gabbro	Western
795009	1013655	42	Grano-Diorite	Western
778372	1005301	32	Granite	Western
794490	1014893	42	Granite	Western
792651	1015217	32	Schist	Western
788346	1000860	48	Schist	Western
702476	967556	48	Granite	Western
801124	999430	41	Granite	Western
543218	635423	4.6	Gneiss	Southern
552117	589711	16	Gneiss	Southern
506667	426218	8	Gneiss	Southern
		6.9	Gneiss	Southern
		7	Gneiss	Southern
507084	611719	11	Gneiss	Southern
530455	656615	2	Gneiss	Southern
500477	652554	11	Gneiss	Southern
551780	662439	19	Gneiss	Southern
557507	574263	10	Gneiss	Southern
539483	656450	14	Granite	Southern
551780	586169	12	Gneiss	Southern
557507	574263	9.2	Gneiss	Southern
530483	656348	10.6	Gneiss	Southern
506781	426421	12	Gneiss	Southern
557408	574480	10	Gneiss	Southern
496940	498134	16	Gneiss	Southern
433362	579529	31	Gneiss	Southern
426130	622321	9	Granite	Southern
425280	621398	17	Gneiss	Southern
425280	621398	13.8	Granite	Southern
429098	630305	14	Granite	Southern
410088	699963	2	Granite	Southern
456489	605641	30	Gneiss	Southern
405217	604897	2.3	Granite	Southern

497238	405353	4.68	Granite	Southern
395393	602177	5	Granite	Southern
476745	624599	1	Granite	Southern
412163	416038	1	Granite	Southern
476745	624519	2	Granite	Southern

Annex 2: Hydraulic conductivity

Easting	**Northing**	**Hyd. conductivity (m/d)**	**Basement Region**
492909	1547913	3.31	Northern
493308	1548392	0.99	Northern
494052	1549376	9.91	Northern
494325	1549815	0.33	Northern
494670	1550061	13.04	Northern
494950	1550111	8.22	Northern
495211	1550512	14.61	Northern
495277	1551160	5.43	Northern
495690	1551804	4.63	Northern
495930	1551534	4.4	Northern
496470	1551975	0.32	Northern
495997	1552107	5.78	Northern
496623	1552897	3.28	Northern
496562	1543308	1.26	Northern
512948	1551992	6.5	Northern
512889	1552056	1.05	Northern
513040	1551990	2.82	Northern
578251	1539695	1.54	Northern
513929	1552313	11.3	Northern
580926	1538004	2.99	Northern
513929	1552313	19.56	Northern
495143	1550309	18.5	Northern
494562	1548810	16.33	Northern
578361	1539596	1.61	Northern
514029	1552214	2.06	Northern
496507	1543128	7.58	Northern
580837	153192	5.34	Northern
579762	1533815	8.3	Northern
576617	1542139	1.31	Northern
580912	1541023	7.06	Northern
580826	1537994	4.42	Northern
		Mean hydraulic conductivity= 6.2	Northern basement
801124	999430	10.51	Western
787851	999657	1.3	Western
795009	1013655	2.58	Western
778372	1005301	1.125	Western
810871	994191	1.5	Western
801124	999430	0.282	Western
787851	999657	0.006	Western
795009	1013655	0.005	Western
778372	1005301	1.95	Western

778786	1022089	0.05	Western
796492	1003966	0.76	Western
782752	1000667	0.014	Western
780318	1000396	0.013	Western
787566	998557	1.82	Western
771826	1013107	0.42	Western
769716	1013053	0.01	Western
770744	1014189	0.77	Western
771285	1012459	0.9	Western
778425	999801	2.05	Western
		3	Western
794490	1014893	0.43	Western
792651	1015217	0.398	Western
788346	1000860	0.282	Western
702476	967556	1.29	Western
801124	999430	3.3	Western
801030	999500	1.82	Western
801684	996177	2.58	Western
810665	997161	1.125	Western
783401	994043	1.4	Western
811011	994920	1.13	Western
778372	1005301	0.06	Western
779831	1004669	0.043	Western
778858	1007157	0.054	Western
		Mean value hydraulic conductivity =1.34	**Western basement**
404194	539598	4.9	South
506667	426218	3.13	South
322663	565497	4.09	South
410088	699963	5.02	South
433362	579529	3.5	South
419750	595777	4.3	South
429098	630305	0.15	South
425280	621398	5.7	South
395393	602177	0.02	South
405217	604897	1.45	South
497238	405353	2.11	South
531771	429132	9.36	South
360100	555570	2.6	South
496940	498134	4.3	South
408969	526105	2.64	South
420015	481751	3.9	South
456489	605641	7.7	South
412163	416038	0.1	South
476745	624519	0.11	South
		Mean conductivity=3.4	

Annex 3: Annual Base Flow Index (BFI), mean daily base flow and specific mean daily base flow of streams in the catchments of the three basement regions

Stream	Ann. BFI	MDBF(m^3/sec)	Specific MDBF(L/s/Km^2)
Uwa	0.69	5.8	20.0
Uwa	0.63	6.8	23.8
Uwa	0.65	4.2	14.8
Uwa	0.67	3.4	11.7
Uwa	0.68	7.4	25.6
Uwa	0.70	5.8	20.2
Uwa	0.71	5.3	18.5
Uwa	0.65	4.2	14.5
Uwa	0.72	5.2	17.9
Uwa	0.74	6.5	22.7
Uwa	0.72	4.6	16.0
Uwa	0.66	3.3	11.3
Uwa	0.72	2.2	7.5
Komis	0.57	1.5	13.3
Komis	0.47	3.2	28.8
Komis	0.67	2.4	21.4
Komis	0.56	2.7	24.2
Komis	0.57	2.6	23.4
Komis	0.67	4.7	42.4
Komis	0.67	5.6	50.2
Komis	0.70	1.4	12.8
Komis	0.73	1.4	12.5
Komis	0.70	2.0	17.6
Komis	0.70	2.1	18.5
Komis	0.76	2.5	22.5
Komis	0.71	2.5	22.1
Sachi	0.67	10.5	18.7
Sachi	0.67	6.9	12.2
Sachi	0.71	10.4	18.4
Sachi	0.68	12.2	21.8
Sachi	0.64	6.9	12.2
Sachi	0.63	7.2	12.8
Sachi	0.65	7.0	12.4
Sachi	0.64	9.3	16.6
Sachi	0.67	10.1	18.1
Sachi	0.66	6.2	11.1
Sachi	0.67	7.6	13.5
Sachi	0.63	6.3	11.3
Dawa	0.43	7.1	0.4
Dawa	0.37	8.4	0.4

Dawa	0.42	4.8	0.2
Dawa	0.40	5.7	0.3
Dawa	0.46	6.0	0.3
Dawa	0.44	7.1	0.4
Dawa	0.43	14.9	0.8
Worei	0.08	0.4	0.2
Worei	0.09	0.9	0.5
Worei	0.10	0.9	0.5
Worei	0.13	2.3	1.3
Worei	0.09	1.6	0.9
Worei	0.26	1.6	0.9
Worei	0.17	2.1	1.2

Annex 4: Individual recession segments and their recession slopes (α_i)

Northern basement region			
Worei stream gauging station No. 121005			
Year	**Segment**	**Slope(α_i)**	**Fitting, R^2**
2003-2004	Part of Slow-flow	0.45	0.983
2003-2004	Part of Slow-flow	0.428	0.971
1998-1999	Part of Slow-flow	0.382	0.907
	Part of Slow-flow	0.548	0.787
	Part of Slow-flow	0.496	0.929
	Part of Slow-flow	0.452	0.906
	Part of Slow-flow	0.372	1
Mean value		**0.446**	**0.926**
2) Southern basement region			
Dawa stream gauging station No. 071001			
Year	**Segment**	**Slope(α_i)**	**Fitting, R^2**
2004	Part of Slow-flow	0.34	0.938
2004	Part of Slow-flow	0.4	0.978
2005	Part of Slow-flow	0.29	0.957
2005	Part of Slow-flow	0.3	0.898
2006	Part of Slow-flow	0.39	0.831
2006	Part of Slow-flow	0.36	0.903
Mean value		**0.35**	0.34
3) Western basement region			
3.1)Sachi stream gauging station No. 115006			
Year	**Segment**	**Slope(α_i)**	**Fitting, R^2**
2002-2003	Part of Slow-flow	0.052	0.925
2002-2003	Part of Slow-flow	0.033	0.992
2002-2003	Part of Slow-flow	0.091	0.974
2002-2003	Part of Slow-flow	0.012	0.965
2003-1	Part of Slow-flow	0.167	0.991
2003-2	Part of Slow-flow	0.056	0.987
2003-3	Part of Slow-flow	0.167	0.991

2001-2002	Part of Slow-flow	0.044	0.959
2001-2002	Part of Slow-flow	0.013	0.919
2002	Part of Slow-flow	0.1	0.91
Mean value		**0.0735**	**0.925**
3.2)Uwa stream, gauging station No. 115009			
Year	**Segment**	**Slope(α_i)**	**Fitting, R^2**
2004-2005	Part of low-flow	0.036	0.981
2004-2005	Part of low-flow	0.037	0.825
2004-2006	Part of low-flow	0.05	0.919
2003-2004	Part of low-flow	0.016	0.941
2003-2004	Part of low-flow	0.022	0.915
2003-2004	Part of low-flow	0.01	0.976
2002-2003	Part of low-flow	0.011	0.931
2002-2003	Part of low-flow	0.011	0.962
2002-2003	Part of low-flow	0.016	0.945
1999-2000	Part of low-flow	0.026	0.984
1999-2000	Part of low-flow	0.017	0.929
1999-2000	Part of low-flow	0.031	0.952
Mean value		**0.023583**	**0.938**
3.3)Komis stream, gauging station No. 115010			
Year	**Segment**	**Slope(α_i)**	**Fitting, R^2**
1999-2000	Part of low-flow	0.023	0.956
1999-2000	Part of low-flow	0.01	0.984
2000	Part of low-flow	0.035	0.988
1996-1997	Part of low-flow	0.015	0.976
1996-1997	Part of low-flow	0.008	0.975
1997	Part of low-flow	0.039	0.964
1997	Part of low-flow	0.018	0.981
1995-1996	Part of low-flow	0.023	0.953
1995-1996	Part of low-flow	0.009	0.982
1996	Part of low-flow	0.029	0.962
1996	Part of low-flow	0.016	0.952
Mean values		**0.0204**	**0.970**

Annex:5 Published article

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Crystalline basement aquifers of Ethiopia: Their genesis, classification and aquifer properties

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abstract

The crystalline basement rocks of Ethiopia were traditionally described as one system of regional aquiclude. This attribution was made disregarding variations in groundwater occurrence and potential which often times is promising in some geologic settings. Systematic studies addressing their genesis and spatial variations are lacking. Based on a thorough review of existing data and field observations, this work has shown that the genesis of basement aquifers is the result of complex interplay between the present/past climate and geomorphic processes which are tectonically controlled. It thus follows that the groundwater occurrence and the type of aquifer exhibit important contrasts on the surfaces of crystalline basement terrains of Ethiopia. Three coherent zones have been identified in this work based on their genesis, thickness of regolith, mechanisms of flow and storage properties: (a) in Western Ethiopia the aquifer is characterized by a vertical profile of fractured low to high grade bedrocks mantled by thick weathering profiles leading to high groundwater storage but low hydraulic conductance, (b) in Northern Ethiopia the weathered mantle is stripped to negligible thickness; groundwater occurs in high conducting but low storage fractured low grade bedrocks, (c) in the Borena lowlands (the southern basement region, the occurrence of groundwater is associated with wadi beds. The orientations of wadi beds follow regional fractures. These fractures control groundwater flow regime and enhance preferential weathering of bedrocks. The presence of alluvial sediments (mostly derived from gneiss and inselbergs of gneisses and granites) over the weathered mantle, facilitates infiltration into the weathered mantle and fractured bedrocks underneath. This enhances groundwater storage and movement both in the regolith and fractured bedrock. Elsewhere outside the wadi beds, duri crusts limit vertical recharge and groundwater availability to the bedrock; aquifers are of intermediate type with regard to hydraulic properties. Potential remnants of weathered mantle are still visible but contribute little to groundwater flow.

It is therefore suggested here that more comprehension about groundwater in crystalline basement rocks of Ethiopia could be gained given the comparison is made based on the genesis of the aquifers as related to tectonics and climate induced stripping and deep weathering history.

1. Introduction

Crystalline basement rocks occur in tropical region of sub-Saharan Africa, India, South America and Australia (Wright, 1992). Aquifers of basement rocks occur within the weathered residual overburden (the regolith) and the fractured bedrock (Wright, 1992; Acworth, 1987; Chilton and Foster, 1995; UNESCO, 1984). Regoliths are developed over the bedrock by weathering process. The thickness of weathered mantle and the corresponding aquifer properties depend on a complex combination of controls that include bedrock characteristics, climate (past and present),age of land surface; relief and other site specific factors (UNESCO, 1984; Acworth, 1987; Wright, 1992; Jones, 1985). The vertical heterogeneity of aquifer properties depend on the type of regolith lithology (Acworth, 1987; Chilton and Foster, 1995). Fig. 1 depicts typical weathering profile and the vertical heterogeneity of aquifer properties (Hydraulic conductivity and effective porosity) of regolith and bedrock.

Several researches from Africa, (Foster, 1984; Acworth, 1987; Taylor and Howard, 1998, 2000; Edet and Okereke, 2005) and from India (Dewandel et al., 2006) emphasize that the hydrogeological characteristics (mainly hydraulic conductivity and storage) of the weathered mantle and the underlying bedrock derive primarily

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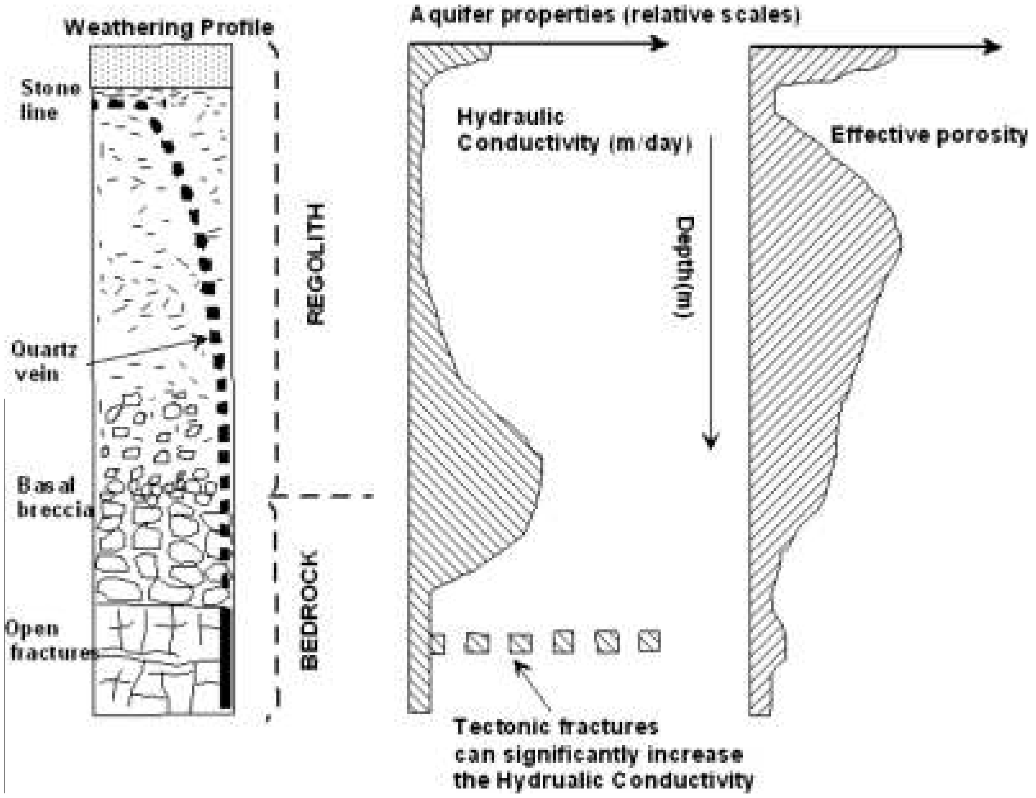


Fig. 1. The vertical profiles of hydraulic conductivity, transmissivity, effective porosity and storage for the regolith – fractured bedrock profile. (After: Acworth, 1987; Chilton and Foster, 1995.)

from the geomorphic processes of deep weathering and stripping. These authors underline the significance of tracing the geomorphic evolution of weathered land surfaces over basement rocks. They emphasize that identifying the dominant geomorphic process operating on surfaces, is of vital importance to comprehend the hydrogeological characteristics of basement rocks.

Particularly for Ethiopia, we came across no model that explains the hydrogeological set up and genesis of basement aquifers. Cherenet (1993), EIGS (1988), EIGS (1996) and many unpublished regional Hydrogeological studies (Alamirew et al., 2005; Belete et al., 2003; Belete et al., 2004; GSE, 2002; GSE, 2003) consider the Precambrian basement terrains of the country as regional aquiclude or very poor aquifers regardless of their spatial differences in terms of groundwater occurrence and potential. A literature based model depicting the polycyclic evolution of weathering surfaces over the basement bedrocks of the country has recently been developed by Kebede (2013). However, research on linkage between geomorphic processes and the hydrogeology of the crystalline basement terrains of the country is lacking. Like elsewhere, it is assumed that such understanding will foster our knowledge on basement hydrogeology of Ethiopia. Systematic studies that address the spatial and vertical heterogeneities of basement aquifers are absent. Albeit the spatial variation and vertical heterogeneities, the basement aquifers were interpreted as one regional aquiclude or poor aquifer.

The main objectives of this work therefore are a) to verify the validity of the previously developed, literature based deep weathering-stripping model of Kebede (2013) through field observation and b) to investigate the linkage between the validated weathering-stripping model with groundwater potential of the basement terrain.

2. Description of basement terrain and associated weathering-stripping processes

2.1. Geologic setup

In Ethiopia, the crystalline Precambrian basement terrains are exposed in the peripheral parts of the country: North, South, West, Southwest and East (Kazmin, 1972; Tefera et al., 1996; EIGS (Ethiopian Institute of Geological Surveys), 1988) (Fig. 2). They cover about 23% of the land area of the country (Cherenet, 1993) and over10 million people reside on these terrains and tap groundwater from basement aquifers for consumptive water uses.

The terrain comprises a wide variety of volcano-sedimentary and plutonic rocks, metamorphosed to varying degree of schist to amphibolites facies being intruded by several generations of granitoids and Gabbros (Kazmin, 1971).

The northern crystalline basement is part of Arabian Nubian Shield (ANS) (Fig. 2 label 1) that consists of low-grade metamorphic rocks of Volcano-sedimentary succession, mafic–ultramafic complexes that are intruded by granites and granodiorites (Beyth, 1972; Garland, 1980; Tadesse, 1997).

The southern, the eastern and part of the western basement rocks constitute part of the Mozambique Belt (Fig. 2 labels 2–4). These rocks are composed of high grade poly deformed rocks (gneisses, migmatites, granulites) and schistose which are intruded by plutonic rocks of gabbroic-to-granitic compositions (Alemu and Abebe, 2007; Kebede and Koeberl, 2003; Ayalew et al., 1990). The distribution of outcrops of basement rocks in Ethiopia marks the transition zone between the Arabian Nubian Shield and Mozambique Belt (Kazmin et al., 1978; Bonavia and Chrowicz, 1993).The proportion of high grade belts (Mozambique Belt) is significantly

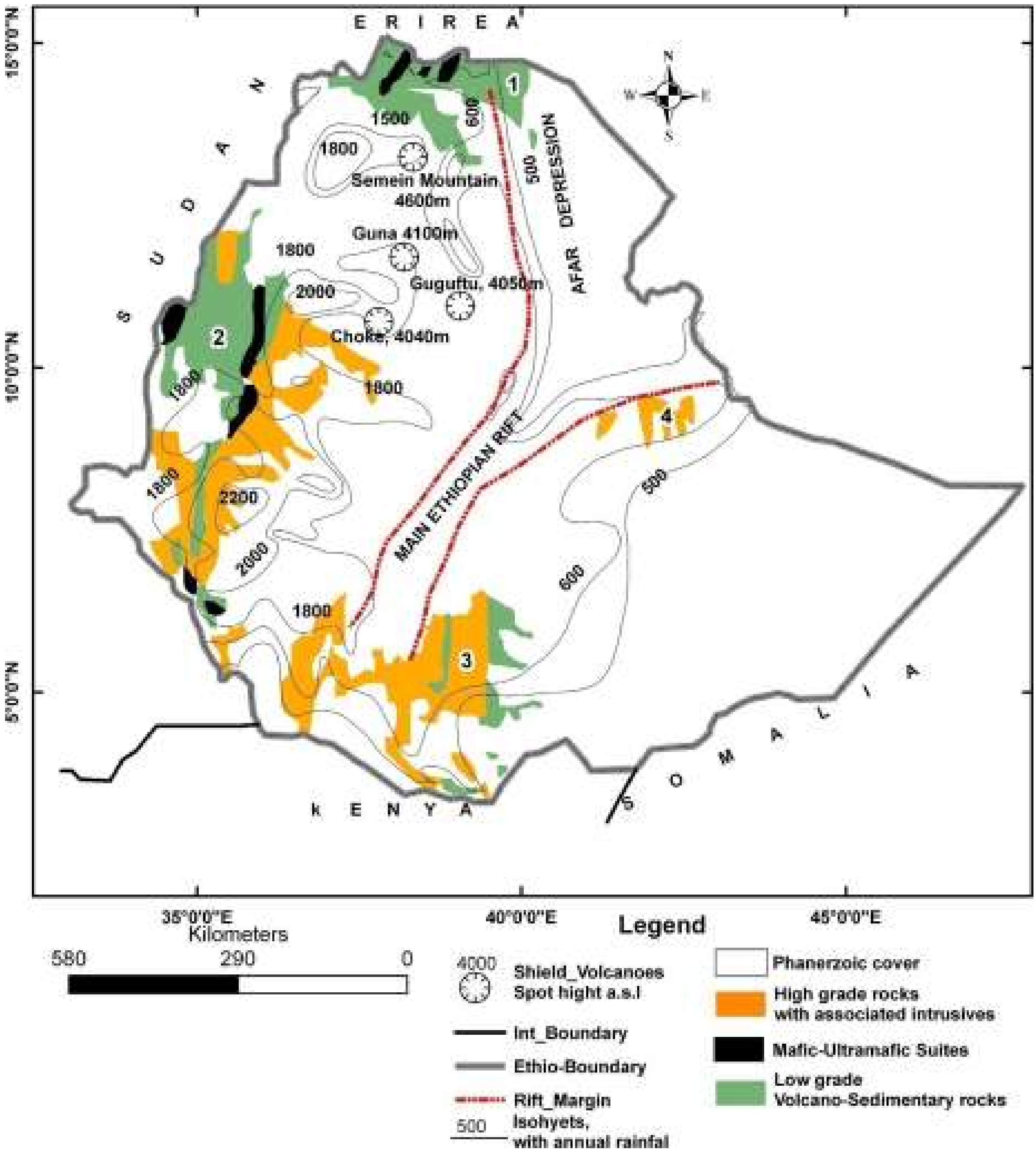


Fig. 2. Distribution of Precambrian basement terrain of Ethiopia (simplified from EIGS, 1996). Numbers (1, 2, 3, and 4) show the locations of exposures of basement rocks in North, West, South and East. The map also depicts the distribution of annual rainfall. Locations of centres of late Cenozoic shield volcanoes with elevations are also indicated.

high in the western, Southern and Eastern Ethiopian basement terrains (Fig. 2 labels 2–4) signifying that the Precambrian basement rocks of Ethiopia marks the transition zone between the Arabian Nubian Shield and Mozambique Belt (Kazmin et al., 1978; Bonavia and Chrowicz, 1993). Mafic–ultramafic intrusive belonging to the ophiolitic sequences are especially common in the low grade metamorphic rocks. The common examples include the ultramafic rocks in north western part of northern region (Tadesse et al., 1999), in the western Ethiopia mafic–ultramafic belt represents the best exposure of the metamorphosed mafic and ultramafic suites of dunites, peridotites and pyroxenites (Alemu and Abebe, 2007; Ayalew and Peccerillo, 1998; de Wit and Chewaka, 1981); ultramafics and gabbros in South west Ethiopia (Davidson, 1983; Yihunei and Hailu, 2007). Granitoids considered to be Pre-syn- and post tectonics are widely exposed in all the metamorphic terrains (e.g. Alemu and Abebe, 2007) in the west, (Ayalew et al., 1990) in southern and Western Ethiopia (Tadesse et al., 1999; Asrat et al., 2001, 2004) in the North.

2.2. The Polycyclic weathering-stripping model in Ethiopia

The polycyclic model of deep weathering-stripping over the Ethiopian basement bedrocks is well described in the recent work of Kebede (2013).The model can be summarized into four major stages of weathering-stripping processes which were shaped by

Table 1
List of data used in the analysis.

Basement region	BHLLG*	BHPT*	HDY*	SpgY*
Northern	172	122	649	26
Western	93	74	91	1580
Southern	100	32	311	29
Total	364	228	1051	1902

BHLLG* – Boreholes with lithologic logs.
BHPT* – Borehole with test pumping.
HDY* – Hand dug wells with yields.
SpgY* – Spring with known yield data.

phases of glaciations, tectonic quiescence, uplifting and optimal climate.

The first stage involves complete stripping of Precambrian surfaces of Ethiopia by late Carboniferous-Permian glaciations. Coltorti et al. (2007) contends that the erosion was so intense that it was able to planate the Northern Ethiopian basement landscape to altitude not too far from sea level.

The second stage was the development of thick regolith cover during the Cretaceous period. The process of deep weathering in this period was favored by prolonged relative tectonic quiescence and a more humid-warm climate as a result of new position of the region nearer to equator in sub tropical climatic setting (Kebede, 2013); evidences show the regolith cover developed during this time reaches locally up to 150 m. The development of thick weathering mantle during late Cretaceous over the Precambrian bedrock surfaces was also noted elsewhere (e.g. in East Africa Uganda; Taylor and Howard, 1998, 1999) and South Africa. (Partridge and Maud, 2000; Tyson and Partridge, 2000).

The third stage was the stripping of the deeply weathered mantle following the Cenozoic uplifting of Ethiopia (Afar dome).The regional uplift that resulted in the formation of Afar dome accompanied the eruption of the plume-related volcanic rocks (Sengor, 2001; Pik et al., 2003). Burke and Gunnel (2008) suggested that erosion started as the Afar dome started to rise and before the eruption of the Ethiopian traps began. He intended that the absence of lateritic cover over the African surface over a roughly circular area of �1000 km diameter centred on the Afar dome is attributed to this erosion process.

This process resulted in near complete removal of weathered mantle from the Northern Precambrian basement rocks which are located nearer to the centre of the uplift (margin of the rift system) (Fig. 2). The western and the southern regions are far from the centre of the uplift attaining relatively lower relief as a result stripping was a slower process compared to the northern region. In the southern basement terrain especially in the Borena lowlands, the process of stripping was continued at a slower rate leaving behind swarm of inselbergs dotting the extensive plains. In the western region, the process of stripping was not able to induce complete removal of cretaceous weathering mantle. As a result, extensive preserved paleo-weathering mantle is observed in the areas rapidly capped by Cenozoic volcanics.

The fourth stage is operating from late Miocene to present and involves the regionalization of complex and contemporaneous weathering and erosion processes. The regionalization of these processes follows the development of different climate and landscape because of Cenozoic uplift and late Cenozoic volcanism (mainly shield volcanoes).

The late Cenozoic prominent shield volcanoes over the North western part of the Ethiopian plateau (e.g. Choke, the Semen Mountain, Guna and Guguftu) (Fig. 2) further rise the altitude of the plateau well over 4000 m a.s.l (Fig. 2) forming an efficient orographic barrier to moisture-bearing winds, thus controlling the distribution and amount of rainfall in the country (Fig. 2). The northern region is isolated from heavy and prolonged rains and remained rain shadow region. The western region of the country however, remains under heavy and prolonged rain fall while arid to semi arid conditions have been active in the Borena low land areas since late Miocene.

The variation in rainfall amount and distribution over different lithologies cause the regionalization of geomorphic process regime and environmental conditions that gave rise to regionalization in rates of weathering-erosion processes over the Precambrian and Tertiary volcanic bedrocks.

The model has shown that the geomorphic processes in all the stages are the results of alternating cycles of uplifting and tectonic quiescence. Much of this uplift occurred in the past 30 Ma through the combined effects of the rising Afar mantle plume and rift-flank flexuring of the Afar Depression and the Main Ethiopian Rift (Pik et al., 2003; Gani et al., 2007).

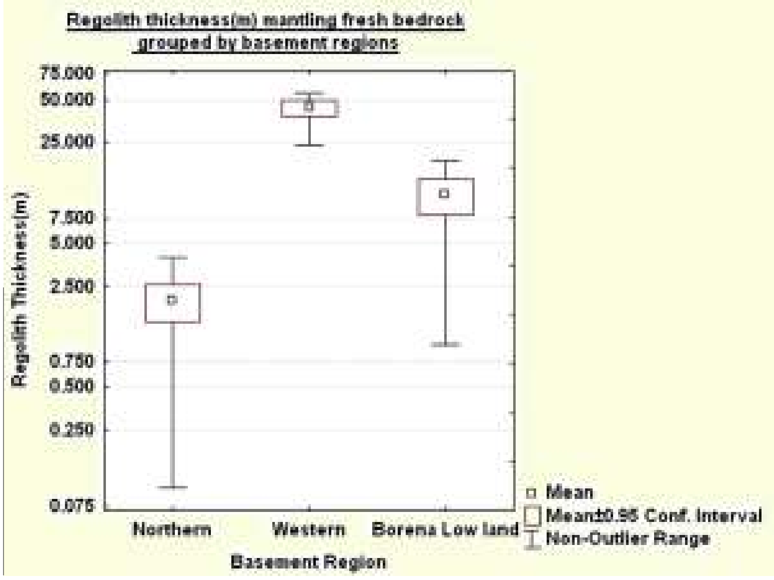
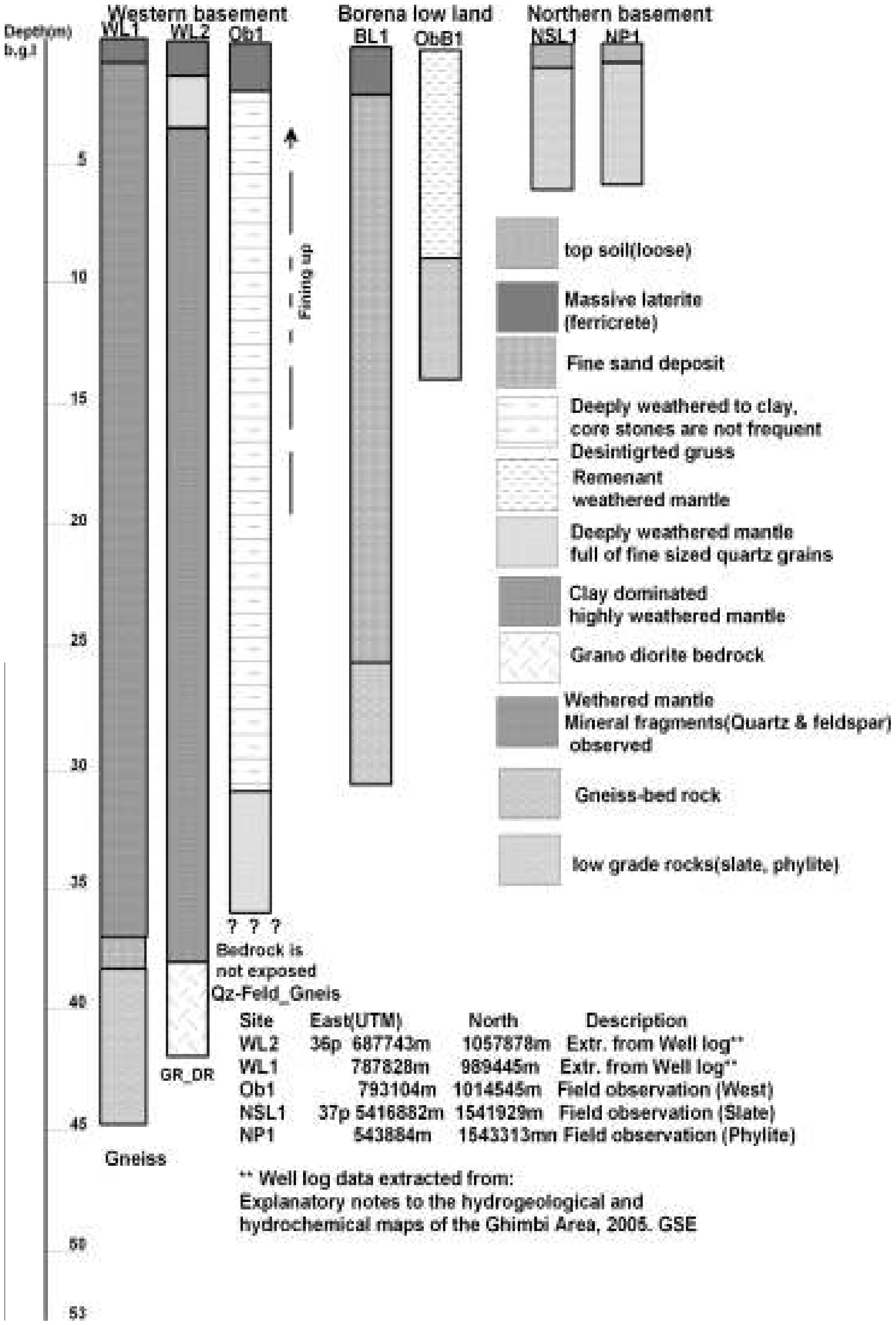


Fig. 3. Regolith thickness mantling the fresh bedrock of Precambrian Basement rocks: the Northern basement region; the Western basement region and the Southern basement region (Borena lowland).



Site	East(UTM)	North	Description
WL2	36p 687743m	1057878m	Extr. from Well log**
WL1	787828m	989445m	Extr. from Well log**
Ob1	793104m	1014545m	Field observation (West)
NSL1	37p 5416882m	1541929m	Field observation (Slate)
NP1	543884m	1543313mn	Field observation (Phylite)

** Well log data extracted from:
Explanatory notes to the hydrogeological and hydrochemical maps of the Ghimbi Area, 2005. GSE

Fig. 4. Weathering profiles constructed from well logs and field observations from the three basement regions.

3. Methods

The methods used in this study involve the verification of existing poly cyclic deep weathering-stripping model. The reliability of the model is checked by field evidences such as variation in regoilth thicknesses and contacts between the Tertiary volcanic and weathered surfaces over the basement rocks. The knowledge from the model, geomorphic data obtained from extensive field campaign, pumping test data, lithologic logs and data on specific base flow indices are used to analyze the linkage between the weathering-stripping model and the hydrogeology of basement aquifers of the country. Close observation to road, stream and slope cut along selected traverses enabled the description of weathering profiles (thicknesses and vertical heterogeneity in texture) on each lithologic type in each region. Lithologiclogs from wells drilled in basement terrain have been collected from data base of respective Regional Water Resources Bureaus and Water Works Construction Enterprises. Data lacking geographic locations and those with incomplete records are discarded. The data have been plotted on geological map of each region to check its reliability with respect to lithology and data with inconsistent lithologic descriptions has been discarded. The lithologic logs are then re-interpreted in terms of weathering-fracture bedrock profiles and the depths to bedrock are estimated. The pumping test data of the same wells are used to

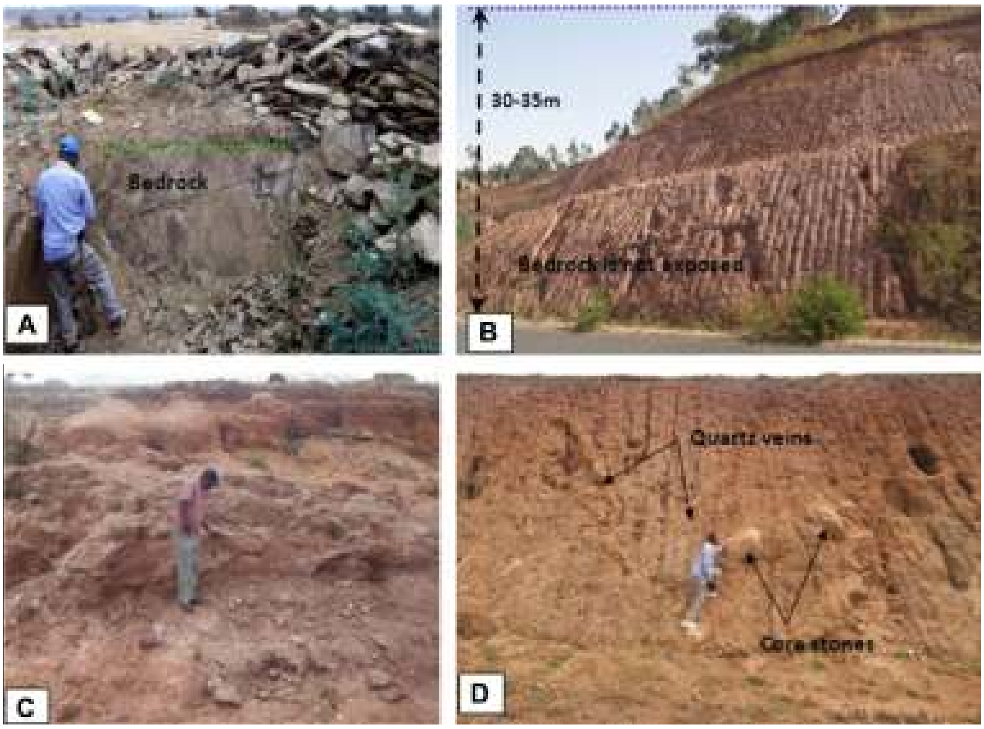


Photo 1. The variation of regolith thicknesses on different Precambrian basement regions of Ethiopia: (A) Slate with very thin regolith mantling the bedrock with absence of the saprolite (near Hawzen, northern basement region). (B) Thick (35 m) weathering profile on Precambrian basement rock exposed in road cut; note that the bedrock is not exposed western basement region). (C) Preserved regolith with elluvium (wash surface on the top) south basement region. D) Weathering profile over gneiss bedrock exposed along new road cut, quartz veins and core stones indicate that the profile is the result of insitu weathering West basement region.

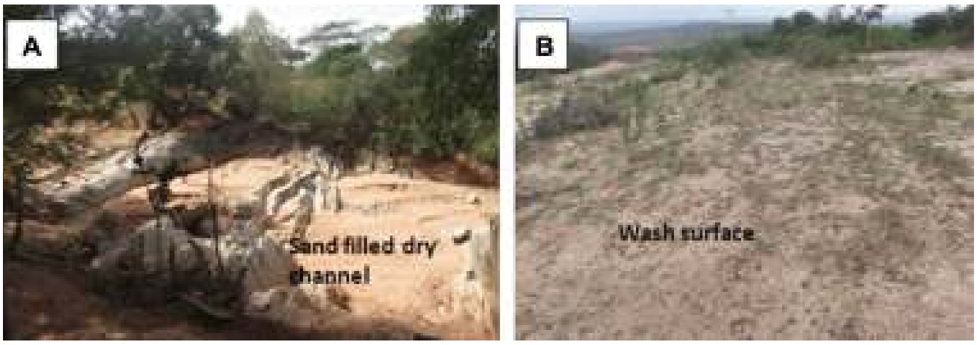


Photo 2. Sand filled dry channel near Dawa village (A); wash surface dominantly of quartz, feldspar and rock fragments on the gentle slope along the road side to Yabello near Bule Hora locality (B) – manifestations of erosion; (the Borena low land).

investigate the hydraulic characteristics of basement aquifers in each region. 364 Litho-logs and 228 pumping test data are used (data used are shown in Table 1). Pumping test data with short duration(less than 12 h) are rejected and the results from constant-discharge analysis are used.

In case of ambiguity, raw data of drawdown and time was reanalysed using constant-discharge method. Specific base flow indices for streams draining basement terrains are used to investigate the bulk storage capacity of the catchments in each basement region.

4. Result and discussion

4.1. Variation in weathering profiles

The result from the analysis of field observations and lithologic logs of water wells showed significant variation in thickness of regolith over the bedrocks the basement rocks (Fig. 3).

In the western basement region the regolith thicknesses vary from about 10 m to about 90 m on different lithologies (Fig. 4). On gneissic bedrocks, thickness ranges from 25 m to 65 m, on diorite-gabbroic it ranges from 15 m to 85 m; on schist it varies from15 m to 70 m and on granite 25 m to 55 m.

In the northern basement region, the result of field observations on rock exposures, road cut and the interpretation of litho logs gives the depth- to-fresh bedrock to vary from about 0 to about 10 m with mean value about 2 m (Fig. 3). Lowest thickness of weathering mantle observed over the bedrocks of phylite, slates (Photo 1) and black meta-limestone.

In the low lands of Borena the basement rocks are overlain by sandy alluvial deposit in wadi beds (Photo 2). This alluvial deposit commonly reaches up to 25 m as it is observed from litho logs of boreholes (Fig. 4). In areas of gentle slopes the bedrock grades upward to remnants of regolith mantle capped by wash surface (Photo 1C). The thickness of this mantle in places reaches up to 10 m.

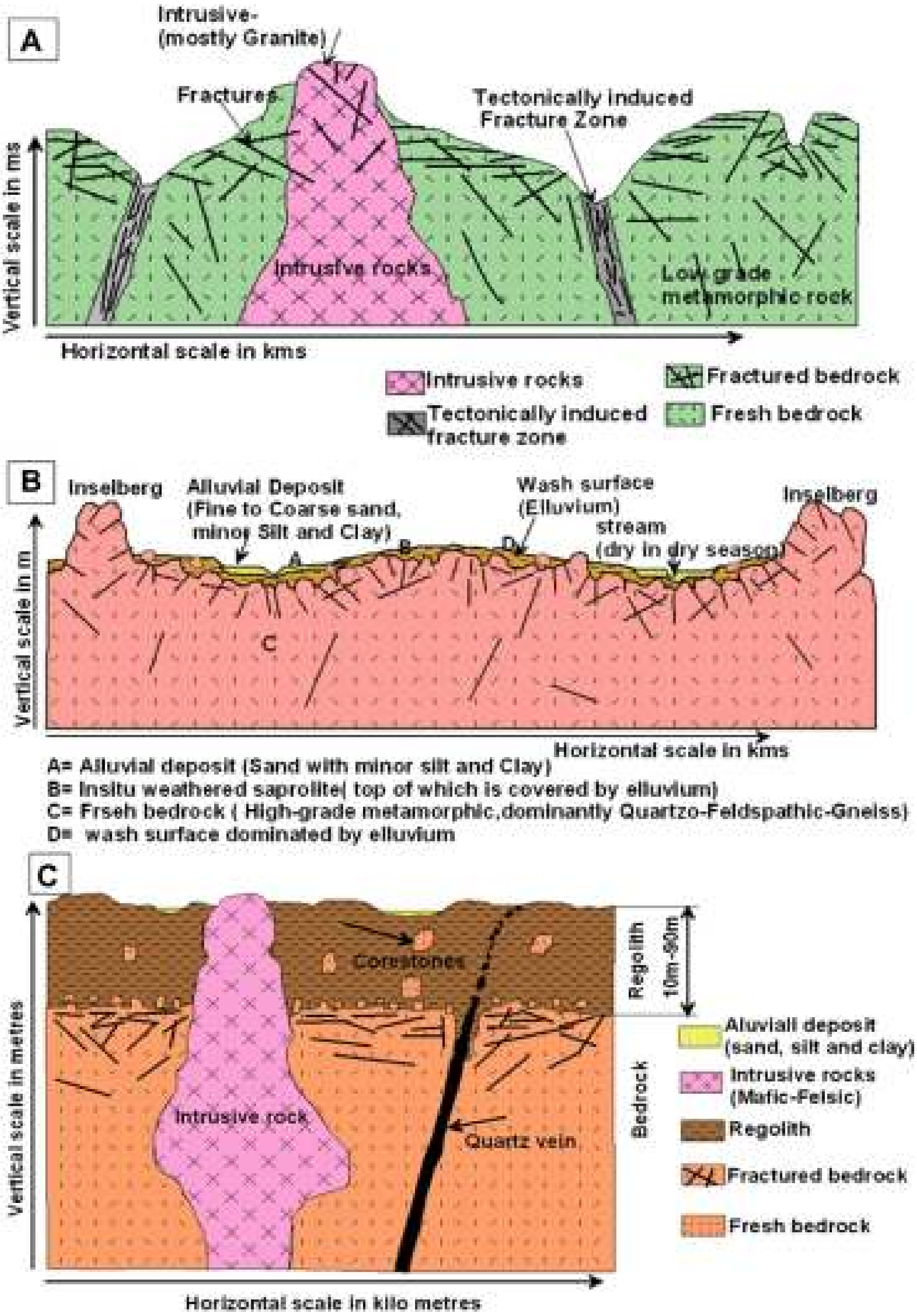


Fig. 5. Schematic representations of the regionalized weathering profiles of Precambrian basement rocks. (A) The Northern basement weathering profile (Tigray area); truncated weathering profile. (B) The Borena plain profile; reduced thickness of weathering mantle over the bedrock with relatively thick alluvial sediments filling dry river channels. The presence of inselbergs exhibit the process of deep weathering was followed by stripping. (C) The western basement weathering profile (West Wollega area); thick and complete weathering profile on interfluves.

In addition to variation in thicknesses there are also textural variations of the weathering profile with depth. All the profiles from western region generally develop thick saprolite over the bedrock. Thick weathered mantle (saprolite) develops over diorite bedrock (WL2 in Fig. 4). It is clayey in texture with no traces of core stones. In high grade rocks (gneisses) the mineral fragments of quartz and feldspar are observed in saprolite. The abundance of quartz grains increases with depth. This is clearly observed in (Ob1 in Fig. 4) where fine grained quartz is observed at the basal part of weathered mantle. The bedrock for this column is not exposed; but elsewhere downstream quartzo-feldspathic gneiss is observed; bedrocks are rarely exposed in the western region. In general the weathering profiles in the western region mirror the ‘‘classic weathering profile’’ (Wright, 1992) for basement rocks (WL1, WL2, Ob1 in Fig. 4). Nonetheless, the profiles from northern region have showed considerable deviation from the ‘‘classic weathering profile’’ in that the sap rock and saprolite column is totally missing (NS1, NP1 in Fig. 4). The profile from Borena low land show generally two types of weathering profiles: In wadi beds alluvial sediments of dominantly quartz grains overlay either

Photo 3. Field photo showing the stripped Precambrian basement rock (B) directly overlain by pre-Mesozoic sandstone (A); no regolith mantle is observed. (Western basement region, a locality called Harqumbe). In the lowlands of Borena, the basement bedrocks grade to weathered mantle in gently slope areas of hill sides, where as in wadi beds alluvial sediments overlay the recent weathered mantle. In some places in this region, the weathered mantle is capped by basalt. This can be used as validation for the previously developed model. Therefore, field observation shows that the previously developed model appears convincing.

Table 2
Variations of well yields for wells depth between 50 and 150 m. Yield data are taken from pumping test data in each region in a representative catchment(source: Bureaus of Water, Mine and Energy of Tigray and Oromiya regions).

Basement regions (sample catchments)	No. of water wells	Yield range (l/s)	Mean yield (l/s)
Northern	122	0.4–25	5.7
Western	92*	0.5–8	2.8
Borena lowland	100**	0.2–3.5	1.5

[*] Yield test for 18 wells is by air lift (blowing during drilling).
[**] Yield test for 68 wells by air lifting.

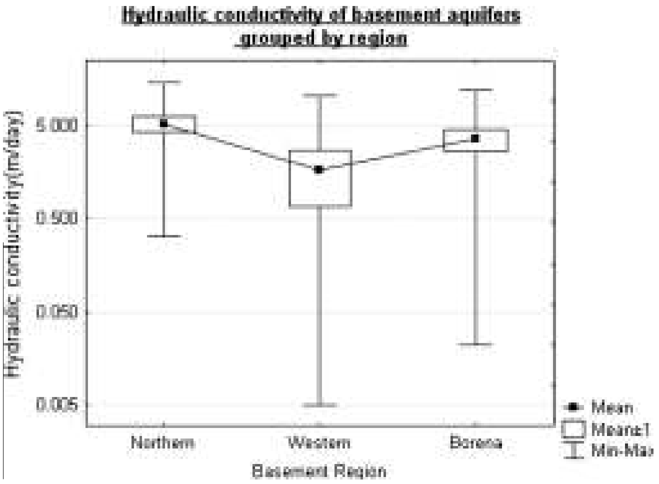


Fig. 6. Variation of hydraulic conductivity with the basement region; (data extracted from testing pump reports in each region).

weathering mantle or bedrock (BL1 in Fig. 4). In areas with very gentle slope (interfluves)the bedrock is mantled by preserved weathered mantle capped by wash surfaces (ObB1 in Fig. 4; Photo 2B). Abundant coarse grained quartz floaters are common on the wash surface (Photo 2B).

The very humid and warm western basement region with dominantly gneisses and low grade Mafic-ultra-mafic rocks, diorites and gabbros intrusive bodies develop thick weathering profiles (Figs. 3 and 5C).The variation in regolith thicknesses over lithologies of different bedrocks under the effect of the same climatic factor (e.g. rainfall amount and temperature); can be attributed to the variation in mineral composition of different lithologies.

In the northern region, limited rainfall and higher relief together with abundance of low grade metamorphic rocks of stable mineral compositions such as slates and phyllite, weathering-limited condition prevailed resulting in very thin or nil regolith cover over the basement bedrocks (Fig. 5A).

The Borena low land is far from the centre of the uplift. This gives the area a low flat relief (Fig. 5B). But there is clear evidence for stripping as evidenced from remnants of regoliths as thick as 10 meters capped by wash surfaces at very gentle slopes (Photo 1C). The presence of calcretes covering the extensive plains of the area manifests the area is under arid/semi arid condition. The low relief and the aridification of Horn of Africa (Pierre et al., 2006) (including southern and SE Ethiopia) led to no prominent development of drainage network to trigger deeper incision. Consequently deeply incised valleys are not common and River valleys are commonly broad and are filled by alluvial sediments dominantly composed of sands (Photo 2A).

The variation in rates of deep weathering- stripping processes over the basement terrains of Ethiopia, is thus resulted in the production of three contrasting weathering profiles corresponding to (Northern, Western and Southern-the Borena lowland) (Fig. 5).

Furthermore, field observation reveals that, in western region the basement bedrock commonly grades to weathering mantle. Nevertheless, in some places (Photo 3) the basement is capped by pre-Mesozoic sandstone; in that case the basement bedrock is directly overlain by pre-Mesozoic sedimentary rocks (Photo 3).This could be an evidence for Paleozoic complete stripping suggested by Coltorti et al. (2007) and it corresponds to the presumed stripped surface of Kebede (2013).

4.2. Variations in aquifer properties

Review and analysis of existing pumping test data from wells in the three basement regions show significant contrasts (Table 2 and Fig. 6) in well yields and hydraulic conductivities. Higher values of well discharges and hydraulic conductivities are observed in wells from the northern basement region (Table 2 and Fig. 6). Wells from the western basement region possess the lowest hydraulic conductivities but intermediate well yields. Those wells from Borena lowland in southern basement region attain the least yield but intermediate values of hydraulic conductivities- a consequence of low recharge.

Higher values of discharge and hydraulic conductivities in wells from the northern basement region can be attributed to the conductive role of fractures which characterize bedrock aquifers.

The lower values of well yields and hydraulic conductivity values in the western basement region show the role of storage capacity of thick regolith cover mantling the bedrock. Abundant springs and seepages (natural groundwater discharge) are observed in the field.The springs have low discharge values that commonly vary from 0.005 L/s to 0.5 L/s. The low values of groundwater discharge albeit high rainfall amount (1800–2200 mm/ann.) in this region (Fig. 2) can be attributed to high storage capacity of thick regolith cover over the bedrock.

Comparison of specific base flows of some catchments draining the three basement regions are made to support the interpretation of aquifer properties in the three regions. The values showed considerable contrasts (Table 2).

Highest mean specific base flow (8.8 L/s/km^2) has been exhibited by streams draining the western basement terrain. This shows that the base flow in the streams is sustained by slow release of water from the regolith manifesting higher storage capacity of this medium.

Those streams draining the southern basement region show mean specific value of 2.5 L/s/km^2 which is the intermediate between the other two regions.

Significantly low (as compared to the two regions) mean specific base flow value of 0.79 L/s/km^2 of Worei stream in the northern basement terrain is attributed to thin or absence of regolith cover that buffers the out flow. Hence flow is transmitted through open fractures (high hydraulic conductivity) and as runoff to incised drainage system leading to generation of high peak flow in the stream (Fig. 7).

Thus the significant variation in specific base flows can be attributed to contrast in bulk storage properties of catchments in each region.

4.3. Linkage between geomorphic processes and hydrogeology of basement rocks of Ethiopia

The hydrogeological characteristics of the weathered crystalline rocks are derived from long-term, deep weathering- stripping process (Taylor and Howard, 2000). The geomorphic processes are still active, and the present day climatic conditions (mainly rainfall) continue to drive these processes modifying the already existing landscapes.Thus the hydrogeology of basement rocks of Ethiopia differs primarily by their vertical heterogeneity in the aquifer structures. The difference is further enhanced by rainfall variation. The contrasting geomorphic processes since Miocene resulted in differences in vertical heterogeneity of weathered mantle-fractured bedrock profiles in the basement terrain of the country (Fig. 5).

In the western region, the prevailing wet and warm conditions favoured the active and contemporaneous geomorphic processes (weathering and stripping) leading to the development of landscape dominated by gentle convex interfluves over the preserved thick regolith mantle (Fig. 5C). Thick weathering mantle developed over the recent (late Miocene) basalt bedrocks (observed in the field) in this region is prominent evidence for continued regolithization after the emplacement of the volcanics. The recent regolithization over the volcanic rocks is also described as the younger regolith by Kebede (2013). Deep incision of the preserved weathered mantle over basement rock is not common albeit high annual rainfall (1800–2200 mm) (Fig. 2) owing to the low relief of the weathered surface. Much of the rainfall is transmitted through weathered profile to be added to groundwater reserve (as groundwater recharge). On its percolation in vadose zone it continues to drive the weathering process. It is likely that the dissociation and disintegration of the existing weathering mantle could result in further enhancing the storage capacity of the regolith.

This is exhibited by the existence of high specific base flows in stream draining this region (Table 3). As a result, significant amount of shallow groundwater is stored in the weathering mantle owing to the higher recharge and high storage capacity.

Groundwater discharge is by means of abundant springs and sustained base flows in the streams- a consequence of high storage capacity of the thick regoilths in the region. Groundwater

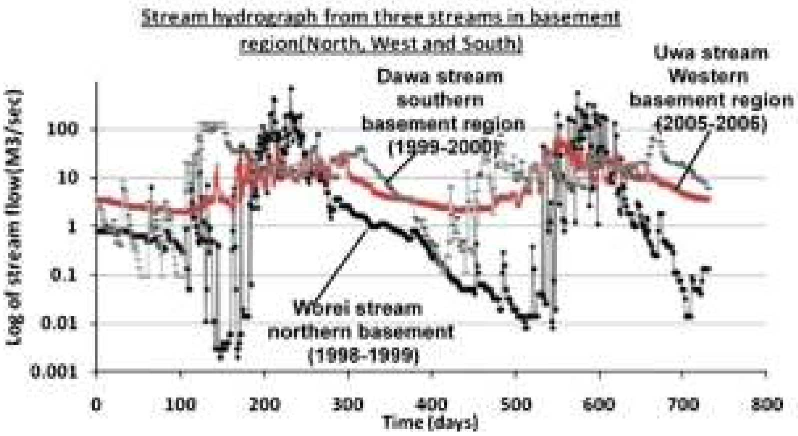


Fig. 7. Stream hydrographs from the three basement regions; the stream draining the northern basement catchment has the rapid rise and recession flows owing to thin regolith mantle- a consequence of lower storage capacity but higher hydraulic conductance.

Table 3

Table depicting specific base flow in some rivers draining the western, southern (Borena lowland) and northern basement terrains. The higher specific base flow indicates the sustained groundwater discharge to the rivers. (Data source: Alamirew et al., 2005; Zewedie, 2011.)

Name of river	Basement region	Specific base flow (L/s/km^2)	Data source
Aleltu	Western	5.89	Alamirew et al. (compiler) (2005)
Komis	Western	9.46	Alamirew et al. (compiler) (2005)
Hujur	Western	9.19	Alamirew et al. (compiler) (2005)
Ouwa	Western	10.57	Alamirew et al. (compiler) (2005)
Dawa(melka guba)	Southern	0.66	Zewdie (compiler) (2011)
Dawa(Shiftu)	Southern	0.34	Zewdie (compiler) (2011)
Genale(Chenemasa)	Southern	4.84	Zewdie (compiler) (2011)
Mormora	Southern	4.16	Zewdie (compiler) (2011)
Worei near Maikenetal	Northern	0.79	
Mean specific base flow (for indicated rivers)		(L/s/km^2)	
• Western basement region		8.8	
• Southern basement region		2.5	
• Northern basement region		0.79	

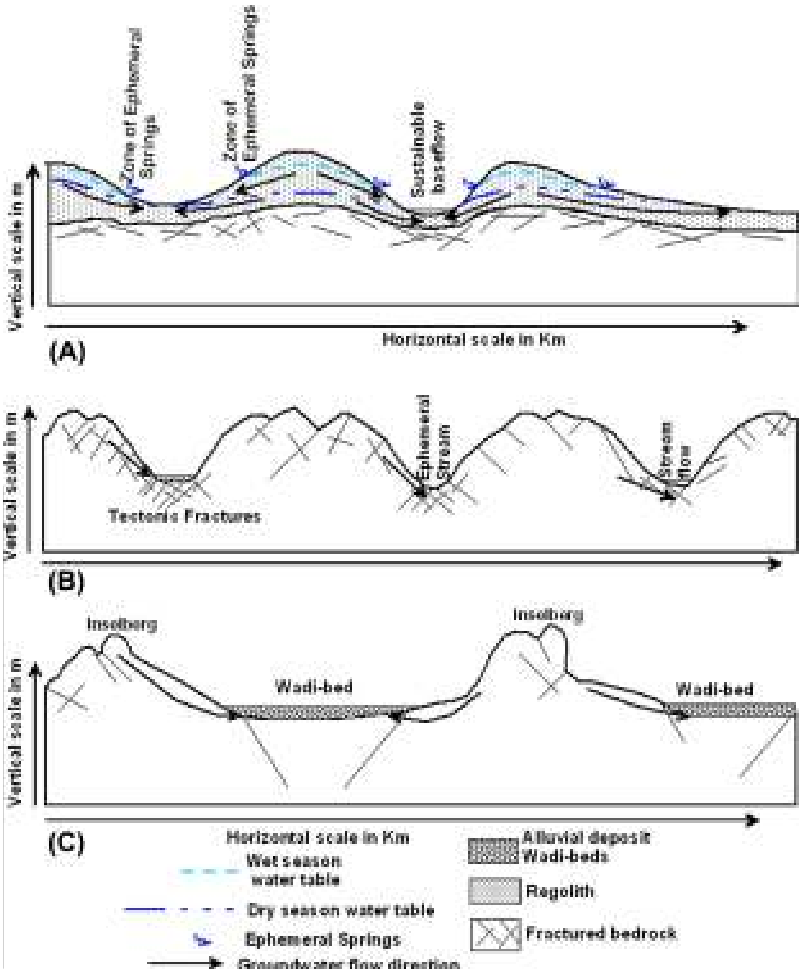


Fig. 8. Conceptual sections depicting the categories of basement aquifers in three regions of Ethiopia: (A) high storage-low conductive type aquifer on deeply weathered surface of Western basement region; (B) low storage-high conductive type aquifer on stripped surface of Northern basement region; (C) Mixed/intermediate type aquifer (groundwater occurrence associated with wadi beds/Alluvial deposits) over regional fractures.

occurrence and movement in this region is thus, in the weathering mantle and the underlying fractured bedrock. The weathered mantle plays the storage role and the fractured bedrock constitutes the conductive role. Development of groundwater is by means of capping springs, hand dug wells and shallow bore holes which is generally a result of shallow aquifer system. However, deep wells extended to the top of bedrocks can tap highly conductive sap rock zone. Higher yielding deep wells could be possible because of high storage from the regolith mantle and higher hydraulic conductivity from the sap rock (fractured bedrock).

In the northern basement region, the surface has been subjected to active erosion since late Miocene (Kebede, 2013) that retained the present day landscape feature. A regime of ''weathering-limited'' is prevailing over the low-grade fractured bedrocks owing to the higher relief and low rainfall. This condition results in the development of thin weathered layer or absent exposing the fractured bedrocks to the surface (Fig. 5A). Much of the inflow from rainfall is transmitted through open fractures and surface runoff to deeply incised drainage system to generate high stream flows (Fig. 7). Consequently discharges from catchments in the region are characterized by rapid rise and recession flows owing to thin regolith mantle- a consequence of lower storage capacity but higher hydraulic conductance.

Direct recharge is little on this surface relative to the deeply weathered surface in the western region. However, significant recharge takes place through tectonically induced fracture zones, foliations and joints. Therefore occurrence and movement of groundwater in Northern crystalline basement rocks is mainly controlled by fractures and other discontinuities (joints and foliations) (Fig. 7; Table 3).

The southern basement region of Borena lowland has been affected by the prevailing arid conditions as a result of east African aridification (Pierre et al., 2006; Kebede, 2013) since late Miocene. The prevalence of calcretes capping the extensive plains of Borena lowlands are manifestations of intensified evaporation. The calcrete capping facilitates runoff than infiltration. Direct recharge is limited because of the influence of high evaporation. The presence of wash surfaces (Photo 2) manifest the operation of erosion under low relief conditions leading to the deposition of sand sized sediments in wide river channels(wadi beds).The alluvial sediments are derived from gneiss bedrocks and inselbergs of gneisses and granites. The wadi beds follow regional fractures. These fractures control groundwater flow regime thereby enhancing preferential weathering. The presence of these sediments over the weathered mantle facilitates infiltration into the weathered mantle and fractured bedrocks underneath. This enhances groundwater storage both in the regolith and fractured bedrock. Groundwater development is commonly by means of traditionally dug large diameter community wells called Eelas in rural areas. Most of the Eelas are located in wadi beds and fracture traces that are outlined by linear arrangement of vegetation, signifying the presence of a systematic linkage between fracture orientations and the regolith development.

Table 4
Aquifer classifications, groundwater occurrence and, proposed mode of groundwater exploitation in the basement aquifer of Ethiopia.

Basement Region	Groundwater occurrence	Proposed exploration methods	Proposed methods of development
Northern	Fractured bedrock	Hunting and mapping of fractures and discontinuities (density, orientations)	Dug wells, shallow & deep boreholes
Low lands of Borena	Alluvial (wadi-beds) regional fractures	Mapping of wadi beds, sediment deposits regional fractures	Non-conventional schemes: Sand dams, subsurface dams connection to floods and improved river bed excavations and infiltration galleries Conventional schemes: hand dug wells shallow wells
Western	Regolith-fractured profile	Identifying and mapping catchments with thick regoliths, using base flow indices as an element in exploration strategies	Capping springs, large diameter dug wells and shallow bore holes Deep wells up to sap rock zone (top of the bedrock)

4.4. Basement aquifer classification and groundwater resources implication

As a result of regionalization of geomorphic histories (differences in rate of weathering and stripping), over different lithologies being driven by the late Cenozoic to present climate, groundwater occurrence and the types of aquifers exhibit important contrast in basement rocks of Ethiopia. The following generalized categories of aquifers are thus, proposed based on the existing data and field observation for the three basement regions (Fig. 8; Table 4):

1. On the deep weathered surface (the western basement region), the composite profile of weathered mantle-fractured bedrock over low to high-grade bedrocks constitute the aquifer and it is classified as high storage-low conductance type aquifer.
2. In the northern basement region (on the stripped surface), the weathered mantle is stripped to negligible thickness; groundwater occurs in high-conducting but low-storage fractured low-grade bedrocks.
3. In the Borena lowlands (the southern basement region), the occurrence of groundwater is mostly associated with wadi beds. The occurrence and orientations of wadi beds follow regional fractures. These fractures control groundwater flow regime and enhance preferential weathering of bedrocks. The alluvial sediments (mainly sandy) on top of the sequence serve as infiltration media to aquifers underneath. The aquifers are of intermediate storage and conductivity. Remnants of weathered mantle are still visible on gentle slopes but contribute little to groundwater flow and storage as they are capped by duricrusts (calcretes).

The complete understanding of basement aquifers genesis and their variation in aquifer properties have practical importance on exploration and development of groundwater resources in these aquifers. This includes the choice of appropriate technologies for groundwater exploration and development methods with respect to aquifer types in each region. Table 4 summarizes some potential proposed exploration and development methods with respect to basement aquifers in each region.

5. Conclusion

This study demonstrates that the geomorphic processes of deep weathering and stripping which are controlled by uplift and tectonic quiescence are responsible for the occurrence of aquifers in basement rocks of Ethiopia. The regionalization of these processes following the climate variation since late Miocene has resulted in vertical heterogeneities in weathered-fractured profiles leading to the development of aquifers with contrasting hydraulic properties in each region (Northern, Western and the Borena lowland). Therefore, unlike the previous Hydrogeological classification which categorizes basement rocks of the country as a regional aquiclude or poor aquifer , this study shows that groundwater occurrence in the basement terrain of Ethiopia is, region-specific (i.e. spatially controlled).The spatial variability is explained by the model which in turn is tied to genesis of the aquifers.

Furthermore promising groundwater zones particularly in shallow regolith zones could be identified if the model is applied.

Thus it is here suggested that the existing premise on hydrogeology of crystalline basement rocks in common use in the country is revised as proposed in this work which takes into account the genesis of the aquifers with respect to geomorphic processes.

The study also validates the reliability of weathering-stripping model previously developed for the country. This can be used as a basis for basement aquifer classification. It also corroborates the weathering-stripping model approach which is in use elsewhere (e.g. India, Uganda) is also applicable in Ethiopia for basement aquifer classification on regional scale. Nevertheless, (a) the basement rocks of Ethiopia are dominantly low-grade and (b) they have undergone repeated deformations related to uplifting. This process favors repeated stripping reducing the thickness of regolith. This contrasts the widely described thick regolith profiles from stable cratonic part of Africa. In Ethiopia thick regolith profile is attributed only to the western basement region which account to about 1/4 of the basement cover.

Furthermore, this study highlights that recognition of the linkage between geomorphic processes and hydrogeology together with classification of basement aquifers has practical significance on methodologies and strategies for groundwater exploration and development.

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