ABSTRACT
Precambrian Crystalline Basement rocks underlie much of southern and eastern Africa north of the Limpopo Valley where the Basement aquifer forms the primary source of domestic water supply for most rural communities. Groundwater occurrence within Precambrian Basement rocks depends upon lithology, weathering patterns, structure (fracturing) and recharge. Soil type, palaeoclimate, the age of the erosion surface and drainage patterns play a significant part in aquifer development. The older erosion surfaces often offer the thickest regolith, although upper layers may be of clay grade material – the conundrum is, therefore, greater storage but possibly less recharge capacity. Data from Malawi, Zimbabwe and Uganda illustrate the complex relationship between groundwater potential, depth of weathering, and the age of the erosion surface. However, the low yields common to the Basement aquifer hinder interpretation, and more information are required to investigate the relationships in more detail.

INTRODUCTION
Much of southern and eastern Africa, located north of the Limpopo River, is underlain by Precambrian Crystalline Basement rocks (Fig. 1). The development of groundwater resources within this region indicated the occurrence of shallow groundwater in fracture zones in the semi-arid areas of eastern Botswana and southern Zimbabwe; in the near-surface weathered zone in Madagascar, Malawi, Uganda and Zambia; and in combinations of these target horizons in central and northern Zimbabwe and Tanzania. Geophysical siting and borehole drilling and construction methodologies evolved to enable rapid installation of low-cost and low-maintenance hand-pumped water supply boreholes for rural communities throughout southern and eastern Africa. The near-surface weathered and underlying fractured zones are important as they are the main source of water for many of the people living in the drought-prone savannah areas.

The installation of large numbers of rural water supply boreholes during the period 1980 to 2000 was accompanied by a perception that the hydrogeology of the Precambrian Basement aquifer was fully understood. Responsibility for further development of the aquifers was devolved to non-hydrogeologists at inter-country district level government working with national and international non-governmental organisations (Robins et al, 2006). Emphasis moved to the installation of low-cost hand-pumped borehole units maintainable at village level. Large numbers of boreholes continue to be installed but drilling records are no longer seen as a routine project requirement by Aid agencies or government institutions; and little attention is now given to identifying those regions where groundwater potential may be more favourable than others.
Work undertaken in the 1970s and 1980s alluded to a contention that the regolith was likely to be better developed beneath the older erosion surfaces than the younger ones. It was observed that the regolith was generally thicker beneath the African erosion surface than the post-African erosion surface so offering greater storage and possibly a more sustainable resource potential (McFarlane et al., 1992). Subsequently it was realised that the older the erosion system the more likelihood that clay grade material would be present in the shallow part of the regolith and that this might inhibit recharge (e.g. Jones, 1985; Wright & Burgess, 1992).

It is difficult to prove that the older erosion surfaces do indeed offer a more sustainable resource as useable data on sustainability are not collected and resort needs to be made to surrogate information such as borehole yields. Borehole yields are universally low in the Basement aquifer and comparison between those from one erosion surface to those from another show little variation unless sufficient numbers of data are available with which to make statistically meaningful comparisons. This may one day be possible, using a statistical approach combined with data handling on a regional basis within a GIS format. In the meantime it is useful to revisit the role of the erosion surface and its relative age and to illustrate differences with the limited data that are currently available.

GEOLOGICAL SETTING

The regional geological system comprises several ancient compact meta-igneous cratons surrounded by metamorphic mobile belts upon which have been deposited ancient Proterozoic sedimentary sequences (Key, 1992) (Fig. 1). The main lithologies of the Basement rocks are:

- High-grade metamorphic rocks – craton areas – granitic gneisses and schists.
- Low- to high-grade metamorphic rocks – greenstone belts – amphibolites, phyllites and schists.
- Igneous intrusions – granite plutons and dolerite dykes.

Fig. 1  Precambrian Basement Aquifers north of the Limpopo (after Foster et al., 2006)
The formation of Archaean cratons culminated with granite emplacement at about 2500 Ma. The Limpopo Mobile Belt is also Archaean with its development linked to movement of the older cratons. Elsewhere early greenstone belts formed above mantle plumes on thin mobile crust. The development of the Proterozoic mobile belts reflects collisions between cratons. The intra-tropical uplifted area of eastern and southern Africa contains the main cratons which are surrounded by brittle fracture affected mobile belts. The Limpopo and Mozambique mobile belts were affected by strike-slip faulting that resulted in rifting from the mid-Cretaceous period during the break-up of Gondwana. Karoo and later sediments were deposited within the rifts. Gurnis et al (2000) reviewed the erosion surface observations of King (1967), Partridge and Maud (1987) and others, placing them in the context of the tectonic uplift of the southern and central African plateau which has taken place since Miocene times.

Groundwater collects at the interface between the basement rocks, acting as an aquiclude, and the weathered regolith (Jones, 1985). The greatest thickness of regolith often occurs below the oldest erosion surfaces (McFarlane et al, 1992). The composition of the regolith reflects the pattern of weathering processes experienced after the Dwyka glaciation and associated peneplanation. These processes reflect changes in climate due to variations in global atmospheric conditions, as experience during the late Cretaceous (Schmitt, 1999), as well as the movement of the African plate across different latitudes. Thickness of weathering can also be related to bedrock type. With this in mind, this paper reviews the influence of the main erosion surfaces on the distribution of groundwater in the Basement rock aquifers of southern and eastern Africa north of the Limpopo using examples from the available data that have been gathered and archived.

WEATHERING AND AGE

Geomorphological investigation of the erosion surfaces of eastern and southern Africa were investigated by Dixey (1946), King (1967) and Lister (1987), and critically reviewed in the context of southern Africa by Partridge & Maud (1987). Within the near surface zone, Ollier & Pain (1996) and Taylor & Eggleton (2001) relate patterns of regolith formation to soils and landforms in tropical and arid areas. Tropical weathering and the formation of soils were investigated by Nahon (1991) and Tardy (1997) who developed pedological weathering profiles. These studies all highlight the importance of groundwater in the processes of regolith formation.


Erosion surfaces that were active at specific periods in the geological record are retained as features in the present day landscape. The surfaces occur at specific ranges of elevation throughout southern, eastern and central Africa (Dixey, 1946; Lister, 1987). These surfaces result from prolonged patterns of erosion, or peneplanation, caused by sub-continent-wide patterns of uplift and tectonic activity. Later patterns of weathering at these erosion surfaces are related to variations in palaeoclimate. Six surfaces are recognised: Gondwana (mid to end Jurassic), Post-Gondwana (early Cretaceous), African (mid-Cretaceous to end Oligocene), Post-African (Miocene), Pliocene (Pliocene) and Quaternary (end Pliocene to the present day).
The Gondwana and post-Gondwana pedeplanation has now largely been removed by subsequent erosion surfaces, being preserved as a series of isolated residual topographic highs. The last glaciation to affect southern and eastern African cratons was the Dwyka glaciation and general peneplanation, and its end defines the start of the weathering processes that created the modern regolith mantle (Table 1). The African surface is, therefore, the oldest widespread erosion surface that remains in evidence to this day. The African erosion surface occurs at elevations above 1000 m above sea level (asl) along the central north-south topographical divide (Fig. 2). Weathering to depths of 30-50 m has been recorded in parts of Malawi and Uganda. The erosion surface formed after widespread faulting due to late Karoo rifting throughout central and southern Africa and peripheral warping of the sub-continent.

Table 1 Palaeoclimatic events (after Ollier and Pain, 1996)

<table>
<thead>
<tr>
<th>Period</th>
<th>Climatic Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwyka</td>
<td>Cooler with glaciation affecting present day southern and central Africa</td>
</tr>
<tr>
<td>Triassic</td>
<td>Drier and warmer</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Uniformly warm and wet with little latitudinal gradient</td>
</tr>
<tr>
<td>early Cretaceous</td>
<td>Cooling</td>
</tr>
<tr>
<td>mid to late Cretaceous</td>
<td>Very warm; subtropical at pole; elevated CO₂ (x10 present levels) and O₂ levels</td>
</tr>
<tr>
<td>end Cretaceous</td>
<td>Brief cooling</td>
</tr>
<tr>
<td>Palaeocene to early Eocene</td>
<td>Warm and wet</td>
</tr>
<tr>
<td>end Eocene (~35 Ma BP)</td>
<td>Cooling, start of Antarctic freezing</td>
</tr>
<tr>
<td>Oligocene</td>
<td>Cooler, drier, seasonality appears</td>
</tr>
<tr>
<td>late Oligocene</td>
<td>Re-warming and a decrease in Antarctic ice; sea level rises (African erosion surface)</td>
</tr>
<tr>
<td>early Miocene (15 Ma BP)</td>
<td>Start of cooling; permanent east Antarctic ice cap</td>
</tr>
<tr>
<td>end Miocene (~ 6Ma BP)</td>
<td>West Antarctic ice joined East Antarctic ice; big cooling; glaciation in the Arctic; Mediterranean dries up; sea level fall peaks at 4.5 Ma BP (Post-African erosion surface)</td>
</tr>
<tr>
<td>late Pliocene</td>
<td>Warming continued</td>
</tr>
<tr>
<td>2.4 Ma BP</td>
<td>North Polar ice cap appears; the start of the real cooling; at least 17 major coolings (Pliocene and Quaternary erosion surface)</td>
</tr>
<tr>
<td>18 000 BP</td>
<td>Peak of ice age, and deglaciation by 14 000 BP</td>
</tr>
</tbody>
</table>

The Post-African erosion surface of Miocene age occurs at elevations below 1000 m asl, for example, in Zimbabwe and Malawi, where the thickness of weathering varies between 15 to 30 m. The erosion surface formed in response to widespread tectonic uplift and long-term sea level fall. The African surface weathered zones were eroded to reveal the areas of rounded granite inselbergs that rise above the Post-African erosion surface. The Pliocene age erosion surface occurs at elevations below 800 m asl and is characterised by deep valleys, widespread outcrop and little weathering in interfluve areas. This erosion surface formed in response to general land-surface uplift. The Quaternary erosion surface of end of Pliocene to Recent age is characterised by the deposition of alluvial deposits along the incised middle and lower reaches of the main rivers and not by an erosion surface as such.
Weathering processes and regolith thickness reflect changes in elevation due to tectonic activity, groundwater temperature and chemistry, and not just the age of the erosion surface. The typical weathering profile (Fig. 3) includes a superficial lateritic layer (1) of seasonal mainly lateral water flow. Below, occurs a mottled clay layer (2) that grades downward to a fine saprolite (4), which is thickest in the older profiles. A small quantity of water may be found within this layer, the upper part between horizons 2 and 3 being the zone of water table oscillation. The base of layer 3 may occasionally be marked by the presence of smectite clay. The water table will fall to the base of layer 4 during prolonged drought, whilst layer 5 is coarse-grained saprolite, in which groundwater is stored, the base of which commonly marks the weathering front. Limited weathering along decompression zones of horizontal fracturing may be observed within the upper parts of the underlying bedrock. Patterns of groundwater throughflow are sub-parallel to topography, with groundwater discharging to local spring and stream systems (Fig. 4). Where layers A and B (layers 1 to 4 in Fig. 3) are very thick then recharge to a thin layer C will be inhibited so that it may contain only small quantities of poor quality water.
Fig. 3  Weathering profile, layers 1-5 explained in the text. (after Tardy, 1997; Nahon, 1991)

Water flow horizons in the regolith (layers see Fig. 3)
A - base of the mottled clay rich zone (layers 1 and 2)
B - base of the fine saprolite zone (layers 3 and 4)
C - base of the coarse saprolite zone (layer 5)
D - limit of weathering within the bedrock due to decompression fissuring

Fig. 4  Typical cross-section showing sub-parallel patterns of groundwater flow through the regolith zones
GROUNDWATER OCCURRENCE MATRIX

Working in Zimbabwe, Gear (1977) and Gear and Makoni (1979) correlated aquifer lithology, thicknesses of weathering and borehole yields with rainfall data and erosion surface distributions, the latter defined by Lister (1987). This enabled better understanding of groundwater resource distribution within the Basement rock aquifers which was used for more effective and sustainable installation of abstraction boreholes.

It was apparent that the thicker the saprolite the better the yields obtained from boreholes drilled into layers 4 and 5 (Fig. 3). Groundwater may occur within a series of weathered layers beneath the weathering front (C) but their occurrence diminishes with depth within layer D (Fig. 4). These layers may relate to former deeper water levels, the deepest of which probably marks the depth limit of regional baseflow. In Zimbabwe, these features were recognised as apparent ‘palaeokarst’ horizons within granitic gneiss bedrock. These zones are sub-horizontal and sub-parallel to topography, their water-bearing capacity may be enhanced by the presence of sub-vertical fracture/joint planes. Only during recent times, with the increasing frequency of borehole failures during prolonged droughts, has it been appreciated that deeper weathering may result in thicker clay development in layers 2 and 3, which in turn may inhibit the amount of recharge water received in layers 4 and 5 (Fig. 3). This poorly appreciated relationship between rainfall recharge and the more productive coarse saprolite zone needs to be better appreciated for the promotion of long-term sustainable aquifer development. Although large numbers of boreholes have been drilled, few relevant data have been collected with which to address this issue.

Given that most Precambrian Basement lithologies are common to the countries of the southern and eastern Africa region, hydrogeological information obtained from an area characterised by a particular environment/erosion surface/tectonic regime can be translated to similar environments elsewhere. Therefore, a matrix of country specific aquifer types can be constructed using a framework of present day climates against palaeoclimates/erosion surfaces and tectonic activity related to a range of weathering/hydrogeological environments (Table 2). The matrix may be populated with summary hydrogeological descriptions derived from the results of available hydrogeological case histories from individual countries. The hydrogeological summaries assist in the understanding of groundwater occurrence within specific geological, geomorphological and palaeoclimatic parameters and can be linked to detailed databases and relevant cross-sector information within a GIS format. A similar classification was made by Gear (1977) and Gear and Makoni (1979) in Zimbabwe whilst Taylor and Howard (1996) applied it more recently in Uganda.

Table 2. Hydrogeological environment matrix

<table>
<thead>
<tr>
<th>Palaeoclimate / Erosion Surface</th>
<th>Present day climate</th>
<th>Sub-tropical summer-rain, semi-arid</th>
<th>Tropical climate with long dry spells</th>
<th>Tropical climate with short dry spells</th>
</tr>
</thead>
<tbody>
<tr>
<td>African</td>
<td>Zimbabwe</td>
<td>Tanzania</td>
<td>Madagascar, Uganda</td>
<td></td>
</tr>
<tr>
<td>Post-African</td>
<td>Botswana, Zimbabwe</td>
<td>Malawi, Tanzania, Zambia, Zimbabwe</td>
<td>Madagascar, Uganda</td>
<td></td>
</tr>
<tr>
<td>Pliocene</td>
<td>Botswana, Zimbabwe</td>
<td>Malawi, Tanzania, Zambia, Zimbabwe</td>
<td>Madagascar, Uganda</td>
<td></td>
</tr>
<tr>
<td>Gondwana break up</td>
<td>Botswana, Zimbabwe</td>
<td>Tanzania</td>
<td>Madagascar</td>
<td></td>
</tr>
<tr>
<td>Rifting</td>
<td></td>
<td>Malawi, Tanzania, Zambia, Zimbabwe</td>
<td>Madagascar, Uganda</td>
<td></td>
</tr>
</tbody>
</table>
The matrix shows those countries, according to their present day climate, which contain each of the three key erosion surfaces or are affected by either of the two key tectonic events. Summary project data linked to databases of archived information can be developed to describe specific hydrogeological environments in each of these countries. The matrix shows that the older African erosion surface and its associated deep weathering is present in parts of Zimbabwe, Tanzania, Uganda and Madagascar across the full range of present day climate, from sub-tropical semi-arid to tropical with only short dry spells.

The lithological influence may also be important and can be built into the matrix as a third dimension. It comprises the geographical distribution of each lithological type: high grade meta-sediments and meta-volcanics – greenstone belt, which weathers at the greatest rate around the periphery of the plutons, Proterozoic low grade meta-sediments and finally the igneous plutons and gneissic complex which are likely to weather at the slowest rate to form inselbergs. The matrix can now be interpreted in two dimensions – firstly the influence of the age of the erosion surface and the thickness of weathering along with the influence of major tectonic features, and secondly, by overlaying the lithological type, and the degradable potential of the local country rock. It would be a short step to develop a second overlay which describes groundwater potential within the weathered basement.

Malawi provides some useful examples. Much of Malawi is underlain by Precambrian Basement Complex igneous and metamorphic rocks. Karoo strata, Cretaceous igneous and sedimentary rocks and Recent alluvium occur within the rift valley now partly occupied by Lake Malawi. McFarlane et al (1992) used data from 1500 boreholes to correlate terrain characteristics, weathering profiles and yields from Basement aquifers below the African erosion surface in central Malawi. They conclude that optimum borehole yields were to be obtained from boreholes that penetrated both the lower saprolite and the underlying fractured basement layers.

The Mangochi area in south-eastern Malawi is underlain by Precambrian gneisses intruded by younger granites and syenites that typically form rounded inselbergs (King and Dawson, 1976). Rifting occurred during Late-Karoo to Cretaceous and Tertiary to Recent times. King and Dawson (1976) describe four erosion surfaces in the Mangochi area:

- Post-Gondwana surface - residuals (up to 1800 m) (early to late Cretaceous)
- African surface (late Cretaceous to early Miocene) - eastern plateau (700 to 1400 m)
- Post-African surface (late Miocene and Pliocene) - rift scarp and eastern plateau
- Quaternary surface - lakeshore plain (470 to 610 m)

Georeferenced hydrogeological logs and site elevations from 97 boreholes installed by the Mangochi Rural Water Supply and Sanitation Project during 2003-2004 are available (GITEC, 2006). Of these, 71 were located on the African erosion surface, 16 on the Post-African surface and 10 at the junction of the two surfaces (Fig.5). Logs provide information on thicknesses of soil, upper saprolite, lower saprolite and fractured basement layers. Detailed drill penetration rate logs identify these layers. Blow yields obtained during down-the-hole hammer drilling at regular intervals and at water strikes allow determination of water yields from each layer. At Mangochi, the data indicate that the thickness of weathering varies between 15 to 60 m beneath the African surface and 10 to 30 m below the Post-African surface. Borehole yield distributions are similar for both layers: 75% have yields = 1.0 l/sec and 90% have yields = 2.0 l/sec (Fig. 6). The African surface lies at 950-1100 m asl, and the Post-African surface at <1000 m asl (Fig. 7).
In Zimbabwe, 60% of the land area is underlain by Precambrian Basement igneous and metamorphic rocks. Karoo sedimentary rocks and basaltic lavas crop out in southern and north-western Zimbabwe. Much of the north-west area is mantled by Post-Karoo to Recent age Kalahari Beds. Recent alluvium occurs along river valleys in the southern Lowveld area where sand rivers are common. The hydrogeological properties of the weathered zones present beneath the area underlain by Precambrian Basement strata in Zimbabwe are listed in Table 3.

Table 3 Palaeosurfaces and weathered zone aquifer properties (after Interconsult, 1985)

<table>
<thead>
<tr>
<th>Lithology / Erosion Surface</th>
<th>African</th>
<th>Post-African / Pliocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocks of the Old Gneiss and Granite Complex, the Younger Granites, Paragneiss of the Limpopo and Zambezi Mobile Belts underlie 60% of Zimbabwe. Ground surface elevations are 500-1400 m asl, rainfall is 500-1200 mm per annum.</td>
<td>Weathering &gt;30-50 m deep T &lt;10 m$^2$d$^{-1}$ SC 30-50 m$^3$d$^{-1}$m$^{-1}$ Yields 50-100 m$^3$d$^{-1}$ Bh depths 40-50 m TDS&lt;1000mg$l^{-1}$ pH 6.5-8.5</td>
<td>Weathering 10-40 m deep Water table&lt;15 m deep T 1-10 m$^2$d$^{-1}$ SC 2-20 m$^3$d$^{-1}$ Yields 10-50 m$^3$d$^{-1}$ Bh depth 30-40m TDS&lt;1000 mg$l^{-1}$</td>
</tr>
</tbody>
</table>

T – transmissivity, SC – borehole specific capacity, TDS – total dissolved solids

Hydrogeological data were obtained from two project areas underlain by Basement rocks:
- the Nyamazura/Romsley area of Manicaland Province, eastern Zimbabwe as part of the 1984 Intensive Resettlement scheme, and
the Victoria province of southern Zimbabwe as part of the 1984 Accelerated Drought Relief Programme (Hydrotechnica, 1984).

Drilling sites in both areas were located on zones of weathering and/or fracturing using topographic and geological maps, aerial photograph interpretation and geophysical survey results. The boreholes were test pumped using a reciprocating pump for 3 hours followed by a recovery test, or by bailing for 30 minutes whilst recording the rate of water level recovery. Geological data were used to construct weathering profiles for the crystalline basement rocks. In deeper boreholes thinner zones of weathering related to regional groundwater baseflow levels were noted below the level of the nominal weathering front. Borehole test pumping results provided information on groundwater occurrence in weathered zones and fracture zones.

In southern Zimbabwe yields of 0.1 to 0.8 l s\(^{-1}\) were obtained from fractured basement 8 to 40 m deep mainly below Post-African and combined Pliocene/Post-African erosion surfaces. In contrast, in eastern Zimbabwe yields of 0.1 to 0.8 l s\(^{-1}\) were obtained from weathered and fractured basement 11 to 45 m deep mainly below the Post-African erosion surface (Figs. 6 and 7).

For Uganda, Taylor and Howard (1996) published data from a series of boreholes drilled to investigate groundwater occurrence in weathered Precambrian Basement strata below the African erosion surface in the Aroca catchment. This area receives relatively high rainfall and the weathered zone, 10 to 40 m thick, produces borehole yields of up to 1.6 l s\(^{-1}\) (Figs. 6 and 7).

**EROSION SURFACES, DEPTH OF WEATHERING AND BOREHOLE YIELD**

Data from Zimbabwe and Malawi and from the Aroca area of Uganda are summarised in Figs. 6 and 7. Yield and depth to bedrock data presented within Fig. 6 demonstrate generally similar depths of weathering beneath all three erosion surfaces, i.e. 10-50 m. However, boreholes that indicate a thicker zones of weathering, e.g. to 60 m, only occur below the African surface. Borehole yields within the weathered zones below the Pliocene and Post-African erosion surfaces are mainly less than 1 l s\(^{-1}\), whereas higher yields, up to 2 l s\(^{-1}\), are obtained within the weathered zones below the African and African/Post-African erosion surfaces.

The elevations of the African surface, the Post-African surface and the Pliocene surface are consistent across Malawi, Zimbabwe and Uganda apart from some small deviation within the southern Zimbabwe Post-African/ Pliocene surface. Even more apparent is the striking difference in borehole yields derived from the older African erosion surface compared with either the Post-African or the Pliocene erosion surfaces. However, this is influenced by the higher rainfall and consequent higher yields available in Uganda. Fig. 7 also illustrates the generally low yielding nature of boreholes in the Basement below the Pliocene and Pliocene/Post African erosion surfaces throughout much of Zimbabwe, in an area of low rainfall much affected by periodic drought conditions, as indicated in Fig. 6.
CONCLUSIONS

Various geologists and geomorphologists have observed the presence of distinctive styles and thicknesses of weathering below the widespread erosion surfaces developed in association with the general uplift of the southern and central African plateau region since the Miocene. Patterns of weathering associated with palaeoclimatic and present climate conditions have been defined by pedologists and geomorphologists who recognised that water flow formed an integral part of the regolith weathering process. Hydrogeologists working on drought relief borehole drilling projects in Zimbabwe during the mid-1980s attempted to correlate weathered and fractured Basement rock zones (the aquifer) with erosion surfaces. Although the relationship of the age of the erosion surface and groundwater potential was first illustrated in Zimbabwe in the late 1970s and studied within Malawi and Zimbabwe during the late 1980s, it
is useful to revisit and to highlight the idea that the older, African, erosion surface supports the thickest weathering and the greater groundwater potential – and likely also the greatest sustainability - despite the development of clays in the uppermost saprolite. While sub-regional borehole yield averages tend to obscure differences between areas because yields are generally less than 1 to 2 l/s, comparison of yield against ground elevation picks out the yield differences between the three major erosion features.

Given the large national borehole data bases that now exist in some SADC countries, there may be sufficient borehole data for this preliminary survey to be extended through application of these data within a GIS format to better test the matrix system. When this is achieved the matrix so derived could be usefully applied to areas of low data density to better predict groundwater occurrence.

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