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Gneiss, fractures and saprolite: field geology for hydrogeology of the central Cauvery Catchment, south India

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Gneiss, fractures and saprolite: field geology for hydrogeology of the central Cauvery Catchment, south India

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Saprock and subhorizontal fractures in orthogneiss, north of Bangalore, Karnataka, India.

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Foreword

This report describes the geological observations and interpretations made following two reconnaissance field trips in October 2017 and April 2018 by Maarten Krabbendam and Romesh Palamakumbura, in the central Cauvery catchment in South India. The goal of the reconnaissance was to provide geological constraints to hydrogeological modelling to be undertaken as part of the UPSCAPE Project. The main geological constraints dealt with are fractures and the character of the regolith.

Acknowledgements

Sian Loveless, Sarah Collins, Bentje Brauns and Alan MacDonald are thanked for inviting us along in the first place, for teaching us the rudiments of hydrogeology, and for providing stimulating discussions. Veena Srinavasan (ATREE) and Shekar Muddu (IISC) are thanked for inspiring thoughts and insights, and to show us the importance of this work. Rajesh is thanked for guiding us safely through Bangalore traffic and across the Indian countryside, as well as taking us time and again to wonderful local food.

The research underlying this report was carried out under the UPSCAPE project of the Newton-Bhabha programme "Sustaining Water Resources for Food, Energy and Ecosystem Services", funded by the UK Natural Environment Research Council (NERC-UKRI) and the India Ministry of Earth Sciences (MoES), grant number: NE/N016491/1.

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1 Introduction

Groundwater is a vital resource in southern India. The average rainfall is c. 850 mm/yr, but is highly seasonal: most precipitation falls as part of heavy monsoon rains, alternating with extended dry periods. As a consequence, groundwater is not only important for providing drinking water to cities such as Bangalore, but also for irrigation, which allows farmers to grow multiple harvests per year, needed to feed the growing urban population of India.

The Cauvery catchment (c. 80,000 km^2) in Peninsular India drains nearly 3 % of India's landmass. Its tropical setting (10.9-13.3 ºN), diverse terrain and strong west-to-east precipitation gradient (>3000-500 mm a^{-1}) mean that surface and groundwater availability is regionally variable and, depending on local demand patterns, is a critical and widely limiting factor for agriculture. The catchment is largely underlain by hard-rock aquifers except in the Cauvery delta, underlain by deltaic sediments. Although predominantly rural, parts of the catchment have experienced considerable urban and economic growth over recent years, most markedly centred around the cities of Bangalore, in Karnataka, and Coimbatore, in Tamil Nadu. Shared between the states of Karnataka and Tamil Nadu, the Cauvery has long presented water management challenges at the local, regional and basin scale. Competing water demands, which span administrative boundaries, continue to present significant issues for integrated water management in the catchment.

The UPSCAPE project has been funded by Newton and Baba. Its aims are to develop novel methods for upscaling the hydrogeological understanding from rural and urban experimental sub-catchments to catchment wide scale, and to use this understanding to inform modelling of different anthropogenic catchment modifications on both sub-catchment and catchment-wide scale. The project consortium involves scientists Centre for Ecology & Hydrology (CEH), the Indian Institute of Science Bangalore (IISc), British Geological Survey (BGS), Ashoka Trust for Energy and the Environment (ATREE), the University of Dundee (UoD) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Bangolore (Bengaluru), in the eastern part of the state of Karnataka, is among the fastest growing cities in Asia, with a population growing from 5.1 million in 2001, to 8.4 million in 2011, and an estimated 10-12 million up (Wikipedia page on Bangalore Demographics). The city is situated on an upland plain with gently undulating relief, with some higher hills to west (Figure 1). Bangalore is situated on a broad drainage divide between the Arkavathi river to the west (a tributary of the Cauvery or Kaveri river) and the Ponnaiyar river to the east. Around Bangalore itself, rivers are small and commonly seasonal.

Having no significant perennial rivers, Bangalore has always been susceptible to droughts. Traditionally, settlements relied on a system of streams and manmade lakes (locally termed 'tanks') to store monsoon rainwater for the dry season (Suresh, 2001). As the population grew, the lakes were unable to meet the city's growing water demand. Water is being pumped from rivers and reservoirs up to 100 km away and 500 m lower than Bangalore, requiring vast amounts of electricity (Suresh, 1999; Grönwall *et al.*, 2010; Sawkar, 2012). Despite this, there is a shortfall in supply to the city. Surface water is augmented with groundwater supplies, with some 100,000 registered private boreholes, and possibly an additional 300,000 unregistered wells in Bangalore (Raju et al., 2008; Sawkar, 2012). Borehole depths can be up to 200-300 m. Estimated groundwater abstraction appears to exceed recharge, but the pattern of groundwater variation in monitored boreholes is poorly understood (Grönwall *et al.*, 2010). It is not clear to what extent borehole locations are dictated by underlying geology.

In order to better understand the hydrology and hydrogeology of the Cauvery catchment, the Groundwater team of the UPSCAPE project is analysing groundwater levels, chemistry and age from three subareas: The Milli catchment north of Bangalore, the Berambadi catchment near Gundlupet, south of Mysore, and Bangalore city itself. The project is also collecting catchment wide datasets. Some of the geological fieldwork was thus focussed on these areas.

The main hydrogeological hypotheses to be tested is: "*There is evidence of significant lateral groundwater connectivity over a distance of 10 km or greater within the hard rock (basement) portion of the Cauvery Basin*". The secondary hypothesis is: "*Vertical variability in permeability within the fractured basement controls available groundwater yields and can be forecast by understanding the geological setting".*

In terms of the reconnaissance field geology the questions we attempt to answer in this report are:

1. What is the character and distribution of the weathered zone (regolith)?
2. What is the character and distribution of fractures in the bedrock of the Cauvery catchment? Is there a relatively uniform distribution of fractures or are there systematic differences between different domains?
3. What conceptual models for the geology (relevant for hydrogeology) can be constructed for the Cauvery catchment or sub-catchments?

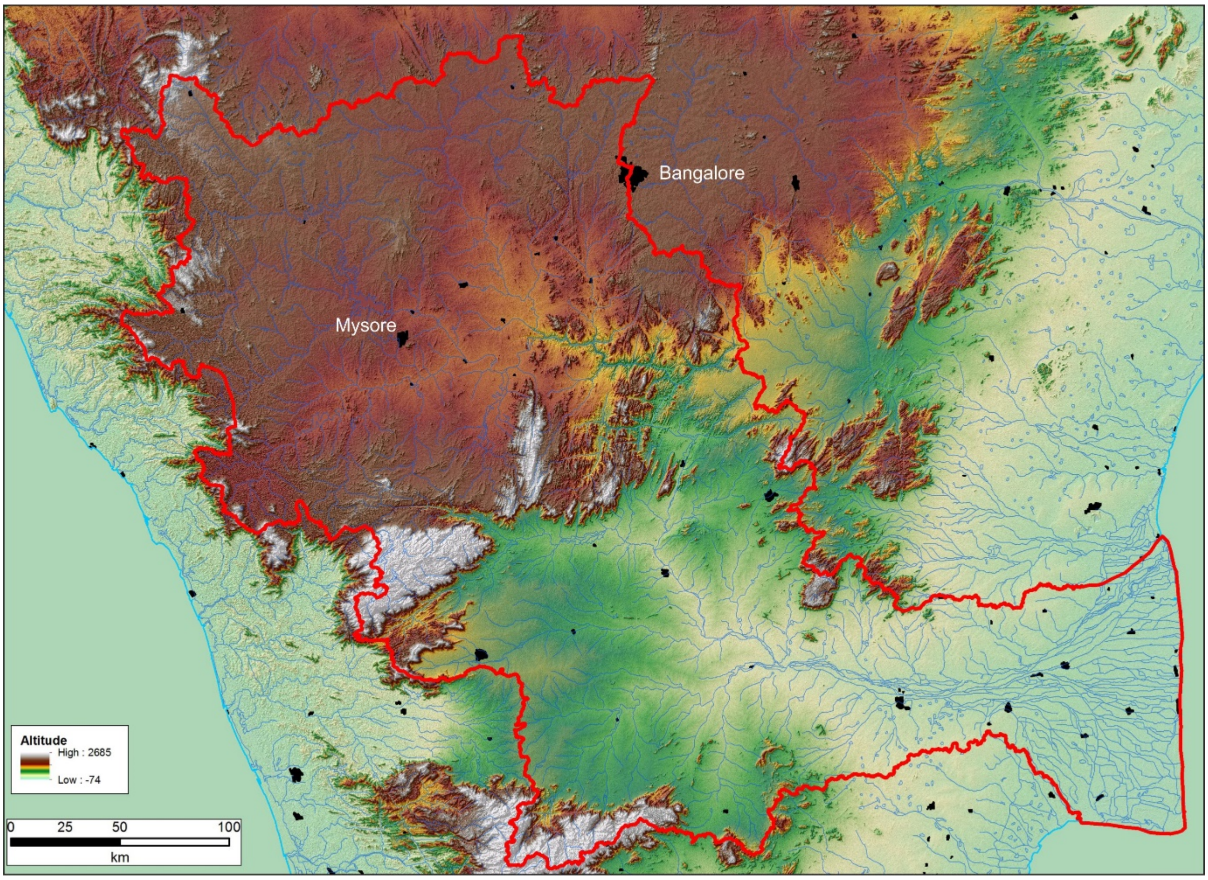


Figure 1. Overview map of the Cauvery catchment, outlined in red, in south India. Urban areas in black. NASA 30 m SRTM terrain map as background.

2 Fieldwork: Methods, datasets and bias

2.1 FIELDWORK; BIAS AND LIMITS OF FIELD OBSERVATIONS

The fieldwork for this study has in essence been of reconnaissance character. Geological field observations focussed mainly on quarries and some tanks, stream sections and other natural outcrops. These features were first identified by satellite and airphoto analysis (see Section 2.4, Datasets used, below). In the field, Google Earth and Google Maps were accessed on a 3G enabled mobile phone to exactly locate field sites. General geological observations were made, focussing on lithology, fractures and nature of regolith. Some regolith sections were logged with normal sedimentary logging techniques. More detailed fracture analysis will be included in a separate report. In total some 90 field sites were visited, covering an area of c. 10 000 km^2; the field locations are shown on a map in Appendix 1 and the coordinates are given in Appendix 2.

In any geological fieldwork, the nature and distribution of the outcrop results in a potential observational bias, and this is particularly true when studying fractures. Fractured rock tends to weather faster, with a thicker weathering and soil layer and supports more vegetation growth, and is thus less likely to be exposed. Conversely, unfractured rock tends to weather slower, supports less soil formation and vegetation and is thus more likely to be exposed. Outcrops on inselbergs are thus biased towards unfractured rock, whereas outcrops in river beds may be biased towards fractured rocks, as fluvial incision exploits the fractured rocks. Quarries for decorative stone are biased towards unfractured rock, although quarries for aggregate maybe more representative. Overall, the chance of encountering outcrops of densely fractured rock is lower than of encountering outcrops of unfractured rock, the corollary being that in this report the occurrence of densely fractured rock may be underrepresented. In addition, quarries are limited in depth; most quarries are some 10-30 m deep, with the deepest quarries some 40-50 m. Thus only 10-50 m below the ground surface can be observed, and to what extent these observations are representative for deeper fracture networks should be considered.

2.2 REGOLITH TERMINOLOGY

Earth scientists from different disciplines (geology, engineering geology, hydrogeology, soil science) use different definitions and terminology for describing weathering zones and weathered rock (e.g. Acworth, 1987; Dearman, 1995; Chilton and Foster, 1995; Fookes, 1997; Nesbitt and Markovics, 1997; Girty et al., 2014). In this report we broadly follow Chilton and Foster (1995) and use the term ‘saprock’ for the lower regolith unit of weathered rock, with patchy sand and clay and blocks of fresh to weathered rock, and ‘saprolite’ for the upper unit of predominantly unconsolidated sandy clay and sand, with occasional rock fragments. The boundary between ‘saprock’ and ‘saprolite’ as used herein is approximately the distinction between (stiff) soil and (friable) rock in engineering geology terms, and lies approximately between weathering grade III and IV (Dearman, 1995). Importantly, the boundary between saprock and saprolite is commonly gradational, and patches or layers saprolite may occur within a saprock unit and vice versa; as a consequence there is some inherent inaccuracy in these definitions.

2.3 LINEAMENT ANALYSIS

Lineaments, suggesting the presence of major subvertical fracture zones, can be recognised on satellite imagery or DTM elevation data. NASA SRTM (Shuttle Radar Topography Mission) 30m data was used, and portrayed as elevation, hillshade and as slope in ArcGIS. Strictly speaking this is a rather interpretative exercise: a lineament is in itself only a linear geographic feature. However, the best explanation for very straight, linear and negative linear terrain features is an underlying fracture zone (e.g. Singhal and Gupta, 2010). Slightly curved lineaments, or lineaments that have adjacent positive and negative topographic expressions are more likely to be lithological boundaries, possibly related to strongly sheared gneisses. Some positive lineaments are identified as dyke traces (see Section 6.5 on Dykes).

2.4 DATASETS USED

For lineament analysis and general geomorphological terrain assessment the following data were used:

- SRTM 30 m DTM from NASA Shuttle Radar Topography Mission Global 1 arc second (SRTMGL1) data (version 003) available from the U.S. Geological Survey.
- Sentinel Satellite imagery
- Satellite imagery available through ArcGisOnline (http://goto.arcgisonline.com/maps/World_Imagery). Used imagery include: 15m TerraColor imagery at small and mid-scales (591M down to 72k) which in South India appears to be captured in a wet season; 2.5m SPOT Imagery (288k to 72k) which appears to be captured in a dry season and 0.6m Digital Globe imagery (below 72k), which appears to be captured in a wet season.

2.5 FRACTURE ANALYSIS – OUTCROP SCALE

Linear scanlines were used to assess fracture sets that had one consistent orientation, for instance a vertical scanline was used to measure the fracture spacing or density of a dominant set of subhorizontal fractures. Due to limited field time and/or safety considerations (e.g. vertical quarry faces), linear scanlines were performed on scaled field photos.

More detailed fracture analysis will be presented in a subsequent report. We use the definition of fracture density of Davies and Reynolds (1996) and Singhal and Gupta (2010), where linear fracture density (1D fracture density) is the number of fractures per unit length (unit m^{-1}) and is the reciprocal of the average fracture spacing (unit m) over the length of the scanline. Note that these definition differ from those used in Mauldon et al. (2001).

3 Geology: Setting

The bedrock geology of the Cauvery catchment is dominated by the Archaean-Paleoproterozoic of the Dharwar craton. The Dharwar Craton is bound to the north by the c. 66 Ma Deccan Trap flood basalts, to the west by the Arabian Sea rift, to the east by the Paleoproterozoic Cuddapah basin and the Eastern Ghats orogenic belt. To the south, the Dharwar Craton is bound by the major E-W trending Moyar shearzone. A number of ductile shearzones splay from this shearzone into a north-south trending set of shearzones, which appear to diminish in intensity northward (Peucat et al., 2013; Chardon et al., 2008). South of the Moyar shearzone are the Paleoproterozoic Nilgiri Hills granulites and younger, Neoproterozoic mountain belts. The Dharwar Craton is normally subdivided into the Eastern Dharwar Craton, with the north-south trending Closepet granite batholith as a convenient boundary (e.g. Naqvi and Rogers, 1987; Meert et al., 2010, but see Peucat et al., 2013 for a different subdivision). The Western Dharwar Province comprises meta-igneous migmatitic tonalitic gneisses with amphibolites as well as supracrustal rocks termed the Dharwar Schists or Dharwar and Sargur supergroups (Rao, 1962; Meert et al., 2010). The Eastern Dharwar Craton comprises mainly tonalitic and granodioritic gneisses (locally termed the Peninsular Gneiss), especially in the area around Bangalore, although schist belts of supracrustal origin occur further north and east, and include the gold-bearing Kolar belt (Naqvi and Rogers, 1987).

The metamorphic grade in the Dharwar Craton increases from greenschist-facies conditions in the north (T =450-500°C; P = 4-5kb), through widespread amphibolite-facies conditions (T = 500-600°C; P = 5-7kb) in the centre, to granulite-facies conditions in the 'charnockite domain' in the south (T = 700-800°C; P = c. 8kb) (Raase et al., 1986). Commonly the charnockite area is seen as a separate geological domain, even though it comprises the same lithological components of both the Eastern and Western Dharwar cratons. Lower-grade, retrograde shear zones may occur in higher-grade rocks.

All the above rocks are cut by Paleoproterozoic dolerite dykes. Most dykes are east-west trending (Bangalore Dyke Swarm), but minor dyke swarms trend NW-SE and N-S (e.g. French and Heaman, 2010). The dykes are not deformed or metamorphosed at high temperatures, indicating that no ductile reworking occurred after the Early Palaeoproterozoic, implying that the Dharwar Craton had >2 billion years of time to gather brittle fractures.

The geological history of the area can be summarised as follows (Meert et al., 2010):

- 3000 – 2600 Ma: Formation of the Peninsular Gneiss by intrusion of the bulk of tonalite and granodiorite, as well as deposition of supracrustals in the Western Dharwar Province (e.g. Friend and Nutman, 1991).
- 2510 Ma: Metamorphism of the Dharwar craton, including granulite-facies metamorphism in the south, and intrusion of the Closepet granite (e.g. Friend and Nutman, 1991, Jayananda et al., 1995, Peucat et al., 2013).
- 2360 – 2200 Ma: Intrusion of dolerite dykes (French and Heaman, 2010).

After c. 2200 Ma no new rocks were formed in the study area. The craton was (and is) subjected to stresses generated by more distal tectonic events such as the Early Neoproterozoic Eastern Ghats mountain belt to the east; Late Neoproterozoic Pan-African mountain belts to the south; rifting and breakup of Gondwana during the Cretaceous, and the India-Asia collision, starting in the Palaeogene at c. 45 Ma and continuing to the present day. Uplift and erosion is indirectly recorded by deposition in adjacent basins, such as the 1900-1300 Ma Cuddapah Basin to the east (e.g. Anand et al., 2003) and the Permian-Jurassic 'Gondwana basins' near the Godavari River in the NE (Chakraborty et al., 2003). Sediment was deposited in Cauvery delta from the Later Jurassic onwards, with a major pulse of deposition in the Late Cretaceous (Chari et al., 1995); the Cauvery deltaic deposit comprises a sequence of sandstones and shales, with minor limestone and conglomerate, topped by alluvium (Ramkukar et al. 2004). Intense weathering during the Palaeogene of south India has been documented by Ar/Ar dating of Mn oxides in weathering profiles in the northern part of the Mysore Plateau (Bonnet et al., 2014). These studies together suggests that the Cauvery catchment was operating and producing sediment by weathering and denudation for at least the last 100 ma or so – see also Gunnel (1998) for this long term weathering and erosion.

4 Geomorphological overview: Subdivision into domains

There is a strong connection between lithology, geomorphology, regolith development and land-use, and hence with hydrogeological characteristics. We have subdivided the central Cauvery catchment into a number of domains (Figure 3):

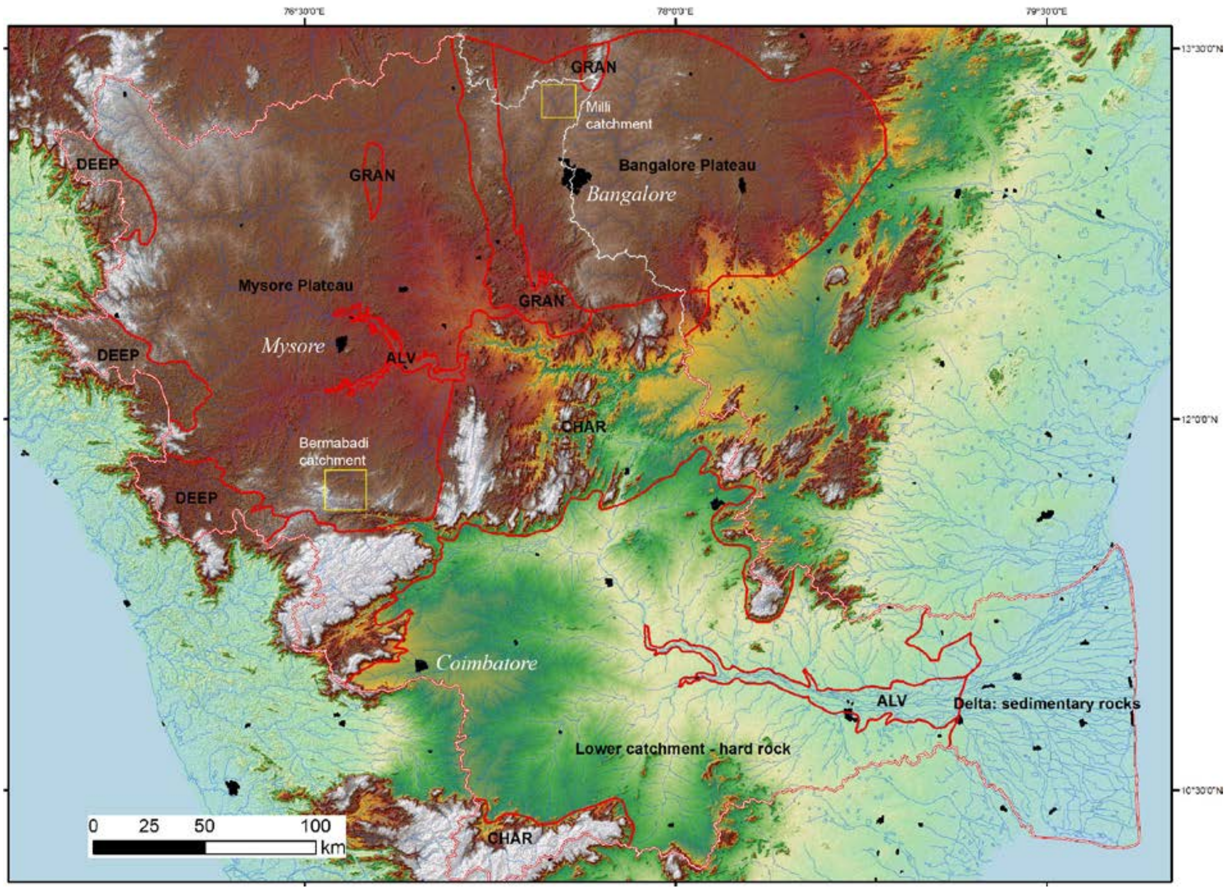


Figure 2. The Cauvery catchment, with different domains shown. Note that the Bangalore Plateau extends eastward beyond the Cauvery catchment boundary. NASA 30 m SRTM terrain map as background. The two smaller Milli and Berambadi catchments (yellow retangles) that are the focus of hydrogeological observations are shown. GRAN = granite domain; CHAR = charnockite domain; DEEP = deeply weathered domain; ALV = alluvium domains.

1. The Bangalore Plateau (Figure 2, 3), comprising Peninsular Gneiss of the Eastern Dharwar Craton. Although geographically commonly counted as part of the Mysore Plateau, we have separated it from the Mysore Plateau to the west. The Bangalore plateau ranges in altitude between c. 800-900 m. To the east and SE, and along the Arkavathi River, the plateau gradually descends to c. 500-700m, with minor incision and development of inselbergs suggesting a component of headward erosion (Figure 3). In the west, the Peninsular Gneiss of the Bangalore Plateau is bound by the younger Closepet granite batholith, marked by distinct inselbergs that locally rise up to c. 1200 m. This suggests that there was a higher plateau, which has been gradually weathered and eroded downward. Thus the plateau has a component of both vertical erosion ('downwearing')

and headward erosion. To the south, the Peninsular Gneiss is bound by charnockite with its characteristic incised landscape of the Cauvery Canyon.

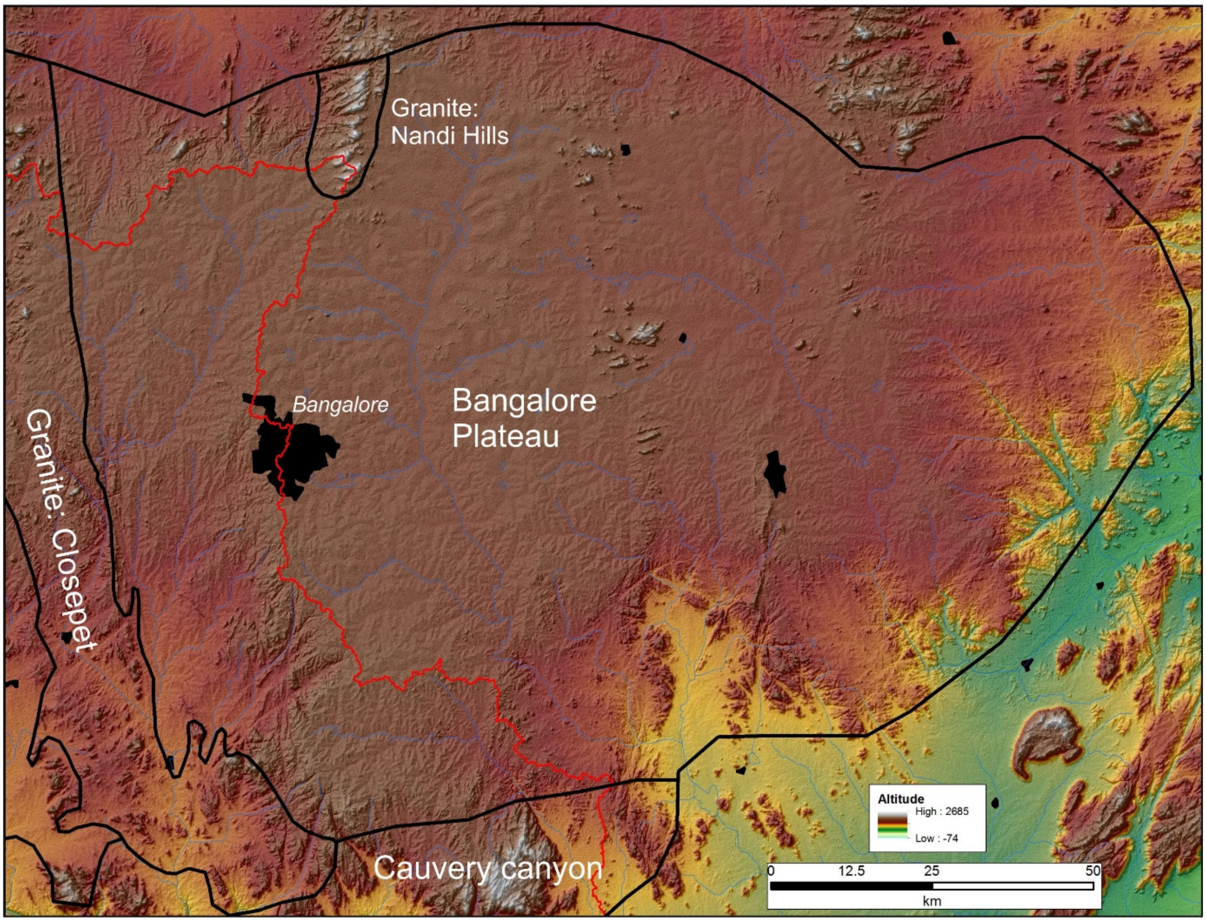


Figure 3. Bangalore plateau, NASA 30 m SRTM terrain map as background. Boundary to the south with the Cauvery canyon is gradual, as is the plateau boundary to the lower ground in the SE. Inselbergs are clearly visible as hills: some isolated, some in groups. Note abundance of inselbers in the Nandi Hills and the Closepet Granite area.

2. The Granite domain, which occurs in the north-south trending Closepet batholith and in the Nandi Hills north of Bangalore Plateau. The granite landscape is characterised by pronounced inselbergs, separated by straight valleys (Figure 4). The inselbergs are typically 100-300 m above the surrounding terrain, but inselbergs of 400-500 m high also occur, in particular in the Nandi Hills. The inselbergs are typically barren on their tops and flanks, with seepage stripes showing evidence of run-off. Corestones, freed from their saprolite mantle, are common on the surface on tors and on the flanks of inselbergs.

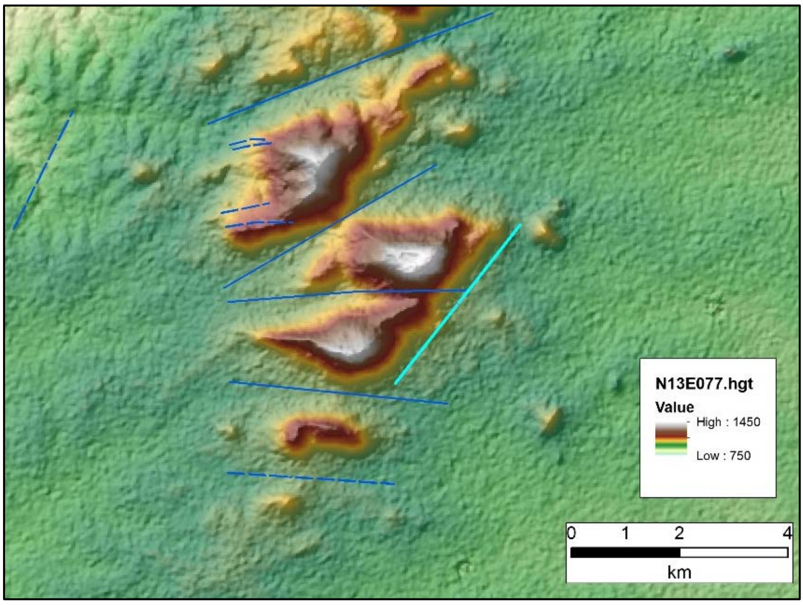


Figure 4. NASA SRTM 30 m DTM image, of the granite inselbergs of the Nandi Hills, north of Bangalore. Valleys in between inselbergs are fracture controlled.

3. The Mysore Plateau, for the purposes of this report, is the plateau around Mysore, bound to the east by the Closepet granite (Figures 5, 6). Lithologically, the Mysore Plateau comprises both Peninsular Gneiss and the supracrustals (metasedimentary and metavolcanic rocks) Dharwar Schists of the Western Dharwar Craton. Geomorphologically the plateau is very different to the Bangalore plateau. It comprises a flat part at an altitude of 600-680 m, surrounded by hills ranging from 800-2000 m asl. The altitude of lowest part of the plateau is tightly constrained by the Cauvery Falls near Shivanasamudra, a set of waterfalls that form a sharp local base level. (Note: the name Cauvery Falls here is used herein to include the Bharachukki and Gaganachukki falls). On the flat part of the plateau, the Cauvery River and some of its tributaries show meanders and floodplains (in part separated out as the Alluvium domain), with gently rolling hills as interfluves. The drainage pattern is mixed, with some dendritic elements and some structurally controlled elements. Higher up in the catchment to the north, west and south, hills rise higher and are at least in part controlled by lithology. True isolated inselbergs are rare (the Chamundi Hill near Mysore is an exception, related to a well-defined, small granite pluton) or not pronounced. The Berambadi catchment, the focus of some of the hydrogeological work in the UPSCAPE project, lies in the southern part of the plateau (Figure 6). The valley base levels in this area are between 760-850 m asl, whereas most hills bordering the catchment and forming interfluves are between c. 900 – 1100 m asl, rising up to c. 1450 m on the Gopalswami Hills. No isolated inselbergs occur, and all hill are remnant interfluves, which are strongly lithologically controlled (see below). Curiously, although the supracrustals nominally represent 'softer rocks', they commonly form the higher hills – an apparent contradiction that is discussed in section 6.2.

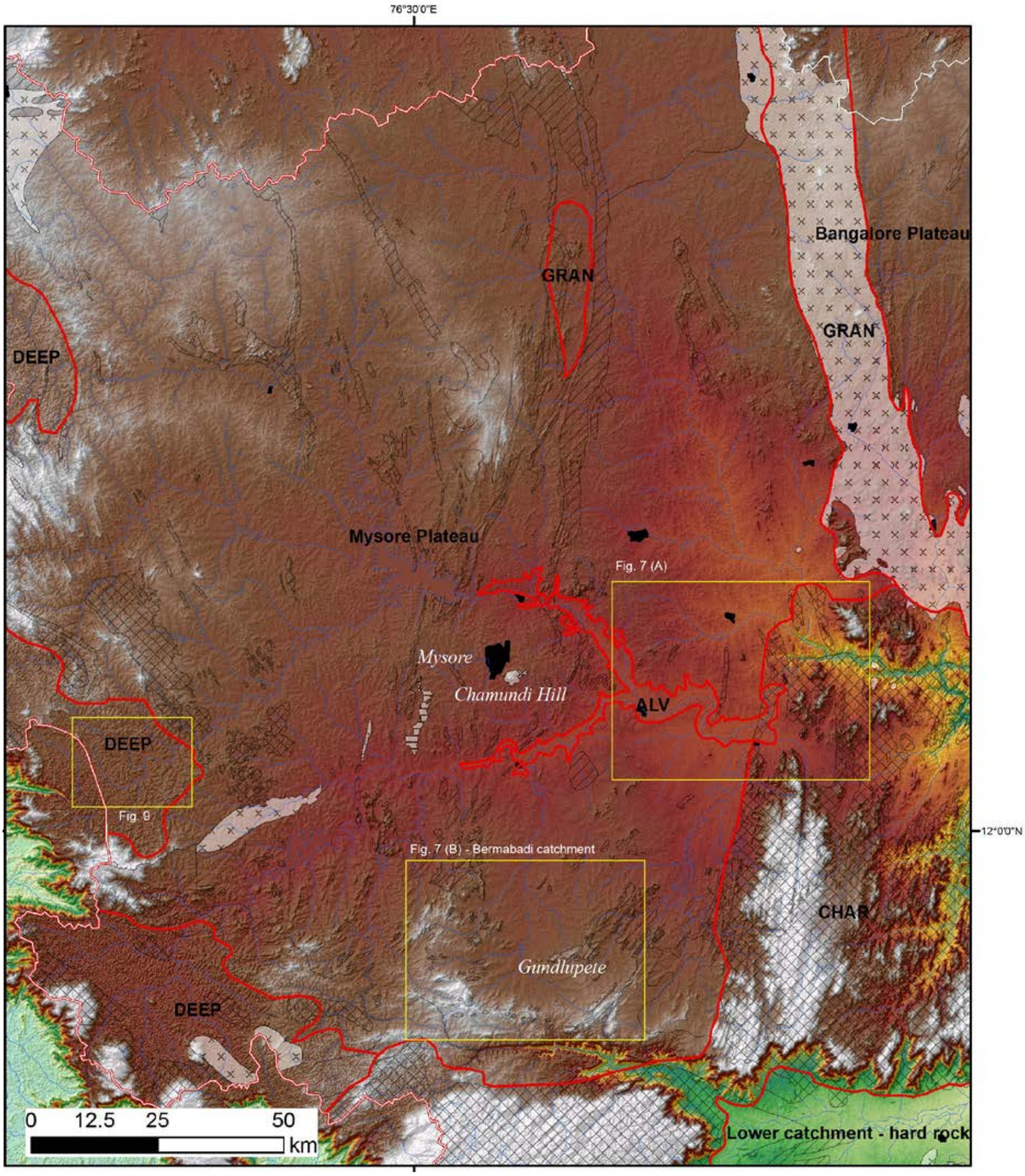


Figure 5. Mysore Plateau, upstream from the Cauvery Canyon. Hatching = supracrustal units (schist, amphibolite, etc); cross-hatching = charnockitic lithologies; white with crosses = granite. NASA SRTM 30 m DTM image, with hill shading.

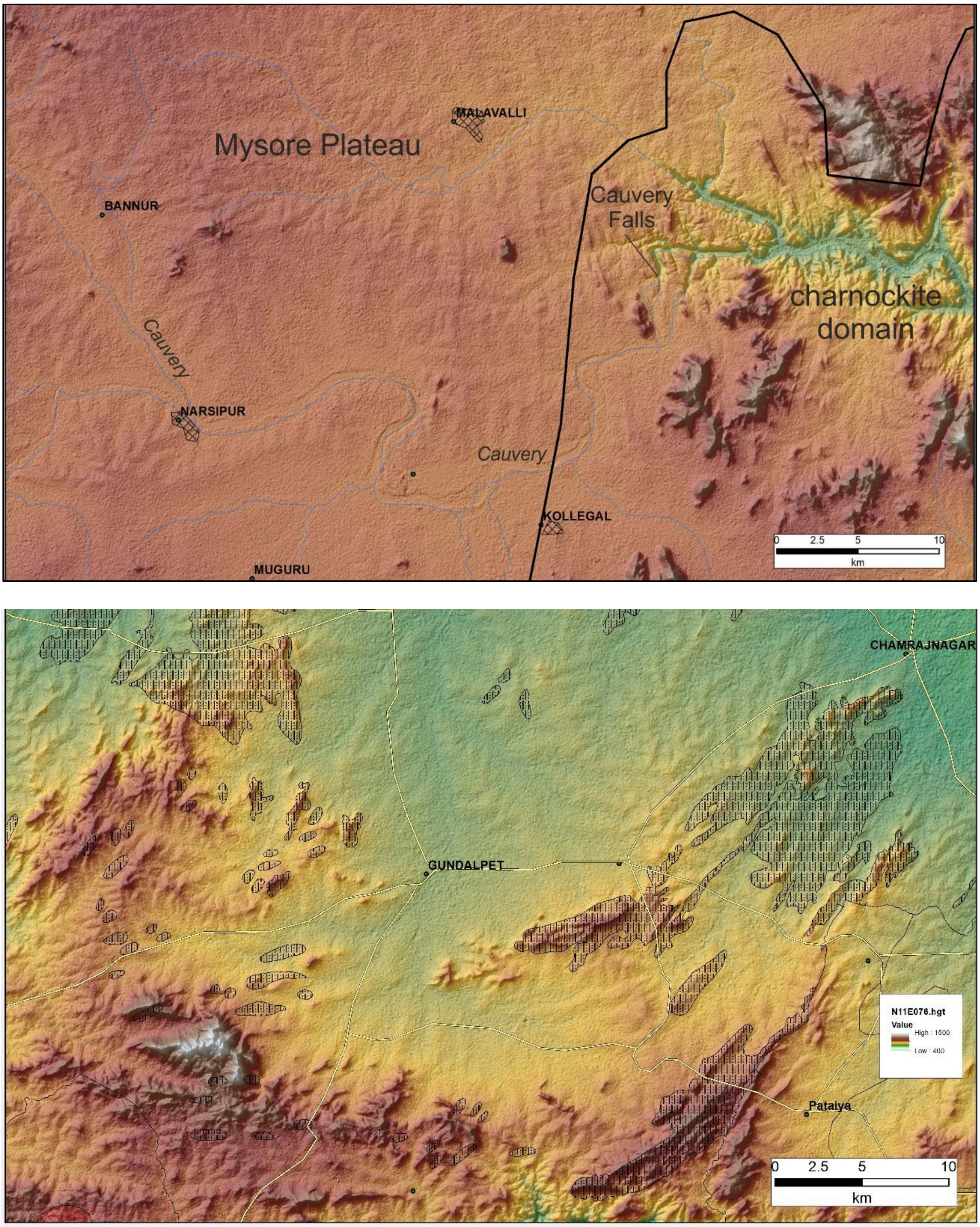


Figure 6. (A- top) Lower part of the Mysore plateau and upper part of the Cauvery Canyon. The Cauvery river on the Mysore Plateau shows meandering and floodplains; below the Cauvery Falls, the Cauvery River shows strong incision (B - bottom) the Berambadi catchment, in the southern part of the Mysore plateau. Hatching indicates mapped amphibolite and pelitic schist units. Note broad strike swing. NASA SRTM 30 m DTM image, with hill shading.

4. The <u>Charnockite domains</u>, typified by the Cauvery canyon, shows a strongly dissected, high-relief landscape of mountains and valleys, south of the Bangalore plateau, situated between the Cauvery Falls in the west and the Hogenakkal Falls in the east (Figure 6,7). Further to south, this domain includes the Biligirirangan and Mahadeswaramalai mountains (e.g. Kale et al., 2014). Relative relief is high: between the Cauvery and Hogenakal Falls the Cauvery River itself drops from c. 600 m to c. 250 m asl (see also Kale et al., 2014), whereas the overall relief ranges from 250 – 1350 m. The Cauvery canyon domain is lithologically characterised by charnockite, or more precisely granulite-facies gneisses, which have a gradational boundary with the Peninsular Gneiss of the Bangalore Plateau to the north. The Cauvery River itself has an east-west trend, but most tributaries are north-south trending, resulting in a rectangular drainage pattern, suggesting strong control by structural weaknesses.

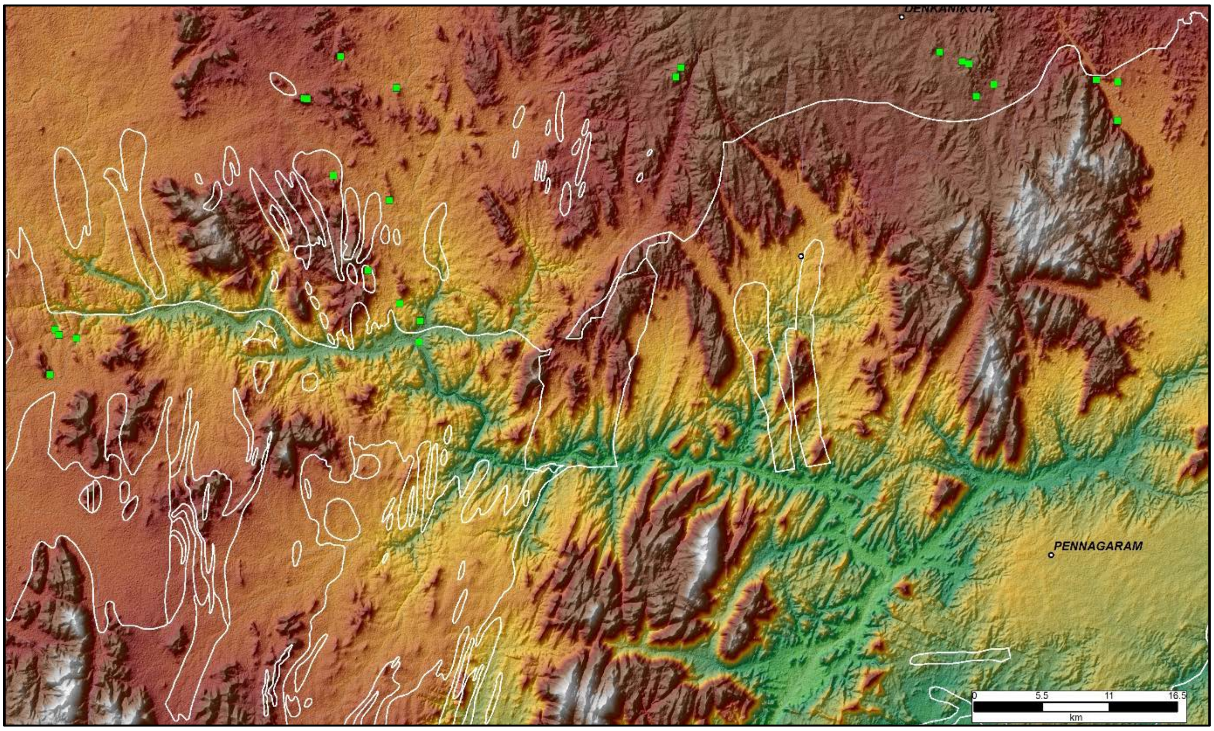


Figure 7. NASA SRTM 30 m DTM image of the Cauvery Canyon valley system, typical for the charnockite domain. Charnockite units outlined in white. Green squares are visited localities.

5. <u>Deeply weathered domain</u>. This occurs on the highest level of the Cauvery catchment in the Western Ghats, west of the Mysore Plateau, typically above c. 800 m ASL. The landscape is typified by a collection of half dome hills (‘downs’ or ‘demi-oranges’, see Gunnel, 1998), with low-gradient streams (Figure 8). The terrain is characterised by a very thick weathering mantle, which includes unconsolidated saprolite at its top. Bauxite cappings have been reported (Gunnel, 1998), but not seen in this study. The terrain corresponds to palaeosurface interpreted by Gunnel (1998) of Late Cretaceous to Palaeocene age, i.e. having a long history of weathering combined with limited erosion. A variety of lithologies, e.g. charnockite, tonalitic gneiss and granite likely underlies this terrain, but has not been studied in detail.

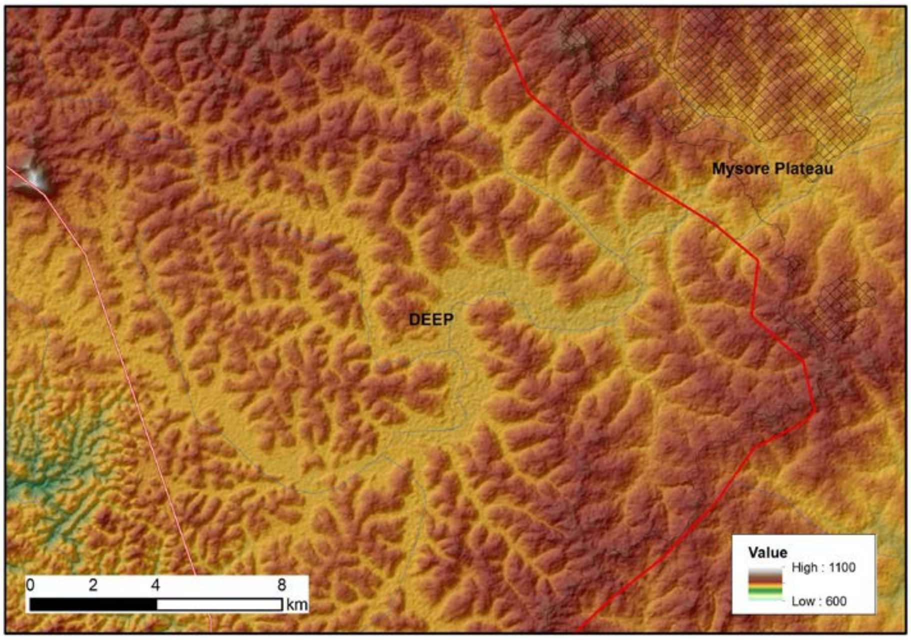


Figure 8. NASA SRTM 30 m DTM image of deep weathering with characteristic rounded hills and low-gradient streams. Location of Figure: see Figure 5.

6. Alluvium domain. Significant alluvium deposits occur along the floodplains of the Cauvery River and some of its tributaries, specifically where the river flows across low-relief landscape. Land use in this domain is quite specific, with covered in rice paddies or used for sugar cane; crops not widely grown elsewhere in the region. The alluvium occurrence on the Mysore Plateau is described below; the occurrence in the lower catchment in Tamil Nadu was not visited.
7. Lower catchment-hard bedded domain. This part of the catchment is in a low lying area (< 250 m), downstream from the Cauvery canyon, sloping gently towards the Cauvery Delta. The area generally has a low relief, with some inselbergs. The area was not visited as part of this study. There is likely a widespread but relatively thin weathering mantle, as this surface has undergone the most erosion (Gunnel 1998); it is likely there are patchy development of alluvium deposits. A variety of rocks occur within this domain. High inselberg massifs commonly composed of charnockite occur at the margins, in places giving 1500-2000 m of relief.
8. Cauvery Delta. Again, this has not been visited during this study. The delta comprises a sequence of sandstones, mudstone with minor limestone that thickens seaward, reaching a thickness of 6 km offshore (Narasimha Chari et al. 1995). Accounts of its stratigraphy are provided by Ramkukar et al. (2004), Nallapar Reddy et al. (2013). The Tertiary Cuddalore Formation, the highest lithology of the deltaic system, is known to be a productive aquifer, and has been studied in the Ponnaiyar River Basin, somewhat north of the Vauvery Delta itself (Jeevenandam et al., 2007).

In addition, the character of dolerite dykes (Section 6.5), which cross-cut all lithologies, and the regolith (Section 5) is described.

5 Regolith and Quaternary deposits

Part of the fieldwork aim was to understand the nature and distribution of the overlying regolith and Quaternary deposits, as they form the shallow aquifer, down to a depth of 10-30 m. We focus on the composition, thickness and extent of the regolith and Quaternary deposits and how these vary both locally and regionally across the four domains.

5.1 BANGALORE PLATEAU REGOLITH

The regolith on the Bangalore plateau is predominantly exposed in small tanks (reservoirs) and quarries. There is some bias within these outcrops. The tanks are generally shallow (and fairly full at the time of our field work in October 2017) and therefore did not provide complete sections of regolith down to bedrock. Conversely, quarries tend to be located where bedrock is close to surface, in areas of relatively thin regolith. Hence, it is important to consider the extent to which the exposed sections are representative of the wider area.

Well exposed regolith was studied south of Doddaballapura town (localities 3 and 5), in two small tanks (Figure 9). The sections expose *c*. 2-4 m of regolith, but no basal bedrock contact was seen. The regolith sections are light brown to maroon red coloured. The section is variable in weathering extent, with areas of granular and friable 1-2 m-sized blocks of rock to areas of sandy clay. In general, the lower 1 to 1.5 m of the section comprised weathered blocks of rock (saprock), which are elongate and continue into the upper part of the section. The upper part of the section is generally dominated by saprolite of sandy clay.

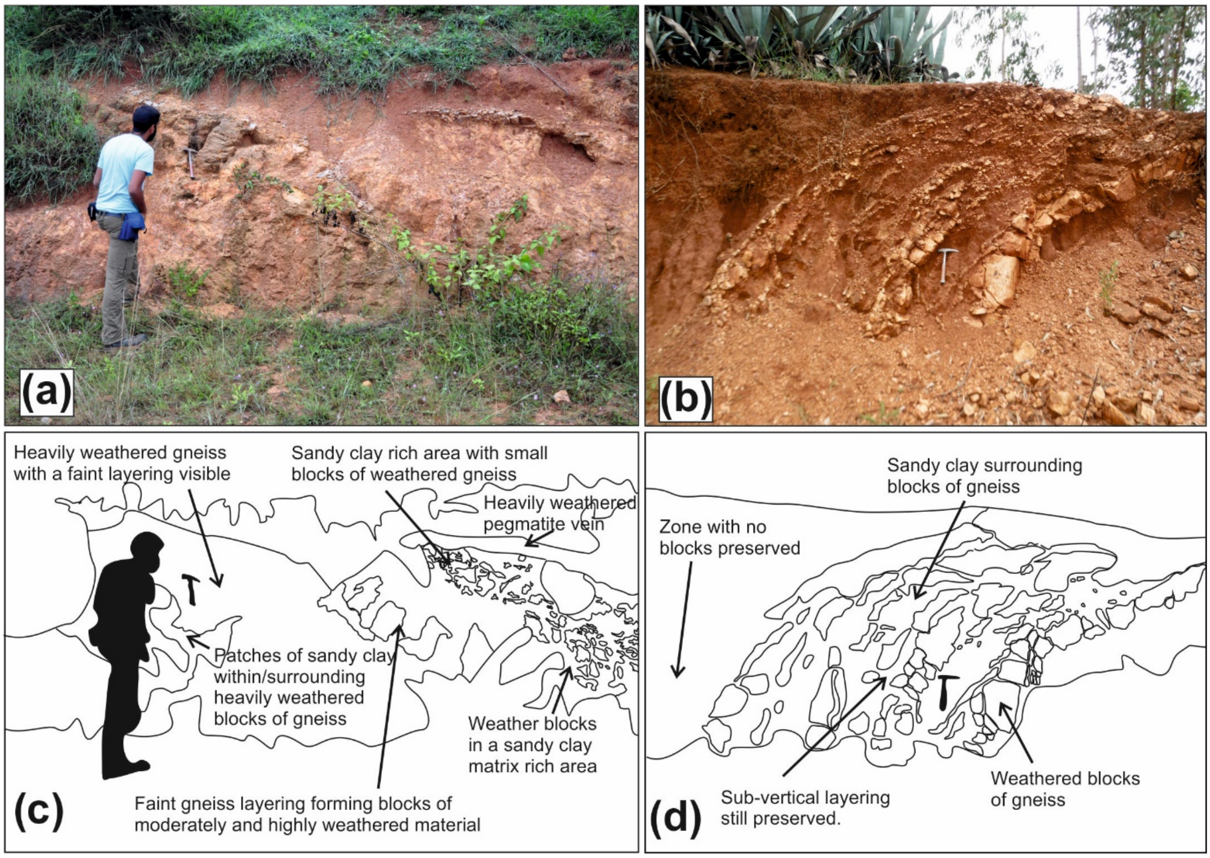


Figure 9. Photographs (a, b) and sketches (c, d) of regolith sections from tanks and just south of Doddaballapura town. (Photograph (a) is from locality 3 and photograph b is from Locality 5).

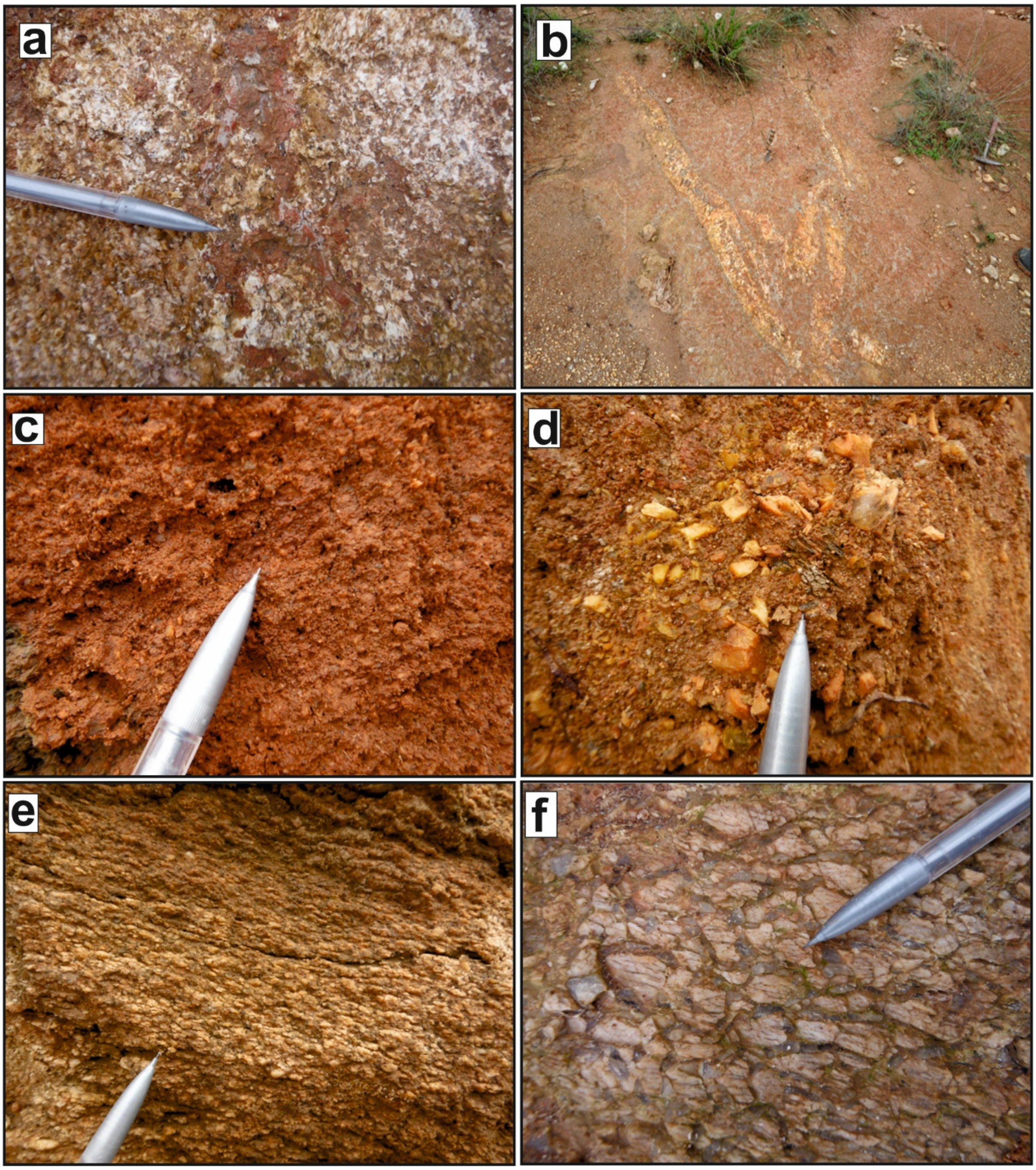


Figure 10. Photographs of various regolith sections in tanks and quarries north of Bangalore. (a) partial weathering of plagioclase to red clay (Locality 3); (b) various degrees of weathering picking out original gneiss layering (Locality 3); (c) clay-rich saprolite with iron-oxide coating grains of predominantly quartz (Locality 15); (d) sandy claeye gravel saprolite with large grains of plagioclase and quartz (Locality 15); (e) weathered gneiss – saprock (Locality 15); and (f) close up of gneiss saprock, showing weathered grain boundaries (Locality 3).

The blocks of weathered rocks contain remnant gneissic layering. The weathered rock that continues into the upper part of the section comprises crystals up to 2 cm in size, and form heavily-weathered layers within the upper sandy clay unit. There is a continuum in the weathered rock from blocks where quartz and plagioclase are still visible, but with weathered crystal boundaries (Figure 10e, f); to blocks where the quartz is surrounded by a brownish red clay. Some darker minerals are visible within the reddish clay. The blocks are observed to form sub-vertical to sub-horizontal disarticulated layers, which sit in a brownish red-coloured sandy clay matrix.

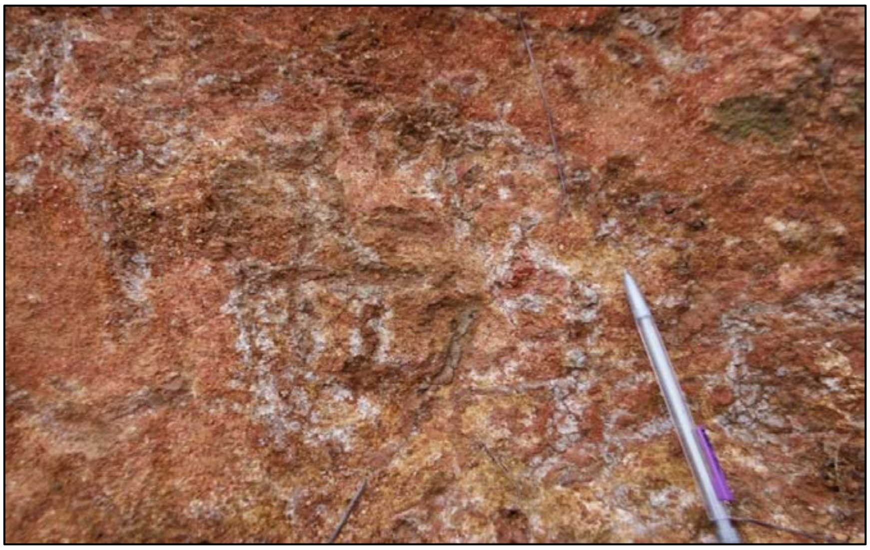


Figure 11. "Dendritic" oxidation weathering pattern within saprolite; south of Doddaballapura town (Locality 3).

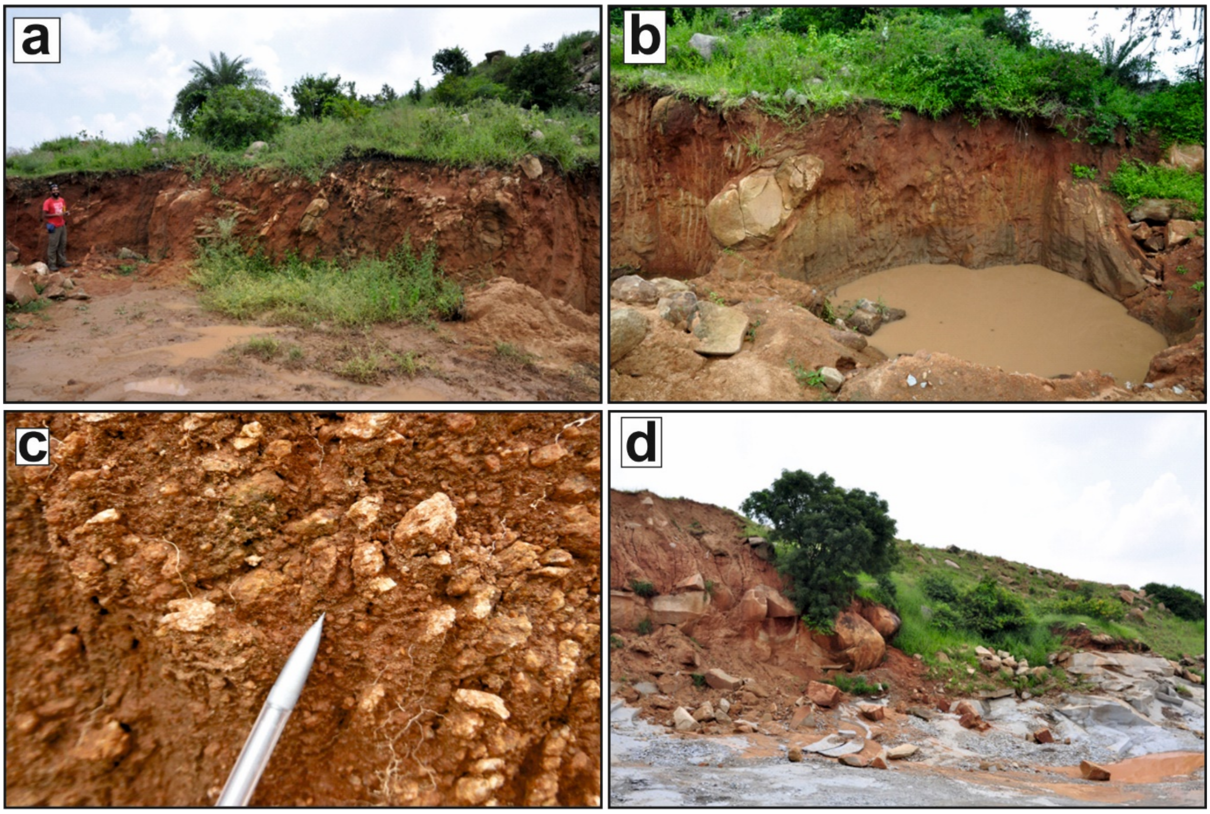


Figure 12. Photographs of relatively fresh to heavily-weathered blocks and grains in regolith sections exposed in tanks and quarries to the west of Bangalore (Locality 15). (a) Small elongate heavily weathered blocks, orientated along original gneiss layering; (b) relatively fresh isolated fresh blocks of gneiss in a sandy clay saprolite; (c) large (0.5-2 cm) grains of plagioclase in sandy clayey gravel saprolite; and (d) large fresh blocks of gneiss in basal regolith section, above fresh gneiss.

The reddish brown saprolite that surrounds and overlies the weathered blocks of gneiss comprises a maroon-red to light brown clay with 0.5-2 mm-sized, angular grains of uncoloured to occasionally iron-oxidised quartz and occasional 1-10 mm-sized grains of plagioclase (Figure 10a-d). The ratio of sand to clay in this unit varies: in most areas the unit is clay-rich, but in some areas the unit becomes dominant in sand-sized grains of quartz, plagioclase and occasional biotite or muscovite. The unit is generally homogenous with no signs of the original gneiss layering, but with occasional root traces preserved (Figure 11).

At Locality 5, some 10-20 cm wide, heavily weathered dykes occur in the regolith. The dykes are weathered to a dull maroon-coloured saprolite and comprise small pseudo morphs of plagioclase phenocrysts, now altered to clay. The weathered dykes are straight and truncate the remnant gneiss layering in the saprolitic gneiss. The boundaries between the dyke and the surrounding saproltiic gneiss appear un-fractured and relatively tight.

Regolith was also observed in quarries, where the basal contact with the underlying gneiss is exposed. In general, gneiss quarries are found on higher ground, with regolith exposed on the top of the section, ranging in thickness from 2 to 6 m, and typically comprising saprock, but little or no saprolite. Blocks of gneiss in the saprock vary from heavily weathered to relatively fresh (Figure 12, 13). The blocks vary in size and shape from 30 cm to 5 m, and from broadly equant to elongate-shaped. Similarly, to the regolith sections observed in the tanks, the blocks also sit in maroon red-coloured matrix that varies from sand dominant to a sandy clay.

The contact between the regolith and the underlying gneiss is often a remarkably sharp planar contact marked by a subhorizontal fracture, as seen in a number of quarries across the Bangalore plateau (Figure 13). Typically, the upper few metres of gneiss, directly below the regolith contact, has more frequent sheet joints (10-50 cm spaced), which are locally infilled with a thin (<2 cm-thick) clay.

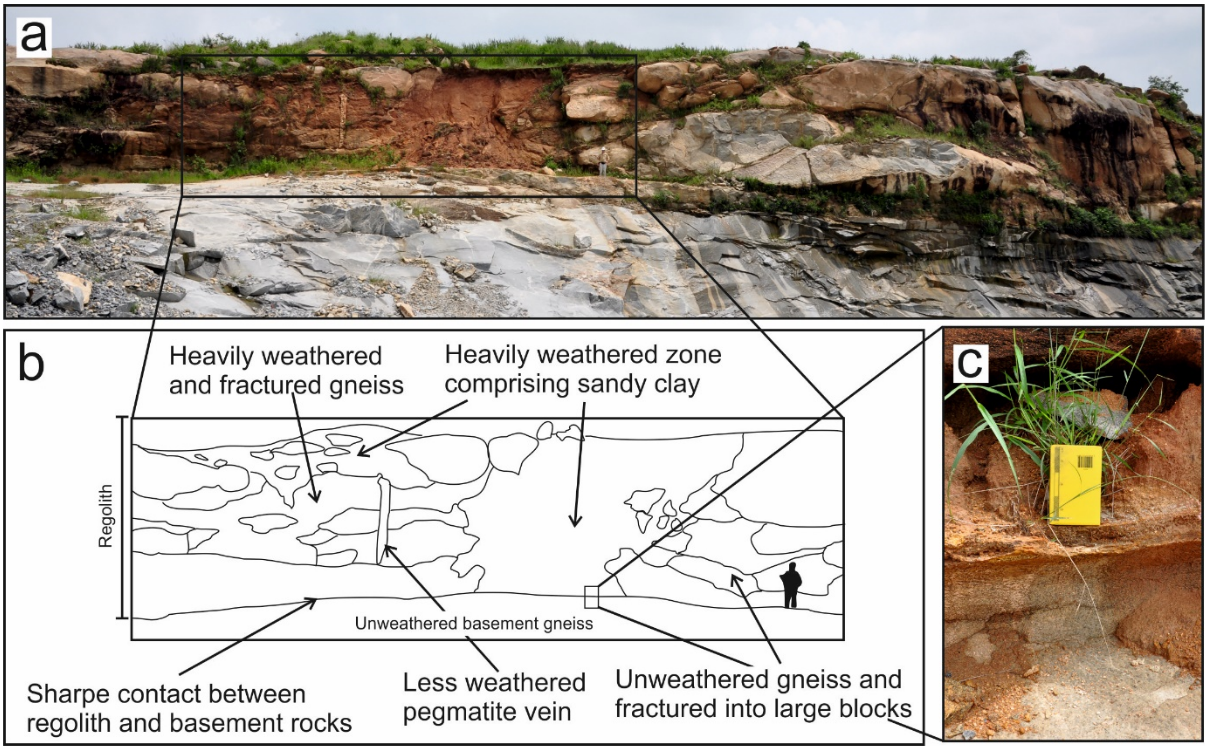


Figure 13. Photographs and sketches of regolith section exposed in quarry, west of Bangalore (Locality 15). (a) Overview photograph; (b) a sketch from central part of the photograph

showing variability and key characteristics of the regolith; and (c) a photograph of the sharp contact between the fresh basement gneiss and the regolith.

5.2 BANGALORE PLATEAU - QUATERNARY SEDIMENTS AND GEOMORPHOLOGY

In places, the regolith is erosionally overlain by a 1 to 2 m-thick gravel and sand deposit (Figure 14). The gravel and sand is poorly sorted, matrix-supported and contains sub-angular to sub-rounded clasts 2-10 cm across, of fresh to slightly weathered gneiss. The matrix is a fine to medium-grained reddish sand. No sedimentary organisation structures or sorting of clasts were visible in the deposit. The deposit is interpreted as colluvium (slope wash) deposited on the hill slopes in this area. The clasts are likely to the have been sourced from older regolith, on higher slopes rather than failure of cliff lines. Hence, the sub-rounded to sub-angular nature of the clasts is likely to the due to weathering processes rather than sedimentary transport processes.

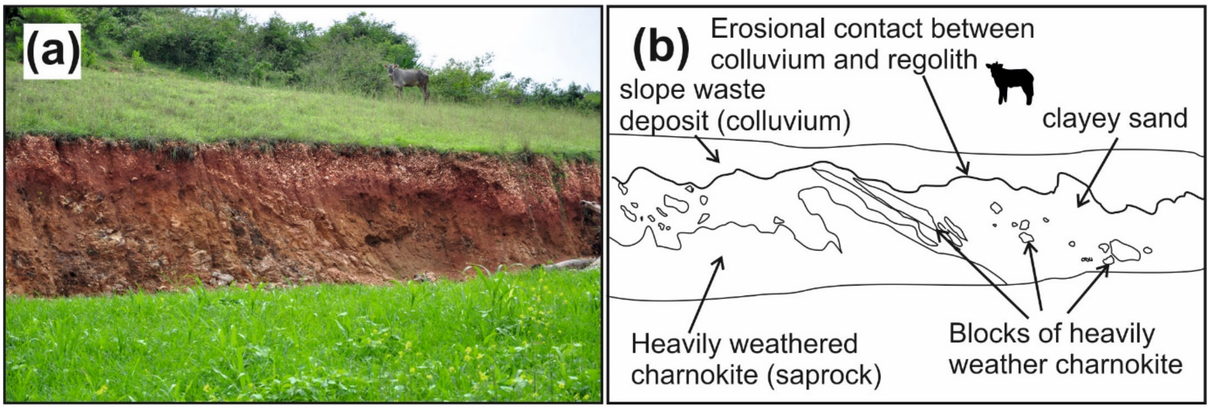


Figure 14. Photograph and sketch of the regolith section in the charnockitic bedrock area; saprock erosionally overlain by hill slope colluvium, south of Denkanikota at locality 29.

In a number of flat areas, a 30 to 40 cm-thick soil horizon is observed to have developed on top of the regolith. The soil is a red colour and contains occasional 1-5 cm clasts of gneiss and is rich in organic matter such as roots. The soil forms a graded contact with the sandy clays of the underlying saprolite. The soil and the regolith can be distinguished by a clear change in colour, as the regolith is light brownish red of the regolith, whereas the soil is a crimson red (terra rossa type colour). Furthermore, the regolith is highly variable in colour and texture, whereas the soil is homogenous in colour and texture.

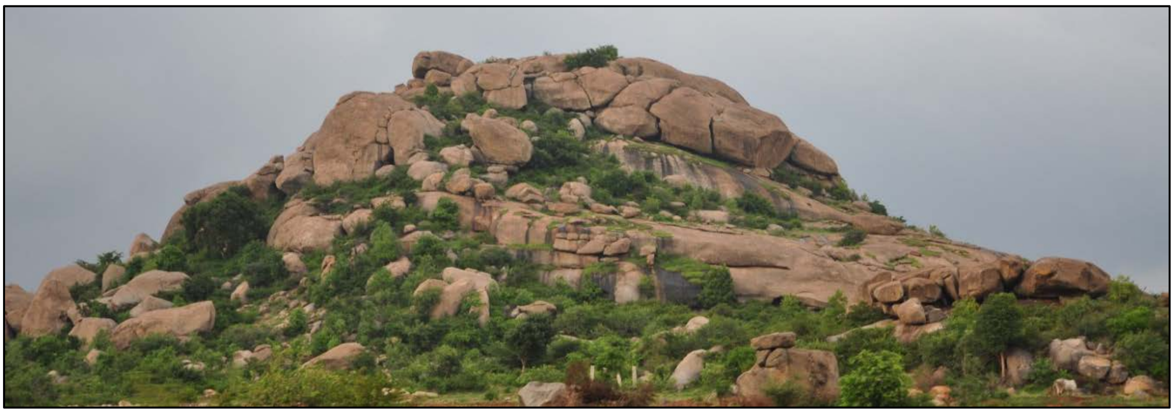


Figure 15. Tor-like inselberg, south-eastern edge of the Bangalore plateau with exposed charnockitic basement and a scattering of corestones (locality 44).

The topography of the south-eastern margin of the Bangalore plateau comprises a number of steep sided valleys, which are cutting into the margins of the plateau (Figure 3). In addition, up to c. 40 km away from the south-eastern edge of the plateau are a number of isolated inselbergs. On the tops and flanks of the incised fluvial topography and inselbergs there is significant bedrock exposure (Figure 15), which indicates a variation in regolith thickness from several metres to none. Isolated corestones are often observed strewn across the exposed bedrock (Figure 15), which are likely to have been left behind after an older phase of weathering and regolith development. On occasion, corestones are also observed away from major topography and sitting directly on regolith in flatter areas.

5.3 GRANITE REGOLITH

The granite landscape in both the Closepet granite and the Nandi Hills is characterised by isolated hills (inselbergs) on generally flat or gently undulating topography. The granite inselbergs are interpreted as the remains of an earlier plateau (e.g. Gunnel, 1998). The regolith distribution of the inselbergs across this terrain is highly sporadic. In general the regolith is observed on gentle slopes within and surrounding the inselbergs. The hills tops and steeper slopes of the inselbergs are typically barren without regolith (Figure 16a).

The studied granite regolith sections were approximately 1 to 3 m thick and a pinkish red colour (Figure 16b). The regolith sections that were studied did not show the contact with the bedrock and therefore the maximum thickness of the granite regolith is uncertain.

The regolith comprises a 1 to 3 m lower saprock comprising heavily weathered granite blocks surrounded by a clayey sand (Figure 16b). The blocks of weathered granite range in size from 50 cm to 2 m and highly variable in the degree of weathering. The original fresh granite comprises a gneissose layering, which can be observed in weathered granitic blocks and in the alignment of the blocks in the lower part of the regolith (Figure 16b). This lower unit grades into a relatively thin upper of clayey sand (saprolite), < 1 m thick. This upper unit is not always present in the observed sections. In some areas the granite saprock is composed only of a 1 to 2 m-thick unit of slightly weathered granite, where quartz, plagioclase and potassium feldspar crystals remains but their crystal boundaries have been partially weathered (Figure 16e). This is a friable unit and can be easily crumbled by hand.

Fresh blocks of granite (corestones) ranging in size from 1 to 3 m are observed within (Figure 16c) and overlying (Figure 16g) the regolith. Although the blocks of granite are generally fresh, some weathering is noted along the edge of the block at the contact with the clayey sand. The fresh and isolated corestones are predominantly observed on the top and flanks of the granite inselbergs.

Where granite is barren, weathering does continue, but any loose regolith material is eroded away, presumably by slope wash. Surface weathering features include incipient formation of grus-like weathering profiles (Figure 17a), weathering pits and shallow gullies (Figure 17b), fairly typical for granite weathering (e.g. Twidale, 2012). This type of weathering develops in the absence of soil that can retain moisture. Any rock that does weather to a finer-grained, poorly consolidated state, is washed away periodically to leave the rock surface barren.

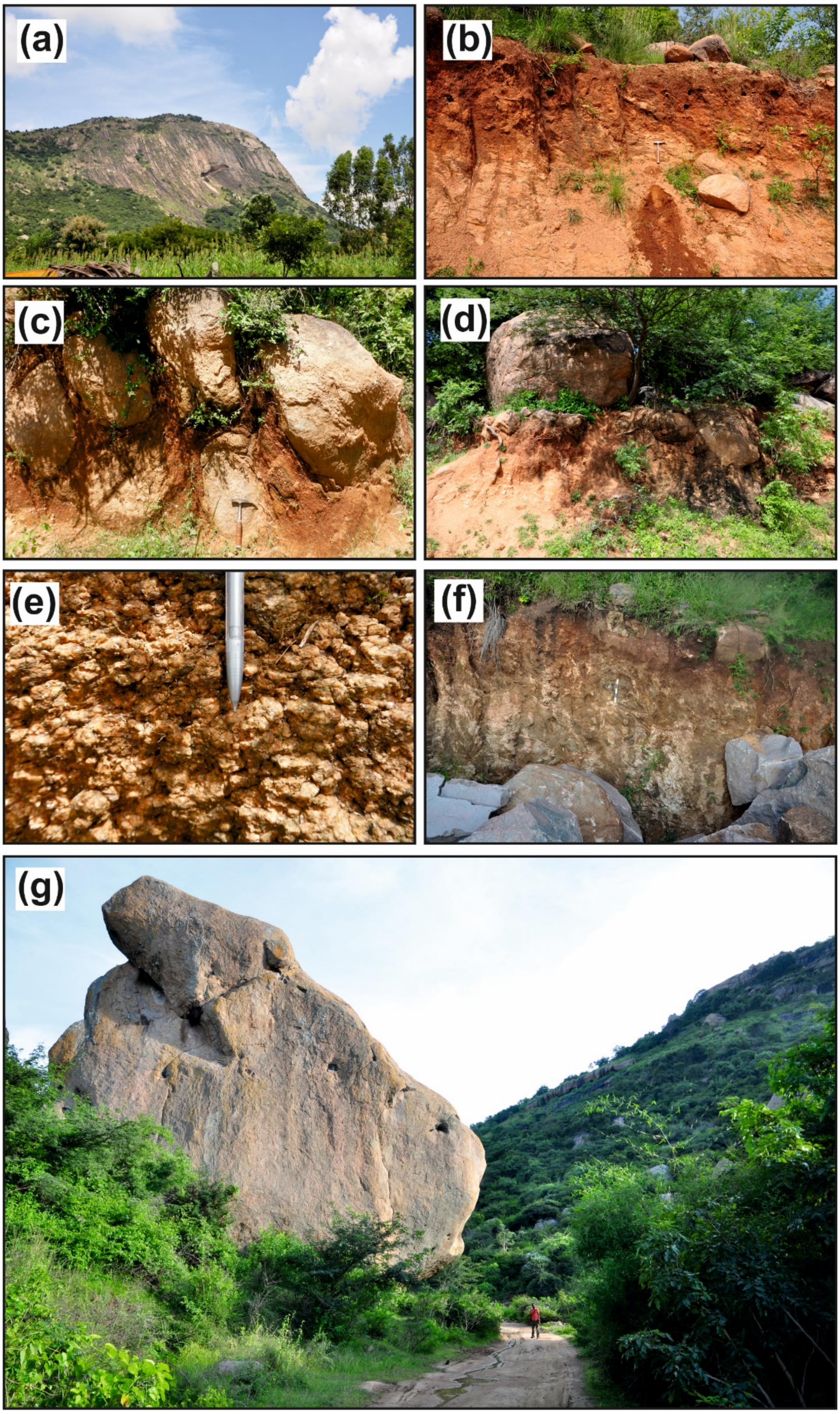


Figure 16. Granite regolith distribution and nature. (a) The Nandi Hills inselberg with regolith and colluvium on gentler gradients, and exposed granite on top and steeper slopes bedrock (locality 2); (b) granite regolith section, predominantly saprock with a thin clayey sand saprolite (locality 66); (c) fresh granite block (corestones) in regolith (locality 66); (d) fresh corestones resting directly on regolith (locality 66); (e) granite saprock, with weathered crystal boundaries but quartz, plagioclase and K-feldspar still present (locality 66); (f) granite regolith section in a col between two inselbergs (locality 83); (g) large corestone on the flanks of granite inselbergs (locality 83).

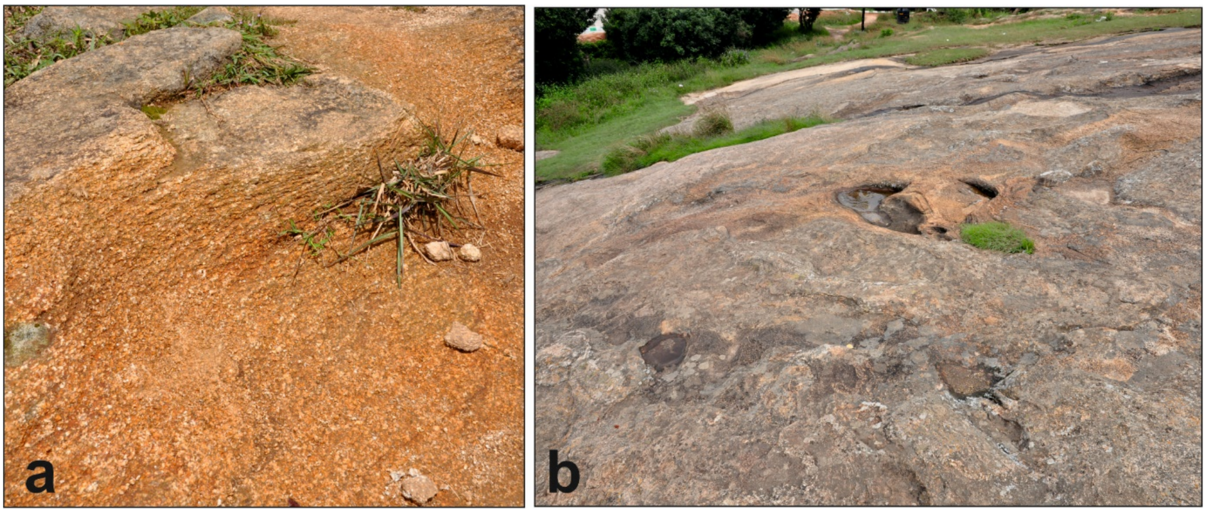


Figure 17. (a) 'Grus' type weathering on barren granite, in absence of soil. (b) Weathering pits and shallow gullies, on barren granite. Locality 2, Tipu Fort inselberg, Nandi Hills.

5.4 MYSORE PLATEAU REGOLITH

Regolith was studied in broadly two settings in the Berambadi catchment area: (i) in quarries, mostly on small hills, and (ii) in small road and stream sections, which provide an insight into the regolith and Quaternary cover on the flatter topographic areas.

The regolith exposed in quarries is patchy and variable in thickness from 0.5 to 5 m. It generally comprises three parts: (i) A fresh but heavily fractured basement gneiss unit with heavily weathered fractures (Figure 18); (ii) a saprock layer composed of heavily weathered and fractured gneiss (Figure 18); and (iii) a unit of saprolite comprising clayey sand to sandy clay matrix with heavily weathered blocks of gneiss. The thickness of the regolith across the heavily fractured and fresh gneiss is highly variable in this area from 2 to 5 m thick. The extent of fractures and the degree of weathering of fractures is highly variable across the region. Heavily weathered sub-horizontal fractures are observed, and are locally seen to be connected to the surface (Figure 19a). In addition, heavy weathering is also observed along sub-vertical fractures that connect to sub-horizontal fractures (Figure 19a).

The saprock layer contains faint but visible remnant layering but has been heavily weathered and is therefore relatively soft. This unit is observed to vary in thickness from 1 to 5 m over a small area of less than 100 m (Figure 18). The contact between the lower fresh gneiss and the saprock is a sharp boundary (Figure 18-19). The weathered gneiss unit varies from moderately to heavily weathered in nature, and is often heavily fractured with short (<1 m) interconnecting fractures. The moderately weathered gneiss retains much of its original character, comprising dark grey to black and white layers. In contrast, the heavily weathered gneiss comprises light and slightly darker brown coloured layers (Figure 19c). Harder, less weathered layers are occasionally observed, comprising large quartz and plagioclase crystals that were likely originally pegmatite veins (Figure 19c). Similarly to the Bangalore plateau, the weathering appears to have altered plagioclase to clay, but has not affected the quartz crystals. The saprolite in the Berambadi is observed to discontinuously overlie the weathered gneiss unit and varies in thickness from 30 cm to 1 m.

Across the Berambadi Catchment area there is a significant variation in the nature and extent of each unit. Generally, it is likely that the fractured fresh gneiss and weathered gneiss units are always present, as these are less susceptible to erosive processes. The upper unit of saprock to saprolite with blocks of weathered gneiss with clayey sand matrix is discontinuous in the observed quarry sections and it is likely that this is also the case the catchment scale, as this unit is more susceptible to erosion.

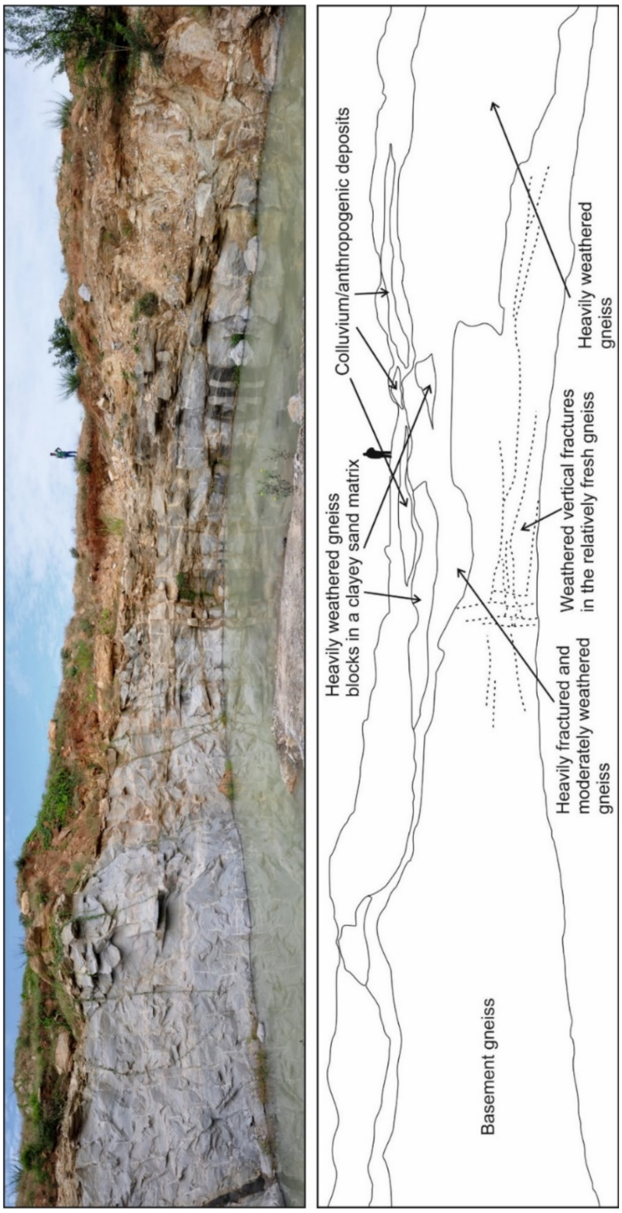


Figure 18. Photograph and sketch of regolith and basement gneiss in a quarry, NW of Gundlupete, Berambadi catchment (locality 105).

Elsewhere on the Mysore Plateau, regolith is fairly thin and mainly comprises saprock. Saprolite has been observed in flatter areas and fur4hter to the west, eg. in a tank west of Honsur (localities 191 and 193).

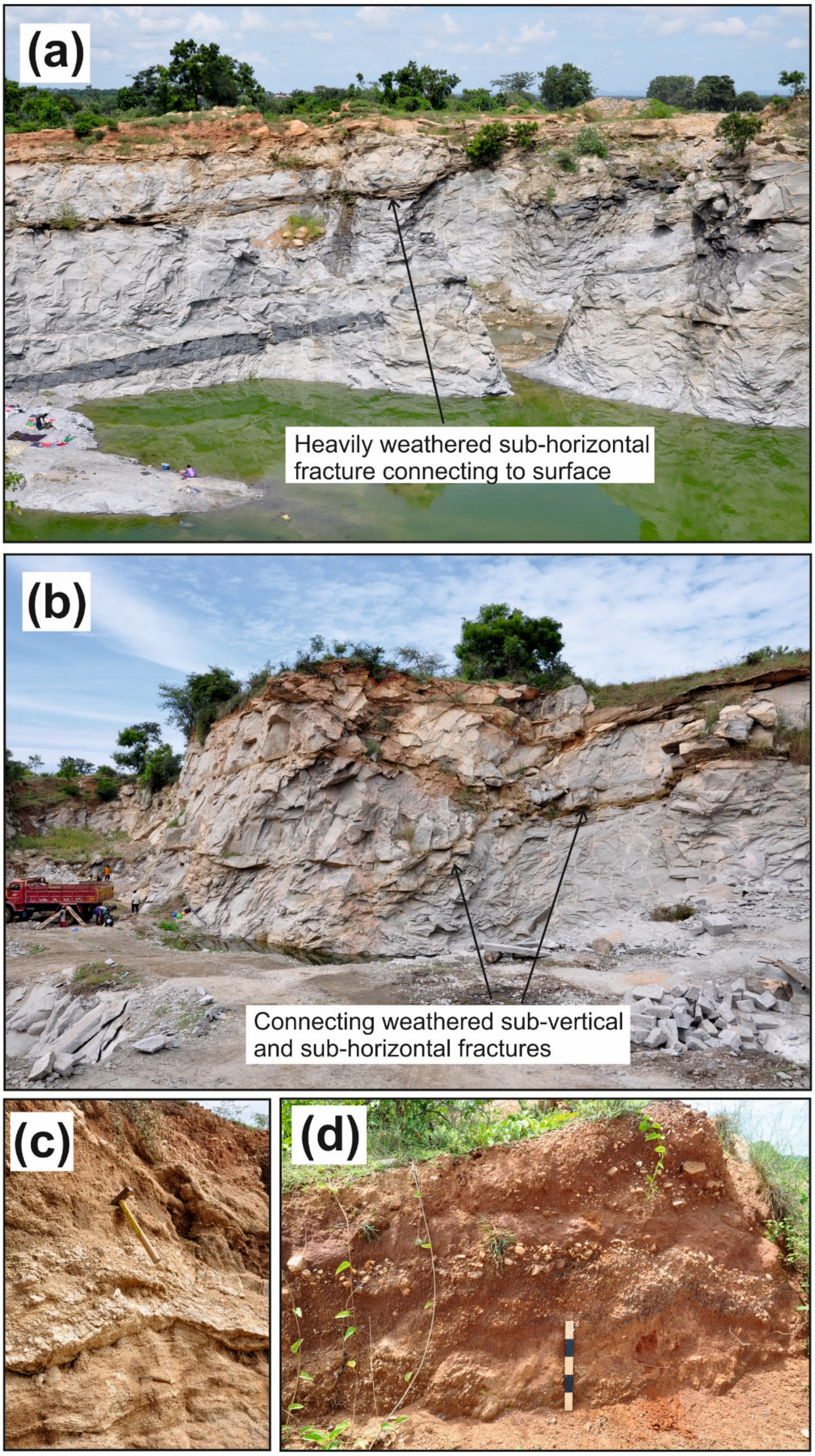


Figure 19. Photograph of weathered fractures and regolith from the Berambadi Catchment (Locality 105). (a) Heavily weathered sub-horizontal fracture that connects to the surface, in otherwise fresh gneiss; (b) connecting heavily weathered sub-vertical and sub-horizontal fractures; (c) heavily weathered gneiss with a less weathered pegmatite vein; and (d) colluvium/anthropogenic sands and gravel that locally overlie the regolith in quarries.

5.5 MYSORE PLATEAU QUATERNARY SEDIMENT

The Quaternary cover in the Berambadi Catchment is patchy, commonly absent, and in other areas is up to 3 m thick. In general, the Quaternary deposits are observed to overlie regolith. The underlying regolith comprises weathered blocks of gneiss in a sandy clay matrix. A more evolved saprolite, without blocks of gneiss is not observed in this region. Often overlying the regolith is a poorly-sorted angular gravel comprising heavily weathered clasts, which is likely to be a gravel lag suggesting sub-aerial exposure of the regolith resulting in the erosion of the upper part of the regolith. Deposits fall into two categories: colluvium on hill slopes and alluvium/lacustrine deposits on flat ground.

5.5.1 Alluvium / lacustrine deposits

The section north of Gundlupete (Locality 106, Figure 20a) occurs on flat ground, and was seen in a large drainage ditch. It comprises just over 3 m of sediment, which rests directly on regolith. The exposed regolith comprises a saprock layer composed of heavily weathered gneiss, which grades into a thin saprolite layer composed of sandy clay with blocks of heavily weathered gneiss. Along the upper surface of the saprolite is a pale white nodular, 20 cm-thick unit, with nodules varying in size from 1 cm to 5 cm (Figure 20a). The nodules appeared to have an inter-grown texture. In cross-section the nodules have a pale grey to pale red core and orangey to brownish-red rims, and have a spherical layering pattern. The nodules are cemented together with a pale white, fine-crystalline cement. In the cores of the nodules 0.5 to 1 mm grains of quartz and plagioclase are observed. Some of the matrix between the nodules is infilled with a fine-grained sand.

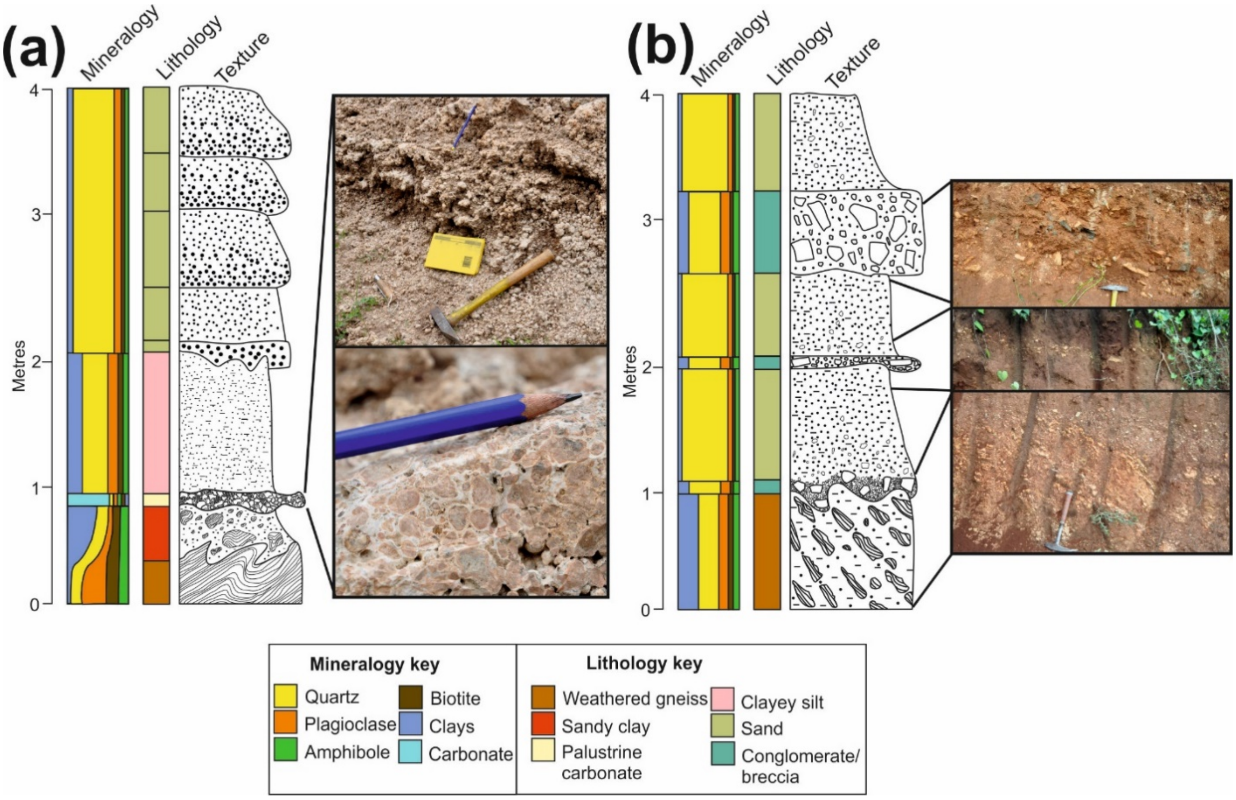


Figure 20. Sedimentary logs through the upper part of the regolith and the overlying Quaternary cover deposits in the Berambadi catchment, south of Gundlupete. Sedimentary logs (a) and (b) are of regolith overlain by colluvium, localities 106 and 120 respectively.

A positive acid test was carried out on the nodules, suggesting that they are composed of calcium carbonate. The carbonate nodules are interpreted as a secondary precipitate representing a palustrine (wetland) environment, such the edge of a small lake, under climatic conditions of high evapotranspiration (Alonso-Zara, 2003).

Overlying the regolith is a fine to medium-grained sand of 1-3 metres thickness with black organic material, which is likely to be a sub-aerial windblown deposit. There are some centimetre-scale coarse to medium-grained sand beds with normal grading, which are likely to be of a fluvial origin. The gravels that are occasionally observed within the sands, have an erosive base and poorly-developed organisation of the clasts, which suggests a short-lived high-energy debris flow-type deposit, or high-energy fluvial deposition. Other than the secondary palustrine carbonate observed locally within the upper parts of the regolith, the Quaternary-aged cover deposits are not cemented and are generally soft. We note that this deposit is rare and of very limited extent.

5.5.2 Colluvium

The section with interpreted colluvium in the Berambadi catchment was studied in a section several kilometres south of Gundlupete on the road to Bandipur (Locality 120, Figure 20b), in an area of gently sloping topography. The base of the section is regolith, which comprises heavily weathered 5-30 cm blocks of gneiss surrounded by a maroon red sandy-clay matrix. The top of the regolith forms an unconformity surface, which is infilled with a 30 cm thick gravel, composed of sub-angular clasts of weathered gneiss in a fine to medium-grained sand matrix.

Overlying this unit is an approximately 1 m-thick unit of a dark brown clayey silt to fine-grained sand without sedimentary structures. The silt unit is not cemented, and crumbles easily. Erosively overlying the silt is a discontinuous 20 cm-thick coarse-grained sand, which is conformably overlain by a 40 cm-thick medium to fine-grained sand. This is overlain by a 1.5 m-thick medium to coarse-grained sand unit comprising 2 cm thick and 5 to 10 cm long channel of fining upwards sand. The entire sand unit is a light brown to reddish colour and predominantly comprises quartz with minor amounts of plagioclase and other mafic minerals. Similarly to the lower silt unit, the upper sand unit is not cemented and is therefore relatively soft and easily crumbles.

Overlying the gravel is an approximately 3 m thick medium to coarse-grained dark maroon red angular sand, with occasional sub-angular 5-10 cm heavily weather clasts. In addition, the sand also contains millimetre size black organic material, and patches of grains with a black coating. Within this sand are multiple continuous gravel layers of 30 cm and 50 cm thick. The gravels comprise sub-angular, 5 to 30 cm-size, moderately to heavily weathered clasts of granitic gneiss, amphibolite and quartz. The gravel is matrix supported with a fine to medium-grained, dark brown sand matrix. There is some organisation of the gravel into faint 15 cm thick layers, with poorly-developed southward clast imbrication. The gravel beds have an erosive basal contact with the underlying sand.

Colluvium is also widespread on the flanks of hills composed of supracrustals. This colluvium is dominated by cobbles of quartz-rich psammite and quartzite, further described in Section 6.2.1.2.

5.6 THE CAUVERY CANYON REGOLITH ('CHARNOCKITE DOMAIN')

The Cauvery Canyon represents a distinctly different topography to the Bangalore Plateau and the Berambadi catchment. The canyon has developed where the basement gneiss has increased in metamorphic grade to granulite-facies charnockite, i.e. a significantly harder rock type than further north (see section 6.4.1: Charnockite Domain: lithology). The canyon flanks show much steeper topography than is seen elsewhere in the region.

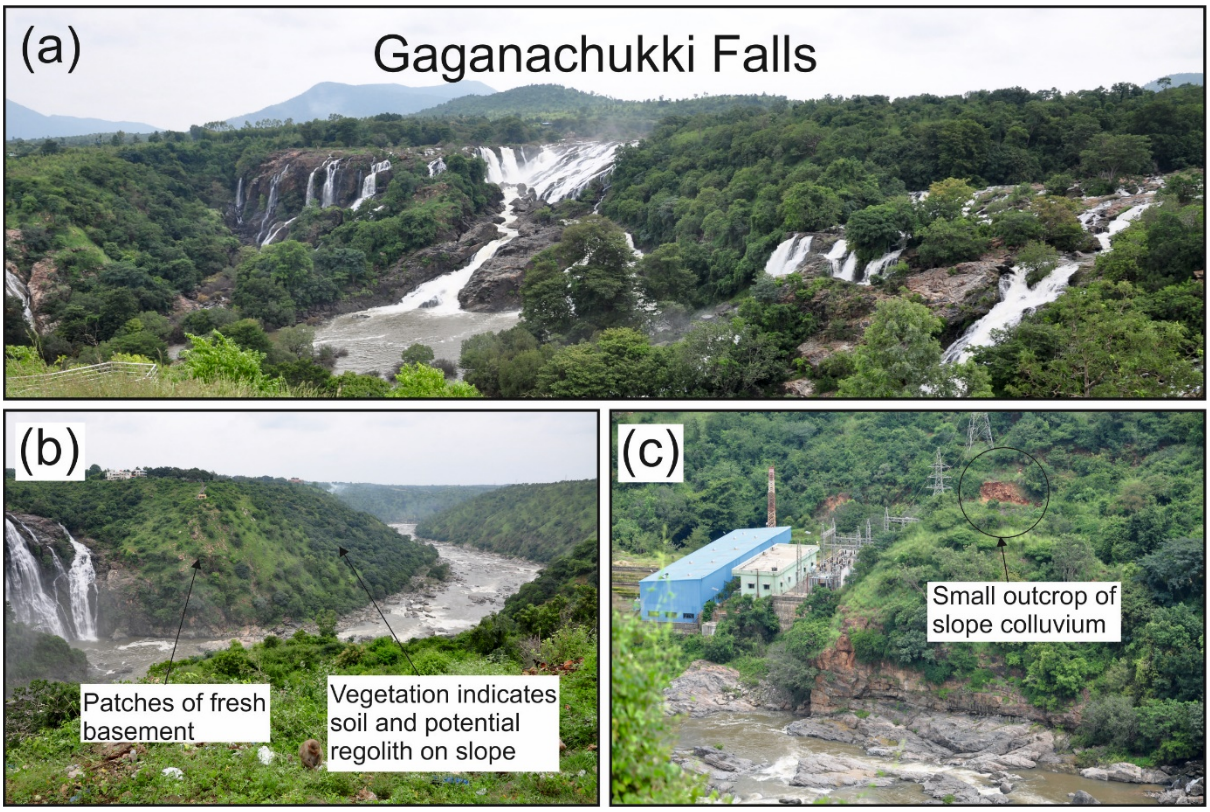


Figure 21. Photographs from the Gaganachukki Falls to show the distribution of the regolith in the Cauvery Canyon (locality 92). Including: (a) an overview photograph of the Gaganchukki Falls shows the topography of the canyon, especially the steep canyon walls; (b) patches of fresh rock and vegetated areas suggesting soil and potentially regolith preserved on the slopes; and (c) a small outcrop of regolith/colluvium on the lower flanks of the canyon.

Along the flanks of the Cauvery Canyon the distribution of the regolith appears to be very patchy. On the same canyon flank area there were patches of relatively thin (< 2 m thick) regolith and patches of exposed fresh basement charnockite (Figure 21a). Locally regolith reaches *c.* 6 m and is overlain by (or mixed with) colluvium (slope wash) (Figure 21c).

An example of the regolith overlying the charnockitic gneiss was observed in a section at the base of a steep slope near Panchupalli reservoir (Locality 44, Figure 22). The lower saprock part of the section shows remnant gneiss layering. In this unit there are still visible grains of quartz, plagioclase, biotite and pyroxene, but grain boundaries have started to weathered, resulting in loss of rock strength and integrity. Low Schmidt hammer rebound values of 12-31 are recorded in this unit, emphasising the lack of strength (fresh gneiss and charnockite gave Schmidt hammer values from 60-75).

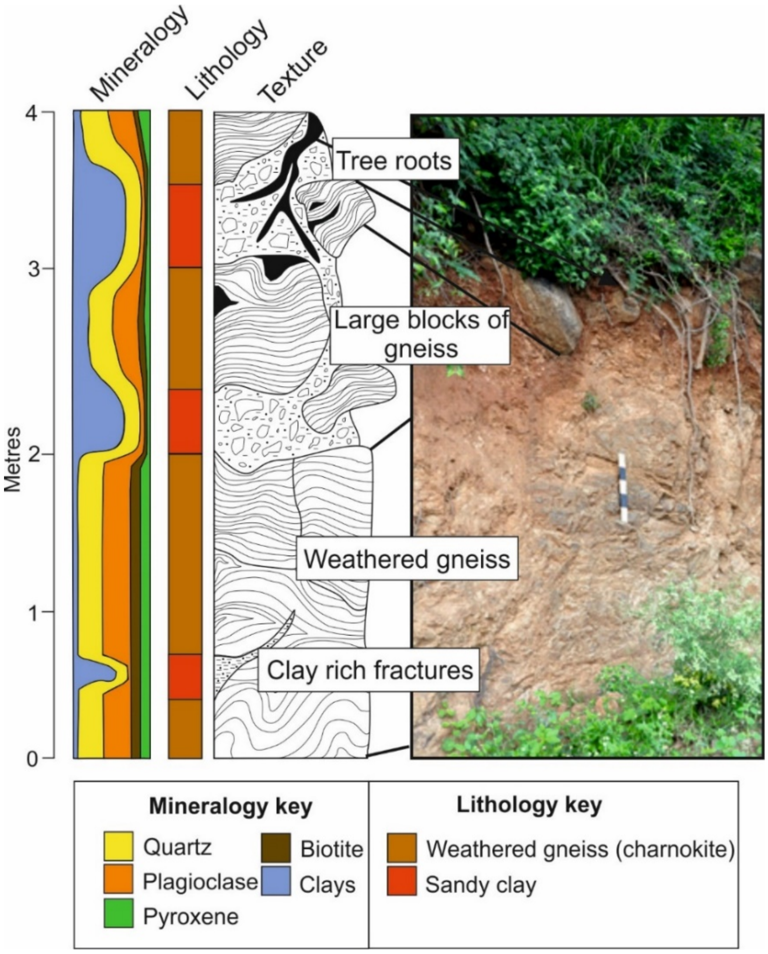


Figure 22. Sedimentary log through the regolith on the southern margin of the Bangalore Plateau in charnockitic gneiss. Estimated relative mineralogy is also shown based on field observations (road cut adjacent to Panchupalli reservoir at locality 44).

The higher saprolite unit is 1-3 m thick unit comprises blocks of weathered to fresh gneiss in a gravel-sand-clay matrix, with clasts up to 5 cm. The sand in the matrix is predominantly angular 0.5 to 1 mm grains of quartz and occasional pyroxene, which have am iron oxidation staining (Figure 22). The weathered blocks of gneiss generally contain their original mineralogy (quartz + plagioclase + pyroxene + biotite) but is friable due to partial weathering of the plagioclase. The edges of the blocks show onion-skin type weathering, which grade into the surround sandy clay matrix. On occasion, there are relatively fresh and fresh blocks of gneiss, which have sharp boundary with the surrounding sandy clay matrix. These fresh blocks are interpreted as blocks rolled down from the steep slope above: in essence here is a mix of residual regolith and colluvium.

5.7 CAUVERY RIVER ALLUVIUM

Significant river alluvium occurs adjacent to the Cauvery River and its main tributaries within the Mysore Plateau domain (Figure 23). Alluvium-covered areas are typically cultivated with rice paddies and sugar cane. Alluvium occurs mainly on recent floodplains. Higher level alluvial deposits – up to 10-15 m above present-day river level possibly represent early Holocene river terraces, now above the floodplain level because of river incision. Much of the natural river terrace architecture has been modified by construction of ‘bunds’ and other man-made structures to aid irrigation.

The 'alluvium domain' is defined as the downstream part of the Cauvery River on the Mysore Plateau. The domain runs from the central part of the plateau to the eastern edge bounding the charnockite domain (Figure 2). This part of the Cauvery River on the Mysore Plateau is observed to have the thickest and most extensive alluvium deposits. Downstream in the charnockite domain the Cauvery River is actively incising and no significant alluvium occurs (see Section 5.6). The western limit of the alluvium domain extends to the central part of the Mysore Plateau and represents the approximate point where the river system changes to predominantly smaller tributaries dominant, which is associated with a reduction in the amount of alluvium sediment.

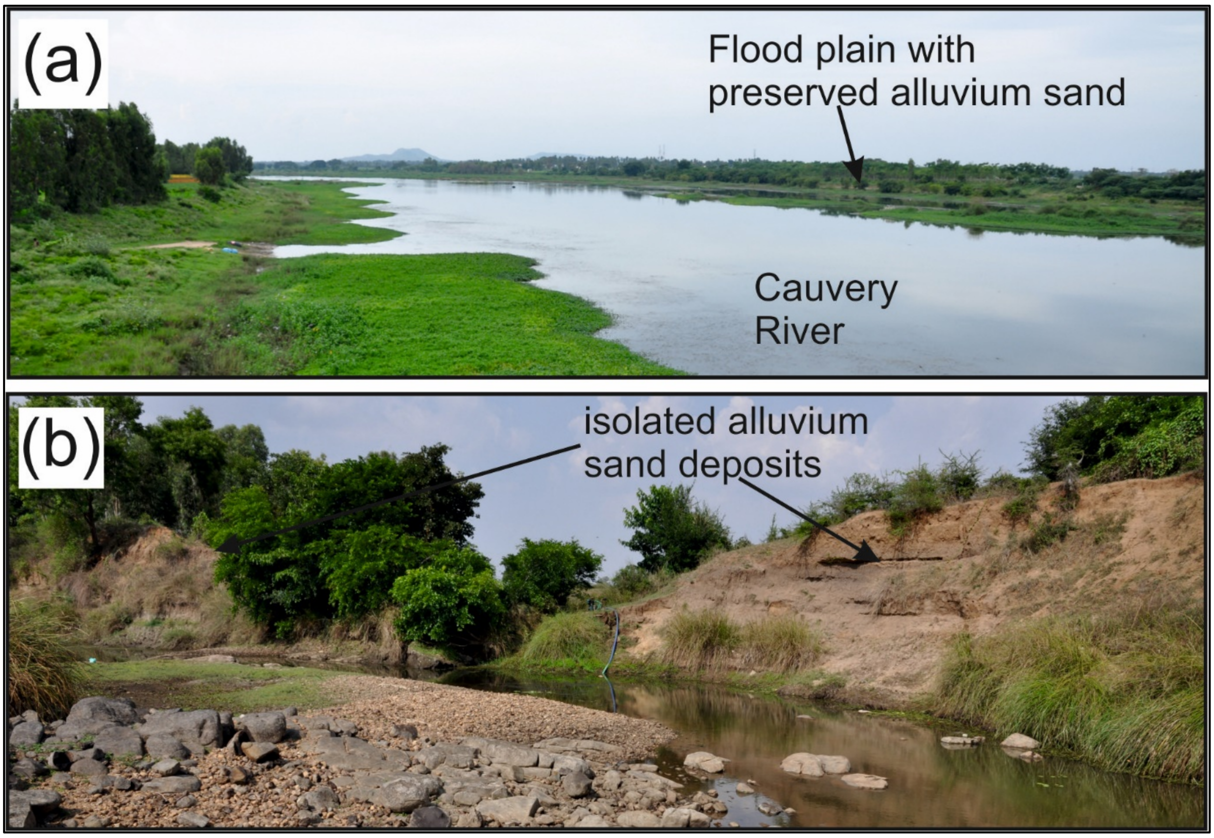


Figure 23. Photographs of the alluvium associated with the Cauvery River, including: (a) alluvial plain, near the confluence of the Cauvery and Kabini rivers, at Narasipura (Locality 104); and (b) isolated alluvium sand in a tributary to the Cauvery River 2 km SW of Hunsur (Loc. 202).

The alluvium occurs adjacent to the present river channel on surrounding flood plains, which are 1-3 km wide. The thickness and distribution of alluvium across the river and its tributaries is extremely variable (Figure 23). The alluvium deposits (Figure 23-24) medium-grained sand to silt and varies from being loose to stiff. The sand when preserved is on the banks of current river channels and comprises cross-bedding, ripples and coarser-grained sand channels of approximately 5–10 cm in size. Away from the current river channel the sand is either massive or planar-bedded. The entire unit is highly variable in thickness from less than 5 m to nearly 10 m. In general the deposits appear to be highly discontinuous likely due to subsequent fluvial erosion. On occasion lenses of clay that are 2 m thick and approximately 5–10 m long are also observed in the lower part of the alluvium deposits. Carbonate nodules and black organic matter are observed within the lower clay horizon (Figure 24).

In the main Cauvery river, the river bed itself comprises hard, fresh bedrock, consistent with continuous fluvial erosion, presumably mainly during monsoon. In smaller river, e.g. south of Honsur, (Locality 202), the river bed comprises bedrock, weathered to variable degrees.

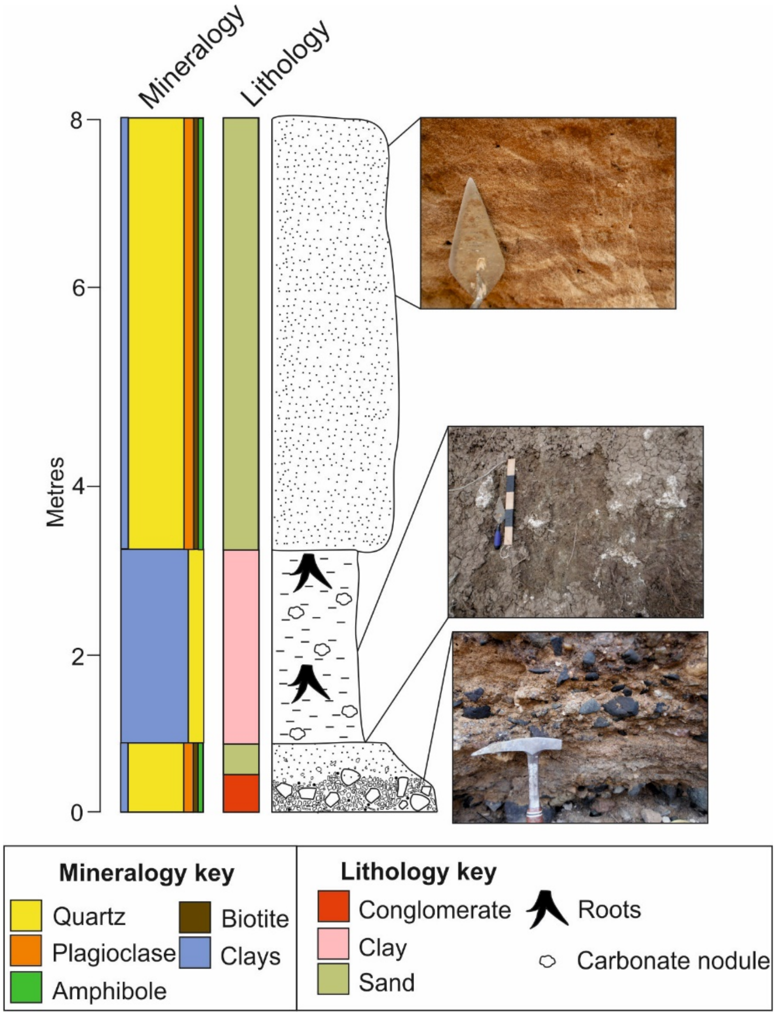


Figure 24. Sedimentary log and photographs of the alluvium sediments observed on a tributary to the Cauvery River, south of Honsur (Locality 202).

Elsewhere on the Mysore Plateau floodplains, Valdiya and Rajagopalan (2000) reported black, carbonaceous lacustrine deposits. In our study (by no means systematic) we did not observe these – but they may occur in or below floodplains not studied herein.

5.8 DEEPLY WEATHERED DOMAIN

The deeply weathered domain is found at over 900 m above sea-level along the western and south-western edge of the Mysore Plateau, rising up to the Western Ghats (Figure 2). The rolling hill topography (Figure 8) and low-gradient drainage systems characterise these high plateau areas and are notably different from the rest of the Cauvery catchment. The most significant characteristic of this domain is the thick and extensive saprolite blankets and lack of fresh bedrock exposure.

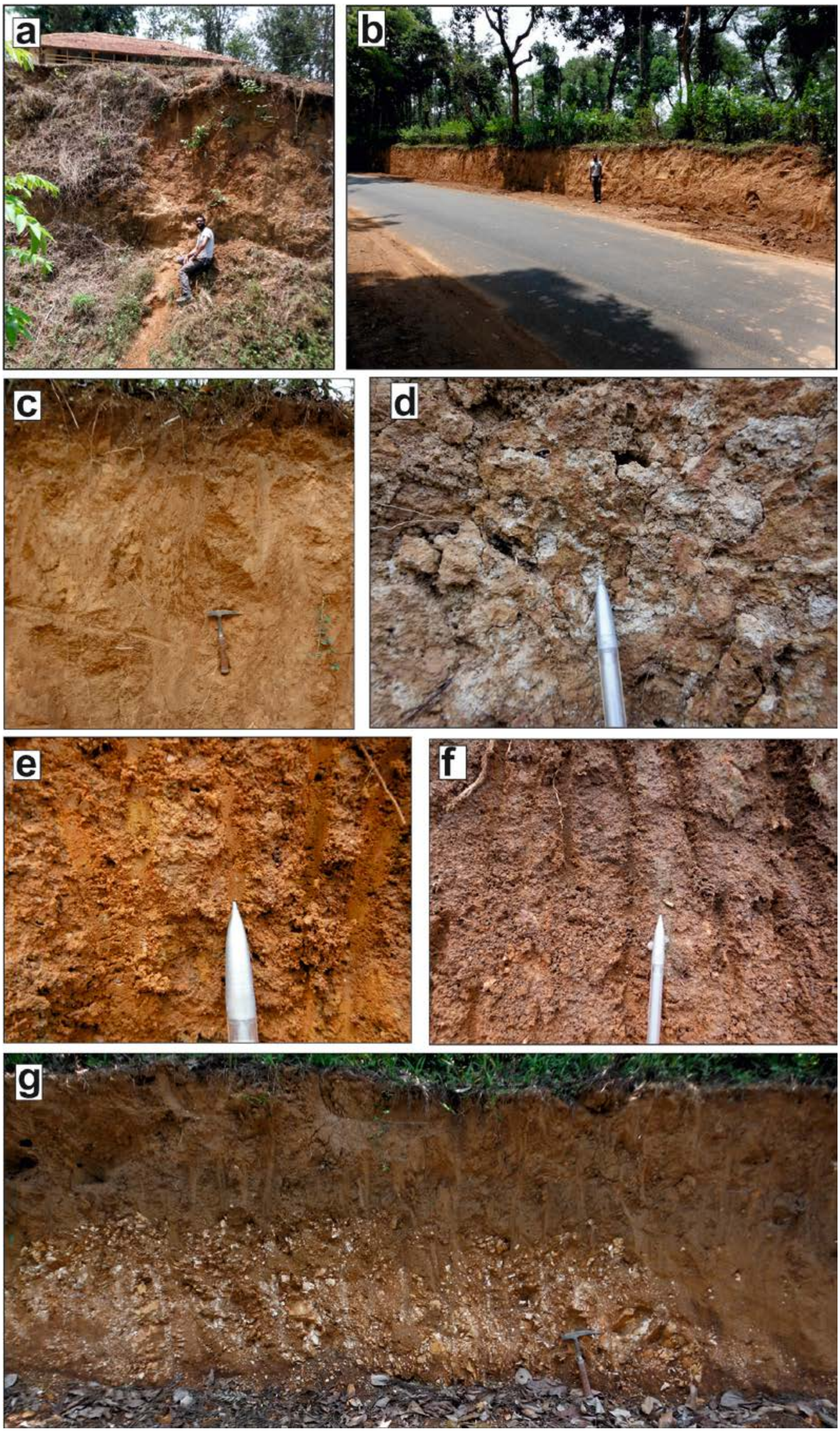


Figure 25. Photographs of saprolite in the deep-weathering domain to the west of the Mysore Plateau. The photographs come from localities 197, 198, 200 and 201.

All exposures (mainly road cuts) show thick saprolite at least 2-7 m (Figure 25a) with no exposed saprock or bedrock. The observed saprolite comprises unconsolidated clayey sand to sandy clay (Figure 25c), with some section showing more gravelly (Figure 25d). The saprolite is a reddish orange to maroon colour. On occasion there are fragments of bedrock observed within the saprolite, probably derived from pegmatite veins which appear to be the most resistant to weathering (Figure 25e). Occasional root traces occur (Figure 25b). The thick saprolite is likely to be underlain by an equally thick saprock and weathered bedrock zone, based on other regolith models (Acworth, 1987; Nesbit et al., 1997), potentially giving an overall thickness of the weathering mantle of several tens of metres.

On the eastern edge of the domain, west of Hunsur, the saprolite thins and both saprock and bedrock are exposed. In total the lower saprolite and saprock in this area is approximately 5 m thick (Locality 193). The base of the regolith comprises weathered gneiss that has little to no structural integrity. This is grades into saprock that comprises a gruss of quartz, plagioclase and fragments of gneiss, which is surrounded by sand and clay. Carbonate nodules are observed to be scattered throughout the unit. The saprock grades into the saprolite, which comprises variable amounts of sandy clay and clayey sand. Overlying the entire unit is a 1 m thick soil that is rich in organic matter and is comprised of a clayey silt. Thus, overall we see a thinning of the weathering zone from west to east, concomitant with the lowering of the topography.

5.9 REGOLITH AND QUATERNARY DEPOSITS: SUMMARY

Two major components of regolith weathering profiles are defined: (i) lower saprock unit and (ii) an overlying saprolite unit (terminology of Chilton and Foster, 1995). The lower saprock unit typically comprises weathered rock or large blocks of fresh to weathered rock embedded in a gravel, sand to clay matrix. The saprock unit generally grades into the saprolite layer where the blocks become smaller and the unit becomes dominated by a fine-grained sand to clay, with minor gravel. The saprolite is then overlain by soil, which comprises fine-grained sand, silt, clay and organic material.

The most evolved regolith is occurs in the Western Ghats, west of the Mysore Plateau, with thick (> 6m) saprolite and presumably equally thick saprock beneath, forming a continuous blanket. On the Bangalore Plateau substantial saprolite was only encountered on flat topography. The saprock comprises weathered gneiss, with clayey sand commonly developed along fractures. The saprock is only locally overlain by saprolite, comprising a gravel and sand to sandy clay with root traces preserved. The entire regolith section on the Bangalore Plateau and much of the Mysore Plateau ranges from 2–6 m thick, thickening in the western Mysore plateau to the Western Ghats to > 10 m. Lateral variation in the degree of weathering in the saprock layer is common with segments of the saprolite found within the saprock layer.

On the Bangalore Plateau, the regolith is typically bounded at the base by a subhorizontal fracture, suggesting that the base of the regolith is a relatively planar surface. The relative low clay content of saprock and saprolite in the area is corroborated by geochemical studies on the regolith in the Cauvery catchment (e.g. Sharma and Rajamani 2000, 2001; Rajamani et al. 2009) that show a relative low CIA (Chemical Index of Alteration).

In the Berambadi catchment (southern Mysore Plateau) the regolith is similarly predominantly composed of saprock with only occasional saprolite. The saprock in this area is highly variable in thickness from 1–5 m, varying from massive to moderately weathered gneiss to blocks of gneiss in a clayey sand matrix.

The regolith observed on the Closepet Batholith was extremely variable from 1 to >3 m thick, with large areas with no regolith (e.g. bare bedrock at or close to surface). The distribution of the regolith on the granite is strongly controlled by topography, with regolith absent on the granite inselberg tops and flanks, and saprock preserved on gentler slopes. The saprock comprises a clayey sand with blocks of fresh to weathered granite. In addition, fresh corestones are observed both on top of the granite regolith and on exposed fresh granite.

Finally, the regolith on the charnockitic gneiss in the Cauvery Canyon, is predominantly comprised of a saprock unit with colluvium. The saprock comprises a heavily weathered gneiss layer, overlain by a clayey sand with large (30 cm to 1 m) blocks of weathered gneiss. It is rare to find the saprolite component of the regolith in this region.

In general, across the entire study area the Quaternary deposits were of two types: (i) colluvium/slope wash, and (ii) fluvial deposits. The colluvium deposits were found on steeper slopes (> 10°) as 0.5–2 m thick deposits that erosionally overlie saprock. Colluvium typically comprises a poorly-sorted angular gravel with clasts varying in size from 1–30 cm (but locally larger) and predominantly comprising clasts of gneiss and vein quartz, with a fine to medium-grained sand matrix. Hill slopes on the Bangalore Plateau and the Granite hills are associated with patches of slope wash.

The fluvial deposits occur on flatter ground, commonly in recent floodplains or slightly higher river terraces (often modified by construction of ‘bunds’) and are composed of unconsolidated, medium-to-fine-grained sand to silt, with occasional gravel horizons and range in thickness from 1–7 m. Where observed, the fluvial deposits were found to erosionally overlie fresh bedrock or saprock. The distribution of the Quaternary deposits is highly variable across all the regions.

6 Lithology and Fracture Patterns

6.1 BANGALORE PLATEAU: PENINSULAR GNEISS

6.1.1 Lithology

The Peninsular Gneiss of the Bangalore Plateau are typically pale-grey, felsic, meta-igneous rocks of broadly tonalitic-granodioritic composition, with quartz, plagioclase and biotite as the main minerals. Mafic enclaves, likely originating as xenoliths, are common and are dominated by amphibole and plagioclase (amphibolite); ultramafic enclaves also occur but are less common. Veins, lenses, enclaves and patches of more K-feldspar-rich granitic rock occur, in particular in the south and to the west, closer to the Closepet granite. Coarse pegmatitic granite veins occur widely, but are generally only tens of centimetres wide.

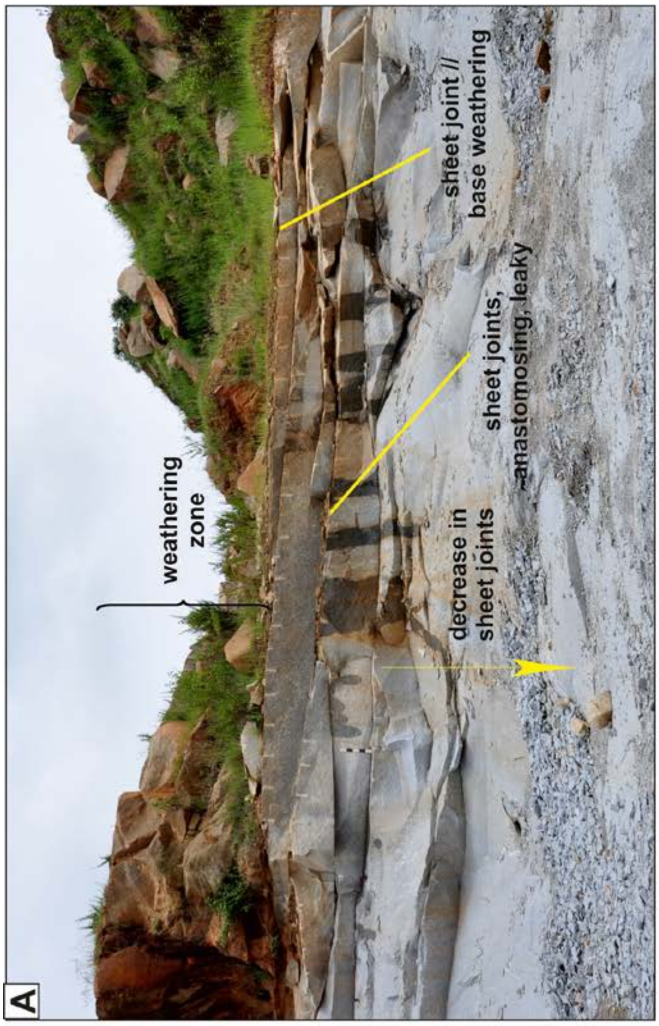
The gneisses of the Bangalore Plateau are not strongly layered. Original intrusive relationships are commonly preserved and strong gneissosity (gneissic fabric) is not prevalent. Little migmatisation has been seen, except close to the Closepet Granite. Much of the lithological heterogeneity is due to intrusive relationships, rather than deformation. One can argue that on much of the Bangalore plateau, the Peninsular Gneisses are not true gneisses; rather they are gneissose tonalitic rocks (Robertson 1999). Locally, however, more strongly sheared gneiss occurs, for instance close to the Closepet batholith in the west. Very locally, sheared-out amphibolite bodies have resulted in bands of schistose amphibolite, or mafic schist (Figure 27).

6.1.2 Fractures

Much of the Peninsular Gneiss of the Bangalore Plateau is massive with only widely spaced fractures. The great number of quarries that produce decorative stone (e.g. kitchen work tops) in the area testifies to the poorly fractured nature of the rock.

6.1.2.1 Subhorizontal Fractures.

Subhorizontal fractures are widespread below the basal weathering surface. In the outcrops observed, their vertical spacing is between 0.5–3 m, down to 5–10 m bgl (below ground level), below which their spacing increases markedly (Figure 26). In some quarries, a continuous subhorizontal fracture marks the sharp basal weathering surface (Figures 13 and 26). Further subhorizontal fractures beneath this major fracture commonly form a well-connected anastomosing network *c*. 5–10 m thick. Close to the surface (<10 m bgl) some vertical fractures have been seen that link two subhorizontal fractures. The subhorizontal fractures most likely developed as sheeting joints, related to exhumation ('unloading') and topographic curvature (see Martel, 2017 for an overview), these structures are unrelated to tectonic events. The subhorizontal fractures play a clear role in surface weathering, in allowing groundwater to penetrate and for weathering to proceed. Also, many subhorizontal fractures are leaky in the visited quarries, suggesting good (horizontal) conductivity extending below the weathering mantle itself.



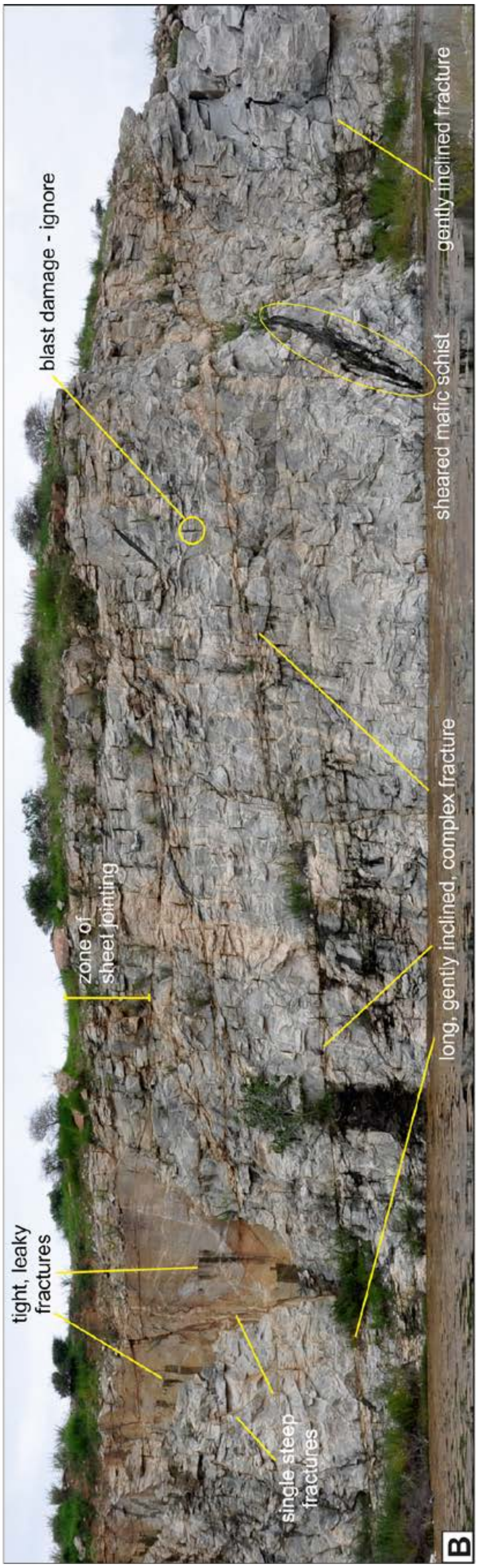


Figure 26. (A) Subhorizontal – formed by sheet jointing – in top 5 m. Note sharp basal weathered surface, marked by a sheet joint; anastomosing nature of sheet joints, and decrease of sheet joints with depth. Scale is 50 cm. Locality 9, quarry west of Bangalore. Scale bar is 50 cm. (B) Vertical fractures and gently inclined fracture within massive gneiss (to the right). Locality 6; quarry c. 9 km ESE of Dodballapur. Height of outcrop c. 15 m.

6.1.2.2 SUBVERTICAL FRACTURE ZONES – REMOTE SENSING

Lineaments, recognised on satellite and DTM imagery, suggests the presence of major subvertical fracture zones. Strictly speaking this is a rather interpretative exercise; a lineament is in itself only a linear *topographic* feature. However, the best explanation for a very straight, negative linear terrain feature is an underlying fracture zone. Assuming that the negative lineaments are fracture zones, such fracture zones can be seen to cross-cut the granite-gneiss boundary west of Bangalore (Figure 27). Several sets of fracture zones are seen at this scale: a NW-SE set, a NNE-SSE set, and an ENE-WSW set.

Fracture-related lineaments are best developed (i.e. have the clearest geomorphological expression) were the overall topography is sloping, for instance towards the Arkavathi River SW of Bangalore, and on the edges of the Bangalore Plateau (Figure 3). Conversely, the lineaments seem to 'disappear' on the flatter parts of the plateau; here the vertical fractures zones are likely to exist, but have no geomorphological expression, presumably because there is less erosion due to a lower energy environment. It is difficult to constrain the location of vertical fractures without lineament-expression on flatter areas of the plateau.

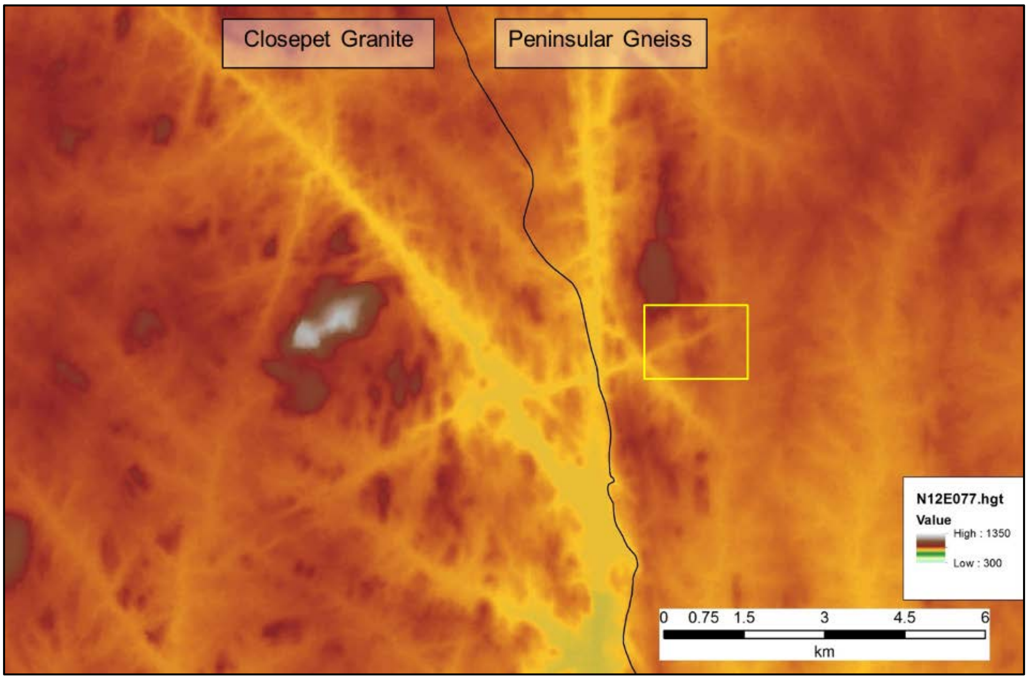


Figure 27. NASA SRTM 30 m DTM image, with hill shading of area west of Bangalore, showing lineaments, interpreted as vertical fractures zones cutting the granite-gneiss boundary. Box indicates locality quarry shown in Figure 28.

6.1.2.3 SUBVERTICAL FRACTURE ZONES – OUTCROP OBSERVATIONS

Subvertical fractures are, by their nature, loci for vegetation and deeper weathering, so are in general poorly exposed. Two subvertical fracture zones where studied at outcrop. The first one was found after a targeted search in an area quarried for aggregate near Huluvenahalli, *c.* 25 km WSW of Bangalore (within yellow box of Figure 27). The WSW-ENE trending lineament can be traced for *c.* 10 km and cuts the granite-Peninsular Gneiss boundary. In the field it forms a prominent valley, but no outcrops were found in the centre of the lineament. Outcrops 20–40 m away from the centre show vertical fractures with *c.* 10–20 cm spacing (Figure 28a). In one location (Locality 19) a vertical fracture showed weathering over a width of 40–50 cm (Figure 29b). Weathered material is a grus-like sandy gravel, easily penetrated by a knife. Within this wide zone are remnant of quartz veins, demonstrating that this fracture zone had a long history, and functioned as a fracture at depths of over 2–3 km.

Figure 28. Vertical fractures associated with vertical fracture zone in quarried area near Huluvenahalli, c. 25 km WSW of Bangalore, Locality 17 and 19. (a) Vertical fractures; (b) Vertical fracture with deep weathering.

The second field occurrence was encountered serendipitously in a quarry (Figure 29); this fracture zone had no clear geomorphological expression and was not evident as a lineament (Locality 41; 8 km SE of Denkanikota). The quarry produces decorative gneiss, and the surrounding rock is a massive grey gneiss, with few vertical fractures and a subhorizontal sheeting joint system, with a spacing of 1–5 m (Figure 29a). The subvertical fracture zone, in contrast, comprises a steep zone of intensely fractured rock. Seepage is abundant, as is vegetation growth (Figure 29b). Several interconnnected joint sets occur within the fracture zone, leaving triangular rock fragments, 10–20 cm across. All this suggest significant porosity and conductivity. The boundary of the vertical fracture zone with the massive gneiss is remarkably sharp, with massive and shattered gneiss only some 5 m apart.

Figure 29. (a) Vertical fracture zone within massive gneiss with widely spaced sheet joints. Note digger machine at top for scale. (b) detail view of fracture zone. Locality 41; Quarry 8 km SE of Denkanikota. Height of outcrop c. 5 m.

6.1.2.4 Single fractures – background jointing

Whereas the sheeting joints and the vertical fracture zones are the most prominent fracture systems within the massive Peninsular Gneiss, other fractures do occur, such as single inclined fractures and single subvertical fractures. In a large quarry complex (Figure 26B), *c.* 9 km east of Dodballapur (Locality 6 and 7), a number of such fractures were observed. Subvertical and gently inclined, single fractures occur in this quarry as an orthogonal, connected system. The fractures are discoloured, indicating relatively long-lived permeability. A long (> 100 m), shallowly inclined fracture rises from > 8 m bgl to the weathered zone, and hence connects to the shallow aquifer, as well as to the vertical fractures described above. This fracture is not considered a sheet joint, as it is not parallel to the surface (e.g. Martel, 2017); rather it is probably connected in origin with the subvertical fractures. There thus appears to be a broadly orthogonal system of widely spaced fractures in the massive gneiss. The spacing of this system is difficult to ascertain as it appears to be larger than exposed in outcrop in most quarries, i.e. in excess of 20–50 m for vertical fractures and > 20 m for subhorizontal fractures. The fracture network in this quarry may be the best example of the deeper fracture system that underlies the Bangalore plateau, but because this has only been seen in one quarry it is unclear to what extent it is representative for the wider plateau. Borehole video analysis may be better suited to constrain this fracture network.

Vertical fractures were also found in a shallow (artisanal) quarry, 6 km SE of Denkanikota (Locality 25). Tight/closed vertical fractures, filled with epidote occur here, indicating old and deep incipient fracturing. Open but tight, discoloured fractures occur here also in a disconnected, *en echelon* arrangement, with a horizontal spacing of c. 20 m.

6.2 MYSORE PLATEAU: SHEARED GNEISS (BERAMBADI CATCHMENT)

6.2.1 Lithology and ductile structures

The Mysore Plateau contains a wider range of lithologies that the Bangalore Plateau. The main lithologies are: (i) massive gneiss similar to that observed on the Bangalore Plateau; (ii) sheared gneiss, in particular in the southern part of the Bermabadi catchment, (iii) a range of supracrustal rocks that occur as lenses within the meta-igneous gneisses. These lenses are 1–5 km wide and tens of kilometres long. The supracrustal rocks include micaschist, psammite (metasandstone), quartzite, amphibolite and (more rarely) metalimestone.

6.2.1.1 MASSIVE AND SHEARED GNEISS

The massive gneiss is similar to that on the Bangalore plateau, and comprises felsic grey gneiss (mainly qtz + plag + biot) with locally mafic, amphibolite (likely to be of intrusive rather than extrusive origin) enclaves or layers probably somewhat more abundant than around Bangalore. Gneissosity in these massive gneisses is fairly well developed with a typically wispy layering of felsic/intermediate composition and locally more distinct mafic layers (Figure 30).

The sheared gneiss is also a mix of felsic grey gneiss and amphibolite, as well as some granitic material, possibility the result of anataxis (in situ melting/migmatisation). The difference with the massive gneiss is the widespread occurrence of a strongly to very strongly developed gneissosity (Figure 31) defined by: (i) alternation of felsic/intermediate layers, (ii) migmatitic layering (iii) pegmatite layers; (iv) biotite foliation planes continuous for several metres, (v) sheared out, thin (<10–100 cm) amphibolite layers; (vi) mineral foliation, e.g. by amphiboles in amphibolite and biotite in felsic gneiss. In places, the foliation is so strong that the rocks should arguably be termed gneissose schists than gneisses. In most outcrops, the gneissic foliation was steep to subvertical (Figure 31). In some places (e.g. Locality 133), the foliation is inclined.

Overall, sheared gneiss is more common in the south (Berambadi catchment), occupying 40–60% of the rock, compared to farther north near Mysore. Also in the Berambadi catchment the foliation appears to swing from an east-west trend in the south towards a more NE-SW or north-south trend north of Gundlupete. Both these issues are consistent with the mapping of shear fabrics by Chardon et al. (2008). We noted that a number of mapped units such as supracrustals in the Berambadi catchment, appear to consist of the sheared felsic/mafic meta-igneous gneiss described above.

Figure 30. Massive gneiss on the Mysore Plateau. (a) Massive gneiss with vertical sheared amphibolite layers (black streaks to the right). Locality 108; quarry 3 km west of Gundlupete. (b) Felsic gneiss with gneiss fabric and thin intermediate/mafic layers. Locality 105, quarry 20 km north of Gundlupete. Scale has 10 cm divisions. (c) Massive grey gneiss with folded granitic intrusion. Locality 184; quarry 26 km NNW of Mysore. (d) Transition to sheared gneiss: 'tramline' gneiss, high grade shearing in grey to felsic gneiss. . Locality 185; quarry 32 km NNW of Mysore

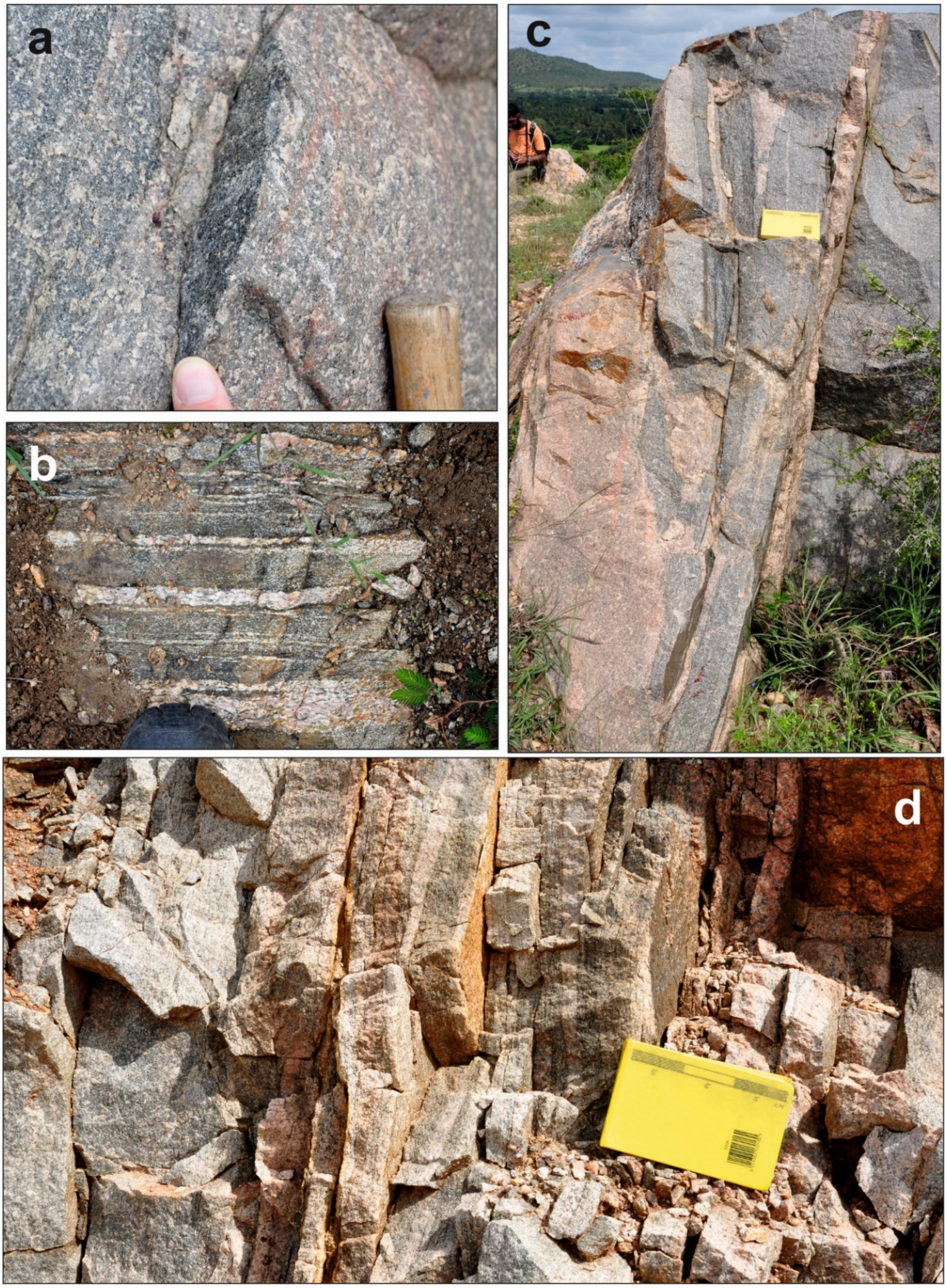


Figure 31. Sheared gneiss in the Berambadi catchment, all with steep to vertical attitude. (a) Continuous biotite foliation plane, moderately sheared gneiss. Locality 109, 3.5 km west of Gundlupete. (b) Sheared layered amphibolite and pegmatite; Locality 115, 13 km NNW of Gundlupete. (c) Moderately sheared gneiss, with folds and some continuous biotite foliation planes reactivated as fractures. Locality 111, 3.5 km west of Gundlupete. (d) Strongly sheared migmatitic gneiss, with fractures (brown discoloration) along biotite foliation planes. Locality 110, 3.5 km west of Gundlupete.

6.2.1.2 SUPRACRUSTALS

Numerous kilometre-scale lenses or belts of supracrustals occur on the Mysore Plateau, commonly referred to as Dharwar Schists or Dharwar supracrustals (e.g. Naqvi & Rogers 1987), surrounded by Peninsular Gneiss. Many of these belts have a clear positive geomorphologic expression, in that elongate hills approximately coincide with the outcrops of the supracrustal rocks (see Figure 6B); in most cases the bedding and fabric is steeply dipping.

In the course of this study a number of these where visited. In road cuts and pits, a supracrustal belt near Kunigal (locality 157) comprises schistose amphibolite, garnet-mica schist and psammite (Figure 32a). Retrogressed minerals (chlorite) occurs. The rocks occur as very thinly (centimetre-scale) bedded, with this thin apparent bedding likely the result of intense shearing. The rocks are densely fractured, with fracture spacing < 5–10cm, are fairly friable and weathered to incipient saprock at least down to 5 m bgl.

A mafic to ultramafic unit, strongly retrogressed and possibly metasomatised (with hornblende, epidote and calcite and numerous vein fills of unidentified minerals) was seen in a large a quarry 15 km south of Mysore (Locality 171). The unit was shot through by several sets of carbonate veins.

Crystalline marble (metalimestone) with thin layers and boudins of quartzite (Locality 176; Figure 32b) was seen on flat outcrops and a quarry 18 km SW of Mysore. Interestingly, regolith was thin or absent over these rocks. In contrast to other supracrustals, fracture spacing was wider.

A belt NE of Mysore, well exposed on Karighatta Temple Hill, but also in the exposed bed of the Cauvery River comprises mica-schist finely interbedded with psammite, thin-bedded quartzite and amphibolite. These rocks are similarly thin-bedded and densely fractured (Figure 32c). This unit was intruded by a non-foliated porphyritic granite. Much of the local hillslope are covered by thick (1–2 m) colluvium that is rich in angular cobbles of quartzite and quartzitic psammite (Figure 32d, e). In the lower ground nearer to the Cauvery River, a ridge of quartzite with a strong mylonitic shear fabric is well exposed as a low upstanding ridge (Figure 32f).

The apparent contradiction of relatively soft and friable supracrustal rocks (compared to the more massive gneiss surrounding these units) forming upstanding hills and ridges, can be explained by the observed colluvium and the weathering characteristics of the rocks. The quartzite and quartz-rich psammite to a lesser degree are less susceptible to weathering than the feldspar-bearing gneisses. Commonly it is strata of this lithology that forms the ridges (Figure 32f) or spines of larger hills. Colluvium, rich in quartzite or quartz-rich cobles mantles other, more easily weathered lithologies such as mica-schist. This colluvium itself is also resistant to weathering. The cobble size implies it is also resistant to slope wash, in contrast to the finer grained saprolite that develops over feldspathic gneiss. Thus, the colluvium forms a protective carapace that overlies more susceptible units such as the mica-schist. Thus, overall, the weathering-controlled denudation of the supracrustals is marginally slower than the feldspathic gneisses.

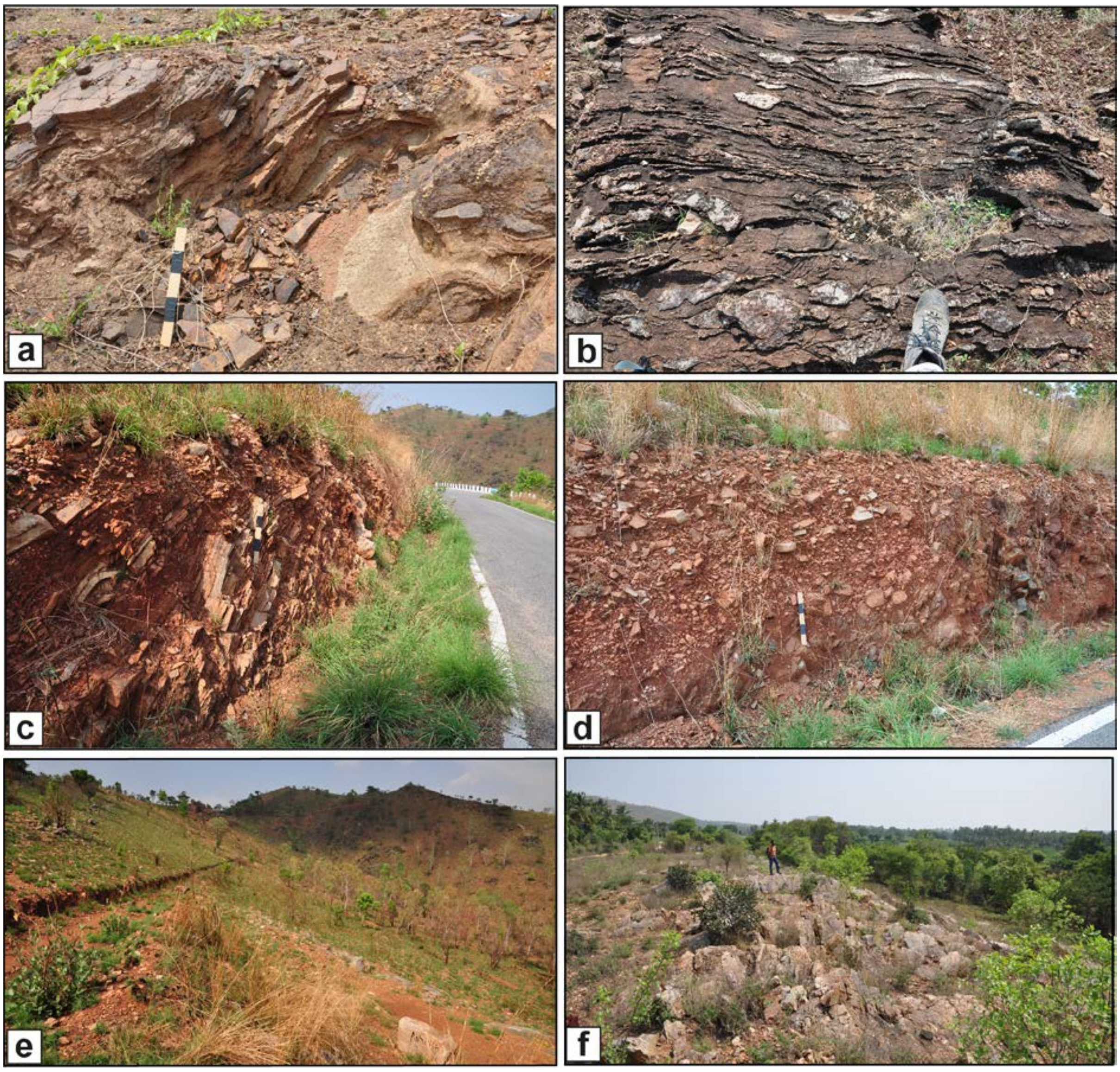


Figure 32. Supracrustal rocks on the Mysore Plateau. (a) Thinly layered amphibolite, garnet-mica schist and psammite; sheared, fractured and weathered. Locality 157, Pit next to road, south of Kunigal. (b) Metalimestone with layers and lenses of quartzite. Planview; bare rock surface, no regolith. Locality 176, SW of Mysore. (c) Thinly bedded/sheared psammite, with minor mica schist, with steep dips. Locality 168; Karighatta Temple Hill, 15 km NNE of Mysore. (d) thick colluvium, rich in quartz-rich psammite clasts. Locality 168. (e) Hilly relief underlain by supracrustal sequence. Locality 168. (f) Upstanding ridge of steeply dipping quartzite beds. Locality 162, adjacent to Cauvery River, 14 km NNE of Mysore

6.2.2 Fractures

6.2.2.1 FRACTURE IN MASSIVE GNEISS

The fracturing in the Berambadi area is closely related to the earlier shearing. In the massive gneiss, fracturing is somewhat similar to that in the Bangalore area. Subhorizontal sheeting joints are well developed broadly parallel to the ground surface and abundant near the surface (with spacing of 1–2 m) and decreasing in abundance with depth (Figure 33). Again, these fractures may have an anastomosing pattern.

Figure 33. (A– top) Gently inclined, to subhorizontal fractures. Fracture in centre has been weathered and contains 5-10 cm thick layer of grus-like sand-gravel material. Locality 110; Small abandoned quarry on hill, west of Gundlupete. (B – bottom). Set of subhorizontal sheet joints in massive gneiss. Note diverging set: a top set parallel to the topography, and a lower set showing doming. Locality 184; Large quarry 26 km NNW of Mysore.

Some sheeting joints occur as a group of 2 or 3; in one case this led to the development of a deeply weathered zone some 10 cm thick, well below fresher rock. Compared to Bangalore, however, vertical fractures (at depths > 25 m) are more common, and occur broadly parallel to foliation planes in even slightly sheared gneiss. Overall, the ‘background’ jointing network in the massive gneiss of the Mysore plateau is somewhat denser than on the Bangalore plateau, as far as can be observed in the upper 25 m (Figure 30a, 33).

6.2.2.2 Fractures in sheared gneiss and supracrustal rocks

In more strongly sheared gneiss with better developed foliation, fracturing becomes much more intense (smaller spacing). Foliation-parallel fractures, usually steeply dipping, are particularly common, and developed preferentially along continuous biotite-foliation planes, evidently exploiting a readily available relatively weaker plane (Figure 32 and 35). Where the spacing of the vertical fractures is less than 10–50 cm, fractures normal to foliation appear to link the foliation-parallel fractures ('ladder fractures'). The fractures have broadly the same spacing as the foliation-parallel set, creating an orthogonal fracture network with approximately cubic blocks. It is possible that these later ladder fractures become more abundant closer to the surface (like sheeting joints) but this could not be confirmed, as no deep enough outcrops were available for comparison. Broadly speaking, the more intense the gneissic layering, the more dense the fracture network is. Within well-fractured, sheared gneiss however, continuous sheeting joints have not been observed, presumably because the surface-parallel stresses required for sheet jointing cannot build up (Jahns, 1943; Martel, 2017).

Figure 34. Strongly sheared gneiss, with vertical fractures parallel to foliation and abundant 'ladder' fractures normal to foliation. Some layers are more deeply weathered than others (note tree). Locality 133, dolerite quarry, 14 km east of Gundlupete.

There is no evidence in the Berambadi catchment for major fracture zones or recti-linear lineaments (and associated discrete fracture zones); curvilinear lineaments appear to be associated with lithological layering, rather than fracturing.

Fracture networks in many supracrustal rocks are similar to those in sheared gneiss, likely because both rock types have narrow spaced (<10 cm) lithological layering (compare Figure 32 and 35).

6.3 GRANITE DOMAIN

6.3.1 Lithology

Much of the granite is homogeneous coarse granite, with cm-scale K-feldspar phenocrysts in a matrix of plagioclase, quartz and biotite and with minor amphibole. Occasional xenoliths of mafic gneiss occur. In the southern part of the Closepet Granite, however, the boundary with the surrounding Peninsular Gneiss appears more gradual with magmatic rocks, with evidence of magma mingling and abundant xenoliths of gneiss (see also Moyen et al., 2003).

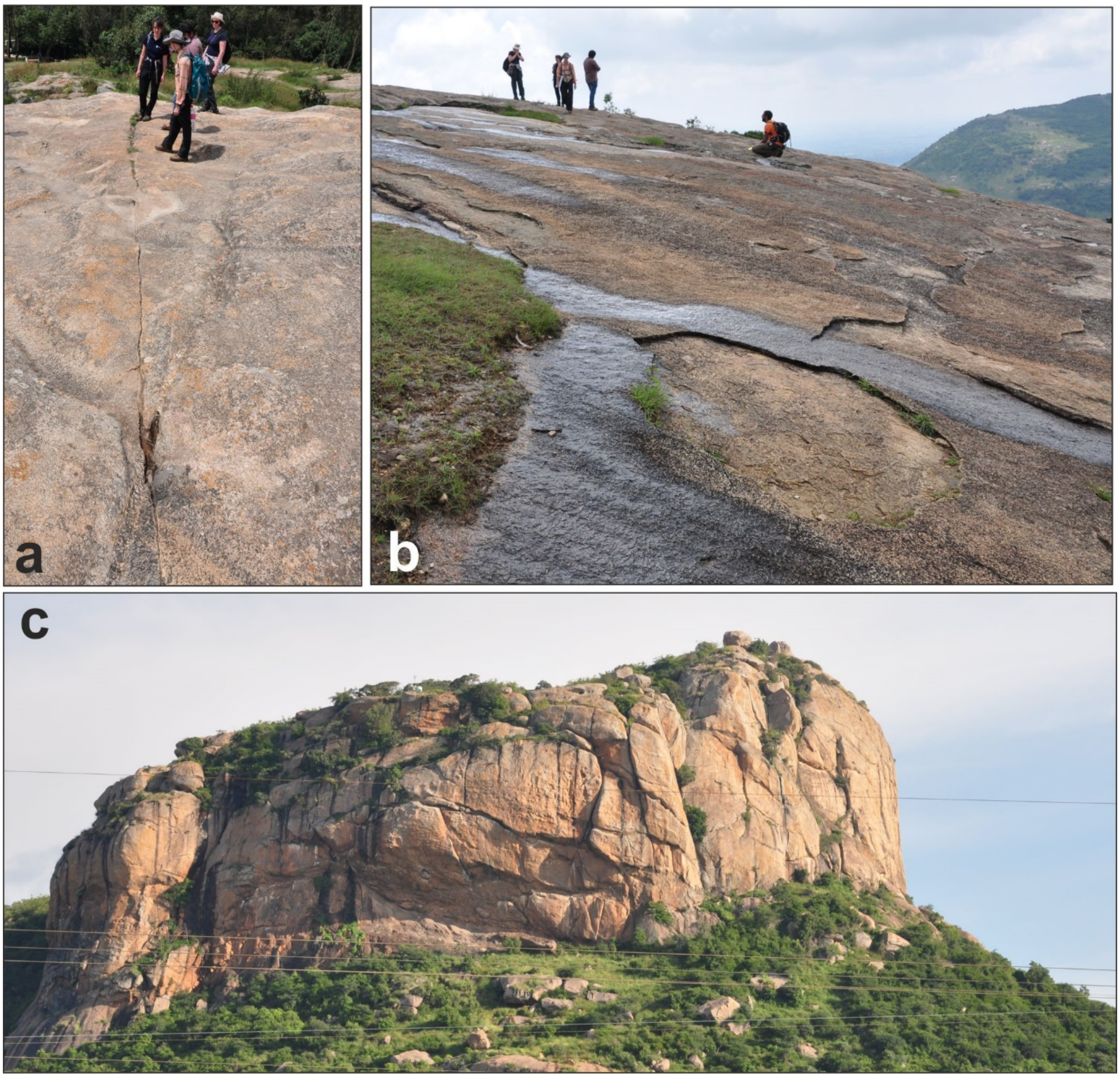


Figure 35. (a) Single, tight vertical fracture in granite. Locality 2, Tipi Fort, Nandi Hills. (b) Incipient, poorly developed sheet jointing in granite, same locality. (c) View of granite inselberg, with widely spaced horizontal and vertical fracture, southern part of the Closepet Granite, c. 9 km SW of Kanakpura.

6.3.2 Fractures

Granite is typically massive compared to gneiss, with few fractures. Sheeting joints do occur, but again are rare compared to within the gneiss, with flanks of inselbergs free of joints over stretches of several hundreds of metres (Figure 15a, 35). Even on strongly convex curving surfaces, sheet jointing is rare to absent, or only involves thin sheets (Figure 35b). Single vertical fractures in granite are very rare and where observed are unconnected to others (Figure 35a). Large-scale vertical fracture zones are likely to occupy linear valleys in between inselbergs; these have a spacing of >1 km. No vertical fracture zones in granite have been studied in detail.

6.4 CHARNOCKITE DOMAIN

6.4.1 Lithology

Charnockite is used here as a general term (following local usage), covering a range of granulite-facies lithologies, which includes charnockite *sensu-stricto* (a rock comprising quartz + feldspar + hypersthene), but also other granulite-facies rocks with different compositions, such as enderbites, khondalite and mafic granulite. The protolith of the charnockites is a suite of TTG (tonalite-trondhjemite-granodiorite) gneiss, together with more mafic and some metasedimentary rocks (khondalite), (Naqvi and Rogers, 1987; Peucat et al., 2013). The transition to the lower-grade, amphibolite-facies Peninsular Gneiss to the north is widely seen as gradual, rather than marked by a distinct shear zone (Naqvi and Rogers 1987). The important differences between the charnockite and the amphibolite-facies Peninsular Gneiss for the purposes of this study are:

- The mafic minerals in charnockite are typically pyroxene ± amphiboles, rather than micas; in the Peninsular Gneiss the mafic minerals are biotite ± amphibole. The charnockitic rocks thus contain less if any hydrous minerals;
- Charnockite is considerably harder than Peninsular Gneiss. Schmidt Hammer rebound values are in the order of 70–74, as opposed to 60–65 for biotite-bearing Peninsular Gneiss;
- The texture of the rock is more ‘indurated’ and compact. Pseudotachylite has been observed, attesting to brittle behaviour under high confining stresses.

The weathering behaviour and the resultant weathering profile is potentially different (see section 5.6). On the one hand, pyroxene should be chemically less stable under atmospheric conditions than its more hydrous counterparts according to the weathering series of Goldich, (1938); this appears to be offset however by the more indurated, compact nature of the rock, which impedes fluid infiltration along grain boundaries.

6.4.2 Fractures

No systematic study of fractures in the charnockite was undertaken, in part because few quarries exist in this rock, so the following relies on only a few natural and road cut outcrops. It is clear from the DTM that large, long fracture zones exist (Figure 7), with a dominant NNE-SSW orientation and subsidiary sets at other orientations. These fracture zones have controlled the development of the tributaries of the Cauvery River in the Cauvery canyon domain, although the Cauvery River itself cuts right across this trend.

One particular feature of the outcrop-scale fractures is that only in the isolated charnockitic rocks were isolated, disconnected fractures observed, possibly indicating a high fracture toughness of the granulite-facies rocks (Figure 36a). Many fractures are tight and filled either with pseudotachylite (a glassy melt rock) or epidote (Figure 36b, f), indicating that these fractures developed when the rock was still deeply buried. These fracture fills are still present close to the surface, so that such fractures do not appear to contribute to enhanced permeability. Fracture patterns observed appear to comprise multiple cross-cutting sets of joints, typically resulting in triangular or rhomboidal blocks (Figure 36d, e).

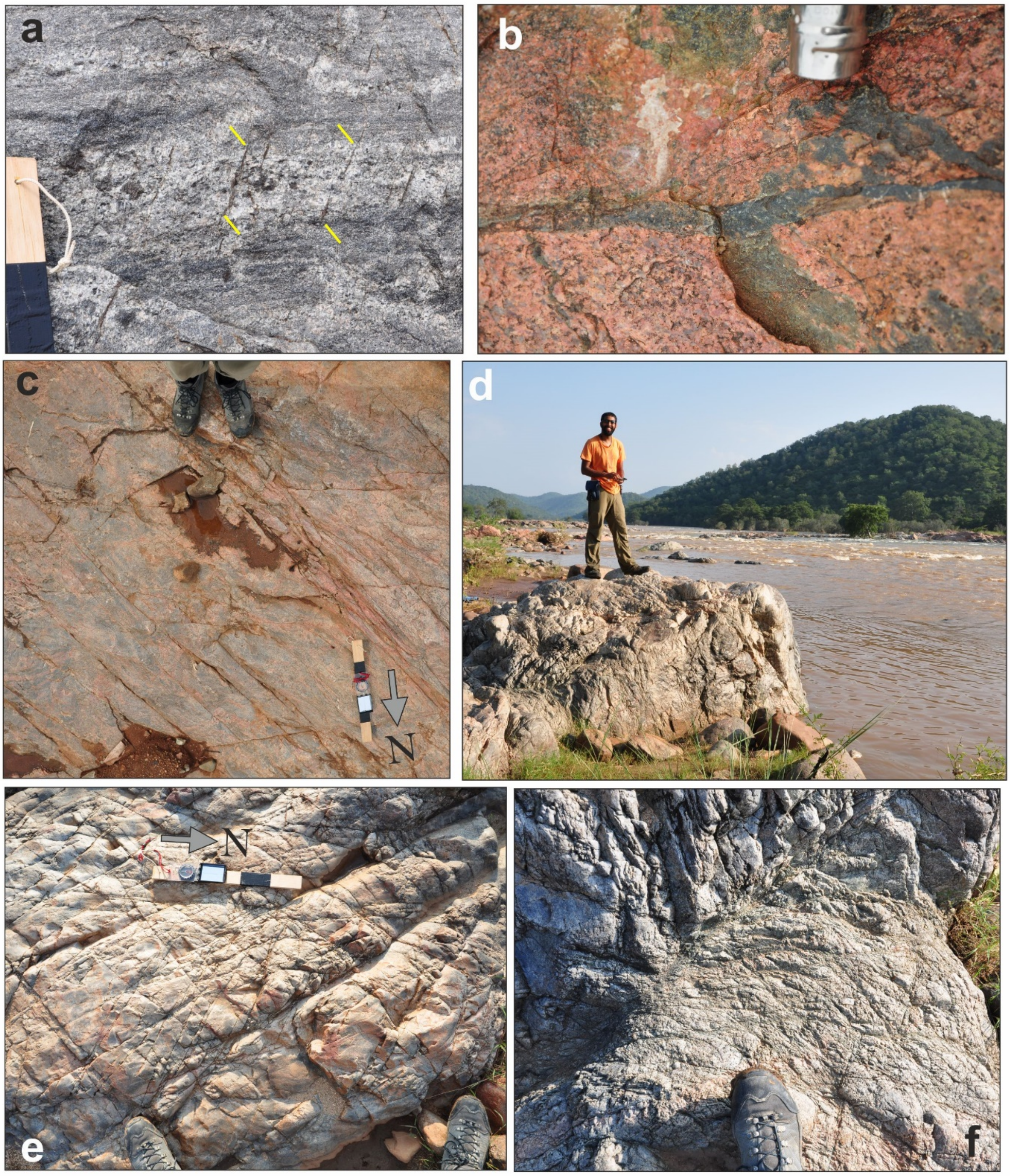


Figure 36. Fractures in granulite-facies gneisses ('charnockite'). (a) Isolated, non-connected fractures (yellow pointers), road cut, next to Pacnhapalli reservoir, Locality 46. (b) Fractured

charnockitic gneiss, with probable pseudotachylite in river bed at bridge; SW of Kanakapura, Locality 89. (c) East-west and NW-SE fracture sets, Locality 89. (c) Outcrop of fractured charnockitic gneiss in Cauvery canyon, rapids just east of Arkavathi-Cauvery junction, c. 4 km NW of Mekedatu, Locality 69. (e) Tight, cemented fractures, Locality 69. (f) Fault, with tight, cemented fractures, Locality 69.

Near the confluence of the Arkavathi and Cauvery rivers, an upstanding outcrop of densely fractured charnockite was studied (Figure 36 d,e,f). The high fracture density near the confluence of the two valleys compared with those at Mekadatu gorge, suggests that this fracturing may occur in or adjacent to major fracture zones that controlled valley formation. Fracture density is high, and includes a small fault zone and its damage zone (Figure 37f). Despite this fracturing, the outcrop has survived high-energy monsoon rapids (present-day river sediment is characterised by round boulders *c*. 0.5 m across). Thus, despite high fracture density, the outcrop retained relatively high rock-mass strength. Overall, this suggests that fractures in the granulite-facies domain are tight and commonly filled, and not representing high permeability.

6.5 DOLERITE DYKES

Dolerite dykes are composed of a uniform dark grey, medium grained dolerite, generally without foliation. The dykes are typically 25–50 m wide and tens of kilometres long, cross-cutting all other rock types (e.g. French and Heaman, 2010). Dyke traces are readily seen on satellite imagery; they appear as positive lineaments that are broadly straight, but with occasional dog-legs, junctions or small offsets across later faults. On satellite images taken in the dry season they appear greener, likely because they are not cultivated, and support bushes rather than tilled fields (Figure 37). During fieldwork this was confirmed; visited dyke localities showed the dykes to protrude 3–7 m above the surrounding plain, and they are vegetated by bushes and small trees (Figure 37). In one locality (Locality 2), the dyke trace was marked by a linear collection of freed corestones (i.e. with surrounding saprolite removed), 0.5–2 m across (Figure 37). The corestones themselves showed little sign of weathering apart form a thin (<1 cm) weathering rind, suggesting very sharp basal weathering surface.

Figure 37. Dolerite dyke: dolerite corestones 0.5-1.5 m across, with thin weathering rim. Trace of dyke marked by positive feature, c. 5 m above surrounding terrain. Locality, 2, south of Doddaballapura.

6.5.1 Fractures in dykes

Two localities were studied. One east-west trending dyke was quarried down to *c*. 50 m within poorly fractured charnockite gneiss near the Panchapalli reservoir, 17 km ESE of Denkanikota (Locality 48, Figure 38a). Fracture spacing in the dolerite is wide (3–6 m; vertical line-survey; see Appendix C), with some subhorizontal fractures, but also a number of inclined fractures, dipping up to *c*. 40°.

The other locality was a dolerite quarry ESE of Gundlupete (Locality 133), on the Mysore plateau. The wall rock here comprises sheared gneiss with a strong vertical layering and foliation, and a dense fracture pattern developed mainly parallel to the vertical layering, but also with ladder fractures (Figures 31, 38). The dolerite dyke has a dominant subhorizontal set of fractures (Figure 38) that largely cut across the entire dyke (spacing *c*. 0.6 m, vertical line-survey; see Appendix C). Along the strike of the dykes, the fractures show more of an anastomosing pattern, with triple junction every 10–20 m or so. A worked face with a thin (1–2 m) screen of dyke-rock still present shows copious seepage along these horizontal fractures and suggests good connectivity with the wall rock. Altogether this dyke shows a higher fracture density than the dyke in charnockite, but lower fracture density compared to the wall rock.

Both localities showed groundwater seepage in the dolerite close to their exposed margins, but seepage diminished away from the dyke margin. The dyke margin appeared to be a continuous discontinuity plane that is likely to allow groundwater flow.

Overall it appears that fracturing in dykes is less than in the wall rock. However, fractures do occur in the dykes, so this effect is relatively minor. On the regional scale, and using remote sensing it appears that the vertical fracture zones (‘lineaments’) cross-cut the dykes, so these would provide pathways across the dykes on a large-scale.

Figure 38. (a) Dolerite quarry; wall rock is charnockite. Note exposed inclined fracture plane (arrowed in), and seepage from subhorizontal fractures. Locality, 48, near Panchapalli reservoir, 17 km ESE of Denkanikota. Quarry is c. 50 m deep in the centre. (b) Dolerite quarry; wall rock is sheared gneiss (see also Figure 32). Locality 133; 15 km ESE of Gundlupete.

7 Conceptual geology-hydrogeology models

Different conceptual models can be defined for each domain by combining the observations from geomorphology, bedrock geology, regolith depth, superficial cover, character and extent and the observed fracture networks. It should be emphasised that these conceptual models are only constrained by reconnaissance-type fieldwork and thus may change or be refined or quantified with more detailed geological and hydrogeological work. We also suggest some further possible tests of the hypothesized conceptual models.

7.1 CONCEPTUAL MODEL FOR BANGALORE PLATEAU: PENINSULAR GNEISS

For the Bangalore Peninsular Gneiss – including the Milli Catchments, our conceptual model is shown in Figure 39. A shallow aquifer exists almost everywhere (Figure 39a), comprising a weathered zone typically of saprock 5–10 m thick, with thin soil on top. The saprock comprises weathered rock, normally gravel and sand-sized particles, with low clay content. It is likely that this saprock has relatively high storage and permeability. Substantial, thick (>1 m) nonconsolidated saprolite overlying saprock has only been found in topographically flat-lying areas. Saprolite contains significantly more clay than saprock, and thus may have rather variable permeability. It is surmised that on steeper slopes, slope wash by monsoon rains erodes the unconsolidated saprolite. This implies that the presence of saprolite may be constrained with slope analysis of DTMs: as a first pass we suggest that the presence of significant saprolite is only likely if slopes are <10°.

The weathered zone overlies a zone of sheet jointing in otherwise fresh rock; sheet joints diminish in density below *c*. 5–10 m. This zone would have low storage, but high horizontal permeability. Typically, the weathered zone is bounded at the base by a marked sheet joint. This means that the base of the weathered zone is a fairly planar surface, with little horizontal variability (unlike some other gneiss terrains, e.g. Krabbendam and Bradwell, 2014). For modelling purposes this implies that the shallow aquifer can probably be modelled as a single shallow aquifer of fairly uniform thickness. The weathered zone is absent on barren hilltops; these areas could potentially be constrained using false colour satellite imagery such as ETM.

The deeper aquifer of the Bangalore Plateau comprises two main components (Figure 39b). The bulk of the rock comprises impermeable gneisses, with a widely spaced (>5–10 m) network of fractures (joints). Due to limited exposure, however, the nature of this fracture network is poorly constrained by this study, and further study of borehole videos may better constrain this network. The second component are the wider facture zones. These form a well-connected, triangular (in plan-view), network on a kilometre scale and represent vertical zones of likely high storage and conductivity. Along the plateau edges, these fracture zones coincide with topographic lineaments and drainage systems, with a likely connection between surface and ground water. However, on the flatter parts of the plateau, the fracture zones have no geomorphological expression. This means (a) that their exact location and spacing is not known, although we are certain that they do exist; and (b) that there may be a connection between surface water ingress and groundwater where fracture zones occur, but how and where this happens is unclear. If fracture zones occur oblique to slope, this further implies they may set up groundwater flow oblique to slope.

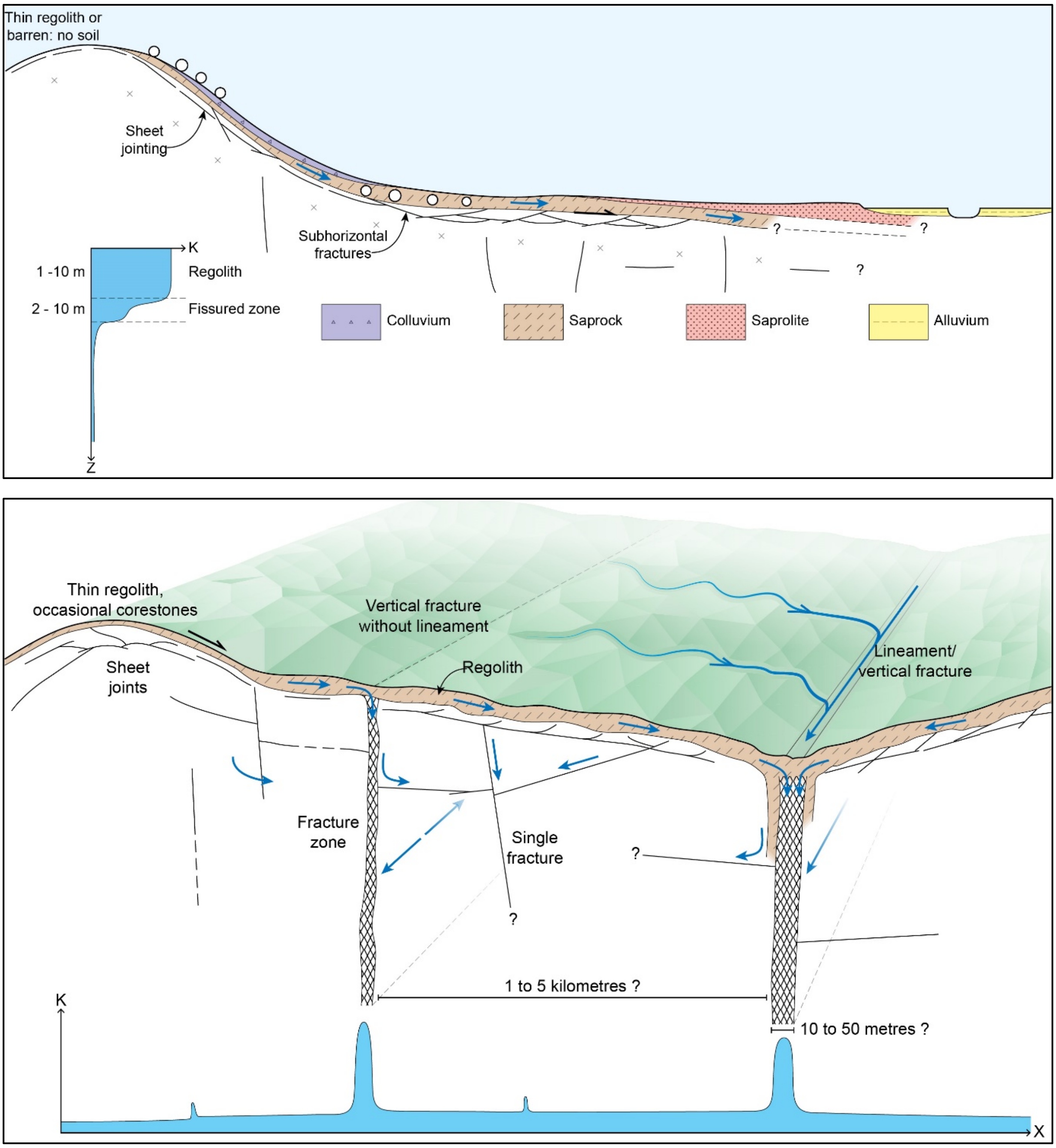


Figure 39. (top) Conceptual model for the shallow aquifer of the Bangalore Plateau, with suggested, qualitative variability of permeability (k) with depth (z). (bottom) Conceptual model for the deeper aquifer of the Bangalore Plateau, with suggested horizontal variability of permeability.

7.2 CONCEPTUAL MODEL FOR MYSORE PLATEAU: BERAMBADI CATCHMENT

For the Berambadi catchment in the upper reaches of the Mysore Plateau, our conceptual model is very different (Figure 40). The bedrock here comprises two components; sheared gneiss and more massive gneiss. The sheared gneiss (comprising both igneous and supracrustal rocks) is characterised by well-developed foliation and gneissosity, commonly subvertical. The foliation, and in particular foliation planes marked by mica, have been extensively re-activated as brittle structures, so that dense networks of mainly subvertical fractures with subsidiary horizontal fractures has developed (Figures 31, 34). Fractures are likely to tighten with depth, but only gradually so, so that there is no sharp boundary between the shallow and deep aquifer. Likewise, the weathered zone has an irregular lower boundary, with deeper weathering occurring in some lithologies (Figure 34). Thus, the lower boundary of weathering zone is likely to be irregular and gradual (Figure 40). Both storage and permeability are relatively high, although it is possible that permeability is strongly anisotropic, i.e. higher parallel to foliation than perpendicular.

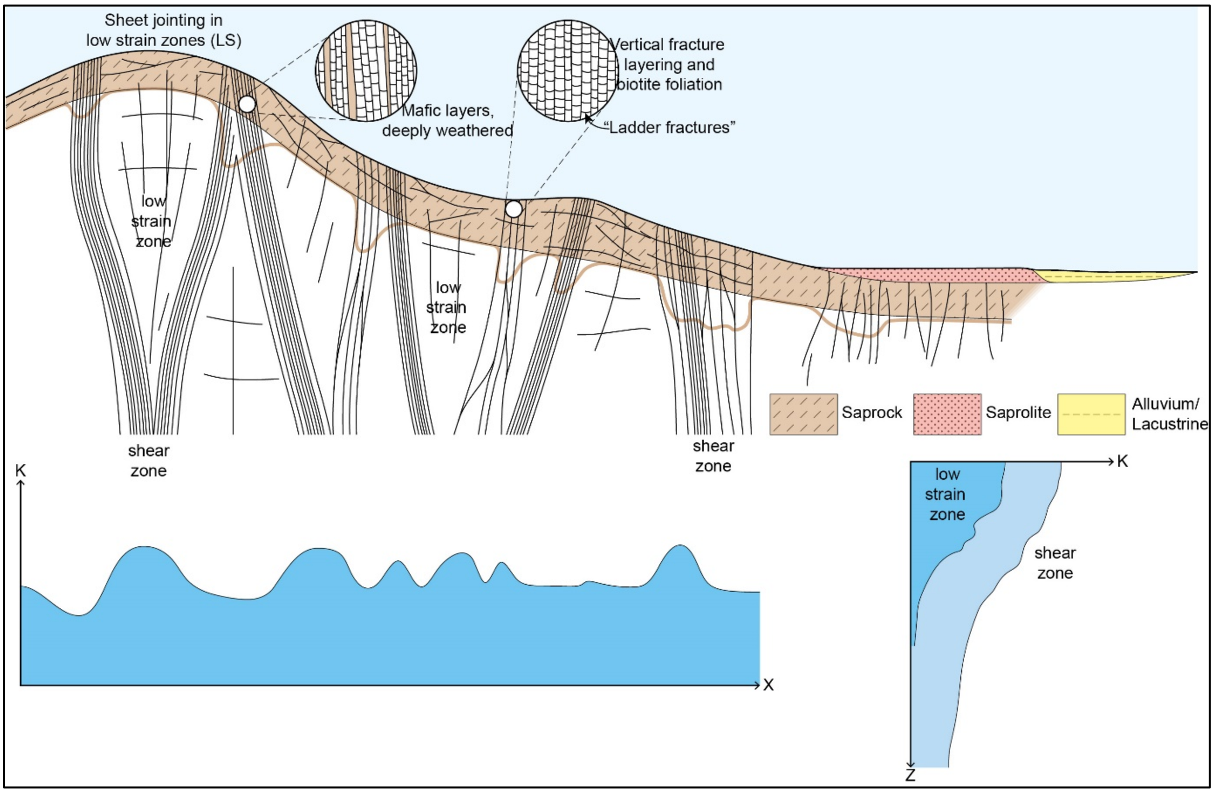


Figure 40. Conceptual model for the Mysore plateau – Berambadi catchment, with vertical and horizontal variation of permeability (k).

The massive gneiss has similarities to the gneiss on the Bangalore Plateau, in that subhorizontal fractures are present and form a relatively sharp basal boundary to the weathering zone, with more massive gneiss beneath (Figures 18, 19, 30, 33). However, the 'background jointing' of massive gneisses is a denser network in Berambadi than on the Bangalore plateau; in addition gently inclined fractures maybe deeply weathered themselves, providing a connection between the surface and deep aquifer.

Overall, the sheared gneisses are more fractured, and have higher permeability than the massive gneiss. In comparison with other gneiss terrains, it is likely that the sheared gneiss form an anastomosing network on the kilometre scale, around domains of more massive gneiss (Figure 41). One problem is the relative amount of sheared versus massive gneiss in the area; this has not been resolved, but on the basis of number of outcrops of sheared versus massive gneiss likely lies between ratios of 30/70 to 70/30. Further north on the Mysore plateau, the proportion of sheared gneiss appears to decrease. Although high fracture densities occur in the well-mapped supracrustal rocks.

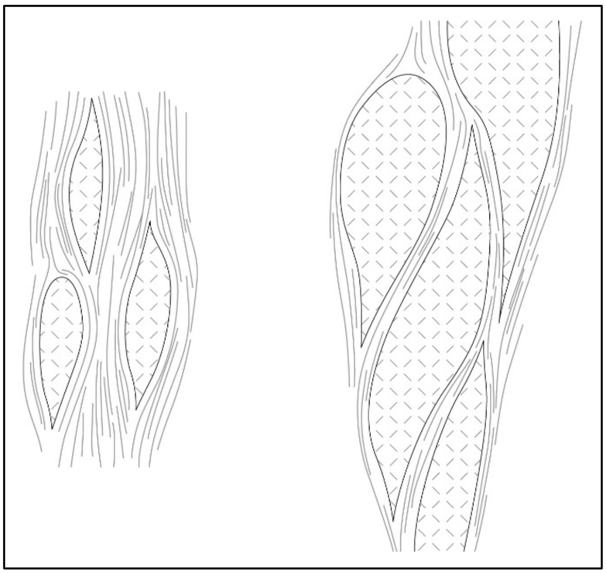


Figure 41. Likely anastomosing pattern of sheared/massive gneiss, showing possible variation in proportion of sheared gneiss versus massive gneiss on the Mysore Plateau: 30/70 or 70/30?

7.3 CONCEPTUAL MODEL FOR THE GRANITE TERRAINS

Much of the granite occurs in inselberg landscapes, with inselbergs separated by fault-controlled valleys. The upper slopes are typically barren, or only have thin regolith, which would result in run-off into surficial material on lower slopes (Figure 42). Material on lower slopes comprises likely both regolith and colluvium, and may have fair storage and permeability; lower slopes of inselbergs are recognised as good locations for groundwater extraction (e.g. Macdonald et al., 2005). Overall, granite is not likely to have a very productive deeper aquifer.

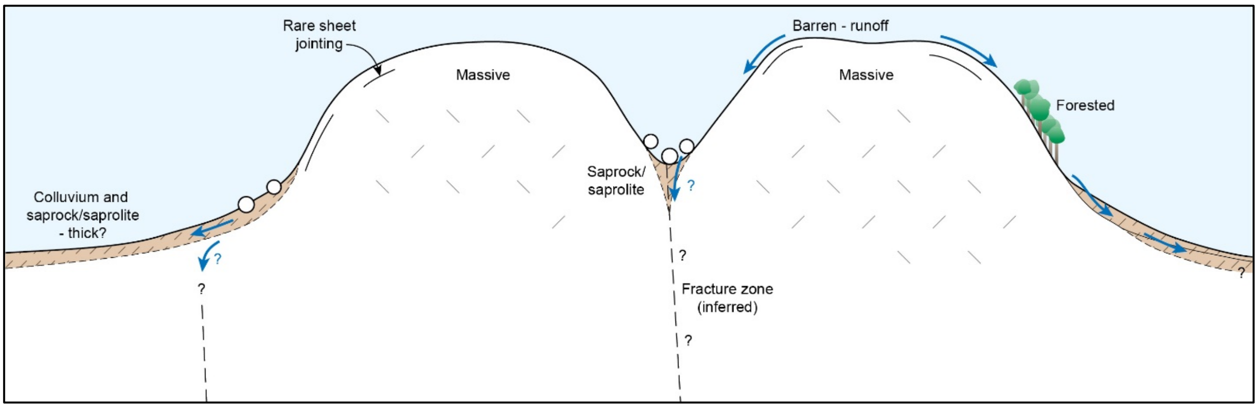


Figure 42. Conceptual model for the granite terrain.

7.4 GROUNDWATER FLOW IN THE CHARNOCKITE DOMAIN.

Groundwater flow in the charnockite domain is poorly known. Most fractures encountered appear to be tight and cemented (Figure 36); suggesting limited conductivity of charnockite rocks, however, no large fracture zone has been encountered and studied. Surficial deposits (regolith and colluvium) are typically present, but only thin (*c*. 5 m max). Much of the charnockite domain has steep topography, so it is likely that most water moves parallel to slope within the thin surficial layer, as well as surface run-off.

7.5 CONCEPTUAL MODEL FOR ALLUVIUM DOMAINS

In the alluvial domain adjacent to the main river, it is likely that the most significant upper aquifer is provided by the alluvial sediments (Figure 43). The sediments appear to be dominated by sand rather than clay, providing both good storage and conductivity. Below the alluvial sediment, bedrock is largely fresh: in the main Cauvery channel, no saprock was observed; whereas in the tributary rivers, the bedrock was weathered. Altogether this suggests that conductivity in the lower aquifer is very limited, so that there is a very large contrast between the high conductivity in the upper aquifer, with low to very low conductivity below. The alluvium domain is also important for the interaction between groundwater and surface water: there is likely to be a transfer from the aquifer to the river, but in times of flooding, this may be reversed. The construction of major dams (e.g. the Krishna Raja Sagara dam NW of Mysore) likely has modified this process.

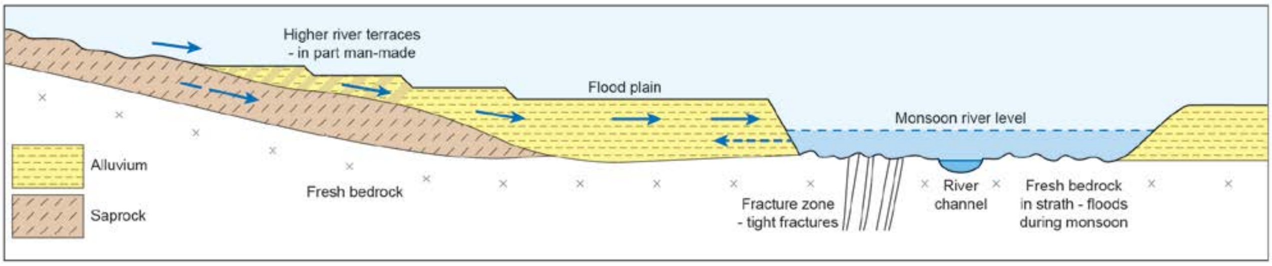


Figure 43. Conceptual model for groundwater flow in the alluvium deposits of floodplains. In smaller rivers, the river bed may include saprock; in the main Cauvery, the river bed is fresh bedrock.

7.6 CONCEPTUAL MODEL FOR DYKES

Dykes are recognised as having a potential effect on groundwater storage and permeability. Depending on the fracture density with respect to the country rock, however, this may be enhanced or reduced: Bromley et al., (1994) showed that in Botswana, dolerite dykes > 10 m thick act as barriers, whereas dykes < 10 m thick do not. In the case of both the Bangalore and the Mysore plateaus, it appears that the fracture density of the dykes is somewhat less than the country rocks, so that the dyke may function as a relative groundwater barrier (Figure 44). This is consistent with electrical resistivity imaging across a dyke in eastern Karnataka as performed by Chandra et al. (2006) who showed increased electrical resistivity down to >40 m bgl, interpreted to indicate lower permeability, as well as groundwater tests by Dewandel et al. (2011) in the Hyderabad area, for a quartz vein.

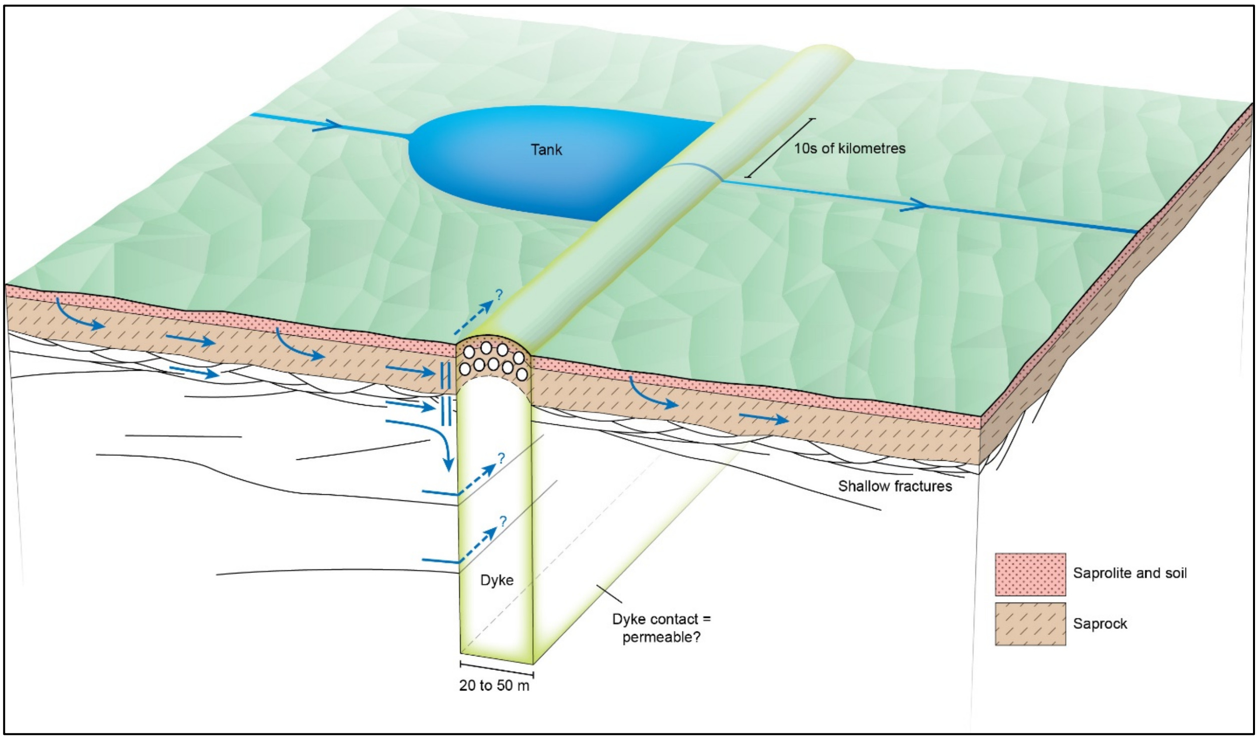


Figure 44. Conceptual model for groundwater flow in the presence of a dyke, at right angles to groundwater flow.

The dyke-wall rock contact is itself in essence also a major fracture and may thus, conversely, function as a planar groundwater conduit along the dyke, resulting in anisotropic groundwater flow. A dyke would only function as a groundwater barrier, however, if it is orientated at high angles to the local groundwater flow (typically parallel to topographic gradient): if it is orientated at a small angle to the topographic gradient, it may have only a minor effect. The real effect of a dyke can conceivably be tested by comparing yields of boreholes on either side of a dyke oriented at high angles to topographic gradient (e.g. Dewandel et al. 2011).

8 Summary and conclusions

The upper Cauvery catchment can, on the basis of geology and geomorphology, be subdivided into several domains. The distribution of regolith as well as the fracture networks are very different in each of these domains, and these different domains can be seen as an emerging set of basement fracture-regolith typologies, each likely with its own particular hydrogeological properties. The implication is that appropriate hydrogeological parameters for modelling purposes are likely to be different in different domains: in other words modelling the Cauvery catchment as a single entity with uniform properties is unlikely to be appropriate.

The Bangalore Plateau comprises Peninsular Gneiss of the Eastern Dharwar Craton and is a gently sloping plateau, incised at its edges. The regolith is relatively thin (5–10 m), mainly comprising saprock, with saprolite only preserved in flat-lying areas. The base of the regolith is typically sharp and relatively flat, so there are limited variation in the regolith thickness. Sheet joints are well developed down to 15–20 m bgl (below ground level); but few sheet joints occur deeper down. The regolith and the fissured zone represent a shallow aquifer down to 10–20 m bgl with good permeability. Below the fissured zone the gneiss is typically massive, with widely spaced ‘background jointing’, which have limited permeability. However, a set of larger scale fracture zones (complex zones of intense fracturing) probably 5–20 m occurs occur as a triangular (in plan-view) interconnected set, with a 1–10 km spacing. These fracture zones can be seen with remote sensing at the plateau edges, but not easily discernible on the more gently sloping parts of the plateau, although there is no reason to believe they do not occur there, below the regolith. The fracture zones are thought to be highly permeable conduits, potentially important for regional groundwater flow.

The Mysore plateau comprises Peninsular Gneiss as well as supracrustal rocks (Western Dharwar Craton). In the studied area around Berambadi (near Gundlupete) a significant part of the bedrock comprises strongly sheared gneisses, often with a sub-vertical attitude. These sheared gneisses have a dense fracture pattern, typically with long vertical fractures and shorter, connecting 'ladder fractures'. Supracrustal rocks have similar fracture patterns, but also form the higher ground and is often covered by colluvium. More massive gneiss in-between zones of sheared gneiss is similar to the Peninsular Gneiss on the Bangalore plateau, but has a somewhat higher fracture density. It is likely that the higher fracture density implies higher permeability in the deep aquifer. The regolith in on the Mysore plateau is similar in character as that on the Bangalore plateau, but has a more gradual and irregular bases, so that the regolith thickness maybe more variable.

The granite terrain is dominated by inselbergs with valleys in between. The granites are poorly fractured, with little groundwater potential. The inselbergs themselves are often bare bedrock with no upper aquifer, however thicker regolith and colluvium occurs on the lower slopes and in the valleys. The valleys are likely fracture controlled, but the character of these fracture zones (as opposed to fracture zones in gneiss domains) has not been studied.

The charnockite domain shows a multitude of fractures, but the fractures appear to be tight and commonly cemented. Groundwater flow in charnockite is poorly constrained, but the overall hydrology of the domain will be dominated by the steep topography, so that run-off is likely to be more dominant than groundwater flow.

Alluvium domains occur in the upper catchment on the Mysore plateau, and in the lower part of the Cauvery catchment (the latter was not studied). In the upper part of the catchment, floodplains show significant thicknesses of alluvium sediment, dominated by sand, and hence with good storage and conductivity. In the main Cauvery River, this alluvium likely overlies fresh rather than weathered bedrock, so that groundwater flow and storage in this domain is controlled by the upper, sedimentary aquifer, rather than the lower bedrock aquifer.

A deeply weathered domain occurs in the uppermost, western part of the Cauvery catchment, in the Western Ghats. This is the only domain where a thick (>6 m) and widespread blanket of saprolite occurs, presumably underlain by an equally thick layer of saprock. The nature of the bedrock below the weathered zone in this domain remains unclear.

Finally, dykes appear to have a lower fracture density than adjacent rocks and hence function as a relative groundwater barrier in all settings, but flow may be enhanced along the dyke.

What emerges is a method of using field and remote sensing observations (both geological and geomorphological) that can assist in subdividing a particular catchment into appropriate domains or typologies for hydrogeological modelling. Further work will focus on quantifying the differences in fracture density in the different domains, as well as linking the above observations better to hydrogeological properties and parameters required for modelling, so as to test the hydrogeological interpretations.

References

ACWORTH, R. 1987. The development of crystalline basement aquifers in a tropical environment. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 20, 265-272.

ALONSO-ZARZA, A M. 2003. Palaeoenvironmental significance of palustrine carbonates and calcretes in the geological record. *Earth Science Reviews*, Vol. 60, 261-298.

ANAND, M, GIBSON, S, SUBBARAO, K, KELLEY, S, and DICKIN, A. 2003. Early Proterozoic melt generation processes beneath the intra-cratonic Cuddapah Basin, southern India. *Journal of Petrology*, Vol. 44, 2139-2171.

BONNET, N J, BEAUVAIS, A, ARNAUD, N, CHARDON, D, and JAYANANDA, M. 2014. First 40Ar/39Ar dating of intense Late Palaeogene lateritic weathering in Peninsular India. *Earth and Planetary Science Letters*, Vol. 386, 126-137.

BROMLEY, J, MANNSTRÖM, B, NISCA, D, and JAMTLID, A. 1994. Airborne Geophysics: Application to a Ground-Water Study in Botswana. *Groundwater*, Vol. 32, 79-90.

CHAKRABORTY, C, MANDAL, N, and GHOSH, S K. 2003. Kinematics of the Gondwana basins of peninsular India. *Tectonophysics*, Vol. 377, 299-324.

CHANDRA, S, RAO, V, KRISHNAMURTHY, N, DUTTA, S, and AHMED, S. 2006. Integrated studies for characterization of lineaments used to locate groundwater potential zones in a hard rock region of Karnataka, India. *Hydrogeology Journal*, Vol. 14, 1042-1051.

CHARDON, D, JAYANANDA, M, CHETTY, T R, and PEUCAT, J J. 2008. Precambrian continental strain and shear zone patterns: South Indian case. *Journal of Geophysical Research: Solid Earth*, Vol. 113.

CHARI, M N, SAHU, J, BANERJEE, B, ZUTSHI, P, and CHANDRA, K. 1995. Evolution of the Cauvery basin, India from subsidence modelling. *Marine and Petroleum Geology*, Vol. 12, 667-675.

CHILTON, P J, and FOSTER, S. 1995. Hydrogeological characterisation and water-supply potential of basement aquifers in tropical Africa. *Hydrogeology Journal*, Vol. 3, 36-49.

DAVIS, G H, and REYNOLDS, S J. 1996. Structural geology of rocks and regions. *Structural geology of rocks and regions. 2nd edition*. (Wiley.)

DEARMAN, W. 1995. Description and classification of weathered rocks for engineering purposes: the background to the BS5930: 1981 proposals. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 28, 267-276.

DEWANDEL, B, LACHASSAGNE, P, ZAIDI, F K, AND CHANDRA, S. 2011. A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers: example of a quartz reef in granitic terrain in South India. *Journal of Hydrology*, Vol. 405, 474-487.

FOOKES, P G. 1997. *Tropical residual soils: A Geological Society Engineering Group working party revised report*. (London: The Geological Society.) ISBN 1897799381

FRENCH, J E, and HEAMAN, L M. 2010. Precise U–Pb dating of Paleoproterozoic mafic dyke swarms of the Dharwar craton, India: implications for the existence of the Neoarchean supercraton Sclavia. *Precambrian Research*, Vol. 183, 416-441.

FRIEND, C, and NUTMAN, A. 1991. SHRIMP U-Pb geochronology of the Closepet granite and Peninsular gneiss, Karnataka, South India. *Journal of the Geological Society of India*, Vol. 38, 357-368.

GOLDICH, S. S. 1938. A study in rock-weathering. *The Journal of Geology*, Vol. 46, 17-58.

GIRTY, G, GEBHART, K, REPLOGLE, C, MORTON, N, PURCELL, J, PARIZEK, J, CARRASCO, T, ERRTHUM, R, and GROOVER, K. 2014. Reconstructing the regolith from erosionally exhumed corestone and saprock derived from the Cretaceous Val Verde tonalite, Peninsular Ranges, southern California, USA: a case study. *Catena*, Vol. 113, 150-164.

GRÖNWALL, J T, MULENGA, M, and MCGRANAHAN, G. 2010. *Groundwater, self-supply and poor urban dwellers: a review with case studies of Bangalore and Lusaka.* (IIED.) ISBN 184369770X.

GUNNELL, Y. 1998. The interaction between geological structure and global tectonics in multistoreyed landscape development: a denudation chronology of the South Indian shield. *Basin Research*, Vol. 10, 281-310.

JAHNS, R H. 1943. Sheet structure in granites: its origin and use as a measure of glacial erosion in New England. *The Journal of Geology*, Vol. 51, 71-98.

JAYANANDA, M, MARTIN, H, PEUCAT, J-J, and MAHABALESWAR, B. 1995. Late Archaean crust-mantle interactions: geochemistry of LREE-enriched mantle derived magmas. Example of the Closepet batholith, southern India. *Contributions to Mineralogy and Petrology*, Vol. 119, 314-329.

JEEVANANDAM, M, KANNAN, R, SRINIVASALU, S, AND RAMMOHAN, V. 2007. Hydrogeochemistry and groundwater quality assessment of lower part of the Ponnaiyar River Basin, Cuddalore district, South India. *Environmental monitoring and assessment*, Vol. 132, 263-274.

KALE, V S, SENGUPTA, S, ACHYUTHAN, H, and JAISWAL, M K. 2014. Tectonic controls upon Kaveri River drainage, cratonic Peninsular India: Inferences from longitudinal profiles, morphotectonic indices, hanging valleys and fluvial records. *Geomorphology*, Vol. 227, 153-165.

KRABBENDAM, M, AND BRADWELL, T. 2014 Quaternary evolution of glaciated gneiss terrains: pre-glacial weathering vs. glacial erosion. *Quaternary Science Reviews*, Vol. 95, 20-42.

MACDONALD, A, DAVIES, J, CALOW, R, and CHILTON, J. 2005. *Developing groundwater: a guide for rural water supply.* (ITDG publishing.) ISBN 185339596X

MARTEL, S J. 2017. Progress in understanding sheeting joints over the past two centuries. *Journal of Structural Geology*, Vol. 94, 68-86.

MAULDON, M, DUNNE, W, and ROHRBAUGH JR, M. 2001. Circular scanlines and circular windows: new tools for characterizing the geometry of fracture traces. *Journal of Structural Geology*, Vol. 23, 247-258.

MEERT, J G, PANDIT, M K, PRADHAN, V R, BANKS, J, SIRIANNI, R, STROUD, M, NEWSTEAD, B, and GIFFORD, J. 2010. Precambrian crustal evolution of Peninsular India: a 3.0 billion year odyssey. *Journal of Asian Earth Sciences*, Vol. 39, 483-515.

MOYEN, J-F, NÉDÉLEC, A, MARTIN, H, AND JAYANANDA, M. 2003. Syntectonic granite emplacement at different structural levels: the Closepet granite, South India. *Journal of Structural Geology*, Vol. 25, 611-631.

NALLAPA REDDY, A, JAIPRAKASH, B, RAO, M, CHIDAMBARAM, L, AND BHAKTAVATSALA, K. 2013. Sequence stratigraphy of late Cretaceous successions in the Ramnad sub-basin, Cauvery Basin, India. *Proc. XXIII Indian Colloquium on Micropaleontology and Stratigraphy and International Symposium on Global Bioevents in Earth's History.* Geological Society of India, Special Publication, 78-97.

NAQVI, S M, and ROGERS, J J W. 1987. *Precambrian geology of India*. (Oxford University Press.) ISBN 0195036530

NESBITT, H W, and MARKOVICS, G. 1997. Weathering of granodioritic crust, long-term storage of elements in weathering profiles, and petrogenesis of siliciclastic sediments. *Geochimica et Cosmochimica Acta*, Vol. 61, 1653-1670.

PEUCAT, J-J, JAYANANDA, M, CHARDON, D, CAPDEVILA, R, FANNING, C M, and PAQUETTE, J-L. 2013. The lower crust of the Dharwar Craton, Southern India: Patchwork of Archean granulitic domains. *Precambrian Research*, Vol. 227, 4-28.

RAASE, P, RAITH, M, ACKERMAND, D, and LAL, R. 1986. Progressive metamorphism of mafic rocks from greenschist to granulite facies in the Dharwar Craton of South India. *The Journal of Geology*, Vol. 94, 261-282.

RAJAMANI, V, TRIPATHI, J K, and MALVIYA, V. 2009. Weathering of lower crustal rocks in the Kaveri river catchment, southern India: implications to sediment geochemistry. *Chemical Geology*, Vol. 265, 410-419.

RAJU, K, MANASI, S, and LATHA, N. 2008. *Emerging Ground Water Crisis in Urban Areas: A Case Study of Ward No. 39, Bangalore City*. (Institute for Social and Economic Change Bangalore.) ISBN 817791152X

RAO, B R. 1962. *A handbook of the geology of Mysore State, Southern India.* (Bangalore Printing and Publishing Company.)

RAMKUMAR, M, STÜBEN, D, AND BERNER, Z. 2004. Lithostratigraphy, depositional history and sea level changes of the Cauvery Basin, southern India. *Annales Géologiques de la Péninsule Balkanique*, Vol. 65, 1-27.

ROBERTSON, S.J. 1999. BGS Rock Classification Volume 2, Classification of metamorphic rocks. British Geological Survey Research Report, RR 99-02

SAWKAR, R. 2012. Evaluation of Surface, Ground and Sewage Water for Sustainable Supply of Potable Water to Bengaluru. *Journal of the Geological Society of India*, Vol. 80, 877-880.

SHARMA, A, and RAJAMANI, V. 2000. Weathering of gneissic rocks in the upper reaches of Cauvery river, south India: implications to neotectonics of the region. *Chemical Geology*, Vol. 166, 203-223.

SHARMA, A, and RAJAMANI, V. 2001. Weathering of charnockites and sediment production in the catchment area of the Cauvery River, southern India. *Sedimentary geology*, Vol. 143, 169-184.

SINGHAL, B B S, and GUPTA, R P. 2010. *Applied hydrogeology of fractured rocks.* (Springer Science and Business Media.) ISBN 9048187990

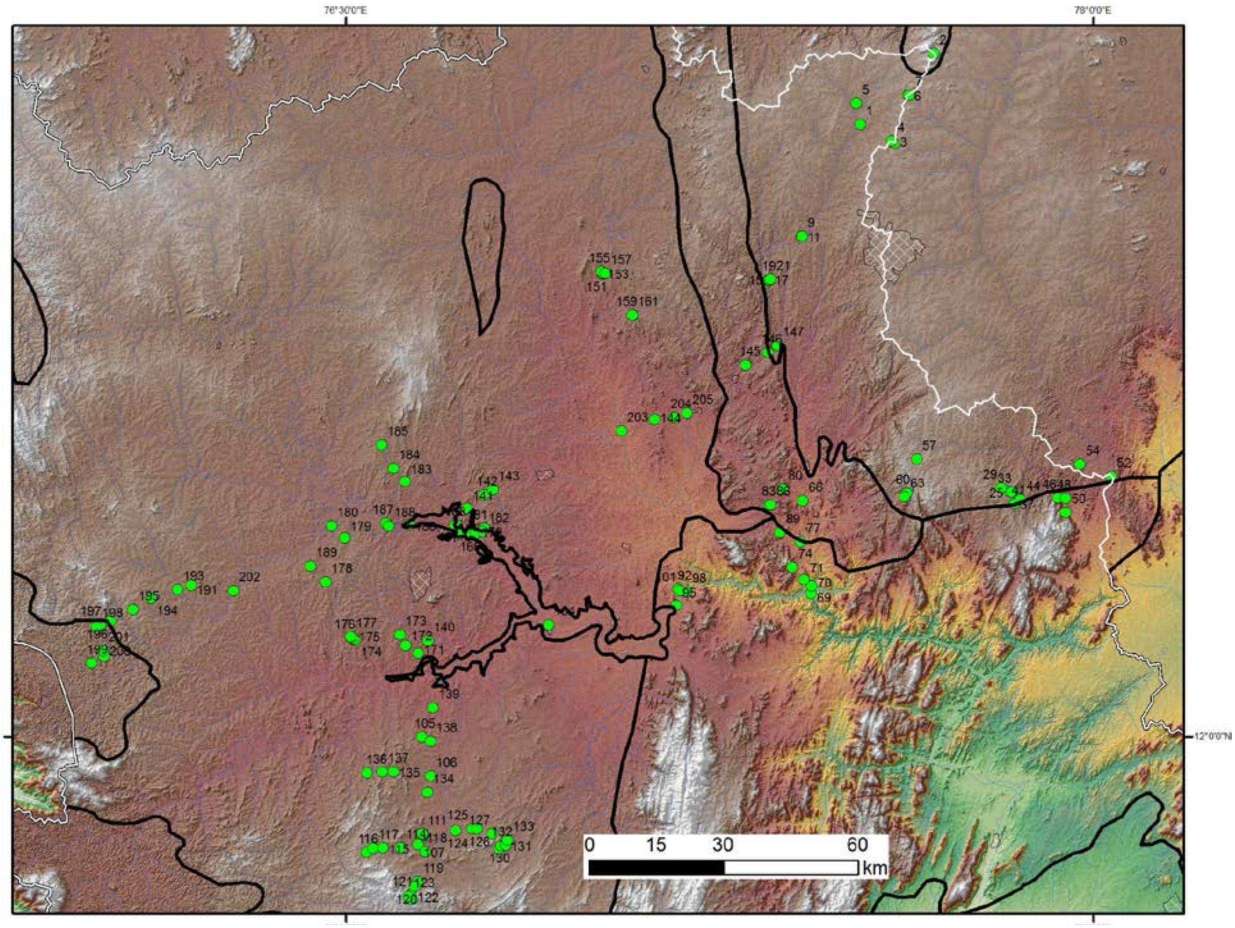
SURESH, T. 1999. Impact of urbanisation on groundwater regime: a case study of Bangalore city. in *Groundwater in the Urban Environment*. CHILTON, J (editor). *International Contributions to Hydrogeology*, Vol. 21. 251-258. (Rotterdam: A.A. Balkema.)

SURESH, T. 2001. An urban water scenario: A case study of the Bangalore metropolis, Karnataka, India. *IAHS Publication*, Vol. 268, 97-106.

TWIDALE, C. R. 2012. *Granite landforms*. (Amsterdam: Elsevier).

VALDIYA, K, and RAJAGOPALAN, G. 2000. Large palaeolakes in Kaveri basin in Mysore Plateau: Late Quaternary fault reactivation. *Current Science*, 1138-1142.

Appendix A: Field localities – map



Appendix A. Map showing field localities. Overlapping numbers not shown.

Appendix B: Field localities - coordinates

Grid references and short descriptions of visited localities. Coordinates in Decimal Degrees.

Locality	Y (Easting)	X (Northing)	Locality Description	Summary	Date
1	13.2282	77.5324	Roadcut; dolerite dyke and boulders, south of Doddaballapura	dyke	04/10/2017
2	13.3716	77.6802	Nandi Hill, Tipu Fort	gran insel	04/10/2017
3	13.1911	77.6003	tank with saprock and clayey saprolite	saprock	05/10/2017
4	13.1951	77.5954	waste quarry	gneiss section	05/10/2017
5	13.2703	77.5248	red tank quarry, with saprolite, SW of Dodbalapur.	saprolite	05/10/2017
6	13.2869	77.6291	Gneiss slab quarry, east of Dodballapur.	gneiss quarry	05/10/2017
7	13.2872	77.631	Gneiss quarry 2 fracture exposure	gneiss quarry	05/10/2017
8	13.0042	77.415	thick regolith and sheet jointing in gneiss; quarry west of Bangalore	regolith and gneiss	07/10/2017
11	13.0046	77.416	gneiss regolith; quarry west of Bangalore	Gneiss regolith	07/10/2017
13	12.9147	77.3475	gneiss shear zone; quarries near Huluvanahalli; west of Bangalore	gneiss shear zone	07/10/2017
15	12.9165	77.3483	Saprock in quarries near Huluvanahalli; west of Bangalore	sap rock	07/10/2017
17	12.9165	77.3487	vertical fracture zone in lineament; quarries near Huluvanahalli; west of Bangalore	vertical frac zone	07/10/2017
19	12.9173	77.3502	Vertical fractures, parallel and Vertical fracture zone; adjacent to lineament; quarries near Huluvanahalli; west of Bangalore	vert frac zone	07/10/2017
21	12.9177	77.3521	massive gneiss adjacent to fracture zone / lineament; quarries near Huluvanahalli; west of Bangalore	gneiss fractures	07/10/2017
25	12.4922	77.8312	Round inselberg, quarried, south of Denkanakoti	gneiss outcrop	08/10/2017
29	12.4991	77.8146	Quaternary deposit and regolith, on slope, south of Denkanikota.	regolith and Quart	08/10/2017
33	12.4906	77.8361	Road side dyke heavily fractured, SE of Denkanikota.	Fractured dyke	08/10/2017
37	12.4672	77.8413	Gneiss quarry with dyke and vertical fracture; SE of Denkanikota.	gneiss quarry	08/10/2017
41	12.4667	77.8416	Gneiss quarry, big. With vertical fracture zone, 20m + wide. SE of Denkanikota.	vert frac zone	08/10/2017
44	12.4754	77.8543	View inselbergs, SE of Dekanikota.	inselbergs	09/10/2017
46	12.4789	77.9292	Dam Overview in near charnockite	dam overview	09/10/2017
48	12.4772	77.945	Deep quarry in dolerite, near Panchapalli.	dyke quarry	09/10/2017
50	12.4489	77.9447	thick sap-rock; pit; south of Panchipalli Reservoir	Charnockite Saprock	09/10/2017
52	12.521	78.0363	Inselberg, near Rayakottal	Inselberg	09/10/2017
54	12.5463	77.9732	small gneiss hill with ultra mafics, between Rayakottal and Hosur.	bt-gneiss +ultramaf	09/10/2017
57	12.5569	77.6457	plateau saprolites and soil; west of Denkanikota	saprolites and soil	10/10/2017

60	12.4879	77.6256	regolith on flank of plateau, near Tamil Nadu / Karnatak border; WSW of Denkanikota	saprock & saprolite	10/10/2017
63	12.4811	77.6217	Photo view, edge plateau near Tamil Nadu / Karnatak border; WSW of Denkanikota	view, saprock	10/10/2017
66	12.473	77.4174	Granite corestones & saprock/grus, south of Kanakapura.	granite / grus	10/10/2017
69	12.2868	77.434	heavily fractured charnockite gneiss beside Kauvari River / Arkavathi River junction	charnock fractured	10/10/2017
70	12.3021	77.4348	1.5m thick saprock beside road	1.5m thick saprock	11/10/2017
71	12.3153	77.4198	3m thick weathered mafic gneiss to saprock; pit north of Mekedatu	gneiss saprock	11/10/2017
74	12.3393	77.3966	Incised valley slopes, with horizontal fractures; charnokite; north of Mekedatu	horizontal fractures	11/10/2017
77	12.3906	77.4124	granitic gneiss quarry now used now for farming	granite gneiss	11/10/2017
80	12.496	77.3767	granite on side of hill that has been slightly quaried; SW of Kanakapura	granite outcrop	11/10/2017
83	12.4652	77.3499	Corestone paradise - granite; SW of Kanakapura.	saprolite inselbergs	11/10/2017
86	12.4649	77.3522	4m thick saprock and colluvium, between corestones. SW Of Kanakapura.	saprock & colluvium	11/10/2017
89	12.4087	77.3713	Fractured charnockite in river bed at bridge; SW of Kanakapura.	fractured charnokite	12/10/2017
92	12.2961	77.1676	Cauvery Falls Viewpoint ,north side	charno gorge	12/10/2017
95	12.2631	77.1639	Schistose gneiss shearzone with colluvium, west of Cauvery Falls	schistose SZ	12/10/2017
98	12.2896	77.1833	Barachukki Falls; (south Cauvery Falls); in granulite gneiss	waterfall	12/10/2017
101	12.2922	77.1707	Barachukki Falls; (south Cauvery Falls); in granulite gneiss. From east. Saprock,	falls.	12/10/2017
104	12.2242	76.9075	alluvium over bank deposit; River Cauvery	alluvium overbank	12/10/2017
105	11.9981	76.6523	gneiss quarry with horizontal fractures	gneiss quarry	13/10/2017
106	11.9212	76.6698	Drainage tributary of saprock, calcareous nodules, fluvial deposit and soil. North of Gundlupete.	soil fluvial & calcr	13/10/2017
107	11.7823	76.6455	Gneiss shear zone; tank exposure; west of Gundlupete	gneiss shear zone	13/10/2017
108	11.8014	76.6572	Gneiss quarry with E-W vertical fractures. Deep quarry in Inselberg, just west of Gundlupete.	Fractured gneiss	14/10/2017
109	11.8037	76.6557	Gneiss outcrop above quarry; on Inselberg, just west of Gundlupete.	gneiss outcrop	14/10/2017
110	11.8039	76.656	Shearing in gneiss; subhorizontal fractured; small abandoned quarry, west of Gundlupete.	sheared gneiss	14/10/2017
111	11.8041	76.6548	Gneiss with shearing along a. potential fold hinge. Quarried surface on hill, west of Gundlupete.	sheared gneiss	14/10/2017
112	11.8044	76.6542	Small, abandoned quarry with multiple trending vertical fractures and layer of garnet amphibolite. West of Gundlupete.	fractured gneiss	14/10/2017
113	11.8048	76.6543	Pink & grey gneiss, multiple trending vertical fractures. Small, abandoned quarry, west of Gundlupete.	fractured gneiss	14/10/2017
114	11.7764	76.6102	saprock and soil	saprock and soil	14/10/2017

115	11.7769	76.5752	Schistose gneiss shear zone with 'tramline' gneiss; roadcut NW of Gundlupete.	tramline gneiss	14/10/2017
116	11.7671	76.5417	1 m thick soil or maybe saprolite	1 m thick soil	14/10/2017
117	11.7752	76.5549	Schistose, sheared gneiss; weathered, in shallow pit adjacent to road; NW Gundlupete	schistose gneiss	14/10/2017
118	11.7681	76.6602	gneiss outcrop	gneiss outcrop	14/10/2017
119	11.7081	76.6437	road side gneiss	road side gneiss	14/10/2017
120	11.6982	76.6385	Saprock, saprolite, colluvium, and soil, on Gundlupete- Bandipur road.	saprolite and soil	14/10/2017
121	11.6806	76.6302	Saprock; road cut in Tiger reserve near Bandipur.	saprock	14/10/2017
122	11.6728	76.6333	Outcrop of massive rock may be gneiss clearly not sheared.	gneiss?	14/10/2017
123	11.6782	76.6249	highly sheared schist potentially sedimentary schist some quartz veining; road cut in Tiger reserve near Bandipur.	Sedimentary schist	14/10/2017
124	11.8111	76.7208	gneiss in tank	gneiss	15/10/2017
125	11.8148	76.7544	gneiss in tank	gneiss	15/10/2017
127	11.8049	76.7944	tank		15/10/2017
128	11.7743	76.8083	Sheared and rotten gneiss with amphibolite. Roadcut ESE of Gundlupete.	shear gn&amph	15/10/2017
129	11.7803	76.812	Edge of field. Sheared granitic gneiss. Verti frac.	shear granite	15/10/2017
130	11.7806	76.8117	sheared q-f-bt +- grt gneiss + ultramafic, Hill outcrops; east of Gundlupete.	sheared gneiss	15/10/2017
131	11.7825	76.8196	Sheared gneiss; q-f-bt-+-grt, Kfsp. Verti Fractures. Road cut to hill with temple, east of Gundlupete.	shear gneiss	15/10/2017
132	11.781	76.8208	hilltop, temple , massive q-f-grt gneis; east of Gundlupete.	gneiss, massive	15/10/2017
133	11.7925	76.8243	Big dolerite quarry , with very fine layered, sheared gneiss. ESE of Gundlupete	v lay gneiss; dol	15/10/2017
134	11.8881	76.6648	fresh rock close to surface	gneiss	16/10/2017
135	11.9285	76.5956	sheared and massive gneiss with saprock, saprolite, colluvium, and soil; NW of Gundlupete	Metaigneous gneiss	16/10/2017
136	11.9263	76.543	Saprock and 'supracrustals' or sheared gneiss in ditch; NW of Gundlupete	Supracrustals	16/10/2017
137	11.9285	76.5736	schistose gneiss with pegmatite; saprock in ditch; NW of Gundlupete	schistose gneiss	16/10/2017
138	11.9906	76.6703	sheared gneiss / saprock along road	sheared gneiss	16/10/2017
139	12.0575	76.6748	sheared gneiss / saprock along road	sheared gneiss	16/10/2017
140	12.1917	76.6659	sheared gneiss / saprock along road	sheared gneiss	16/10/2017
141	12.4574	76.7434	? sheared gneiss along road	? sheared gneiss	16/10/2017
142	12.4844	76.7778	massive gneiss along road	massive gneiss	16/10/2017
143	12.495	76.795	saprock along road	saprock	16/10/2017
144	12.636	77.1195	massive gneiss, 10m corestone along road	massive gneiss	16/10/2017
145	12.7458	77.3034	massive granite inselbergs	inselbergs	16/10/2017
146	12.77	77.348	thick 6 m saprock along road	saprock	16/10/2017
147	12.7843	77.3664	massive gneiss, quarry, horizontal fractures	gneiss	16/10/2017
151	12.9282	77.0164	natural outcrop in dry stream bed; south of Kunigal, Photo 7-10	mass gne-dyke	21/04/2018

153	12.9293	77.0146	Quarry, c. 10 m deep; south of Kunigal. photo 11-ff	mass gneiss; 4m rego	21/04/2018
155	12.9331	77.0137	Cut along track .Fuji 2268 ff. > 2 m saprock, weathered rock; corestones. Small dolerite dyke weathered into corestones. Much grus; little / no clay.	saprck >2m	21/04/2018
157	12.9294	77.0205	Cut below road, south of Kunigal. photo 14 ff. Amphibolite schist, + grt-mica schist + psammite; thinly bedd; sheared and fractured.	amph schist,xshear	21/04/2018
159	12.8459	77.0762	Setof abandoned quarries in gneiss, with saprock sections. Photo 18 ff.	gneiss saprk	21/04/2018
161	12.8465	77.0748	Quarry in gneiss with sheet joints & some vertical faults (with horizontal slickesides).	mass gneis qua	21/04/2018
162	12.4117	76.7269	Ridge amongst floodplain. Quartzite, rexx Photo 25-27 & 2273-2277.	qtzite ridge	22/04/2018
163	12.4062	76.7264	Cauvery river bed. Amphibolite schist,sticking out. Fine bedded / foliated. Fine grained. Fractured but tight.	amph schi	22/04/2018
164	12.4071	76.7532	Cauvery river bed, just below dam. Massive gneiss with ?pseudo tachylite. Photo 33 - 36. Few open fractures.	mass gne;pseudotach	22/04/2018
165	12.4048	76.7533	Fractured and slightly weathered gneiss. Just below dam in Cauvery river bed.	Frac cauvery gneiss	22/04/2018
166	12.4053	76.7543	Foliated granite (or k-feldspar rich gneiss). Just below dam in Cauvery river bed.	Foliated granite	22/04/2018
167	12.4253	76.7219	Supracrustals and granite, on temple hill, east of Sirangapatna.	supracrustals	22/04/2018
168	12.4233	76.7193	supracrustal colluvium that is rich in psammite	supracrustal colluvi	22/04/2018
169	12.4072	76.7616	Floodplain of Cauvery. >3 m of fine well sorted sand; quite hard packed - diff to break in fingers.	fine sand/floodplain	22/04/2018
170	12.4065	76.7615	Gneiss on edge of river with fractures. Many photos for fractures.	Fractured gneiss	22/04/2018
171	12.1675	76.6449	Big abandoned quarry; south of Mysore. Amphibolite shot through with Carbonate veins.	Amph-CS-calc vein	23/04/2018
172	12.1824	76.6201	Long N-S quarry ; south of Mysore. Amphibolite / calc vein complex.	Amph-calc vein	23/04/2018
173	12.2041	76.6088	Active quarry ; same amphibolite calc vein complex as other quarries.	Amph - calc vein	23/04/2018
174	12.1934	76.5193	Ditch, friable saprock of amphibolite at 1 m bgl.	amph saprock	23/04/2018
175	12.1953	76.5154	Ditch, saprock, very frable at 1 m bgl. Calcfied amphibolite ; very rotten.	saprock; calcy amph.	23/04/2018
176	12.1984	76.5103	Hard, flat outcrop // road. Hard crystalline marble. Fizzes well. Vertical fabric; N-S. Grain size 3-5 mm. No regolith on top....Quartzite layer to east; also thin quartzite layers & boudins within marble. Photo 69	xx marble.	23/04/2018
177	12.2008	76.5098	Quarry with marble and quartzite	marble and quartzite	23/04/2018
178	12.3106	76.4602	Sand in tank, 2-3m. Saprock close by.	sand	23/04/2018
179	12.3982	76.4983	Saprock >7-8 m bgl	saprock	23/04/2018
180	12.4227	76.4716	Reservoir bed. Muvh rock/saprck close to surface, So saprock = thin (~5m); any saprolite < 2 m. Total regolith average probably < 10 m. Or, say 2-10m.	thin regolith	23/04/2018

181	12.4178	76.7783	Series of quarries in massive gneiss with sheet joints . Photo 73 ff. E-W vertical fractures ; no N_S fractures	mass gneiss	24/04/2018
182	12.4118	76.7756	Terrace, c. 20 m above river. Here fresh gneiss overlain by some man-made deposit, or colluvium. So NO saprock.	fresh BR below terra	24/04/2018
183	12.5125	76.6198	Road cut and wee hill, NW of Mysore. Gneiss; variably sheared. Photo82-86 & 2355 - 2361	gneiss; sheared.	24/04/2018
184	12.5381	76.5953	Quarry in massive gneiss. Tonalitic gneiss; not granite. Map is wrong.	mass gneiss	24/04/2018
185	12.5854	76.5724	gneiss quarry with early stages of shearing developing	slight shear gneiss	24/04/2018
186	12.4244	76.628	Cauvery river bed, N of Mysore. Good gneiss,with good gneiss fabric; but not super sheared. Massive ; no weathering; all eroded by water (potholes, scallops). Some E-W fractures, but massive over 10s of metres.	mass gneiss fresh	24/04/2018
187	12.4277	76.5803	fresh BR below < 2m regolith or man mode	thin cover	24/04/2018
188	12.4228	76.5868	Cauvery river below dam	BR in river	24/04/2018
189	12.3421	76.43	> 4 m saprock in road cut	saprock, >4m	25/04/2018
191	12.3025	76.19	Supracrustals Saprock , in tank, 3 m section. West of Hunsur.	supracrustals Saproc	25/04/2018
193	12.2953	76.1626	Tank, dug out; 4m section of saprock, saprolite and soil. West of Hunsur. photo 132-140	saprolte/saproc k	25/04/2018
194	12.2774	76.1096	Complete regolith section in tank: fresh rock; saprock; saprolite. W of Honsur	comp regolith sect	25/04/2018
195	12.2543	76.073	saprock at surface	saprock	25/04/2018
196	12.2307	76.0281	Tank/check dam. No BR at base; so 4m+ of regolith; probably 1-2m saprolite. Slowly more saprolite going W.	tank; 4m+ rego	25/04/2018
197	12.2243	76.008	4m saprolite, on bedrock in river construction hole	4m saprolite	25/04/2018
198	12.221	76.0002	Cut, 2m deep in village. 0.5 m brown soil; 1.5 m of red-brown saprolite. = clayey, gravelly sand. grit ~2-3mm. Coffee plantations.	clay / sand saprolit	25/04/2018
199	12.1473	75.9902	Slope / road cuts. > 5-7 m of clayey red saprolite. South of Tilimali	Saprolite, > 7 m	25/04/2018
200	12.1604	76.0152	Double road cut, south of Tilimali. >2.5 m of pure saprolite. Cont for >200m, so extensive.	saprolite blanket.	25/04/2018
201	12.1725	76.0125	Road cut. Sandy / clayey saprolite, with locally remnants of pegmatite. phot 2387 - 2389	sapro >2m	25/04/2018
202	12.2926	76.2745	Bedrock river bed - mostly rotten gneiss ; wirh ~ 8 m of alluvium fine sand; some clay /calcrete nodules.	8m ALV-SAND; BR	25/04/2018
203	12.6133	77.0543	Bridge near Maddur. supracrustals Saprock & saprolite, in tank, 3 m section. West of Hunsur	bedrock in river	26/04/2018
204	12.6405	77.1588	> 5 m saprock in holes...	> 5 m saprock	26/04/2018
205	12.6492	77.1843	Slow river; no bedrock seen sticking out. No clear what bed is.	river bed??	26/04/2018

Appendix C: Scanline survey in dolerite dykes. Spacing of horizontal fractures, by vertical line-survey:

Locality 133.

15 km ESE of Gundlupete (Locality 133: N 11.7925 – E 76.8243).

Dolerite quarry; wall rock is sheared gneiss.

24 fractures in 14 m:

Average Spacing =58 cm; n = 24.

Locality 48a

Near Panchapalli reservoir, 17 km ESE of Denkanikota (: N 12.477 – E 77.945).

Dolerite quarry; wall rock is charnockite gneiss.

14 fractures in 48 m: Average spacing = 3.4m; n = 14.

8 fractures in 48 m: Average spacing = 6 m; n = 8.

10 fractures in 48 m: Average spacing = 4.8 m; n = 10.