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► To cite this version:

Laurent Barbiero, H.R. Parate, Marc Descloitres, Adelphe Bost, S. Furian, et al.. Using a structural approach to identify relationships between soil and erosion in a semi-humid forested area, South India. CATENA, Elsevier, 2007, 70 (3), pp.313-329. <10.1016/j.catena.2006.10.013>. <hal-00323578>

HAL Id: hal-00323578

<https://hal.archives-ouvertes.fr/hal-00323578>

Submitted on 26 Feb 2009

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1 **Using a structural approach to identify relationships between soil and erosion in a semi-humid**
2 **forested area, South India**

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18

19 **Abstract**

20

21 Biogeochemical and hydrological cycles are currently studied on a small experimental forested
22 watershed (4.5 km²) in the semi-humid South India. This paper presents one of the first data referring
23 to the distribution and dynamics of a widespread red soil (Ferralsols and Chromic Luvisols) and
24 black soil (Vertisols and Vertic intergrades) cover, and its possible relationship with the recent
25 development of the erosion process. The soil map was established from the observation of isolated
26 soil profiles and toposequences, and surveys of soil electromagnetic conductivity (EM31, Geonics

1 Ltd), lithology and vegetation. The distribution of the different parts of the soil cover in relation to
2 each other was used to establish the dynamics and chronological order of formation. Results indicate
3 that both topography and lithology (gneiss and amphibolite) have influenced the distribution of the
4 soils. At the downslope, the following parts of the soil covers were distinguished: i) red soil system,
5 ii) black soil system, iii) bleached horizon at the top of the black soil and iv) bleached sandy saprolite
6 at the base of the black soil. The red soil is currently transforming into black soil and the
7 transformation front is moving upslope. In the bottom part of the slope, the chronology appears to be
8 the following: black soil > bleached horizon at the top of the black soil > streambed > bleached
9 horizon below the black soil. It appears that the development of the drainage network is a recent
10 process, which was guided by the presence of thin black soil with a vertic horizon less than 2 m deep.

11 Three distinctive types of erosional landforms have been identified:

- 12 1. rotational slips (Type 1);
- 13 2. a seepage erosion (Type 2) at the top of the black soil profile;

14 Types 1 and 2 erosion are mainly occurring downslope and are always located at the intersection
15 between the streambed and the red soil-black soil contact. Neutron probe monitoring, along an area
16 vulnerable to erosion types 1 and 2, indicates that rotational slips are caused by a temporary water
17 table at the base of the black soil and within the sandy bleached saprolite, which behaves as a plane
18 of weakness. The watertable is induced by the ephemeral watercourse. Erosion type 2 is caused by
19 seepage of a perched watertable, which occurs after swelling and closing of the cracks of the vertic
20 clay horizon and within a light textured and bleached horizon at the top of black soil.

- 21 3. a combination of earthflow and sliding in the non-cohesive saprolite of the gneiss occurs at
22 midslope (Type 3). Type 3 erosion is not related to the red soil-black soil system but is
23 caused by the seasonal seepage of saturated throughflow in the sandy saprolite of the gneiss
24 occurring at midslope.

25

26

1 *Keywords:* Erosion, Structural Analysis, Electromagnetic Induction, Chromic Luvisol, Vertisol,
2 South India.

3

4 **1. Introduction**

5

6 In recent years, several studies are carried out to understand the bio-geochemical cycles of major
7 and trace elements, to calculate the mechanical erosion and chemical weathering rates, to estimate
8 the role of the major parameters (relief, climate, lithology, vegetation, anthropisation...) that are
9 likely to control the chemical weathering processes, to quantify the effects of rock chemical
10 weathering on the carbon cycle and to find its potential role on climate changes (Gaillardet et al.,
11 1997; 1999; Oliva et al., 2003). The integrated study of small watersheds is one of the best way to
12 provide direct and accurate information for the analysis of ecosystems. Although this integrated
13 ecosystem approach is common for the temperate zone, it has not yet been widely applied to the
14 tropics and especially under semi-humid climate (White et al., 1998, Braun et al., 2005). Such a
15 study is currently developed on small experimental watersheds in South India, namely, surface and
16 groundwater flow (Descloitres et al., 2007), regolith thickness and chemical weathering, physical
17 erosion, dynamic of the soil cover and including interactions among the aforementioned aspects
18 (Braun et al., 2006). Although it is today widely known that internal transformation of a soil cover
19 can influence or even govern landscape evolution through intensification or decrease of physical
20 erosion (whatever could be the parental material or topographical gradient, Boulet et al., 1977;
21 Planchon et al., 1987; Filizola and Boulet, 1996; Barbiéro et al., 1998; Furian et al., 1999), the soil
22 cover itself is still a black box in many studies on soil erosion. Moreover, very little is known about
23 natural erosion in forested areas in South India where human activity is minimal, although features of
24 erosion have been observed. The aim of this study is to identify the dynamic and to present the main
25 factors intrinsic to the soil cover that govern natural erosion on a forest area with a widespread red
26 and black soil system, by using a structural and a spatially distributed approach.

1

2

3 **2. Site**

4

5 In South India, the Western Ghats parallel to the western coast of the peninsula form an
6 orographic barrier, inducing an important climatic gradient, with annual rainfall decreasing
7 progressively from about 5000 mm in the west, to less than 750 mm just 80 km to the east (Pascal,
8 1982; Fig. 1). The climatic sequence (climosequence) is associated with changes in landscape
9 geomorphology from convex hills intermittent with flat floors to long concave glacis (Gunnell and
10 Bourgeon, 1997; Gunnell, 2000). In connection with the geomorphological changes, the soil types
11 (FAO-ISRIC-ISSS, 1998) range from Ferralsols to thin red soils (Chromic Luvisols) associated with
12 black soils (Vertisol, Vertic intergrades) in the climatic semi-humid transition area, and in the semi-
13 arid area we find Calcic Luvisol and Calcic Vertisol (Murthy et al., 1982; Pal and Despande, 1987;
14 Bourgeon, 1991; Jacks and Sharma, 1995, Gunnell, 2000). This association of red soils (Luvisols)
15 and black soil (Vertisols) is widespread on the semi-humid to semiarid area of the Deccan plateau
16 (Bourgeon, 1991). The passage in the clay mineralogy from the kaolinite-dominated humid area to
17 the smectite-dominated semi arid area is achieved progressively via an intermediate area with 2:1 K
18 clay such as illite and sericite (Bourgeon and Pedro, 1992).

19 Red soils occurring in the current seasonal semihumid to semiarid conditions (<1500 mm annual
20 rainfall and high evapotranspiration) have been considered as Paleosols or relict soils (non buried
21 Paleosols) that formed in an earlier period with a moister climate than the present, but this assertion
22 is still under debate. Some authors consider that the climatic conditions are not conducive to the soil-
23 forming processes of red soils such as deep weathering and kaolinite formation (Bronger and Bruhn,
24 1989; Brückner and Bruhn 1992). However, Gunnell and Bourgeon (1997) emphasize that the
25 presence of clay minerals yielding an X-Ray diffraction peak at 7 Å in dry climatic zone does not
26 necessarily mean that these are inherited from a Paleosol formed in more humid periods in the past.

1 They suggested further analysis, and in particular the comprehensive down-profile consideration of
2 the entire spectrum of minerals, before reaching a conclusion. In the prevailing semiarid conditions
3 (<900 mm annual rainfall), secondary carbonate is currently accumulating in the saprolite and lower
4 parts of the red soil horizons (Bronger et al., 2000). Micromorphological studies of the calcrete in
5 the semiarid area reveal a multistage origin (Durand et al., 2006a) and recent dating of calcrete
6 nodules suggests fairly stable climatic conditions at the ≥ 200 ky time scale (Durand et al., 2006b).

7 The climatic and pedoclimatic conditions are decisive in the formation of red soils (Bourgeon,
8 1991), whereas the formation of black soils depends mainly on the slow down of the solution and
9 lack of drainage usually in bottom part of the landscape. In Black soils, the presence of smectite clay
10 minerals causes appreciable shrink–swell, which induces formation of cracks and distinctive
11 structural elements such as wedge-shaped peds with smooth or slickensided surfaces (Bourgeon,
12 1991).

13 Field work was carried out on a 4.5 km² watershed located in Bandipur National Park, close to the
14 Mulehole check post at 11° 44' N and 76° 27' E (Karnataka state, Chamrajnagar district). The
15 watershed area is mostly undulating with gentle slopes and the elevation of the watershed ranges
16 from 820 to 910 m above sea level. Because it belonged to the hunting reserve of the Maharaja of
17 Mysore, the region has been preserved from agricultural activity at least since the 17th century. Later
18 it was incorporated into the Bandipur National Park, and today the only human activities are limited
19 to surveillance by the rangers of the Forest Department.

20 The studied site is located in the climatic semi-humid transition area (Fig. 1) and the mean annual
21 rainfall (n = 20 years) is 1120 mm. The climate is characterized by recurrent but non-periodic
22 droughts, depending on monsoon flows. The mean yearly temperature is around 27°C. Streams are
23 temporary, flowing for a few hours to a few days after the stormy events of the rainy season. Rainfall
24 and runoff measured at the outlet of the Mulehole watershed were respectively 431 mm and 1 mm in
25 2003, 1216 mm and 59 mm in 2004, and 1434 mm and 181 mm in 2005.

1 The substratum belongs stratigraphically to the Precambrian Dharwar supergroup (Moyen et al.,
2 2001) and consists of gneiss with amphibolites and quartz dykes. The mean strike value is N80°,
3 with a dip angle ranging from 75° to the vertical. The vegetation consists of dry deciduous forest
4 (Pascal, 1982, 1986; Agarwala, 1985) where 4 different types of vegetation have been identified: 1 -
5 a forest with vegetation mainly dominated by three species, namely *Anogeissus latifolia*, *Terminalia*
6 *alata* and *Tectona grandis*, called 'ATT facies'. 2 - a vegetation called 'Shorea facies' characterized
7 by the presence of *Shorea roburghii* and *Lagerstroemia microcarpa*. 3 - the 'Swamp facies'
8 consisting of grass-covered glades with scattered trees (*Ceristoides turgida*). 4 – the discontinuous
9 'riverine facies' along the talwegs characterized by the presence of *Syzygium cumini*, *Mangifera*
10 *indica*, *Ficus recemosa* and *Derris indica*. The first 3 above-mentioned vegetation 'facies' have been
11 identified in the Mulehole watershed, whereas the fourth one was not clearly developed and/or
12 occupied very small area.

13

14

15 **3. Method**

16

17 *3.1. Study at the watershed scale*

18

19 A contour Digital Elevation Model (DEM) was generated from 2780 topographical measurements
20 on the area (Fig. 2), with higher density close to the talwegs and to the main topographical changes.
21 An exhaustive GPS georeferenced survey of the streambeds and the soil erosion pattern was carried
22 out for the entire watershed. The eroded soil volume was roughly estimated by measuring the length,
23 width and thickness of each eroded area in relation to the surrounding non-eroded area.

24 Electromagnetic induction is becoming widespread for soil survey in general, although it has been
25 used mainly for the monitoring of spatial and temporal changes in soil salinity (Corwin et al., 2005).
26 Preliminary studies on the watershed have shown that red and black soils have a different apparent

1 electrical conductivity (EC). Therefore, soil distribution was first attempted by conducting an
 2 electromagnetic conductivity survey, using an EM31 portable device (Geonics Ltd, Ontario,
 3 Canada). The device measures an apparent conductivity (EC_m values) in milliSiemens per metre
 4 (mS/m). The EM31 has a fixed 3.66 m space between the coils (transmitter and receiver) and the
 5 measurements were carried in the vertical dipole configuration, which affords an investigation depth
 6 of about 4 to 6 m (McNeill, 1980). The measurements were carried out along 31 North-South
 7 oriented transects and with a space of 100 meters between the transects (Fig. 2). The measurement
 8 points were taken and stored automatically by a data logger every 5 seconds. A Global Positioning
 9 System (GPS) was coupled with the EM31 device in order to get the geographical coordinates of
 10 each measurement point (Cannon et al., 1994). The survey was carried out in January 2004, i.e. in the
 11 middle of the dry season.

12 The EC_m data underwent a geostatistical treatment before kriging. Duplicates were removed from
 13 the data set before treatment, on the basis of a 2 m tolerance in the X and Y directions. These
 14 duplicates are due to local difficulties in progressing through the vegetation or in crossing obstacles
 15 (topographic accidents) during the survey. A chi-squared test showed that the data might not be
 16 assumed to have a normal distribution. Therefore, the calculation was performed on a theoretical
 17 distribution of the data by lognormal transformation as recommended by Dowd (1982),

18

$$19 \quad z(x_i) = \ln(s(x_i)) \quad (1)$$

20

21 where $s(x_i)$ is the EC_m data at x_i , $z(x_i)$ is the log-transformed data. An estimate of the samples
 22 variogram is given by the formula:

23

$$24 \quad \gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (z(x_i) - z(x_i + h))^2 \quad (2)$$

25

1 Where $N(h)$ is the number of pairs of points and $z(x_i)$ and $z(x_{i+h})$ are the logarithms of the EC_m
2 values at x_i and x_{i+h} . Raw and directional variogram were calculated to detect a possible anisotropy in
3 the field. The kriged map is built from a model of variogram fitted to the sample variogram.

4 In order to relate the EC_m map to the soil distribution, forward modelling was carried out using
5 the PCloop software (Geonics, Ltd) and was based on (i) the theoretical response of the EM31 over
6 an horizontally layered medium (McNeill, 1980); (ii) resistivity measurements of representative
7 horizons in red and black soils along soil profile; and (iii) resistivity logging down auger holes
8 drilled into representative soils (Ferralsols, Luvisols and Vertisols).

9 A geological survey was carried out from the identification of about 300 georeferenced rock outcrops
10 within the watershed and the extrapolation of the data was carried out using the EC_m survey.

11 The development of vegetation depends narrowly on the hydric regime of the soil, and
12 consequently on the type and thickness of soil. Therefore, a survey of the three main types of
13 vegetation, namely the ATT, Shorea and Swamp facies was carried out across the watershed in order
14 to extrapolate the soil data.

15

16 *3.2. Comprehensive study along soil sequences*

17

18 Two soil sequences were studied on the watershed (Fig. 2). An existing spoon-shaped erosional
19 landform (rotational slip type) was targeted for the excavation of a 80 m long trench (T1) in order to
20 understand the soil morphology of the portions of landscape vulnerable to soil erosion (Fig. 3, Fig.
21 4a). The second soil sequence (T2) located where the streambed appears to be currently incising (just
22 a few meters upstream from the current incision, Fig. 4e), was studied in order to understand if any
23 specific morphology of the soil cover could favour the development of the talweg.

24 The soil pattern was studied in detail, emphasizing the geometrical relationships between the
25 different horizons identified from basic field observations (colour, texture, structure, porosity,

1 presence of coarse elements, intensity of biological activity...). The procedure follows routine
2 techniques developed by Boulet et al. (1982) and Fritsch et al. (1992).

3 In the first step, 2D electrical imaging was performed around toposequence T1 to locate the red
4 soil / black soil contact and to characterise its morphology. Five boreholes were drilled down to the
5 saprolite in the red soil, black soil and transition area, along a line parallel located at a distance of 5
6 m from T1 (Fig. 3). The different horizons of the boreholes were identified and compared to the
7 description from the trench T1 in order to map the layout of the red soil – black soil system. Soil
8 moisture was monitored during the rainy seasons 2004 and 2005 through neutron probe
9 measurements (soil moisture probe type I.H. II, Didcot Instrument Co. Ltd., Abingdon Oxon,
10 England). Measurements were carried out at every 10 cm, every 15 days, and daily during heavy
11 rainy periods. Between two successive neutron probe measurement periods, the boreholes were
12 clogged with inflatable rubber tubes inserted into the holes in order to prevent any infiltration from
13 the topsoil runoff or along the hole during rainfall.

14 For each horizon, a relationship was established between the neutron probe measurements and the
15 volumetric water content. For this purpose, bulk samples were collected while drilling holes and
16 immediately placed and sealed in metallic boxes. Simultaneously the neutron probe measurements
17 were carried out at the corresponding depth. Gravimetric water content was determined in the
18 laboratory by weighing the samples before and after oven drying for 24 hours at 105 °C. This
19 procedure was carried out at the end of the dry season (dry state) in the monitored holes and at the
20 end of the monsoon season (wet state) in new holes drilled at about 50 cm away from the previous
21 ones. The bulk density was measured using the paraffin method on aggregates collected along the
22 trench T1 in each horizon (Singer, 1986). The volumetric water content in the boreholes was
23 estimated by multiplying the gravimetric water content by the bulk density of the corresponding
24 horizon.

25 The calibration was established for each horizon using linear regression between the volumetric
26 water content against the R/Rw ratio, where R denotes the number of counts per second of neutron

1 probe in soil and R_w denotes the number of counts per second in a water standard. The calibration
2 was established on a volumetric water content range of 16 to 31% in red soil (horizons 2, 3, 4 and 5),
3 21 to 35% in black soil (horizons 7, 8, 9, 10 and 11), 12 to 30% in organic topsoil horizon (6), and
4 13% to 29% in the saprolite (horizons 1 and 13).

7 **4. Results**

9 *4.1. EC_m measurements and EC_m survey*

11 From the 10935 EC_m measurement points, 439 duplicates were discarded before treatment. The
12 conductivity values range between 0.1 and 52 mS/m, with an average value of 7.21 mS/m, and a
13 standard deviation of 7.06 mS/m. The variation coefficient (0.98) indicates a low dispersion of the
14 data around this average value.

15 The experimental variogram built from log-transformed EC_m data is presented in Fig. 5. A slight
16 anisotropy is detected by comparing the raw and directional variogram, showing a higher
17 dependence of the EC_m values in the direction $N63.6^\circ$ (East-Northeast/West-Southwest). This
18 anisotropy was taken into account for the kriging computation. In $N63.3^\circ$ direction the experimental
19 variogram shows a nugget effect of almost zero, a range of about 300 m and the scale of 0.105 (log
20 value), and therefore it fits better with an exponential model with the following characteristics: Scale
21 = 0.105; range = 300 m.

22 The kriged map presented on Fig. 6 shows that the soil electromagnetic conductivity is not
23 distributed regularly throughout the watershed. High conductivity values are located in the flat
24 bottom part of the watershed and on some areas on the crest line, while low conductivity values are
25 mainly observed along the slopes.

1 4.2. Geology

2

3 As presented on the lithological map (Fig. 7), most of the watershed is developed on paragneiss
4 (peninsular gneiss) and basic rocks (amphibolite and derived facies). The latter cover about 17% of
5 the watershed and are not related to any particular topographic locations. They can be found
6 anywhere, namely in the valley bottom, along the slope or on the crest line. Paragneiss is dominant
7 and consist mainly of quartz, feldspar (plagioclase and potassic) with a low quantity of biotite.
8 Bedrock exposures are usually poorly weathered, except along the talweg at the higher third of the
9 watershed where the gneiss occurs as non-cohesive loose saprolite.

10

11 4.3. Vegetation survey and soil-vegetation relationships

12

13 The ATT vegetation type is dominant, covering about 70% of the watershed, and has developed
14 on both, thick red soils and thin black soils with a vertic horizon usually less than 1 m thick. A few
15 isolated *Ceristoides* trees have developed into the ATT type although they are usually associated
16 with Swamp vegetation. In this case, the presence of the *Ceristoides* is always associated to higher
17 EC_m values and with the presence of a 0.5-m-thick black soil developed from an alternation of metre-
18 thick veins of gneiss and amphibolite saprolite. However, *Ceristoides* is absent in the southeastern
19 part of the watershed with ATT vegetation type and high EC_m values. Observations carried out along
20 auger holes and a pit indicated that in this area, close to the topsoil (e.g. at 0.3 m depths), we also
21 find the presence of a conductive saprolite consisting of weathered amphibolites.

22 The Swamp vegetation type is mainly located in the low parts of the watershed with some spots
23 along the crest line, and always associated with higher EC_m values. Field observations indicated that
24 it grows exclusively on thick black soils (>2 m) in the lower part of the watershed as well as on the
25 crest, covering about 5% of the area. The *Shorea* vegetation type covering about 15% of the

1 watershed occurs on very shallow red soil overlying a sandy gneiss saprolite found very close to the
2 topsoil (0.2-0.4 m below the topographic surface).

3 4 4.4. Soil distribution

5
6 The map presented on Fig. 8 was drawn from the overlay of EC_m , lithology and vegetation survey
7 and crosschecked with about 60 isolated soil observations. A clear relationship was observed
8 between the soil electromagnetic conductivity and certain soil characteristics explained below.
9 Ferralsols are usually 2 to 3 m thick and have lower conductivity, whereas Luvisols are thinner and
10 have higher conductivity. Since the EM31 response depends on both the thickness and the apparent
11 conductivity, no significant contrast was detected with this method, and it does not make it possible
12 to discriminate the spots of Ferralsols from the surrounding Chromic Luvisols. Therefore, both
13 Ferralsols and Luvisols have been grouped together into a red soil unit. The boundary between red
14 and black soils was identified at an EC_m value of 8-10 mS/m (0.9 to 1 log value) and EC_m values
15 above 18 mS/m (1.26 log value) indicates thick black soil, and this boundary is strictly in agreement
16 with the distribution of the Swamp vegetation type. However, although the relationship between EC_m
17 and soil type was tested in many places on the watershed, it was not valid for the south-eastern part
18 where the saprolite of an amphibolite type rocks was observed close to the topsoil and associated to
19 higher EC_m values (Fig. 7).

20 The major part of the watershed is covered by red soils that are about 1 or 2 meters thick and can
21 reach about 4 meters at certain locations. Thin red soils (about 0.2 to 0.5 m thick) overlying loose
22 gneiss saprolite and associated with the *Shorea* vegetation are mainly located on the central wash
23 divide between the two main talwegs and in a discontinuous crescent-shaped area along the slopes.
24 Black soils have developed on two types of location: (i) the low-lying area, occupying the lower part
25 of the slope and the flat valley bottoms. Black soil areas are about 2 m thick at the perimeter but can
26 reach more than 6 meters at the centre. They have developed from both gneiss and amphibolite

1 saprolite. (ii) At higher levels black soils are about 0.2 to 0.5 m thick, except at the depressions (50 to
2 100 m in diameter) on the crest line where the black soils can reach 2.5 m. They are always
3 associated with gneiss, which alternates with amphibolites.

4 5 4.5. Streambed features and soil-streambed relationships

6
7 Although the stream is meandering in the valley bottom, there is no undermining of the banks in
8 the convex curves or point-bar deposits inside meanders, and the stream seems to have sunk on its
9 own bed. The bottom of the streambed is steep-sided of about 2 to 4 m and flows on the hard
10 saprolite on the lower 2/3 of the watershed, and on the soil cover on the upper 1/3 part of the
11 watershed. At several places of lower third of the watershed, roots of trees such as *Tectona grandis*
12 are occasionally crossing the streambed at about 1 m from the bottom (Fig. 4g). A peculiar
13 distribution of streambed was observed in relation to the black soil developed downslope: When the
14 streambed enters a black soil area, it does not flow straight through it but gets around the thick black
15 soil area and meanders into the thin black soil as shown on Fig. 8.

16 17 4.6. Types and distribution of erosion spots

18
19 All the erosion spots are located in the vicinity of the talwegs (i.e. less than 30 meters). Three
20 main types of erosion were identified (Sidle et al., 1985) and their descriptive statistics are given in
21 Table I.

22 The first and the most widespread type is a rotational slip (25 sites) with vertical edges, whose
23 standard dimensions are about 5 m wide, 25 m long and 2 m deep (Fig. 4a and d). In most of the
24 slips, the material has been subsequently evacuated towards the stream. This type of erosion is well
25 developed in the bottom area and within the lowest third of the watershed. All the slips are
26 distributed at the crossing between the streambeds and the iso-conductivity line of 11 mS/m, i.e. very

1 close to the contact between red and black soils. More precisely they are slightly inside the black soil
2 area (Fig. 8) and always develop towards the red soil domain.

3 The second type (14 sites) refers to superficial erosional scars whose widths and lengths are about
4 2 or 3 meters, respectively, with depths of about 0.5 m thick (Fig. 4b). This landform is provoked by
5 occasional seepage occurring at the top of the black soils at a textural contrast between a clay horizon
6 and the sandy topsoil horizons with many coarse elements such as ferruginous nodules, quartz, etc. It
7 was found in several places such as at the bottom parts of the watershed, along the slopes and close
8 to the crest line.

9 The third type (7 spots) is much wider than type 1 and 2 and the average eroded soil volume
10 reaches 3300 m³ per spot (Fig. 4c). Although the lower part is predominantly a flow movement, the
11 upper part involves recurrent small sliding. It has developed in the vicinity of the streambeds, but
12 only at places where the non-cohesive saprolite of the gneiss is close to the topsoil. In other words it
13 occurs within the uppermost third of the watershed and at the intersection between the streambeds
14 and the crescent-shaped area where the *Shorea* vegetation was surveyed.

15

16 4.7. Soil morphology at the red soil-black soil contact

17

18 Fig. 9a shows the soil distribution pattern along the contact between red and black soil, which can
19 be easily divided into two domains. Upslope, a 3 m-thick red soil overlies white gneiss saprolite. In
20 the saprolite (1) the structure and the sub-vertical foliation of the rock itself is still preserved. Five
21 horizons (2 to 6) have been distinguished in the red soil. From the bottom to the top of the profile,
22 these horizons differs mainly by their colour evolving from grey (7.5YR6/1), brown (7.5YR4/4),
23 reddish-brown (7.5 to 5YR4/4) then red (5YR4/3 to 4/2), and also by the structure evolving from
24 angular blocky to micro-aggregate and granular. Ferruginous nodules (3 to 6 mm) are observed from
25 the top of the gneiss saprolite to the topsoil horizon (6), with a maximum of concentration at the top

1 of horizon (4). The above-described horizons (2 to 6) are parallel to each other and to the topography
2 of the slope.

3 Downslope, lateral morphological changes occur from the bottom of the soil to almost close to the
4 topsoil, where clay films coat the structural faces of the soil aggregates. The presence of clay films
5 defines horizon (7), which intersects horizons (2), (3), and (4) without changing their respective
6 structures. The clay films become thicker in horizon (7) while moving downslope and it
7 progressively turns into a 10 to 20 cm-thick clay horizon (8), which is dark red-brown (5 to
8 7.5YR3/2 to 4/2) with a coarse angular blocky structure. The blocks are compact, hard and separated
9 by vertical and sub-horizontal cracks but without slickensides. Horizons (7) and (8) have many
10 ferruginous nodules, and they extend the maximum of nodules observed into horizon 4. Horizon (9)
11 differs from horizon (8) wherein the colour shifts to dark brown (5 to 7.5YR3/2 to 2/2) and the
12 structure becomes clearly vertic (15 cm wide) with sub-horizontal slickensides. Horizon (10) below
13 (9) is horizontal, concordant with the flat valley bottom occupied by black soil cover on the right side
14 of Fig. 9b. It is more greyish (10YR3/1 to 3/2) and the vertic structure of about 7 to 8 cm is still
15 dominant but with an angular blocky sub-structure. At horizon (11) the soil material progressively
16 turns into saprolite of the gneiss in which the lithologic structure is still preserved. Isolated volumes
17 of the saprolite preserving the orientation of the parental material are observed up to the base of
18 horizon (10).

19 In addition to the above-mentioned description, two bleached horizons have been identified,
20 discriminated from a contrast in colour (lighter) and texture (more sandy) and structure (massive).
21 The first one (12) lies above horizons (7) and (8), evolving downslope progressively from dark
22 (5YR3/2) clay-sand to light (7.5YR4.5/3) sand. In this horizon the bleaching increases downslope
23 and there is a higher proportion of coarse elements (centimetre-sized angular quartz fragments,
24 ferruginous nodules). The presence of nodules is an extension from the already mentioned nodules in
25 horizon (4), (7) and (8). At the upslope part of horizon (12), the coarse elements are separated from
26 each other by a sandy clay matrix whereas downslope they are more frequently in contact with each

1 other. Towards the stream, horizon (12) becomes thicker and its organisation intersects the black soil
2 system comprising of horizons (8) to (11). Horizon (12) is itself intersected by the incision of the
3 talweg, but a similar sandy bleached material, although cemented probably by amorphous silica, was
4 observed in the middle of the streambed.

5 A second bleached horizon (13) is observed within the saprolite of the gneiss between 11 and 1. It
6 is about 0.8 meter thick close to the streambed, wedge-shaped and extends up to 30 m upslope.

7 Sequence T2 is located across a depression developed along a red soil-black soil contact (Fig. 10).
8 The layout along T2 is almost similar to that along T1, except that it is not intersected by the incision
9 of the streambed (Fig. 4e). In the depression, a sandy horizon, with location and characteristics
10 similar to those of horizon (12) of T1, has developed at the top of the vertic clay horizon. At the
11 downslope of horizon 12 although the texture is sandy, the vertic structure of a previously clay
12 horizon is preserved (Fig. 4f) probably due to the cementation by amorphous silica. The shape and
13 the size of the structure are similar in every respect to that observed in the clay vertic horizon (10).

14

15 *4.8. Hydrodynamic behaviour of the red soil-black soil system*

16

17 There is a strong contrast in the evolution of the water contents between A5 and A2 whereas
18 along A3, A1 and A4 the evolution is intermediate. Therefore, the description here will be limited
19 along these two end members, i.e., A5 for the red soil and A2 for the black soil. At the end of the dry
20 season, a uniform 20% volumetric water content is found along the red soil profile A5 (Fig 11a,
21 curve 1). At the beginning of the rainy season, the moisture content increases and the moisture front
22 lowers regularly down to the saprolite (curve 2). During the wet season, the volumetric water content
23 remains almost uniform along the profile, oscillating from about 30% immediately after the rainy
24 events (curve 3) to 27% after draining the gravity water (curve 4).

25 Along A2, at the end of the 2004 dry season (Fig 11b, curve 1), the water content was more
26 contrasted. Values of about 20% at 0.2 m depth increased progressively to about 27% in the vertic

1 clay horizon (9) and (10) between 0.8 to 1.8 m depth, and decreased again down to 20% in the
2 saprolite (11) and, at further depth, reached 15 to 19% in the bleached horizon (13). Similar to what
3 was described along the red soil profile, a regular progression of the moisture front is observed at the
4 beginning of the wet season at the topsoil horizons (6) and (12) (curve 2 and 3). When the moisture
5 front reached the clay horizon (8) and (9), the water rapidly descends to the bottom of the clay
6 horizon (10) until the top of the saprolite (11) and the moisture content reaches 35% (curve 4). A
7 strong rainfall event occurred on August 5, 2004 (Fig. 11c, curve 2). The water content increased by
8 about 3 to 5% all along the profile whereas an abrupt increase was observed at 3 m in horizon (13).
9 The water content increased up to 65% but this value is not reliable because it is beyond the
10 calibration range of the neutron probe (maximum water content of 35%). A few hours later the water
11 content had decreased again to about 20%, indicating that the water drained out quickly at horizon
12 (13) (curve 3).

13 In 2005, the moisture conditions at the end of the dry season (Fig. 11c, curve 1) were very close to
14 those at the same period in 2004 (Fig 11b, curve 1). The 2005 rainy season started earlier but with
15 two main rainfall events in April and July separated by a dry period. In the black soil, a different
16 behaviour of the moisture front was observed during these two rainy periods. During the first one,
17 similar to what was observed during the previous rainy season of 2004, the moisture front reached
18 clay horizon (8) and moved quickly along the profile A2 down to the top of the saprolite (11). During
19 the dry interval, the moisture content decreased along the profile, and particularly in the topsoil
20 horizon. At the following rainfall event, the moisture content increased again in the topsoil horizons
21 with maximum water in the sandy horizon (12) (Fig 11c, curve 4). After a few days, the water
22 content increased again in the clay horizons (8), (9) and (10).

23

24

25 **5. Discussion**

1

2 *5.1. Reliability of the EC_m survey*

3

4 The experimental variogram built from EC_m data shows no nugget effect, which emphasizes that
5 there is no variability in EC_m response at short distance. The absence of a nugget effect testifies to
6 the stability of the EC_m values measured by the EM31 device. It also indicates that the high density
7 of measurements is sufficient to take into account the variations and describe the spatial structure of
8 conductivity at short distance. Moreover, the interspace between the transects (100 m) is below the
9 range value of 300 m shown on figure 5, indicating that the density is also sufficient for a good
10 assessment of EC_m distribution between the transects. The elaborated EC_m map is therefore a reliable
11 tool for the extrapolation of soil and rock data on the studied area, and to discuss soil distribution.

12

13 *5.2. Hydrological behaviour of an area vulnerable to erosion*

14

15 The neutron probe monitoring carried out along sequence T1 shows two different types of
16 hydrological behaviour of the black soil during the season.

17 At the beginning of the wet season, the cracks of the vertic clay horizon are open, favouring
18 infiltration down to the saprolite after the moisture front reached the vertic horizons (9 and 10). This
19 distinctive behaviour has often been described in black soils of South India (Hodnett and Bell, 1981).
20 Several authors have observed that the cracks are usually open down to 2 m deep at the beginning of
21 the wet season, and ending at the slickenside zone which is most strongly expressed at or just below
22 the depth of the cracks in thick black soils (Kalbande et al., 1992). A similar information is given by
23 Hodnett and Bell (1981), who found essentially no infiltration below the black soils where the clay
24 horizons were deeper than 2 m whereas large quantities of water infiltrates at places where the
25 saprolite is observed at less than 2 m deep and is reached by the cracks.

1 The effect of the swelling and closing of the cracks is emphasised with the neutron probe
2 monitoring in 2005. During the first rainy event, the cracks are open and allow a fast distribution of
3 the water down to the saprolite, whereas during the second one, the cracks are closed which
4 significantly decreases the infiltration that results in the formation of a perched watertable in the
5 subsurface at horizon 12. Radhakrishna and Vaidyanadhan (1994) reported that the seasonal changes
6 in water infiltration in some black soils can shift from more than 70 mm.h^{-1} at the beginning of the
7 rainy season to less than 0.1 mm.h^{-1} after swelling and closing of the cracks.

8 The monitoring along T1 also indicates a substantial but fleeting increase in the moisture content
9 observed below 3 m depth during the floods (Fig 11c, curves 2 and 3). It is attributed to a lateral flow
10 from the streambed into the porous horizon (13). The water is very quickly evacuated from horizon
11 (13), which confirms that bleaching in this horizon can be attributed to a currently ongoing process.

12

13 *5.3. Soil distribution and relative chronology in the soil cover*

14

15 On the one hand, black soils mainly occur in the valley bottom although not exclusively, because
16 they are also found at certain spots along the slope and at the crest line. On the other hand, black
17 soils are sometime related to the presence of amphibolite, but they are not exclusively on
18 amphibolites alone since they are frequently observed on gneiss saprolite as well. Therefore,
19 although dry climate ($< 1200 \text{ mm}$), downslope topography and lack of drainage are considered
20 important factors in the development of black soils, our observations suggest that both topography
21 and lithology have influenced their formation.

22 The soil cover morphology, comprising the layout of the horizons in cross section and more
23 precisely the concordances or discordances between several sectors of the soil cover, make it
24 possible to draw the relative chronology in the formation of the soil-streambed system. Five different
25 ensembles are distinguished, namely the red soil, the black soil, the bleached horizon (12), the
26 streambed, and the bleached horizon (13), and they are referred as systems A to E on Fig. 9b and 10.

1 The red soil system A is developed along the slopes under good drainage conditions, and consists of
2 horizons concordant with the slope topography. The regular evolution from the saprolite of the gneiss
3 to the topsoil suggests that this material is autochthonous and has developed from the gneiss. B is the
4 black soil system with horizons concordant to the flat valley bottom and developed under bad
5 drainage conditions. The following two arguments allow us to conclude that B progresses at the
6 expense of A. 1. At the contact between the two systems A and B, we observed that B is developing
7 from the base of the red soil system, first with the clay films on the structural faces of horizon (2), (3)
8 and (4). The clay films are located around and not within the aggregates, and this pattern must be
9 interpreted as formation and not destruction of clay material. 2. The morphology of the red soil is
10 intersected by that of the black soil, indicating that the latter has developed more recently and at the
11 expense of the red soil material. Within horizon (11), isolated volumes of the saprolite still preserve
12 the orientation of the parental material, which indicate autochthony. The same is observed at the base
13 of the black soil on the right side of the stream, and no morphological discontinuity nor evidence of
14 alluvial/colluvial deposits has been detected towards the top of the black soil profile. Therefore, we
15 suppose that the black soil has developed on autochthonous material. This point could be debated
16 because the vertic horizon is known to homogenise the material due to the shrinkage-swelling effect,
17 and could have removed a possible discontinuity in the soil profile. The structural approach alone
18 does not make it possible to settle the argument.

19 On the left side of the stream, the morphology of the black soil B is in its turn intersected by the
20 horizon (12) (C), which has therefore developed subsequently after B. Because C starts occurring
21 close to the topsoil and just downslope from the contact between A and B, it suggests that C is
22 induced by lateral and sub-surface drainage at the top of B where a perched watertable is fleetingly
23 occurring during rainfall. It develops downslope due to a longer duration of the episaturation.

24 The fourth system (D) is the streambed itself, which intersects B and C. The black soil
25 morphology B is horizontal and observed on both sides of the stream, and the vertic horizons (10)
26 and (11) of the B system are in particular intersected by the streambed D. We conclude that the soil

1 cover, previously continuous and almost horizontal, was removed by the later incision of the
2 streambed, which is also confirmed by the presence of roots crossing the streambed.

3 The streambed D also intersects unit C. The chronology of C with respect to the formation of the
4 streambed is debatable. On the one hand, C could have been provoked or favoured by the drainage
5 induced by the talweg and therefore have developed subsequently. On the other hand, C could have
6 developed first and have been subsequently incised by the streambed. The soil cover morphology
7 along sequence T2 shows that C is continuous and had developed before the incision of the
8 streambed D (Fig. 4). Therefore, and because of the similarity in the morphology of both T1 and T2,
9 it suggests that the same had occurred at T1.

10 Eventually, the bleached horizon (13) E has developed at the base of the black soil and within the
11 saprolite of the gneiss. E intersects the red soil-black soil contact and is almost horizontal, i.e.
12 concordant with the water level in the stream. Therefore we attribute the bleaching in E to the fast
13 oscillation of the watertable induced by the stream and highlighted by the neutron probe monitoring.
14 E is well developed on the left side of the stream in the gneiss saprolite, i.e. towards the red soil
15 system. On the right side of the stream, however, the thickening of the vertic clay horizons (10) and
16 (11) obstructs its development and it is therefore only a few decimetres wide.

17

18 *5.4. Downslope landscape evolution*

19

20 We previously concluded that the development of the streambed is a recent process that took
21 place after the development of the soils. Moreover at the watershed scale, we observed that the
22 streambed lies within the thin black soil, skirting around the thick black soil area. It suggests that the
23 thin black soils have favoured or guided the development of the drainage network. Based on the
24 above-mentioned observations of the relative chronology and hydrological behaviour of the soil
25 cover we can propose a model of recent evolution for this downslope part of the landscape described
26 in four steps (Fig. 12):

1 At stage 1, red soils occupy the slope, whereas black soils are developed on the flat valley bottom.
2 At the beginning of the rainy season, the cracks are opened down to about 2 m deep in the thick
3 black soil area and they end within the clay horizon, which prevents deep drainage. However, close
4 to the border of the black soil area, although the cracks reach the same depth, they end at the sandy
5 and permeable saprolite located below that enables the infiltration of a large quantity of water during
6 the first events of the rainy season.

7 At stage 2, the chemical erosion or leaching is likely to have provoked the formation of a
8 depression that will develop preferably in the thin black soils. Infiltration in the black soils occurs
9 only at the onset of the wet season. During the rainy season and after the closing of the cracks,
10 permeability of the black soils decreases and the depression behaves as a gutter collecting the runoff
11 water. In its turn, the flow of water in the depression at the outer part of the black soil will favour the
12 soil bleaching and horizons will progressively turn sandy.

13 Soil bleaching leads to stage 3 that corresponds roughly to the morphology observed along
14 sequence T2. Observations at sequence T2 confirm that the formation of the streambed is preceded
15 by the presence of the depression along the contact between red soil and black soil where the
16 bleached system C has developed. The central part of the system C is cemented and a vertic structure
17 is observed. The vertic structure could not have developed within the sandy material observed at
18 present in system C but within a swelling clay horizon of the system B. During bleaching and
19 textural change from B to C, the vertic structure is supposed to disappear. The presence of the vertic
20 structure in C suggests that cementation and bleaching have occurred simultaneously, which made it
21 possible to maintain the vertic structure in the sandy material C. On the left and at the contact
22 between A and B the soil solution slows down, favouring the formation of clay coating around
23 aggregates through over saturation of the soil solution with respect to silicate clays that led to the
24 development of horizons (7), (8) and (9).

25 At stage 4, the streambed had developed down to the saprolite of the gneiss into the depression
26 and in the sandy horizons of system C. A portion of C is preserved because of cementation by

1 amorphous silica. The presence of the streambed could favour the bleaching in horizon (12) at the
2 top of the vertic clay. During the rainy season, the rapid oscillations of the watertable provoke the
3 bleaching in the saprolite and the formation of system E.

5 5.5. *Soil erosion relationships*

7 The afore-described model for the formation of the soil cover is in agreement with the
8 observations made at several scales on our study site. At the watershed scale, the model explains why
9 the streambed is passing through the thin black soil area instead of crossing directly through the
10 middle of the flat bottom area covered with thick black soil. At the scale of the sequence, the model
11 is in agreement with the soil morphology observed along T2 and T1, respectively before and after the
12 incision of the streambed. It also agrees with the hydrological behaviour in the black soil along soil
13 profile A2. The development of the natural erosion in this area can be explained through the
14 interaction of the stream and its distribution, with the type of soil cover and its hydrological
15 behaviour. We will consider landform types 1, 2, and 3 successively.

16 Rotational slips (type 1) and seepage erosion (type 2) occur close to the contact between red and
17 black soil. The type 1 features are favoured by the presence of system E. The neutron probe
18 monitoring shows that a temporary watertable occurred very fleetingly within E when the water level
19 was up in the stream. The thickening of the vertic clay horizon is obstructing the development of the
20 system E towards the centre of the black soil area, but it developed predominantly from the
21 streambed towards system A into the permeable saprolite. Because the system E is the plane of
22 weakness for the erosion type 1, the rotational slips are also predominantly developed towards the
23 red soil system A, and concern the whole soil cover down to the saprolite.

24 Seepage erosion (type 2) develops in system C at the upper part of the black soil. Because of the
25 swelling in the black soil, the cracks get closed usually in the middle of the wet season, i.e. during
26 the month of July. Later, heavy rainfall and less infiltration provoke the formation of a perched

1 watertable within C and the water flows sub-superficially towards the streambed. Whatever the
2 process of clay elimination may be (leaching, ferrolysis...), the bleaching increases downslope
3 resulting in a relative accumulation of the coarse elements, which become contiguous. Hence the
4 whole bleaching process increases the vulnerability to erosion, which probably occurs in soaked (C)
5 material during heavy rainfall, leading to sub-surface seepage erosion at the contact between (B) and
6 (C).

7 The third type of erosion is not related to the red soil-black soil system, but to the non-cohesive
8 sandy saprolite of the gneiss when it is exposed close to the topsoil. The erosion is due to the
9 seasonal throughflow seepage of the watertable occurring within the sandy saprolite over the less
10 permeable fractured rock during the rainy season. The combination between earthflow and sliding
11 (type 3) occurs mostly in midslope positions (Fig. 8) and further studies should focus on it as a
12 possible regional feature. In this case, these large erosional scars could influence the geomorphologic
13 landscape evolution at wider scale and further study should also focus on the agreement between
14 midslope erosion and the regional geomorphologic model proposed by Bourgeon and Gunnell (1998)
15 and Gunnell et al. (2003).

16

17

18 **6. Future directions**

19

20 The objective of this study was to understand the distribution, dynamics and the factors intrinsic
21 to the soil cover that are likely to influence or even govern the development of present and recent
22 natural erosion in the forested area of South India. This aim was tackled through a structural
23 approach of the soil cover, which includes the overlay of various types of survey at the watershed
24 scale (electromagnetic induction, soil, geology, vegetation), and the study of concordances-
25 discordances between horizons along representative soil sequences.

1 The present erosion is not randomly distributed. Three different types of erosion have been
2 identified: Downslope rotational slips are governed by a temporary watertable within a bleached
3 saprolite at the base of black soil-red soil transition. Seepage erosion is caused by a perched
4 watertable occurring after closing of the cracks at the top of the vertic clay horizon of black soil. At
5 midslope, a combination of earthflow and sliding occurred at places where the non-cohesive sandy
6 saprolite of gneiss is exposed close to the topsoil.

7 Our study highlights the relative chronology in the development of the downslope soil cover and
8 in particular we show that the geomorphology of valley bottoms and their erosion have been recently
9 reactivated with the development of streambeds. Further research effort should focus on the study of
10 the pedological processes prior or subsequent to the development of the streambeds in order to
11 identify their contribution to the quality of the stream water. In particular, because silica cemented
12 horizons have been observed at several points along the streambed, they are likely to be integral
13 components of the soil system. Therefore, further study should focus on the identification of the soil
14 forming processes that provide aqueous silica to this part of the system.

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16

17 **Acknowledgments**

18

19 This study was supported through the research project “Kabini river basin” of ORE-BVET
20 (Observatoire de Recherche en Environnement-Bassin Versant Expérimentaux Tropicaux,
21 www.orebvet.fr), the French national programs “ECCO-PNRH” and “ACI-Eau” funded by
22 IRD/INSU/CNRS, the Indo-French Centre for the Promotion of Advanced Research (IFCPAR WA-
23 3000), and the Embassy of France in India. We thank Dr C. Camerlynck from UMR 7619 Sisyphe,
24 University of Paris 6 for providing the EM31 equipment, Dr R. Wins (BRGM) for its contribution to
25 the geological survey, the Karnataka Forest Department for providing the access to the site, and Dr.
26 Vasanthi Dass for editorial advice.

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7

8

9 Figure captions

10

11 Table I: descriptive statistics of the erosion area at Mulehole watershed.

12

13

14 Fig. 1: Climatic gradient on the backslope of the Western Ghats (black lines are isohyets), main river
15 course and location of the Mulehole studied site in southern India (modified from Gunnell and
16 Bourgeon, 1997).

17

18 Fig. 2 : The studied watershed of Mulehole, topography (in metre), streams, North-South Ecm
19 measurement transects (.....) and soil sequences T1 and T2.

20

21 Fig. 3 : Plan view of the toposequence T1, red and black soils distribution, streambed and neutron
22 probe access holes.

23

24 Fig. 4 : a) a rotational slip erosional landform (erosion type 1) was targeted for the excavation of a 80
25 m long trench (T1); b) seepage erosion (type 2) at the top of black soil profile; c) midslope erosional
26 landform (type 3) resulting from the combination of seepage and mass movements into the non

1 cohesive material of the gneiss saprolite; d) rotational slip, the material has been partially evacuated;
2 e) linear depression where the stream is currently incising; f) detail of the profile in the depression of
3 T2 showing the vertic structure (defined by vertical and sub-horizontal cracks indicated by arrows)
4 preserved in the sandy material due to silica cementation (knife is about 25 cm); g) roots of *Tectona*
5 *grandis* crossing the streambed at about 1m high from the bottom, indicating recent incision.

6

7 Fig. 5 : Experimental variogram for electromagnetic conductivity (EC_m) data and adjusted model.

8

9 Fig. 6 : Kriged map of soil electromagnetic conductivity (EC_m) at the Mulehole watershed.

10

11 Fig. 7 : Lithological map of the studied area.

12

13 Fig. 8 : Soil cover on Mulehole watershed and distribution of erosion spots. 1- rotational slip; 2-
14 seepage erosion at the top of black soil; 3- seepage erosion and mass movement in non-cohesive
15 saprolite at midslope.

16

17 Fig. 9 : Cross section along the toposequence T1, showing a: the morphology of the red soil-black
18 soil system (numbers refers to the horizons described in the text); b: Relationships with the
19 development of the stream and the erosion type 1 and 2 (letters refers to the different steps in the
20 development of the soil cover and streambed described in the text; cross-hatched area is part of (C)
21 cemented by amorphous silica).

22

23 Fig. 10 : Morphology of the soil cover along the toposequence T2 showing the development of
24 bleached horizon 12 in the depression before the incision by the stream (numbers refer to the
25 horizons described in the text, and letters refer to the different steps in the development of the soil
26 cover and streambed described in the text).

1

2 Fig. 11 : Neutron probe monitoring along red soil profile A5 (a), and black soil profile A2 (b) and
3 (c), numbers on the curves refer to comments in the text.

4

5 Fig. 12 : Four-stage model showing the relative chronology in the recent formation of the soil cover
6 at downslope. 1. Initial red soil-black soil contact (arrows denote the water flow along cracks and
7 within the saprolite); 2. Development of the depression in the thin black soil; 3. Bleaching in the
8 depression and hardening due to amorphous silica; 4. Incision of the stream and bleaching in the
9 saprolite below the black soil (system E).

10

1

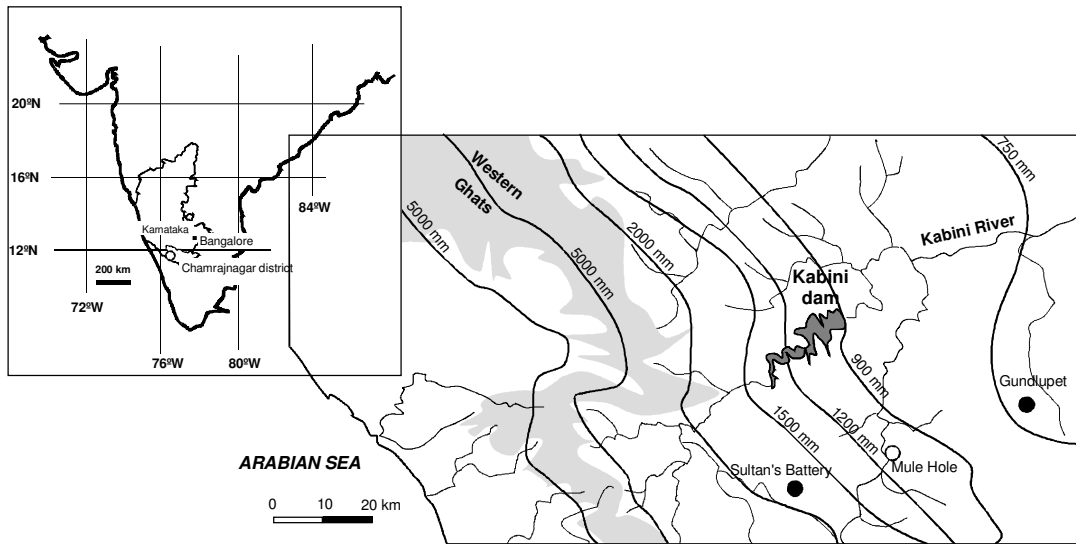
Erosion type	Number of spots	Mean eroded soil volume m ³	Standard deviation of eroded soil volume
Type 1: rotational slips	25	250	48
Type 2: seepage erosion	14	5	1.4
Type 3: recurrent combination of earthflow and sliding	7	3300	926

2

3 Table I: descriptive statistics of the erosion area at Mulehole watershed.

4

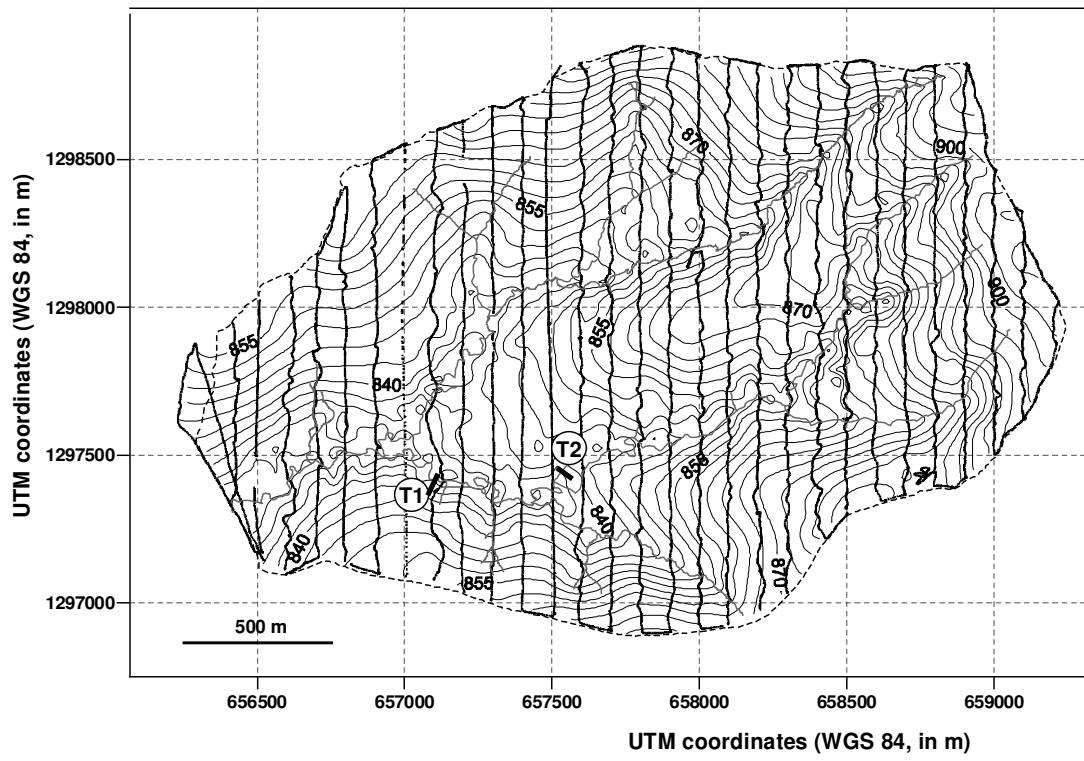
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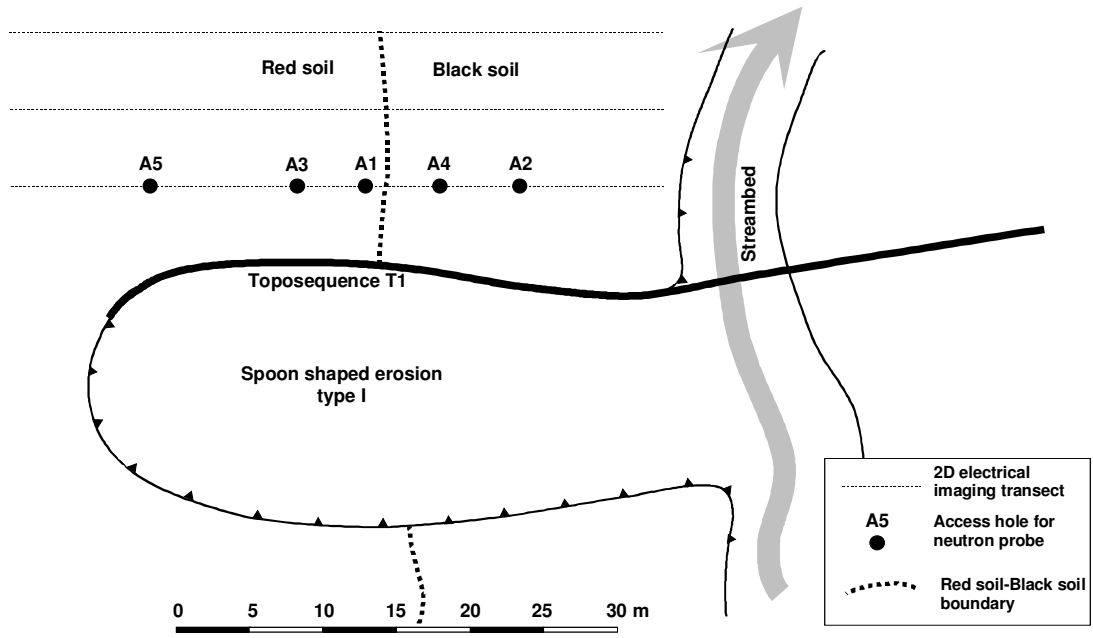
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1 Fig. 2 :



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1 Fig. 3 :



2
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1 a



2 b



c



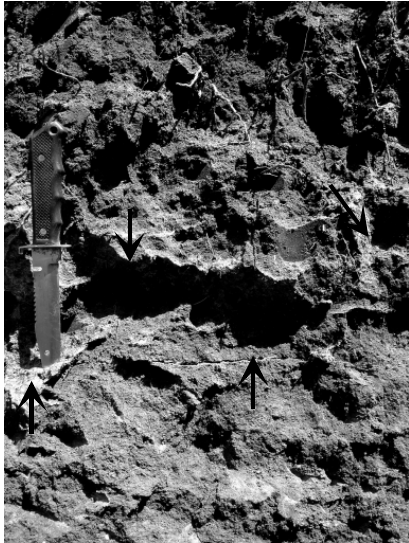
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e

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Fig. 4:



f

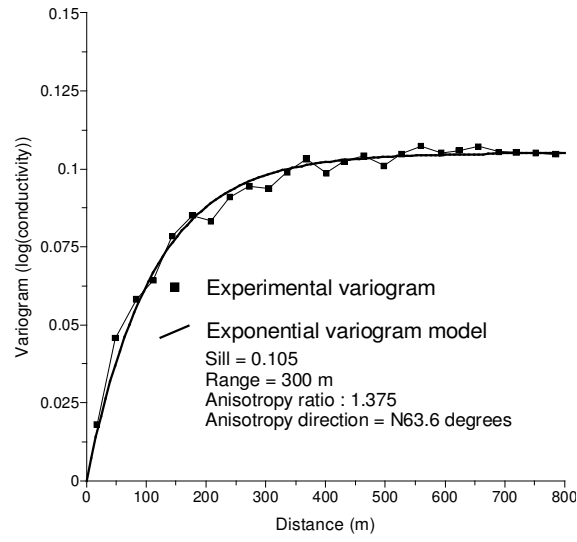


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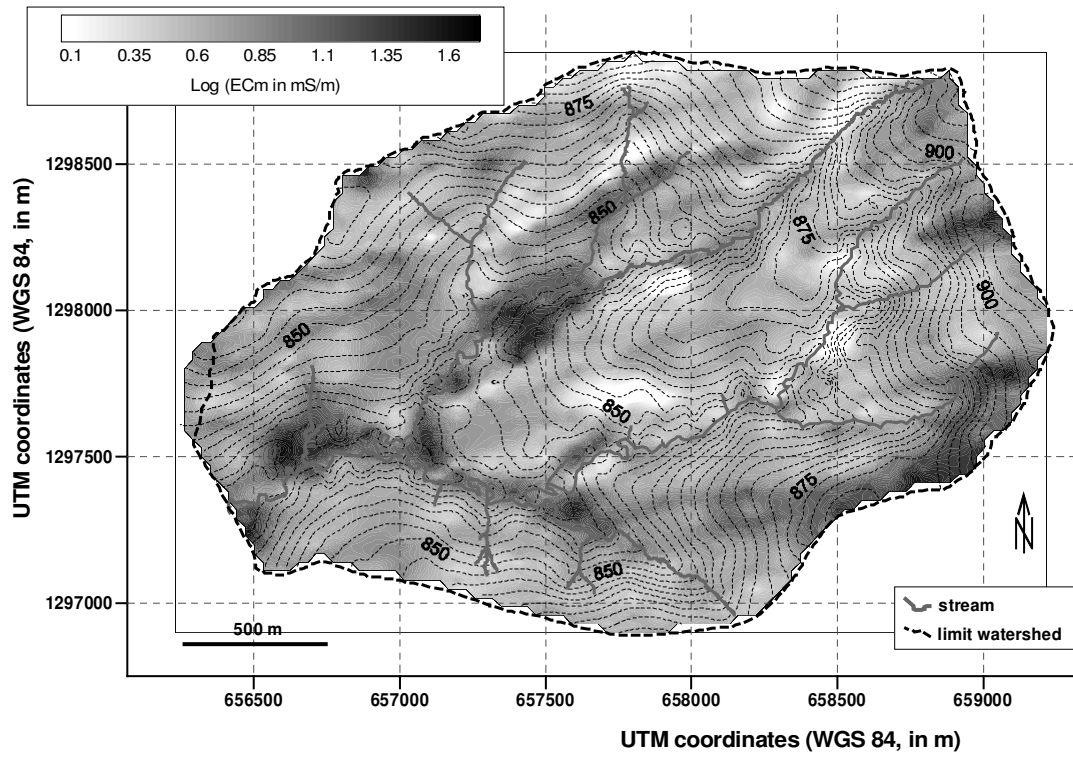
Fig. 4 (end):

1 Fig. 5 :



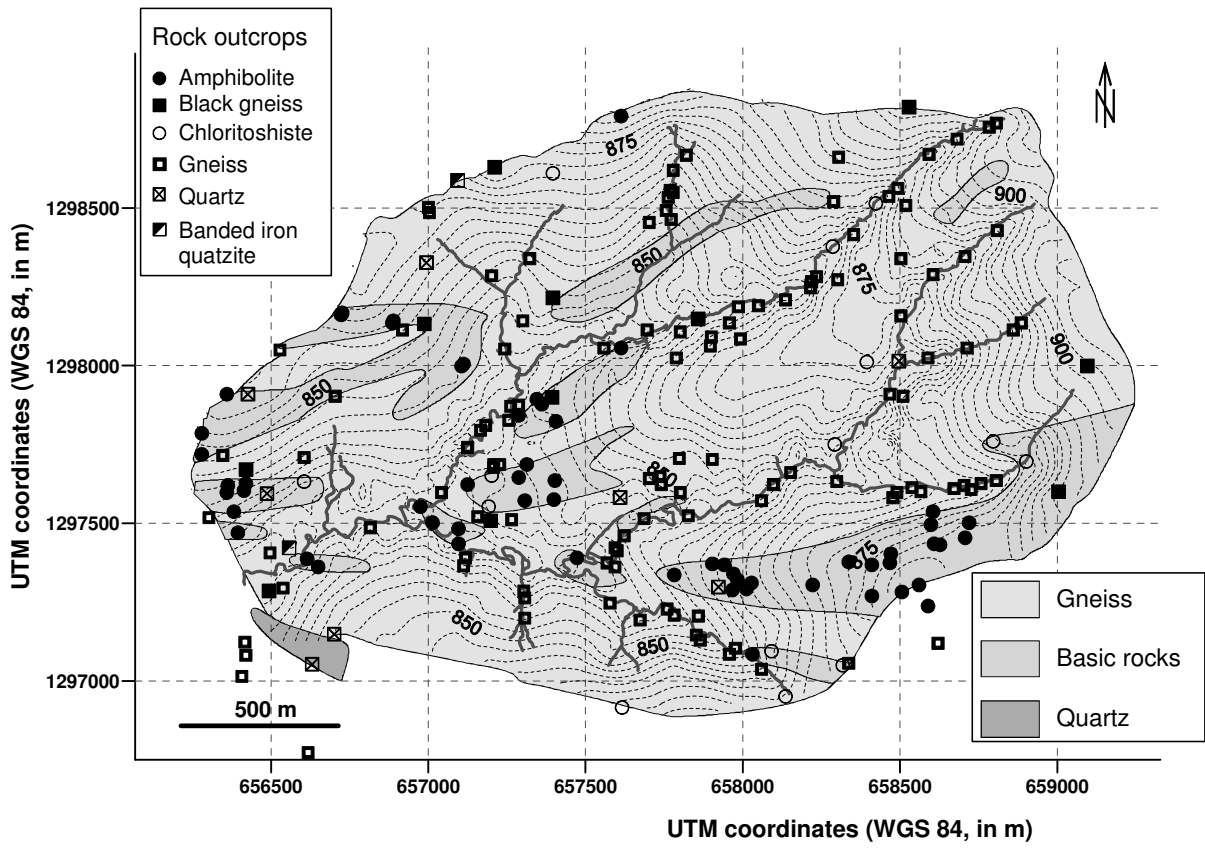
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1 Fig. 6 :



2
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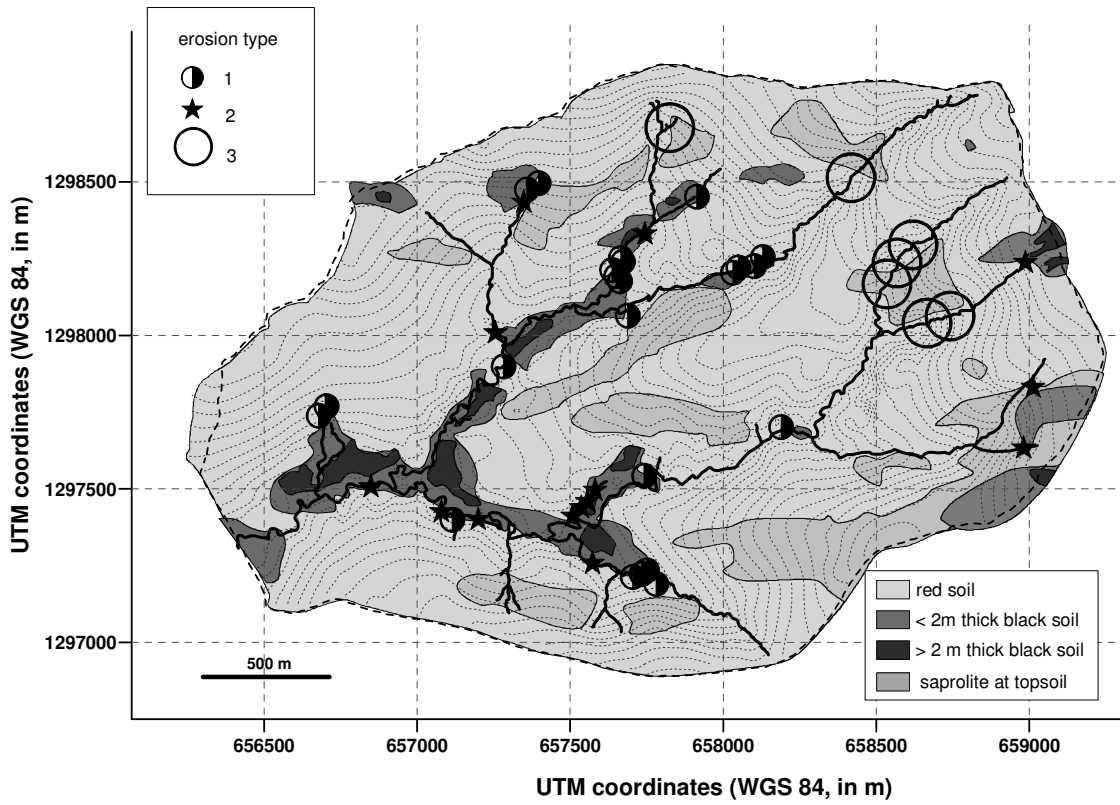
1 Fig. 7 :
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1 Fig. 8 :

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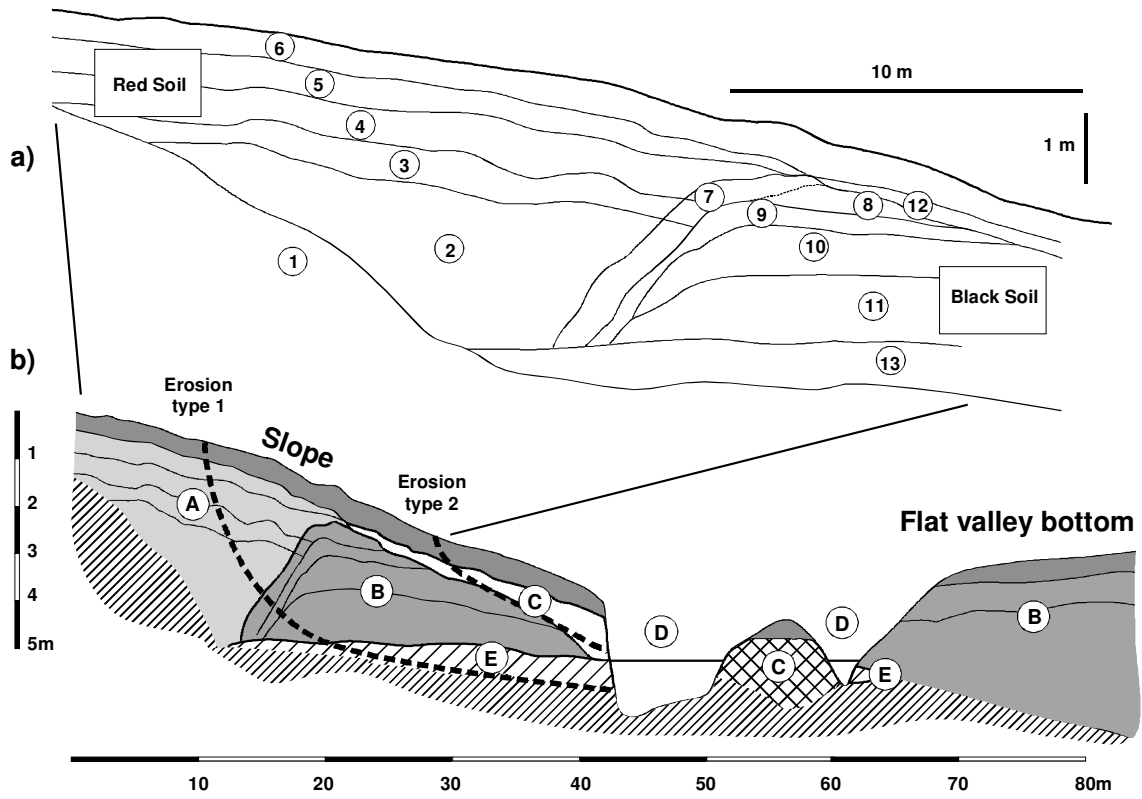
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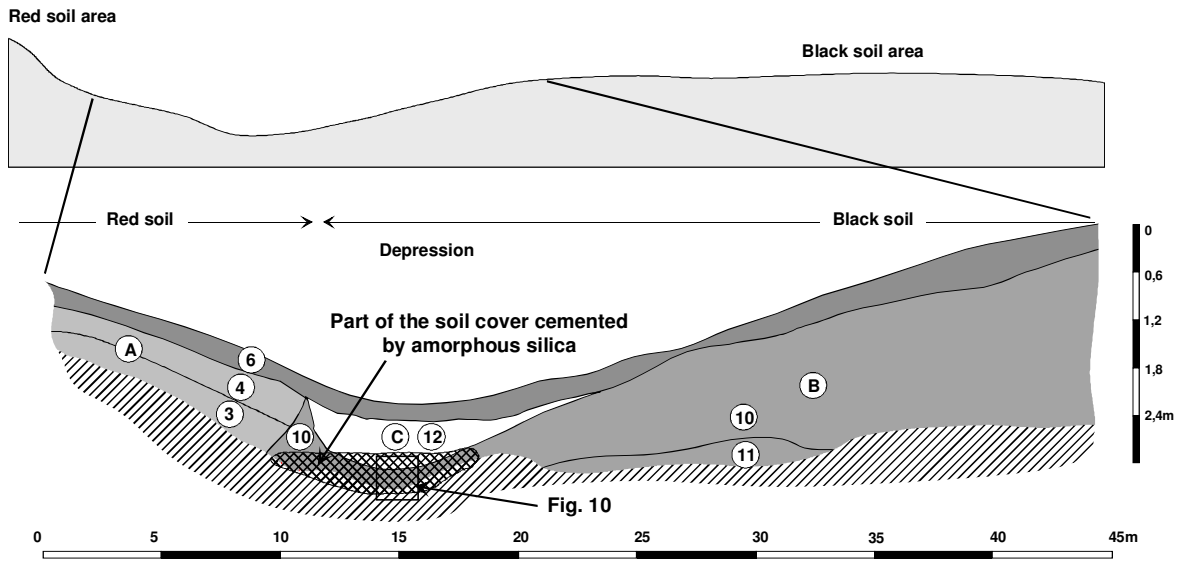
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1 Fig. 9:



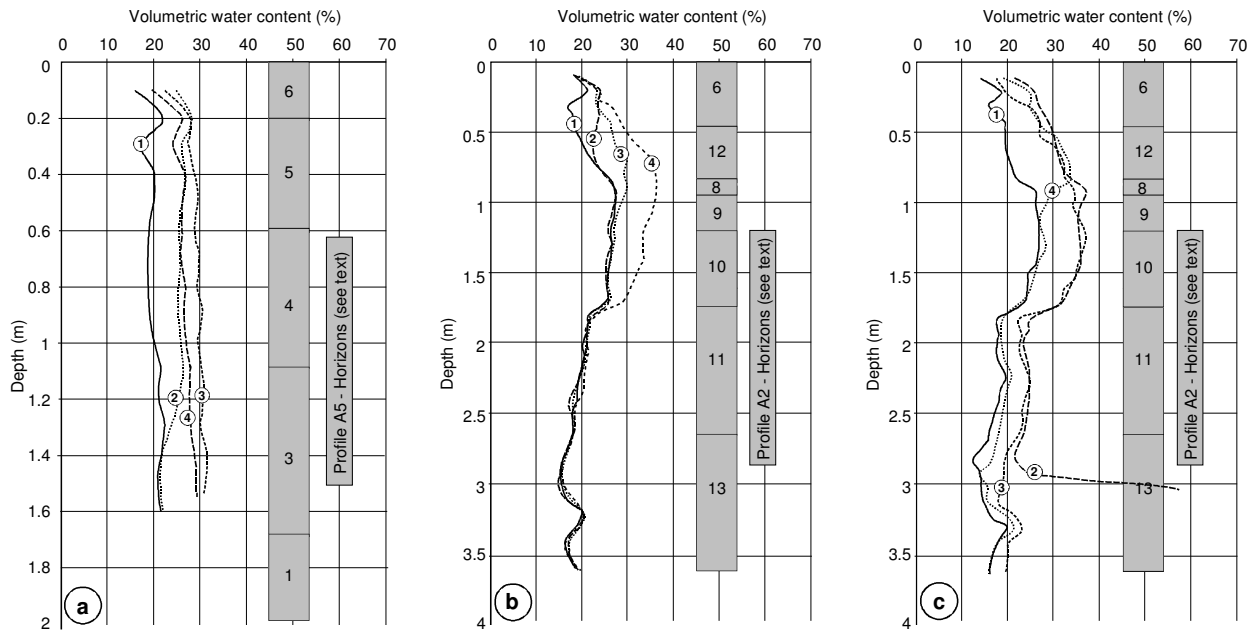
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1 Fig. 10 :



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2 Fig. 11 :
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1 Fig. 12 :
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