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Elemental Geochemistry of Soils in Relation to Lithology and Topography : A Case Study from Penneru River Basin, Kadapa District, Andhra Pradesh

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Abstract: In part of the Pennar basin, YSR Kadapa district, Andhra Pradesh, soil transect studies on Gandikota formations with six profiles were conducted. These studies were conducted to examine differences in weathering patterns of soils in relation to lithology and topography. The soils on Gandikota formations have ochric epihorizons ranging in color from reddish yellow to brown and brown to dark brown cambic horizons. Middle slopes show lithological discontinuities with erratic sand-to-silt ratios. It seems that these soils are slightly acidic to strongly alkaline with a high capacity for cation exchange, exchangeable sodium percentage, and a ratio of CEC/clay greater than 0. 7. Clayeness ($mAl_2O_3/mSiO_2$), calcification, and sodification are dominant pedogenic processes with low to moderate variability of major oxides in the Bss horizons and moderate variability of alkali oxides. According to the CAL MAG index, the paleo-mean annual rainfall estimate is 1261.05 ± 94.98 mm, compared to 650 mm at present. Log (Na_2O/K_2O) versus log (SiO_2/Al_2O_3) plots show low SiO_2 content in lower slope soils, indicating sediment from immature litharenites and arkose fragments. Based on the A-CNK-FM ternary diagram, these soils are moderately weathered on lower and middle slopes. Transect soil studies in the Penneru river basin will provide geochemical clues that vary with topographic positions and provide insight into soil properties at the landscape level.

Keywords: bivariate plot; cuddapah basin; geochemistry; shrink-swell soils; weathering indices; ternary diagram

1. Introduction

The catenary studies have clearly bought out the systematic variations in soil properties of both factorial[1] and with respect to site specific process domains.[2] The soil variations in a given landscape is measured of its and the contrast between adjacent polypedons in terms of management, productivity and other meaningful terms.[3] In catenary soils, anisotropic characteristics such as pedogenic horizonation reflects the depositional episodes with varying strata of differential weathering and lack of parent material uniformity.[4] The lateral movement of soil constituents are dependent on degree of change in permeability of strata and the slope gradient that runs continuously down ward from crest to the base of the slope.[5] The catena that shows eroded uplands and deposition on the lower slopes having uniform soil cover usually termed as erosion Catena.[6] These catenary studies were made on weathering and pedogenesis of soil with respect to distribution, mobilization and transfer of particles, colloids and solutes on hill slopes[7] but interpretations are often difficult due to local topography and land use.[8] The chemical weathering studies in different lithology and climatic conditions were made on ultramafic soils along a climatic gradient in south-western British Columbia,[9] felsic metamorphic rocks from Coweeta hydrologic laboratory, North Carolina, USA,[10] in granitic terrain of Borborema Province, Pernambuco state, northeast Brazil[11] and serpentine soils from Malaysia.[12] The weathering indices are commonly used to assess soil pedogenesis[13] and for evaluating the impact of climate on soil surface weathering.[14] Chemical weathering indices have shown the influence on sequences of soils developed in contrasting environments and served as a valuable tool to predict the influence of climate on weathering rates, soil development stage, and soil formation processes.[15]

In India, chemical weathering studies have been reported for the ferruginous soils of Kerala,[16] in soils associated with the laterite of the Nellore shale belt[17] and in the Shrink-swell soils of the Yavatmal district., Maharashtra.[18] Various molar ratios of elemental oxides and weathering indices have been derived and interpreted to assess the aging patterns of red and black soils in the Purna Valley.[19] In lateritic soils of the Malabar region, the SiAlFe ternary diagram was constructed to assess the degree of kaolinization and used clustering techniques to group soils according to chemical affinity[20] and in the

Table 1. Particle size distribution and chemical properties of soils Elemental composition of soils

Pedon No. & Horizon	sand	silt	clay	Sand/ Silt	Silt/silt+ Clay	pH	OC	$CaCO_3$	CEC	Exchangeable bases			
										Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
	%						%			--------cmol/kg--------			
Pedon 1													
A	37.47	33.50	29.03	1.12	0.54	5.80	0.39	6.45	28.4	20.00	5.00	0.29	0.21
AC1	22.88	40.59	36.53	0.56	0.53	5.78	0.34	5.46	20.3	14.00	5.00	0.31	0.14
AC2	39.27	31.41	29.32	1.25	0.52	6.15	0.31	5.95	27.8	16.00	8.00	0.31	0.18
Pedon 2													
A	13.90	51.66	34.44	0.27	0.60	5.99	0.47	3.48	17.4	11.00	4.00	0.21	0.17
AC1	9.52	54.76	35.71	0.17	0.61	5.36	0.33	3.97	14.8	8.00	4.00	0.19	0.16
AC2	12.51	51.95	35.54	0.24	0.59	4.82	0.27	5.46	23.6	16.00	4.00	0.23	0.15
Pedon 3													
Ap	63.53	15.36	21.11	4.14	0.25	4.44	0.41	9.4	19.4	12.50	4.00	2.10	0.41
Bw1	69.85	9.42	20.73	7.42	0.25	4.40	0.37	13.8	16.8	12.50	2.00	1.41	0.30
Bw2	14.64	52.16	33.20	0.28	0.61	4.37	0.33	10.4	18.3	11.00	5.00	1.26	0.25
Bw3	19.27	46.88	33.85	0.41	0.58	4.32	0.29	16.8	13.1	7.00	3.00	2.00	0.17
Pedon 4													
Ap	29.22	38.61	32.17	0.76	0.55	5.84	0.67	5.9	53.6	31.00	12.0	0.85	0.58
Bw1	30.88	40.78	28.35	0.76	0.63	5.73	0.61	6.9	46.4	30.00	9.00	1.08	0.37
C1	75.00	7.69	17.31	9.75	0.43	5.65	0.57	12.3	18.4	11.00	4.00	1.95	0.33
2Bw1	38.04	32.13	29.83	1.18	0.52	4.94	0.47	18.8	34.2	21.00	8.00	1.45	0.17
C2	75.92	4.82	19.27	15.76	0.29	4.84	0.42	20.8	17.2	12.00	4.00	0.98	0.21
3Bw1	20.00	45.61	34.39	0.44	0.57	4.80	0.39	20.8	25.3	18.00	4.00	2.16	0.16
4Bw1	14.24	63.77	21.99	0.22	0.74	4.34	0.34	25.7	21.4	15.00	3.00	2.51	0.20
4Bw2	19.06	40.47	40.47	0.47	0.50	4.26	0.31	26.7	26.5	18.00	5.00	2.59	0.20
Pedon 5													
Ap	22.98	31.29	45.73	0.73	0.41	6.50	0.53	11.4	53.0	32.00	9.00	4.32	1.12
Bw	16.58	37.32	46.10	0.44	0.45	6.34	0.45	15.8	51.8	31.00	8.00	4.16	0.41
Bss1	17.38	27.54	55.08	0.63	0.33	5.96	0.43	13.8	50.4	30.00	8.00	3.14	0.39
Bss2	9.99	21.95	68.06	0.45	0.24	5.93	0.40	16.8	49.3	29.00	8.00	2.97	0.40
Bss3	10.43	25.93	63.64	0.40	0.29	5.89	0.34	20.8	48.2	29.00	9.00	4.18	0.31
Pedon 6													
Ap	15.87	33.95	50.18	0.47	0.40	6.42	0.67	4.46	49.9	29.00	9.00	7.84	0.48
Bw	27.01	20.27	52.71	1.33	0.28	6.41	0.59	9.42	48.6	27.00	9.00	3.67	0.67
Bss1	26.45	15.14	58.41	1.75	0.21	6.27	0.53	10.4	50.4	28.00	7.00	5.74	0.43
Bss2	19.96	36.78	43.27	0.54	0.46	5.86	0.51	13.8	51.8	29.00	9.00	4.11	0.46
Bss3	17.62	25.17	57.21	0.70	0.31	6.13	0.48	18.8	50.0	28.00	9.00	4.12	0.49

soils of the Garhwal region of the small north-western Himalayas.[21] In subsequent studies on shrinking soils, the CAL MAG index[22] was used to estimate reliable annual mean precipitation (MAP) and also correlated with a chemical weathering index.[18,19] The crescent-shaped Cuddapah Basin is a Proterozoic and intracratonic sedimentary basin covering 44,500 km^2. The basin is filled with a succession of igneous and sedimentary rocks more than 10 km thick from the Cuddapah and Kurnool groups and would have developed in a rift environment and in the presence of offshore deposits representing the influence of tides and storms.[23] The study area is part of the Kadapa Basin near Jammalamadugu representing the Gandikota formations with receding soils developed under the ustic and isohyperthermic soil temperature regime. An excellent area for probing the effects of human activities on soil weathering patterns in agricultural landscapes. Studies on the geochemical assessment of soil catena in relation to lithology and land use at the study site are rare and almost unattended. In this context, the present study is important for evaluating soil geochemical models in order to trace pedogenic processes and their influence on soil fertility and development. Taking into account the weathering indices using geochemical and physicochemical data, the present study carried out a pedological evaluation of vertisols, inceptisols, and entisols developed on the Gandikota formations of the Kadapa basin.

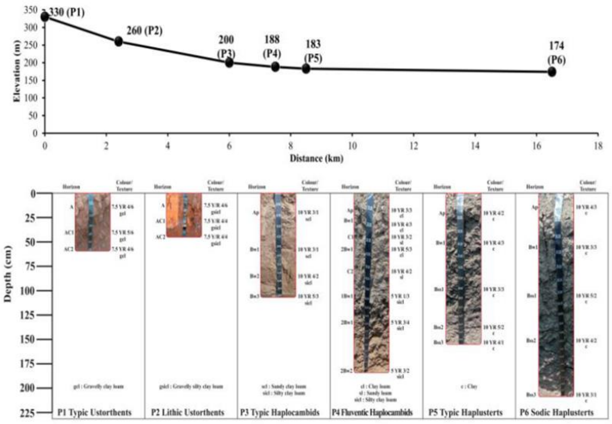

Fig. 1. Soil –landscape system on Gandikota formations

2. Experimental Section

2.1. Details of study area

On the basis of visually distinct sections of the landscape, the soil transect crosses the Pennar river basin at the east. It is characterized by a range of Gandikota quartzite hills. We selected two profiles within the landscape segments for each slope / topographic position. Six sites across the landscape were chosen within a minimum distance of 500 m. Sixty percent of the slopes are covered with stones (quartzitic pebbles and stones), but the amount of stone reduces toward the western side with deep shrink-swell soils used for growing jowar and cotton. The distribution of soils in relation to topography is depicted in Fig. 1. Based on field data, soils with A-AC horizons occur on upper slopes (Kottala (P1), and Mallambhavi (P2)) whereas soils on the middle slope have Ap-Bw horizon sequence in Kondapuram (P3) and Ap-Bw-C-Bw-C-Bw horizon sequences in Kanneluru (P4) and of very deep well, moderately well-drained, Ap-Bw-BSS horizon sequences in soils of Seshareddipalli (P5) and Peddapasupula (P6) site. Table 1 shows details on the location, slope position, vegetation and horizon sequences, and depth. The upper part of the transect has quartzite outcrops, while the lower part has black soil deeper than 2 meters. A layer of unconsolidated Tadipatri formations overlie the quartzitic in the middle of the transect (clay loam that is micaceous to the touch, with dusky red horizons below 1 m) beneath the quartzitic. According to this analysis, slopes can be divided into three components, upper, middle, and lower. Despite the absence of a rectilinear component, this transect exhibits long, low-angle foot slopes with small middle slope sections that "hinge" together with the upper slope and lower slope concavities. In the Kadapa basin, six soil profiles had been dug and defined soil morphology.[24] An overall of 25 horizon samples had been gathered and defined from six profiles of the Penneru basin. The soil catena was selected on the idea of earlier information of soils and water regimes in Penner. The soil transect was constructed with six profiles intended to capture the transitional area between upper and lower slopes.

2.2. Laboratory analysis

We collected horizon wise soil samples and kept for air dried. To obtain a fine earth fraction, we passed the soil through a 2 mm sieve. The fine earth was stored in polyethylene bags to be analysed for particle size, chemical properties, and elemental composition. The particle sizes of soil components such as sand, silt, and clay were determined using the hydrometer method. Hydrogen peroxide was used to consider removing the organic matter, which was then mixed with sodium metaphosphate. After transferring the soil contents into a 1L cylinder, they were thoroughly mixed to obtain hydrometer readings after 40 seconds, 2, 5, 15, 30, 60, 240, and 1440 minutes, with a blank as a reference. The temperature of the solution was noted when taking measurements the reading, and the correction factor was applied accordingly.[25] The pH was determined using a soil-to-water ratio of 1:2, organic carbon (Walkley-Black titrimetric method) and calcium carbonate (acid neutralization method, $CaCO_3$) percent according to the standard method.[26] The cation exchange capacity (CEC) and exchangeable cations, i.e. Na^+, K^+, Ca^{++} and Mg^{++} were determined according to standard laboratory methods.[27] For the total elemental analysis, we took one (1.00) g of finely powdered in a Teflon (poly tetra fluoro ethylene) beaker and treated it with 10 ml of $HClO_4$-HNO_3 (I: I mixture) to destroy the organic matter in soils. A small amount of perchloric acid was added to wash off the sides of the flask and heating was continued for an additional 15 minutes to dehydrate the silica. The residue was dissolved in 25-30 ml of warm double distilled water and filtered through Whatman 42 filter paper and the filtrate were collected in a 250 ml volumetric flask. The residue was washed with 0.5 M HCl and finally the volume was made up to 250 ml. The residue was washed with warm distilled water and then cooled in a desiccator. The proportion of SiO_2 was calculated from the weight of the residue.[28] 100 ml of acid extract were placed in a 250 ml beaker and ammonium chloride was added. A red colored precipitate of iron and aluminum was obtained by adding ammonium hydroxide in the presence of ammonium chloride. This precipitate was washed with warm distilled water until free from chlorides and weighed to obtain sesquioxides. The total iron, calcium, magnesium, sodium, potassium, copper, manganese and zinc concentrations were determined in silicic acid-free acid extract using an atomic absorption spectrometer (VARIAN AA240FS). The alumina was estimated by subtracting the total iron from sesquioxide.

2.3. Calculation of Weathering Indices

For each ratio, the percent of major elements were first divided by molecular weight to facilitate the calculation of molar ratios. The weathering indices worked out from molar ratios such as Chemical Index of Alteration (CIA),[29] Chemical Index of Weathering (CIW),[30] CAL MAG index[29] and Weathering Index of Parker (WIP).[31] The CaO* in the formulas, is considered as the silicate fraction of the rock. In order to calculate for CaO* from the silicate fraction, the assumption was that CaO values were accepted only if CaO < Na_2O, the concentration of CaO is the same as that of Na_2O.[32] By adopting this procedure, the ratio of the secondary aluminous mineral to feldspar, and forms a basis for the measure of the intensity of weathering in the soils. Bivariate and Ternary diagram The A-CN-K and A-CNK-FM by plotting CIA were constructed for evaluating weathering trends, weathering products, and clay minerals.[29] The bivariate plots were constructed to assess pedoclimate and also lithological products.

2.4. Statistical Analysis

Descriptive statistics, correlation matrix, linear and multiple regression analysis, and ANOVA were calculated in profile soil samples from the Jammalamadugu Proddutur tract of the Pennar River Basin using the Social Science Statistics Package (SPSS) software version 10.[33]

3. Results and Discussions

3.1. Grain size distribution

The data on the grain size distribution showed that the Kottala soils (P1) on the upper slopes have almost the same amounts of sand (W = 32.72%), silt (W = 35.40%) and clay (W = 31.88%), but with a maximum silt of 40.59 percent and clay of 36.53 in the AC1 horizon of the Kottla soil (P1). The silt consisted of more than 50 percent (W = 52.79%) and clay of 35.23 percent, but recorded maximum of 54.76 percent silt and 35.71 percent clay in AC1 horizons of Mallambhavi soils (P2). The ratio of sand to silt is less than 1 in the entire profile. The ratio of silt to silt plus clay is more than 0.5. In Kondapuram soil (P3), the sand content showed a gradual decrease with depth from 69.85 percent to 14.64 percent in Bw and had a weighted mean of 43.92 percent. This soil showed a gradual increase in silt (9.42 to 52.16%) and clay (20.73 to 33.85%). The sand to silt ratio is 4.14 for

Table 2. Elemental composition of soils

Pedon No& Horizon	SiO_2	R_2O_3	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	MgO
Pedon 1								
A	60.3	28.9	27.8	4.1	0.5	0.1	3.7	1.1
AC1	60.6	29.2	25.7	5.6	0.5	0.1	3.7	1.3
AC2	61.2	29.1	25.8	4.3	0.5	0.1	3.4	1.7
Pedon 2								
A	83.9	8.6	6.5	2.1	0.4	0.1	3.7	1.4
AC1	80.7	10.0	8.5	1.6	0.4	0.1	3.8	1.3
AC2	82.2	10.0	7.1	2.9	0.5	0.1	3.5	1.6
Pedon 3								
Ap	59.7	27.7	24.5	6.2	0.9	0.2	3.6	1.5
Bw1	61.3	28.9	22.8	6.1	0.6	0.3	2.8	1.2
Bw2	84.7	8.6	6.7	1.9	0.7	0.2	2.9	1.2
Bw3	82.2	10.0	7.0	3.0	0.7	0.2	2.8	1.2
Pedon 4								
Ap	62.3	28.6	21.0	7.6	1.0	0.2	2.7	1.3
Bw1	63.5	27.9	22.0	7.9	0.9	0.2	2.4	0.9
C1	83.0	9.5	7.3	2.2	0.8	0.1	2.5	0.7
2Bw1	63.5	26.6	20.1	6.5	0.9	0.2	2.7	0.8
C2	81.8	7.8	5.9	2.0	0.8	0.2	2.7	0.8
1Bw1	82.7	9.3	7.1	2.3	0.7	0.3	2.5	1.2
2Bw1	85.2	7.6	4.8	2.8	0.6	0.1	3.7	1.4
2Bw2	81.3	8.7	7.2	1.6	0.7	0.2	3.6	1.3
Pedon 5								
Ap	65.5	26.9	19.3	7.6	0.8	0.1	3.6	1.1
Bw1	61.5	28.9	24.6	7.3	0.6	0.1	2.6	0.8
Bss1	66.7	26.2	17.7	8.6	0.7	0.1	2.5	1.0
Bss2	63.3	30.1	23.5	6.6	0.7	0.1	2.6	1.1
Bss3	60.2	31.2	25.0	8.2	0.6	0.1	2.5	1.0
Pedon 6								
Ap	66.3	26.4	19.2	7.2	0.9	0.1	2.6	1.0
Bw1	63.2	29.6	21.3	8.4	0.6	0.2	2.3	0.9
Bss1	61.3	31.9	23.5	9.4	0.7	0.2	2.5	1.0
Bss2	61.0	30.7	22.6	8.2	0.5	0.1	3.7	1.3
Bss3	61.8	30.9	22.0	8.8	0.7	0.2	3.7	1.3

the Ap horizon, but sank to 0.28 in Bw2, while the ratio of silt to silt plus clay with values from 0.31 to 0.61 shows an increasing trend (Table 1). The Kanneluru soil on middle slopes (P4) showed strong variations in the supply of sand and silt, especially in C1 - 2Bw1 - C2 with a sand-silt ratio of 9.75 to 15.76 and a silt-to-silt plus clay ratio from 0.20 to 0.52. The Seshareddipalli Soil (P5) and Peddapasupula (P6) on lower slopes show a gradual increase in clay and silt to silt plus clay values of less than 0.5 and a sand to silt ratio of more than the unit value in some layers in P6.

3.2. Chemical characteristics

The soils of the upper slopes (P1 and P2) were slightly acidic (pH <6.5), but changed to moderately alkaline (W= 8.47) in the soils of the middle slopes (Kondapuram-P3 and Kanneluru - P4) strongly alkaline (W = 8.68) to lower slopes (P5 and P6). The vertical gradient of the soil reaction in P4 showed moderately alkaline in the upper horizons, but strongly alkaline in the lower B horizons, while soils on lower slopes show strong alkalinity in all profiles. The occurrence and gradual increase of alkalinity in soils of the Chitravathi river basin in the Kadapa region has been reported.[34] The electrical conductivity was less than <1 dS m^{-1} with the depth and the weighted mean value also indicates that these soils were not salty (Table 1). These soils are low in organic carbon (weighted mean <0.5%), except in Peddapasupula soil (P6) where the weighted mean is 0.53 percent to be classified as medium. In general, these soils showed a decreasing trend but were more focused on Ap horizons. The weighted mean value of the $CaCO_3$ content for topsoil is less than 6 percent (W = 5.92% for P1 and 4.30% for P2). The weighted mean value for $CaCO_3$ was 20.28 percent (P4) and 12.79 percent in Kondapuram soil (P3) with increasing tendency towards depth. These soils have a CEC greater than 25 cmol (p^+) kg^{-1} except in P2 and P3. The CEC was greater than 50 cmol (p^+) kg^{-1} in soils on lower slopes (P5 and P6). Among the exchangeable bases, Ca is dominated with slight inflictions in depth. Besides Ca, Mg dominated with a weighted mean of 3.41 cmol (p^+) kg^{-1} in P3 to 8.54 cmol (p^+) kg^{-1} in P6. Exchangeable Na was low (less than 0.3 cmol (p^+) kg^{-1} in P2) but showed a weighted mean of 1.63 cmol (p^+) kg^{-1} in P3 to 4.68 cmol (p^+) kg^{-1} in P6. The depth distribution of exchangeable Na was irregular, but mainly concentrated in B horizons of P4 and in Ap layers of P5 and P6. Soils on upper slopes (P1 and P2) and middle slopes (P3 and P4) had exchangeable K (less than 0.3 cmol (p^+) kg^{-1}) but exceeded the weighted mean of 0.47 cmol (p^+) kg^{-1} (P5) to 0.5 cmol (p^+) kg^{-1} (P6). The depth functions of CEC and exchangeable bases show that generally more than 20 cmol (p^+) kg^{-1} with irregular trends in P4, but fairly even in soils with lower topographic gradients of more than 50 cmol (p^+) kg^{-1}. The soils on the upper slopes (P1 and P2) and on the middle slopes (P3) showed irregular trends with exchangeable Ca of 20 to 30 cmol (p^+) kg^{-1}. These soils were rated as high.[35] The presence of $CaCO_3$ in these profiles under semi-arid to arid climates was associated with cascading changes of higher pH and higher exchangeable Ca with low soil organic carbon (less than 0.5%). The higher pH value at the $CaCO_3$- containing soil in the study area was attributed to the weak buffering caused by the $CaCO_3$ dissolution.[36] The $CaCO_3$-bearing site in the Kadapa Basin exists an imbalance with wet-dry shifts like the adjacent calcareous limestone cliffs and their alluvial-colluvial inputs, so the site is likely to continue to maintain high pH and base saturation. These regression equations clearly showed that cation exchange capacity was a function of organic carbon and clay, while BD was a function of clay and $CaCO_3$, and pH was a function of $CaCO_3$ and Ex Na levels. The pH and CEC of these soils to OC, $CaCO_3$, Ex. Na and clay were worked out and derived regression equations. The relation of pH as given under:

$$BD\ (Mg\ m^{-3}) = 1.22 + 0.0044\ (CaCO_3\ \%) - 0.003\ (Clay\ \%) \quad (1)$$

F = 8.24 at 2 and 25 df, p value of 0.0018 (Adj. R^2 of 0.35*)

$$pH = 6.45 + 0.0799\ (CaCO_3\ \%) + 0.2813\ (Ex.\ Na,\ cmol\ (p^+)\ kg^{-1}) \quad (2)$$

F = 30.85 at 2 and 25 df, R^2 of 0.69 **

$$CEC\ (cmol\ (p^+)\ kg\text{-}1) = -23.789 + 74.02\ (OC\ \%) + 0.6703(Clay\ \%) \quad (3)$$

F = 50.63 at 2 and 25 df, R^2 of 0.79**

The elemental composition of the soils showed that SiO_2 was a major component with a weighted mean of 60.69 percent for P1 on upper slopes, but had increased to 82.24 percent in P2. The mean SiO_2 is 70.44 percent for B horizons and 68.26 percent for A horizons. The transect mean is 69.66 ± 10.11 percent. The coefficient of variation is low at 14.52 percent (Table 2). The SiO_2 data showed that soils on upper slopes had a mean of 71.46 ± 11.86 percent, but soils on middle slopes showed a slight increase with a mean of 74.26 ± 10.87 percent and a decrease in their content in soils on lower slopes with a mean of 63.06 ± 2.35 percent. These soils showed little variability with a CV less than 15 percent. The depth functions of SiO_2

Table 3. Molar ratios of elemental oxides in soils

Pedon NO/ horizon	Molar ratio's				
	$mSiO_2$/ mR_2O_3	mAl_2O_3 /$mSiO_2$	mNa_2O+mK_2O / mAl_2O_3	mFe_2O_3/ $mCaO$	$mCaO$+$mMgO$/ mAl_2O_3
P1					
A	2.1	0.5	0.0	1.3	0.2
AC1	3.5	0.3	0.0	0.6	0.4
AC2	3.6	0.3	0.0	0.5	0.4
P2					
A	18.2	0.1	0.1	0.2	1.6
AC1	14.5	0.1	0.1	0.2	1.2
AC2	15.7	0.1	0.1	0.3	1.5
P3					
Ap	3.6	0.2	0.1	0.6	0.4
Bw1	3.9	0.2	0.0	0.9	0.4
Bw2	18.2	0.1	0.2	0.2	1.3
Bw3	15.7	0.1	0.2	0.4	1.2
P4					
Ap	4.1	0.2	0.1	1.1	0.4
Bw1	4.0	0.2	0.1	1.3	0.3
C1	16.1	0.1	0.1	0.4	0.9
2Bw1	4.4	0.2	0.1	0.9	0.4
C2	19.5	0.0	0.2	0.3	1.2
1Bw1	16.5	0.1	0.2	0.4	1.1
2Bw1	21.9	0.0	0.2	0.3	2.1
2Bw2	16.9	0.1	0.1	0.2	1.4
P5					
Ap	4.6	0.2	0.1	0.8	0.5
Bw1	3.6	0.2	0.0	1.1	0.3
Bss1	4.9	0.2	0.1	1.3	0.4
Bss2	3.9	0.2	0.0	1.0	0.3
Bss3	3.4	0.2	0.0	1.3	0.3
P6					
Ap	4.7	0.2	0.1	1.1	0.4
Bw	4.0	0.2	0.0	1.5	0.3
Bss1	3.5	0.2	0.1	1.5	0.3
Bss2	3.7	0.2	0.0	0.8	0.4
Bss3	3.7	0.2	0.1	0.9	0.5

clearly showed irregular depth trends in soils on upper slopes (P1 and P2), gradual increase in P3, irregular but gradual increase below the C2 horizon of P4 and slight inflictions in soils on lower slopes (P5 and P6). SiO_2 had a positive relationship to silt (r = 0.44*, significant at 5%) and negative to clay (r = -0.383 *, significant at 5%) and CEC (r = -0.641**, significant at 1% level). R_2O_3 (sum of Al_2O_3 + Fe_2O_3) showed an increasing trend with depth in soils on lower slopes (P5 and P6), but a drastic decrease in its content in P2 (Mallambhavi soil -P2) with a weighted mean of 9.52 percent. The soils in B horizons have a weighted mean of 15.77 percent for P3 and 14.39 percent for P4. In P4 soils, the R_2O_3 content decreases rapidly from the C2 horizon. The soils on lower slopes (P5 and P6) have a mean of 29.27 ± 2.10 with little variability. The high variability of R_2O_3 is observed in soils on medium slopes (CV= 58.9%) and on upper slopes (CV=55.54%). R_2O_3 has a significantly negative relationship with Silt (r=-0.438*) and a positive relationship with OC (r = 0.395 *) and CEC (r = 0.712**). In addition to SiO_2, Al_2O_3 dominated with a weighted average of 26.34 percent for P1, 7.33 percent for P2 on upper slopes, 14.59 percent for P3 and 9.80 percent for P4 on middle slopes and 21.66 percent for P5 and 22.11 percent for P6. The depth distribution was irregular, except in P1, where its distribution decreased with depth. The Al_2O_3 contents in P2 and in P4 on the C2 horizon to 2 Bw2 horizon were

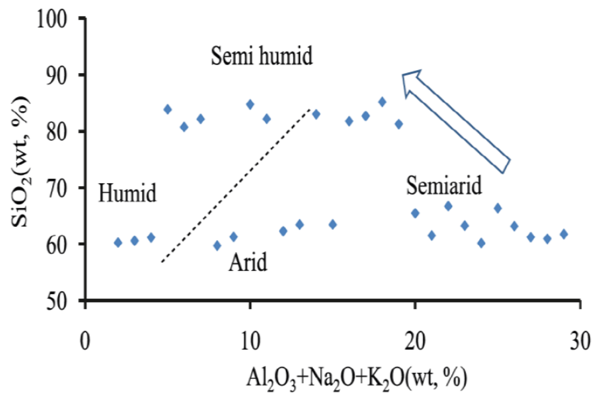

Fig. 2. Bivariate plot of SiO_2 versus Al_2O_3+Na_2O+K_2O (wt,%)

below 10 percent. The variability is high in soils on upper (CV 62.23%) and middle slopes (CV 62.05%). The bivariate representation between SiO_2 vs (Al_2O_3 + K_2O + Na_2O) for paleo climatic conditions[39] during the deposition of the sediments in the basin has been widely accepted and used to draw paleoclimatic conclusions by many workers. The diagram SiO_2 vs. (Al_2O_3 + K_2O + Na_2O) (Fig. 2) shows reasonable semi-dry to semi-humid climatic conditions in the area. It has been reported that sedimentation within the Kadapa Basin was considered to be multi-phase and was dominantly influenced by near-surface marine deposit conditions with periodic development of carbonate platforms[40] and having more Proterozoic clastic deposits than in the Paleoan Proterozoic Carbonate Deposit.[41,42,43]

3.3. Molar ratios

The molar ratios showed clear variations in relation to the landscape and also within the horizons, as shown in (Table 3). The soils on the upper slopes (P1 and P2) have a mean value of 9.60 and 7.26 for SiO_2/R_2O_3 with a CV of 75.64 percent (highly variable). This ratio is very variable in soils on medium slopes (CV of 60.58%) with a mean value of 12.06 ± 7.30, but with little variability (CV of 14.08%) in soils on lower slopes (P5 and P6) with a mean value of 4.04 ± 0.57.

The molar ratio of SiO_2/ Al_2O_3 represents the clay content of the soils with high variability in soils at the top (CV of 78.63% for SiO_2/Al_2O_3 and for 88.40% for Al_2O_3/SiO_2) and medium slopes (CV of 62.82% for SiO_2/Al_2O_3 and 75.02% for Al_2O_3/SiO_2). The mean value is 11.36 ± 8.93 for SiO_2/Al_2O_3 for soils on upper slopes, but increased slightly to 14.78 ± 9.29 in soils on medium slopes and decreased to 4.98 ± 0.78 for soils on lower slopes. The Al_2O_3/SiO_2 (clay content) showed a clear increase in clay in the soil of the lower slopes with a mean value of 0.21 ± 0.03 and showed little variability. This finding is consistent with an increase in clay in the particle size data for the same transect. These results were in agreement with the results of the geochemical characterization of shrink swell soils in the district of Yavatmal in Central India. The calcification index in soils on upper slopes (P1 and P2) has a mean value of 0.79 ± 0.53 with a CV of 67.53 percent and 0.83 ± 0.47 in soils on medium slopes (P3 and P4), however reduced to a mean of 0.33 ± 0.06 with little variability (CV 18.93%) in soils on lower slopes. These soils had an overall mean of 0.70 ± 0.52, but slight changes in the mean values of the A (0.63 ± 0.45) and B horizons (0.65 ± 0.46). This ratio quantifies the accumulation of pedogenic calcite and dolomite.[44] This index has an intrinsic relationship with a CaO / MgO ratio. The soils of the upper

Table 4. Weathering indices

Pedon NO/ horizon	Weathering index			
	CIA	CALMAG	CIA-K	WI
P1				
A	79.98	86.99	81.25	4.27
AC1	78.29	72.74	79.72	6.31
AC2	80.03	72.20	81.34	6.38
P2				
A	48.48	39.80	50.27	6.51
AC1	54.49	46.56	55.97	6.48
AC2	51.16	41.54	53.38	6.60
P3				
Ap	76.80	71.08	79.08	6.84
Bw1	80.35	75.30	82.07	5.36
Bw2	53.22	45.63	56.46	5.58
Bw3	54.53	47.75	58.11	5.53
P4				
Ap	78.67	73.42	81.89	5.68
Bw1	80.97	78.14	83.81	4.53
C1	59.41	55.65	63.83	4.44
2Bw1	77.69	75.44	80.69	5.01
C2	51.68	47.88	55.83	4.95
1Bw1	56.91	50.01	60.78	5.22
2Bw1	40.14	33.18	42.61	6.54
2Bw2	50.24	43.52	52.88	6.52
P5				
Ap	72.91	68.70	75.35	6.04
Bw1	82.69	79.59	84.57	4.37
Bss1	77.69	73.01	80.45	4.73
Bss2	82.08	77.19	84.15	4.86
Bss3	83.32	79.01	85.20	4.62
P6				
Ap	77.90	74.03	80.92	4.94
Bw1	82.13	78.31	84.28	4.37
Bss1	81.97	78.30	84.30	4.72
Bss2	76.17	70.24	77.56	6.28
Bss3	75.21	69.79	77.11	6.42

slopes show a mean value of 2.07 ± 0.65 with moderate variability (CV 31.47%), but show a low variability in soils of the middle (mean value 1.93 ± 0.32, CV of 16, 78%) and lower slopes. These soils on lower slopes show strong alkalinity, as reported in basaltic soils of central India[45] and in soils of Chitravati soils in the Kadapa Basin.[46] The parameter helps in providing information about the pH of the soil during weathering under arid to semi-arid climatic conditions prevailed today. In soils on upper slopes Fe_2O_3 / CaO has a mean of 0.51 ± 0.43, but increases from 0.57 ± 0.37 on middle slopes (P3 and P4) and from 1.12 ± 0.25 on lower slopes (P5 and P6). In the upper and middle slopes, the variability of this ratio is high, but in the lower slopes, it is moderate. It is similar to the observation made in Meghalaya[47] and in shrink-swell soils in Purna valley.[48] Fe mobility was high as compared to Ca in this transect, and the ratio did exceed 1 in slopes with lower slopes. Using Fe_2O_3/CaO, we can estimate the intensity of leaching,[49] but the ratio is again influenced by CaO content. In the Pennar basin, the pedocomplex has the least Fe_2O_3/CaO ratio because of $CaCO_3$ accumulation and CaO concentrations in its middle portion, which is in agreement with the low leaching indices. Under semiarid conditions with high evaporation to precipitation[50] and water accumulation, values of the molar ratios Na_2O + K_2O/Al_2O_3 below 1 indicate low salinity. Salinization is significant when the threshold value is 1.[51] In the Pennar basin, a low value may indicate well-drained soils.

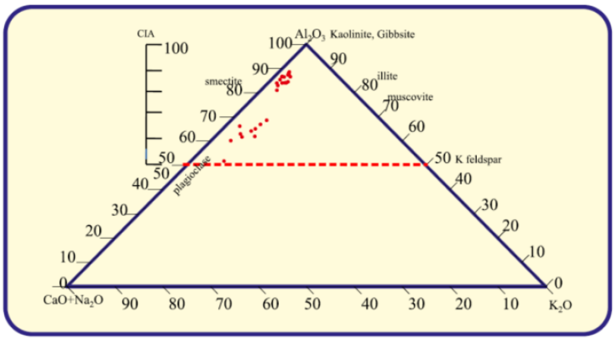

Fig. 3. Triplot diagram of A-CN-K

Table 5. ANOVA summary for CIA and CALMAG index

Source of variation	Df	CIA			CALMAG		
		MSS	F	p	MSS	F	p
Horizons	1	772.87	7.10	0.014	833.90	6.17	0.021
landforms	2	583.50	5.36	0.013	840.75	6.23	0.007
Horizons X landforms	2	452.66	4.16	0.029	497.58	3.68	0.041
Error	22	108.91			135.06		
Total	27						

3.4. Weathering indices

The soils on the upper slopes have a mean CIA of 65.61 ± 15.5% with moderate variability (CV of 23.69%). Middle slopes (P3 and P4) have moderate soil variability (22.84% CV with a mean of 63.38 ± 14.48%). The lower slopes (P5 and P6) have a mean of 79.21 ± 3.69 with low variability (CV of 4.65). The soils on lower slopes have undergone more chemical weathering than those on middle and upper slopes.

The CIA-K index increased slightly from upper slopes (66.99 ± 15.22%) to middle slopes (66.5 ± 14.21%) but decreased to lower slopes (81.39 ± 3.65 percent) with low variability. The CAL MAG index also showed similar trends of variation, ranging from 58.08 ± 15.59 percent for soils on middle slopes to 74.82 ± 4.19 percent for soils on lower slopes (Table 4). The mean weathering index is the highest for soils on lower slopes, but the lowest for soils on upper slopes, with a value of 6.09 ± 0.90 percent. Weathering ratios vary moderately with horizons A and B, but exhibit low variation with Index A and weathering index. For both A and B horizons, these soils show no significant differences in mean. ANOVA analysis indicated a significant difference in CIA and CALMAG indexes between land units, horizons, and their interactions (Table 5). The depth functions of weathering ratios indicated that CIA values were in between 50 to 60 in soils of upper slopes (P2) and below C2 horizon in P4 with decreasing depth trends. The soils on lower slopes had shown subtle changes with depth but values were in between 70 and 82 indicating moderate weathering. Similar kinds of trends were recorded for CALMAG index.

3.5. Triplot diagrams

A triangular plot with molecular proportions of A-CN-K (Fig. 3) for Pennar soils showed a CIA value of 60 to 70, with few samples falling into the range of shale with equal proportions of plagioclase and potassium feldspar. The diagram showed the smectic -illite phase due to the removal of Na and Ca in solution due to the breakdown of plagioclase. The CIA can also be represented in ternary diagrams A-

CN-K. The heavy arrow in the diagrams represents the theoretical weathering path that is to be expected with material weathering of this initial composition.[52] This path should run parallel to the ACN boundary and reflect simultaneous Ca, Na and K losses. The graphs suggest the effects of adding K to the samples as a result of metasomatism.[52] The premetasomatized CIA values of the samples examined can be obtained from the diagram using the methods described by Fedo et al. (1995).[44] The CIA range is between 60 and 85, which indicates low to moderate degree of chemical weathering in the Pennar Basin. The MAP values were determined by CIA-K[52] and by CALMAG.[53] The two MAP estimates were named CIA-MAP and CAL-MAP. Using the CALMAG index, the mean annual rainfall is calculated using the following equation: MAP = 22:69 * CAL MAG + 435.8 (R^2 = 0.90**). This equation is applied to the B horizons within 25 to 100 cm on the lower slopes of the basin (P5 and P6) of individual profiles. The average annual rainfall is 1261.05 ± 94.98 mm. The mean annual precipitation was calculated with CIA-K, using the regression equation as defined mean annual precipitation (mm) = $221e^{0.0197CIA\text{-}K}$ (R^2 = 0.72). Using this equation, the mean annual rainfall (mm) was 912.28 ± 288 mm versus the current rainfall of 650 mm. A similar exercise in applying this regression was used in calculating the paleo-rainfall for shrink-sleeper soils of the Yavatmal district with probable rainfall of 587 to 1749 mm. where the tonality (mAl/mSi) was observed earlier than in the study area. This high clay content in soils on lower slopes (P5 and P6) have slow to very slow hydraulic conductivity with increasing the residence time of soil water saturation and favours the accumulation of aluminum-containing phase, which accelerates the silicate weathering.[54] For this reason, the chemical weathering patterns evaluated on the basis of the molar ratios showed clear variations in relation to the topography even under rain-fed conditions (oxidized environment).

4. Conclusions

The conclusions from the soil transect study showed significant variations in the distribution of clay in relation to landforms and horizons with its maxima in Bss horizons of soils on lower slopes. These soils are slightly acidic in the upper slopes, but moderately to highly alkaline in the middle and lower slopes with less than 0.5 percent organic carbon, a downward increase in calcium carbonate, and moderate to high cation exchange capacity. The elemental composition of the soil transect indicated that SiO_2 was a major component with a weighted mean of 60.69 on upper slopes, but increased to 82.24 percent in Kondapuram soil (P3). The SiO_2 had a positive relationship with silt (r=0.45*) and a negative relationship with clay (r = 0.38*) and CEC (r = 0.64**). In addition to SiO_2, Al_2O_3 dominated with a decreasing tendency towards depth, while the Fe_2O_3 content gradually increased from the upper slopes to the lower slopes. The K_2O/Na_2O value is greater than 1 in all soils, which indicates a pedocomplex with quartz arenite with SiO_2 of less than 70 percent. The bivariate diagram between $SiO_2/(Al_2O_3+ K_2O+Na_2O)$ was used to draw the paleoclimate as semi-arid to semi-humid climatic conditions of multi-phase, flat marine deposits. Using molar ratios, the dominant pedogenic processes are clay ($mAl_2O_3/mSiO_2$) and calcification ($mCaO + mMgO)/ mAl_2O_3$) with high variability in upper and middle slopes. The ternary diagram of A-CN-K showed the appearance of the smectite-illite phase with moderate weathering under semi-arid climatic conditions.

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Conflicts of Interest

The authors declare no conflict of interest.

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