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Calcareousness and Subsoil Sodicity in Ferruginous Alfisols of Southern India : An Evidence of Climate Shift

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Abstract : *We report alkaline, sodic and smectitic ferruginous Alfisols from semi-arid part of southern India. Such Alfisols on micro-low (ML) position in a catena are spatially associated with non-sodic soil at micro-high (MH) positions. The soils of the MH are well drained, sandy clay loam to sandy clay in texture, acidic to slightly alkaline with less $CaCO_3$ and non-sodic. However, soils on ML is clayey, alkaline (9.1 – 9.4) and calcareous (10-13%) with high available water content and high sodicity (ESP 16-41%). The saturated hydraulic conductivity (sHC) of the ML soils is almost nil in the sub-surface horizons due to high ESP resulting in dispersion of clay and clogging of soil pores. Mineralogical studies indicate the presence of smectite-kaolinite (Sm-K) interstratified mineral, which was formed during the past humid tropical climate, where as the formation of the high charge smectite occurred during the prevailing semi-arid climate in both MH and ML soils. Sm-K is dominant in MH soils whereas smectite is dominant in ML soils. Micro- topography of the study area indicates that the ML positions are repeatedly flooded with surface water during brief and high-intensity showers, which provided steady supply of alkalis by hydrolysis of feldspars at MH sites leading to precipitation of calcium carbonate at high pH, development of subsoil sodicity and persistence of Sm-K and smectite in ML sites. Due to formation $CaCO_3$ and concomitant development of sub-soil sodicity, the sHC of the ML soils were impaired. Similar micro-topographical situation in the formation of sodic and non-sodic soils on ML and MH positions respectively was reported earlier in soils of the Indo-Gangetic Plains (IGP), but in swell-shrink soils of central India a reverse situation was observed. The present study, however, indicates the need of a detailed study to explain the development of sodicity in soils of red and black soil associations in tropical India. Earlier studies by NBSS&LUP (ICAR) demonstrated that the formation of sodic soils is the result of climate shift from humid to semi-arid climate during the Holocene period. The study reaffirms the need of precise understanding of pedogenic processes for pragmatic land resource inventory even at larger scales for proper management of soil resources.*

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It is widely believed that the ferruginous Alfisols are generally formed in high rainfall areas, and thus are acidic, non-calcareous, non sodic, and kaolinitic in nature. However, in tropical Indian environment, these soils occur in varied ecosystems ranging from arid to per humid region and are developed on different parent materials. They are acidic to neutral in reaction, have noncalcareous to calcareous, and their clay fractions contain smectites alongside dominant amount of kaolin clay minerals. Therefore, the relationship between their spatial distribution at different soil taxonomic categories (Soil survey staff, 2006) and the present soil forming factors is extremely difficult to establish (Murali *et al*., 1978; Rengasamy *et al*., 1978; Rengasamy, 1983). These semi-arid tropical (SAT) soils are considered as relict paleosols (Pal and Deshpande, 1987; Pal *et al*., 1989). Earlier reports on the ferruginous soils of Indian SAT indicated the evidence of initiation soil degradation due to aridity and reflected in the formation of pedogenic carbonates (PC) and concomitant development of subsoil sodicity (Pal *et al*., 2000; Srivastava *et al*., 2001). These authors, however, did not elaborate the possible role of micro topography in the formation of sodic ferruginous soils in SAT as demonstrated earlier in the formation of sodic soils in SAT environments of the Indo-Gangetic Plains (IGP) (Pal *et al*., 2003). In the present paper, we demonstrate the role of micro-topography in the formation of calcareous and sodic Alfisols with smectite as dominant mineral alongside small amount of Sm-K mineral in a catena under SAT climate of Andhra Pradesh where climate shift from humid to semi-arid did occur in the Holocene period.

Materials and Methods

Three Alfisols occurring in a transect (a soil catena) were selected from the research farm of CRIDA (ICAR), Hyderabad during the detailed soil survey of the farm on 1:5000 scale. The farm is located in an undulating topography under SAT climatic condition in the Rangareddy district of Andhra Pradesh. Soils were sampled from MH (P1 and P3) and ML (P2) positions (Fig. 1). These are developed in granite-gneiss parent material and classified (Typic Rhodustalfs: P1, Typic Natrustalfs: P2 and Typic Haplustalfs: P3) as per Soil Taxonomy (Soil Survey Staff, 2006). The morphological properties of each pedon and its individual horizons were described following the procedure of soil survey manual (Soil Survey Division Staff, 1995, Bhattacharyya *et al.,* 2009). The particle size distribution was determined by the international pipette method after removal of organic matter, $CaCO_3$ and Fe-oxides. Sand, silt, clay and fine clay fractions were separated according to the size segregation procedure of Jackson (1979). The sHC, $CaCO_3$ equivalent, cation exchange capacity (CEC), and extractable cations were determined by standard procedures (Richards, 1954; Piper, 1966;

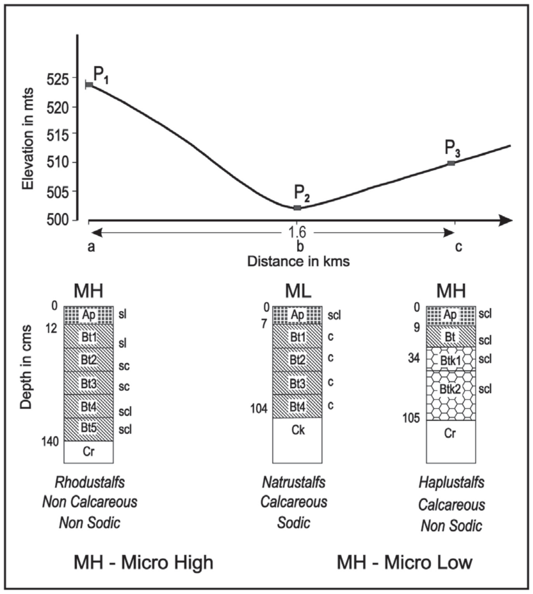


Fig. 1. *Schematic diagramme of the landscape representing the pedon sites in Rengareddy District, Andhra Pradesh*

Jackson, 1973). For mineralogical analysis, silt and clay fractions were subjected to X-ray diffraction (XRD) of the parallel oriented Ca/K saturated samples with a Philips diffractometer using Ni-filtered Cu-Kα radiation and at a scanning speed of $2^0 2\theta$/minute.

Results

Morphometric properties indicate that soils are reddish brown to dark reddish brown in colour with hue of 5YR to 2.5YR, deep, with well-developed structures and clay enriched B horizons (Table 1) and are grouped as ferruginous soils (Rengasamy *et al*., 1978). The Pedon 1 is non calcareous unlike the other two (Table 1). Soil structure varies from sub angular to angular blocky and consistency as sticky and plastic indicating good amount of clay. Texture varies from sandy clay loam to clay with fine and coarse gravels range from 10-60%.

MH soils

Physical and chemical characteristic (Tables 1 & 2) show that out of the two pedons in MH, P1 is acidic (pH 5.3 to 6.5) whereas P3 is alkaline (pH 8.0-8.4) with an increasing trend of pH with depth. The soils have high clay content just below the plough layer indicating that these soils are formed in the past humid climate which is common in ferruginous soils of SAT climate (Pal *et al*., 1989; Chandran *et al*., 2000). Available water content (AWC) of the soils are relatively low and varies from 5.3 to 9.3%. The soils have better sHC than the soils at the ML position (Table 1), but it is less than the threshold limit of 10 mm/hr except the surface soils of Pedon 1. The organic carbons in these soils are low, owing to the SAT climate and low organic inputs during the cultivation

In contrast to the general understanding that ferruginous soils are devoid of inorganic carbon ($CaCO_3$), laboratory studies indicate that these soils contain some amount of $CaCO_3$ even though the pH is <5.5 in Pedon 1 (Table 2). This indicates that the laboratory determination of carbonate should be made mandatory in the routine analysis, because it is an

Table 1. *Morphological and physical properties of soils*

Lab. no.	Horizon	Depth (cm)	Matrix Colour (M)	Texture[1]	Structure[2]	Efferve-scence[3]	B.D (Mg m^{-3})	Water retention (%) 33 kPa	1500 kPa	AWC	sHC (cm hr^{-1})	COLE	LE
					Pedon -1, Hayatnagar1(Typic Rhodustalfs)								
6418	Ap	0-12	5 YR 4/4 D& 3/4	gsl	f 2 sbk	nil	1.7	10.1	4.8	5.3	2.44	0.09	0.08
6419	Bt1	12-29	2.5 YR 3/4	sl	f 2 sbk	nil	1.6	16.1	10.4	5.7	0.66	0.08	
6420	Bt2	29-55	2.5 YR 3/4	sc	f 2 sbk	nil	1.6	15.6	10.1	5.6	0.26	0.07	
6421	Bt3	55-86	2.5 YR 3/4	sc	m 2 sbk	nil	1.9	18.2	11.2	7.0	0.85	0.09	
6422	Bt4	86-102	2.5 YR 3/4	scl	m 2 sbk	nil	1.6	19.2	11.2	7.9	0.15	0.09	
6423	Bt5	102-140	2.5YR 3/4	scl	m 2 sbk	nil	1.6	15.2	8.8	6.4	0.82	0.09	
	Cr	140^{+}			Weathered granite-gneiss.								
					Pedon -2, Hayatnagar 9. (Typic Natrustalfs)								
6457	Ap	0-7	7.5 YR 4/3 D & 3/3	gscl	m 1sbk	ev	1.6	17.8	9.2	8.6	0.39	0.10	0.22
6458	Bt1	7-20	5 YR 3/4 D & 3/3	c	c 2 abk	ev	1.6	28.2	14.0	14.2	0.07	0.15	
6459	Bt2	20-60	5 YR 3/4 R	c	c 3 sbk	ev	1.9	38.7	16.5	22.1	Nil	0.22	
6460	Bt3	60-83	5 YR 4/4	c	c 3 abk	ev	1.6	48.8	18.7	30.0	Nil	0.27	
6461	Bt4	83-104	5YR 4/4	c	c 3 abk	ev	1.5	48.5	22.6	25.9	Nil	0.27	
	Ck	104^{+}			Weathered granite gneiss with calcium carbonate								
					Pedon 3, Hayatnagar14 (Typic Haplustalfs)								
6492	Ap	0-9	2.5 YR 3/4 D& 3/3	scl	m 1 sbk	es	1.6	10.4	4.8	5.6	0.31	0.05	0.06
6493	Bt	9-34	5 YR 3/4 M	scl	m 2 sbk	es	1.7	15.2	6.7	8.5	0.35	0.06	
6494	Btk_1	34-68	5 YR 3/4 M	scl	m 2 sbk	ev	1.5	18	8.6	9.3	0.57	0.07	
6495	Btk_2	68-105	5 YR 3/4 M	scl	m 2 sbk	ev	1.7	15	6.7	8.3	0.16	0.05	
	Cr	105^{+}			Weathered granite-gneiss.								

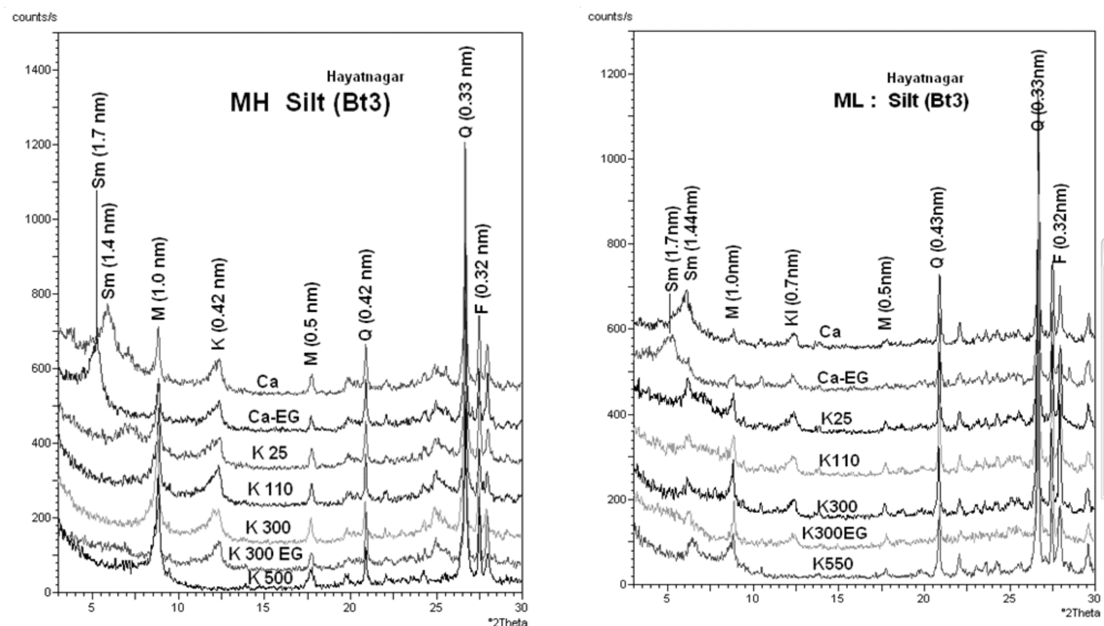
[1]: gsl: gravelly sandy loam, sl: sandy loam, scl : sandy clay loam, sc: sandy clay, c: clay
[2] f : fine ,m: medium, c: coarse. 1 : weak, 2 moderate,3 :strong, sbk: subangular blocky, abk: angular blocky;
[3]es : strongly effervescent, ev: violent effervescent;
BD- bulk density; sHC –saturated hydraulic conductivity; COLE – coefficient of linear extensibility, LE-linear extensibility.

indication of initiation of carbonate precipitation and concomitant development of subsoil sodicity in ferruginous Alfisols of SAT climate. Both MH and ML soils are calcareous but the content of Ca CO_3 is low in light texture soils than heavy textured soils suggesting the definite role of texture in its accumulation in the soil profile under SAT climate. Ca^{2+} ion is dominant in the exchange sites followed by Mg^{2+} in soils of MH positions.

X-ray diffractogram of the silt indicate these soils (Fig. 2a) have dominant peaks at 1.4, 1.0 and 0.7 nm. The 1.4 nm mineral expands to 1.7 nm on glycolation and collapses readily to 1.0 nm peak on K saturation and heat treatment indicating the presence of high charge smectite (low charge vermiculite) in the sample, a weathering product of biotite mica. Kaolin and smectite are the dominant minerals in the total clay fraction with subordinate amount of mica and quartz (Fig. 3a). The 1.4 nm peak of smectite shifts entirely to 1.7 nm during glycolation and but does not collapse to 1.0 nm region during K saturation at ambient temperature, but does so only at 110°C indicating presence of both high and low charge smectite. On glycolation the 0.7 nm peak of kaolin, shifts

Table 2. Particle size distribution and chemical properties of soils

Horizon	Size class and particle diameter (mm) (%)				pH (1:2)			EC	Organic	Carbonate
	Sand (2-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Fine Clay (<0.0002)	H_2O	1 *N* KCl	Δ pH (-ve)	(1:2) dS m^{-1}	carbon (%)	as Ca CO_3 Equivalent (%)
				Pedon-1,Hayatnagar 1. (Typic Rhodustalfs)						
Ap	73.0	18.3	8.7	5.4	6.5	4.1	2.4	0.09	0.7	0.8
Bt1	58.0	27.2	14.8	9.5	5.3	4.1	1.2	0.07	0.5	0.9
Bt 2	54.2	10.7	35.1	24.5	5.3	4.3	1.0	0.09	0.6	0.9
Bt3	54.8	8.7	36.5	16.7	5.7	4.5	1.1	0.09	0.4	0.7
Bt4	59.7	11.9	28.4	11.5	6.4	4.2	2.2	0.06	0.2	1.0
Bt5	71.2	6.4	22.4	15.1	6.5	4.3	2.2	0.05	0.1	1.2
				Pedon -2, Hayatnagar 9. :(Typic Natrustalfs)						
Ap	56.0	10.8	33.2	9.9	8.2	7.3	0.9	0.14	0.8	7.4
Bt1	46.1	10.7	43.2	12.9	9.1	7.6	1.5	0.29	0.3	10.6
Bt2	44.2	12.3	43.5	12.8	9.2	7.9	1.3	0.41	0.2	9.9
Bt3	40.5	17.7	41.8	13.0	9.4	7.9	1.5	0.63	0.2	10.0
Bt4	45.3	12.1	42.6	15.5	9.2	7.9	1.3	0.11	0.2	12.6
				Pedon 3, Hayatnagar 14LTypic Haplustalfs)						
Ap	66.8	12.6	20.6	14.9	8.0	5.9	2.2	0.12	0.5	2.1
Bt	65.7	13	21.3	9.5	8.2	7.2	1	0.13	0.7	11.1
Btk_1	51.6	14.5	33.9	8	8.2	7.5	0.8	0.12	0.6	31.6
Btk_2	63.7	9.0	27.3	20.9	8.4	7.3	1.1	0.14	0.3	22.8



(a) (b)

Fig. 2. *Representative XRD of Silt fraction (50-2μm) of MH and ML soils Ca- ca saturated, Ca_EG: Ca saturated and glycolated, K25, K110, K300, K 550, K300 EG: K-saturated and heated to 25,110,300, 550^{0}C and glycolated respectively. Sm=smectite , KI= kaolin, M=mica, Q=quartz and F=feldspar*

towards low angle side indicating that it is not a true kaolinite but interstratified with smectite. This was further confirmed from the broad base and branches in the tips of 0.7 nm peak. This is common in ferruginous soils of southern India (Pal *et al*., 1989; Chandran *et al*., 2000, 2005). The fine clay fractions of MH soils are dominated by 0.7 nm mineral with smectite and mica in subordinate amounts (Fig. 4a). The broad 0.7 nm peak on glycolation indicates that it is not a discrete kaolinite but appears to be interstratified with smectite, indicating this to be a smectite-kaolinite mineral (Sm-K).

ML soils

These soils are alkaline in reaction (pH 8.0 to 9.4) with pH increasing with depth. In contrast to the MH, these soils have high AWC (8.6 – 30.0%) (Table 1). High AWC is due to high exchangeable sodium and clay smectite in these soils. In Typic Natrustalfs (P2) the sHC in subsurface layers is zero even after 5 days of saturation (Table 1), indicating the impairment of soils' hydraulic properties. In contrast to the MH soils, exchangeable Mg^{2+} is dominant in these soils followed by Na^{+}. ESP is high in the subsurface soils and it ranges from 16 to 41% (Table 3). Kadu *et al*. (2003) observed that the hydraulic properties of the soils were impaired due to dispersion of clay when the exchange complexes are dominated by Na^{+} and/or Mg^{2+}. However, in the soils of MH position ESP is <2 and thus not considered detrimental for crop growth.

Mineralogy of the soils indicate that silt is dominated by smectite with subdominant amount of mica, (both muscovitic and biotitic), kaolin, feldspar and quartz (Fig. 2b). A part of the 1.4 nm peak shifts to 1.7 nm region on glycolation but when K saturated and heated to 550^{0}C, a trailing of the 1.0nm peak at high angle side was observed,indicating the hydroxy interlayering in the of smectite. Total clay fraction is also dominated by smectite with very small amount of kaolin and mica (Fig. 3b). The 1.4 nm peak readily shifts to 1.77 nm region on glycolation but does not contract to 1.0 nm on K-saturation and heating at ambient temperature. This along

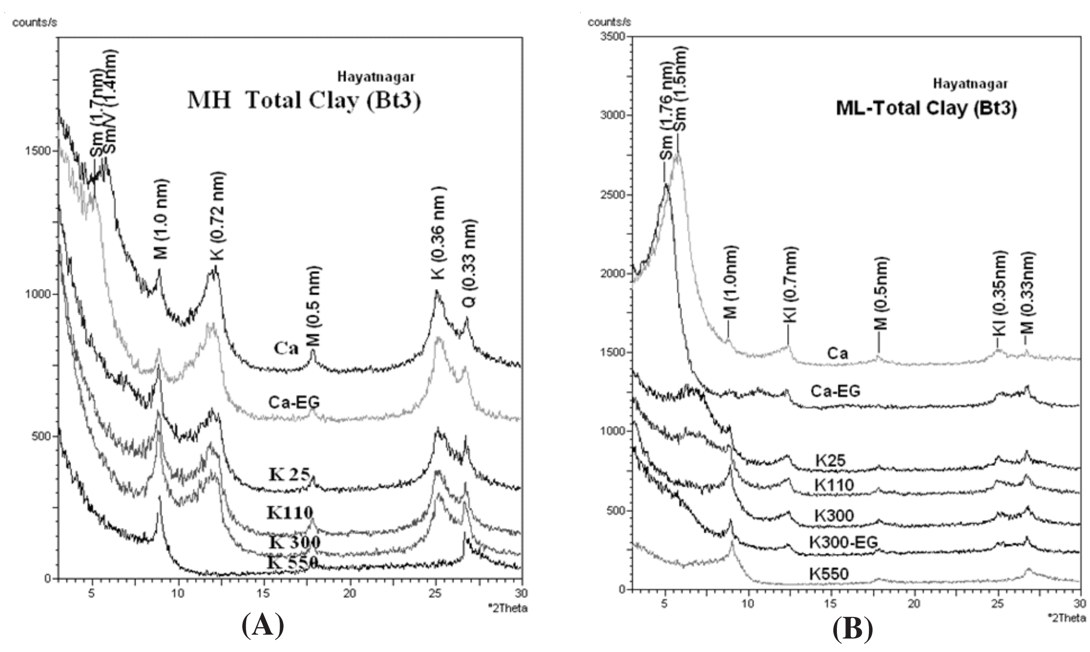


Fig. 3. *Representative XRD of total clay (2-0.2μm) of MH and ML soils Ca- ca saturated, Ca_EG: Ca saturated and glycolated, K25, K110, K300, K 550, K300EG: K-saturated and heated to 25,110,300, 550^{0}C and glycolated respectively. Sm=smectite, KI= kaolin, M=mica, Q=quartz*

with its expansion behaviour on glycolation of the K-saturated and heated samples at 300⁰C indicate the presence of both high and low charge smectite. The 0.7 nm mineral is interstratified with expanding lattice mineral i.e. smectite.

In contrast to the MH, fine clays of ML soils are dominated by smectite with very small amount of kaolin. This smectite peak does not entirely contract to 1.0 nm at 25^0 and 110^0C. For complete contraction, heating of the K saturated samples at 300^0C was necessary (Fig. 4b). This observed contraction behaviour of smectite on K saturation at ambient temperature and heating to 300^0c indicates presence of both high and low charge smectite in this fraction. The presence of high charge smectite was further confirmed as K-saturated and heated (300^0C) sample did not expand beyond 1.0 nm peak on glycolation (Ross and Kodama, 1984).

Discussions

The above results indicate that the soils in a catenary sequence had contrasting chemical and mineralogical characteristics. The soils at MH are acidic or less alkaline,

Table 3. Exchange properties of soils

Horizon	Extractable bases (cmol (p+) kg^{-1} Soil)					CEC soil	B.S. (%)	CEC clay (cmol (p+) kg^{-1} Clay)	ESP	EMP	Ca/Mg ratio
	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sum						
Pedon-1, Hayatnagar 1,(Typic Rhodustalfs)											
Ap	4.0	2.1	0.0	0.3	6.4	8.1	79	99	0.5	26	2
Bt1	4.4	4.5	0.2	0.2	9.3	14.2	65	96	1.4	32	1
Bt 2	6.6	3.6	0.2	0.2	10.6	15.2	70	43	1.6	24	2
Bt3	7.4	4.9	0.3	0.3	12.9	15.0	86	41	2.1	33	1
Bt4	8.8	6.5	0.3	0.2	15.8	18.6	85	66	1.7	35	1
Bt5	11.0	6.9	0.3	0.2	18.4	22.0	83	99	1.4	31	2
Pedon -2, Hayatnagar 9,(Typic Natrustalfs)											
Ap	13.3	3.3	0.3	0.3	17.2	18.6	92	56	1.5	18	4
Bt1	8.4	7.7	3.8	0.2	20.1	24.0	84	56	15.9	32	1
Bt2	2.9	10.3	8.9	0.2	22.4	24.0	93	55	37.2	43	0.3
Bt3	2.2	12.2	10.7	0.3	25.4	26.1	98	62	41.2	47	0.2
Bt4	2.6	11.2	11.0	0.3	25.1	27.0	93	63	40.7	41	0.2
Pedon 3, Hayatnagar14, 9Typic Haplustalfs)											
Ap	11.4	2.2	0.2	0.2	14	14.6	96	71	1.6	15	5
Bt	11.3	1.5	0.3	0.2	13.2	16.2	82	76	1.6	9	8
Btk_1	15.2	1.6	0.3	0.2	17.3	17.6	98	52	1.5	9	10
Btk_2	11.2	1.6	0.3	0.2	13.3	18.6	71	68	1.5	9	7

CEC: cation exchange capacity, BS –base saturation, ESP- exchangeable sodium percent, EMP— exchangeable magnesium percent

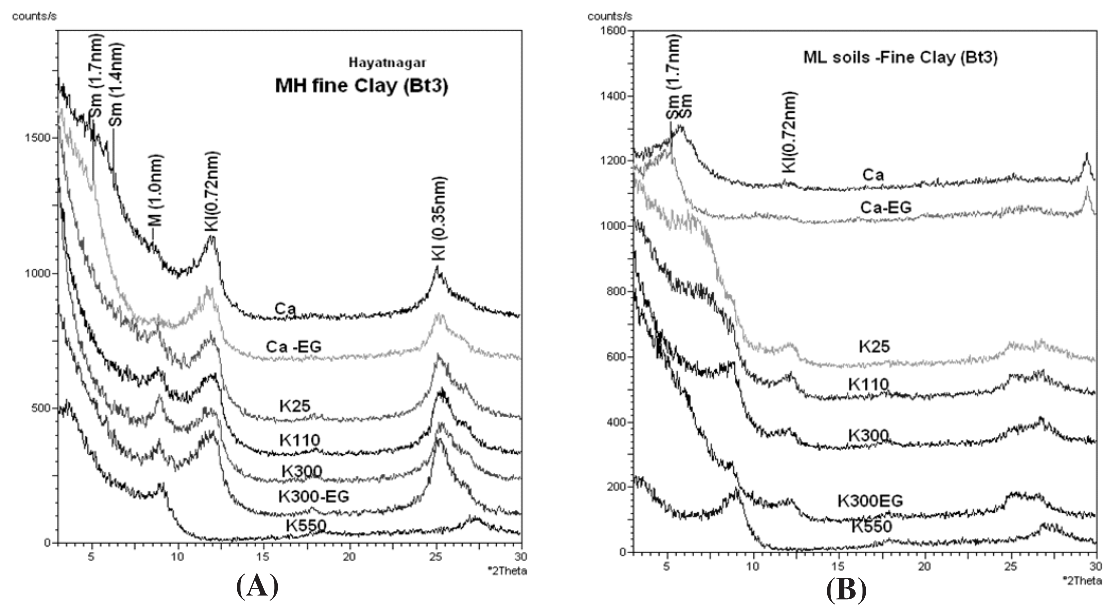


Fig. 4. *Representative XRD of fine clay (<0.2μm) of MH & ML soils Ca- ca saturated, Ca-EG: Ca saturated and glycolated, K25, K110, K300, K 550, K300EG: K-saturated and heated to 25,110,300, 550^{0}C and glycolated respectively. Sm=smectite , KI= kaolin, M=mica.*

and those at ML are highly alkaline due to accumulation of bases from the higher topographic position. The microlows are repeatedly flooded with surface water during brief high-intensity showers, and so the soils are subject to cycles of wetting and drying. This provides a steady supply of alkalis by hydrolysis of feldspars, leading to precipitation of calcium carbonate at high pH and development of subsoil sodicity. This impairs the hydraulic properties of soils and eventually leads to the development of Alfisols with a relatively high ESP in the subsoils. The semi-arid climate and topography interact to facilitate greater penetration of bicarbonate-rich water in ML than MH positions. The sHC of the soils at ML position is almost zero in the subsurface layers due to higher amount of clay smectite and ESP. The SAT climate of the area induced precipitation of carbonates which in turn has increased Na^{+} ion in the exchange complex (Pal *et al*., 2000). This is common in black soil regions of India wherein SAT climate induces the precipitation of calcium carbonates with a concomitant development of subsoil sodicity (Vaidya and Pal, 2002). The formation of $CaCO_3$ and illuviation of clay can be considered as the two pedogenic processes occurring simultaneously as contemporary events in the drier climates in ML position. Similar micro-topographical situations in the formation of sodic and non-sodic soils on ML and MH positions, respectively was reported earlier in soils of IGP (Pal *et al*., 2003). In contrast to this, in swell-shrink soils of central India, a reverse situation was observed; sodic soils occur in MH and non sodic soils as ML position.

The clay mineralogical make up indicates that MH soils are dominated by kaolin, and ML soils with smectite probably due to differences in drainage conditions. The presence of kaolin in all the fractions of these soils of semi-arid climate and its occurrence as Sm-K interstratified mineral indicate the prevalence of humid climate in the past (Pal and Deshpande, 1987; Chandran *et al*., 2000). Smectite clay minerals are ephemeral in the humid tropical climate and they transform into kaolinite (Pal *et al*., 1989, Bhattacharyya *et al*., 1993). Therefore, the associated ferruginous soils with huge amount of smectite were formed in the humid climate of the past geological period. But the high charge smectite in the silt and clay fraction are the weathering product of biotite during the present SAT environment. Therefore, the climate change from humid to semiarid in the Holocene period is also reflected through the transformation of smectite to Sm-K and formation. Huge amount of smectite in the soils of ML position is preserved due to replenishment of bases in the micro depression. Earlier studies demonstrated the initiation of development of sodicity in ferruginous soils of south India as a result of climate shift from humid to semi-arid climate during the Holocene period (Chandran *et al*., 2000; Srivastava *et al*., 2001). Natarajan *et al*. (2006) also reported high $CaCO_3$ and ESP in ML soils of Sivagangai block of Tamil Nadu, in association with ferruginous soils in lateritic landscape but no explanation for such contrasting chemical environment was offered. Thus the development of $CaCO_3$ and sodicity in the soils of ML position may be widespread due to the replenishment of bases from surrounding MH areas, in similar SAT areas of southern India. Although the rate of formation of carbonates in such SAT soils is not alarming at present, but due care is needed while irrigating these soils.

Conclusions

The development of calcareousness and subsoil sodicity alongside the formation of high charge smectite in ferruginous soils of southern India is due to climate shift from humid to semi-arid during the Holocene period. The initiation of the natural degradation in terms of impairment of hydraulic properties of soil may become wide spread if the climatic aridity is continued. Therefore, management intervention to minimize the effect of this natural degradation is to be initiated to arrest such a menace. The study further reaffirms the need of precise understanding of pedogenic processes for pragmatic land resource inventory even at larger scale for proper management of soil resources.

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