GRAIN CUTANS RESULTING FROM CLAY ILLUVIATION IN CALCAREOUS SOIL MATERIAL

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INTRODUCTION.

The process of illuviation in calcareous soil materials is still a controversial subject. A common opinion is that the presence of carbonates hinders the development of argillic horizons (Frei, 1967; Gile and Grossman, 1968; McKeague and St. Arnaud, 1969; Birkeland, 1974, p. 111; Allen and Goss, 1974) and that only after carbonates have been leached is clay illuviation effective. Inhibition of the translocation is generally attributed to flocculation of the clay by Ca^{++} ions. On the other hand it was also found and claimed that clay migration is active in calcareous materials (Reynders, 1972; Goss et al., 1973; de Meester and van Schylenborgh, 1966; van Schuylenborgh, 1972, p. 463).

Experimental data demonstrate a complex interrelationship of several parameters on clay mobility. Brewer and Haldane (1957) found that clay illuviation and orientation was not affected by the Kind of cation, and Hallsworth (1963) found that Ca saturation enables clay illuviation at low electrolyte concentration.

The absence of illuviation cutans in calcareous B_t horizons is generally ascribed to the engulfing and disruption of the cutans by authigenic carbonate accumulation (Gile and Grossman, 1968; Allen and Goss, 1974). Disruption of clay cutans is attributed to other factors as well, such as shallowness of the argillic horizon and the consequent access to it by roots and fauna, high energy wetting,

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swelling (Gile and Grossman, 1968) and unstable aggregates (Buol and Hole, 1961).

Beside the inhibiting effect of carbonate on clay illuviation experiments also indicate that silt size material inhibits clay migration (Brewer and Haldane, 1957; Dumanski, 1970).

The object of this study is to report the occurrence of clay illuviation in calcareous soil materials and to discuss the micromorphological aspects related to the recognition of such and illuviation.

MATERIAL AND METHODS

The study was undertaken on a loessial Serozem soil (classified according to the Israeli system of Dan et al., 1972). This would now be correlated with Haplargids according to the American soil taxonomy, taking into consideration the evidence for illuviation from the present study, but was previously correlated with Calciorthids. The profile (EH-1) is from the northern Negev, near Beer Sheva, a loessial landscape with an arid climate, Mean daily temperature is 20 ºC and mean annual rainfall, concentrated essentially to the winter months December to March, is 235 mm.

The profile is situated on a nearly level upland where the erosional and depositional processes are believed to be in a steady state. The profile is a cumulative one (Dan and Yaalon, 1968 and 1971) and was built up slowly by eolian dust deposition. The dust originates from the Sinai and Sahara deserts (Yaalon and Ganor, 1973; Yaalon and Dan, 1974; Ganor, 1975). The current rate of accretion is between 20-28 μm per year and about equal as regional erosion (Yaalon and Ganor, 1975).

Particle size distribution was determined according to the modified Beam (1911) method. Fine clay was separated by centrifugation at 3600 rpm (Bascomb, 1974). Car bonate content was determined in the total soil and in the separated granulometric fractions using a volumetric calcimeter. Conductivity, pH and soluble salts were determined in the soil saturation extract (Richards, 1954). Cation exchange capacity and exchangeable cations were determined according to Bower et. al. (1972) and Richards (1954).

Thin sections were prepared from undisturbed samples using impregnation techniques described by Fitzpatrick (1970). Micromorphological descriptions and nomenclature are according to Brewer (1964), with additional terms used for calcareous fabrics.

RESULTS

The main characteristics and data of the profile are given in Tables 1 to 3 and Fig. 1.

The profile has two calcic horizons : an upper B_{1ca} with 5-10% carbonate nodules and one at 1 m depth overlying a gypsic horizon (B_{23ca} + cs) with ~30% carbonate nodules. Additionally a buried calcic B horizon of the quartzic Arid Brown paleosol occurs at 2.5 m depth. This paleosol resulted from soil development in calcareous sand with imbedded eolian dust.

Total clay increases mainly between A and the upper B horizon (Tables 2 and 3 and Fig. 1). The fine clay fraction (< 0.2 μm) does not contain any carbonates. Illuviation of the non-carbonate clay can thus be followed independently from carbonate leaching. The ratio of fine clay to non-carbonate clay increases from 0.42 to 0.8 in the upper B horizon at ~80 cm depth (Table 3) and fine clay increases from 3.1 to 10.2 in volume percent (Table 3), both indicating illuviation of fine non-carbonate clay. In the thick B horizon below this, the ratio remains at 0.75 and the volume percent of fine clay also remains at the same level, which may indicate similar degree of illuviation while the profile grew through eolian accumulation.

Micromorphological characteristics.

Detailed micromorphological descriptions of this profile (EH-1) were published in a previous paper (Wieder and Yaalon, 1974) which focused the discussion on carbonate crystallization. The main micropedological features are summarized below.

Skeleton grains are mainly of coarse silt and fine silt fractions. They are composed of angular to subangular quartz grains and few feldspar, hornblende, glauconite and opaque grains. Microstructure is loose in the A and compact in the B horizons, particularly in the calcic horizons. The related distribution varies from intertextic to agglomeroplasmic in the A to pophyroskelic in the B horizons. Voids are interconnected vughs in the A, skew planes in the calcic and vughs and channels in the other B horizons. Carbonate nodules are mainly soft, irregularly shaped orthic nodules in the calcic horizons and displaced, intrapedonic, disorthic nodules in the other horizons.

Relevant to the present study is the occurrence of widespread single grain cutans. They occur either as single grain cutans (Fig. 2) or as grain cutans interconnected by clay bridges (Fig. 3) forming distinct larger brown spots free of carbonates, which have patterns different than the surrounding matrix in which very high amounts of microcalcites are present. These clay coatings on the grains are relatively thick, well oriented and with a distinc reddish-yellow nuance. The looser the microstructure, the more widespread are the grain cutans and the brownish spots which include interconnected clay bridges. In the compact zones of the calciasepic fabric few embedded grain cutans occur. In the deep paleosolic buried horizons, void argillans occur with continuous to striated orientation and the grain cutans are strongly oriented on large skeleton grains.

It is also worth stressing that a very high content of single grain cutans occurs in the gypsic horizon (130-158 µm). Between the gypsic horizon and the buried calcic B horizon of the quartzic Arid Brown soil grain cutans are absent.

In similar loessial Dark Brown soils from the semiarid climate, which are richer in non-carbonate clay than the investigated loessial Serozem but still include microcalcites in the plasma, brownish spots of grain cutans interconnected by clay bridges and free of microcalcites also occur frequently. A large part of the grain cutans is incorporated into the plasma as embedded grain cutans (Fig. 4).

INTERPRETATION AND DISCUSSION

Two main aspects have to be clarified concerning clay illuviation in calcareous loessial material : (1) is the textural difference which exists between A and B horizons a result of clay translocation, of sedimentary deposition, weathering or of all these together ? (2) if the illuviation process is active, how is it expressed in thin sections? .

The micromorphological evidence, when supported by the increase of fine clay with depth, suggests an illuviation process. Increase of fine clay in argillic horizons in the form of thick illuviated coatings was observed by several authors (Bartelli and Odell, 1960; Khalifa and Buol, 1968; Soil Survey Staff, 1967). Increase in the ratio of fine clay to total clay in the B horizon also characterizes illuviation in Argids (Nettleton, 1972; Hendricks, 1974).

Our microscopical study indicates that the micromorphological form of the illuviation cutans in the calcareous soil material is in the form of single grain cutans (Fig. 2) and/or brownish spots of well-oriented clay cutans interconnected by clay bridges (Fig. 3). The occurrence of coatings on sand grains is the usual form of illuviated clay in column experiments (Brewer and Haldane, 1957 ; Halls worth, 1963; Dumanski, 1970) and in argillic horizons in desert soils (Gile snd Grossman, 1968; Hendricks, 1974; Nettleton, 1972). Grains cutans and bridges are also the main forms of clay accumulation of mechanically infiltrated clay in desert alluvium (Walker and Crone, 1974; Crone, 1975).

The soil forming conditions in the Serozem and Arid Brown soils are somewhat different from those quoted above. The Haplargids in New Mexico (Gile and Grossman, 1968) and in Arizona (Hendricks, 1974) have grain cutans in reddish soil material (5YR), leached completely of carbonates. The Israeli loessial soil material is highly calcareous, with a 10YR hue, and the clay coatings are found in grains from very fine sand to coarse silt. The grain cutans occur preferentially where the structure is loose and usually not in close proximity of microcalcite, which suggests that a microenvironment with less carbonate is preferred for clay deposition. Though orientation of the fine clay on coarser sand grains is better expressed, probably due to a larger force exerted by the contracting clay suspensions during drying (Brewer and Haldane, 1957), the sorption of clay film on very fine sand grains is not negligible.

In the loessial Serozem there is an increase of fine clay between A and the upper B horizons corresponding to volume increase of 6 % of fine clay (Table 3). Because a similar increase is found throughout the thick B horizon, this raises the question of the maximal depth of the active illuviation zone.

Distribution of grain cutans with depth suggests that the active zone of clay illuviation extends until the main calcic horizon at 100-130 cm. This horizon results from leaching and nodulization during the wetter year (Wieder, 1977). Similarly, Nettleton et al. (1975) related the clay maxima in Argids of Nevada, Arizona and California to wetter years. In profile EH-1 the upper calcic horizon (25-55 cm), which is only moderately developed, did not retard clay illuviation. Within the well developed calcil horizon (100-130 cm) the original forms of clay cutans and bridges become partly disrupted due to the very high accumulation of secondary carbonate. The clay is then incorporated into the plasma.

The observation that fine clay content did not decrease with depth in the deeper B horizons is no doubt related to the cumulative character of the profile, the surface growing upward. The buried horizons do not contain grain cutans, probably because of their destruction with time.

In the buried calcic horizon of the quartzic Arid Brown Soil (234-265 cm) the ratio of fine clay to non-carbonate clay is very high (0,90, Table 3) indicating that illuviation was more intensive in the sandy than in the loessial material. This is evident micromorphologically as grain cutans on large sand grains and as void argillans. The ability of clay to adhere on larger sand grains is the main reason of the better defined argillic horizon in this horizon. Nettleton et. al. (1969) have reached a similar conclusion. The greater extent of illuviation in the quartzic Arid Brown soil material is also related to a longer time of clay translocation, a possible higher precipitation in the past and a smaller content of silt particles which have a certain disruptive effect on oriented clays (Dumanski, 1970).

Possible alternative processes of clay enrichment which are not of illuvial origin need to be clarified. The difference in clay content between A and B horizon is unlikely to be due to sedimentation. The identical soil material in the two horizons (uniformity in colour, silt content, kind of skeleton grains) and the catenary distribution of the soils exclude such an alternative. The possibility of differential weathering between A and B horizon, as suggested by Nikiforoff (1937), can be rejected as well. The calcareous medium in the arid conditions does not allow strong decomposition or neoformation. Additionally, the amount of primary weatherable minerals is not higher in the A horizon, compared with the older B horizon according to a detailed modal analysis (Wieder, 1977). Finally, there remains the possibility of inherited grain cutans from eolian dust. Dust samples collected by Ganor (1975), however, show significantly fewer grain cutans which are thinner and have not yet the distinct reddish-yellow nuance which is observed in the pedogenic grain cutans. This colour is the result of fine clay accumulation in higher concentration, and some release of iron from clay as suggested by illuviation patterns in other studies (Thorp et al., 1959; Dalrymple, 1967; Walker, in press).

The occurrence of grain cutans which are not of illuvial origin should be distinguished separately. For instance, the very high amount of grain cutans in the gypsic horizon ($_{24cs,}$ 130–158 cm) is not likely to be due to illuviation. The amount of non-carbonate clay was found highest near gypsum crystals, with a large part of them in the form of grain cutans. It is suggested that this is the result of partial dissolution of fine carbonate because of the competition for Ca-ions when carbonates are associated with gypsum. The occurrence of higher amounts of grain cutans in the gypsic horizon could be also related to neomorphic palygorskite. The possible relation between palygorskite and gypsum occurrence is discussed by Yaalon and Wieder (1976) and Eswaran and Barazanyi (1974). This assumption is supported by the Mg content in the clay suspension (following dry sieving of the sand) which is twice as high as ... other clay samples*

* Mg analysis carried out in the gypsic horizon of EH-1 $B_{24cs,}$ 130–158) indicates that Mg content in clay suspen

Mechanism of clay mobilization and migration.

The question of how dispersion and mobilization of the illuviated clay occurs in an environment rich in exchangeable Ca will be considered briefly. In order to get deposition of oriented clay on sand grains, a prior dispersion of the clay and cycles of wetting and drying are necessary (Brewer and Haldane, 1957 ; Bartelli and Odell, 1960; Dumanski, 1970; Gile and Grossman, 1968).

A possible mechanism of clay mobilization in calcareous soils could be like that proposed by Hallsworth (1963) and van Schuylenborgh (1972), who postulated migration of clay at a low Ca^{++} ion concentration during the early stages of wetting when equilibrium with calcite has not yet been reached.

Mechanical dispersion may thus occur under conditions of relatively low electrolyte content in the A horizon (Fig. 1, middle) which has a relatively weak structure and disperses under the impact of rain drops on the initially dry soil surface. The dispersed clay moves downward, in suspension, utilizing the relatively large pores in the surface horizon. In the subsurface horizons flocculation is induced by a higher electrolyte content or by dessication in places where the microstructure is less compact and also where the local carbonate concentration is lower.

Clay mobilization could also be facilitated by soluble products of organic decomposition (Dalrymple, 1967). This seems to be supported by the frequently brownish clay spots in channels which resemble biogenic pores. Highly developed clay skins in such channels were observed also by Thorp et. al. (1959) and Khalifa and Buol (1968).

In conclusion, though there is good evidence of clay illuviation in calcareous environments, its extent and the process of clay mobilization require further study.

sion, after dry sieving of the sand, is 3.02 % whereas in the other clay sample it is 1.32 %.

TABLE 1 Morphological characteristics of Profile EH-1
Loessial Serozem overlying Quartzic Arid Brown soil →

Horizon & depth cm	Colour	Texture	Structure
A 0-25	light yellowish brown 10YR 6/4 (dry) yellowish brown 10YR 5/4 (wet)	loam	weak fine subangular blocky breaking into** medium to fine granular
B_{1ca} 25-55	as above	clayey loam	moderate coarse subangular blocky strong fine subangular
B_{21} 55-77	as above	clayey loam	moderate v. coarse subangular blocky strong medium to fine subangular blocky
B_{22} 77-100	as above	clayey loam	moderate v. coarse subangular blocky strong subangular blocky
$B_{23ca+cs}$ 100-130	as above	clayey loam	moderate v. coarse subangular blocky to blocky fine subangular blocky to blocky
B_{24cs} 130-158	as above	clayey loam	moderate v. coarse subangular blocky to blocky fine subangular blocky to blocky
B_{3ca} 158-193	as above with locally reddish yellow 7.5YR 7/5 (dry) and 7.5YR 5.5/4 (wet)	clayey loam	moderate v. coarse subangular blocky to blocky medium to fine subangular blocky to blocky
C_{ca} 193-234	pink to reddish yellow 7.5YR 6/5 (dry) strong brown 7.5YR 5/6 (wet)	clayey loam	weak coarse subangular blocky to blocky strong fine subangular blocky to blocky
II B_{ca} 234-265	reddish yellow 7.5YR 6/6 (dry) strong brown 7.5YR 5/5/4 (wet)	loam	weak coarse subangular blocky to blocky medium fine subangular blocky to blocky

Boundary	Carbonate nodules*	$CaCO_3$ %	Bulk density (g/cm^3)	Remarks
gradual wavy	very few	23.0	1.34	
gradual wavy	5–10%	28.6	1.55	many pedotubules
gradual wavy	2–5%	28.8	1.62	many pedotubules
abrupt clear	1–2%	29.0	1.5	
gradual wavy	~30%	31.4	1.68	gypsum (crystalline)
gradual wavy	1–2%	22.9	1.67	gypsums crystals (3%)
gradual wavy	10–15%	24.8	1.65	
gradual wavy	10% hard	44.0	1.61	
	30% hard	49.2	1.68	

* Visual estimate according to comparison chart (Yaalon, 1966)

** The words "breaking into" are not repeated in the following description of the compound structure.

TABLE 2 : Profile EH-1, Particle size distribution

Horizon	Depth	C l a y (μm)			S i l t	
		Fine clay	Coarse clay	Total clay	Fine silt	Coarse silt
		<0.2	0.2-2	<2	2-20	20-50
	cm	%	%	%	%	%
A	0-25	6.1	16.0	22.1	16.1	23.5
B_{1ca}	25-55	14.5	18.5	33.0	17.3	26.1
B_{21}	55-77	16.7	18.5	35.2	17.5	26.0
B_{22}	77-100	15.2	21.2	36.4	18.1	23.9
$B_{23ca+cs}$	100-130	13.8	13.8	32.6	19.4	21.3
B_{24cs}	130-158	13.2	17.8	31.0	17.1	26.9
B_{31ca}	158-193	17.7	18.2	35.9	21.2	16.7
B_{32ca}	193-234	13.1	21.3	34.4	28.3	13.7
II B_{bca}	234-265	12.8	12.0	24.8	33.0	10.0

→

(µm)	S a n d (µm)						
Total silt	Very fine sand		Fine sand	Medium sand	Coarse sand	Very coarse sand	Total sand
2-50	50-63	63-125	125-250	250-500	500-1000	1000-2000	50-2000
%	%	%	%	%	%	%	%
39.6	19.7	7.2	7.6	1.6	1.2	1.0	38.3
43.4	11.2	5.5	4.8	1.3	0.6	0.2	23.6
43.5	9.7	5.0	5.1	1.1	0.3	0.1	21.3
32.0	9.7	4.8	5.6	1.2	0.3	-	21.6
40.7	17.8	7.1	1.5	0.2	0.1	-	26.7
44.0	14.4	6.7	2.7	0.6	0.5	0.1	25.0
37.9	10.6	5.1	8.7	1.2	0.2	0.3	26.2
42.0	4.5	3.1	12.2	2.8	0.8	0.2	23.6
43.0	5.5	3.8	15.7	3.2	2.1	1.9	32.2

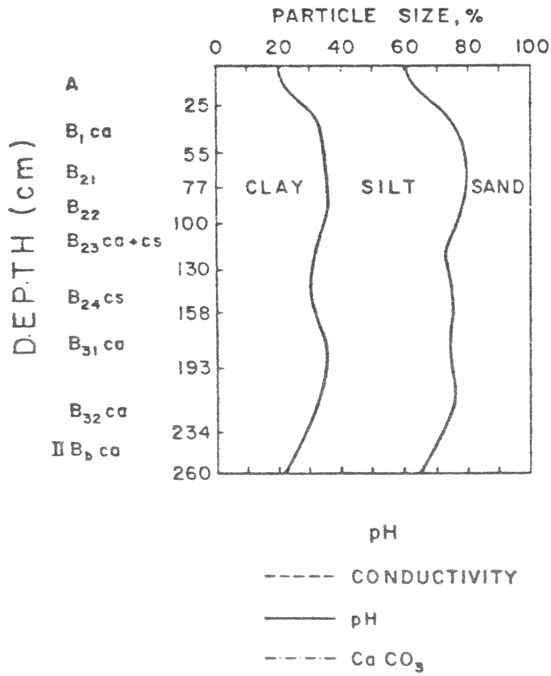
TABLE 3 : Profile EH-1, clay and non-carbonate clay content

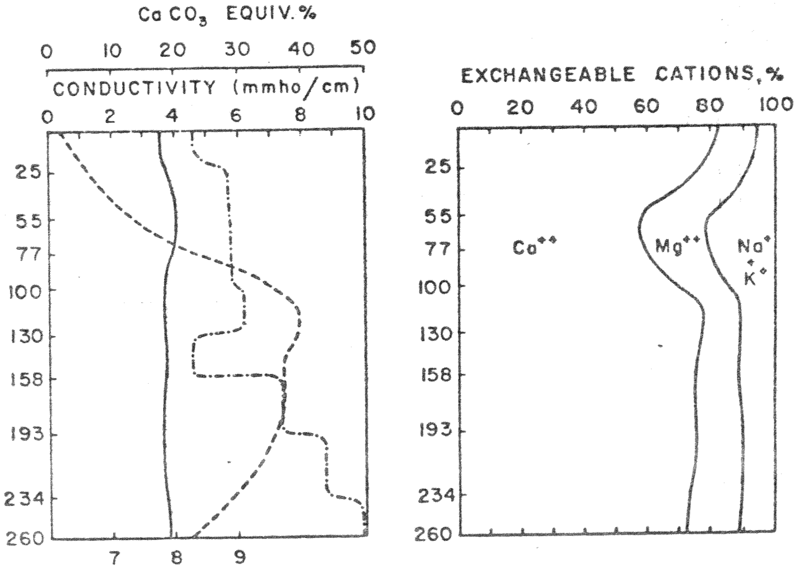
Horizon	Depth	Total clay <2 µm	Non-carbonate clay <2 µm
	cm	%	%
A	0-25	22.1	14.4
B_{1ca}	25-55	33.0	19.8
B_{21}	55-77	35.2	19.9
B_{22}	77-100	36.4	20.5
$B_{23ca+cs}$	100-130	32.6	17.4
B_{24cs}	130-158	31.0	21.2
B_{31ca}	158-193	35.9	20.4
B_{32ca}	193-234	34.4	18.1
II B_{bca}	234-265	24.8	14.2

Fine clay <0.2 μm %	Fine clay / Total clay %	Fine clay / Non-carbonate clay %	Fine clay in %, per vol.
6.1	0.27	0.42	3.1
14.5	0.44	0.73	8.5
16.7	0.47	0.83	10.2
15.2	0.42	0.74	8.6
13.8	0.42	0.79	8.7
13.2	0.42	0.62	8.3
17.7	0.49	0.87	11.0
13.1	0.38	0.72	8.0
12.8	0.51	0.90	8.1

Fig. 1 →

EH I/up LOESSIAL SEROZEM





Ca CO3 EQUIV. %
0 10 20 30 40 50
CONDUCTIVITY (mmho/cm)
0 2 4 6 8 10
25
55
77
100
130
158
193
234
260
7 8 9
EXCHANGEABLE CATIONS, %
0 20 40 60 80 100
Ca++
Mg++
Na+ + K+

LIST OF FIGURES

1) Particle size, $CaCO_3$, conductivity, pH and exchangeable cation distribution of profile EH-1.

2) Single grain cutans (top right) in B_{1ca} (25-55 cm) of EH-1; crossed polarizers, 100x.

3) Interconnected grain cutans of brownish colour (top - right), in EH-1 (25-55 cm); crossed polarizers, 100x.

4) Embedded grain cutans in B horizon of a loessial Dark Brown soil; crossed polarizers, 150x.

SUMMARY

Caly illuviation in a calcareous environment was found in deep loessial Serozems and similar soils in the arid northern Negev, Israel. An upland profile studied in detail is cumulative, built up from eolian desert dust, strongly calcareous throughout with several calcic horizons in the subsoil. A diagnostic gypsic horizon occurs in the lower B horizon.

Illuviation is interpreted from micromorphology and from the increase of fine clay (0.2 m) in relation to non carbonate clay. It shows a calculated volumetric increase of about 7 % of fine clay between the A and upper B horizons (25 80 cm depth). The micromorphological

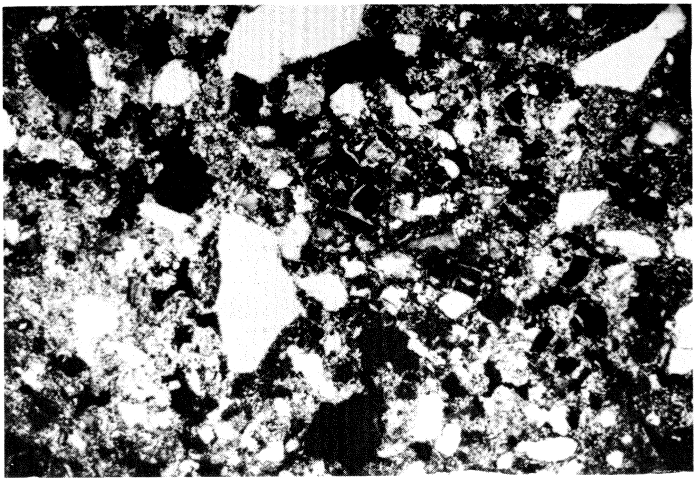


Fig. 2

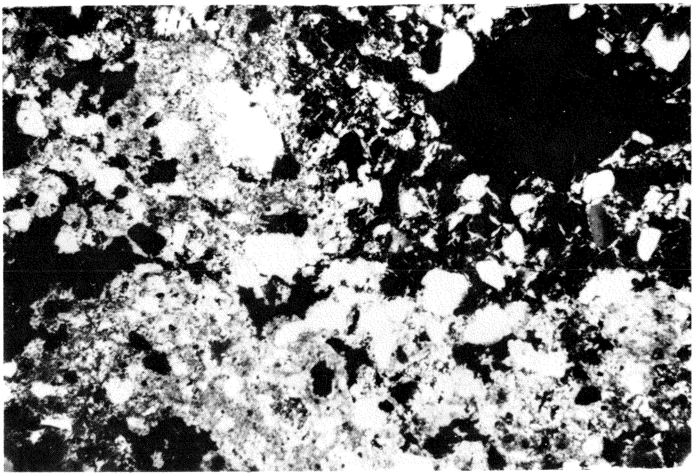


Fig. 3

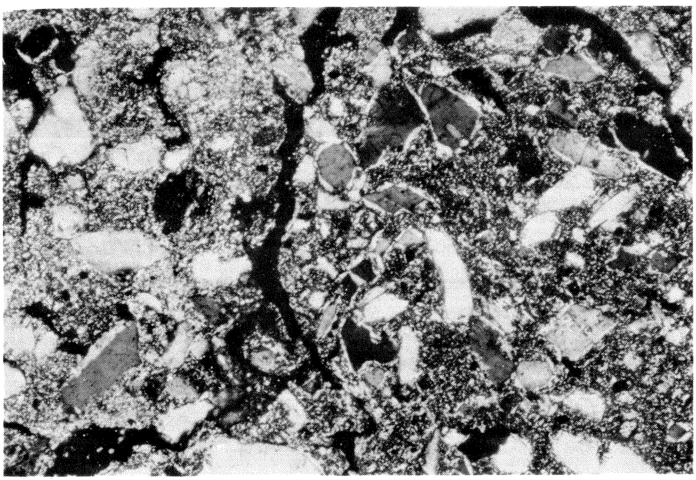


Fig. 4

forms of illuviation are expressed as birefringent single grain cutans and local brownish spots which include grain cutans interconnected by clay bridges. These cutans which coat the very fine sand and coarse silt grains are relatively thick, well-oriented and occur preferentially in locally loose microstructure. Usually they are not in close proximity to the pedogenic microcalcite. In addition to clay illuviation, the main soil forming process in these soils is intrapedonic redistribution of carbonates and nodulization and it is thus different from the carbonate leached soils in which pedogenic grains were reported previously.

Aspects of clay mobilization in a calcareous medium and the possible occurrence of grain cutans not of illuvial origin are also discussed.

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