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Lithic fabric, saprolite and pedoplasmation: The canvas of soil formation

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Abstract : Soil formation is a complex interplay involving lithic-fabric, saprolite, and pedoplasmation, which dictate the evolution of soil parent materials and their vertical differentiation. The transformation of loose sediments and coherent rocks during the initial stages of soil formation is underpinned by intricate mechanisms. Bioturbation drives soil material formation from loose sediments, while the transformation of coherent rocks involves the development of saprolite through weathering, succeeded by the pedoplasmation process. Pedoplasmation signifies the metamorphosis of saprolite into soil material, marked by transitions from saprolite fabric to B horizons, that often manifests as micro-scale shearing, resulting in alternating lithic and soil fabrics. The preservation of lithic fabric is prolonged in iron oxide-rich regions; however, mineral recrystallisation and alteration gradually convert lithic and soil fabrics. Micromorphological analysis unveils the intricate characteristics and transformations within saprolite profiles, which exhibit distinct patterns attributed to bedrock types and climatic conditions. Rock diversity, encompassing igneous, metamorphic, and sedimentary types, engenders distinctive transformations inherent to each rock type, yielding features ranging from mineral modifications to void development. Micromorphological changes are investigated employing various techniques and tools *viz*., X-ray diffraction, X-ray micro-tomography, 3D microstructure characterisation, and spectral induced polarisation (SIP) tomography, which provide valuable insights into the micro-pedo complex. This study unveils the geological tapestry of soil formation, portraying lithic fabric, saprolite, and pedoplasmation as pivotal sketches in the ongoing saga of the Earth′s surface evolution.

Keywords: *Soil morphology, weathering, pedological transformations, micromorphological features, pedoplasmation*

Introduction

Soil formation is a long-standing process eventuated by the transformation of existing rocks into soil parent materials and then to vertically differentiated

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horizons with time. Various transformation actions are attributed to the loose sediments and coherent rocks during the initial stages of transformation. Pedoturbation, particularly bioturbation, results in soil material formation from loose sediments (Kooistra and Pulleman 2018), while coherent rocks lay on two disparate steps: (i) formation of saprolite (weathered rock) through weathering, followed by (ii) the conversion of saprolite into soil material which can be referred as pedoplasmation. (Zauyah *et al.* 2018). Pedoplasmation is a transition between saprolite fabric and a B horizon (Flach *et al*. 1968). This might result in the development of repeated micro-scaled shears on the saprolite, which exemplifies the formation of millimetre-sized parallel layers of alternating lithic fabrics and soil fabrics.

The iron oxide saturated spots can preserve lithic fabric for a longer period (Sycheva *et al*. 2022). The gradual transformation of lithic fabrics to soil fabrics in lower layers of laterites occurred due to kaolinite recrystallisation and conversion of kaolinite mesomorph to fine-grained aggregates with some random fabrics (Muller and Bocquier 1987). Minerals and altermorphs combined are responsible for the formation of preserved lithic fabrics in a saprolite (Stoops and Mees 2018; Stoops *et al.* 2020). In the soils of humid areas, saprolite reaches nearly 50m depth, which allows it to develop a part of regolith (Holbrook *et al*. 2019). Most of the tropical and subtropical soils are developed from saprolites through deep weathering of fabrics (Suhr *et al.* 2018). Saprolites in various rocks of tropical, subtropical, temperate and Mediterranean areas have been studied with submicroscopic and micromorphological techniques (Schaefer *et al.* 2002; Scarciglia *et al.* 2005; Jimenez-Espinosa *et al.* 2007). micromorphological studies are limited and focused more on the mineral weathering of saprolite.

Lithic fabric, saprolite, and pedoplasmation collectively contribute to the intricate canvas of soil formation by representing different stages and processes in the transformation of bedrock into mature soil. The lithic fabric represents the initial geological material, while saprolite reflects the intermediate stage, where physical and chemical weathering has started to break down minerals and create voids. Pedoplasmation, on the other hand, signifies the advanced stage of weathering characterised by the accumulation of organic matter, clay minerals, and microbial activity, leading to the development of fertile topsoil, where they illustrate the dynamic and complex nature of soil formation, highlighting the interplay of geological, chemical, and biological processes over time.

Geochemical and pedochemical weathering

Weathering is a fundamental geological and environmental process that shapes the Earth's surface over time. It involves the breakdown and alteration of rocks and minerals, but there are distinct mechanisms through which this transformation occurs, depending on the environmental context (Wray and Sauro 2017). Two primary modes of weathering, each driven by a unique set of factors and processes, are geochemical weathering and pedochemical weathering.

Geochemical and pedochemical weathering processes play a fundamental role in shaping the characteristics of the lithic fabric, saprolite, and pedoplasmation within soils. Geochemical weathering contributes to the breakdown of minerals in lithic materials, while pedochemical weathering influences the alteration of rocks and minerals in the soil matrix. Understanding these weathering processes is crucial for comprehending how lithic fabrics evolve into saprolites and, eventually, the development of pedoplasmation, which collectively forms the canvas of soil formation.

Table 1. Major features of geochemical and pedochemical weathering

Parameter	Geochemical Weathering	Pedochemical Weathering
Description	Chemical breakdown of rocks and minerals through reactions with external agents like water, oxygen, and acids (Blattmann et al. 2019; Rambabu *et al.* 2020).	Chemical alteration of r ocks and minerals due to interactions with substances found in the soil or regolith (Osman 2013).
Primary Agents	Water, oxygen, carbon dioxide, acids, and other chemical compounds from the atmosphere and surface water (Sidkina *et al.* 2022; Roylands *et al*. 2022).	Soil-derived substances such as organic matter, microbes, and organic acids produced by plant roots (Erens 2015)
Key Processes	Dissolution, oxidation, hydrolysis, and carbonation are common processes involved (Oludare 2017).	Ion exchange, complexa tion, chelation, and precipitation are prevalent processes (Shrivastav *et al.* 2020)
Environmental Factors	Climate, temperature, precipitation, and the presence of certain minerals can influence geochemical weathering rates (Anderson 2019; Vinnarasi *et al.* 2021).	Soil composition, moisture content (Pawlik and Šamonil 2018) , microbial activity (Singh *et al.* 2023), and the types of plants and vegetation (Chandran *et al* . 2021) in an area play significant roles
Speed of Weathering	Generally faster, especially in regions with high rainfall and elevated temperatures. (Clift 2020; Hack 2020).	Generally slower, but can be significant in soils with high organic matter and microbial activity (Tsolova *et al*. 2019).
Common Locations	Typically, more pronounced in expo sed rocks and mineral outcrops (Talapatra and Talapatra 2020).	Mainly occurs in soils and regolith layers where minerals come into contact with organic matter and root exudates (Osman 2013).
Products of Weathering	Often results in the formation of soluble ions that can be transported away from the weathering site (Hayes *et al*. 2012).	May lead to the formation of secondary minerals, organic matter -rich horizons, and clay minerals in the soil profile.
Example	Acid rain causing the dissolution of limestone to form caves.	Plant roots releasing organic acids that alter the soil pH and mineral content (Shrivastav *et al.* 2020).

Geochemical and pedochemical weathering are distinct processes involved in the chemical alteration of rocks and minerals (Table 1). Geochemical weathering is primarily driven by external agents such as water, oxygen, and acids, with common processes including dissolution, oxidation, hydrolysis, and carbonation. It operates faster, especially in regions with high rainfall and elevated temperatures, typically affecting exposed rocks and leading to the formation of soluble ions. In contrast, pedochemical weathering occurs due to interactions with substances in the soil, including organic matter, microbes, and plant root-derived organic acids. Key processes encompass ion exchange, complexation, chelation, and precipitation. While pedochemical weathering generally proceeds slower, it can be significant in soils rich in organic matter and microbial activity, often resulting in the formation of secondary minerals, organic matter-rich horizons, and clay minerals in the soil profile. These two processes collectively contribute to the complex weathering of Earth′s surface materials.

Lithic fabric: formation and transformation

Lithic fabric refers to the characteristics and arrangement of rock fragments or lithic materials (gravel, stones, pebbles, and larger rock fragments) within a soil horizon or layer. Formation of lithic fabric occurs through the combination of relict minerals such as quartz and alteromorphs such as biotite, garnet *etc.* (Nahon 1991). Loss of clay alteromorphs and putrification of gibbsitic and ferruginous pseudomorphs and resistant clay minerals are two dominant features of weathering processes. An increase in volume due to expansion of biotite, granite and gneiss causes fabric deformation. In addition, crystal formation exerts pressure, which leads to the deformation of fabric, especially due to the calcite and gypsum formation. According to Marcelino *et al.* (2018) and Stoops and Marcelino (2018), the separation of fragments by losing their optical continuity is observed in coarse grains of quartz. Due to pedoturbation, pedoplasmation takes part in the saprolite of sedimentary as well as metamorphic rocks through the variation in the layers of constituents (Stoops *et al.* 2018). Homogenization and defragmentation of saprolite due to the process of bioturbation creates channels, chambers, vughs and passage features with pedoplasmated coatings of kaolinite-hematite saprolite (Stoops *et al*. 2020; de Freitas *et al*. 2021). As the size of constituents impacts the transportation of materials, the voids are found to be more abundant in fine-grained materials than in coarse-grained materials. Moldic voids established through congruent dissolution are important in pedoplasmation, contributing to weathering profile production.

Saprolite Profile

The worn rock that retains a minimum of some of the initial structure of the rock is called saprolite. It serves as an origin of plant nutrients, filters and retains water, and contributes significantly towards the silicate carbon sink as it is the deepest part (da Silva *et al.* 2022). Weathering of profiles can be reciprocated to lower and upper saprolites. Altered compact rocks called saprock, overlying unweathered igneous rock, belong to lower saprolite. They are subjected to successive losses in their original lithic fabric nature as well as compactness towards the surface and represent upper saprolite (Tonui *et al.* 2003; Stoops and Schaefer 2010). Saprolites are products of long-term chemical weathering that exceeds the rate of erosion with downward progression (Hayes 2019). It has been observed in tropical as well as humid temperate regions, where the relief provides an environment for the accumulation of weathered products, and these materials exhibit palaeofeatures. In general, saprolites have three-dimensional variability in their nature, resulting under the influence of different bedrock (Fig 1).

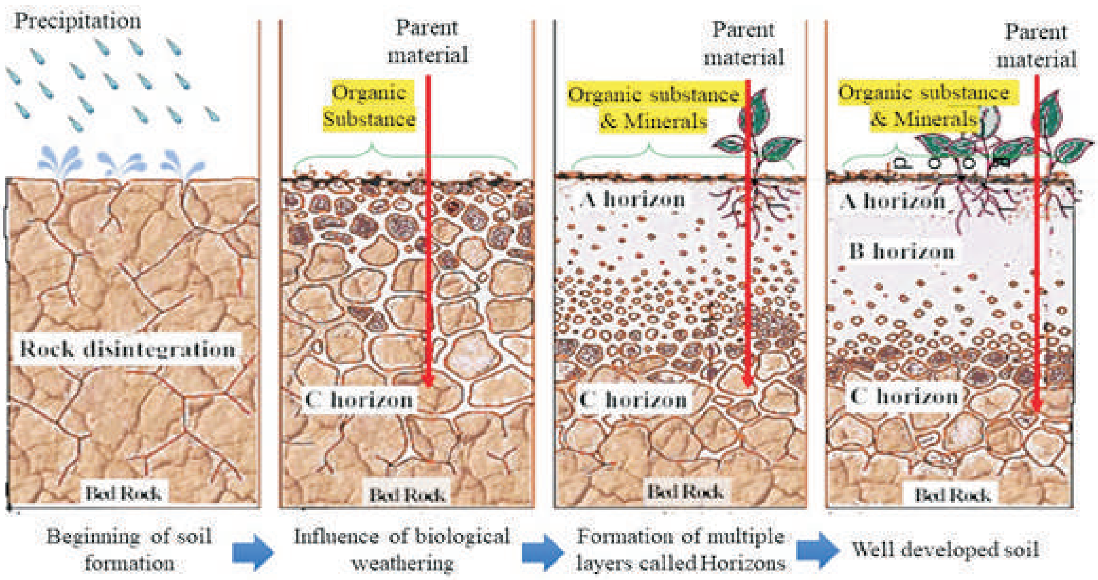


Fig. 1. Diagrammatic representation of the transformation of rocks indicating the major pedogenic transformations

Micro-morphological features

` Weathering of primary minerals followed by illuviation, neoformation (including iron oxide accumulation and neoformed clays) and biological activities resulted both vertical and horizontal variabilities in fabric and mineralogical composition, degree of weathering and hydrological condition of the parent rock (Kuhn *et al.* 2018; Finlay *et al.* 2020; Kogel-Knabner and Amelung 2021; Menezes *et al.* 2022), that results in the micro-morphological characteristics of saprolite profile (Table 2) and distinct micro-morphological changes.

Table 2. Micromorphological features of saprolite profile

Associated micro-morphological features	Reference(s)
Coatings and infillings of clay and iron oxides, hypo coatings, impregnated nodules and excrement infillings in tropical saprolites.	Vepraskas *et al.* 2018
Development of calcite and/or soluble salts infillings contributed in the physical weathering of rocks and minerals in arid areas.	Owliaie *et al*. 2018; Sevin *et al.* 2020
Weathering of original lithic fabric causes development of voids and secondary minerals, which led to breakup of lithic fabric found in upper saprolite	Stoops and Schaefer 2010
Bedding or schistosity partially controlled the mechanical and thermal stress on rocks resulted in the formation of voids in saprolites, which differ in number and/or size with degree of weathering and it can fill in the weathered products. These voids act as a primary path for weathering solutions in rock and oversee spheroidal weathering paradigms	Meunier 1983; Buss *et al*. 2008.
Quartz grains are affected by mechanical fracturing and chemical weathering, where fractures get filled with illuvial clay and weathering alters surface morphology respectively	Stoops and Marcelino 2018; Iglesias-Martínez *et al.* 2020; Sandeep *et al.* 2022
When feldspar undergoes weathering in tropical saprolites, it is gradually substituted by clay minerals like halloysite and kaolinite, while in regions with lower h umidity, 2:1 phyllosilicate form. In arid areas, biotite commonly transforms into vermiculite along with clay minerals in mixed layers. Moreover, altered forms often include kaolinite layers tinted by iron oxides.	Stoops and Mees 2018; Bonnet *et al.* 2022; Warr 2022; Volf *et al.* 2023
Initial changes in pyroxenes caused by iron oxides coating cleavage planes and fractures as well as fading of crystal boundaries occurred at Mediterranean climate.	Certini *et al.* 2006
Pyroxenes weathering begins from goethite coated cracks and extends to boxwork pattern by the uniform dissolution of remnant minerals. Under drier climates, alteromorphs can be formed from olivine and pyroxenes, which consists of expandable 2:1 clays and oxides of iron.	Mulyanto *et al* . 1999; Chesworth *et al*. 2004
Amphiboles such as actinolite undergo a slow change in a Mediterranean climate as they are replaced by a yellow -brown trioctahedral vermiculite. This replacement is most common in fractures and cleavage cracks.	Abreu and Vairinho 1990

Features such as coatings, infillings, void development, and mineral transformations provide concrete examples of how pedoplasmation and weathering influence the lithic fabric and saprolite in soil formation. They serve as tangible evidence supporting the concepts and dynamics described in several investigations, enhancing the understanding of the intricate relationships between soil development and micromorphological changes in different geological and climatic contexts.

Coatings and infillings of clay and iron oxides, as reported in tropical saprolites (Table 2), demonstrate the influence of chemical alteration on mineral composition and soil characteristics. In arid areas, the development of calcite and soluble salts infillings highlights the role of physical weathering in shaping the soil matrix. The weathering of lithic fabric and the formation of voids in saprolites, influenced by factors like bedding and schistosity, further illustrate the complex processes involved in soil development. Additionally, the alteration of specific mineral types, such as feldspar, biotite, pyroxenes, and amphiboles, in response to different climatic conditions underscores the diversity of pedochemical weathering reactions. These transformations include the substitution of minerals, the formation of clay minerals and oxides, and the gradual replacement of original mineral phases. The interplay between chemical and mechanical weathering, as well as climatic influences, leads to the intricate micro-morphological features observed in soils and saprolites, ultimately shaping the landscape and soil characteristics in various regions.

Petrological features

Pedo-features are imperative evidence of the intricate processes and micro-morphological changes occurring during soil formation, emphasizing the role of parent rock composition in shaping soil characteristics. It enriches the understanding on lithic fabric and pedoplasmation contribution to the diverse canvas of soil profiles, enabling researchers and soil scientists to better comprehend the intricate interplay between geological factors and soil development (Table 3).

Table 3. Mineralogical changes on various rock types

Rock types	Characteristic pedological features	Reference(s)
Granite	Depended on structural and textural properties of parent rock. Inter, intra, and transmineral planar voids were produced as a result of mechanical weathering of the lower saprolite	Scarciglia *et al.* 2005; *Popli et al.* 2022
	The voids formed can be filled with sesquioxides and amorphous clays. The appearance of speckles brought on by freshly generated mineral inclusions, where alteromorphic or pseudo morphic weathering occurs in saprock.	Ghosh and Guchhait 2020; Broz 2022.
	Major weathering products observed at tropics are kaolinite, halloysite and gibbsite and in temperate region are illite, vermiculite and chlorite.	Sequeira Braga *et al.* 2002; Picanço *et al.* 2019; Tsozue 2020; Pospíšilova 2021
	Sericitization of perthite and plagioclase near grain centers by hydrothermal alteration. In addition, clay mineral formation has reported on the walls of plagioclase grooves in the saprock	Stoops and Dedecker 2006; Yuguchi *et al.* 2019; Gawad *et al.* 2022.
	Alteration of biotite by exfoliation may occur on continuous weathering, that found common in upper saprolite.	Popli *et al.* 2022; Neves *et al.* 2023.
	The change in biotite is evident through a reduction in pleochroism and a decline in interference colors, implies a transformation into layered biotite-vermiculite and iron oxides along the cleavage planes or edges of the crystal, that may give dark brown to black stains.	Pitty 2020.
	Voids of saprolites were distinguished by yellowish to reddish brown clay particles as infillings. Crevices with ferruginous coatings, nodules and microcrystalline quartz (Chalcedony) nodules were also reported	Stoops and Marcelino 2018

Gabbro	In a temperate climate zone various transformation were observed such as Hornblend weathered to smectite and goethite	Egli *et al.* 2021
	Feldspar altered to kaolinite	Zhu *et al.* 2019
	Chlorite transformed to interlayered chlorite-vermiculite	Nadeau and Harris 2019
Andesitic	Ferruginous coatings are reported in the crevices of saprolite and these cracks decreases from upper saprolite towards the lower saprolite.	Stoops and Marcelino 2018; Hassan Ahmed 2022
	In the upper saprolite plagioclase psuedomorphically substituted by kaolinite and mica mixture, while in lower saprolite, plagioclase weathered to sericite, kaolinite and smectitie.	Salama *et al.* 2016; Mei *et al.* 2021; Bonnet *et al.* 2022
	Total pseudomorphic replacement of plagioclase by kaolinite through weathering is possible through the fissures and cleavage planes in saprock zone of dacite profile	Gu *et al.* 2007, Anda and Dahlgren 2020
	Feldspar altered to illite, kaolinite, hallo ysite and gibbsite and biotite altered to chlorite and vermiculate through long process.	Warr 2022
	In saprolites, vermiculite may fill in voids along the cleavages formed on weathering of pryoxenes to kaolinite, that exhibited decline in pleochroism.	Certini *et al.* 2006; de Sousa *et al.* 2023
	Feldspar altered partially to vermiculite, in the environments of temperate region. Formation of iron oxide in the groundmass due to the alteration of ferromagnesian minerals occurred in the tropics.	Drees *et al.* 2003; Bakhsh 2019
	In the tropics, andesite undergoes spheroidal weathering, in which weathered plagioclase products moves towards the outer boulder shell where amorphous materials disappear leaving behind mouldic voids.	Mulyanto and Stoops 2003; Szymański and Szkaradek 2018
	In the Antarctician environment, upper saprolite existed in optically isotropic yellowish colour due to the hydrothermal mineralization of pyrites.	Schaefer *et al.* 2008; Basibuyuk and Yalcin 2019
	Oxidation of sulphides and mobilization of iron results in chemical weathering, secondary sulphate formation and generate an amorphous iron oxide phase. Hence voids covered by clay and nodules of iron oxides are considered as pedofeatures. Saprolites of this zone shows undifferentiated and speckled b fabrics, also the intergranular voids are filled with isopachous amorphous silica cement.	Gu *et al.* 2007; Szymański and Szkaradek 2018
Gneiss	Thick saprolites (>20m) can be produced by the weathering of gneiss along with plethora of core boulders.	Schaefer *et al.*. 2002; Ibraimo *et al.* 2004; Simas *et al.* 2005; Muggler *et al.* 2007
	Saprolite formation can be identified in 2 phases based on micromorphology. The first phase describes on the conserved micromorphological features of parent rock and phy sical weathering process for the microfracture development in lower saprolite or saprock.	Le Pera *et al.* 2001; Helvacı *et al.* 2018
	Formation of further chemical weathering of minerals and micro cracks defines the second phase, in which alteration of feldspar, garnet and biotite forms ferruginous compounds and clay minerals.	Biondino *et al.* 2020
	Development of biotit e on gneiss by the process of chloritization. Formation of cracks due the garnet weathering in gnesis, were filled with iron oxide obtained by biotite weathering results in a boxwork fabric	Baidya *et al.* 2019; Castro *et al.* 2022; Oziegbe and Oziegbe 2023

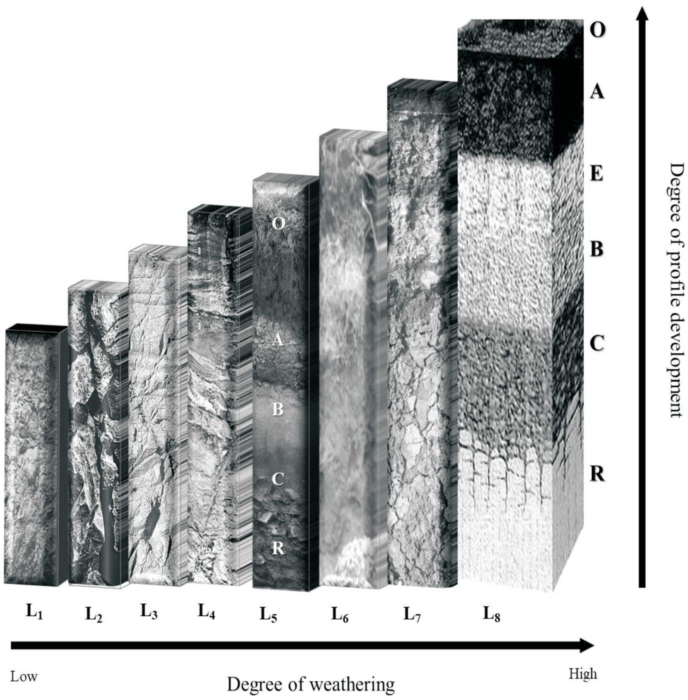
	Occurrence of primary minerals with gibbsite, dominant gibbsitic alteromorphic structures and the existence of ferruginous zones of voids attributes distinct features of saprolites on gneiss.	Simas *et al.* 2005; Budihal and Pujar 2018; Stoops and Mees 2018; Budihal and Manjunatha 2023
Schists	Saprolites on micaschists can be occurred varied depths in temperate to tropic zones.	Maurizot 2020; Pintaldi *et al.* 2021
	Parallel arrangement of muscovite and biotite crystals occurs in deeper saprolite with straig ht voids and interlocking quartz crystals along with schistosity. Wide voids are observed in upper saprolite	Cerri *et al.* 2020; Hancock 2020
	Two kinds of weathering in feldspar one of which is insitu replacement by gibbsite and the other one is vacuoles inside the grains and embayments at their edges are produced by dissolution	Budihal and Pujar 2018; Cardoso *et al.* 2019
	Iron segregation, void clay coatings and ferruginous coatings on trans mineral cracks in the upper saprolite.	Ghosh and Guchhait 2020; Verrecchia and Trombino 2021
Amphibolite	Distinct core stones with weathered center comprising alternate layers of epidote, clinzoisite and actinolite, in a groundmass constitute the saprolite on an amphibole schist.	Okrusch *et al*. 2020; Soloviev *et al.* 2020
	Lower saprolite contains pale yellow weathering rims by kaolinite, while upper kaolinite contains dark brown weathering rims consist of fine -grained gibbsite or kaolinite filled in the iron oxide schistosity network.	Malla Noubisi *et al.* 2021
	According to morphological standards, on alteration clinozoisite and epidote form gibbsite and actinolite, where actinolite exhibit rapid weathering	Dill and Kolb 2019; de Luchi *et al.* 2021
	Reddish or golden coatings on the lithic fabric of very thin saprolite layer of amphibolite are specific character obtained from the temperate climate, where vermiculate is the dominant lay mineral.	Popli *et al.* 2022
	Transmineral cavities coated with iron oxide is considered as a pedofeature in saprolite.	Bigot 2021
Serpentinite	In the lower saprolite profile of serpentinite exhibits weathered chlorite, plagioclase, pyroxenes, chalcedony and serpentine with iron oxide deposition, while in upper saprolite profile, serpentine is further altered and contains iron oxide in the fissures.	Garcıa *et al.* 197_4
	With the preserved lithic fabric, lower saprolite profile consists of antigorite crystals, magnetite with altered iron oxides, Chlorite with partial alteration to kaolinite, a chrysolite veins	Zauyah et al. 2018
	kaolinite replace serpentine with lithic fabric preservation. Iron oxide coatings and hypocoatings along the planar voids, disappearance of kaolinite from upper saprolite and limpid authigenic clay coatings in some voids of lower saprolite were observed.	Stoops *et al.* 2008
Phyllites and Slates	Phyllites and slates are prone to intensive weathering which produces thick saprolites	Briški 2020
	They exhibit fine grained structure with quartz and sericite alignment observed biotite, muscovite, graphite grains and iro n content in these rocks.	El Desoky *et al.* 2020; Pellant and Pellant 2020
	Quartz > muscovite > biotite is the typical stability pattern that is revealed by the minerals′ weathering. Biotite initially transforms into a mica -vermiculite interstratified cla y mineral after losing its pleochroism. With an extinction pattern akin to a mosaic, sericite weathers to kaolinite.	Zauyah et al. 2018

Siliciclastic	Rocks consists of grained quartz and illite -type mica as layers wirh hydroxy aluminum interlayers	Andrade *et al.* 2019; Akker *et al.* 2021
	Iron oxide coatings between the fractures of polycrystalline quartz	Molenaar and Felder 2018
Calcareous	Calcareous rocks undergo complete weathering due to dissolution of original rock and obtained impure limestone, marls may form distinct patterns	Dasgupta and Ghosh 2018 ; Manica *et al.* 2020
	Lime stone saprolite has rippled layers of limestone and siltstone with coating of iron oxide in the fractures and also with clay coatings.	El Aref 2023; Bradwell and Ballantyne 2021

Each rock type exhibits distinct weathering patterns, mineral transformations, and micromorphological changes within their respective saprolites (Table 3). For instance, granite weathering results in the formation of voids filled with sesquioxides and clays, while diorite experiences alterations in upper, middle, and lower saprolite layers, including the transformation of biotite to kaolinite and feldspar to gibbsite. Gabbro undergoes weathering transformations such as the conversion of hornblende to smectite, andesitic rocks exhibit the pseudomorphic replacement of plagioclase by kaolinite, and gneiss forms thick saprolites with distinctive micro-morphological features. Schists display parallel arrangements of muscovite and biotite in deeper saprolites, while amphibolite saprolites contain core stones with weathered centers. Serpentinite exhibits changes in chlorite, serpentine, and iron oxide deposition within its saprolite profiles. Phyllites and slates are prone to intensive weathering, resulting in fine-grained structures with mineral transformations. Siliciclastic rocks feature iron oxide coatings between quartz grains, and calcareous rocks undergo complete weathering through dissolution and the formation of distinct patterns. These detailed insights into rock-specific pedological features enhance our understanding of how geological compositions influence soil development and micromorphological changes.

Pedoplasmation

Pedoplasmation was introduced by Flach *et al.* (1968) who identified it as the formation of soil B horizons from weathered rock termed saprolite (Fig 2). The integration of refractory residual primary minerals and secondary minerals into the soil matrix fades the rock texture utilizing groundwater action, faunal burrowing, and clay illuviation, referred to as pedoplasmation (Fedoroff 2009). The pedoplasmation activities in the region of transition separating soil and saprolite, as well as the formation of clays along with the pore network, are closely tied to mineral assemblage alterations caused by primary mineral dissolution. Channels were detected in different layers in the transition zone across the saprolite along with the overlying soil and were therefore associated with a higher level of pedoplasmation, owing mostly to biological activity in the transformation between the soil as well as the saprolite (dos Santos *et al.* 2018). Physical characteristics of pedoplasmated zones were juxtaposed with the characteristics of indurated or packed subsurface materials with fluvial and aeolian origins by Kew *et al.* (2010). Based on SEM and microprobe investigations, they concluded that these subsurface materials have a less porous micro mass instead of saprolite, which exhibits pedoplasmation, may be due to closely packed clay minerals.



L_1 : Rocks and minerals
L_2 : Disintegration (physical weathering)
L_3 : Formation of saprolite
L_4 : Decomposition (chemical weathering)
L_5 : Differentiation of horizons (Major horizons- O, A, B, C, R)
L_6 : Particle re-orientation (illuviation
L_7 : Soil aggregation
L_8 : Mature soil profile

Fig 2. Step-by-step depiction of soil weathering and development with pedoplasmation

For instance, weathering is more severe in black shales as opposed to siltstones. The latter are moderately worn subangular pieces overlaid with less coarse material with empty cracks, whilst black shales have generalized fissures followed by simultaneous linear disintegration where pedoplasmation appears to be promoted. Pyrite crystals were also discovered in this profile above silex pieces, implying that pyrite is connected with black shales (Ruiz 2019).

Techniques for pedo-feature investigation

Attribution of micropedo-complex can be executed with different approaches, which overlies various pedo-characters that are indispensable in the study of micropedo environment. There are distinct techniques used in the examination of micro pedological features (Table 4).

Table 4. Various techniques applied for evaluation of pedo-characters

Analytical techniques	Operational framework	Key outcomes	Developed by
Oedometer-collapse tests	Collapsibility of the loess using single-oedometer and double - oedometer	Varying amounts of collapsibility may be caused by mineral concentrations and microstructural factors including pore size distribution and particle sphericity.	MWRPRC 1999

Combination of spatial time domain reflectometry (TDR) and surface electrical resistivity tomography (ERT)	Spatial resolution for vertical soil water content (1D TDR device - Campbell Scientific TDR100), surface electrical resistivity (2D ten-channel SYSCAL Pro Switch resistivity meter - IRIS Instruments, France), and seasonal soil temperature (ERT surveys)	Pellucid horizontal and vertical fluctuations in soil electrical resistivity were seen in 2D ERT pictures, and these variations were quantitatively correlated with changes in soil water content. Surface ERT provides 2D information integrated across a larger area of soil than spatial TDR does. The accuracy of soil water monitoring can be increased altogether with a higher spatial resolution when surface ERT and spatial TDR approaches are combined.	Fan *et al.* 2015
X-ray diffraction	Clay minerals in the loess using Bruker D8 Advance X -ray diffractometer	Calcite was found at 3.03 x 10^{-10}, 2.28 x 10^{-10}, 1.91 x 10^{-10} and 1.87 x 10^{-10}, quartz at 3.34 x 10^{-10}, 4.26 x 10^{-10}, 1.82 x 10^{-10}, and 2.45 x 10^{-10} and plagioclase at 3.19 x 10^{-10}, 4.03 x 10^{-10}, and 3.76 x 10^{-10}.	NEA 2018
X-Ray micro-tomography	X-ray images of an angular Leighton Buzzard Sand (LBS) specimen and a spherical glass bead (GB) specimen are examined non-destructively (by synchrotron micro-tomography at the BL13W beam-line of the Shanghai Synchrotron Radiation Facility (SSRF))	During the pre -peak shearing phase, there is a notable shift in the mean coordination number (CN), which subsequently stabilizes after reaching its peak. This CN pattern is consistent across particles of different sizes as shearing progresses. During shear, branch vectors in rounded grain boundaries become aligned with the loading direction, whereas in angular boundaries, they concentrate horizontally, departing from their initial nearly isotropic distribution.	Cheng and Wang 2018
3D microstructure characterization	Particle size distribution, pore size distribution, particle morphology, particle orientation and pore orientation	The range of particle size is 10 x 10^{-6} - 50 x 10^{-6} while pore size of particles is 2 x 10^{-6} to 40 x 10^{-6}. In the morphological aspect increase in diameter causes reduced sphericity. The orientation of 67% of the particles lies between 0° and 45° although pores oriented in direction > 45°	Wei *et al.* 2019
Soil Microstructure Analysis System (SMAS)	Geometrical and morphological indices of soil pore areas, perimeters, equivalent lengths, equivalent diameters, roundness, morphological ratios, the number of components in a given area, apparent porosity, anisotropic rates, fractal dimensions, and probability densities, among others and particles at the microscale using SEM	Based on the measured values of roundness and morphology ratio, a classification criterion for the form category of sand particles is given.	Tang *et al.* 2020
Spectral induced polarization (SIP) tomography.	Water content, particle size properties, cation exchange capacity (CEC), and permeability in the field	A potent geophysical technique for visualizing soil features is Spectral Induced Polarization (SIP), which operates in the frequency range of 0.25–25 Hertz.	Revil *et al.* 2021

Different techniques encompass a wide range of methodologies, from traditional tests like oedometer-collapse tests and X-ray diffraction to more advanced approaches like X-ray micro-tomography, 3D microstructure characterization, and Spectral Induced Polarization (SIP) tomography. These methods offer valuable insights into soil properties such as collapsibility, mineral composition, microstructure, particle size distribution, pore size distribution, and more. Researchers have applied these techniques to study diverse aspects of soil behavior, including water content, electrical resistivity, particle morphology, and even geophysical parameters like cation exchange capacity (CEC) and permeability. By employing these analytical tools, scientists can gain a comprehensive understanding of soil properties and behavior, which is crucial for various applications in geology, agriculture, and environmental science.

Investigation on the properties of granular materials (Table 5) adhere to the circularity, roundness, compactness, sphericity, aspect ratio and mod-ratio which altogether describes the shape of the material (Cox and Budhu 2008).

Table 5. Archive of grain shape characterization approaches (Cox and Budhu 2008)

Shape characteristic	Definition	Salient features	Reference(s)
Sphericity	Ratio of grain volume to that of smallest circumscribing sphere	2-D chart developed to facilitate application (Rittenhouse 1943) Measurement relates to form Measurement in computer programs differ from the original definition	Krumbein 1941
Roundness	Ratio of the curvature of grain edges/corners to overall grain	2-D chart developed to facilitate application (Krumbein 1941) Measurement relates to angularity and texture Measurement in computer programs differ from the original definition	Wadell 1932
Fourier series	Shape (wave of profile) estimated by expansion of periphery radius as function of angle of grain′s center of gravity by Fourier series	Unable to correctly analyze highly irregular or re - entrant particles	Ehrlich and Weinberg 1970
Fourier descriptors	Calculation of shape descriptors from the Fourier series coefficients	Problems with other Fourier series methods are overcome, i.e. re-entrant particles Applies FFT algorithm and utilizes boundary information only	Beddow and Vetter 1977
Fractal dimension	2-D value ranging from 0–1; describes the ability of a rugged boundary to occupy void space	Highly dependent on segment lengths chosen to measure profile Measurement relates more to roughness or texture of grain rather than form	Kaye 1982

Various analytical techniques are used to study soil properties, including mineral composition, microstructure, and geophysical parameters. These techniques are valuable for characterizing soils as they contribute to the appraisal of the processes and factors involved in the formation of soils from parent materials, whereas the analytical techniques discussed are tools used to analyze and study existing soils.

Conclusion

The intricate canvas of soil formation is portrayed with the labyrinthine reciprocity of lithic fabric, saprolite and pedoplasmation. The dynamic processes of pedological transformation exist from the initial stages of rock formation to the development of vertically differentiated horizons and distinct actions that shape soil morphology. The manifestation of this process is evident through transitions from saprolite fabric to B horizons, often characterized by repeated micro-scale shears resulting in the formation of alternate lithic and soil fabrics. Over the time, lithic fabric has been significantly preserved by iron oxide-rich regions, whereas mineral recrystallization and modification cause the lithic fabric to change into soil fabric. Investigations into micromorphology further illuminate the complex characteristics and transformations taking place within saprolite profiles. Weathering-induced fractures, changes in mineral content, and the creation of crevices and secondary minerals are characteristics of how the original lithic fabric has changed. Saprolite profiles exhibit variability, reflecting bedrock types and climatic conditions. The weathering of profiles corresponds to upper and lower saprolites, where chemical weathering exceeds erosion rates, resulting in the accumulation of weathered products. Micromorphological characteristics vary with pedogenic processes, influencing fabric, mineralogy, and degree of weathering. The diverse rock types, from igneous, metamorphic and sedimentary, offer unique scenarios for soil formation. Each rock type undergoes specific transformations, producing a spectrum of features from mineral alterations to void formations. This intricate interaction between rock characteristics and environmental conditions underscores the complexity of soil development. Different techniques range from traditional methods like X-ray diffraction for identifying clay minerals to advanced methods like Spectral Induced Polarization (SIP) tomography for visualizing soil features in the field, which are crucial for advancing our understanding of soil behavior, composition, and geophysical properties. This exploration into the lithic fabric, saprolite, and pedoplasmation unveils the remarkable processes that shape our soils system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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