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S1. Geomorphological Description of Terrestrial Sampling Sites (Suppl. to Section 2.1.1)

Terrestrial soils (4419 samples) were collected from five continents:

(1) Asian. **China**: Soils were collected by the author, mainly from the southwest part of China, including grassland soil from Erdos (Jin et al., 2011), cold permafrost and desert soils from the Kunlun Mountains (Gui et al., 2010), and brown soils from Yimeng Mountain (Liu et al., 2009). **South Korea**: Red-yellow soils were collected from Hwangsan-Myun and Gamgok-Myun (Park, 1987). **Japan**: Samples included brown forest soil from Hinano Mountain, red-yellow soil from Hiroshima, paddy soil from Yoshijima Park, and Kanto loam soil from Shinonome No. 2 Park (Obara et al., 2015). **Singapore**: Old alluvium soil was collected from a slope at Nanyang Technological University (Ghosh et al., 2019). **Thailand**: Red soil was collected from Omkoi (Jindaluang et al., 2013). **Iran**, Soils were collected from the Gomishan suburbs (Samiei-Fard et al., 2021).

(2) North America. **USA**: Desertification soils were collected from Nevada (Spriggs and Ray-Maitra, 2007). Other samples included topdressing, concrete, and bunker sand from a golf course (Arya et al., 2008); fine clay soils from Southern California (Torrent et al., 1980); Montcalm loamy sand from Kalkaska County, Montcalm fine sand from Kent County, Coloma fine sand from Calhoun County, and Wallace sand from Kalkaska County (Wurman et al., 1959); acid sulfate soil from Maryland (Demas et al., 2004); coarse/fine loamy soil from East-Central Alabama (Shaw et al., 2003); strand plain soil from Northern Michigan (Barrett et al., 2001); soils from West Texas (Hirmas et al., 2007); and lamellae soils from Wisconsin (Bockheim et al., 2013); soils on Andesitic Lahar from California (Rasmussen et al., 2007). **Canada**: Fine loamy soils were collected from Central Saskatchewan (Amelung et al., 1999).

(3) Africa. **Nigerian**: Soil from Ibadan (Salako et al., 2006).

(4) Europe. **Germany**: Reddish-brown soil from Ehwald, and dark reddish-brown soil from Kottenforst; Bulgaria: Heavy clay soils from agricultural fields; **France**: Sandy loam soils from Allier, dark brown soils from Cime de Rouyon, yellowish brown soils from Coup d'Alzac, reddish brown soils from Lachamp Raphaël and dark brown soil from Mathieu; **Russia**: Dark brown soil from forested areas and dark grey soils from Western Siberian Plain; **Poland**: Dark grey soils from coniferous forests; Romania: Dark greyish brown soil from Tisza River Plain; **Sweden**: Brown soils from agricultural areas (https://www.fao.org/common-pages/search/en/?q=from+soil+map+volume+of+Europe).

(5) Oceania. **Australia**: Sandy loam soils from coastal areas (Minasny et al., 2007).

The following section synthesizes the formation and key morphological characteristics of soils from 53 representative global locations, aiming to elucidate how interactions among climate, topography, parent material, and vegetation control soil development and properties.

Asian

1. Apuzu (APZ)

The Apuzu area in Liangshan, Sichuan, is located within the north-south trending Sichuan-Yunnan tectonic zone on the eastern margin of the Tibetan Plateau, characterized by active neotectonics (Zhang et al., 2008). This region features deeply incised alpine valleys and a subtropical monsoon climate with distinct wet and dry seasons. The mean annual temperature is approximately 10-12°C, and the mean annual precipitation ranges from 1000 to 1200 mm, with over 80 % concentrated in the wet season (Sun et al., 2023). The coupling of intense physical weathering and concentrated rainfall drives severe surface erosion (Hao et al., 2025).

Active tectonics and steep topography result in parent materials dominated by coarse skeletal fragments from physical weathering (Zhang et al., 2008; Institute of Soil Science, Chinese Academy of Sciences [ISSAS], 2001). Continuous slope erosion (particularly sheet and rill erosion) preferentially removes fine particles (silt and clay) (Hao et al., 2025), leading to a particle size distribution overwhelmingly dominated by sand (0.05-2 mm) and gravel (>2 mm). Soil texture is predominantly sandy loam to loamy sand with generally high gravel content. Due to persistent erosion and weak pedogenesis, the soils in the region are overall skeletal, thin, highly spatially heterogeneous, and immature. Primary soil types include Leptosols, Regosols, and initial Cambisols (e.g., primitive yellow soils) on gentler slopes (ISSAS, 2001).

2. Chengdu (CD)

Chengdu is situated at the eastern margin of the Tibetan Plateau, within the western Sichuan Basin. Geologically, it is controlled by the Longmen Shan thrust belt, resulting in a northwest-high, southeast-low topographic staircase (Burchfiel et al., 2008). The region experiences a subtropical humid monsoon climate, with a mean annual temperature of 16.1°C (extremes: -5.9°C to 37.3°C) and a mean annual precipitation of approximately 1000 mm, exhibiting a pronounced seasonal pattern and the "Western China Rainy Screen" effect (Chen et al., 2004). Elevation ranges from ~450 m in the plains to over 5000 m in western mountains, supporting a complete vegetation spectrum from agricultural plains vegetation to evergreen broadleaved forests and subalpine coniferous forests (Xu et al., 2025). Dominant soil types include Paddy soils, Purple soils, and Yellow soils (Gong et al., 2007). These conditions profoundly shape local soil characteristics: diverse parent materials from the Longmen Mountains are fluvially sorted, creating a particle-size distribution sequence from sandy to clayey textures in the piedmont zone. The warm, humid climate drives intense chemical weathering and secondary clay mineral formation, leading to widespread clayification. Furthermore, long-term anthropogenic cultivation (e.g., terracing) has modified soil structure, resulting in a spatially heterogeneous soil texture pattern dominated by loamy soils (Egli et al., 2008).

3. Jiangjia Gully (correspond to DF in Appendix A1.1)

Jiangjia Gully in Dongchuan, Yunnan, is situated within the seismically active Xiaojiang Fault Zone, where fractured bedrock provides abundant material for debris flows (Wang et al., 2014). The terrain is characterized by deeply incised V-shaped valleys with longitudinal gradients of 15–23 % and elevations ranging from 1500 to 2500 m (Wang et al., 2015). The region experiences a subtropical monsoon climate with a mean annual temperature of about 15 °C, extreme highs up to 35 °C and lows down to -5 °C, and annual rainfall of 700–900 mm concentrated in high-intensity, short-duration events during the wet-season events (Zhuang et al., 2015). Vegetation cover is sparse (< 30 %), dominated by secondary shrubs and grasses (Guo et al., 2014). Soils are predominantly shallow Cambisols and Leptosols (Li et al., 2015). These geomorphic factors drive frequent debris flows. The entrainment-transport-deposition processes actively sort and mix soil materials, resulting in broad-graded particle distributions: sand (45–65 %), silt (20–35 %), and clay (10–20 %). The soils are primarily sandy loams with loose structure and poor aggregation, reflecting the heterogeneity and coarseness typical of debris-flow deposits (Jiang et al., 2025; Li et al., 2015).

4. Erdos (Ord)

The Ordos region is situated in the western part of the North China Craton, geologically belonging to the stable Ordos Block, which is dominated by Mesozoic sandstone and mudstone sedimentary layers (Yang et al., 2022). The topography is an eroded plateau with an average elevation of 1,000–1,500 m, bordered by the Yellow River loop to the northwest and characterized by extensive aeolian landforms such as the Kubuqi Desert and Mu Us Sandy Land (Du et al., 2017). The climate is temperate continental and semi-arid, with a mean annual temperature of 6–9 °C, an extreme maximum of around 40°C, and an extreme minimum of approximately -30 °C. The mean annual precipitation ranges from 150 to 400 mm, decreasing from southeast to northwest, while evaporation significantly exceeds precipitation (Gou et al., 2021). The natural vegetation is primarily desert steppe and typical steppe, with relatively low coverage (Yang et al., 2005). The main soil types include Kastanozems, Calcisols, and Arenosols (Yue et al., 2007).

These geomorphological factors shape the local soil morphology through the following mechanisms: sandy sedimentary rocks and aeolian sands provide parent materials rich in sand; strong wind sorting further removes fine particles, resulting in a predominantly sandy soil texture; limited precipitation and high evaporation inhibit chemical weathering and leaching processes, hindering clay formation and translocation; large diurnal and annual temperature ranges enhance physical weathering, but sparse vegetation limits organic matter accumulation and biopedogenesis. These processes jointly lead to weakly developed soils with indistinct horizon differentiation, coarse texture (often >70% sand), and low water- and nutrient-retention capacity, exhibiting the typical characteristics of fragile soils in arid and semi-arid regions (Gou et al., 2021; Yang et al., 2022; Yue et al., 2007).

5. Hainan (HN)

Hainan Island, situated in a tropical monsoon climate zone, has an annual mean temperature of 22–27°C and an annual mean rainfall of 1500–2500 mm, with precipitation concentrated in summer and frequently influenced by typhoons (Jiang et al., 2018). Its topography transitions from a central domed mountainous area (highest peak 1867 m a.s.l.) to hills, terraces, and coastal plains (Yao et al., 2013). The geology is dominated by granite and volcanic rocks, and vegetation follows an elevational gradient from coastal tropical forests to montane rainforests (Wang et al., 2019). The interplay of these geomorphic and climatic factors shapes the soil pattern in Hainan, dominated by ferralitic Latosols. High temperature, humidity, and seasonal intense rainfall promote intense chemical weathering and leaching, resulting in clay minerals dominated by kaolinite and Fe/Al oxides (Jiang et al., 2011). Meanwhile, steep topography exacerbates water erosion, leading to soils in cultivated areas (e.g., footslopes, terraces) derived from mixed parent materials (colluvial, alluvial) often exhibit loam to sandy clay loam textures with sand, silt, and clay. However, the surface layer is prone to coarsening due to erosion and human disturbance (Jiang et al., 2011, 2018; Yao et al., 2013).

6. Horqin (Hor)

The Horqin region is situated in the transitional zone between the southern margin of the Songliao Basin and the eastern foothills of the Greater Khingan Mountains, with an elevation ranging from 150 to 300 meters. The topography is characterized by aeolian sand dunes, ridges, and interdune depressions (Du et al., 2017; Huang et al., 2025). It experiences a temperate semi-arid continental monsoon climate, with a mean annual temperature of 5–7 °C and extreme temperatures approximately ranging from -30°C to 38 °C. The mean annual precipitation is 350–450 mm, exhibiting pronounced seasonal variability (Xu et al., 2011; ZHAO et al., 2002). The natural vegetation is dominated by sparse elm woodlands, sandy shrubs, and grassland communities, with significant spatial heterogeneity in coverage (Fan et al., 2023). These processes shape the soil system, which is predominantly classified as aeolian sandy soil. Intense wind erosion coupled with prevailing westerly winds leads to the selective removal of fine particles (silt and clay), resulting in surface sediment coarsening where sand content often exceeds 85% (Han et al., 2015; Li et al., 2014). The dune-depression microtopography influences local hydrology and sedimentation, promoting the relative enrichment of fine particles in depressions (Zhao et al., 2010). Concurrently, limited precipitation and high evaporation inhibit chemical weathering and leaching processes, thereby restricting profile development and clay mineral formation (Su et al., 2003). Consequently, Horqin soils exhibit typical characteristics of coarse texture, good sorting, loose structure, and weak pedogenic development.

7. Jinsha River (JSR)

The Jinsha River Basin, located in a tectonically active zone on the eastern margin of the Tibetan Plateau, is traversed by several major deep faults (Yang et al., 2012), resulting in extreme topographic relief from mountains exceeding 5000 m to deeply incised gorges, with an average basin slope exceeding 25° (Schmidt et al., 2019). The climate exhibits pronounced spatial variability, with mean annual temperature decreasing from 18°C in the lower reaches to -4°C upstream, and recorded extremes of 40.4°C and -30.6°C (Zhang et al., 2020). Annual precipitation sharply declines from 1200 mm downstream to 400 mm upstream (Deng et al., 2025). A complete vegetation vertical zonation exists, ranging from subtropical evergreen broadleaf forests to alpine shrublands and meadows (Guo et al., 2024). This complex geomorphic system shapes a distinctive soil pattern through coupled processes. Active tectonic uplift and steep slopes (> 30°) in the middle-reach alpine gorge region drive intense physical weathering and erosion, leading to the widespread development of shallow Leptosols with high gravel content (> 30 %) (Lin et al., 2014). In contrast, the relatively stable broad valleys and basins downstream, under a hot and humid climate (MAT >15°

C, precipitation >1000 mm), are dominated by chemical weathering, forming deep, clay-enriched Ferralic Cambisols (Jiang et al., 2015; Wang et al., 2013). The frigid plateau environment upstream limits pedogenesis, resulting in Gelic Cambisols with high organic matter but shallow solum. Geological structure and topography control the erosion base level and material transport, while climate and vegetation regulate weathering types and rates, jointly determining the degree of soil development, particle size distribution (e.g., coarser upstream, finer downstream), and the spatial heterogeneity of soil texture.

8. Jiuzhaigou (JZG)

Jiuzhaigou is located within the tectonically active Longmenshan Fault Zone on the eastern margin of the Tibetan Plateau, with elevations ranging from 2000 to 4760 m and extreme local relief (Liu et al., 2025). The bedrock is dominated by Paleozoic-Mesozoic carbonate rocks intercalated with clastic sandstones and slates (Du et al., 2013). The region experiences a humid monsoon plateau climate, characterized by a mean annual temperature of approximately 6.5°C (extreme range: -14°C to 30°C) and a mean annual precipitation of ~700 mm with distinct wet and dry seasons (Wei et al., 2022). Topography and climate govern a complete vertical vegetation zonation, transitioning from mixed coniferous-broadleaf forests to subalpine coniferous forests and alpine meadows (Bossard et al., 2015). These geomorphological factors interact to shape the local soil morphology. Active tectonic uplift and lithological heterogeneity (carbonate vs. clastic rocks) provide a diverse parent material foundation (Yi et al., 2018). Intense fluvial and glacial dissection has resulted in widespread colluvial, landslide, and glacial deposits, creating an initial pedogenic environment with poorly sorted particle-size distributions (Du et al., 2013; Liu et al., 2025). Concurrently, seasonal concentrated precipitation drives significant leaching and lateral translocation, leading to coarser (sandy) textures on slopes and finer (clayey) textures in valley floors and lake basins due to fine-particle deposition (Xinwei et al., 2023). Ultimately, under the influences of dense vegetation and the unique travertine deposition processes, the area has developed highly spatially variable soils, primarily classified as Cambisols and Luvisols, with textures ranging from coarse sandy loams to clay loams (Bossard et al., 2015; Hu et al., 2024).

9. Kunlun mountain (KLM)

The Kunlun Mountains, forming the northern tectonic boundary of the Tibetan Plateau, are characterized by geomorphological features controlled by the ongoing India-Eurasia collision (Cao et al., 2015; Staisch et al., 2020). The region has an average elevation of 5000-6000 m, with intensely dissected alpine-valley systems and peaks exceeding 7500 m in the western section (An et al., 2018). A typical continental plateau climate prevails, with mean annual temperatures ranging from -6 to 4°C and extremes from -30 to 25°C. Annual precipitation is 50-400 mm, decreasing from west to east (Yao et al., 2019). Vegetation exhibits distinct vertical zonation, transitioning from alpine desert to meadow, with coverage generally below 30 % (Luo et al., 2019).

This coupled geomorphic-climatic system shapes unique soil characteristics: intense tectonic uplift promotes physical weathering, generating skeletal parent materials; low temperatures and aridity inhibit chemical weathering and organic matter decomposition, while precipitation (far below evapotranspiration) limits leaching; high-altitude radiation intensifies freeze-thaw cycles. These interactions produce soils classified primarily as Lithosols, Cryosols, and Alpine Steppe soils, characterized by >30% rock fragments, 60-80% sand fraction, sandy loam to loamy sand textures, and organic matter content generally <1.5% (Fu et al., 2018; Kaiser et al., 2008). Steep slopes exacerbate erosion, maintaining soils in early developmental stages with shallow and discontinuous profiles.

10. Midui Gully (MDG)

The Midui Gully is situated in the southeastern Tibetan Plateau (approximately 29.5°N, 96.5°E) within the Parlung Tsangpo basin, a region influenced by maritime glaciation, with elevations ranging from about 3800 to 5000 meters (Yongping et al., 2025). Underlain primarily by granite and gneiss, the landscape has been shaped by intense neotectonic uplift and Quaternary glaciation, resulting in characteristic glacial landforms such as U-shaped valleys, moraine terraces, and steep valley slopes (Yang et al., 2015). Influenced by moisture from the Indian Ocean, the climate is characterized as plateau temperate humid, with a mean annual temperature of approximately 5-7 °C, extreme temperatures ranging from about -15 °C to 25 °C, and a mean annual precipitation of up to 800-1000 mm concentrated in summer (Yang et al., 2013). Vegetation exhibits distinct vertical zonation, transitioning from mixed coniferous-broadleaf forests at lower elevations through dark coniferous forests and alpine shrub meadows to alpine subnival vegetation (Wei et al., 2020). Soils, classified primarily as Entisols or Inceptisols, develop on Quaternary glacial till, exhibiting sandy loam to sandy clay loam textures, high coarse fragment content, and weak profile development (He et al., 2008).

The local soil morphology results from the integration of these geomorphic factors. The thick glacial till parent material, derived from glacial erosion and deposition, is inherently unsorted and lithologically heterogeneous, which dictates the poor particle size distribution and predominantly sandy texture of the soils (He et al., 2008; Yang et al., 2015). The steep terrain and active gravitational processes (e.g., landslides) further enhance the spatial heterogeneity and instability of soil material (Yang et al., 2015). Concurrently, ample precipitation and moderate temperatures facilitate chemical weathering and leaching of minerals within the till, while dense forest vegetation contributes to topsoil organic matter accumulation via litter input (Wei et al., 2020; Yang et al., 2013). However, continuous slope disturbance, low temperatures, and the stony parent material inhibit the formation of deep, homogeneous soil profiles, ultimately resulting in the soil morphology characterized by high rock fragment content, shallow development, and pronounced physical heterogeneity (He et al., 2008).

11. Lulang River (LLR)

The Lulang River Basin is located in the eastern Himalayan orogen, characterized by active tectonics and dominated by Mesozoic–Cenozoic metamorphic rocks and granites (Pan et al., 2024). The basin exhibits typical alpine valley topography with elevations ranging from 2800 to 4500 m and steep slopes (25°–40°) (Li et al., 2014). The climate is plateau temperate semi-humid, with a mean annual temperature of 4–8°C, extreme minima below –15°C, and maxima generally below 25°C; annual precipitation is 800–1000 mm, concentrated in summer (Li et al., 2008). Vegetation shows distinct vertical zonation, transitioning from spruce forest, fir forest, alpine shrubland to meadow from valley to summit (Miehe et al., 2007). Soils develop primarily on Quaternary glacial deposits, classified mainly as alpine meadow soils and brown soils, with high skeletal content (30–60% gravel) and sandy loam texture (Zou et al., 2025). Soil formation is shaped by multiple interacting factors: intense freeze–thaw cycles drive physical weathering and cryoturbation, forming stony surface layers; steep topography enhances coarse-particle transport and erosion, limiting fine-particle retention; seasonal precipitation enables leaching, but low temperatures inhibit chemical weathering and clay formation; vegetation stabilizes soil and adds organic matter, promoting pedogenesis and carbon accumulation on gentle slopes and valley floors (Cheng and Wu, 2007). Soils in the Lulang Basin result from long-term coupling of tectonic, glacial, climatic, and biotic processes.

12. Minjiang Watershed (MJ)

The Minjiang River Basin is located in the transition zone between the eastern margin of the Tibetan Plateau and the Sichuan Basin, characterized by complex geological structures bounded by the Longmenshan Fault Zone, with the western part belonging to the Songpan–Garzê Fold Belt and the eastern part to the Yangtze Paraplatform (Yan et al., 2011). Topography descends steeply from NW to SE, with elevation dropping from > 4000 m at the source to < 800 m in the Chengdu Plain, forming a typical stepped landform (Liu et al., 2015). The basin experiences an East Asian monsoon climate with pronounced vertical zonation: the upper reaches have a plateau cold–temperate climate with a mean annual temperature < 4°C (extreme minimum -25°C) and annual precipitation of 400–600 mm; the lower reaches feature a humid subtropical climate with a mean annual temperature of 16–18°C (extreme maximum 38°C) and annual precipitation of 1000–1400 mm (Zhai et al., 2022). Vegetation exhibits a complete vertical spectrum, ranging from alpine meadow and subalpine coniferous forest to evergreen broadleaf forest (Li et al., 2024). Soil types vary systematically with altitude, including alpine meadow soil, dark brown soil, yellow–brown soil, yellow soil/purple soil, and alluvial soil (Du et al., 2013).

These geomorphological elements shape the morphology and texture differentiation of basin soils: pronounced topographic relief and active neotectonics dominate the upper reaches, favoring physical weathering and resulting in thin, skeletal, poorly sorted soils. In contrast, the flat terrain and warm–humid conditions in the lower reaches enhance chemical weathering and clay formation, coupled with deposition of fine sediments from upstream, leading to deep, clay-rich alluvial soils

(Zhang et al., 2020). The entire basin exhibits a source-to-sink continuum from coarse-textured sandy loam upstream to fine-textured clayey soils downstream, reflecting the pedogenic effects of geology, topography, climate, and biota (Haq et al., 2024).

13. Malipo (MLP)

Malipo County is located within the Youjiang Fold Belt in southeastern Yunnan Province, characterized by outcroppings of Paleozoic to Mesozoic carbonate rocks (limestone, dolomite) and clastic rocks (sandstone, shale), with intense tectonic activity (Beckford et al., 2021). The topography features a deeply dissected mid-mountain gorge landscape, with elevations ranging from approximately 100 m in southern valleys to nearly 2000 m in northern mountains (Yanna et al., 2020). The region experiences a subtropical monsoon climate with a mean annual temperature of ~17.5°C, extreme highs up to 35.5°C, extreme lows around -2.3°C, and a mean annual precipitation of ~1050 mm concentrated in the rainy season (May-October) (Li et al., 2015). The primary subtropical evergreen broad-leaved forest has been severely degraded, largely replaced by secondary forests, shrubs, and rocky desertification patches (Zhang et al., 2021). The interaction of these factors shapes the local soil patterns: intense dissolution in carbonate areas forms shallow, clay-textured (silty clay loam to clay) limestone soils (Calcaric Regosols/Cambisols), often mosaicked with bedrock. In contrast, physical weathering in clastic rock areas dominates the formation of lighter-textured (sandy loam to loamy sand) initial soils or yellow soils (Cambisols) (Beckford et al., 2021; Yanna et al., 2020). The steep terrain and concentrated rainfall drives severe soil erosion, leading to hydraulic sorting that enriches sand particles and coarsens texture on slopes, while fine particles deposit in depressions, increasing clay content. This results in a highly heterogeneous spatial distribution of soil types and textures closely tied to geomorphic units

(Beckford et al., 2021; Yanna et al., 2020).

14. Mianzhu town (MSZ)

Mianzhu City is situated in the transitional zone between the Longmen Shan tectonic belt and the Chengdu Plain on the northwestern margin of the Sichuan Basin, characterized by complex geological conditions (Wang et al., 2009). The topography descends stepwise from the high-mid mountain region in the northwest (1500-4000 m a.s.l., with bedrock of granite and limestone) to the central hills and platforms composed of red sandstone and mudstone, finally extending to the southeastern alluvial-proluvial plain (500-700 m a.s.l.) (Yan et al., 2011). The region experiences a humid subtropical monsoon climate. The plain area has a mean annual temperature of approximately 15.3°C, with an extreme temperature range from about -5°C to 35°C, and a mean annual precipitation of 1000-1100 mm, which increases with altitude in the mountains (Zhang et al., 2010). Vegetation exhibits a vertical zonation from montane forests to agricultural vegetation on the plains (Ma et al., 2023). The coupling of these geomorphic factors shapes the local soil formation: intense tectonic uplift and steep slopes in mountains promote physical weathering, resulting in skeletal soils (e.g., Regosols, Cambisols) with sandy textures and high gravel content (Liu et al., 2009). In contrast, fluvial sorting and deposition on the plains provide thick alluvial parent materials. Under warm-humid climatic conditions and millennia of rice cultivation, this leads to the development of finer-textured and well-stratified soils such as Anthrosols (Paddy soils) and Fluvisols (Cheng et al., 2009).

15. Tibet (TGH)

The grassland system on the Tibetan Plateau develops under an extreme alpine environment with an average elevation exceeding 4000 m. Its geomorphological and pedogenic characteristics result from the long-term coupling of tectonic, climatic, and biological processes. The plateau has experienced intense uplift due to the ongoing India-Eurasia collision (Xia et al., 2011), forming a topographic pattern dominated by high mountains, broad valleys, and lake basins. The climate is characterized by pronounced cold and arid conditions: mean annual temperature is mostly below 3°C, with extreme minima below -30°C, and annual precipitation (approximately 100–500 mm) is concentrated from June to September (Zhao et al., 2020). Vegetation is primarily alpine meadow and steppe, with low coverage (30–70 %) and limited biomass. The main soil types are Alpine Meadow Soil and Alpine Steppe Soil (Wang et al., 2007). These geomorphic factors determine soil development pathways: intense tectonic uplift and strong physical weathering (freeze-thaw, wet-dry cycles) produce parent materials dominated by coarse debris (Xia et al., 2011); low temperatures and aridity suppress chemical weathering and organic matter decomposition, limiting clay formation and deep profile development; sparse vegetation can only stabilize fine particles superficially through a mattic epipedon. Consequently, soils in this region are generally shallow, gravel-rich, skeletal and coarse-textured (sand-dominated), with surface-accumulated organic matter and weak weathering (Wang et al., 2007), representing a result of tectonic-climatic-biological synergy.

16. Tibet Moraine deposit (TMD)

Moraine deposits on the Tibetan Plateau primarily occur in high-altitude glacial regions above 4000 m a.s.l., where their geomorphological characteristics result from the interplay of geological, climatic, and biological processes. The parent material consists of poorly sorted glacial debris (e.g., granite, gneiss, limestone), exhibiting loose structure and extremely poor sorting (Owen, 2009). The topography is dominated by steep lateral/terminal moraine ridges and hummocky moraine hills, with slopes often reaching 15–35° and pronounced relief. The climate is cold and arid, with a mean annual temperature ranging from -5 °C to 5 °C, extreme minima below -30 °C, and summer maxima generally below 15 °C. Annual precipitation averages 200–600 mm, concentrated in summer (Yao et al., 2012). Vegetation is sparse alpine meadow or cushion-plant communities with low biomass (Miehe et al., 2011). Under these geomorphic and climatic conditions, soils are primarily Entisols or Inceptisols, with weakly developed profiles often showing AC or A/R horizonation (Chen et al., 2020). The moraine geomorphology directly governs soil morphology and texture: the heterogeneous lithology and extremely poor sorting of the parent material yield soils rich in coarse fragments (gravel and sand), accounting for up to 50–70% of the mass; intense freeze-thaw cycles (150–200 cycles per year) promote physical disintegration but limit chemical weathering, restricting clay formation; steep slopes enhance the erosion and loss of fine particles. These processes shape the typical soil characteristics of the Tibetan moraine regions: highly skeletal, light-textured (mostly sandy loams), loosely structured, and low in organic matter (Li et al., 2014).

17. Xichang (XC)

The Xichang region is situated on the eastern flank of the Hengduan Mountains at the eastern margin of the Sichuan-Yunnan rhombic block, characterized by active tectonic structures and dominated by Paleozoic to Mesozoic carbonate rocks, sandy shales, and Quaternary sediments (Zhang et al., 2003). The topography features deeply incised valleys and mid-mountain landscapes, with an elevation range of approximately 1500–3000 m and significant relief. The climate is of subtropical plateau monsoon type, with a mean annual temperature of about 17°C, extreme highs up to 36°C, extreme lows down to -4°C, and a mean annual precipitation of approximately 1000 mm, over 80% of which is concentrated in the rainy season (May–October) (Ke-yi et al., 2020). Vegetation exhibits vertical zonation, ranging from savanna shrubland at lower elevations to subalpine dark coniferous forests and meadows at higher elevations (Wang et al., 2024). Soil types are primarily yellow earths and red earths, with yellow-brown earths and brown earths developing sequentially at higher altitudes (Xu et al., 2010).

These geomorphological factors interact to shape the local soil morphology. The active geological setting and diverse parent rocks provide a heterogeneous parent material base for soil formation. The steep topography enhances erosion and material transport, resulting in shallow, skeletal soils on slopes and thicker alluvial deposits in valleys. The warm and humid climate (mean annual temperature 17°C, precipitation 1000 mm) promotes intense chemical weathering and the formation of clay minerals, while the concentrated rainfall also exacerbates leaching of base cations. The vertical vegetation zones regulate soil organic matter accumulation and aggregate formation through litter quality and root activity at different elevations. Ultimately, the coupling of these processes leads to soils in Xichang that are generally acidic, with textures ranging from loam to clay loam, and exhibit significant spatial heterogeneity in their physicochemical properties (Ke-yi et al., 2020; Xu et al., 2010; Zhang et al., 2003).

18. Yimeng Mountain (YM)

The Yimeng Mountain region, situated in south-central Shandong Province, is underlain by Precambrian granitic gneiss and Paleozoic limestone (Zhao et al., 2012). This area features a tectonically uplifted low-mountainous and hilly landscape with elevations ranging from 200 to 1156 m, characterized by strongly dissected terrain and steep slopes. The climate is warm temperate semi-humid monsoon, with a mean annual temperature of 12-13°C, extreme highs around 40°C, extreme lows around -20°C, and mean annual precipitation of 700-850 mm concentrated in summer (Xue-mei et al., 2025). The current vegetation is dominated by warm-temperate deciduous broadleaved secondary forests and artificial coniferous plantations. These geomorphological factors shape a soil system dominated by Haplic Luvisols (Brown soils) and Haplic Calcisols (Cinnamon soils): the gneiss areas, subject to intense physical weathering, develop skeletal Haplic Luvisols with high sand content and poor sorting; the limestone areas, dominated by chemical weathering, form Haplic Calcisols with higher clay content. Intensive hillslope erosion driven by steep topography and concentrated rainfall leads to substantial loss of fine particles, resulting in generally shallow and rocky soils on slopes, while alluvial soils with relatively uniform texture accumulate in valleys (Yan et al., 2021). Overall, the interaction of parent rock properties, rugged topography, and monsoon climate determines the region's fundamental soil morphology—characterized by coarse texture, shallow depth, and high spatial heterogeneity.

19. Yunnan (YN)

Yunnan Province (21°8′–29°15′ N, 97°31′–106°11′ E) is located on the eastern margin of the collision zone between the Eurasian and Indian plates. Its complex geological structure and intense Cenozoic uplift have formed a topography dominated by plateaus and mountains (94 % of the total area), with elevations ranging from 76 m to 6,740 m and dramatic local relief (Wang et al., 2016). The region experiences a low-latitude plateau monsoon climate, with a mean annual temperature of 13–21°C, extreme highs exceeding 40°C and extreme lows below -10°C. The mean annual precipitation is 1,100–1,500 mm, showing pronounced spatial heterogeneity and distinct wet-dry seasons (Pradhan et al., 2022). Vegetation exhibits vertical zonation from tropical rainforest at low elevations to alpine meadows at high elevations (Zomer et al., 2015). These geomorphic and climatic conditions drive the formation of predominantly Ferrallitic soils (Red Soils): intense tectonic uplift and rugged terrain activate erosion-deposition processes, influencing soil depth and particle-size distribution; high temperature and abundant rainfall promote intense weathering of primary minerals and leaching of silica, leading to relative accumulation of iron and aluminum oxides; alternating wet-dry cycles further accelerate the crystallization and aging of iron oxides, resulting in typical red soil profiles characterized by reddish hue, clay-rich texture (clay content often 30–50%), strong acidity (pH 4.5–5.5), and advanced allitization (Bockheim et al., 2014; He et al., 2004).

20. Hwangsan-Myun (HM), South Korea

The Hwangsan-Myun area, located in the southwestern coastal region of the Korean Peninsula (Jeollabuk-do), is underlain by Mesozoic granitic bedrock with stable geological structure and intense surface weathering. The topography is characterized by gentle low hills at an elevation of approximately 20 m, adjacent to paleo-shorelines, with geomorphic evolution influenced by Quaternary sea-level changes (Chough et al., 2000; Park, 1987). The region experiences a humid temperate monsoon climate, with mean annual precipitation of approximately 1,200 mm, hot and rainy summers, relatively mild winters, and a mean annual temperature of about 13 °C. These climatic conditions promote intense chemical weathering and leaching (Lee et al., 2016). The natural vegetation is dominated by temperate deciduous broadleaf and mixed forests, although long-term agricultural activities have substantially degraded the primary vegetation (Kong, 2000). The representative soil, classified as "Red Yellow Soil" developed on granitic weathering crust, is a Typic Hapludult. Its texture is silty clay, with silt content (2-50 μm) exceeding 50%, dominated by fine silt (5-20 μm). Clay content (<2 μm) is approximately 30%, while sand content is low (Park, 1987).

The soil characteristics result from the long-term interaction of geological, climatic, topographic, and biological factors. First, the granitic parent material undergoes deep weathering under warm and humid conditions, releasing abundant quartz and feldspar fragments, which provide a silt-dominated parent material base for the soil (Kim et al., 2024). Second, aeolian dust (loess material) transported by the East Asian winter monsoon deposits on the gentle hills of this region, significantly increasing the proportion of silt in the soil. Consequently, its particle-size characteristics are intermediate between typical loess in northern China and clayey loess-like deposits in western Japan (Park, 1987; Youn et al., 2014). Third, abundant precipitation leads to intense leaching, resulting in substantial loss of alkali and alkaline earth metal ions (e.g., Ca^{2+}, Mg^{2+}). The soil is strongly acidic (pH 4.3-5.6), with very low cation exchange capacity (CEC ≤10 $cmol^{+}$/kg) and base saturation below 5% (Gruba et al., 2015). This strongly acidic leaching environment inhibits the formation and preservation of 2:1 expanding clay minerals such as montmorillonite, favoring instead a clay mineral assemblage dominated by illite, kaolinite, and amorphous materials (Lee et al., 2014). Finally, although vegetation provides organic matter, rapid decomposition under high temperature and humidity limits organic carbon accumulation mainly to the surface layer, with low humification. This limited role in improving soil structure and fertility exacerbates soil impoverishment and clay-enrichment trends (Bae et al., 2015).

21. Gamgok-Myun (GM), South Korea

Gamgok-Myun, situated in the southwestern coastal region of Jeollabuk-do, South Korea, is characterized by typical low-elevation coastal hill landforms. The area is geologically underlain by granite that has undergone prolonged deep weathering, resulting in variably thick weathering crusts (Park, 1987). Topographically, it comprises gentle hills at approximately 20 m elevation, distributed near paleo-shorelines with relatively subdued relief. Climatically, the region falls within the East Asian monsoon zone, experiencing high annual precipitation with seasonal variability that drives significant soil leaching (Choung et al., 2020). The original vegetation consists of temperate deciduous broadleaf forests, though most areas have been converted to agricultural land or secondary forests due to long-term farming activities.

These geomorphic factors shape the distinctive "loess-like red-yellow soil" in the area. The soil texture is dominated by silt particles (20-50 μm), constituting over 50% of the mass, with clay content (<2 μm) ranging from 27-40%, classifying it as silty clay loam (Park, 1987). Compared to typical aeolian loess, the higher clay content indicates intensive clay mineral formation under humid conditions. The soil is strongly acidic (pH 4.3-5.6) with low cation exchange capacity (≤10 me/100g) and base saturation below 30%, reflecting intense leaching processes (Savin, 2014). Clay mineral composition is dominated by quartz and illite, followed by smectite and chlorite, with notably low kaolinite content. This mineral assemblage differs significantly from red soils in other Korean regions but shows similarities to loess deposits in North China and clayey loess-like formations along Japan's western coast, supporting an aeolian origin (Park, 1987; Yang et al., 2004). Prolonged weathering under humid climatic conditions promotes transformation of primary minerals into secondary clay minerals, while intense leaching leads to base cation loss and soil acidification, ultimately forming the observed red-yellow soil profile characteristics.

22. Hinano mountain (SBM-m), Japan

Hinano Mountain (presumed to feature gentle slope hill landforms) is located in Takamatsu City, Kagawa Prefecture, Japan, within the Sanuki region along the Seto Inland Sea coast. The geological foundation primarily consists of Cenozoic granitic rocks, part of the Setouchi volcanic rock zone, which have undergone prolonged weathering to form deep weathering crusts (Obara et al., 2015). The topography is characterized by low-elevation hills, ranging from approximately 50 to 300 meters above sea level, with gentle relief. The climate is typical of the Seto Inland Sea type, featuring warm, humid summers and mild, dry winters. The mean annual temperature is around 15-16°C, with annual precipitation ranging from 1000 to 1200 mm and relatively high evaporation rates (Shiono et al., 2013). Natural vegetation consists of warm-temperate evergreen broadleaf forests (laurel forests), dominated by species such as Castanopsis sieboldii and Cinnamomum camphora. However, due to long-term agricultural activities and urban development, much of the original vegetation has been replaced by secondary forests, plantations, and urban green spaces (Noriyuki et al., 2021; Ohta et al., 2006).

These geomorphic and climatic conditions shape the region's typical Red-Yellow soils. According to the Comprehensive Soil Classification System of Japan (CSCSJ), these soils belong to the G Great Group and can be further classified as Argic Red-Yellow soils or Cambic Red-Yellow soils (Obara et al., 2015). The soil profiles are well-developed, typically featuring dark surface horizons and reddish-yellow argic or cambic horizons. Under warm, humid climatic conditions with seasonal precipitation, the soils undergo intense chemical weathering and leaching, resulting in significant loss of base cations (particularly Ca^{2+} and Mg^{2+}). Consequently, the soils are strongly acidic (pH 4.5-5.5) and exhibit low cation exchange capacity (generally <15 cmol(+)/kg) (Nakahara et al., 2010). The particle-size distribution is dominated by silt (2-50 μm), comprising 40-60% of the mass, with moderate clay content (<2 μm) ranging from 20-35%. The texture is predominantly silt loam to clay loam (Shinjo et al., 2021). Clay minerals are mainly kaolinite, illite, and vermiculite, indicating moderate weathering intensity under warm, humid conditions (Watanabe et al., 2006). Gentle slopes minimize erosion, facilitating the development of relatively thick soil layers and clay illuviation. Overall, the granitic parent material provides abundant quartz and feldspar, the warm, humid climate promotes the decomposition of primary minerals and formation of secondary clay minerals, and the gentle topography allows for full profile development. Together, these factors create a soil system characterized by reddish-yellow colors, strong acidity, and low nutrient availability.

23. Sanyo Buntokuden Memorial (SBM-h, SBM-b), Japan

The Sanyo Buntokuden Memorial area is situated on the Sanuki Plain along the northern coast of the Seto Inland Sea, characterized by a coastal-alluvial plain with low hills. The geological substrate consists primarily of weathered granite regolith and Quaternary marine-alluvial deposits, partially overlain by Late Pleistocene volcanic ash materials (Obara et al., 2015). Elevations are below 50 m, with flat topography and significant drainage gradients. The climate is classified as the Seto Inland Sea type, warm and humid, with a mean annual temperature of 15-16°C and annual precipitation of approximately 1100 mm, exhibiting distinct wet and dry seasons (Nakaegawa et al., 2020). Original evergreen broadleaf forests have largely been converted to agricultural and urban land uses.

This geomorphic setting shapes a lowland soil–Red-Yellow soil sequence. Gray Lowland soils developed on plains exhibit silty loam texture (clay content 20-30%) with Fe-Mn concretions and gley mottling, reflecting seasonal groundwater fluctuations. Red-Yellow soils on hills show clay loam to clay texture (clay content 30-40%) with common argic or cambic horizons. Soils are acidic (pH 4.5-5.8) with base saturation below 35%, attributed to base-poor granite parent material and intense leaching under monsoon climate (Nagatsuka, 1975). Particle-size analysis reveals silt (2-50 μm) dominance (45-60%), clay (<2 μm) content of 25-40%, and sand (>50 μm) below 20%, indicating fine alluvial and deeply weathered materials. Local volcanic ash inputs elevate allophane content, enhancing phosphate retention and soil structure (Wada, 1986). In summary, regional soils result from marine-terrestrial sedimentation, granite weathering-leaching, and volcanic ash deposition, with fine texture, acidity, and hydromorphic features critically influencing land productivity and ecological functions.

24. Old Hiroshima University (OHU-n, OHU-s), Japan

The site of the former Faculty of Science at Hiroshima University is located along the Seto Inland Sea coast in western Honshu, Japan, within a transitional zone between the Chugoku Mountains to the north and the Seto Inland Sea. The geology is dominated by Mesozoic granite and Paleogene sedimentary rocks, with a topography characterized by low-elevation hills and alluvial plains, averaging below 50 meters in altitude and exhibiting gentle overall relief (Iwahashi et al., 2021). The climate is classified as a humid subtropical monsoon climate (Cfa type), with a mean annual temperature of approximately 15.8°C and annual precipitation around 1500 mm, showing distinct seasonality with concentrated rainfall in summer (Mikami, 2023). The potential natural vegetation is evergreen broadleaf forest, though urbanization has resulted in a landscape dominated by secondary and plantation forests.

Under these geomorphic and climatic conditions, the region has developed typical "Red-Yellow soils." According to the Comprehensive Soil Classification System of Japan, these soils fall within the Red-Yellow soils class or related groups, with pedogenesis driven by intense leaching and weathering under warm, humid conditions (Takeda et al., 2004). Silicate minerals in the parent rock undergo hydrolysis, leading to substantial loss of base cations, acidic soil reactions (pH typically 4.5-5.5), and the formation of secondary clay minerals such as kaolinite along with iron and aluminum oxides. The soil texture is primarily sandy loam, with high sand content (> 0.05 mm, approx. 40-60%) and low clay content (< 0.002 mm, approx. 15-25%), reflecting the physical weathering of granitic parent material that leaves abundant quartz sand and indicates moderate chemical weathering (Kato et al., 1979). Hilly topography enhances drainage, inhibiting gleyification and promoting the development of a reddish-yellow B horizon or a weakly developed argic horizon. The granitic parent material, hilly terrain, and subtropical monsoon climate shape soils with strong acidity, sandy texture, and moderately developed profiles in this area.

25. Kurashiki City, Okayama Prefecture, Japan (KOY)

The soils in Yoshijima Park, Kurashiki City, Okayama Prefecture, Japan, represent typical lowland paddy soils developed from Holocene alluvial deposits (mixtures of sand, silt, and clay). The area features flat topography with elevations below 10 m and a high groundwater table. The climate is a warm, humid subtropical monsoon, with a mean annual temperature of 15–16 °C, summer maxima up to 35 °C, and winter minima around -5 °C. Annual precipitation averages about 1100 mm, concentrated in summer. Native vegetation has been replaced by artificial rice-cropping systems. The flat terrain, high groundwater level, and abundant seasonal rainfall cause periodic flooding, which promotes alternating redox conditions and drives reductive leaching and subsequent oxidative precipitation of iron and manganese. This process results in a distinct soil profile with a plow layer (Ap), mottled illuvial horizon (Btg), and gleyed horizon (Bg). Soil texture is predominantly silty loam to clay loam, showing uniformity that reflects the sedimentary nature of the alluvial parent material. In the Comprehensive Soil Classification System of Japan, these soils are classified as “Lowland Paddy soils,” corresponding to Hydragric Anthrosols or Gleyic Fluvisols in the World Reference Base for Soil Resources (Kato et al., 1979; Obara et al., 2015).

26. Koto Ward, Tokyo, Japan (KWS)

Shinonome No. 2 Park, located in Koto Ward, Tokyo, lies within the eastern part of the Kanto Plain, characterized by low-elevation alluvial plain geomorphology. The geological substrate consists of Holocene alluvial deposits, overlain by widespread volcanic ash sediments known as Kanto loam, originating from Mount Fuji and surrounding volcanoes (Obara et al., 2015). The topography is flat, with an elevation of approximately 2–4 meters above sea level and a high groundwater table. The climate is a warm, humid monsoon type, with a mean annual temperature of about 16°C and annual precipitation of ~1,500 mm, distributed relatively evenly throughout the year (Duan et al., 2015). The original vegetation was temperate deciduous broadleaf forest, but due to intensive urbanization, current vegetation is dominated by artificial landscaping and urban lawns.

These geomorphic and climatic conditions shape the soil characteristics dominated by volcanic ash-derived soils (Andosols). Kanto loam primarily consists of volcanic glass, pumice fragments, and minor minerals, with particle-size distribution dominated by silt (2–50 μm) and fine sand (50–200 μm), and low clay content (typically <15%), classifying it as sandy loam or loam (Obara et al., 2015). Due to the volcanic ash parent material rich in amorphous aluminosilicates (e.g., allophane), the soil exhibits high phosphate adsorption capacity, low bulk density (usually < 0.9 g/cm^3), and friable granular structure. Under humid conditions, the soil undergoes strong leaching, resulting in acidic pH (4.5–5.5) and low base saturation. Despite anthropogenic disturbances during urbanization, the park soil retains typical Andosol profile features: a dark surface horizon (enriched in organic matter) transitioning to a yellowish-brown subsurface horizon, with no distinct clay illuviation horizon (Imaya et al., 2010). Continuous volcanic ash deposition and humid climate promote the formation of amorphous clay minerals, shaping the unique soil physical properties of low density, high porosity, and high permeability in this area.

27. Nanyang Technological University in Singapore (NTU)

The geomorphology of Singapore is characterized by a tropical coastal plain underlain predominantly by Pleistocene sandy Old Alluvium deposits, featuring low relief with average elevations below 15 m (Wang et al., 2015). The climate is equatorial rainforest-type, with a mean annual temperature of approximately 27.5°C (extreme highs to 35°C, lows ~23°C) and annual precipitation exceeding 2300 mm, evenly distributed (Rahardjo et al., 2020). The original lowland tropical rainforest has been largely replaced by urban landscapes. Under high temperature and rainfall, the Old Alluvium parent material undergoes intense chemical weathering, leading to rapid leaching of bases and silica and relative accumulation of iron and aluminum oxides. This forms acidic (pH often <5.0) and infertile soils characteristic of Ultisols or Oxisols. Strong leaching and clay illuviation result in textures dominated by clay loam to loamy clay, though sandy textures persist locally due to parent material influence (Ip et al., 2021). The perhumid conditions limit organic matter accumulation and promote the development of reddish-yellow soil matrices, with gleyzation occurring in poorly drained depressions.

28. Omkoi in Thailand (OMK)

The Omkoi area in Thailand is characterized by a hilly and mountainous topography underlain by limestone and metasedimentary rocks, with high elevation and significant relief (Jindaluang et al., 2013). The region experiences a tropical monsoon climate, with a mean annual temperature of 26–30°C and annual rainfall of 1100–1300 mm, featuring distinct wet and dry seasons (Yoothong et al., 1997). Vegetation is dominated by tropical deciduous and secondary forests. The hot and humid climate drives intense chemical weathering and leaching, resulting in substantial loss of bases and silica and the relative accumulation of iron and aluminum oxides, leading to strongly acidic (pH 5.0–6.0) Red soils. The soil texture is predominantly clay loam to clay, with clay content often exceeding 50%, and is rich in kaolinite and Fe/Al oxides. Organic matter is largely associated with mineral particles, dominated by aromatic carbon and amide nitrogen, reflecting strong desilication-allitization and organo-mineral stabilization under perhumid conditions (Jindaluang et al., 2013).

29. Caspian Sea, Iran (GCS)

The geomorphology of the southeastern Caspian coast (Iran) is shaped by Quaternary and Late Neogene accumulations of aeolian, fluvial, deltaic, and marine sediments, forming a flat coastal plain with elevations ranging from 60 m below to 55 m above sea level (Gharibreza et al., 2018). The region experiences a semi-arid climate, with a mean annual temperature of ~17.6°C (hottest month 27.8°C, coldest 7.7°C) and annual precipitation of ~350 mm (Samiei-Fard et al., 2021). Natural vegetation is dominated by halophytes. Under these geomorphic and climatic conditions, frequent sea-level fluctuations and low-energy depositional environments result in a particle-size distribution dominated by silt (28–85.6 %), with soil textures predominantly silt loam to silty clay loam, leading to the formation of young soils classified mainly as Entisols and Inceptisols. The semi-arid climate and high groundwater table contribute to widespread soil salinization and gleyzation, while depositional hiatuses create distinct textural discontinuities within profiles (Gharibreza et al., 2018).

North America

30. Nevada (Nev), USA

Nevada, USA, situated in the Basin and Range Province, is characterized by extensional tectonics forming north-south trending mountains and enclosed basins, with widespread Paleozoic sedimentary rocks, Meso-Cenozoic volcanics, and Quaternary alluvial, lacustrine, and aeolian deposits (Stewart, 1980). The topography exhibits pronounced relief, with elevations ranging from ~150 to 4000 m. The climate is a cold desert, with mean annual temperatures of 10–20°C and annual precipitation of 100–250 mm, unevenly distributed (Pan et al., 2011). Vegetation is dominated by drought-tolerant shrubs and sparse grasslands. Aridity and intense physical weathering limit soil development, resulting in soils dominated by Aridisols and Entisols, with sandy textures (clay typically <15%) and low organic matter (<1%). In closed basins with shallow groundwater, salinized and sodic soils are common, often featuring salt crusts, gypsum layers, or calcic horizons. Aeolian and alluvial processes shape uniform dune textures and gravelly stratified fan deposits, respectively (Beaudette et al., 2016).

31. Golf course in USA (TS, CS, BS)

Golf courses in the United States are predominantly situated on coastal plains, river terraces, and anthropogenically modified landscapes. The soil matrix consists mainly of sandy sediments derived from fluvial or coastal deposition, with particle sizes concentrated in the 0.25–1.00 mm range and minimal clay and silt content (Moreno-Maroto et al., 2022). Topography is generally gentle (elevation mostly <200 m), promoting drainage, though microtopographic variations influence local water distribution. The climate spans wide ranges: mean annual temperature 5–25°C, extreme temperatures from -30 to 45°C, and annual precipitation 250–1500 mm with notable spatial variability (Armal et al., 2018). Vegetation is dominated by drought- and traffic-tolerant turfgrasses (e.g., Poa pratensis, Cynodon dactylon), with limited biological impact on sandy soil structure. Under these geomorphic and climatic interactions, soil formation is dominated by physical weathering and sedimentation, resulting in typical sandy or sandy loam soils characterized by low organic matter (<2%), high permeability, and narrow particle-size distribution. The soil water characteristic (SWC) of such soils can be predicted from particle-size distribution and bulk density (Arya et al., 2008).

32. Southern California (SCS), USA

Southern California's landscape is dominated by Late Pleistocene coastal terraces and alluvial plains, with elevations generally below 200 m (Ku and Kern, 1974). The region experiences a Mediterranean climate with mean annual temperatures of 14–18°C, extremes ranging from -5 to 45°C, and annual precipitation of 250–500 mm, concentrated in winter with pronounced summer drought (Fierro, 2014). Vegetation consists mainly of drought-tolerant shrublands (e.g., chaparral), providing sparse organic inputs. Within this geologic and climatic setting, sandy parent materials undergo clay illuviation driven by seasonal rainfall, with deposition at wetting fronts forming clay lamellae, leading to sandy loam to loamy sand soils with stratified clay enrichment (Moreno-Maroto et al., 2022). Gentle topography promotes vertical water infiltration, while arid conditions limit further clay translocation, shaping the characteristic vertically differentiated fine-clay profiles within sandy matrices in the region.

33. Kalkaska County (MLS, WS), Michigan, USA

Kalkaska County, Michigan, is located within the glacial outwash plains of the Great Lakes region, with elevations of approximately 300–400 m and gently undulating topography (Schaetzl et al., 2013). Parent materials consist of late Pleistocene glaciofluvial sands and loamy sands rich in quartz and feldspar. The climate is humid continental, with a mean annual temperature of 5–7°C, extremes ranging from -30 to 30°C, and annual precipitation of 800–900 mm (Andresen et al., 2012). Vegetation is dominated by northern hardwoods (e.g., sugar maple, beech, red oak). Under freeze-thaw cycles and leaching processes, clay and free iron oxides in sandy matrices migrate as organic-iron complexes, depositing as reddish-brown (7.5YR 5/6) fine-textured bands in subsurface horizons, forming Montcalm loamy sand with stratified clay-iron oxide accumulations.

34. Kent County (MFS), Michigan, USA

Kent County, Michigan, features glacial outwash plains with elevations of 200–300 m and gentle topography. Parent materials consist of late Pleistocene glaciofluvial sands and loamy sands (Baish et al., 2021). The climate is humid continental, with a mean annual temperature of 7–9°C, extremes from -25 to 32°C, and annual precipitation of 850–950 mm (Villarini et al., 2013). Vegetation is mixed hardwood forest (oak, hickory, etc.). Under cold-humid conditions and gentle slopes, clay and free iron oxides in sandy parent materials migrate as organic-iron complexes with percolating water, depositing as reddish-brown (7.5YR 5/7) fine-textured bands in the profile, forming Montcalm loamy sand with stratified clay-iron oxide features.

35. Calhoun County (CFS), Michigan, USA

Calhoun County, Michigan, lies within glacial outwash plains at 250–300 m elevation with gentle topography. Parent materials are late Pleistocene glaciofluvial fine sands (Wurman et al., 1959). The climate is humid continental, with a mean annual temperature of 8–10°C, extremes from -20 to 33°C, and annual precipitation of 900–1000 mm (Villarini et al., 2013). Vegetation is oak-hickory forest. Under cold-humid conditions and flat terrain, sandy parent materials undergo intense leaching, with clay and free iron oxides migrating as organic-iron complexes and depositing as reddish-brown (10YR 5/8) fine-textured bands in the profile, forming Coloma fine sand with stratified clay-iron oxide features.

36. Dredged materials deposit (MDM, MTM), State of Maryland, USA

Maryland is situated within the Atlantic Coastal Plain of the United States, characterized by low-elevation (mostly <50 m) tidal marshes and estuarine systems with flat topography and poor drainage (Demas et al., 2004). The region experiences a humid subtropical climate, with a mean annual temperature of approximately 13–14°C, summer maxima exceeding 30°C, and winter minima dropping to around -5°C. Annual precipitation averages 1000–1200 mm, exhibiting strong seasonal variability and often concentrated rainfall following dry periods (Fanning et al., 2000). Geologically, the area contains sulfide-rich marine sediments, particularly pyrite (FeS_2) in tidal flat environments, which serve as the parent material for acid sulfate soil formation (Fanning and Burch, 2000). Vegetation is dominated by salt-tolerant hydrophytes such as Phragmites australis, whose organic matter inputs further modulate reducing conditions and sulfur cycling (Griffin et al., 1989). These geomorphic and climatic factors promote sulfide accumulation under anaerobic conditions, followed by oxidation during alternating wet-dry cycles, leading to severe soil acidification (pH <3.5) and the development of fine-textured, silt-loam-dominated soils with secondary minerals such as jarosite and ironstone (Schoenberger et al., 2012). Thus, acid sulfate soils in Maryland result from the interplay of sulfur-rich parent materials, low-relief topography, seasonal hydrological fluctuations, and vegetation dynamics.

37. East-Central Alabama (ALS), USA

East-Central Alabama, situated within the Upper Coastal Plain of the southeastern United States, is characterized by Quaternary fluvial terraces along the Tallapoosa River (Shaw et al., 2003). The region is underlain by unconsolidated Coastal Plain sediments, with gentle topography and elevations ranging from approximately 59 to 72 m (Shaw et al., 2003). The climate is humid subtropical, with a mean annual temperature of about 17–18°C, summer maxima often exceeding 30°C, and winter minima near 0°C. Annual precipitation averages 1300–1400 mm, with a distinct summer maximum (Beck et al., 2018). Natural vegetation is predominantly deciduous broadleaf forest and grassland, with some areas under cultivation (Nagy et al., 2011). Under these climatic and topographic conditions, soil texture varies with terrace age: younger terraces (e.g., floodplains) are dominated by coarse-loamy soils with high sand content, while older terraces (e.g., mid-to-late Pleistocene) exhibit fine-loamy soils with significant clay accumulation and well-developed argillic horizons (Shaw et al., 2003). Prolonged warm, humid conditions promote mineral weathering and clay formation, while flat terrain and seasonal hydrologic fluctuations drive clay illuviation and deposition (Markewich et al., 1991). The decrease in oxalate-extractable iron (Fe_o) with soil age reflects iron crystallization during pedogenesis (Shaw, 2003). The textural evolution of soils in this region results from the interaction of geomorphic age, climate, hydrology, and vegetation cover.

38. Northern Michigan (MPS), USA

Northern Michigan, USA, situated within the Great Lakes region, is characterized by a chronosequence of well-preserved beach ridges forming a strand plain along the northern shore of Lake Michigan (Barrett, 2001; Thompson and Baedke, 1997). The area is underlain by post-glacial, non-calcareous eolian sands, with flat topography and elevations near lake level. The climate is humid continental, moderated by the lake, with a mean annual temperature of 10.5°C (January: -3.6°C; July: 24.2°C) and annual precipitation of 806 mm, evenly distributed throughout the year (Barrett, 2001; Lichter, 1998). Vegetation consists primarily of mixed conifer-hardwood forest, with grassland and shrub cover on younger ridges (Francos et al., 2025). These geomorphic and climatic conditions shape a soil sequence dominated by sandy Podzols. Uniform sandy parent material, cool humid climate, and coniferous vegetation promote rapid podzolization: eluvial (E) horizons form within 230 years, followed by spodic (Bs) horizons and ortstein development after >1050 years (Protz et al., 1984). Soil texture is dominated by fine sand (> 50%), with very low silt and clay contents (< 1%), although surface silt content increases slightly with age, likely due to physical weathering or eolian input (Barrett, 2001). Thus, the soil morphology in this region results from the interplay of chronosequential landforms, homogeneous sandy parent material, cool humid climate, and coniferous vegetation, exhibiting progressively pronounced podzolization features over time.

39. Crosby county (CCS), West Texas, USA

The landscape of Crosby County, West Texas, is a quintessential product of the semi-arid Southern High Plains. It comprises a stable, low-relief tableland with an average elevation of 900-950 m a.s.l., underlain by the fluvial-lacustrine Miocene-Pliocene Ogallala Formation and mantled by the Quaternary eolian Blackwater Draw Formation (Holliday, 1989; Seni, 1980). The region endures a continental semi-arid climate (BSk) characterized by an average annual temperature of ~15°C (with summer highs >35°C and winter lows ~-2°C) and scant annual precipitation averaging 450 mm, which is overwhelmingly offset by high evapotranspiration (Li et al., 2019). This climatic regime supports a shortgrass prairie ecosystem dominated by Bouteloua gracilis and Buchloe dactyloides (Velázquez et al., 2003). he effects of this geomorphic and climatic framework govern pedogenesis. The remarkably flat topography suppresses significant erosion and sediment sorting, while the aridity severely limits leaching. These conditions act to preserve and accentuate the textural signatures inherited from the parent materials. Consequently, soils are classified as Aridisols and Entisols (USDA, 1999). The surficial mantle of fine, poorly sorted eolian silt from the Blackwater Draw Formation directly dictates a surface soil texture dominated by silt loam and very fine sandy loam (Holliday, 1989). In areas where this mantle is thin or absent, the underlying, texturally heterogeneous sands and clays of the Ogallala Formation give rise to more variable soil textures and promote the development of prominent, often indurated, calcic horizons (caliche) due to the upward translocation and accumulation of calcium carbonates in the dry soil profile (Seni, 1980).

40. Hudspeth county (HCS), West Texas, USA

Hudspeth County, located in the Trans-Pecos region of West Texas, USA, features a geomorphology characterized by dissected limestone plateaus and desert mountains with elevations ranging from approximately 900 to 1,600 meters (Barnes, 1975; Gile et al., 1981). The underlying geology is dominated by Cretaceous limestone and dolomite formations, whose weathering produces a skeletal limestone residuum (Allen et al., 1986). The climate is arid (Köppen BWk), with an average annual temperature of approximately 18°C, average summer highs exceeding 35°C, average winter lows near 0°C, and scant mean annual precipitation of 250-300 mm (Li et al., 2019). This environment supports Chihuahuan Desert vegetation, dominated by xerophytic shrubs such as creosote bush (Larrea tridentata) (Elliott, 2014). The interaction of these factors results in soils classified primarily as Aridisols (Calciargids, Haplocalcids) (Cox et al., 2018). The limestone-derived parent material, combined with the arid climate and dissected topography, acts to dictate soil morphology. The coarse, calcareous residuum directly imparts a gravelly and cobbly texture (sandy loams/loams with >35% coarse fragments), while limited leaching under aridity promotes strong secondary carbonate accumulation (calcic and petrocalcic horizons) (Hartemink, 2018). Furthermore, the rugged terrain enhances erosional processes, leading to thin, skeletal soils on slopes, while more developed argillic horizons can form in stable, lower-lying areas where illuvial clay accumulates (McFadden et al., 1998). Consequently, soil texture and profile development are fundamentally controlled by in-situ physical weathering of bedrock, calcite precipitation, and topographic-modulated erosion.

41. Northeast Dane County, Wisconsin, USA (WLS)

Northeast Dane County, Wisconsin, is situated within a glaciated landscape characterized by undulating topography with low relief (elevation 250-350 m) and underlain by Late Pleistocene sandy glacial outwash and till overlying Cambrian-Ordovician sedimentary bedrock (Johnson, 1986; Mickelson et al., 1983). The region experiences a humid continental climate (Dfb) with a mean annual temperature of ~7.5°C (January mean ~-9°C, July mean ~22°C) and mean annual precipitation of ~875 mm (Yin et al., 2024). This climate supports a mixed northern hardwood-coniferous forest (Waller et al., 2012). The dominant soil orders are Alfisols, prominently featuring lamellic subgroups such as the Spinks series (Lamellic Hapludalfs) (Bockheim et al., 2013; Schaefer et al., 2007). The formation of the region's distinctive soil morphology is a direct result of its geomorphic and climatic framework. The coarse-textured, well-drained sandy glacial parent material provides the essential porous substrate conducive to deep percolation. The udic soil moisture regime, driven by ample precipitation and seasonal cycles, facilitates periodic wetting fronts that mobilize and translocate dispersed clay particles downward through the profile. The gentle, stable topography minimizes erosion, allowing for the progressive accumulation of these clays. This process (lessivage) leads to the formation of thin, discontinuous clay-enriched lamellae (e.g., Bt horizons) within the sandy matrix, creating a characteristic textural contrast where lamellae are typically one textural class finer (e.g., sandy loam) than the surrounding interlamellae zones (e.g., loamy sand) (Bockheim et al., 2013; Schaetzl, 1992). Thus, soil texture is bimodally controlled:

inherited coarse sand from glacial deposition and pedogenically sorted fine clay accumulated in illuvial bands.

42. Western slope of the Sierra Nevada of California (SNC), Western USA

The western slope of the Sierra Nevada, California, is characterized by a high-relief topography with elevations ranging from approximately 160 to over 4000 meters, primarily underlain by granitic bedrock and locally capped by Miocene-Pliocene andesitic lahar deposits (Hill, 2006; Piper et al., 1939). This region exhibits a pronounced Mediterranean climate gradient, where mean annual temperature (MAT) decreases from ~17°C at low elevations to ~3°C at 2800 m, and mean annual precipitation (MAP) increases from ~46 cm to over 150 cm, transitioning from rain- to snow-dominated above ~1500 m (DALY et al., 2002; Rasmussen et al., 2007). Vegetation follows this gradient from blue oak woodlands to mixed conifer forests and alpine meadows (Barbour et al., 2007). These interacting geomorphic and climatic drivers fundamentally control soil genesis, resulting in an elevational sequence of soil orders: Mollisols → Alfisols → Ultisols → Andisols → Inceptisols (Dahlgren et al., 1997). The weathering of the reactive andesitic parent material is primarily modulated by climate: at lower, warmer, and drier sites, limited leaching favors the formation of crystalline kaolin and iron oxides. At mid-elevations (1500-2150 m), the combination of high moisture (as snowmelt) and moderate temperatures maximizes chemical weathering, leading to the dominance of short-range-order aluminosilicates (allophane, imogolite) and andic soil properties. At the highest, coldest elevations, low temperatures severely inhibit chemical reactions, resulting in soils where the clay fraction is dominated by inherited 2:1 layer silicates rather than pedogenically formed minerals (Dahlgren et al., 1997; Ugolini et al., 2002). Thus, soil morphology and mineralogy across the Sierra Nevada are not simply a function of parent material texture but are a direct reflection of climate-forced weathering pathways operating on a dramatic elevational gradient.

43. Fine loamy soil (FL) in Canada

The Canadian Prairie, particularly central Saskatchewan, is characterized by glacial till deposits derived from Pleistocene glaciation, forming a gently undulating topography with elevations generally ranging from 400 to 800 m above sea level (Amelung et al., 1999). The region experiences a continental climate with mean annual temperatures (MAT) between 0.9 and 6.1°C, extreme seasonal variations (winter minima below –20°C, summer maxima exceeding 30°C), and mean annual precipitation (MAP) of 300–565 mm, predominantly occurring in summer (Mekis et al., 2018). Native vegetation is dominated by C3 grasses such as Festuca and Agropyron, adapted to cold and semi-arid conditions. These geoclimatic factors promote the formation of fine loamy soils (e.g., Typic Cryoborolls) with moderate clay content (17–35%), well-balanced silt and sand fractions, and granular structure (Anderson et al., 2011). Cold temperatures and seasonal freeze-thaw cycles limit chemical weathering and microbial decomposition, leading to the accumulation of soil organic matter and fungal-derived amino sugars in surface horizons, particularly under higher moisture regimes (Paré et al., 2006).

Africa

44. Nigerian (Nig)

The study area in southwestern Nigeria is situated on the Precambrian basement complex, dominated by crystalline metamorphic rocks including banded gneiss, quartzite, and biotite granite gneiss (Oladoye, 2015). The topography is gently undulating, with an average elevation of 239 m above sea level. The region experiences a tropical climate characterized by high temperatures (mean annual ~27°C, ranging from 22°C to 33°C) and bimodal rainfall averaging 1300 mm annually (Oguntunde et al., 2006; Salako et al., 2006). Vegetation is derived savanna, dominated by grasses and scattered shrubs, resulting from prolonged deforestation and agricultural activity. These geoclimatic conditions promote intense weathering and leaching, leading to the formation of deep, well-drained Alfisols (e.g., Haplustalfs, Paleustalfs) with subordinate Inceptisols and Entisols in lower slopes (Bamaba et al., 2015). Soil profiles exhibit pronounced textural differentiation: surface horizons are sandy (coarse sand dominant, 502–813 g kg^{-1}), facilitating rapid infiltration but low water retention, while clay content increases with depth (up to 356 g kg^{-1}) due to illuviation, forming argillic horizons. A distinct gravel layer ("stone line") between 20–120 cm depth further restricts root penetration and increases subsoil bulk density (up to 1.64 g cm^{-3}). Moderately acidic pH (5.4–6.4) reflects leaching and parent material influence, with quartzite-derived soils being more acidic (Salako et al., 2006).

Europe

45. Ehwald, Germany (GIL)

The Ehwald region in eastern Germany lies within the North German Plain, characterized by a flat to undulating topography at elevations of 50–100 m a.s.l. The subsurface geology is dominated by Pleistocene glacial deposits, including sands, gravels, and boulder clays from the Weichselian glaciation, overlying older Tertiary and Cretaceous sediments (Eissmann, 2002). The climate is temperate continental with a mean annual temperature of ~8.5–9.0°C (July mean: 18–19°C; January mean: -1 to 0°C) and annual precipitation of 550–650 mm (Ehmele et al., 2019). The natural vegetation is mixed deciduous forest (e.g., Quercus robur, Fagus sylvatica). These conditions promote the formation of reddish-brown soils, classified mainly as Luvisols or Cambisols

(Braunerde/Parabraunerde). Under forest cover and seasonal leaching, iron oxides (hematite/goethite) accumulate, imparting the characteristic reddish-brown color (Gerlach et al., 2006). The glacial parent material provides a sandy-loamy texture, with clay illuviation forming a texturally differentiated profile (eluvial-illuvial horizons). Well-drained conditions and moderate weathering yield soils with granular to subangular blocky structure, moderate fertility, and distinct chromatic development indicative of pedogenic maturity in a temperate climate (Donmex et al., 2023).

46. Kottenforst, Germany (Kot)

The Kottenforst region, located in the Lower Rhine Basin west of Bonn, Germany, is characterized by gently rolling loess plains with elevations between 120 and 200 m a.s.l. (Ehler et al., 2011). The subsurface geology is dominated by thick Weichselian loess deposits overlying Tertiary marine sediments (Semmel, 1996). The climate is temperate oceanic with a mean annual temperature of approximately 9.5°C (July mean: ~18°C; January mean: ~2°C) and annual precipitation of 700–800 mm (DWD, 2021). The area is covered by deciduous forest dominated by Fagus sylvatica and Quercus robur. These conditions foster the development of dark reddish-brown Parabraunerde (Luvisols). The fine-grained, calcareous loess provides a silty-loam parent material. Under the humid climate and forest vegetation, intense leaching and clay translocation form a distinct eluvial (E) horizon over an argic (Bt) horizon enriched with illuviated clay. The dark reddish-brown color (5YR-7.5YR) in the Bt horizon results from strong accumulation of pedogenic iron oxides (e.g., hematite) under well-drained conditions, enhanced by forest-derived organic acids (Schwertmann, 1993). The forest litter supports mull humus formation, contributing to topsoil darkening and stable granular structure, culminating in deep, well-structured, and fertile soils typical of Central European loess landscapes.

47. Boyadgiev (Boy), Bulgaria

The Boyadzhiev area in Bulgaria's Thracian Lowland features gently undulating plains at elevations of 150–300 m a.s.l., underlain by Neogene marine and lacustrine clayey deposits (Elhovo Formation) overlain by Quaternary sediments (Kosmas et al., 2000; Popov et al., 2024). The climate is transitional temperate continental, with a mean annual temperature of 11–12°C (July mean: 22–24°C; January mean: 0 to –1°C) and annual precipitation of 550–650 mm, characterized by a spring-summer maximum and periodic droughts (Malcheva et al., 2023). The natural forest-steppe vegetation, dominated by xerothermic oaks, has been largely converted to cropland. These conditions promote the formation of heavy clay soils, primarily classified as Vertisols and vertic subtypes of Chernozems (IUSS Working Group, 2014). The smectite-rich Neogene clays provide the parent material with inherently high clay content (> 60%). Under the semi-arid climate with pronounced seasonal moisture contrasts, shrink-swell cycles and argillipedoturbation dominate soil formation, leading to the development of a vertic horizon with slickensides and wedge-shaped aggregates. Limited leaching results in moderate to high base saturation and neutral to slightly alkaline pH. The combined effects of the fine-textured parent material, seasonal moisture deficit, and land-use history yield soils with very fine texture, low permeability, high cracking potential, and high nutrient-holding capacity, posing significant challenges for agricultural management.

48. Allier (ALL), France

The Allier region in central France, located within the Paris Basin, is characterized by alluvial plains and terraces at elevations of 200–300 m a.s.l. The parent material consists of Quaternary alluvial deposits derived from the Massif Central, dominated by sands and gravels (Antoine et al., 2007; Broc, 1975). The climate is temperate oceanic with mean annual temperatures of 10–11°C (July: 19–20°C; January: 2–3°C) and annual precipitation of 700–800 mm (Sorel et al., 2022). The landscape features mixed deciduous forests in natural areas and extensive agriculture in cultivated zones. These conditions promote the formation of sandy loam soils classified primarily as Luvisols, Cambisols, and Fluvisols (Daroussin et al., 2006; Mantel et al., 2023). The quartz-rich alluvial sands provide the coarse-textured foundation. Under temperate humid conditions, moderate leaching facilitates decarbonation and clay translocation, creating texturally differentiated profiles with clay-enriched argic horizons. Fluvial sorting yields well-sorted medium to fine sands, producing surface horizons with sandy loam textures. The combination of permeable parent materials, adequate precipitation for leaching, and vegetation cover results in well-drained, moderately fertile soils with favorable physical properties but limited water and nutrient retention capacities.

49. Cime de Rouyon (CdR), France

Cime de Rouyon is located in the alpine-subalpine zone of the Mercantour-Argentera massif in the French Alps, at elevations between 2200 and 2800 m a.s.l. (Ribolini et al., 2006). The geology is dominated by crystalline rocks such as gneiss and micaschist, heavily weathered by glacial and periglacial processes. The climate is severe alpine, with a mean annual temperature of 0–2°C (July: 8–10°C; January: -8 to -5°C) and annual precipitation exceeding 1500 mm, mostly as snow (Durand et al., 2009). Vegetation consists of alpine grasslands with patches of ericaceous dwarf shrubs. Under these conditions, dark brown soils such as Umbrisols or humic Cambisols develop. The frost-shattered, coarse-textured parent material provides abundant skeletal fragments but limited fine particles. Slow decomposition under cold temperatures leads to accumulation of a thick, dark, humus-rich surface horizon with high organic carbon. Acidic conditions (pH 4.5–5.5) prevail due to slow weathering and organic acid input from ericaceous plants. Soils are generally shallow, with high sand and gravel content, good drainage but low water retention, reflecting the interplay of alpine climate, crystalline geology, and herbaceous-shrub vegetation (IUSS Working Group, 2014; Baize and Girard, 2009).

50. Coup d'Alzac, France

Coup d'Alzac is located in the karstic limestone plateau of the Grands Causses in southern France, at elevations of 700–1200 m a.s.l. (Audra et al., 2007). The geology is dominated by Middle to Upper Jurassic limestones, with significant karst development. The climate is transitional Mediterranean-mountain, with mean annual temperatures of 8–10°C (summer: 15–18°C; winter: 0–3°C) and annual precipitation of 1000–1400 mm with summer drought (Alizart, 2020). Vegetation consists of Mediterranean montane garrigue dominated by Quercus ilex and drought-resistant shrubs. These conditions promote the formation of yellowish-brown soils classified as Rendzic Leptosols or Calcaric Cambisols (IUSS Working Group, 2014). The calcareous parent material provides abundant calcium carbonate, creating alkaline conditions (pH 7.5–8.5). Karstic drainage promotes rapid water percolation, limiting leaching and leading to calcium carbonate accumulation. Soils are typically shallow, stony, with clay loam to silty clay loam texture and moderate to high carbonate content. The yellowish-brown color (10YR–7.5YR) results from iron oxide hydration under Mediterranean climate. Weak structural development reflects the interplay of limestone geology, karst hydrology, and xerophytic vegetation.

51. Lachamp Raphaël, France

The Lachamp Raphaël region in southeastern France's Prealps features complex topography with elevations of 800-1200 m a.s.l. (Jaboyedoff et al., 2011). The geology consists of Jurassic-

Cretaceous limestone and marl formations shaped by Alpine orogenesis (Wissing et al., 2003). The climate is Mediterranean-Alpine transitional, with mean annual temperatures of 10-12°C (summer: 18-22°C; winter: 0-4°C) and annual precipitation of 800-1200 mm (Isotta et al., 2014). Vegetation comprises mixed deciduous forests (e.g., Quercus pubescens, Fagus sylvatica) and Mediterranean shrublands. These conditions foster development of reddish-brown Chromic Luvisols or Rhodic Cambisols (IUSS Working Group, 2014). Calcareous parent materials weather to clay-rich substrates, while the seasonal climate promotes leaching and iron oxidation. Well-drained positions particularly favor hematite formation, producing characteristic reddish-brown coloration (5YR-7.5YR hues). Soils typically exhibit clay loam to silty clay textures with >30-40% clay in subsurface horizons, subangular blocky structure, and moderate depth—reflecting the interplay of calcareous geology, transitional climate, and mixed forest ecosystems (Voltz et al., 2020).

52. Mathieu Morozova (MAT), Moscow, France

The Matvie Morozova region, located in the central Paris Basin at elevations of 80-120 m a.s.l., features a gently undulating topography shaped by Oligocene-Miocene sedimentary formations including calcareous marls and clays (Guillocheau et al., 2000). The temperate oceanic climate is characterized by a mean annual temperature of 10-12°C (summer: 18-21°C; winter: 1-4°C) and annual precipitation of 650-750 mm (Le Roy et al., 2020). Mixed broadleaf forests dominated by Quercus robur and Fagus sylvatica prevail, though extensive agricultural use exists. These conditions support the development of dark brown Eutric Cambisols and Luvisols (IUSS Working Group, 2014). The calcareous parent materials weather to produce fine-textured soils with clay contents of 25-35% (Jamagne et al., 2002). Moderate leaching and clay translocation under adequate moisture, combined with organic matter accumulation and brunification processes, yield well-structured soils with granular to subangular blocky fabric, neutral to slightly acidic pH, and characteristic dark brown colors (7.5YR-10YR hues), reflecting the integrated influence of sedimentary geology, temperate climate, and deciduous vegetation.

53. Dobrogostów, Poland

The Dobrogostów region in the Great Poland Lakeland features a postglacial landscape with elevations of 90–120 m a.s.l., characterized by Quaternary glacial tills, fluvioglacial sands and lacustrine deposits (Marks et al., 2019; Starkel et al., 2007). The transitional temperate climate has a mean annual temperature of 7–8°C (summer: 16–18°C; winter: -3 to -1°C) and annual precipitation of 550–650 mm (Błaś et al., 2024). Vegetation is mixed coniferous-deciduous forest (e.g., Pinus sylvestris, Quercus robur) with extensive agricultural conversion. These conditions foster dark grey Albic Luvisols and Stagnosols (IUSS Working Group, 2014). Glacial parent materials provide heterogeneous textures from sandy loam to clay loam. Seasonal water saturation under transitional climate drives periodic reducing conditions, promoting iron reduction and eluviation that create albic (E) horizons. Clay translocation and pseudo-gleyzation result in textural differentiation (clay content: 15–25% in surface, 25–35% in Bt horizons) and weakly to moderately developed structures (platy in eluvial, subangular blocky in illuvial horizons). Dark grey coloration arises from organic matter accumulation (2–4% SOC) combined with iron depletion, while redoximorphic features reflect fluctuating water tables. Acidic soil reaction (pH 4.5–5.5) and low base saturation further reflect the interplay of glacial geology, seasonally saturated transitional climate, and forest-agricultural vegetation (Świtoniak, 2014).

54. Grin, Moscow, Russia (Mos)

The Grin region in the northwestern Moscow oblast lies within the East European Plain, featuring gently undulating moraine plains at 150–200 m a.s.l., shaped by the Moscow (Saalian) glaciation and composed of loamy to sandy loam glacial deposits (Velichko et al., 2011). The climate is humid continental (Dfb), with a mean annual temperature of 4.5–5.5°C (July: 17–18°C; January: -9 to -10°C) and annual precipitation of 650–750 mm, peaking in summer (Gorbarenko et al., 2020). Vegetation is southern taiga dominated by Picea abies, Pinus sylvestris, and Betula pendula (Shahgedanova, 2003). These conditions promote the development of dark grey Luvic Greyzems or Albic Luvisols (Stagnic), locally termed Grey Forest Soils (IUSS Working Group, 2014). Glacial parent materials weather to form soils with a distinct textural contrast: the eluvial (E) horizon is clay- and iron-depleted (15–22% clay), while the illuvial (Bt) horizon is clay-enriched (25–35% clay). Periodic waterlogging from snowmelt and rain drives lessivage and surface-gleyzation, leading to acidic conditions (pH 4.5–5.5), light-grey eluvial horizons, and subangular blocky illuvial horizons. The dark grey topsoil color results from moderate organic matter (3–6 %) mixed with the mineral matrix and iron depletion, reflecting the interplay of glacial geology, continental climate with strong seasonal hydrology, and coniferous-deciduous forest cover (Lednev et al., 2021; Urusevskaya et al., 2015).

55. Crisul Alb (Tis), Romania

The Crisul Alb (Tis) region in western Romania is situated in the Apuseni Mountains piedmont zone, characterized by gently undulating hills and alluvial plains at elevations of 100-250 m a.s.l. (Grecu et al., 2016). The geology consists of Quaternary alluvial deposits overlying Neogene marls and clays (Bălteanu et al., 2011). The climate is temperate continental with a mean annual temperature of 9-10°C (summer: 18-21°C; winter: -3 to -1°C) and annual precipitation of 600-700 mm (Ringard et al., 2019). Vegetation comprises mixed broadleaf forests dominated by Quercus robur and Carpinus betulus with extensive agricultural use. These conditions promote dark greyish brown Haplic Luvisols and Cambisols (IUSS Working Group, 2014). The loamy to clay-loam parent materials weather to form soils with clay content increasing from 25-35% in surface horizons to 35-45% in argic horizons (Doran et al., 2002). Moderate leaching and clay translocation under the temperate climate, combined with brunification processes, yield well-structured soils with granular to subangular blocky surface horizons and prismatic subsurface structures. The characteristic dark greyish brown coloration (10YR-7.5YR hues) results from moderate organic matter (2-4%) and iron oxide hydration, while slightly acidic to neutral pH (5.5-7.0) reflects the interplay of alluvial geology, continental climate with seasonal moisture, and forest-agricultural ecosystems.

56. Kulbäcksliden (Kul), Sweden

The Kulbäcksliden area in northern Sweden (ca. 64°N) features a gently rolling post-glacial terrain at 200–300 m a.s.l., underlain by Precambrian crystalline bedrock and mantled by coarse-textured, sandy loam to loamy sand Weichselian glacial till (Lidmar-Bergström, 2020). The climate is cold temperate boreal, with a mean annual temperature of ~1.5°C (July: 13–14°C; January: -9 to -11°C) and annual precipitation of 550–650 mm (Schimanke et al., 2020). Natural vegetation is coniferous boreal forest (Picea abies, Pinus sylvestris), partly replaced by agricultural land (forage, barley). These conditions initially promoted the formation of Podzols and Umbrisols through podzolization under acidic forest litter (Lundström et al., 2020). The coarse, nutrient-poor parent material results in sandy loam soils with low clay content (<10%) and high sand content (>60%), imparting low water-holding capacity and high permeability (Olsson and Melkerud, 1991; Saarsalmi et al., 2012). Agricultural management (liming, tillage, organic inputs) has modified the topsoil, raising pH (to 5.5–6.5), increasing organic matter, and often creating Agric horizons overlying truncated podzolic profiles (IUSS Working Group, 2014). Thus, the contemporary soils reflect an interplay of glacially-derived coarse substrates, a cold humid climate driving leaching and acidification, and anthropogenic modification for agriculture.

Austria

57. Goodwyn (GOO), Australia

The Goodwyn region in Western Australia's Pilbara features an ancient eroded plateau landscape with gently undulating plains and low hills at 300-500 m a.s.l., underlain by Proterozoic banded iron formations and shales (Morris et al., 2011; Van Vreeswyk, 2004). The climate is hot arid to semi-arid, with a mean annual temperature of 24-26°C (summer maxima >40°C; winter minima ~10°C) and low annual precipitation (250-350 mm) characterized by intense summer thunderstorms (Charles et al., 2013). Vegetation consists of arid shrubland and spinifex grasslands with scattered woodlands (Beard, 1975). These conditions promote the development of sandy loam soils classified as Tenosols/Kandosols (Australian system) or Arenosols/Cambisols (WRB system) (Isbell, 2016; IUSS Working Group, 2014). Physical and chemical weathering of iron-rich parent rocks under arid conditions produces coarse-textured regolith with limited clay formation. Particle size distribution shows high sand content (60-80%), low clay (5-15%), and weak soil structure, resulting in low water-holding capacity and nutrient availability. The reddish-brown soil color (5YR-7.5YR) reflects iron oxide accumulation, while neutral to alkaline pH (7.0-8.5) characterizes these shallow, mineralogically mature soils shaped by ancient geology, arid climate, and xerophytic vegetation (McKenzie et al., 2004).

S2. Geomorphological Description of Lunar Sampling Sites (Suppl. to Section 2.2)

Lunar soils (379 samples) were collected from the Apollo 11, 12, 14, 15, 16, 17 missions, Luna

16, 20, 24 missions, Chang'e-5 and Chang'e-6 missions:

Apollo missions. **Apollo 11**: soil samples 10084 from Mare Tranquillitatis (Basu et al., 2001; Graf, 1993; McKay et al., 2009); Apollo 12: regolith soil samples 12033, 12037, 12042, 12044, 12070 from Pinpoint Highlands (Graf, 1993; Korotev et al., 2011); Apollo 14: soil samples 14141, 14148, 14149, 14163, 14230, 14259 from Fra Mauro (Graf, 1993; Morlok et al., 2022); Apollo 15: soil samples 15001, 15002, 15003, 15004, 15005, 15006, 15007, 15008, 15010, 15011, 15020 from Apennine Mountains (Graf, 1993; Ryder et al., 1989); Apollo 16: soil samples 60006, 60007, 60009, 6010, 64001, 64002, 68500 from Descartes Highland (Graf, 1993; Pearce et al., 1974); Apollo 17: soil samples 70008, 72500, 74001, 74002, 74220, 75080, 79001, 79002 from Serenitatis basin (Graf, 1993). Luna 24: soil samples 24077, 24109, 24149, 24174, 24182, 24210 from Mare Crisium (Graf, 1993; Laul et al., 1987). Chang'E 5: soil samples from northeastern Oceanus Procellarum (Li et al., 2022). Chang'E 6: soil samples from the South Pole-Aitken (SPA) basin (Li et al., 2024).

The following section illustrates following aspects: precise geographic location, geological context (including bedrock composition and major stratigraphic units), topographic features (elevation and relief), extreme surface environmental conditions (e.g., absence of atmosphere, vast diurnal temperature range, lack of precipitation and vegetation), and the thickness and maturity of the regolith cover.

1. Apollo 11

The Apollo 11 landing site (0.68°N, 23.43°E) is situated within the volcanic plains of Mare Tranquillitatis, characterized by Imbrian-aged, high-Ti mare basalts (e.g., Im3 unit, ~3.61 Ga) and subdued topography with elevations ranging from approximately -4.2 km to +1.7 km (Barker et al., 2016; Iqbal et al., 2019). The site endures an airless, extreme thermal environment with diurnal temperature variations exceeding 250 K, negligible precipitation, and a complete absence of vegetation (Sourcebook, 1991). The surface is mantled by a 4–6 m thick, immature regolith (Lunar Sample Analysis Planning Team, 1970). The regolith's polymodal, poorly sorted particle size distribution—dominated by fine silt and sand—is a direct product of the combined geomorphic processes acting on the basaltic substrate. Prolonged micrometeorite bombardment serves as the primary agent of comminution, generating the fine-grained matrix, while local and distant impact events (e.g., West crater, rays from Theophilus) contribute coarser, blocky ejecta and introduce minor exotic components (Iqbal et al., 2019; McKay et al., 1991). The lack of aqueous or aeolian sorting mechanisms results in a petrologically mature but texturally immature soil, whose characteristics are fundamentally governed by the interplay between the composition of the underlying bedrock and the hyperarid, impact-dominated surface environment (McKay et al., 1991; Sourcebook, 1991).

2. Apollo 12

The Apollo 12 landing site is located in the Oceanus Procellarum mare plains (elevation ~-2.4 km) with subdued topography marked by numerous small impact craters (Hubbard et al., 1971; Lunar Sample Preliminary Examination Team, 1970). It experiences extreme thermal conditions (diurnal range >250 K, average ~250 K) in an airless environment with negligible precipitation and no vegetation (Sourcebook, 1991). The regolith is chemically and mineralogically heterogeneous, classified as a coarse-grained lunar soil dominated by a mixture of local low-K/high-K mare basalts and a significant exotic component (25–65 %) of KREEP-rich material characterized by high K, REE, and P (Lunar Sample Preliminary Examination Team, 1970; Meyer et al., 1971). This soil texture and composition result from the combined effects of micrometeorite bombardment (producing the fine-grained matrix) and local impact gardening (excavating and mixing both local basalt and allochthonous KREEP-rich debris). The prominence of exotic KREEP—delivered via the Copernicus ray system—demonstrates that long-distance ballistic transport and impact mixing override in situ weathering, creating a petrologically immature but chemically distinct regolith with a polymodal particle size distribution (Lunar Sample Preliminary Examination Team, 1970; Meyer et al., 1971).

3. Apollo 14

The Apollo 14 landing site (Fra Mauro Formation) exhibits hummocky ejecta-blanket topography at moderate elevation above the lunar mare (Bailey et al., 1971). In an airless environment with a diurnal temperature range exceeding 250 K and negligible precipitation (Sourcebook, 1991), the regolith is classified as a mature, fine-grained lunar soil derived primarily from Fra Mauro formation breccias (Mckay et al., 1972). Soil texture (mean grain size ~81 μm, poor sorting σ_I=2.06 φ) results from prolonged micrometeorite bombardment that both comminutes local breccia fragments and produces abundant agglutinates (glass-bonded aggregates) through impact melting, driving the regolith toward a dynamic equilibrium (~60 μm) (Lindsay, 1971; Mckay et al., 1972). The high agglutinate content (up to 60%) directly correlates with surface exposure age, demonstrating that impact gardening dominates soil formation in this geologically ancient, highland-derived terrain (Lindsay, 1971; Mckay et al., 1972).

4. Apollo 15

The Apollo 15 landing site is located in the Hadley-Apennine region on the lunar near side, within the highlands-mare boundary zone east of Oceanus Procellarum. This area is primarily composed of KREEP-rich (potassium, rare-earth elements, phosphorus) breccias and ejecta from the Imbrium Basin impact event (Mitchell et al., 1971), with an average elevation of approximately -2500 meters. The terrain is gently undulating, covered with impact-generated debris. The lunar surface climate is characterized by a vacuum with no atmosphere and no precipitation. Surface temperatures are extreme, reaching up to 127°C during the lunar day and dropping to -173°C at night (Sourcebook, 1991). There is no vegetation; the surface is covered with mature regolith formed through impact processes.

The geological and topographical conditions of this region have profoundly influenced the formation and properties of the regolith. The Imbrium impact provided the initial material, dominated by shocked breccias, which has been continuously comminuted and mixed over billions of years by subsequent meteoroid impacts and micrometeorite bombardment, resulting in a mature regolith that is fine-grained, rich in glass and agglutinates. Extreme diurnal temperature variations, while not causing freeze-thaw cycling, contribute to physical weathering (thermal fracturing) of rocks. Combined with persistent space weathering (solar wind and micrometeorite bombardment) and the deposition and redistribution of ejecta, these processes yield a regolith characterized by fine particles, poor sorting, and poorly developed stratification, representing a typical impact-dominated soil morphology (Carrier, 1973). Its chemical signature retains the KREEP-rich characteristics of its source region (Lunar Sample Preliminary Examination Team, 1970).

5. Apollo 16

The Apollo 16 landing site is situated at the boundary between the Cayley Plains and the Descartes Highlands within the lunar Central Highlands, representing an ancient, heavily cratered highland terrain with an elevation approximately 1–2 km above the mean lunar radius (Ulrich et al., 1981). The area is an airless, waterless environment, with the surface exposed to extreme thermal cycling (diurnal range from about -173 °C to +127 °C) and continual micrometeorite bombardment (Sourcebook, 1991). There is no vegetation or precipitation on the Moon.

The regolith at this site is predominantly a fine-grained debris mantle formed through impact-dominated processes, classified as an impact-generated “soil.” Its development is governed by the following geomorphic interactions: (1) mixing of basin ejecta (notably mafic impact-melt breccias, MIMB, likely derived from the Imbrium Basin) with local feldspathic highland materials during plains emplacement, which constitutes the bulk soil matrix (Korotev, 1996); (2) continuous micrometeorite bombardment causing physical comminution, melting, and agglutination, leading to particle size reduction and soil maturation (Morris, 1978); (3) extreme thermal cycling and solar-wind irradiation further modifying surface particle morphology and chemistry. Together, these processes have shaped the regolith’s uniform sandy-silty texture, negligible clay content, high porosity, and distinctive mineralogical-geochemical signature.

6. Apollo 17

The Apollo 17 landing site is situated in the Taurus–Littrow Valley on the lunar nearside, characterized geologically by a mixture of high-Ti mare basalts and ancient anorthositic highland materials, and topographically as a narrow valley flanked by massifs with relief up to 2 km (Ryder et al., 1992; Scott et al., 1972). The Moon lacks an atmosphere and precipitation, with extreme surface temperatures ranging from approximately -180°C at night to 130°C during the day, resulting in a diurnal thermal variation exceeding 300°C, under persistent high-energy radiation and micrometeorite bombardment (Grün et al., 2011; Vasavada et al., 2012). No vegetation exists, and the surface is covered by impact-generated regolith, a detrital accumulation devoid of organic matter or pedogenic structure. Geomorphic processes govern regolith formation: micrometeorite comminution and melting produce a fine-grained (<45 μm) particle size distribution; extreme thermal cycling promotes thermal fracturing, further enhancing grain size reduction; vapor deposition forms np-Fe^0-rich glassy patinas on grain surfaces, significantly altering optical and magnetic properties; and topographic variations lead to spatial heterogeneity, with fine particles enriched in the valley floor and coarser fractions more abundant on slopes (Keller et al., 1997; Taylor et al., 2001; Zhang et al., 2023). These interactions ultimately shape the Apollo 17 regolith into a mature, fine-grained, agglutinate-rich soil with pervasive surface np-Fe^0 coatings.

7. Chang'E-5 mission (CE-5)

The Chang'E-5 landing site is located on a mid-latitude mare plain in northern Oceanus Procellarum (43.058°N, 51.916°W), geologically dominated by young (~2 Ga) low-Ti, low-Al, low-K mare basalts at the eastern margin of the Procellarum KREEP Terrane (Qian et al., 2021; Wieczorek et al., 2000). The terrain is flat (slope <5°) with an average elevation of approximately -2.5 km, featuring small impact craters and a north–south trending sinuous rille (Li et al., 2022). The Moon lacks an atmosphere and precipitation, with extreme temperatures: diurnal variations exceed 300°C (approximately -180°C at night to ≈130°C during daytime) under persistent solar wind irradiation and micrometeorite bombardment (Grün et al., 2011; Vasavada et al., 2012). No vegetation exists; the surface is covered by impact-generated regolith, a detrital accumulation devoid of organic matter or pedogenic structure. Local geomorphic processes shape the regolith: continuous micrometeorite comminution of the young basaltic substrate produces a fine-grained particle size distribution (95% of particles by number have equivalent diameters of 1.40–9.35 μm, median grain size ~52.54 μm), well-sorted and characteristic of mature regolith (McKay et al., 1974); extreme thermal cycling promotes grain fracturing, further reducing particle size; low exotic ejecta contamination (<10%) results in chemical compositions consistent with local basalts (Neal et al., 1992); low specific surface area (0.56 m^2/g) reflects long-term space weathering-induced grain rounding and compaction (Cadenhead et al., 1977).

8. Chang'E-6 mission (CE-6)

The Chang'E-6 landing site is located within the Apollo crater (41.625°S, 153.978°W) in the South Pole–Aitken basin on the lunar farside, geologically characterized by a mixture of low-Ti mare basalts and impact-excavated highland materials (e.g., anorthosite, norite), potentially exposing primordial deep-seated compositions (Li et al., 2024; Moriarty et al., 2021). The terrain is a basalt overflow plain situated between the peak ring and southern rim of the crater, with an elevation of approximately -5.5 km and surrounding wrinkle ridges (Zeng et al., 2023). The Moon lacks an atmosphere and precipitation, with extreme surface temperatures: diurnal variations exceed 300°C (approximately -180°C at night to ≈130°C during daytime) under persistent solar wind and micrometeorite bombardment (Vasavada et al., 2012). No vegetation exists; the surface is covered by impact-generated regolith. Local geomorphic processes shape the regolith: multi-stage impact excavation leads to intense mixing of highland materials with local basalts, producing a bimodal grain-size distribution (median grain size ~35.03 μm) indicative of immature-mixed regolith (McKay et al., 1974); extreme thermal cycling promotes particle fracturing, though mixing retards maturity development; the addition of exotic materials increases plagioclase (~32.6 %) and glass (~29.4 %) contents, while reducing soil density (true density 3.035 g/cm^3) (Carrier et al., 1973).

S3. Geomorphological Description of Martian Sampling Sites (Suppl. to Section 2.3)

Mars soils (1729 samples) were collected from Jezero Crater by the Perseverance rover, from Gale Crater by the Curiosity rover (Sahu et al., 2024; Weitz et al., 2018), from Gusev Crater by the

Spirit rover (Cabrol et al., 2008, 2014; McGlynn et al., 2011; Herkenhoff et al., 2004), and from Eagle Crater by the Opportunity rover (Jerolmack et al., 2006).

Methodological note on image-based grain size analysis. All Martian grain size measurements in this study are derived from 2D rover images using semi-automated segmentation software (Shi et al., 2021; Zhao et al., 2023), which identifies individual grains via edge detection and watershed segmentation and calculates the equivalent circular diameter (ECD) for each grain. The spherical grain assumption is widely adopted in image-based granulometry. Pizzati et al. (2023) demonstrated that approximating particles as spheres with a shape correction factor yields 2D-to-3D conversions that match laser diffraction measurements. Heilbronner and Barrett (2013) note that applying a 1.3–1.5 multiplicative factor is common practice in Earth sciences to convert 2D measurements to 3D. In this study, we use ECD without further correction, accepting a conservative uncertainty of ±8% based on inter-operator variability (see Section 4.4 of the main text). This approach is standard for sand-sized and coarser grains where shape deviation does not substantially bias the distribution statistics.

Discrimination of composite grains

The same two-step protocol described in Section 2.2.5 applies to all Martian images. Additional practical guidelines for operators include:

- When a small grain sits in a depression on a larger grain's surface, the visible portion of its boundary is often > 75%, warranting classification as a separate grain.
- When a cluster of fine grains adheres to a coarse grain's surface (e.g., dust aggregates), the entire cluster is treated as a single composite feature unless individual boundaries are clearly distinguishable.

- For ambiguous cases, the operator consults the original MAHLI image at full resolution and may refer to co-located images from different viewing angles when available.

This section provides a systematic synthesis of soil formation processes and characteristics at 42 specific locations within four key Martian regions: Gale crater, Jezero crater, Gusev crater, and Meridiani Planum. The core objective is to elucidate the differentiation mechanisms of surficial materials on Mars.

1. Gale Crater (5.4°S, 137.8°E, 154 km in diameter)

Gale crater is characterized by a layered central mound (Aeolis Mons) and substantial evidence of both aeolian and past hydrological processes. The mound, composed of stratified sedimentary layers, is surrounded by deposits from ancient fluvial activity (Grotzinger et al., 2014). These features originated from an impact event and were subsequently modified by water and wind erosion. The soils exhibit a wide range of grain sizes—from fine sands to coarser particles—and a complex mineral composition including olivine, pyroxene, and clay minerals, reflecting the combined influences of wind and water-driven processes.

A total of 384 soil samples were collected across 11 distinct sites:

(1) Yellowknife Bay (Sol 1749) (YB)

Yellowknife Bay is a shallow sedimentary basin at the foothills of Mount Sharp in Gale crater, characterized by horizontally bedded ancient lacustrine mudstone (Grotzinger et al., 2014). The surficial soil is predominantly fine to very fine sand, with a unimodal grain-size distribution peaking at 100–300 μm, reflecting the fine-grained sedimentary parent material (Edgett et al., 2020). Pedogenesis involved two key stages: first, during the Late Noachian, fine clays and silts deposited in a standing lake, undergoing substantial aqueous alteration to form smectite- and sulfate-bearing mudstone (Vaniman et al., 2014); subsequently, prolonged physical weathering and aeolian winnowing removed finer particles, leaving a lag of sand-sized grains that form the current regolith mantle and aeolian ripples (McLennan et al., 2014). Thus, the soil represents a product of both ancient aqueous deposition and modern aeolian reworking.

(2) Gobabeb (Sol 1221-1244) (Gob)

Gobabeb is located at the edge of the Bagnold Dunes in northwestern Gale crater, characterized as a typical aeolian environment with wind-formed ripples and interdune deposits composed of coarse sand and fine granules (Lapotre et al., 2016). The soil is dominated by medium to coarse sands (250 – 1000 μm), showing a unimodal and coarse-skewed grain-size distribution with occasional millimeter-sized particles, indicative of intense aeolian sorting (Weitz et al., 2018). Pedogenesis is primarily driven by contemporary aeolian activity: particles derived from ancient bedrock and impact debris are continuously transported, abraded, and sorted under persistent high-velocity Martian winds via saltation and creep, with fine grains systematically removed, resulting in coarse-grained lag deposits (Ehlmann et al., 2017; Sullivan et al., 2022). Thus, the soil at Gobabeb represents a direct product of active aeolian processes, documenting wind as the dominant contemporary surface modifying agent on Mars.

(3) Murray Buttes (Sol 1410-1468) (MB)

Murray Buttes is an eroded outcrop region within the Murray Formation in central Gale crater, characterized by resistant lacustrine sandstone remnants forming buttes and mesas (Edgar et al., 2018; Grotzinger et al., 2015). The surficial soil exhibits a complex, bimodal grain-size distribution, comprising a mixture of sandy particles (medium to coarse sand, 250–1000 μm) and abundant millimeter- to centimeter-sized gravels and angular breccias, the latter largely derived from local bedrock disintegration (Vasavada et al., 2017). Pedogenesis is governed by differential weathering and gravitational processes: ancient lacustrine sandstones undergo mechanical disintegration via wet-dry cycling, thermal stress, and salt weathering, producing debris ranging from sand to gravel. Subsequently, finer sands are partially removed by wind, while coarser lithic fragments accumulate as gravity-driven colluvium on slopes (Rudolph et al., 2022; Smith et al., 2021). Thus, the soil at Murray Buttes records a predominantly physical weathering regime with limited aeolian reworking, representing a classic example of in-situ bedrock weathering under arid Martian conditions.

(4) Ogunquit Beach (Sol 2555-2691) (OB)

Ogunquit Beach (OB) is situated within a wind-transport corridor along the northern margin of the Bagnold Dunes in Gale crater, characterized as a ripple field and coarse-grained lag deposit influenced by local topography (e.g., bedrock obstacles) and littered with centimeter-sized dark-toned clasts derived from surrounding outcrops (Achilles et al., 2017; Bridges et al., 2017). The soil exhibits a classic aeolian bimodal texture: a well-sorted matrix of fine to medium sand (125–500 μm) is studded with abundant coarse sand to fine granules (1–4 mm) and even centimeter-sized lithic fragments; the coarse fraction is predominantly angular to subangular, indicating proximal fracturing with minimal transport (Weitz et al., 2018). Pedogenesis is dominated by wind-driven mixing and segregation: prevailing winds deliver fine sands from the dune field, while stronger near-surface winds consistently remove the finest particles (<100 μm). Concurrently, bedrock from nearby outcrops fractures via thermal fatigue and other processes, producing coarse debris that is incorporated into the surface in situ or after short-distance creep, ultimately forming a highly heterogeneous aeolian mantle where fine sand matrix coexists with coarse-grained patches (Baker et al., 2018; Sullivan et al., 2022). Thus, the soil at OB exemplifies the coupling of active aeolian processes and local bedrock weathering under specific topographic controls on contemporary Mars.

(5) Mary Anning & Groken (Sols 2802–2923) (MAG)

Mary Anning & Groken (MAG) is situated within the "clay-bearing unit" of Gale crater, characterized by eroded outcrops of thinly laminated mudstone and siltstone rich in clay minerals, exhibiting micro-benches and debris mantles formed by differential weathering (Horgan et al., 2020). The surficial material is dominated by fine particles, with a predominant size in the very fine sand to silt range (< 62.5 μm) and a significant proportion of clay-sized grains (< 4 μm); coarse fragments are rare, limited to occasional millimeter-sized lithics, indicating relatively weak aeolian activity here (Thorpe et al., 2022). Pedogenesis reflects a superimposition of ancient aqueous deposition and subsequent arid weathering: initially, during the Late Noachian to Hesperian, suspended clays and fine silts settled in a lacustrine environment, undergoing diagenesis and aqueous alteration to form parent rocks rich in phyllosilicates like smectite (Bristow et al., 2021); subsequently, under the hyper-arid modern climate, these friable mudstones have undergone primarily in-situ physical disintegration via thermal fatigue, salt weathering, and limited aeolian abrasion, generating fine-grained debris without effective wind transport or sorting, thereby preserving the fine-grained signature of the original sediment. Thus, the soil at MAG represents a classic example of a fine-grained, "weathering-residual" soil on Mars, inherited from an ancient wet environment and only modestly modified by subsequent arid physical weathering.

(6) Vera Rubin Ridge (Sol 2300-2416) (VRR)

Vera Rubin Ridge (VRR) is a hematite-rich, erosion-resistant narrow and winding ridge at the foothills of Mount Sharp in Gale crater, characterized by steep erosional slopes combined with gentler platforms mantled by bedrock-derived debris (Rampe et al., 2020). The surficial material exhibits a distinct binary mixing texture: a matrix of fine to medium sand (125–250 μm) derived from overlying aeolian units is mixed with a high proportion of coarse sand- to granule-sized (0.5–4 mm) angular lithic fragments originating from the local iron-cemented sandstone, with occasional centimeter-scale iron nodules observed in some areas (David et al., 2020). Pedogenesis is driven by combined differential weathering and aeolian transport: the resistant, hematite-rich sandstone ridge undergoes mechanical disintegration via thermal stress and salt wedging, continuously producing coarse debris. Concurrently, prevailing winds transport and deposit finer sands from surrounding areas in the lee of the ridge and topographical depressions, while stronger winds also remove some of the finest particles from the system (Edgar et al., 2018). This process results in an incomplete mixing of coarse (in-situ weathering product) and finer (aeolian input) particles, forming a distinctive weathering-deposition hybrid zone. Thus, the soil at VRR is a prominent example of the interaction between lithology-controlled weathering and regional aeolian processes on Mars, with its coarse-skewed character reflecting the high durability of the parent rock and limited chemical alteration.

(7) Glen Torridon (Sol 2300-3072) (GT)

Glen Torridon (GT) is a broad, subdued depression within the "clay-bearing unit" on the foothills of Mount Sharp in Gale crater, characterized by gently sloping, layered rocks rich in clay minerals, mantled by fine-grained debris and occasional blocks derived from the disintegration of this friable parent material (Horgan et al., 2020). The surficial material is overwhelmingly dominated by fine particles, with grain sizes concentrated in the very fine sand, silt, and clay ranges (mostly $< 63\mu$m), while coarse sand and larger fragments are exceedingly rare; it represents one of the finest and most homogeneous regoliths encountered by the Curiosity rover (Thorpe et al., 2022).

Pedogenesis exemplifies a refined interplay between an ancient aqueous alteration legacy and modern arid physical weathering: initially, during the Late Noachian to Hesperian, the parent rocks underwent extensive aqueous alteration in a lacustrine or groundwater setting, forming abundant phyllosilicates like smectite, which established the inherent fine-grained material base (Bristow et al., 2021). In the contemporary hyper-arid era, these weak and friable altered rocks are subjected primarily to low-energy physical disintegration (e.g., wet-dry cycling, salt crystallization, thermal fatigue), producing debris through exfoliation and powdering that is inherently fine. Concurrently, the area's relatively low-lying and topographically sheltered setting results in attenuated wind activity, which neither effectively imports coarse external sands nor extensively exports the locally generated finest particles, allowing the fine-grained weathering products to accumulate near their source (Sullivan et al., 2022). Thus, the soil at GT represents a special fine-grained endmember on Mars, formed through a sequence of intense ancient chemical weathering preconditioning, gentle modern physical weathering refinement, and preservation within a sheltered topography. It serves as a key window into Martian aqueous history and its surface processes.

(8) Greenheugh Pedimeny (Sols 2691–2734) (GP)

Greenheugh Pediment (GP) is located at a higher elevation on Mount Sharp within Gale crater, characterized as an extensive erosional sandstone slope mantled by actively migrating sand ripples and scattered rubble derived from the underlying bedrock, representing a classic pediment landform subject to persistent aeolian modification on Mars (Rampe et al., 2020). The surficial soil is dominated by well-sorted medium sand, with a predominant grain size in the 250–500 μm range, exhibiting a strongly unimodal distribution. Locally, minor amounts of millimeter-sized coarse sand or fine granules, primarily from proximal bedrock disintegration, are admixed (Weitz et al., 2018).

Pedogenesis is almost entirely governed by contemporary aeolian activity, embodying a complete "erosion-transport-deposition" cycle: prevailing winds continuously act on the ancient sandstone, generating and liberating sand-sized particles through abrasion and deflation. These particles are then transported via saltation, undergoing sufficient sorting and rounding, before being deposited as extensive, highly uniform sand ripples and sheets across the pediment surface. The wind also efficiently winnows out finer dust-sized particles (< 20 μm) from the system, further enhancing the sorting of the surface sand (Sullivan et al., 2022). Thus, the soil at GP is a product of the modern Martian aeolian environment, where wind efficiently reworks and sorts ancient sediments. Its homogeneous sandy composition and excellent sorting serve as direct evidence of high-energy, sustained wind action.

(9) Sulfate-bearing Unit (Sol 2923-3072) (SBU)

The Sulfate-bearing Unit (SBU) is situated at higher elevations on Mount Sharp in Gale crater, characterized by steep, layered slopes and plateaus dominated by erosion-resistant evaporites, with surfaces extensively littered by sharp, angular rock fragments from differential erosion and minor aeolian sand (Edgar et al., 2018). The surficial material exhibits a coarse-grained, mixed character: the matrix is predominantly composed of coarse sand to fine granules (500–2000 μm), with a high proportion of millimeter- to centimeter-sized angular debris derived from the disintegration of locally sulfate-cemented rocks; the fine sand fraction (< 250 μm) is significantly lower than in the underlying clay-bearing unit (Thorpe et al., 2022). Pedogenesis results from the combined effects of the primary evaporitic fabric and subsequent physical weathering-aeolian erosion in a hyper-arid setting: initially, during the Hesperian period, the evaporation of sulfate-rich brines precipitated hard, brittle evaporite layers whose primary texture favors the formation of relatively coarse crystalline grains and fragments (Grotzinger et al., 2015). Under contemporary extreme aridity, these rocks undergo physical breakdown primarily via thermal stress, salt weathering (salt crystal growth), and gravitational collapse, producing disintegration products that are often large, platy, or blocky (O'Connell-Cooper et al., 2025). Concurrently, although wind activity is strong in this region, the coarse and angular nature of the primary debris limits its long-distance transport and rounding by wind. The wind primarily acts as a selective agent, winnowing away the finer particles (dust and very fine sand) generated during disintegration, thereby further enhancing the coarse-grained lag at the surface (Sullivan et al., 2022).

(10) Mount Desert Island (Sols 1650-1660) (MDI)

Mount Desert Island (MDI) is an isolated hill of iron-rich sandstone located near the Vera Rubin Ridge in Gale crater, characterized as an erosion-resistant bedrock feature mantled by a thin layer of actively migrating sand ripples, with wind-faceted bedrock surfaces and minor disaggregated debris visible (Rampe et al., 2020). The surficial material exhibits a classic aeolian-residual binary texture: a matrix of well-sorted fine to medium sand (125–250 μm) derived from regional aeolian deposition, is intermixed with abundant coarse sand- to granule-sized (0.5–2 mm), dark, sub-angular lithic fragments produced from the physical weathering of the local iron-rich sandstone (David et al., 2020; Weitz et al., 2018). Pedogenesis illustrates a tight coupling between aeolian transport and in-situ weathering at a local scale: prevailing northwesterly winds deliver and deposit fine sands from regions like the Bagnold Dunes, forming sand ripples that drape the bedrock, while simultaneously abrading the bedrock surface (Bridges et al., 2017; Sullivan et al., 2022). Concurrently, the exposed iron-rich sandstone undergoes thermal fatigue and salt weathering under intense insolation and temperature fluctuations, causing mechanical breakdown of the near-surface rock, which continuously generates coarse-grained debris that becomes incorporated into the overlying aeolian sand (Edgar et al., 2018). However, due to persistent wind activity in the area, the finest particles (< 20 μm) generated by weathering are readily removed by wind, while the coarser fragments remain as a lag deposit (Sullivan et al., 2022).

(11) Nathan Bridges Dune (Sols1617-1639) (NBD)

Nathan Bridges Dune (NBD) is located within the core of the Bagnold Dunes in Gale crater, representing a classic large, active dark-toned dune. Its morphology features crescentic or linear dunes with sharp crests and steep slip faces, covered by millimeter-scale ripples, exemplifying the classic form of modern aeolian sand transport on Mars (Lapotre et al., 2016). The soil here consists almost entirely of extremely well-sorted fine to medium sands, with a dominant grain size narrowly concentrated in the 100–300 μm range. The grain-size distribution shows a sharp, unimodal peak, with both coarse particles (>500 μm) and fine particles (<63 μm) present in minimal amounts (Weitz et al., 2018). Pedogenesis is a paradigm of the modern high-energy aeolian environment on Mars, almost entirely governed by wind sorting and transport: sand grains derived from ancient bedrock weathering and impact debris are driven by sustained, high-velocity Martian winds, undergoing long-distance saltation transport and frequent grain-to-grain collisions. This process, through mechanisms of "collisional sorting" and "winnowing," continuously removes particles that are too large (difficult to saltate) or too small (easily suspended and removed) from the system, ultimately leading to a high degree of homogenization in grain size, shape, and density within the dune sands (Sullivan et al., 2022). Limited chemical weathering (e.g., iron oxide coatings) only imparts color to the grain surfaces without significantly altering their size distribution.

2. Jezero Crater (18.38 °N, 77.58 °E, 45 km in diameter)

Jezero crater contains stratified deposits resulting from a complex interplay of volcanic, fluvial, and aeolian processes. Soils in the Séítah and Máaz formations display a diverse mineralogy, including olivine, pyroxene, carbonates, and clay minerals, indicative of fluid interactions and extensive weathering (Sun et al., 2023). Aeolian activity contributes to further soil differentiation, with wind-driven transport sorting grains by size and mineralogy, forming dunes and ripples across the crater floor (Sahu et al., 2024). This dynamic process has produced a heterogeneous soil structure, with grain sizes ranging from fine sands to coarse particles, shaped by the overlapping influences of volcanism, water, and wind.

A total of 722 soil samples were collected from the following 8 sites:

(1) Adziilii Crater (Sol 112-148) (ADZ)

Adziilii Crater (ADZ) is a small, young impact crater approximately 1 km in diameter located on the western edge of the Jezero crater delta plain. Its morphology exhibits a typical pristine bowl-shaped cavity, well-defined rim, and radial ejecta blanket, which overlies and modifies the surrounding ancient deltaic deposits (Sun et al., 2023). The surficial material here exhibits a characteristic mechanical mixture of impact ejecta and underlying sedimentary materials: the soil is predominantly composed of coarse sand- to granule-sized (500–4000 μm), angular to sub-angular impact breccia fragments, intermixed with fine sand- and silt-sized (<250 μm) sediments derived from the underlying delta (Tarnas et al., 2021). Pedogenesis is the result of the instantaneous excavation, comminution, and mixing of ancient aqueous sedimentary strata by an impact event, followed by weak aeolian modification: initially, the impact event instantaneously generated high temperatures and pressures, excavating, fragmenting, and ejecting basal deltaic materials such as lacustrine mudstones and sandstones, forming an ejecta blanket composed of debris ranging widely in size (from dust to boulders), with the coarser fraction deposited rapidly near the crater rim (Mangold et al., 2021). Subsequently, under the modern arid climate, the ejecta has undergone limited physical weathering (e.g., thermal fatigue) and aeolian erosion. Wind has partially removed the finest dust-sized particles from the surface, making the coarse-grained skeleton more prominent, yet the overall structure retains the primary impact-mixed fabric (Scheller et al., 2022).

(2) Artuby Ridge (Sol 170-200, 340-343) (ART)

Artuby Ridge (ART) is an erosion-resistant ridge composed of ancient lacustrine carbonate rocks located at the edge of the Jezero crater floor. Its morphology is characterized by steep, well-bedded cliff faces and debris-mantled gentle slopes, exhibiting wind-etched grooves and minor patches of aeolian sand, representing an exposed primary lacustrine sedimentary unit (Horgan et al., 2023; Sun et al., 2023). The surficial material exhibits a weathering-dominated, coarse-grained fabric: the soil is predominantly composed of medium-coarse sand to granule-sized (250–2000 μm), angular to sub-rounded carbonate rock fragments directly derived from the physical disintegration of the underlying bedrock; the fine-grained matrix (<125 μm) is limited, consisting of minor aeolian sand and rock flour (Tarnas et al., 2021). Pedogenesis results from the combined effects of arid physical weathering of carbonate rocks and limited aeolian activity: first, the hard carbonate bedrock undergoes mechanical fracturing due to long-term thermal fatigue, salt crystallization, and desiccation stress, generating platy or blocky debris along joints and bedding planes that gradually breaks down into sand- and granule-sized particles (Mangold et al., 2021). Concurrently, the regional wind field acts on the ridge surface, producing two effects: it abrades and etches the rock surface, forming ventilacts, and it partially removes the finest rock flour produced by weathering while delivering a limited amount of exogenous fine sand that deposits in topographically sheltered areas (Scheller et al., 2022).

(3) Séítah (Sol 202-286) (SEI)

Séítah (SEI) is a unique altered unit composed of magnesium-rich carbonate and olivine-bearing rocks located in the western floor of Jezero crater. Its morphology is characterized by gently undulating bedrock outcrops thinly mantled by aeolian sand, with surfaces littered with abundant angular rock fragments derived from in-situ bedrock disintegration, presenting a strong physical weathering landscape (Farley et al., 2022). The surficial material exhibits a prominent signature of in-situ weathered debris: the soil is predominantly composed of coarse sand- to granule-sized (500–4000 μm), angular to sub-angular olivine-rich and carbonate rock fragments that are compositionally consistent with the underlying bedrock, indicating their origin from proximal mechanical breakdown; the fine-grained fraction (<125 μm) is low, consisting mainly of limited aeolian sand admixture and rock grinding powder (Tarnas et al., 2021). Pedogenesis results from the intense physical weathering of mafic-ultramafic rocks under extreme Martian aridity, superimposed with weak chemical alteration: unstable minerals like olivine undergo mechanical fracturing and limited aqueous alteration over long periods due to thermal fatigue, salt weathering, and possible local water-rock interactions, leading to reduced rock strength and disintegration along grain boundaries, producing abundant coarse-grained debris (Scheller et al., 2022). Concurrently, regional winds exert limited aeolian sorting on the loose debris, removing some of the fine powder. However, the coarse, angular olivine fragments are resistant to wind transport due to their high density and irregular shape, resulting in the formation of a coarse-grained, in-situ weathering mantle (Scheller et al., 2022).

(4) Three Forks Region (Sol 379-414) (TFR)

The Three Forks Region (TFR) is located on the delta plain of Jezero crater, representing a flat sedimentary area formed by the convergence of multiple ancient channels. Its morphology is characterized by a sandy plain mantled by a thin layer of aeolian sand and scattered with few gravels, exhibiting large-scale aeolian sand ripples across the surface, which reflects ongoing post-depositional wind modification (Sun et al., 2023). The surficial material exhibits classic aeolian sorting-deposition characteristics: the soil is dominated by well-sorted fine to medium sands (125–500 μm), showing a unimodal grain-size distribution. Coarse particles (> 2000 μm) are extremely rare, and the fine silt/clay fraction (<63 μm) is also low, indicating efficient aeolian winnowing (Weitz et al., 2018). Pedogenesis is a product of the tight coupling between ancient fluvial sediments and modern aeolian processes: initially, during the Late Noachian, rivers transported sand-grade sediments from the catchment to this area, forming extensive sandy floodplains or delta-front deposits (Mangold et al., 2021). Subsequently, under the modern arid climate, these unconsolidated or weakly consolidated sandy sediments became abundant sources for aeolian activity. Prevailing winds have subjected them to continuous deflation, transport, and redeposition: wind strips away the fine-grained components (silt and clay) from the original deposit and removes them from the region, while simultaneously transporting sand grains via saltation and redepositing them under the influence of local topography, forming extensive, well-sorted sand ripples and sheets (Scheller et al., 2022).

(5) Skinner Ridge Outcrop (Sol 477-496) (SKI)

The Skinner Ridge outcrop (SKI) is located at the distal edge of the Jezero crater delta, representing an erosion-resistant ridge composed of cross-bedded sandstone. Its morphology is characterized by steep, layered cliff faces and debris-choked footslopes covered with abundant angular rock fragments, exhibiting pronounced wind-etched grooves and minor patches of aeolian sand, representing an original sedimentary unit of the delta front (Mangold et al., 2021). The surficial material exhibits a weathering-dominated, coarse-grained fabric: the soil is predominantly composed of coarse sand- to granule-sized (500–4000 μm), angular sandstone fragments that are compositionally consistent with the underlying cross-bedded sandstone, indicating their origin from mechanical breakdown; the fine-grained matrix (<125 μm) is very low, consisting mainly of limited aeolian sand admixture (Tarnas et al., 2021). Pedogenesis is shaped by the combined effects of physical weathering of sandstone and aeolian erosion in an arid environment: the hard, cross-bedded sandstone undergoes mechanical fracturing along bedding planes and joints due to long-term thermal fatigue, salt crystallization, and aeolian abrasion, producing platy or blocky coarse debris that gradually disintegrates into smaller sand- and granule-sized particles (Scheller et al., 2022). Concurrently, the strong regional wind field exerts selective aeolian erosion on the loose debris, partially removing the finest rock flour generated by weathering and any exogenous fine sand. However, the coarse, angular sandstone fragments are largely retained at the footslope due to their weight and shape, which resist wind transport, resulting in the formation of coarse-grained, debris-rich talus slopes.

(6) Hogwallow Flats (Sol 501-517) (HOG)

Hogwallow Flats (HOG) is a broad, flat area composed of fine-grained sediments located in the southwestern part of the Jezero crater delta plain. Its morphology is characterized as a homogeneous plain mantled by a very thin layer of aeolian sand, with sporadic small gravels and rock fragments scattered across the surface, exhibiting large-scale, low-relief aeolian sand ripples that indicate active contemporary wind modification (Sun et al., 2023). The surficial material exhibits highly aeolian-sorted and mixed characteristics: the soil is dominated by extremely well-sorted fine to medium sands (100–350 μm), showing a sharp, unimodal grain-size distribution. This is intermixed with a minor amount of coarse sand- to granule-sized (500–2000 μm), sub-angular to sub-rounded exotic fragments, likely derived from distant impact ejecta or limited contributions from local bedrock (Newman et al., 2021; Weitz et al., 2018). Pedogenesis exemplifies the intense reworking and homogenization of ancient fine-grained lacustrine/deltaic sediments by modern aeolian processes: during the Late Noachian, quiet-water environments deposited primary materials dominated by silt and fine sand (Mangold et al., 2021). In the modern arid era, persistent strong winds became the dominant agent, subjecting the original sedimentary layer to efficient deflation, saltation transport, and redeposition. The wind not only removed the vast majority of the original silt and clay fractions but also, through repeated collisions and sorting, achieved a high degree of uniformity in grain size and roundness of the sand particles. Concurrently, the wind also incorporated a small number of coarse particles from regional impact events or older strata. However, due to their larger size and density, these coarse grains are typically confined near the surface or within ripple troughs, failing to disrupt the overall homogeneity of the fine-sand matrix (Scheller et al., 2022).

(7) Amalik (Sol 557-581) (AMA)

Amalik (AMA) is located in the transitional zone between the Jezero crater delta plain and the crater floor, representing a gentle slope area composed of a mixture of ancient lacustrine sediments and later volcaniclastic materials. Its morphology is characterized as a heterogeneous plain thinly mantled by aeolian sand, with abundant centimeter-sized dark volcanic lithics and light-toned sedimentary rock fragments scattered across the surface, exhibiting medium-sized sand ripples that indicate moderate-intensity aeolian reworking. The surficial material exhibits a classic polymict, heterogeneous mixing characteristic: the soil consists of two dominant components—a matrix of moderately well-sorted fine to medium sand (125–500 μm) of aeolian origin, and a high proportion of coarse sand- to pebble-sized (2–30 mm), angular to sub-rounded dark (volcanic) and light-toned (sedimentary) rock fragments. These two components are mechanically mixed, with a low content of fine-grained particles (<63 μm) (Tarnas et al., 2021). Pedogenesis results from the combined effects of a complex depositional history and subsequent aeolian winnowing: initially, during the Late Noachian to Hesperian, this area experienced alternating or mixed accumulation of lacustrine fine-grained sediments and volcaniclastic events (e.g., ash fall or lava flow fragmentation) (Mangold et al., 2021). In the modern arid era, prevailing winds have subjected the original mixed deposit to selective deflation and transport: the wind effectively sorts and rearranges the loose, sand-sized material into ripples while removing finer dust. However, the coarse volcanic and sedimentary rock fragments, whose size and weight far exceed the transport threshold of wind, are retained as "lag components" in situ or undergo only limited rolling, resulting in the current "bimodal" or "polymodal" structure where coarse and fine particles coexist (Scheller et al., 2022).

(8) The Observation Mountain (Sol 593-641) (OM)

Observation Mountain (OM) is a prominent isolated massif located in the southwestern crater rim highlands of Jezero crater, composed of ancient bedrock (likely pre-Noachian crustal material). Its morphology is characterized by steep bedrock slopes and broad debris aprons covered with abundant coarse, blocky talus, exhibiting limited patches of aeolian sand and wind-etched grooves, representing an exposed, long-term denuded ancient geologic unit (Farley et al., 2022). The surficial material exhibits an extremely coarse-grained, weathering-residual character: the soil consists almost entirely of gravel- to boulder-sized (> 4 mm, up to several tens of centimeters), highly angular to sub-angular bedrock fragments of likely diverse igneous and metamorphic lithologies; the fine-grained sandy matrix (< 2 mm) is exceedingly low, found only as limited aeolian sand infill between clasts (Tarnas et al., 2021). Pedogenesis is the result of extremely slow, physical breakdown-dominated weathering of ancient, resistant bedrock under hyper-arid conditions over vast timescales: the exposed ancient bedrock has undergone mechanical fracturing primarily through thermal fatigue, salt weathering, limited water-ice phase changes, and micrometeorite bombardment over eons, leading to the production of large-scale, angular rock blocks along primary joints and fractures. These blocks undergo downslope creep or collapse under gravity, accumulating to form extensive talus slopes (Scheller et al., 2022). Concurrently, wind activity in this area is relatively limited, capable of only weak deflation or deposition of the finest dust and minor sand on slopes, and is ineffective at transporting or rounding the coarse blocks.

3. Gusev Crater (14.57 °S, 175.47 °E, 160 km in diameter)

Gusev crater features a relatively flat landscape shaped by both aeolian and fluvial processes. Soils composed of fine sands, silt, and pebbles show a relatively uniform grain size distribution and distinct stratification, reflecting stable depositional conditions. The presence of aeolian dunes and wind-eroded depressions underscores the role of wind erosion in shaping the terrain. Formed by an early Martian impact, the crater contains sedimentary records that capture a transition from wetter to drier climates, offering insight into Mars' environmental evolution and its potential for sustaining liquid water.

A total of 366 soil samples were collected from the following 10 sites:

(1) Columbia Memorial Station (Sol 1-36) (CMA)

The Columbia Memorial Station (CMA) is located on a flat area at the edge of the "Séítah" unit within Gusev crater plains, serving as the landing site and initial exploration zone for the Perseverance rover. Its morphology is characterized as a plain thinly mantled by aeolian sand, with sporadic centimeter-sized rock fragments scattered across the surface, exhibiting small-scale sand ripples and a few impact craters, representing the surface environment encountered early in the rover's mission that has undergone a certain degree of aeolian modification (Farley et al., 2021). The surficial material exhibits aeolian sand-dominated mixing characteristics: the soil is primarily composed of well-sorted fine to medium sand (100–300 μm) forming the main matrix, intermixed with a minor amount of coarse sand- to pebble-sized (> 2 mm), sub-angular to sub-rounded rock fragments (likely from local bedrock disintegration or distant ejecta). The fine dust fraction (<20 μm) is relatively low (Newman et al., 2021; Weitz et al., 2018). Pedogenesis results from the mixing and sorting of local bedrock debris and regional aeolian sands by modern Martian wind activity: the area is adjacent to the olivine-rich "Séítah" bedrock unit, which produces limited coarse debris through processes like thermal fatigue, scattering it across the surface (Scheller et al., 2022). Concurrently, prevailing regional winds continuously transport fine sands from broader source areas (possibly including ancient channel deposits) to this site. After aeolian sorting, these sands are deposited, forming mantling ripples and sheets that partially abrade and bury the local debris. The wind effectively removes most of the loose dust, resulting in a surface dominated by sand, but it is incapable of completely removing or transporting the larger rock fragments over significant distances.

(2) Bonneville Crater (Sol 65-91) (BC)

Bonneville Crater (BC) is a small, young impact crater located on the rim of Gusev crater. Its morphology exhibits the typical simple bowl-shaped structure with a distinct rim and a relatively flat floor, likely containing limited wall-collapse debris and patches of aeolian sand inside, representing the instantaneous modification of the regional original surface by an impact event. The surficial material is anticipated to exhibit a mixed character of impact-excavated parent material and later aeolian deposits: given the current lack of direct rover exploration data for BC crater, by analogy with similar young craters, its soil is likely predominantly composed of coarse sand- to gravel-sized (> 500 μm) angular impact breccia and ejecta blocks derived from the excavated bedrock. Concurrently, fine to medium sands (<500 μm) transported by wind may have accumulated in the topographic lows within the crater, forming a thin mantle (Carr et al., 2014). Pedogenesis results from the combined effects of an instantaneous impact event and subsequent long-term aeolian and gravitational processes: initially, the impact event instantaneously excavated and comminuted the underlying and surrounding original materials (possibly including ancient Gusev strata), ejecting and depositing them around the rim and inside the crater to form a primary impact breccia layer (Melosh et al., 1989). Subsequently, over vast geologic time, the crater has undergone limited weathering and modification, including gravitational collapse of the crater walls, rock fragmentation due to thermal fatigue, and the deposition of regionally sourced fine aeolian sands transported by wind into the crater, coupled with the selective removal of the finest dust (Scheller et al., 2022).

(3) Missoula Crater (Sol 93-111) (MC)

Missoula Crater (MC) is a small, young impact crater investigated by the Perseverance rover between sols 93 and 111 of its mission. Located within Jezero crater, it morphologically presents as a simple bowl-shaped structure with a distinct rim and a floor partially covered by aeolian sand. Rock outcrops and debris slopes are visible on the crater walls, while the flat floor areas exhibit aeolian sand ripples, indicating post-impact modification by aeolian erosion and deposition (Sun et al., 2023).

The surficial material in this region exhibits a notable mixture of impact ejecta and aeolian sands. Based on rover image analysis, the soil is primarily composed of moderately sorted fine to coarse sands (100–1000 μm), which include angular rock fragments from impact ejecta and more rounded sand grains from aeolian sorting. Locally, millimeter- to centimeter-sized coarse particles are scattered, likely derived from proximal bedrock disintegration or residual impact blocks (Newman et al., 2021; Weitz et al., 2018). Pedogenesis reflects the instantaneous modification by the impact event and the subsequent sustained influence of aeolian processes: the impact excavated and fragmented the underlying bedrock, forming an initial ejecta layer dominated by coarse, angular material. Subsequently, under long-term arid conditions, regional winds have subjected the intra-crater and rim materials to deflation, transport, and redeposition. This has resulted in the removal or transport of fine-grained material (such as silt and clay) to topographical lows, while introducing aeolian sands from regional sources into the crater to form mantling layers and ripples, with limited rounding and mixing of the early ejecta (Bridges et al., 2017).

(4) Lahontan Crater (Sol 126-140) (LC)

Lahontan Crater (LC) is a moderate-sized, moderately preserved impact crater located within Jezero crater. Its morphology is characterized by a relatively subdued rim and a floor partially covered by aeolian materials, with layered bedrock outcrops and colluvium visible on the crater walls, and dunes, sand sheets, and scattered rock fragments distributed across the floor, indicating significant post-impact aeolian modification and sedimentation. The surficial material in this region exhibits a composite mixture of impact ejecta, bedrock weathering debris, and aeolian deposits. Based on analogies from remote sensing and rover data, the soil is expected to be dominated by poorly to moderately sorted sand to fine granules (100–2000 μm), including angular debris from the crater wall bedrock, sub-angular blocks from impact ejecta, and sub-rounded sand grains transported by wind. Locally, centimeter-sized coarse particles may be concentrated, derived from wall collapse or proximal ejecta remnants (Newman et al., 2021; Weitz et al., 2018). Pedogenesis results from the multi-stage superimposition of crater formation, physical weathering of bedrock, and regional aeolian activity: the impact event excavated and exposed deeper rock layers, forming primary ejecta and fresh rock faces on the crater walls. Subsequently, under long-term arid conditions, the crater wall rocks undergo physical disintegration such as thermal fatigue and salt weathering, continuously supplying debris to the crater floor. Concurrently, prevailing winds transport regional aeolian sands into the crater, depositing them as dunes and sand sheets in topographic lows, and subjecting the existing debris to aeolian erosion, sorting, and partial mixing; however, coarse impact and weathering products are largely retained in situ or at the foot of slopes due to limited transportability (Bridges et al., 2017; Scheller et al., 2022).

(5) Intercrater Plains (Sol 111-126, 140-1556) (IP)

The Intercrater Plains (IP) refer to the flat to gently sloping areas widely distributed between impact craters within Jezero crater. Their morphology is characterized by homogeneous plains covered by continuous aeolian sand and sand ripples, with scattered rock fragments and millimeter-sized weathering granules on the surface, and occasional traces of paleochannels or erosional gullies, indicating long-term, large-scale aeolian dominance and limited aqueous history (Sun et al., 2023).

The surficial material in this region exhibits highly aeolian-sorted and homogenized characteristics. Based on remote sensing and rover data, the soil is dominated by extremely well-sorted fine to medium sands (80 – 350 μm), forming a covering layer several centimeters to decimeters thick; coarse particles (>1 mm) are rare and mostly sub-rounded, possibly residual from distant ejecta or minor local bedrock contributions; the fine-grained fraction (<30 μm) is significantly depleted due to wind removal (Newman et al., 2021; Weitz et al., 2018). Pedogenesis results from long-term, high-intensity aeolian activity that has thoroughly reworked and homogenized ancient, diverse parent materials. The original materials of these plains may include ancient impact ejecta, volcaniclastic deposits, and limited aqueous sediments. Over vast geologic timescales, these materials have been subjected to sustained deflation, saltation transport, collisional breakage, and aeolian sorting. Prevailing winds have thoroughly mixed and deposited the transportable sand-sized material as extensive sand sheets and ripples, while continuously removing finer dust-sized particles from the area. Larger or denser fragments are gradually buried, fragmented, or localized, ultimately forming the current highly homogeneous, excellently sorted aeolian sand mantle (Bridges et al., 2017; Sullivan et al., 2022).

(6) Columbia Hills (Sol 156-235) (CH)

Columbia Hills (CH) is a series of low to moderate-height hillocks composed of ancient bedrock located within Gusev crater. Its morphology is characterized by undulating terrain with abundant rock outcrops and well-developed colluvium, covered by limited aeolian sand and rock debris, with local weathering rinds and dissolution features visible, representing a long-exposed, ancient geologic unit with a complex weathering history (Arvidson et al., 2004; Squyres et al., 2004).

The surficial material in this region exhibits a weathering-dominated residual-colluvial mixed character. Based on analogies to the Spirit rover's investigations at the Columbia Hills in Gusev crater, the soil is likely dominated by coarse sand- to granule-sized (500–4000 μm) angular to sub-angular bedrock fragments, mixed with minor amounts of fine sand to silt (<250 μm) from aeolian input and in-situ weathering products. The coarse fraction is compositionally diverse, potentially including various igneous and altered lithic fragments, reflecting the heterogeneity of the parent rock (McSween et al., 2006; Yen et al., 2008). Pedogenesis results from the combination of long-term physical and chemical weathering of bedrock under hyper-arid conditions and weak aeolian modification: over hundreds of millions of years, exposed ancient bedrock has undergone thermal fatigue, salt weathering, limited water-rock interactions, and micrometeorite bombardment, leading to mechanical fragmentation and partial mineral alteration, forming residue-dominated coarse debris. This debris moves downslope under gravity, forming colluvial aprons. Concurrently, regional winds subject the loose regolith to limited deflation and accretion, removing some fine-grained material and introducing minor aeolian sand, but insufficient to significantly alter the coarse-grained residual-dominated fabric (Golombek et al., 2006; Sullivan et al., 2008).

(7) Larry's Lookout (Sol 436-513) (LL)

Larry's Lookout (LL) is located within the Columbia Hills region of Gusev crater, representing a small ridge-top position composed of olivine-rich basaltic rocks. Its morphology is characterized by prominent bedrock outcrops covered by a thin veneer of aeolian sand and debris, with angular rock fragments derived from bedrock disintegration scattered around, indicating an exposed bedrock area with active physical weathering and limited aeolian reworking (Arvidson et al., 2004; Squyres et al., 2004).

The surficial material in this region exhibits a weathering-dominated, coarse-grained fabric. Based on in-situ data from the Spirit rover, the soil is predominantly composed of coarse sand- to granule-sized (500–3000 μm), angular to sub-angular basaltic fragments that are compositionally consistent with the underlying olivine-rich bedrock. The fine-grained matrix (<125 μm) is limited, consisting mainly of minor aeolian sand admixture and rock-derived weathering dust (McSween et al., 2006; Yen et al., 2008). Pedogenesis reflects the weathering process of mafic rocks under Martian arid conditions, dominated by physical disintegration with minimal chemical alteration: the olivine-rich basaltic rocks undergo mechanical fracturing primarily along mineral boundaries and micro-fractures due to long-term thermal cycling, salt crystallization, and possible local water-rock interactions, producing abundant coarse, angular debris. Concurrently, regional wind activity is relatively weak, capable of only limited deflation and redistribution of the finest surface dust, and ineffective at transporting or rounding the coarse lithic fragments (Golombek et al., 2006; Sullivan et al., 2008).

(8) Husband Hill (Sol 514-705) (HH)

Husband Hill (HH) is the highest point within the Columbia Hills region of Gusev crater, representing a complex massif composed of multiple lithologies, including basalts, silica-rich debris, and altered rocks. Its morphology is characterized by rocky outcrops, steep slopes, and extensive colluvial deposits across undulating terrain, covered by a thin veneer of aeolian sand and angular rock debris, with local dissolution features and weathering rinds indicating long-term, multi-phase geological modification of an ancient highland (Arvidson et al., 2004; Squyres et al., 2004).

The surficial material in this region exhibits a multi-source mixed, weathering-dominated residual-colluvial character. Based on Spirit rover data, the soil is predominantly composed of coarse sand- to granule-sized (500–4000 μm) angular to sub-angular debris, including basaltic blocks, silica-rich fragments, and altered mineral assemblages. The fine-grained fraction (<125 μm) is limited, consisting mainly of minor aeolian sand and in-situ weathering dust, reflecting the lithological diversity of the parent material and limited chemical weathering intensity (McSween et al., 2006; Yen et al., 2008). Pedogenesis results from the combined effects of multi-phase volcanic activity, impact modification, and long-term arid weathering: early volcanic eruptions and impact events provided diverse lithologies as parent materials; subsequently, under extreme aridity, these rocks primarily underwent thermal fatigue, salt weathering, and weak water-rock interactions, leading to mechanical fragmentation and limited alteration, forming coarse-grained residual debris that accumulated downslope under gravity. Regional wind activity is weak, only capable of limited deflation and redistribution of surface fine-grained material, insufficient to significantly alter the coarse-grained residual structure (Golombek et al., 2006; Sullivan et al., 2008).

(9) El Dorado (Sol 706-711) (EID)

El Dorado (EID) is located near the "Home Plate" region in Gusev crater, representing a field of light-toned dunes rich in sulfate minerals and silica-enriched layers. Its morphology is characterized by extensive dunes and ripples composed of fine-grained, light-toned aeolian material, with virtually no rock outcrops, indicating high aeolian activity and material homogeneity, typical of an active wind transport and depositional environment (Ruff et al., 2011; Squyres et al., 2007).

The surficial material in this region exhibits exceptionally well-sorted fine-grained sand with a unique mineralogical composition. Based on Spirit rover data, the soil is dominated by well-sorted fine to medium sands (100–300 μm), with grains being sub-rounded to rounded, and mineralogically characterized by sulfates (e.g., gypsum), silica phases (e.g., opal), and minor iron oxides. Coarse particles (>500 μm) are rare, and fine dust (<20 μm) is depleted due to aeolian winnowing (Morris et al., 2008; Yen et al., 2008). Pedogenesis results from the intense aeolian reworking of earlier water-rock interaction products on Mars: initially, the area may have formed secondary deposits of sulfate and silica minerals under aqueous conditions. Subsequently, during arid periods, these friable deposits were comminuted, transported, and sorted by wind, forming aeolian accumulations dominated by fine sand. Persistent strong winds not only thoroughly mixed and rounded the sand grains but also winnowed away finer dust, resulting in highly homogeneous and well-sorted surface materials (Greeley et al., 2006; Sullivan et al., 2008).

(10) Home Plate (Sol 1501-2100) (HP)

Home Plate (HP) is located within the Columbia Hills region of Gusev crater, representing a layered plateau composed of volcaniclastic and hydrothermally altered rocks. Its morphology is characterized by a flat top, steep edges, and slopes partially covered by aeolian sand, with visible sedimentary bedding, polygonal fractures, and scattered rock fragments, reflecting a complex history of volcanic eruption, hydrothermal activity, and later aeolian modification (Ruff et al., 2011; Squyres et al., 2007).

The surficial material in this region exhibits a mixed character of volcanic-sedimentary parent material subjected to weak weathering. Based on Spirit rover data, the soil is dominated by moderately sorted fine to coarse sands (100–1000 μm), consisting of mixtures of volcanic glass, crystal fragments, and alteration minerals (e.g., silica and sulfates). Coarse particles (> 2 mm) are mostly angular to sub-angular bedrock fragments, while fine dust (<30 μm) has been partially removed by wind action (Morris et al., 2008; Yen et al., 2008). Pedogenesis results from long-term physical weathering and limited aeolian modification following volcanic eruption and hydrothermal deposition: volcaniclastic deposition and hydrothermal silicification formed the original layered plateau; subsequently, under arid conditions, the rocks primarily underwent thermal fatigue, salt weathering, and weak chemical alteration, leading to surface fracturing and polygonal crack formation. Regional winds subjected the loose material to limited deflation and redeposition, removing some fine particles and introducing minor aeolian sand, but not fundamentally altering the plateau's original structure (Golombek et al., 2006; Sullivan et al., 2008).

4. Meridiani Planum (0.2 °S, 357.5 °E) (~8 000 km^2 in area)

Meridiani is defined by prolonged aeolian erosion and repeated impact events, featuring broad, flat plains interspersed with ridges and dunes formed by sustained wind activity. It is rich in hematite, suggesting past aqueous processes, and contains sulfate minerals indicative of ancient water–rock interactions (Squyres et al., 2004). Soil grain sizes range from fine dust to coarse sand, with notable wind-driven sorting. Mineralogical analyses reveal hematite, olivine, and clay minerals, with spatial variations across the region reflecting complex climatic and geological dynamics. Aeolian processes remain active, with ripples and dunes continuously modifying the surface.

A total of 257 soil samples were collected from the following 6 sites:

(1) Eagle Crater (Sol 1-57) (EAC)

Eagle Crater (EAC) is located in Meridiani Planum and served as the landing site for the Opportunity rover, representing a small, young impact crater approximately 22 meters in diameter. Its morphology is characterized by a shallow bowl-shaped cavity, distinct rim, and a floor partially covered by aeolian sand. The crater walls expose well-defined layered sedimentary rocks ("Burns Formation"), and the surface is scattered with millimeter- to centimeter-sized hematite "blueberry" spherules and sulfate-rich debris, representing an ancient evaporitic sedimentary sequence exposed by impact excavation (McLennan et al., 2005; Squyres et al., 2004).

The surficial material in this region exhibits a pronounced mixture of impact-excavated parent material and aeolian sand. Based on Opportunity rover data, the soil is dominated by moderately sorted fine to medium sands (100–500 μm), which include abundant hematite spherules (1–5 mm in diameter), sulfate-cemented sand grains, and minor angular lithic fragments. Fine dust (<20 μm) is partially depleted due to wind action (Weitz et al., 2006). Pedogenesis results from the exposure of ancient evaporitic strata by an impact event and subsequent aeolian modification: the impact excavated and fragmented the sulfate- and hematite-rich "Burns Formation" sedimentary rocks, dispersing them within and around the crater. Subsequently, under long-term arid conditions, regional winds subjected the loose material to deflation, sorting, and redeposition, removing fine dust while introducing regional aeolian sands into the crater, mixing with local ejecta to form the current surface characterized by coexisting sand grains and "blueberries" (Grotzinger et al., 2005; Sullivan et al., 2008).

(2) Fram Crater (Sol 82-90) (FC)

Fram Crater (FC) is located east of Eagle Crater in Meridiani Planum, representing a small, young impact crater approximately 8 meters in diameter investigated by the Opportunity rover. Its morphology is characterized by a distinct rim, flat floor almost entirely covered by aeolian sand, with thin bedrock exposed on the crater walls and abundant hematite "blueberry" spherules and sulfate-cemented debris scattered across the surface, indicating an evaporitic sedimentary environment exposed by impact and intensely reworked by wind (McLennan et al., 2005; Squyres et al., 2004).

The surficial material in this region exhibits a highly mixed, well-sorted character of aeolian sand and impact ejecta. Based on Opportunity rover data, the soil is dominated by extremely well-sorted fine to medium sands (80–300 μm), embedded with numerous hematite spherules (1–4 mm in diameter) and minor sulfate-rich lithic fragments. Coarse particles (>5 mm) are rare, and fine dust (<20 μm) is significantly depleted due to aeolian winnowing (Weitz et al., 2006). Pedogenesis results from intense aeolian reworking following the excavation of ancient evaporitic strata by an impact event: the impact fractured and dispersed sulfate- and hematite-rich "Burns Formation" rocks onto the surface. Subsequently, under sustained arid conditions, prevailing winds subjected the loose intra-crater material to efficient deflation, transport, and redeposition, nearly completely removing fine dust while introducing regional aeolian sands that mixed thoroughly with local ejecta. Repeated sorting and rounding formed the current homogeneous surface, characterized by a well-sorted sand matrix enriched with "blueberry" spherules (Grotzinger et al., 2005; Sullivan et al., 2008).

(3) Endurance Crater (Sol 95-315) (ENC)

Endurance Crater (ENC) is located south of Eagle Crater in Meridiani Planum, representing a medium-sized impact crater approximately 130 meters in diameter that was extensively explored by the Opportunity rover. Its morphology is characterized by steep layered walls, an expansive flat floor, and locally developed dunes and sand ripples. The crater walls expose a several-meter-thick sequence of the "Burns Formation", including cross-bedded sandstones and evaporite interbeds, representing a complex aqueous sedimentary environment exposed by impact excavation (Squyres et al., 2004).

The surficial material in this region exhibits a diverse mixture of impact ejecta, bedrock weathering debris, and aeolian deposits. Based on Opportunity rover data, the soil is dominated by moderately to well-sorted fine to coarse sands (100–1000 μm), containing abundant hematite "blueberry" spherules (1–5 mm), sulfate-cemented sandstone fragments, and angular bedrock debris. Fine dust (<30 μm) is partially depleted due to intra-crater wind activity, with aeolian sand enrichment observed in topographic lows on the crater floor (Calvin et al., 2009; Weitz et al., 2006). Pedogenesis results from long-term aeolian modification and local gravitational processes following the excavation of a multi-layered sedimentary sequence: the impact exposed interbedded sandstones and evaporites of the "Burns Formation", generating abundant ejecta and wall debris. Subsequently, under arid conditions, winds within the crater subjected the loose material to selective deflation, transport, and deposition, removing fine dust from the crater while introducing regional aeolian sands to form dunes on the floor. Concurrently, the crater wall rocks underwent thermal fatigue and salt weathering, continuously producing debris that rolls downslope (Sullivan et al., 2008).

(4) Heat Shield (Sol 347-356) (HS)

The Heat Shield site (HS) is located east of the Opportunity landing site in Meridiani Planum, representing the localized area where the heat shield of the Opportunity rover actually impacted the surface. Its morphology is characterized by a flat sandy plain scattered with minor metallic debris and impact-ejected rock fragments, covered by a thin veneer of aeolian sand and ripples, with overall gentle topography, indicating a micro-geomorphic unit influenced by both post-landing human intervention and natural aeolian processes (Golombek et al., 2006; Squyres et al., 2004).

The surficial material in this region exhibits a mixed character dominated by aeolian sand with minor artificial and natural debris. Based on Opportunity rover imagery and spectral data, the soil is primarily composed of well-sorted fine to medium sands (80–300 μm) with moderate roundness, mainly derived from regional aeolian sand. This is intermixed with millimeter- to centimeter-sized metallic alloy fragments (from the heat shield) and minor local hematite "blueberry" spherules and sulfate-rich debris (Calvin et al., 2009). Pedogenesis results from the superposition of an artificial impact event and subsequent aeolian modification on a pre-existing aeolian plain: the high-speed impact of the heat shield produced local ejecta and debris scattering. Subsequently, prevailing regional winds subjected the loose surface material to ongoing deflation, transport, and redeposition, gradually removing fine dust and redistributing regional aeolian sands to form ripple layers that mantle both artificial and natural debris. The metallic fragments, due to their high density and size, are largely resistant to wind transport and remain at or near the surface, often partially buried (Grant et al., 2008).

(5) Purgatory Ripple (Sol 461-484) (PR)

Purgatory Ripple (PR) is a large area of active aeolian sand ripples located along the Opportunity rover traverse in Meridiani Planum. Its morphology is characterized by continuous chains of sand ripples approximately 10–20 cm in height, with distinct crest lines, gentle windward slopes, and steep lee slopes. The surface is almost entirely covered by loose sand grains with virtually no rock outcrops, representing a classic high-energy aeolian transport and depositional environment (Sullivan et al., 2008).

The surficial material in this region exhibits highly aeolian-sorted characteristics with good grain roundness. Based on Opportunity rover data, the soil is almost entirely composed of extremely well-sorted fine to medium sands (100–300 μm), with grains being sub-rounded to rounded. The mineralogy is dominated by basaltic sand grains, mixed with minor hematite "blueberry" spherules and sulfate dust. Coarse particles (>1 mm) are extremely rare, and fine dust (<20 μm) is significantly depleted due to persistent aeolian winnowing (Calvin et al., 2009; Weitz et al., 2006). Pedogenesis is a classic manifestation of long-term aeolian sand transport, collisional sorting, and deposition under strong Martian wind conditions: regional strong winds continuously transport sand grains from broad source areas (likely including paleochannels and impact ejecta) via saltation. During transport, grains undergo repeated collisions, breakage, and rounding. Wind continuously removes particles that are too large or too small through mechanisms of "collisional sorting" and "winnowing", ultimately depositing them under the influence of local topography to form well-sorted, regularly shaped ripples (Bridges et al., 2012).

(6) Victoria Crater (Sol 1292-1622) (VC)

Victoria Crater (VC) is located in southwestern Meridiani Planum and represents a large, complex impact crater approximately 750 meters in diameter and 70 meters deep, extensively investigated by the Opportunity rover. Its morphology is characterized by multi-tiered, bench-like crater walls, an expansive flat floor, and locally developed dunes and erosional gullies. The crater walls expose a thick sequence of the "Burns Formation", including prominent cross-bedded sandstones and evaporite interbeds, revealing deep aqueous sedimentary structures exposed by impact and later modified by aeolian processes (Grotzinger et al., 2005; Squyres et al., 2009).

The surficial material in this region exhibits a diverse mixture of impact ejecta, bedrock weathering debris, aeolian sand, and hematite "blueberry" spherules. Based on Opportunity rover data, the soil is dominated by moderately sorted fine to coarse sands (100–1000 μm), enriched with hematite "blueberry" spherules (1–6 mm), sulfate-cemented sandstone fragments, and angular bedrock debris. Fine dust (<30 μm) is partially depleted due to strong intra-crater winds, with aeolian sand and ripple deposits concentrated in topographic lows on the crater floor (Weitz et al., 2006). Pedogenesis results from the combined effects of long-term aeolian erosion, gravitational collapse, and possible local water-ice interactions following the large-scale excavation of a multi-layered sedimentary sequence: the impact exposed interbedded sandstones and evaporites of the "Burns Formation", generating abundant ejecta and wall debris. Subsequently, under extreme aridity, intense winds within the crater subjected the loose material to ongoing deflation, transport, and redeposition, removing fine dust from the crater while introducing regional aeolian sands to form dunes on the floor. Concurrently, the crater wall rocks experienced thermal fatigue, salt weathering, and possibly transient water-ice phase changes, leading to bench retreat and debris shedding (Grant et al., 2008; Sullivan et al., 2008).

5. Methodological Note on Image-Based Grain Size Analysis

All Martian grain size measurements in this study are derived from 2D rover images using semi-automated segmentation software (Shi et al., 2021; Zhao et al., 2023). The workflow is detailed in the main text (Section 2.2.3) and summarized here for completeness.

5.1 Definition of "Semi-Automated"

"Semi-automated" means that while grain boundary detection and size/shape calculations are performed algorithmically (implemented in Mathematica/Python), several steps require manual intervention:

1. Image quality filtering — Blurred or out-of-focus regions are manually masked.

2. Parameter tuning — Thresholds for foreground-background separation are adjusted per image due to variable illumination.

3. Manual correction — Erroneous grain merging (e.g., when two grains touch) is corrected by the operator.

This hybrid approach balances reproducibility with the flexibility needed for heterogeneous Mars images.

5.2 Instrument-Specific Adjustments

MAHLI and WATSON (color, arm-mounted, working distance 2-25 cm, pixel scale 14-77 μm/pixel):

- Use highest available resolution (typically 14-21 μm/pixel) with dust cover open
- Manual masking eliminates out-of-focus areas
- Grain segmentation uses edge detection with adaptive thresholds

RMI (grayscale, mast-mounted, fisheye distortion, ≈ 40 μm/pixel at 2 m):

- Due to fisheye distortion, only the central 40% of the field of view is analyzed (distortion <2%)
- Grayscale images require contrast enhancement (histogram equalization) prior to segmentation

Cross-instrument validation — For 30 co-located targets imaged by both MAHLI and RMI, D_{50} agreement is within ±12% (see main text Section 4.4).

5.3 Resolution Selection

For MAHLI, we exclusively use working distances of 2-10 cm, yielding pixel scales of 14-32 µm/pixel. The focus motor count recorded in each image enables scale calculation using the empirical relationship p = 6.90 + 3.52 × w (p = μm/pixel, w = working distance in cm; Edgett et al., 2012; Minitti et al., 2013). Pixel scales are reported in Dataset S3 metadata.

5.4 Conservative Detection Limits and Dust Mitigation

Following Karunatillake et al. (2014) and Shi et al. (2024), we adopt a conservative minimum detectable grain size of 5-7 pixels (not 3 pixels) for Martian images, corresponding to ~70-100 μm for MAHLI at 14 μm/pixel. The VFS class (<125 μm) is classified based on homogeneous appearance and dust-like chemistry rather than explicit grain counts.

To mitigate dust contamination:

- Preferentially select images acquired after Dust Removal Tool (DRT) brushing when available (Zhao et al., 2021)
- For unbrushed targets, manually mask regions with obvious dust aggregates
- The fine tail (< min detectable size) is truncated, not extrapolated

5.5 2D-to-3D harmonization

The fundamental incompatibility between 2D image analysis and 3D mass-based methods (dry sieving, laser diffraction) is acknowledged. Our approach is comparative rather than absolute: (1) Martian GSDs are processed exclusively through the same image-based method, enabling internal comparisons; (2) Lunar and terrestrial data are mass-based; (3) Cross-method comparisons are performed only at the parameter level (UGSD μ, D_c, n) rather than raw percentages. Where appropriate, we apply stereological conversion (Pizzati et al., 2023): ECD-based distributions are multiplied by a shape factor of 1.3-1.5 when directly compared to sieve data.

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