

Master's Thesis♣

Petrology of Saprolites in Central Hesse

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Abstract

The comprehensive analysis of saprolites from various lithologies endemic to Central Hesse has provided valuable insights into the weathering processes and products of Tertiary Europe. Through the integration of petrology, micromorphology, grain size analysis, and geochemistry, a detailed picture of formation conditions has emerged. Geochemical analyses reveal a consistent enrichment of immobile elements and depletion of alkali components, highlighting the intensity of chemical weathering. Secondary mineralizations of hematite, goethite, and siderite further confirm the transformative effects of weathering on the original rock compositions. Petrographic observations complement these findings, showcasing fine-grained textures, clay coatings, and flow structures indicative of fluid activity. Collectively, these features point to weathering as the dominant alteration mechanism, with little evidence of hydrothermal interference.

The observed alteration patterns provide valuable insights into past climatic conditions, suggesting a history of intense weathering regimes. These results have broader implications for reconstructing paleoenvironments and understanding the mobility of elements during weathering. Additionally, the study highlights the need for methodological advancements in grain size analysis, particularly for fine-grained materials, to improve measurement accuracy. By integrating multidisciplinary approaches, this research contributes to unraveling the complexities of weathering processes and their implications for geological and environmental sciences.

In conclusion, this study underscores the transformative impact of weathering on saprolites, driven by a combination of chemical, physical, and mineralogical processes. Past climatic conditions have facilitated intense chemical weathering, aided by fluid transport, resulting in highly altered mineral assemblages enriched in immobile elements, some of which hold economic significance. These findings enhance our understanding of weathering dynamics and provide a foundation for future investigations into the interplay between geology, climate, and surface processes.

Zusammenfassung

Die umfassende Analyse von Saproolithen aus verschiedenen in Mittelhessen vorkommenden Lithologien hat wertvolle Einblicke in die Verwitterungsprozesse und -produkte des tertiären Europas geliefert. Durch die Integration von Petrologie, Mikromorphologie, Korngrößenanalyse und Geochemie ist ein detailliertes Bild der Bildungsbedingungen entstanden. Geochemische Analysen zeigen eine konsistente Anreicherung von immobilen Elementen und eine Verarmung von Alkalibestandteilen, was die Intensität der chemischen Verwitterung verdeutlicht. Sekundäre Mineralisierungen von Hämatit, Goethit und Siderit bestätigen die transformativen Auswirkungen der Verwitterung auf die ursprüngliche Gesteinszusammensetzung. Petrographische Beobachtungen ergänzen diese Ergebnisse und zeigen feinkörnige Texturen, Tonüberzüge und Fließstrukturen, die auf flüssige Aktivitäten hinweisen. Insgesamt deuten diese Merkmale auf Verwitterung als vorherrschenden Alterationsmechanismus hin, wobei es kaum Anzeichen für hydrothermale Störungen gibt.

Die beobachteten Alterationsmuster bieten wertvolle Einblicke in die klimatischen Bedingungen der Vergangenheit und lassen auf eine Geschichte intensiver Verwitterungsregime schließen. Diese Ergebnisse haben weitreichende Auswirkungen auf die Rekonstruktion von Paläoumgebungen und das Verständnis der Mobilität von Elementen während der Verwitterung. Darüber hinaus unterstreicht die Studie den Bedarf an methodischen Fortschritten bei der Korngrößenanalyse, insbesondere bei feinkörnigem Material, um die Messgenauigkeit zu verbessern. Durch die Integration multidisziplinärer Ansätze trägt diese Studie dazu bei, die Komplexität von Verwitterungsprozessen und ihre Auswirkungen auf die Geologie und die Umweltwissenschaften zu entschlüsseln.

Zusammenfassend unterstreicht diese Studie die transformativen Auswirkungen der Verwitterung auf Saproelite, die durch eine Kombination von chemischen, physikalischen und mineralogischen Prozessen angetrieben werden. Die klimatis-

chen Bedingungen der Vergangenheit haben eine intensive chemische Verwitterung begünstigt, die durch den Flüssigkeitstransport unterstützt wurde und zu einer stark veränderten Mineralzusammensetzung führte, die mit immobilen Elementen angereichert ist, von denen einige wirtschaftliche Bedeutung haben. Diese Ergebnisse verbessern unser Verständnis der Verwitterungsdynamik und bieten eine Grundlage für künftige Untersuchungen des Zusammenspiels zwischen Geologie, Klima und Oberflächenprozessen.

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Chapter 1

Introduction

Saprolites, which are also known as “Weathering mantles” or “Grus” (especially concerning weathering granites), are a widespread feature of landscapes on every continent, occurring at or near the earth’s surface. They are most prominent in tropical to subtropical regions where they regularly exceed depths of 50 m Stoops, Marcelino, and Mees (2018), however, saprolites are not restricted to these locations as they can be as small as a few millimetres thick in temperate regions. In Europe, the distribution of saprolites is varied but is of significant quantities as they are present in central, western, and northern Europe. Locations where the presence of saprolites is well documented include the Iberian Peninsula, the Massif Central in France, parts of the Rhenish Massif in Germany (our study area), the British Isles, the Scandinavian Mountains, and the Fennoscandian Shield Migoń and Lidmar-Bergström (2001); Vazquez (1981).

The word “Saprolite” was coined from the Greek for “rotten rock” (*/sapros lithos/*) by G.F. Becker (1895) to describe bedrock still in the process of pedogenesis and delineate it from the layers further down the line of decomposition. They are the weathering remains of preexisting rocks exposed to atmospheric conditions such as precipitation, diurnal temperature changes, microbial activity, and high oxygen fugacity. They are the product of mineral transformations driven by thermodynamics, as the formation conditions at depth significantly differ from the conditions they encounter after their host rocks are exhumed. Saprolites differ from other weathering products because they remain *in situ*, meaning they develop as a covering, lying directly on top of the unweathered rock, like an outer skin. Due to this lack of mobilization, they also retain their rock fabric, even though the degree to which the fabric preservation varies with depth. The exact rate of weathering and thickness of the weathering mantle depends on the time spent at or close to the surface, the climate, and the rock type Ehlen (2005).

Saprolites frequently constitute a part of a more extensive stratigraphic sequence and usually only serve as a subordinate layer within the weathered profile. The weathered profile or regolith, as a whole, is an aggregate of layers of rock pieces in various stages of disintegration and originating from multiple sources. The A-B-C scheme was first introduced by Orth (1873, 1875) and later evolved by Dokuchaev, Vasily (1879a, 1879b). Improvements by Fowler (1925) brought the scheme to what is recognized today as the most widely accepted approach to the description of soil profiles Tandarich, Darmody, Follmer, and Johnson (2002). However, even though there is a unification of the scheme, there is no unification of the terms within the scheme, and the components are modified by authors to represent a variety of features studied, as evidenced by the review of Tandarich Tandarich et al. (2002).

The German soil classification scheme, as defined in the KA5 Eckelmann et al. (2006), begins the weathered profile with a layer littered with organic material that has just begun to humify and is known as the “O Horizon.” Below this layer is a completely disaggregated and unstructured layer which has lost all structure due to some varying combinations of biological and environmental processes and is known as the “A Horizon” or topsoil. The next layer, called the “E Horizon,” is where acids formed during humification of the organic matter in the previous layers, strip elements from the minerals in its layer and precipitates them further down, in a process called podzolization. Next is the “B Horizon,” which is structurally similar to the A Horizon but includes precipitates formed from the leaching processes in the layers above and less organic material. After that is the “C Horizon,” which has begun to weather but still preserves the structure of the bedrock below it. This layer corresponds to the titular saprolites and can be characterized as being the closest in density to the unaltered bedrock and the least affected by soil-forming processes of all the horizons.

Saprolites are studied by geochemists, civil engineers, hydrologists, geomorphologists, soil scientists, and exploration geoscientists for different purposes. They can serve as aquifers from which groundwater can be tapped or may form hosts for economic deposits through secondary or supergene enrichment for resources such as gypsum, clays, aluminium, manganese, nickel, copper, uranium, iron, gold, and other heavy minerals. Saprolites also serve as a window to the past, through which the events that led to their formation can be observed. Therefore, their study is important to understanding and predicting the effects of current geo-climatic processes.

1.1 Problem Statement

The study of saprolites, deeply weathered rock materials formed *in situ* through chemical weathering processes, is crucial for understanding soil formation, landscape evolution, and palaeoclimatic conditions. While extensive research has been conducted on saprolites derived from individual rock types, there is a notable gap in our understanding of how different precursor rocks within the same geographical area respond to similar weathering conditions over time.

1.2 Chemical Weathering and Soil Formation

The principal weathering mechanism of saprolites is by chemical processes, and their formation is generally promoted by tectonic stability and moderate to low relief Butt, Lintern, and Anand (2000); Stoops et al. (2018). Their existence is simultaneously predicated by the erosion rate, as high erosion rates prevent the accumulation of weathering products on top of their precursor rock and are balanced or slower than the weathering rate.

The principal weathering mechanism of saprolites is by chemical processes and their formation is also generally promoted by tectonic stability (or at the least, low rates) and moderate to low relief Butt et al. (2000); Stoops et al. (2018). Their existence is simultaneously predicated by the erosion rate as high erosion rates prevent the accumulation of weathering products on top of their precursor rock and is balanced or slower than the weathering rate. The effects of weathering are mostly assumed to increase from the top towards the bottom and is therefore depicted as layered, with the surface layer being the most weathered and the layer just above the unaltered bedrock being the least weathered. However the reality is more complex as there is more nuance from the factors that influence the weathering patterns in rock bodies Ehlen (2005).

Meteoric water serves as the main driver for the redistribution of chemical species, by various chemical and physical processes as it moves laterally and vertically through the rock mass. Mineral transformations occur by leaching, remineralization, redox, hydration, hydrolysis, and dehydration reactions. The *in situ* chemical weathering often increases the porosity of the rocks, which then provides a pathway for the movement of meteoric water. The leaching of ions from primary minerals along with the dissolution of intermediate minerals increases the porosity of the rock, as cavities left by these processes can be of significant

sizes and where the cavities overlap, the permeability is improved, thus increasing fluid flow. The deposition of secondary minerals which were previously in solution occurs when there are changes in composition, pressure or a combination of the two. This could be a result of fluid mixing, the fluid exceeding its saturation point (especially when it stagnates for long periods) or when the fluid encounters significantly voids such as fissures, cracks or joint sets during its movement. There may also be alteration of the primary minerals by the exchange of elements or ions with those in the fluid. When there is a net reduction in mass through leaching or dissolution at the margins of the weathering mantle, there is infiltration of water which has dissolved hydrogen ions (acidified water) which may begin to break down the fresh rock, triggering a progradation of the weathering front. This progradation of the weathering front may gradually continue over a long time, up to and beyond 20 Ma Stoops et al. (2018) until a resistant layer is encountered or the conditions that enable leaching or dissolution are no longer present.

The saprolite layer may be differentiated, especially in regions where they are well-developed and are of considerable thickness. In literature such as Tonui, Eggleton, and Taylor (2003) and Butt et al. (2000), the profile is divided into two. A basal layer that is compact and still possesses many of the structural features of the fresh rock but has become porous and is referred to as the “Lower Saprolite”. The upper layer is a friable layer of comparably higher porosity that only retains large-scale rock fabric and is referred to as the “Upper Saprolite”. These two layers are collectively termed as the “Saprolith” Butt et al. (2000); Stoops et al. (2018) and their boundaries overlap with that of the C horizon and the lower part of the B horizon, defined in the KA5. In geological texts, the layers above the Saprolith are termed as the “Pedolith” or “Solum” and they mark the onset of the conversion of minerals into soil. The Pedolith consists of a plasmic/arenose zone, a transitionary mottled zone, the ortstein and soil, and they all form parts of the B horizon Chodorowski (2011); Eggleton (2001). The plasmic/arenose zone roughly corresponds to the midsection of the B horizon, and it chiefly consists of clay or sand, depending on the minerals of the bedrock and the groundwater conditions. The mottled zone is marked by pockets of materials that optically contrast with their surroundings, which is caused by the seasonal rise and fall of the water table leaving minerals in various stages of oxidation or reduction. Lastly, the ortstein is the top section of the B horizon which has accumulated leached iron, silicon or carbonates, thereby forming a cemented layer. In arid to semi-arid environments, the ortstein may be well developed and is termed the

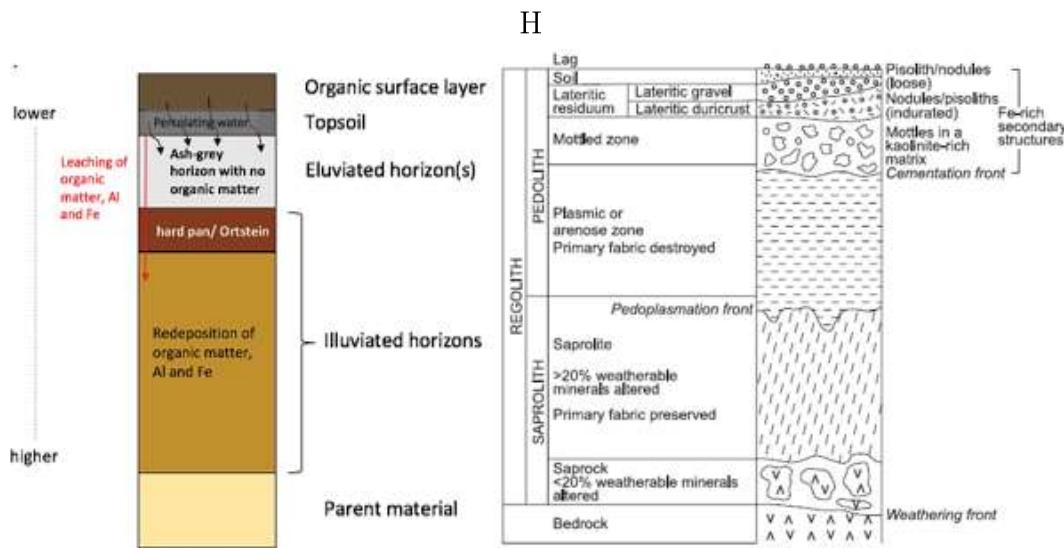


Figure 1.1: Annotated Diagram of the Saprolite Layer Juxtaposing Pedological and Geological Division of the Profile

duricrust.

While there is no unified classification scheme of saprolites, they do not always present in the same fashion. Their differences can be linked to a number of factors which are listed and discussed below:

1. Mineralogy
2. Climate
3. Economic potential

Mineralogy

Saprolites can be distinguished based on the mineral assemblages left behind by the alteration process. Although the resulting materials are ultimately governed by other contributing factors, the mineralogy of the material left behind is of great importance as it informs the economic significance of the saprolites. Saprolites can be divided based on their mineralogy into one of the following:

- Silicate saprolites: which are almost entirely made up of silica rich secondary minerals like quartz, kaolinite and smectites (>2%). They mostly form as a result of the breakdown of silicate rich parent rocks. They are further subdivided based on grain size as plasmic and arenaceous; with the plasmic being made up of clay-sized minerals and the arenaceous being majorly composed of sand to gravel sized minerals. As can be expected, the plasmic

saprolites are rich in clay minerals and are formed from parent material such as volcanic ash, basaltic glass and metapelites, while the arenaceous saprolites are rich in quartz and are formed from parent material such as granitoids and quartzites. They are referred to as “grus”.

- Iron-Aluminium rich saprolites: These saprolites are formed in areas of intense weathering such as areas within the tropical-subtropical belts. High precipitation, high temperatures and abundant organic material combine to produce acidic fluids through the breakdown of organic materials, which percolate through the ground. These acidic fluids are capable of leaching aluminium and iron through the formation of complexes, and they do so as they percolate through the soil profile. These elements are then deposited as oxides in the zone of water table fluctuation, which corresponds to the mottled zone of the geological regolith stratification scheme and the top B horizon of the KA5 classification. These layers which are rich in a combination of iron and aluminium oxides such as diasporite, gibbsite, boehmite, goethite, and haematite, are termed as laterites.
- Carbonate saprolites: Rocks containing carbonates are more liable to weather under atmospheric conditions as they are weak against carbonic acids formed from the dissolution of atmospheric carbon dioxide (CO_2) in meteoric water (acid rain). Acids react with the carbonate minerals, which are mostly made up of calcite and dolomite, to release CO_2 and leach ions of carbon and magnesium. The rate at which carbonate minerals react with meteoric waters is high when compared with the reaction rates of silicate minerals with meteoric water, in all types of settings Bufe et al. (2021). This dissolution of carbonate minerals often drastically increases the porosity and permeability of the rocks, leading to the formation of a network of cavities called karst systems. The dissolved carbonates come out of solution and recrystallize as calcite or dolomite, in fractures deeper in the profile. They are often deposited along with clay minerals when the groundwater goes through different lithologies or when the parent rock is a mix of silicate and carbonate minerals such as marbles and calcsilicate rocks.

Climate

The type of climate greatly informs the rate of weathering, the intensity of weathering, the depth of the weathering profile and type of chemical weathering process,

which in turn determines the mineralogy and the thickness of the saprolites layer. The weathering process is generally accelerated by alternating periods of wet and dry periods, along with temperatures that vary on a daily basis. Conversely the weathering process is slowed down by very low precipitation and stable low temperatures close to the freezing point of water. Combining this knowledge with the climatic conditions around the world, we get the following climate-based division of saprolites:

- Tropical regions: Regions around the equator that receive constant and high amounts of solar radiation throughout the year, while receiving large quantities of rainfall are described here. They are typically a well-developed layer producing a substantial amount of material and have the most intense type of chemical weathering which results in the nearly complete mineral breakdown of primary minerals into secondary clays and iron-aluminium oxides. The amount of leaching is also quite pronounced as most of the silica, alkali metals and alkali earth metals are stripped from the mineral assemblages, leaving behind iron-aluminium dominated complexes. Depending on the rock assemblages present, these conditions are perfect for the creation of sedimentary deposits known as lateritic ores from which minerals such as aluminium, chromium, manganese, iron, cobalt and nickel.
- Temperate regions: These regions have moderate precipitation and seasonal temperature variations. This results in a slower rate of chemical weathering that is more balanced with physical weathering and usually yields a relatively stable mix of primary minerals with secondary minerals in the saprolites. The layer isn't as developed as in tropical regions and the resulting minerals are less concentrated in immobile elements (iron, aluminium, zirconium, etc.). Minerals assemblages are richer in silicate minerals, such as smectites and illites.
- Arid and semi-arid regions: These regions have low precipitation rates and high temperatures which result in high evaporation rates. The primary weathering mechanism here is mechanical, however there is still some redistribution of elements caused by meteoric water from flash flooding. This yields a mix of primary mineral fragments along with secondary minerals in saprolite layers. They are often thin and discontinuous layers which are highly dependent on the subsurface groundwater flow pattern. In arid regions where there is a sizable presence of sulphur such as in pyrite or proximal degassing volcanoes, the sulphides may be oxidized by meteoric

water to sulphuric acids which react with carbonate rocks to form calcium sulphates such as anhydrite, bassanite and gypsum. In other rock types, the weathering followed by intense evaporation results in recrystallized carbonates and salt deposits such as potassium salts, sodium salts, lithium salts and magnesium salts.

Economic Potential

Due to the fact that the weathering of rocks selectively redistributes elements and minerals, thereby concentrating them, the resulting saprolite may be of some significant economic value. The type of ore is a result of a specific configuration of parent material and environmental conditions, and can therefore be used to distinguish saprolites. The different types of ores are listed below:

1. Metallic laterites
2. Clay saprolites
3. Precious metal saprolites
4. Construction and Industrial saprolites
5. Agricultural saprolites
6. Saprolites enriched in critical materials (REE and Actinides elements)

1.3 Analytical Methods for Grain Size Determination

Grains loosened during the weathering process by the accompanying weakening of the crystal structure of the rock were analysed. The goal was to be as comprehensive as possible with classifying all grain sizes in the saprolites and avoid clustering a wide variety of grain sizes into one class and dramatically skewing the distribution curve. To ensure this, a method suitable for measuring coarse grained materials (wet sieving) was combined with methods for measuring fine grained materials (laser diffraction grain size analysis and Köhn pipette analysis).

The wet sieving method is a simple setup that makes use of a stack of sieves that steadily reduce in diameters, to separate grain sizes. It is particularly useful for samples containing fine particles that are prone to agglomeration. Its use of a liquid medium to enhance the separation of grains and ensure better results. The liquid also allows the fine particles that pass through the smallest sieve size to be collected and analysed by the other techniques. While both methods are useful

for particles up to clay sizes, they both assume that they are analysing spherical particles, which can limit its accuracy for irregular shapes.

1.3.1 Principles of Laser Diffraction Analysis

Laser diffraction analysis is a widely used technique for determining the particle size distribution of a sample. It is based on the scattering of laser light by particles in the sample, with the scattering angle inversely proportional to particle size. Larger particles scatter light at smaller angles, while smaller particles scatter it at wider angles. By measuring the intensity and angular distribution of scattered light, the particle size distribution can be determined using mathematical models. The technique employs detectors arranged to measure the scattered light over a wide angular range. A mathematical model, typically based on the Mie theory or Fraunhofer approximation, is then applied to relate the scattering pattern to the particle sizes. The method accommodates both dry and wet dispersions of particles, allowing for flexibility in sample preparation. The speed and ease of operation make it indispensable for quality control and research applications requiring detailed particle characterization.

Mie Theory

Mie theory is a rigorous model used in laser diffraction analysis to relate the scattering pattern of particles to their size. It accounts for the interaction of light with particles of varying sizes, incorporating effects such as absorption, refraction, and diffraction. This theory is applicable to a wide range of particle sizes, including those comparable to the wavelength of light. Mie theory requires detailed information about the optical properties of the material, such as the refractive index and absorption coefficient. Its precision makes it suitable for applications where accuracy is critical, particularly for smaller particles or those with complex optical behaviours.

Fraunhofer Approximation

The Fraunhofer approximation is a simpler mathematical model used in laser diffraction analysis, particularly for large particles relative to the wavelength of the laser light. Unlike Mie theory, the Fraunhofer approach assumes that particles are opaque and neglects light absorption and internal reflections within

the particles. It is computationally less demanding and provides reliable results for larger particles or cases where precise optical properties of the sample are unavailable. However, it is less accurate for particles near or smaller than the laser wavelength, limiting its application in fine particle analysis.

1.3.2 Principles of Köhn Pipette Analysis

The Köhn pipette analysis is a classical sedimentation technique used to determine the particle size distribution of fine-grained sediments and soils. It is based on Stokes' Law, which describes the settling velocity of spherical particles in a fluid under the influence of gravity. This method is particularly effective for analyzing the fine fractions of a sample, such as clay and silt particles, which are difficult to measure using other techniques.

The process begins by dispersing the soil or sediment sample in a liquid, typically water, with the addition of a dispersing agent to prevent particle aggregation. The suspension is then allowed to settle in a calibrated sedimentation cylinder. Larger and denser particles settle more quickly, while finer and less dense particles remain suspended for longer periods. At predetermined time intervals, an aliquot of the suspension is extracted using the Köhn pipette, which is specifically designed to collect samples from a fixed depth in the sedimentation column.

The extracted aliquots are dried and weighed to determine the mass of particles corresponding to the specific settling times. These measurements are used to calculate the size distribution of the particles, as the settling velocity is directly related to particle size according to Stokes' Law. By systematically repeating the sampling at various time intervals, a comprehensive particle size distribution curve can be constructed. Köhn pipette analysis is highly reliable for fine particles and is frequently used in soil science, geology, and environmental studies.

1.4 Thesis Objective

This thesis aims investigate the weathering patterns and characteristics of saprolites derived from three distinct precursor rock types within the central Hesse region of Germany. The study's primary objective is to elucidate the differential weathering responses of these rock types under comparable climatic conditions. The central Hesse region provides an ideal natural laboratory for this investiga-

tion due to its diverse geological setting, which includes a variety of rock types exposed to similar weathering regimes. By simultaneously examining multiple saprolite types within the same area, this study aims to provide a more nuanced understanding of weathering processes and their relationship to rock composition. Furthermore, the integration of palaeoclimatic reconstructions from three distinct saprolite profiles offers the potential for a more robust and accurate interpretation of past environmental conditions in central Hesse.

Specifically, this research seeks to:

- Characterize the mineralogical, geochemical, and textural properties of saprolites derived from three different precursor rock types in central Hesse.
- Analyze the weathering intensity and patterns exhibited by each saprolite type to determine how different rock compositions respond to similar weathering conditions.
- Utilize the palaeoclimatic information preserved within the saprolites to estimate past environmental conditions and compare these reconstructions across the three saprolite types.

The findings of this research will contribute to the fields of petrology, geomorphology, and palaeoclimatology, offering valuable insights into the complex interplay between rock composition, weathering processes, and climate history. Additionally, the results may have practical applications in areas such as soil science, agriculture, and environmental management, particularly in regions with similar geological and climatic characteristics to central Hesse.

Chapter 2

Geological Setting

The study was carried out in localities in and around Central Hesse. The localities range from Weickartshain in eastern Giessen (central Hesse) to Liebenscheid in southern Siegen (North-Rhine Westphalia) and Wasenbach in north-eastern Rhein-Lahn-Kreis (Rhineland Palatinate). A general triangulation of the area is shown in Figure 2.1 and shows that the samples come from an area encompassing a total of 1,432 km².



Figure 2.1: Showing study area dimensions (maps.google.com)

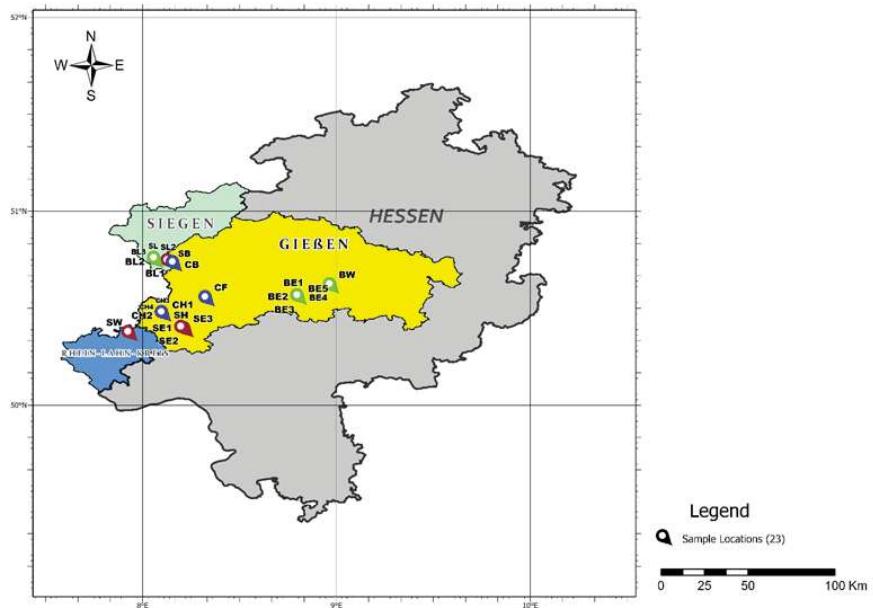


Figure 2.2: Sample locations relative to their position on a map of Hesse

The regional geology of the study area varies greatly in formation time and lithology. The area is chiefly underlain by metasedimentary rocks from the late Palaeozoic era that are crosscut in various locations by Cenozoic volcanics. There are also various sedimentary units stretching geochronologically between the Palaeozoic and the Cenozoic. The units belong to geological provinces of the Rhenish Massif or Rhenish Slate Mountains (“Rheinisches Schiefergebirge” in German) and the Hessian Depression (“Hessische Senke” in German), both of which have been affected by the tectonics of the Tertiary period. The Rhenish massif is made up of smaller geological units and the units which were sampled are the Taunus and Westerwald, located in the southern eastern portion of the province. The Hessian Depression also hosts a number geological units and the unit of interest to our study is the Vogelsberg volcanic field. The three significant units are shown in Figure 2.3 and would be discussed individually for the rest of the chapter.

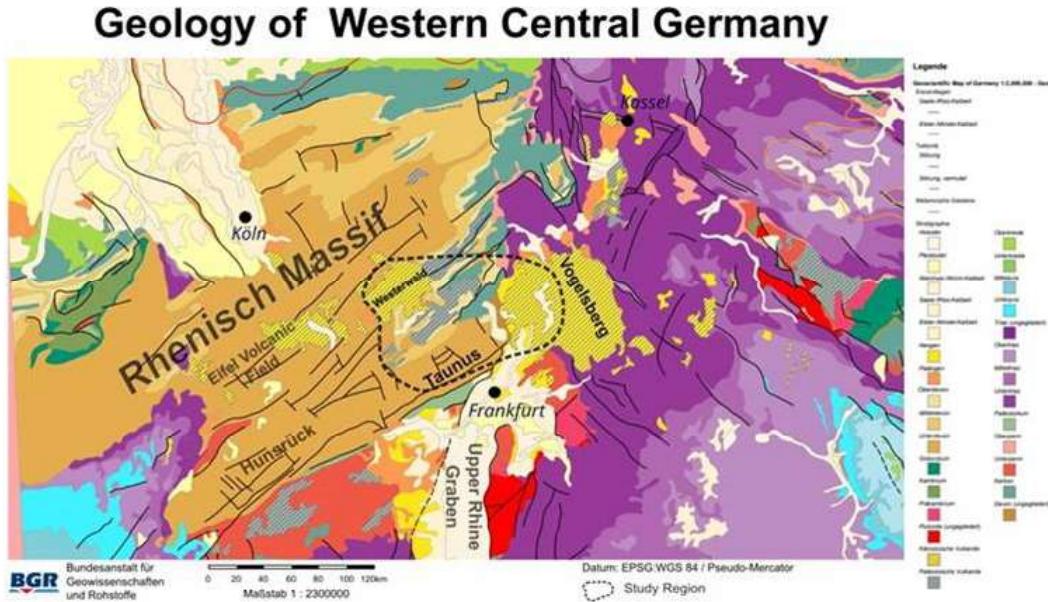


Figure 2.3: Regional Geology of Study Area Modified from (BGR, 2018)

2.1 Taunus

Taunus is the name given to a NW-SE striking mountain range located between Lorch am Rhein and Bad Nauheim with a length of about 75 km Toussaint (2024). It has a shared formation history with the adjacent Hunsrück hills, which are located on the other side of the Rhine river, as both resulted from orogenic events. The mountains are characterized by rugged ridges, deeply incised river valleys and broad plateaus. Together with the Hunsrück hills, they form the southern base of the Rhenish massif.

The Taunus as a geologic structural unit began as series of sedimentary facies that underwent tectonic compression between the Devonian and the Carboniferous periods Doublier, Potel, Franke, and Roache (2012). This was followed by episodic uplift from the Oligocene through to the Quaternary (low rates in the present day) and volcanism that formed two of the largest volcanics in Germany (Vogelsberg and Westerwald) from the Oligocene to the Quaternary El-Kelani, Jentzsch, and Schreiber (1998); Felix-Henningsen (2018); Haase, Goldschmidt, and Garbe-Schönberg (2004); Todt and Lippolt (1980). According to (Felix-Henningsen, 1994a, 2003, 2018) weathering began in the Rhenish massif in a tropical to subtropical paleoclimate during the Upper Mesozoic. This series of events resulted

in an area with a diverse geology that includes phyllites, metabasalts, slates, quartzites, carbonates, shales, greywackes, olistoliths and porphyroblasts Doublier et al. (2012); Salamon and Königshof (2010); Sauer and Felix-Henningsen (2006).

The Taunus is divided into three parts: the Vordertaunus, the Hohertaunus and the Hintertaunus. The Vordertaunus is located at the southeastern end of the province and forms the border between the Rhenish massif and the Upper Rhine Graben. It contains the oldest rocks in the Taunus region with the youngest rocks found between Oestrich-Winkel and Oberursel Toussaint (2024). The rocks of the Vordertaunus are mainly phyllites and slates, with gneiss being found in localities proximal to Wiesbaden. Next, the Hohertaunus or the Taunus ridge/anticlinorium, has the highest point of the Taunus and was formed by intense folding of transitional sedimentary units of a former coastal region. The present day rocks in this region are predominantly quartzites with a characteristic red pigmentation, while shales and sandstones are present in smaller, scattered amounts. Lastly, the Hintertaunus is the broad, gently sloping (when compared to the ridge unit) shoulder of the Taunus field which is mostly composed of Hunsrück slates interspersed with isolated quartzite and greywackes. The Hintertaunus is divided into two by the Idstein basin and its upper limit is defined by the Lahn river. The physiography of the Taunus, with its division is depicted in Figure 2.3.

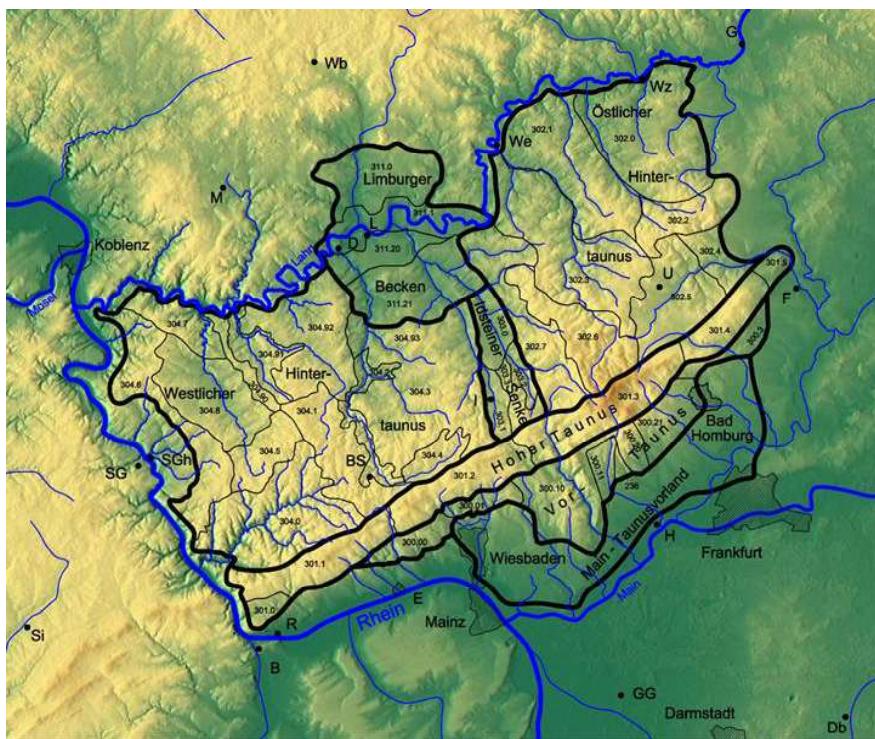


Figure 2.4: Showing the Taunus and its Division into subunits (De-academic.com, 2024)

2.2 Westerwald

The Westerwald is a lowland mountain within the Rhenish massif, northwest of the Taunus and bordered by the Rhine and two of its eastern tributaries (the Lahn and the Sieg rivers). It is a series of gentle rolling hills with the highest peak being an extinct volcano at an elevation of 657 m, called Fuchkaute. Being part of the Rhenish massif, the basement of the Westerwald is made up of metamorphic rocks from the Variscan Orogeny and sedimentary rocks from the Silurian to the Early Tertiary El-Kelani et al. (1998). This base has however been significantly covered by basalts and tuffs from volcanic eruptions as well as Tertiary sediments. The Devonian slates that form the base are seen to outcrop in Koblenz and Siegen, which are both on the edge of the mountain range.

The Westerwald volcanic field is the second largest volcanic field in Germany Haase et al. (2004). It is a part of the Central European Cenozoic volcanic belt which began in the Eocene and has its oldest units in the Eifel. The volcanic belt progressed in an easterly direction and concluded with tectonic movement which resulted in the Eger Graben. According to (Lippolt, 1983), volcanism in

the Westerwald began in the Late Oligocene and continued up to the Quaternary Haase et al. (2004); Todt and Lippolt (1980). The Westerwald volcanics are divided into two fields: The highly differentiated extrusives and intrusives, along with dykes of basanites and alkali olivine basalts of the southwestern region; and the 500 km² basaltic field to the northeastern region El-Kelani et al. (1998); Schreiber (1996). The height of volcanism occurred in the Early Miocene to Middle Miocene, producing the extensive basaltic field of the Northeast. Figure 2.4 shows the Westerwald with the outline of the Volcanics traced out.

The volcanics terminate at Dill syncline in the Northeast. This syncline is of some importance as it hosts deposits of ancient reefs that have been significantly ferruginized. These ferruginized carbonate outcrops are known as the Lahn-Dill type iron deposits and are a local mining site of iron ore Königshof, Becker, and Hartenfels (2016); Schmitt (2024).

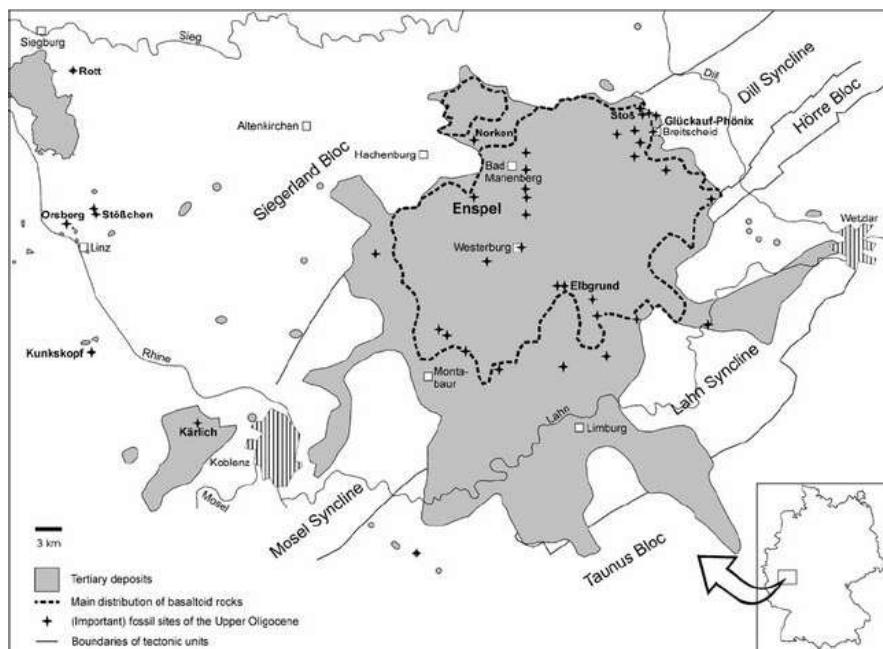


Figure 2.5: Shows the Westerwald with its Tertiary deposits and Volcanic extent (Roček & Wuttke, 2010)

2.3 Vogelsberg

The Vogelsberg is located east of the Rhenish massif, within the Hessian Depression. Along with some parts of the Rhoen and the Knuell, they form the East Hessian highlands. Its placement within a depression means that it creates the

Lahn valley to the west and the Fulda valley to the east. Southwest of Vogelsberg lies the Wetterau basin, which is a continuation of the Hessian Depression and connects the structure to the northern triple junction of the Upper Rhine Graben Ziegler (1992).

The Vogelsberg is also a part of the Central European Cenozoic Volcanic Province. It is the largest Tertiary volcanic field in Germany Haase et al. (2004); Schwarz (1997), with the bulk of volcanism being formed in the Early to Middle Miocene Schwarz (1997); Wedepohl (1985), making it younger than the Westerwald. The stratigraphy beneath the Miocene volcanics are largely unknown, however authors such as (Martha et al., 2014) and (Volker & Menges, 2018) speculate that since the basin caused by the rifting of the Hessian Depression existed before volcanism, there must be sediments of at least Paleogene age. Trisassic sediments of the Bunsandstein are known to have been deposited before the rift began and represent the upper limit of possible substrata of the volcanic field. The volcanic outcrops of the Vogelsberg are mainly alkaline basalts, basanites and tholeiites with subordinate trachyte lavas and phonolites Martha et al. (2014); Schwarz (1997). Like the Westerwald, geochemical studies have shown that a portion of the volcanics are sourced from evolved magma, however these differentiated deposits of pyroclastics, lava flows and intrusives are covered by a thick pile of primitive magma Martha et al. (2014). It has been proposed that deposition occurred in three phases, with the overall geochemistry increasingly becoming silica poor Bogaard and Wörner (2003); Wedepohl (1985).

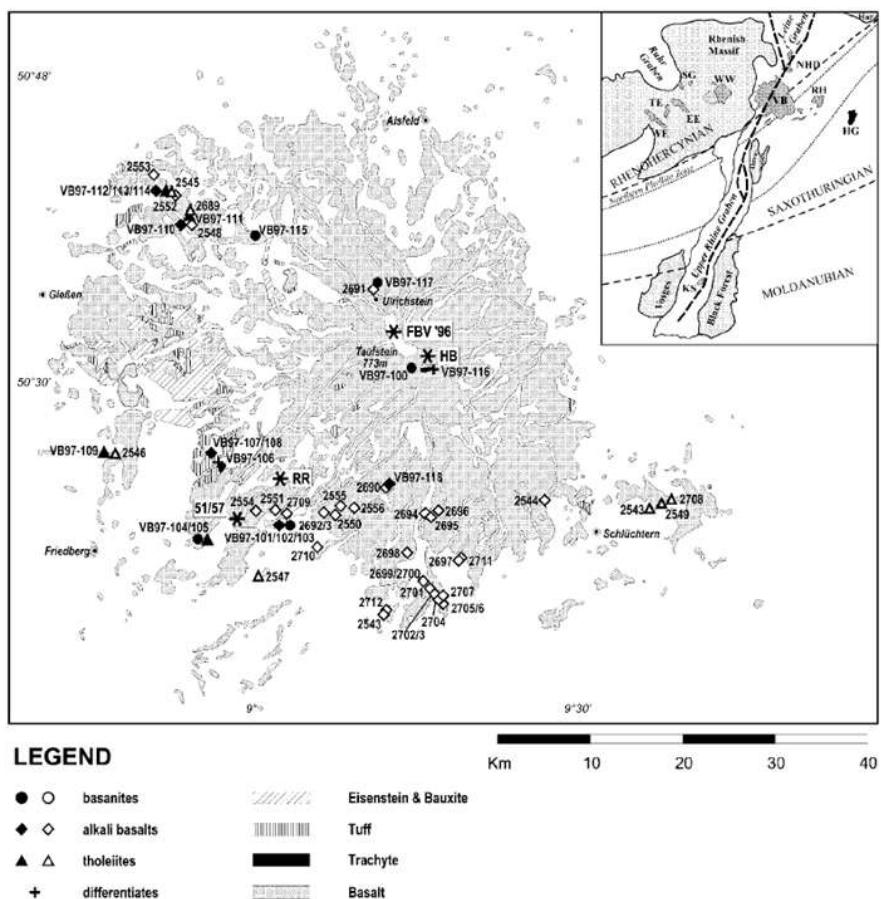


Figure 2.6: Showing distribution of volcanics of the Vogelsberg Volcanic field (Bogaard & Wörner, 2003)