UNVEILING THE GEOLOGICAL SIGNIFICANCE AND INDUSTRIAL APPLICATION OF LIMESTONE: A COMPREHENSIVE REVIEW

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Abstract

Limestone emerges as a fundamental component within sedimentary rock formations, which provides important information about previous geological eras and environmental circumstances. It retains fossils and remnants of extinct living forms because it mostly contains calcium carbonate. These deposits are used as traces of freshwater, marine, and terrestrial habitats from the past. Furthermore, variations in the creation of limestone provide hints about past geological events like tectonic activity and sea level shifts. Scientists can reconstruct previous ecosystems, temperatures, and evolutionary patterns by analysing limestone, which helps us better comprehend Earth's environmental dynamics and history over millions of years. Its versatility extends beyond its geological significance, and its primary uses are in the manufacturing of steel and cement, as well as in the purification of wastewater and the processes involved in the production of bread and sugar. Limestone is also essential for supporting the carbon cycle and improving soil health in agricultural settings. In the review paper, we endeavoured to conduct additional research to comprehend the intricacies of geology and the industrial application of limestone, as well as the need for interdisciplinary collaboration, sustainable practices, and cutting-edge technologies to leverage mineral resources for industrial growth. To be effective, it is essential. This study concludes with a strong call to action, imploring stakeholders to emphasize sustainable practices and encourage interdisciplinary collaboration while using limestone. By adhering to these guidelines, we can maximise the benefits of this priceless natural resource for both industrial use and environmental sustainability while also protecting it for future generations.

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1.0 INTRODUCTION

Limestone, a common sedimentary rock primarily made of calcium carbonate ($CaCO_3$), plays a significant role in geological stories and industrial environments. Its industrial value, combined with its geological significance, highlights its importance as a key component influencing the history of our planet and current attempts (Tanijaya, Tappi and Jabair, 2021). From a geological perspective, limestone is a living reminder of the Earth's turbulent past, having withstood aeons of environmental shifts and geological processes (Lisci, Pires and Sitzia, 2022). Its development provides essential insights into previous habitats, temperatures, and biological evolution (Lawan Muhammad, 2018). It is anchored in the build-up and lithification of marine sediments rich in calcium carbonate. Limestone becomes a tangible repository that preserves fossilised remains and geochemical traces that shed light on the complexities of Earth's history when seen through the lens of paleoenvironmental reconstruction (IUGS, 2022). At the same time, limestone is used in a wide range of industries and uses far beyond its geological roots (Ridha *et al.,* 2013). Limestone is essential to many human undertakings, ranging from building and cement production to agriculture and environmental restoration. Its adaptability as a raw material for soil amendment, road construction, concrete, and lime manufacturing highlights its vital significance in contemporary society (Hwidi, Tengku Izhar and Mohd Saad, 2018). The sustainable management of limestone resources and the reduction of related impacts are shaped by the intersection of environmental considerations, economic issues, and technical developments (Bliss, Hayes and Greta Orris, 2012). This paper aims to clarify the complex interactions between limestone's geological significance and its numerous industrial uses, highlighting the material's role in furthering scientific knowledge, stimulating economic progress, and fostering environmental sustainability.

1.1 Geological Formation of Limestone

Limestones are rocks that contain more than 50% carbonate minerals, at least 50% of which are aragonite or calcite. The colours of limestone range from white to grey to dark grey to yellow, green, blue, and occasionally even black (Silva *et al.,* 2022). A mixture of clayey material, glauconite, or finely dispersed ferrous compounds causes a greenish tint, while the presence of ferric iron causes a reddish or brownish coloration (Müller, 2021). Compared to fine-grained limestones, which are typically indicative of deeper, potentially decreasing circumstances during early diagenesis, coarse-grained limestones typically exhibit lighter colours, which are linked with well-oxidised environments. Magnesium carbonates, dolomite, silica, glauconite, gypsum, fluorite, siderite, sulphides, iron and manganese oxides, phosphates, clays, and organic materials are among the several impurities found in limestone (Rajendran and Nasir, 2014).

A calcareous sandstone, shale, etc. is defined as having a $CaCO_3$ content of slightly less than 50%. Differential weathering frequently occurs in its carbonate portion, giving it the appearance of limestone (Bakhshipouri *et al.,* 2009). Insoluble quartz grains and other materials are typically inconspicuous and readily released during weathering processes. Certain calcareous eolianites that contain less than 30% $CaCO_3$ go on to form karst landforms and other limestone characteristics. The majority of sedimentary carbonate rocks are the result of deposition in marine environments, with paralia and autogeosynclines serving as the main repository in neritic settings. Although it is not as common as that of banks, platforms, and shelves, calcium carbonate can also build up in deep water and in coral atoll structures encircled by an abyssal zone (Fairbridge *et al.,* 1961). Modern seas contain large amounts of calcium carbonate in its dissolved state, but certain requirements must be satisfied for the mineral to precipitate as a solid (Silva *et al.,* 2022). The primary biological process used to precipitate calcite from seawater is shown in Figure 1.

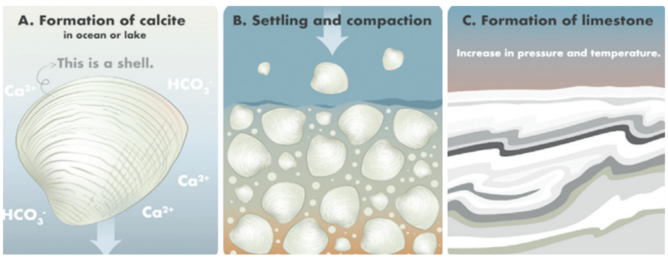

Figure 1: The process by which limestone (a rock) and calcite (a mineral with the formula $CaCO_3$) are formed
Image credit: Rock Archive (Kärt and Ichiko, 2021)

Calcite is used by a variety of marine creatures to form their shells and skeletons, which, when they die, fall to the seafloor, where they are buried and compacted into sedimentary rock (Hwidi, Tengku Izhar and Mohd Saad, 2018). The bone pieces and grains may never make it to the seafloor, though, as calcite dissolves readily (Ziveri *et al.,* 2023). Furthermore, the environments in which those marine species live regulate the deposition of limestone in particular geographical areas. Because limestone formation is restricted, its presence or absence in the geologic record provides information about the climate and geographic circumstances of the era.

2.0 IMPORTANCE OF STUDYING LIMESTONE'S GEOLOGICAL SIGNIFICANCE

It is crucial to comprehend the geological significance of limestone because of its complex relationships to Earth's past, present, and future. First of all, the geological profile of limestone offers priceless insights into the evolution of Earth over time by providing pictures of previous habitats, temperatures, and ecological systems (Peters *et al.,* 2022). Through the analysis of limestone formations' composition, texture, and fossil content, scientists are able to piece together the history of past ecosystems and landscapes, revealing the complex interactions between biological evolution and geological processes (Bykova *et al.,* 2017). Furthermore, the development of industrial minerals depends heavily on the geological features of limestone. Limestone is a widely available and abundant commodity that is used as a basic raw material in many different industries, such as manufacturing, agriculture, and building (Lyubomirskiy *et al.,* 2020). Basically, limestone has had geological importance since the past, and studying the geological origins of limestone provides insights into its role in the earth's systems as well as its effects on industrial processes and human communities. Here, we express its relevance in numerous aspects.

2.1 Paleoenvironmental Reconstruction

Limestone is an amazing archive that has a plethora of knowledge on historical climates, ecosystems, and habitats. The fossilised remnants found in limestone can reveal significant facts on biodiversity patterns, evolutionary processes, and extinct living forms (Ayyat *et al.,* 2021). Through the examination of the sedimentary features and geochemical indicators of limestone formations, researchers are able to piece together historical topographies, monitor variations in sea level, and interpret climate patterns spanning millions of years (Rohling *et al.,* 2022).

2.2 Global Carbon Cycle

Over geological time scales, limestone has a significant impact on atmospheric carbon dioxide concentrations and climate dynamics (Oelkers and Cole, 2023). Limestone functions as a carbon sink by absorbing carbon from the atmosphere and storing it in the lithosphere of the earth through the process of carbonate sedimentation (DePaolo, 2015). Knowledge of the weathering, diagenesis, and carbonate deposition processes in limestone formations helps with climate modelling and sheds light on the flows of carbon between Earth's surface (Rohling *et al.,* 2022). To form their calcium carbonate skeletons, calcareous creatures in marine habitats, including corals, molluscs, and foraminifera, draw dissolved carbon dioxide from the water. These species die, leaving behind carbonate-rich remnants that build up on the seafloor and lithify to produce limestone deposits. Through geological time spans, this mechanism deposits carbon in the Earth's lithosphere, sequestering it from the atmosphere. Figure 2 shows the role of limestone in the carbon cycle (Wallmann and Aloisi, 2012).

Limestone contributes to the global carbon cycle in two ways: first, through carbonate sedimentation, it acts as a sink for carbon dioxide, and second, through weathering and dissolution processes, it produces carbon dioxide.

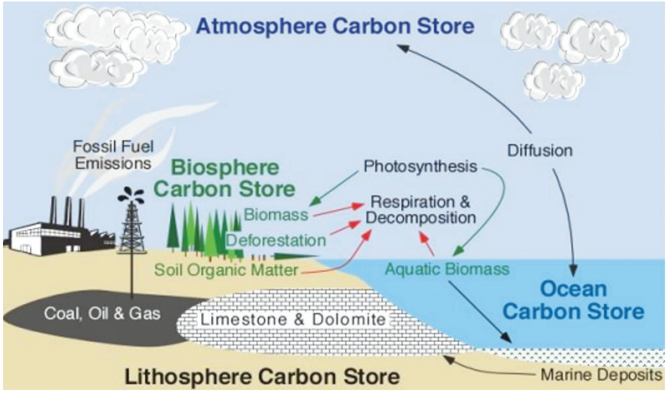

Figure 2: Illustrates the importance of limestone in the carbon cycle

2.3 Topography of Limestone

The physical characteristics of the earth's surface, such as its relief, slope, and height, are referred to as topography. Topography is important in shaping the general characteristics of landforms and influencing different geological and environmental processes in limestone settings. The special morphology of limestone that separates it from other rocks is karst landscapes; because limestone dissolves in water, karst landscapes are created (Zabidi and Freitas, 2006). Surface elements like sinkholes, caverns, and underground drainage networks distinguish these types of landscapes. Because carbon dioxide makes rainwater slightly acidic, it dissolves limestone rock over time, forming subsurface channels and caverns (Veress, 2023). Sinkholes may emerge on the surface due to the collapse of these expanding cavities because of the breakdown of limestone along joints and cracks; caves are also frequently found in limestone locations. The distinctive topography of karst environments is further enhanced by the complex web of underground drainage networks (Stokes, Griffiths and Ramsey, 2010). The limestone formation is affected by erosion, and with time, it forms diverse landscapes, as shown in Figure 2 (Baker, 2015).

3.0 PROCEDURES INVOLVED IN LIMESTONE DEPOSIT FORMATION

The creation of limestone deposits includes an intricate combination of physical, chemical, and biological processes occurring over huge geological time frames (Adenan, Ali and Mohamed, 2017). These activities led to the collection and crystallisation of calcium carbonate-rich minerals, which eventually gave rise to the varied limestone formations visible today (Ehrenberg and Baek, 2019).

3.1 Chemical Precipitation

The action of chemical precipitation is one of the main processes causing limestone deposition (Akinnawo, 2021). When bicarbonate ions (HCO_3^-) from the dissolution of carbonate minerals and the carbon dioxide (CO_2) equilibrium interact with dissolved calcium ions (Ca_2^+), calcium carbonate precipitates from seawater in marine environments. These residues build up on the seafloor over time, creating layers of calcium carbonate sediment that lithify into limestone rocks (Li *et al.,* 2023).

$$Ca_2^+ + 2HCO_3^- \rightleftharpoons CaCO_3 + H_2O + CO_2 \qquad \text{Equation (1)}$$

Calcium ions + Bicarbonate ions⇌ Calcium carbonate (limestone) + Water + Carbon dioxide

This formula depicts the chemical precipitation process that takes place in marine environments when bicarbonate ions (HCO_3^-) and calcium ions (Ca_2^+) react to form calcium carbonate ($CaCO_3$), water (H_2O), and carbon dioxide (CO_2). Over time, the calcium carbonate that precipitates from saltwater builds up on the seafloor and helps to form limestone rocks.

3.2 Biological Accumulation

Biological activity is very important for developing limestone in areas where reefs are formed. Calcium carbonate is extracted from seawater by marine creatures, including corals, microorganisms, and shell-forming mollusks, to build their skeletal systems (Neumann, 1997). Following death, the buildup of these calcium carbonate-rich remnants aids in the creation of biogenic limestone, or limestone reefs and sedimentary strata (Rogers, 2004).

3.3 Lithification

This process turns loose sedimentary particles into cohesive rock formations after calcium carbonate deposits are deposited (Zalzal, 2016). The calcium carbonate sediments undergo compaction and cementation under the pressure of the overlaying sediments and the slow ejection of pore fluids, which consolidates the limestone rocks (Norman, 2015). To give limestone rocks their strength, durability, and resistance to corrosion and weathering (Moftah *et al.,* 2022). The lithification process is an essential part of their production and maintenance. The process of lithification is the final stage of geological processes that turn loose calcium carbonate deposits into cohesive limestone rocks (Al-ramadan, 2006). Coastal processes, such as compaction, cementation, and diagenetic modification, turn sedimentary deposits into durable geological features that shape the terrain and preserve the chronicles of Earth's past (Léonide *et al.,* 2014).

3.4 Diagenetic Alteration

The composition and texture of limestone deposits can be further altered by diagenetic processes such as recrystallisation, cementation, and dolomitisation (Ganai, Rashid and Romshoo, 2018). Larger crystals are formed, and the original sedimentary textures are destroyed through the process of recrystallisation, which is the dissolution and reprecipitation of calcium carbonate minerals (Haywick, 2004). Secondary minerals like silica or calcite precipitate to fill pore spaces and bind sedimentary particles together, causing cementation. Dolomitisation is the process by which dolomite minerals, which are rich in magnesium, replace calcium carbonate to form dolomitic limestone (Memon *et al.,* 2023).

4.0 FACTORS INFLUENCING LIMESTONE DEPOSITION AND LITHIFICATION

The conditions under which limestone deposits aggregate and solidify into rock formations are shaped by a confluence of geological, environmental, and biological processes that impact limestone deposition and lithification (Fenton and Scott, 1932). The following are some of the major variables affecting the lithification and deposition of limestone:

4.1 Geological Environment and Its Impact on Limestone Formation

The conditions under which limestone deposits aggregate and solidify into rock formations are shaped by a confluence of geological, environmental, and biological processes that impact limestone deposition and lithification (Fenton and Scott 1932). The accessibility and geographical distribution of calcium carbonate sediments, which provide the groundwork for limestone deposition in a variety of habitats, are significantly influenced by the geological background (Zhang *et al.,* 2022). First, for limestone production, marine environments, especially coral reefs, and shallow tropical seas, are ideal because shallow tropical seas are ideal for the growth and preservation of creatures that produce calcium carbonate because they have high temperatures, plenty of sunshine, and relatively little input of terrestrial silt (Rohmann, Oceanic and Oceanic, 2014). Calcareous algae, corals, and other creatures that form reefs flourish in these conditions, actively participating in the bio-mineralisation processes that produce calcium carbonate deposits (Bergman *et al.,* 2020). The seabed is exposed to sunlight due to its shallow, clear waters, which allows photosynthetic organisms to grow and use dissolved carbon dioxide for photosynthesis, precipitating calcium carbonate (Paxton *et al.,* 2023).

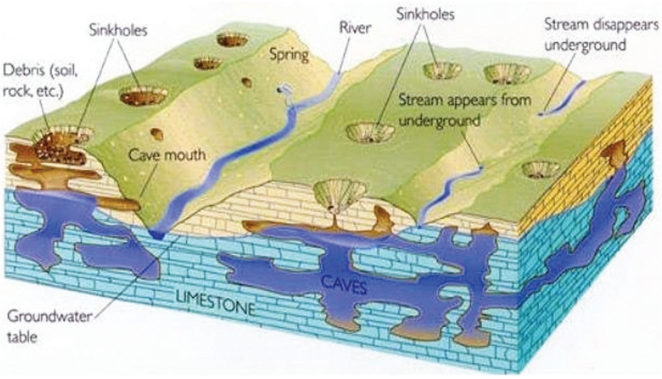

Figure 3: The topography of the karst formed by the formation of limestone

These sediments eventually undergo lithification, which is the process that creates limestone rocks. The second environment is coral reefs. Due to the rapid growth of reef-building corals and related calcareous species, coral reefs, one of the planet's most biodiverse ecosystems, represent hotspots of limestone deposition (Lucey, Haskett and Collin, 2021). Coral reefs are made up of aragonite or calcite calcium carbonate skeletons secreted by corals, which are members of the species Cnidaria (Blakeway, 2018). A wide variety of marine species, such as algae, sponges, and molluscs, find a home and substrate in the complex three-dimensional structure of coral reefs (Hallock, 1997). These organisms' skeletal growth and calcification processes aid in the formation of calcium carbonate sediments (Pastore *et al.,* 2022). Coral reef ecosystems' geological record is preserved through the gradual build-up of coral debris, skeletal components, and biogenic sediments into limestone formations. The stratigraphic distribution is shown in Figure 3 (Wu *et al.,* 2023).

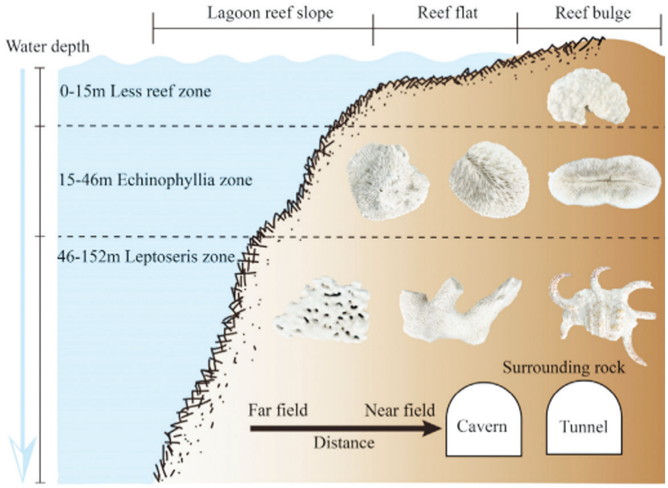

Figure 4: Coral reef of limestone strata schematic diagram

4.2 Weathering and Climate and Its Impact on Limestone Deposition

Limestone alters shape due to weathering and Climate effects and gets damaged over time (Kambakhsh *et al.,* 2024). Pollutants from the atmosphere are gathered by atmospheric water, and surface moisture permits them to enter the stone's pores and accelerate natural processes (Emmanuel and Levenson, 2014). Acidification by contaminating bacteria can be very damaging, especially for limestone. Some human-made substances, such as acids, can have destructive effects on natural stones, and they undergo physical, chemical and biological wear and weathering (Matsubara, 2021). Temperature, precipitation, and humidity all have a significant impact on the chemical weathering and erosion processes that lead to limestone deposition (Hajna, Hajna and Gabrovsek, 2002). The availability and movement of calcium carbonate sediments are shaped by the interaction of weathering dynamics and climate, which eventually affects the formation of limestone (Caserini, Storni and Grosso, 2022).

Warm and humid climates speed up the processes of chemical weathering, which encourages the disintegration of the calcium carbonate minerals found in carbonate rocks (Storage, 2014). The breakdown of carbonate minerals into soluble ions, such as calcium ions (Ca_2^+) and bicarbonate ions (HCO_3^-), shown in equation 2, is accelerated by high temperatures and copious amounts of rainfall (NOAA, 2016). These dissolved ions are carried to downstream ecosystems, such as lakes, rivers, and coastal seas, via surface runoff, groundwater flow, and river discharge. There, they participate in chemical precipitation that leads to limestone deposition. Furthermore, humidity promotes the availability of moisture for chemical reactions, which improves the release of carbonate ions into the aqueous environment and the dissolution of carbonate minerals (Change, 2022).

$CaCO_3 + H_2O + CO_2 \rightarrow Ca_2^+ + 2HCO_3^-$ (Equation 2)

Calcium carbonate + Water+ Carbon dioxide →
Calcium ions + Bicarbonate ions

The above formula (Equation 2) represents the chemical reaction that occurs when calcium carbonate ($CaCO_3$) dissolves in water (H_2O) and carbon dioxide (CO_2), forming soluble bicarbonate ions (HCO_3^-) and calcium ions (Ca_2^+) in an aqueous solution.

4.3 Biological Function and Its Impact on Limestone Deposition

In particular, in marine habitats where carbonate-producing creatures are plentiful, biological factors such as the diversity and quantity of organisms that secrete calcium carbonate play a crucial role in the deposition of limestone (Change, 2022). Reef-forming microbes' carbonate-rich sediments are created by the abundant production of calcium carbonate skeletons and shells by marine creatures like corals, foraminifera, and shell-forming molluscs. Colony corals, in particular, build coral reefs by secreting skeletons of calcite or aragonite, which act as a framework for depositing carbonate deposits. Foraminiferal ooze is a fine-grained mud primarily made of calcium carbonate produced by single-celled creatures called foraminifera with shells made of calcium carbonate. In a similar vein, molluscs that make shells, such as gastropods, cephalopods, and bivalves, secrete calcium carbonate shells that build up on the bottom and aid in the creation of biogenic limestone deposits (Ashley *et al.,* 2014). Because of the number of organisms that produce calcium carbonate and their optimal conditions for chemical precipitation, marine environments, typified by shallow tropical seas, coral reefs, and high biological productivity, serve as the principal locations for limestone formation. Climate dynamics, encompassing temperature, precipitation, and humidity, are essential for fostering chemical weathering processes that facilitate limestone deposition in terrestrial and aquatic habitats by releasing and transporting carbonate ions (Antonelli *et al.,* 2018). Calcareous species produce calcium carbonate skeletons and shells, which eventually accumulate as carbonate-rich sediments. Biological factors, including calcareous organisms' diversity and quantity, also enhance limestone deposition (East, 2020). Earth's history and the dynamic interactions between geology, climate, and biology by considering the interplay between these factors and the complex processes that govern limestone formation and evolution across diverse geological settings.

5.0 CLASSIFICATION OF LIMESTONE BASED ON ORIGIN AND COMPOSITION

Limestone is a type of sedimentary rock classified under carbonate rocks. In a broader sense, it refers to rocks where the carbonate content exceeds the non-carbonate content. A carbonate rock is classified as limestone when the predominant minerals in the carbonate fraction are calcium carbonates ($CaCO_3$) such as calcite or aragonite (Moosavi, 2022). On the other hand, it is termed dolomite when the primary mineral is magnesium carbon ($MgCO_3$) (Brief, 2014). Limestone formations are prevalent in geological records from the Archaean era, approximately 2500 million years ago, to the present day. They exhibit a diverse range of origins, which can be broadly categorised into biological and detrital sources.

i. **Biological Origins:** Limestones of natural origin are largely formed of calcium carbonate generated from the skeletal remains of marine organisms such as corals, microorganisms, and shell-forming molluscs (Geologic Time and Earth's Biological History Table of Contents, 2005). Over geological periods, these species amass calcium carbonate through bio mineralisation processes, creating carbonate-rich strata. These collected sediments change into limestone rock formations through compaction and lithification, conserving the biological traces of former marine ecosystems. Limestone generated in situ by chemical precipitation is categorised as endogenetic. The direct precipitation of calcium carbonate minerals from the solution is the source of this limestone, which frequently occurs in coastal environments with high concentrations of dissolved calcium and carbonate ions (Hashim, 2022). Large-scale limestone deposits are created over time by the build-up of precipitated calcium carbonate, which reflects the chemical reactions that take place inside the Earth's crust (Kaczmarek and Fullmer, 2015).
ii. **Detrital Origin:** Detrital limestone is formed from sedimentary particles that have been mechanically moved and deposited, frequently due to wind, water, or ice erosion, transportation, and deposition processes. Detrital limestone sometimes referred to as exogenetic limestone, is usually composed of carbonate-bearing minerals or pieces of previously existent limestone rocks (Lucia, 1995). Limestone rocks are formed by the compaction and cementation of these fragments in depositional environments like river deltas, beaches, or shallow marine basins.

5.1 Classification of Limestone Based on Texture

Different textures found in limestone are a reflection of its geological past. Well-developed crystal structures found in crystalline limestone result from recrystallisation at high temperatures and pressures. Whereas fossiliferous limestone contains an abundance of fossil remains, clinker limestone is made up of fragments held together by secondary minerals, as shown in Figure 5a (Karim and Ismael, 2017). Round ooids are found in oolitic limestone, while fine-grained calcite crystals are seen in micritic limestone Figure 5b (Young and Edmundson, 1954). Calcite crystals protrude from the coarse crystalline textures of sparry limestone Figure 5c. Every texture offers insightful information on the environmental factors and processes involved in the formation of limestone (Pii and Casey, 1998).

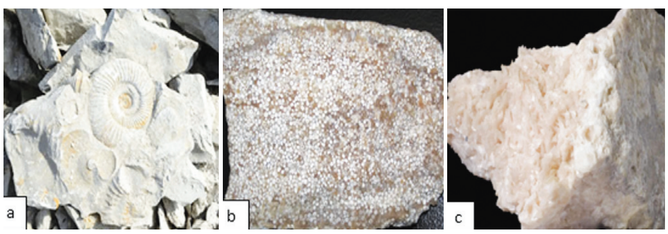

Figure 5 (a): fossiliferous limestone texture,
(b): micritic limestone, (c): crystalline limestone texture
Access online via https://geology.com

6.0 ROLE OF LIMESTONE IN INTERPRETING EARTH'S GEOLOGICAL HISTORY

To understand Earth's geological past through the lens of limestone, one must investigate the variety of forms, patterns of distribution, and distinctive features of limestone throughout various geological epochs (Geologic Time and Earth's Biological History Table of Contents, 2005). This thorough analysis covers several Earth scientific fields, such as sedimentology and stratigraphy. Scientists can reconstruct historical settings, interpret geological processes, and understand the intricate interactions between Earth's dynamic systems across millions to billions of years by combining data from several domains (Wallmann and Aloisi, 2012).

Table 1: An overview of limestone significance in understanding Earth's geological past

Aspect	Description	References
Stratigraphic Record	Limestone formations are useful stratigraphic markers that help with the dating and unit correlation of the rock units. Composite, textural, and fossil content analysis aids in the reconstruction of historical habitats and sedimentary processes.	(Adefris *et al.,* 2022)
Fossil Preservation	Limestone is a valuable resource for learning about historical ecosystems, biodiversity, and evolutionary patterns. Tracking the evolution of species and reconstructing past ecosystems are made easier by the fossils found in limestone rocks.	(Dunbar, 1960)
Paleoenvironmental	Climatic regimes and previous environmental conditions can be inferred from limestone deposits. Certain limestone textures are indicative of paleoenvironmental contexts, which help to deduce historical tectonic events and climate changes.	(Nagar and Town, 2018)
Reconstruction	Historical climatic variations, sea level shifts, and tectonic events by analysing sedimentary formations, geochemical traces, and paleontological data found in limestone rocks.	(Crawley, Holen and Chenoweth, 1985)
Diagenetic Processes	Numerous diagenetic processes affect the texture, porosity, and geochemical properties of limestone. Research on these processes aids in deriving historical chemical interactions and reconstructing the diagenetic history of limestone formations.	(Adenan, Ali and Mohamed, 2017)
Tectonic Significance	Structural characteristics such as folds, faults, and transformations serve as indications of previous mountain-building occurrences and the overall tectonic conditions of a region. The examination of structural geology assists in the reconstruction of previous plate borders, areas of collision, and cycles of mountain building.	(Oost and De Boer, 1994)

The table gives a thorough summary of the significance of limestone in diagenesis, stratigraphy, paleontology, paleo-environmental reconstruction, and tectonics for understanding Earth's geological history.

7.0 INDUSTRIAL APPLICATIONS OF LIMESTONE

Limestone is used in building, industry, and agriculture as a raw material, and its industrial relevance extends far beyond its geological significance. Its versatility in generating agricultural lime, cement, concrete, and lime supports several infrastructure projects and economic sectors across the globe (Amira *et al.,* 2020). For infrastructure planning, economic development, and sustainable resource management, it is crucial to comprehend the distribution and geological characteristics of limestone resources (Korneeva *et al.,* 2019). Beyond its geological significance, limestone is widely used in many sectors of the economy and is a fundamental component of industrial operations.

i. **Construction Industry**

Aggregates, asphalt, and concrete are all produced using limestone, a vital raw resource in the sector (Moftah *et al.,* 2022). Because of its strength, resilience, and adaptability, crushed limestone is used in structural applications, building foundations, and road construction (Malaysia Competition Commision, 2017). Limestone-based products are also prized for their aesthetic qualities, which makes them a top option for landscaping and architectural projects (de Abreu, 2018). Limestone in the cement industry consists of calcium carbonate and magnesium carbonate. The optimal composition of cement rock consists of 77-78% $CaCO_3$, 14% SiO_2, 2.5% Al_2CO_3, and 1.75% Fe_2O_3 (Lawan Muhammad, 2018).

ii. **Manufacturing Sector**

Limestone is utilised not just for cement manufacturing but also for its alkaline characteristics and ability to interact with water, rendering it appropriate for a variety of industrial applications as a crucial precursor in the creation of compounds, including calcium hydroxide, calcium carbonate, and calcium chloride (Shimelis *et al.,* 2022). Limestone is essential in environmental clean-up projects, including wastewater treatment and soil stabilisation, due to its capacity to neutralise acidic pollutants (Sabir *et al.,* 2023). Limestone is essential in metallurgical processes as a flux to remove impurities and improve the efficiency of metal purification methods (Andrew, 2018). Lime, which is made from limestone, is used in chemical production, environmental clean-up, and metallurgy (Panagoda *et al.,* 2023). Calcium carbonate is used in the paint industry as a cost-effective substitute for titanium dioxide, improving opacity and lowering production expenses (Sabir *et al.,* 2023). Similarly, in the paper business, calcium carbonate increases paper opacity, brightness, and printability, leading to increased product performance and reduced environmental impact (Ivaniciuc *et al.,* 2021). Additionally, calcium carbonate is a reinforcing material in plastic manufacture, imparting stiffness, impact resistance, and dimensional stability to polymer composites.

iii. **Industry of Food Production**

Although limestone isn't used directly, its by-products, such as lime and calcium carbonate, are crucial to some parts of the manufacturing of sugar and bread (Shoira, 2006). In processing sugar cane or sugar beet juice, calcium carbonate, which is generated from limestone, is frequently employed as a clarifying agent (Egorova, Puzanova and Nikolaeva, 2021). Proteins, organic debris, and colloidal particles are among the contaminants found in the juice that is collected from sugar cane or sugar beets (Rayburn, Service and Agronomist, 2005). As a flocculant, calcium carbonate is added to the juice to help these contaminants precipitate and be easier to filter or sediment (Qiao *et al.,* 2016). In bread manufacture, Lime (calcium oxide) or calcium hydroxide is used in factory (Garcia-Vaquero *et al.,* 2023). This method adds slaked lime to dough formulations to improve dough handling properties and alter pH levels. Additionally, lime can improve the elasticity and strength of bread dough by promoting the creation of the gluten network (Fernandes *et al.,* 2022). It's crucial to remember that although these goods made from limestone are utilised at certain points in the creation of bread and sugar, they are only used in limited amounts and have auxiliary functions rather than being main elements.

iv. **Applications in Agriculture**

The main purpose of using large amounts of crushed limestone and hydrated lime in agriculture is to improve soil conditions (Rayburn, Service and Agronomist, 2005). Applying agricultural lime, which is made up of finely crushed limestone, to acidic soils lowers their pH, lessens the toxicity of aluminium, and increases the availability of nutrients for plant growth (Lime, 1924). Lime serves various purposes in this context, such as enhancing the texture of clay soils by increasing the granularity of heavy soil through the flocculation of colloidal matter, transforming insoluble potash minerals into a form that is suitable for plant nutrition, creating an environment where soil bacteria can convert vegetable matter into humus, and lowering the acidity of peaty soils (Jones and Mallarino, 2018). Ground limestone is frequently added as a filler in compound fertilisers to increase weight and inhibit caking. However, limestone is only utilised as a carrier when making calcium ammonium nitrate fertiliser. Additionally, grease and silica bricks are made from limestone, which helps raise crop yields and improve soil quality (Santos *et al.,* 2020).

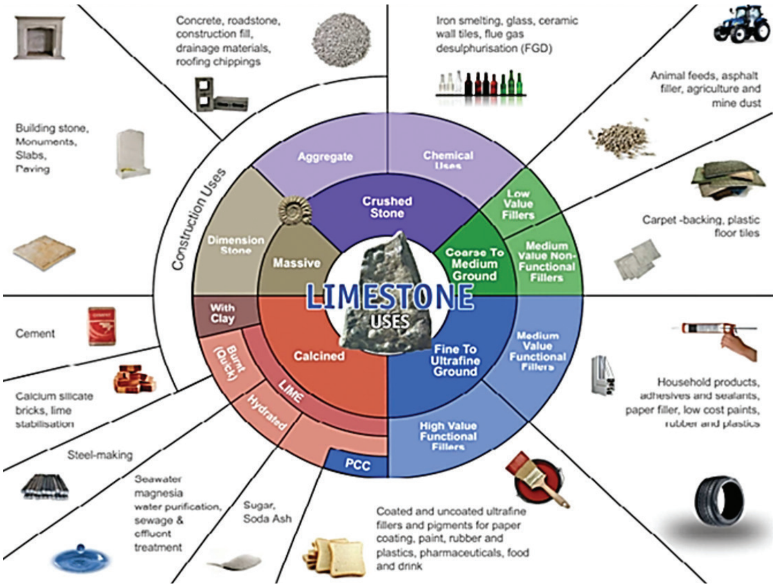

Figure 6: Representation of the various limestone applications in one picture

Limestone resources have economic worth that goes beyond their use in industry; they also support the growth of regional infrastructure and economies (Limestone coast economic diversification, 2012). Initiatives aimed at developing infrastructure, economic planning, and sustainable resource management all depend on an understanding of the distribution and geological characteristics of limestone deposits (Wilson and Amavilah, 2007). To promote industrial growth, construction projects, and economic competitiveness on a local and global level, access to plentiful and high-quality limestone sources is essential (Sindua and Kaihatu, 2022). The above discourse highlights the economic importance of limestone and its diverse industrial uses (Wilson and Amavilah, 2007).

Table 2: Summary of several industrial applications of limestone

Industrial Application	Description	References
Construction Materials	The utilisation of limestone aggregates in the manufacturing of concrete, asphalt, and mortar.	(Přikryl *et al.,* 2016)
Cement Production	One of the widely used cases of limestone is in the manufacture of cement, the importance of cement made from limestone in the construction sector is that it is very durable and resistant to erosion.	(Fauzi, Sidek and Ridzuan, 2020)
Steel Manufacturing	Using limestone as a fluxing agent in the production of steel Limestone's contribution to the purity and quality of steel product.	(Manocha and Ponchon, 2018)
Environmental Remediation	Limestone as a potential low-cost adsorbent for landfill leachate remediation; using limestone in flue gas desulfurization systems for cleaning contaminated water.	(Rosli *et al.,* 2020)
Agriculture	Using limestone in agriculture as a calcium supplement and soil amendment. The advantages of limestone for raising crop yields and soil fertility	(Bay, 2018)
Chemical and Industrial Processes	The use of limestone in the production of chemicals, pulp and paper, and refined sugar. Products made from limestone are used in a variety of industrial areas.	(Micheal and Chukwu, 2023)

The table above provides a concise overview of the wide range of industrial applications in which limestone is essential. Limestone is extremely versatile and can be used in a wide range of chemical and industrial processes, from creating cement and building materials to producing steel, environmental remediation, agriculture, and more. Its extensive use in many industries, which promotes infrastructure growth, environmental sustainability, agricultural production, and manufacturing efficiency, highlights its significance.

8.0 CONCLUSION

The present work has offered a thorough analysis of limestone, encompassing its wide range of industrial uses and geological significance. We highlighted the importance of limestone in Earth's past by talking about its creation processes, fossil content, and paleoenvironmental markers. We also examined its significance in several industrial areas, such as chemical processing, agriculture, environmental clean-up, steel manufacture, cement production, and building.

In geology, industry, and the environment, limestone is extremely important. In terms of geology, it is an essential part of sedimentary rock formations, providing information on historical climatic and environmental circumstances. Limestone is vital to manufacturing cement, steel, building materials, and other products. In terms of the environment, it supports soil health, carbon sequestration, and remediation initiatives, all promoting sustainability and ecosystem health.

Studies should concentrate on expanding our knowledge of the geological processes, fossil content, and environmental effects of limestone. Sustainable development, resource efficiency, and environmentally friendly technologies ought to be the top priorities for industrial operations to reduce environmental damage and encourage the ethical extraction and use of natural resources. We can ensure limestone's long-term sustainability and conservation while optimising its benefits by integrating geological knowledge with cutting-edge industrial practices.

9.0 KEY FINDINGS AND INSIGHTS

Limestone is a sedimentary rock that is a vital repository for Earth's historical records, including fossils and paleoenvironmental markers. Its creation mechanisms, including the deposit of the remnants of marine life and chemical precipitation, provide important climatic and environmental insights. Limestone has a wide range of industrial uses, including the production of cement, steel, building materials, environmental remediation, agriculture, and chemical processes.

Moreover, the geological characteristics of limestone serve as a fundamental basis for numerous industrial industries. Limestone, being a readily accessible and plentiful resource, plays a vital role as a fundamental element in the manufacturing, agriculture, and building sectors. The physical and chemical qualities of this substance are determined by its geological origins, making it crucial for uses such as cement manufacture and soil amendment. Comprehending the geological importance of limestone is crucial for managing resources sustainably and being responsible for the environment. This knowledge helps in making informed choices regarding its extraction, use, and influence on ecosystems. Through the examination of its geological origins, we gain knowledge about its functions within Earth's systems and its impact on industrial processes and human communities, highlighting its ongoing significance in various domains of science and society.

In summary, limestone's diverse economic uses and rich geological history highlight its ongoing importance for Earth sciences and human advancement. We can take advantage of limestone's potential to further scientific understanding, boost economic expansion, and encourage environmental stewardship for future generations by acknowledging and sensibly utilising its significance. ■

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