

Chapter 2

Building Stones

Siegfried Siegesmund and Ákos Török

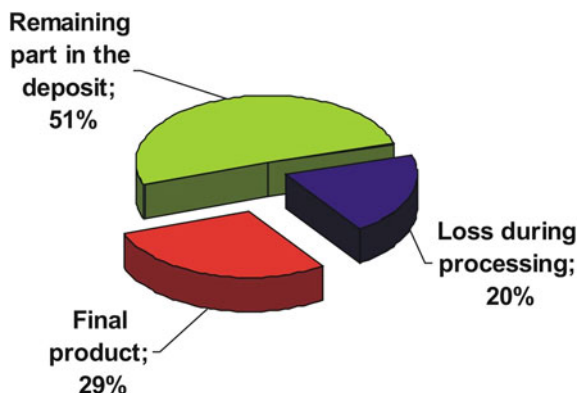
Abstract Most historic structures and many of our recent buildings have been constructed from natural stone. This chapter gives an overview of available natural stone resources and trends in building stone extraction. It documents the various uses of stone from an architectural point of view, showing historic and recent examples in more than a hundred color photos depicting construction periods from prehistoric to recent times. Besides describing the uses of stone, the chapter also provides information on the main rock-forming minerals, their properties and classification, which enables an easier identification of the various stones. Richly illustrated sections outline the main rock groups from igneous and metamorphic to sedimentary rocks, allowing the reader to understand their origin, to recognize various rock types and compare their potential use. Fabric differences, colors, shades and tints of stones and their appearance on facades are also illustrated, helping the reader to distinguish between various types of commercially sold “granites” and “marbles”. By providing detailed descriptions of most stone types with an explanation on their origin, mineralogy, fabric and their potential application, the chapter clarifies the misuse of commercial names and the improper use of stone in engineering and architectural practice. This is often derived from the misidentification of available stones and limited knowledge of stone properties.

2.1 Building Stones as a Natural Resource

Since time immemorial, natural building stones have been considered a valuable and essential part of the building industry. The constructions and monuments that have been created bear witness to extraordinary technical and artistic achievements.

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Fig. 2.1 Worldwide exploitation of natural building stones and the proportion of finished product versus stone resources (after Montani 2003)



In the last several decades, new technologies have led to considerable advances in the excavation and further processing of natural building stones. The possibilities offered by modern design for creating aesthetic interiors and exterior façades have lead to a greater demand in recent years. The forecast for net production has arisen from a continuous production increase, whereby the production volume doubled every 10 years (Montani 2003) until 2008, when economic crises led to a drop in stone production by approximately 40 %. These changes in economic growth bring into question the sustainability of economical stone quarrying and processing. In the future, new deposits have to be developed while older deposits have to be expanded with regard to existing inventories.

The profitability of a deposit is defined by the relationship between the exploitable rock resources (dimension stone) and the non-exploitable rock material (overburden). According to Montani (2003), only a third of the exploited raw material reaches the global market as a finished product, considering the worldwide average in the excavation of natural building stones (Fig. 2.1). From the quarried materials, 51 % occurs as overburden in the deposit as well as 20 % resulting from the loss due to cutting, which is used in the stone industry for further processing. In the future, there will be a great demand for natural building stones. To realize this, more geologic exploration is essential. Detailed surveys and assessments of geological conditions are a necessity in order to utilize a deposit in an optimal way and to ensure sustainable resource protection. In many cases, adequate geological evaluations are missing or non-existent. Indispensable for the development of a deposit is the information on the specific rock formation, its spatial orientation and extent, the depth of the deposit, and characteristics of the overlying rock strata. In addition to large-scale reconnaissance surveys, more precise knowledge is required on factors that can determine the deposit. Knowing these factors has an effect on the respective sizes of the dimension stones and the types of excavation, which, in the final analysis, can determine the quality and quantity of good,

defect-free excavated raw blocks (Mosch 2009). The joint system here plays an important role. The system describes all planar elements that dissect the rock body into individual blocks known as in-situ blocks (Lu and Latham 1999). Disregarding these factors often results in a considerable and avoidable loss during the excavation of dimension stones.

Natural building stones are defined according to EN 12670 (2001) as natural resource rock with use in construction and for the restoration and reconstruction of monuments, where they have a wide range of applications on the international market. They can be used as load bearing elements or for ornamental and decorative elements, e.g. cladding panels or sculptures. The multifaceted possible uses generate a high demand for this resource so that, in the last 30 years, a clear positive balance has been maintained in the production of natural building stones. According to Mosch (2009), three basic quality grades can be differentiated in general for natural building stones: (1) individual blocks, (2) gravestone sector, and (3) building industry (see also Sousa 2010).

The highest requirements are placed on the individual blocks, which are used, for example, in sculptures. A complete homogeneity in color and decor or even special individual needs of the ultimate buyer has to be guaranteed, whereby a very high price is reached in general. In the gravestone sector, a flawless petrography and structural formation of the stone is generally expected. The third grade encompasses all the qualities that are applied in the building industry. A further classification corresponding to the physical and technical construction properties of the materials is possible, which ultimately can be used to determine potential areas of application for the stone (Mosch 2009).

Over the ages, exploitation methods of natural building stones have changed significantly. First, wood edges were watered and the expansion of wood allowed the splitting of larger blocks. This technique is well known from ancient Egypt (Fig. 2.2a). Stone tools were also used, but these were later replaced by metal tools such as chisels and hammers in the exploitation (Shadmon 1989). Handwork and traditional exploitation techniques are still common in the developing world due to low labor costs (Fig. 2.2b). With industrialization, the quarrying techniques have developed significantly, and drilling and cutting equipment is in everyday use (Fig. 2.2c and d). Gang-saw and other techniques allow the exploitation of very large blocks and reducing of block size at quarry level (Fig. 2.2e and f).

The identification of natural stone reserves and the occurrence of stones in nature can be very different in terms of scenery and size (Fig. 2.3a–d). Deposits stretching in small mountains such as the Carrara Marble (Fig. 2.3a) are the most common, but smaller reserves such as boulders are also exploitable (Fig. 2.3b). In contrast, the decorative aspects of stones already become visible at outcrop scale (Fig. 2.3c); however, these are most evident after processing.

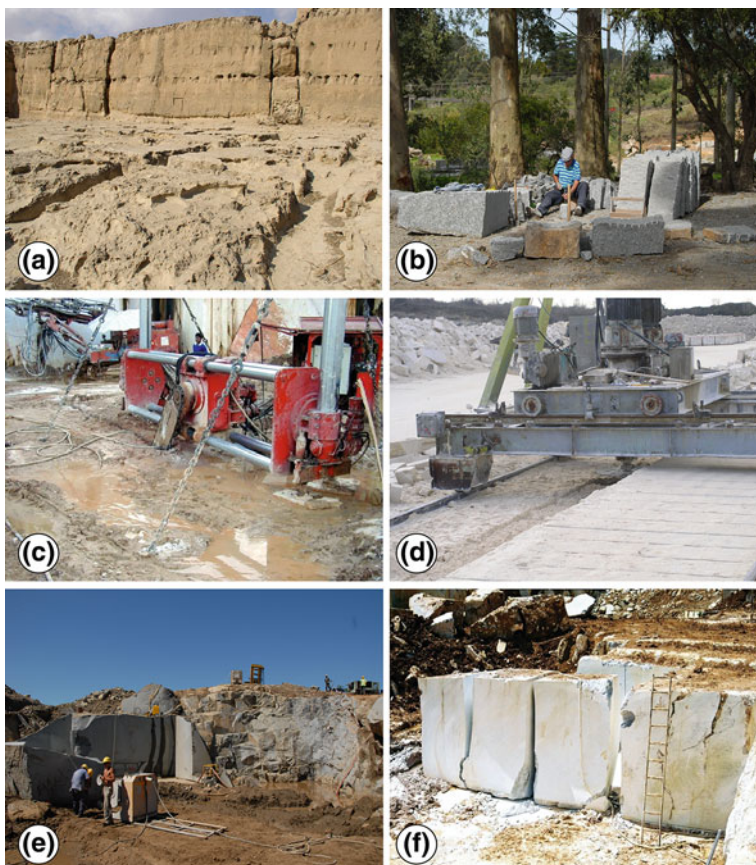


Fig. 2.2 Methods of stone exploitation from the past to present: **a** Prehistoric traces of the use of wood edges to cut the stone (Egypt, Giza), **b** Manual splitting of granite in Uruguay, **c** Drill hole aided extraction, **d** The use of a saw for the extraction of soft porous limestone (Sósokút, Hungary), **e** In-situ gang-saw cutting for stone extraction in the dolerites in Uruguay, and **f** Reducing of the block size at the quarry level (Thailand)

2.2 The Natural Building Stone Market

The building stone industry is part of an important branch in the field of natural resource exploitation in more than 50 countries. Asia and Europe are leaders in the worldwide production of natural building stones (Fig. 2.4).

The European part of dimension stone production amounts to about 38 % and lies behind the Asian states, which manufactured around 50 % of the world production of building stones in 2004 (Montani 2005). The remaining 22 % of world production is distributed across North and South America, Africa, and Oceania. About 75 % of worldwide excavated dimension stones are sustained by 12 countries, which generate a yearly production of >1 Mt of natural building stones.

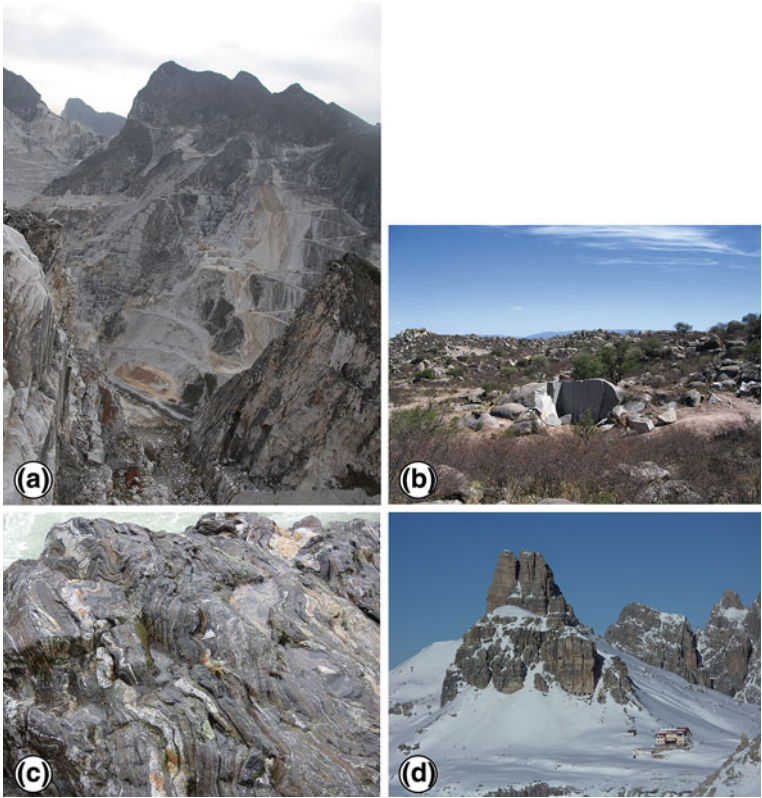
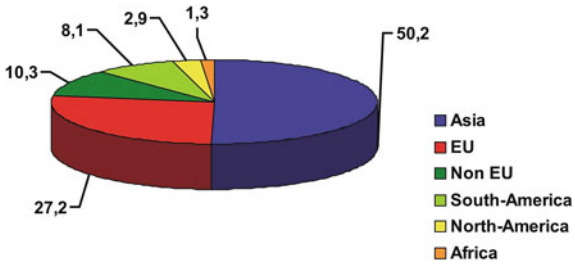


Fig. 2.3 Occurrence of stones in the field: **a** Marble quarries in the Carrara district, **b** Boulder fields of migmatites due to surface weathering in the Cordoba region (Argentina), **c** Outcrop of migmatites with intense folding in the Ivrea-Zone (Italy), and **d** Steep well bedded and fractured dolomite cliffs (Dolomites, Italy)

Fig. 2.4 The percentage of stone production with respect to continents in a more general overview (after Montani 2005)



Six of these top producers are European states, with five of them belonging to the European Union (Fig. 2.5). Four producers are in Asia, two are in America, and one is native to Africa. In descending order, export figures of China, Italy, India, Spain, Brazil, and Portugal were able to sell more than 1 Mt of material on the

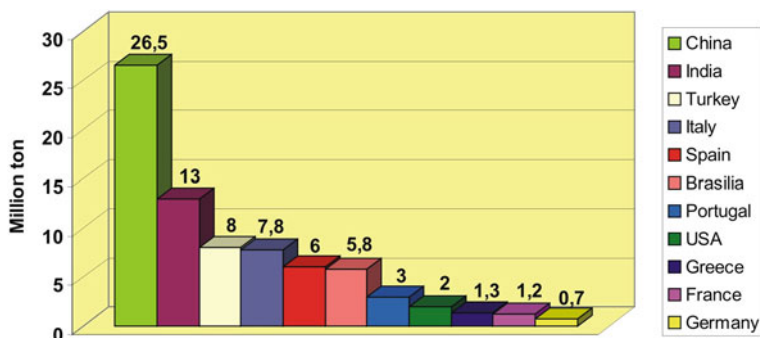


Fig. 2.5 Leading nations in the production of dimension stones and the amount of stone produced in millions of tons (after Montani 2008)

international market. China is the main stone exporter with 11.8 million tons of export in 2008. The leading position of importing countries includes, among others, Germany, Italy, China, and even Spain. The fact that the three latter countries are also situated as leading exporters clearly demonstrates the dominance they have in the international building stone market. Besides the high production rates, these countries also import large amounts of raw materials and semi-finished products, which is the reason why they can cover the various demands of the market through individual and flexible finished products.

Significant economic regions of the European natural stone industry are located mainly in southern Europe with its direct connection to the Mediterranean Sea. Countries like Italy, Spain, Portugal, and Greece cover around 90 % of EU production (European Commission 1998). This is due to the advantageous conditions of regional geology and the long tradition these countries have in the field of natural stone manufacturing. Besides other traditional natural building stone manufacturers, such as Scandinavian countries, both the Czech Republic and Poland have established themselves in the dimension stone sector (Montani 2003). The European contribution to worldwide natural building stone production has declined in the last several years. The overriding cause of this decline is the high production amount and the current processing capacities in countries such as China, India, Brazil, and South Korea, which are also characterized by distinctly lower labor costs (Terezopoulos 2004). Especially impressive is the growth rate of Asian natural building stone production, which is being continuously introduced into the international market. During the 1990s, China concentrated on increasing the exploitation capacity of its deposits and, furthermore, acquired large amounts of raw material from India, Brazil, South Africa, and Norway for processing. Today, China is in a unique position in the Asian region with regards to the large supply of finished products it has to offer from material acquired abroad and from its own deposits. Due to its favorable geographical position near the Pacific Ocean and other sea routes, China has found stable and profitable markets. These include markets in Europe, the West Coast of the USA, and the Middle East, which only played a subordinate role in

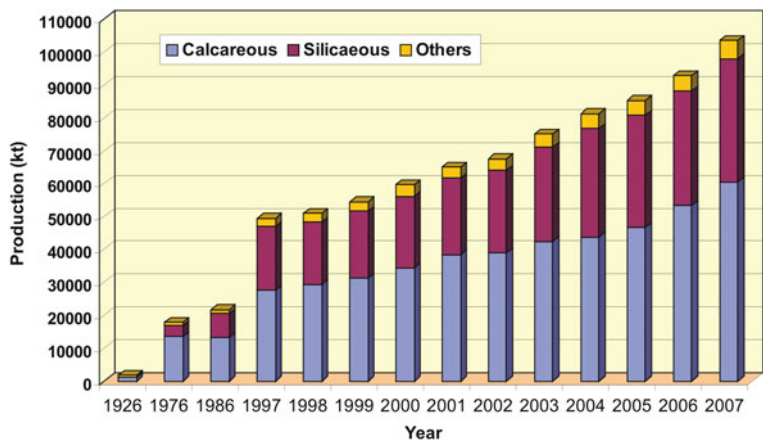
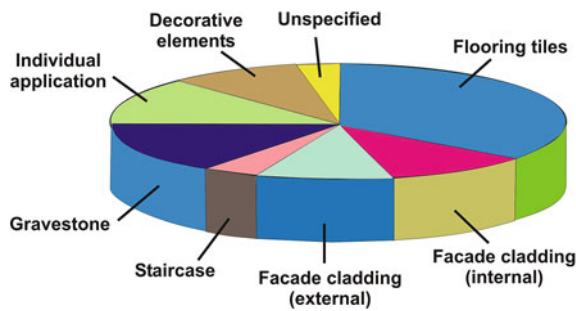


Fig. 2.6 The proportion of major lithotypes in stone production

Fig. 2.7 Different uses of stones and their proportion (modified after Hoffmann 2007)



international trade until a couple of years ago (Bruno and Paspaliaris 2004). The production of ornamental stones was 91.6 million tons in 2007. In terms of various stone types, calcareous stones are the most widely used ones, while other lithologies, such as siliceous stones, are less common in the stone industry (Fig. 2.6).

Natural building stone products range from unfinished raw blocks to semi-finished goods up to polished and refined dimensional stone that can be used for various applications. The building industry processes about 70–75 % (Primavori 1999; Founti 2004) of worldwide exploitable natural resources. These go into the creation of tiles, cladding panels, stairs, or other architectural elements and, thereby, represent the most extensive field for the application of natural stones (Fig. 2.7). Although the construction industry started to replace natural building stones with steel, concrete, glass, artificial stone, and brick over the last three decades, these alternative products could not completely stop the demand for these natural resources. The continuous demand for natural building stones is probably due to the high quality of their appearance, their architectural variability, and their prestigious character, which is evident in many public institutions and representative buildings all over the world (Fig. 2.8).

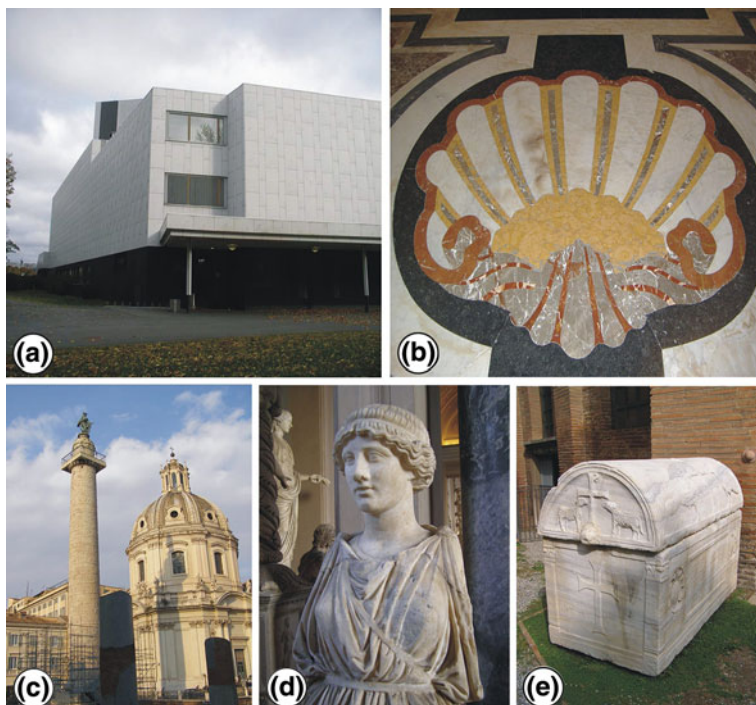


Fig. 2.8 Various uses of stones: **a** External cladding with Carrara marble (Finlandia Palace, Helsinki), **b** Interior flooring (St. Stephan's basilica, Vatican-Rome), **c** Roman stone column (Ravenna, Italy), **d** Marble sculpture (Vatican), and **e** Sarcophagus (Roman period, Ravenna, Italy)

Another consumer of relatively large amounts of natural building stone is the gravestone sector, which processes about 15 % of world production. The gravestone industry prefers semi-finished products in the form of small blocks that can be further processed for individual purposes. In the fields of urban development and craftwork, natural building stones essentially fulfill a functional and/or decorative aspect or add to conservation measures within the framework of protection and preservation of the cultural heritage.

The amount of building stones needed cannot be supplied by existing quarries. Therefore, if the current trend of natural stone use continues, it is imperative that the deposits be managed in a more economically efficient way and expanded with regards to existing inventories. In order to meet the current predictions for the demand of natural building stone, it becomes indispensable that new deposits be developed and exploited. For this, sufficient geological assessments and a basis for planning is absolutely necessary. Architects have two choices, either using dimension stones or returning to artificial stones.

2.3 Architects Point of View

The oldest manifestations of human civilization are undoubtedly connected to the history of grandiose constructions and monumental depictions in stone, which have fascinated architects and sculptors in all cultures (see [Chap. 1](#)). From a design point of view, natural building stones stand for tradition in contrast to the glass and steel that embodies technical progress. The historical examples, and even the present debate on natural building stones, verify that these structures also stand for a demonstration of power, permanence, and representation ([Fig. 2.9](#)). Many successful examples show that natural stone, one of the oldest construction materials in the world, is still being used in modern architecture and is a popular facing material of the 21st century. There is hardly a bank, insurance company, or headquarters of a large corporation that does not utilize this material to decorate their buildings.

Natural building stones, with their different colors and structural variations that change their appearance with varying weather and light, have always fascinated man. Stones always convey a message of eternity. They are unique materials and are enjoying a surprising renaissance today. Due to globalization, thousands of different kinds of dimensional stones exist on the market, and their numbers are rising because they are being used in most countries in the world. Even in modern architecture, where steel, glass, and pre-cast concrete elements epitomize the dominant materials, it is the decorative stones that will characterize the buildings.

Many architects and building owners are increasingly making the decision to use stone cladding façade elements or stone for interior work. Not to be underestimated is the use of natural building stones in urban planning—for example, in garden and landscape architecture as well as in wellness areas. The choice of the right material represents a major challenge. For the selection of the proper stone from an architectural point of view, aesthetics and fashion are important. These cannot be easily expressed in numerical values or in diagrams. However, certain physical and technical properties of stones need to be assessed or measured to fulfill the requirements of durability and long-term stability of the stone structure. Often, the stone is reduced to its interplay of color, which is without a doubt an important sensory perception in human beings. With regard to the choice of material, building owners and architects focus their vision first on the color. It is for this reason that natural building stone dealers use color as the preference for naming their stones (Verde (Green) Andeer, Azul (Blue) Macauba, Verde (Green) Ubatuba, Rosso (Red) Verona, etc.). There is a great variety of stone types that have the same color or similar shade or hue. Red colored stones are found in sedimentary, igneous, and metamorphic rocks ([Fig. 2.10](#)). The same applies for bluish ([Fig. 2.11](#)) and greenish ones ([Fig. 2.12](#)). The use of stone of different colors can give a very different appearance to the same façade ([Figs. 2.10, 2.11, 2.12](#)). Apart from color, the most important role is also played by structural patterns (i.e. the macroscopic appearance). Color and decor is the result of geologically complex processes. On the basis of the diverse decor properties, the



Fig. 2.9 Architectural and historical uses of stones: **a** Megalithic temples of Malta (app. 2500–3200 years BP), **b** Pyramids of Giza, **c** The Acropolis (Athens), and **d** Forum Romanum (Rome)

natural stone is also given a sensual quality, which is accentuated by different surface treatments and finishes.

Color, as used in architecture, is one of the most characteristic and visible aspects of natural stones. An almost infinite choice of colors and décors of natural stones exists, which determines the macroscopic appearance of stones. The color may be due to the presence of so-called idiochromatic minerals or natural pigmentation due to organic or inorganic inclusions and particles. Apart from the influence of color, the macroscopic appearance of stones is fundamentally defined by the fabric (i.e. texture) and, finally, by rock-forming geological processes. Moreover, the aesthetic value of stones and their décors are highly variable due to an increasing amount of surface treatment.

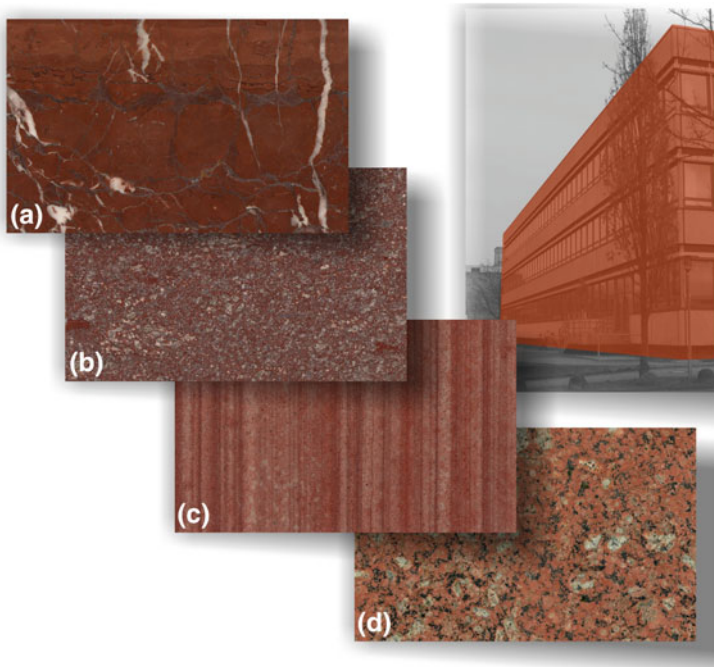


Fig. 2.10 Collection of red stones compiled exclusively on the basis of color. The different rock types originated under different conditions: **a** Compact limestone, **b** Rhyolite, **c** Sandstone, and **d** Syenite. The rocks are completely different with respect to their technical properties and with respect to their constructional applications (Figure by Natursteinarchiv Wunsiedel)

2.4 Confusion Caused by Commercial Names

In the international stone market, a large number of commercial varieties are recognized, whereby a steady increase is observable with progressive globalization. For example, Börner and Hill (2007) collected 13,677 commercial varieties. This large number shows that a great variety of rocks are available on the open market which covers an immense spectrum of colors and decors. The basic problem of this diversity is the arbitrary choice of a commercial or trade name. Therefore, the naming of the stone can result in a complete falsification of the stone's true designation. A good example is the well-known micritic limestone from Belgium, which uses the trade name of Belgian Granite. Sometimes, identical stones are sold under different trade names. Börner and Hill (2007) have shown that the Granite G603 from China is listed on the international market with 67 synonymous terms, e.g. China Sardinia, Padang White, Silverstar, Palace Grey, etc. Some stone introduced internationally astounds with its aesthetic constancy over long periods of time, like the variety Balmoral, which looks the same today as it did before 1900.

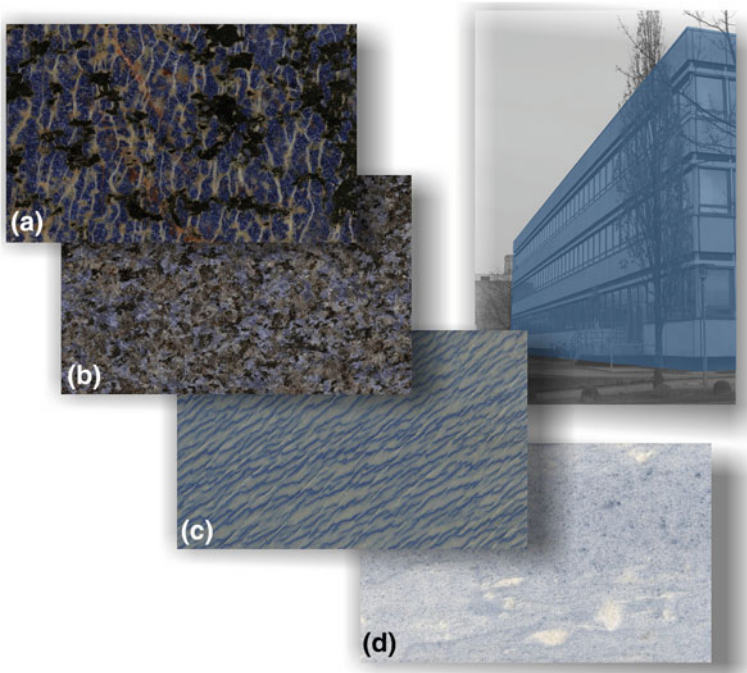


Fig. 2.11 Bluish stones collected with respect to color: **a** and **b** igneous rocks, **c** and **d** are metamorphic rocks; **c** quartzite and **d** marble (Figure by Natursteinarchiv Wunsiedel)

A rock like Verde Guatemala, which is actually a chlorite schist from Guatemala, is also listed in databases as a serpentinite from India. This situation results from the fact that the original deposit in Guatemala is exhausted and the original trade name has been transferred to the Indian serpentinite. Confusion like this, which may also be intentional, leads to a distortion of the market. When an architect or building owner chooses a pattern for construction, it is not always possible to know whether the stone designation is really valid or corresponds to the true trade name. Architects and planners can become irritated, and competitors can even be eliminated. When a stone is praised and published under the trademark name of Porfido Kern® from Trentino (Italy), one comes to the realization that this term is largely unknown in the technical literature. Müller (1996) points out that the naming of natural stones is combined with fantasy names such as Royal, Imperial, Fantastico, Oriental, Oro, Argento, Korall, Christal, and Multicolor, among others. The naming of the stones is done to characterize the material as “noble”, “extraordinary”, “royal”, “unique”, etc. Porfido Kern® from Trentino would represent an especially hard and “healthy” stone.

In a strict sense, a Porfido Kern® is not a variety or assortment, but basically an internal company designation with specific quality characteristics. The porphyry handbook (Tomio and Filippi 1996) describes the stone as an extrusive ignimbrite

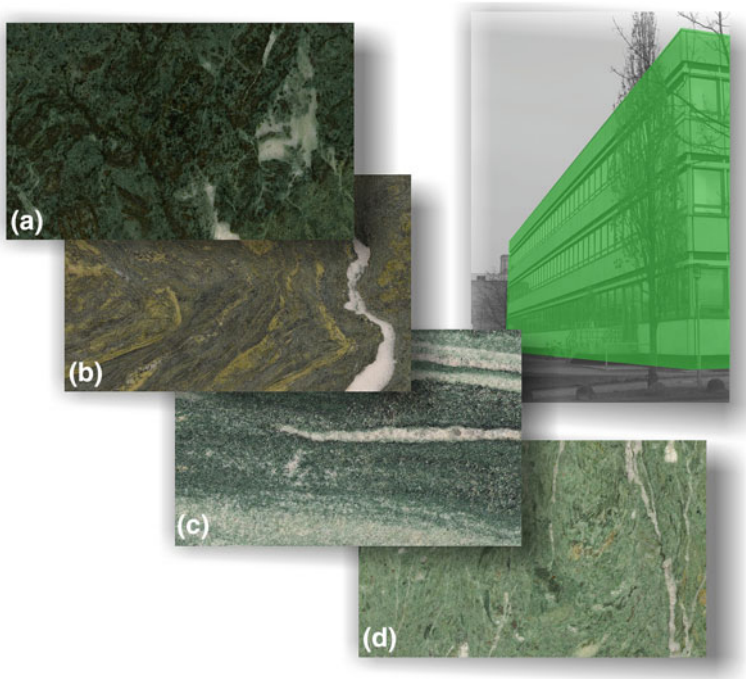


Fig. 2.12 Greenish stones with a very different origin showing comparable colors (see also Fig. 2.10): **a** Serpentine, **b** Chlorite schist, **c** Gneiss, and **d** Dolomitic marble (Figure by Natursteinarchiv Wunsiedel)

rock originating from the region of Trentino in Southern Tyrol (Italy). This is, of course, misleading since porphyry occurs worldwide and is found in all geologic time periods. In the EN 12670 titled “Terminology of Natural Stones”, no description of the stone Porfido Kern[®] is listed. The term “porphyry” is defined as the following according to the “Terminology of Natural Stones” No. 3.569: “Designation for all rocks solidified from a melt containing conspicuous phenocrysts in a fine-grained matrix. The resulting fabric is described as porphyritic”. In the European market, a standard for the designation of natural stones already exists. From the EN 12440 titled “Natural Stones: Criteria for the Designation”, the description of natural stones should contain the trade name, the petrographic affiliation, the typical color, the place of origin, and, if possible, the type of surface treatment, the natural properties, the petrographic name, and the geologic age when applicable (Table 2.1).

The term “marble” is also used differently. Ever since antiquity and even today, the natural stone industry has designated most polishable and attractive rocks as marble. Occasionally, even onyx and gypsum rocks (alabaster) are included under the trade name of marble. In the petrographic nomenclature (see this chapter), the term “marble” is restricted to carbonate rocks formed by metamorphic processes.

Table 2.1 Commercial names of dimensional stones in comparison to their petrographic designation

Commercial name	Petrographic designation
Azul Cielo	Marble
Sankt Nikolaus	Quartzite
Anröchter Dolomite	Calcareous Sandstone
Beola Calvario	Gneiss
Springbok	Quartzite
Verde Orientale	Serpentinite
Petit Granite	Limestone
Pietra Serena	Sandstone
Bardiglio	Marble
Azul Macaubas	Quartzite
Nero Impala	Gabbro
Peperino	Ignimbrite
Naxos	Marble
Halmstad	Migmatite
African Juparana	Migmatite
Verde Serpentino	Chlorite Schist
Anzola	Gabbro
Koesseine	Granite
Blue Pearl	Monzonite
Serizzo Antigorio	Gneiss
Labrador Café	Syenite
Rosso Corallo	Limestone
Rosso Taebri	Travertine
Jaune Imperial	Limestone
Torre Santa Maria	Chlorite Schist
Crema Marfil	Limestone

Within a particular stone assortment, there are varieties true to the normal appearance and ones with different colors. Therefore, Azul Macauba can appear totally white, pale blue, and intense blue. Azul Bahia, one of the most expensive decorative stones, which lies near the petrogenetic field of sodalite-foid syenite to sodalite-foiolite, is frequently traded on the international stone market as granite. Hill (2007) delineated a trade chain that starts with a quarry in Brazil, then moves on to a stone block dealer, and finally reaches Italy for further processing. The processing into untailored slabs and formatting for floors, stairways, or other coverings for export to Germany, e.g. through distributors and sales to craftsmen, creates a very long trade chain. Significant misunderstandings can occur along the trade path because of differences due to language translations. Moreover, complications due to different climatic conditions in the country of origin may cause problems in the country where the material will be used. In the country where the construction site is located, weather conditions can induce freeze/thaw cycles, or the use of corrosive salts for de-icing can lead to negative consequences for the usage properties.

Even the question of color deviations for specific groups of natural stones like “Labrador scuro”, which is sometimes designated a marble, is critical when it is based only on the trade name. According to the EN 12440 (2000), it should be noted that the Labrador scuro is an Emerald Pearl. The number, density, and luminosity of opalescent minerals can vary greatly and, thus, the optical effects connected to them. The trade name is clearly defined and customers who order the Emerald Pearl wish to have a lively stone that is characterized by the luminosity of opalescent feldspars. In Emerald Pearl, the mineral creating the luminous effect is not a labradorite plagioclase, but an anorthoclase. The iridescence is caused by very fine exsolution in feldspar, the so-called cryptoperthite (a hardly recognizable exsolution sub-microstructure in parts of anorthoclase). These exsolution lamellae have thicknesses of about 1,000 Å. For a size comparison, it can be noted that the average thickness of a human hair is about 0.06 mm (600,000 Å). When light encounters these fine exsolution lamellae, it is refracted, reflected, and absorbed. The intensity of the reflected light can vary as a result of the dependency of the composition of the exsolution, the angle of incidence of the light ray, and the thickness of the exsolution lamellae. This then correlates to the color of the minerals or the color play, as in the case above, where it varies between red, blue, and green.

2.5 Geology of Building Stones: Terminology

Building stones are defined as those whose origins are igneous, sedimentary, and metamorphic, and which are used for construction and decoration, fill material, crushed stone, and coarse-grained grit material. In practice, these rocks are differentiated into the so-called hard and soft rocks. Hard rocks, e.g. granite, rhyolite, and basalt, are difficult to process mechanically. In contrast, soft rocks, e.g. weakly cemented sandstones, tuffs, porous limestones, and serpentinites, can usually be easily processed. Various properties characterize natural building stones. These are the physical properties, such as compressive strength, porosity, flexural strength, water absorption, and color and décor (see [Chap. 3](#)).

Rocks are composed of minerals. The rock-forming minerals are relatively few in comparison to the overall number of known minerals. Not all of the combinations and proportions of the known minerals are recognized in nature because of restrictions due to physical and chemical laws. Rocks are seldom homogenous materials, in contrast to minerals. Monomineralic rocks contain only one major mineral. Rocks such as marble or quartzite are mostly constituted by calcite/dolomite and quartz, respectively. Many rocks are also polyphase or polymineralic in composition. Granite, for example, consists of the minerals feldspar, quartz, and mica. In any case, a rock is made up of an infinite number of crystals of one or more minerals. The fabric of a rock describes its internal structure. The term “texture” is usually used in the conventional geological manner for spatial relationships between mineral grains in a rock. It includes such features as grain shape

and size and is combined with microscopic structures such as layering, xenoliths, vesicles, and orbs. The structure of a rock describes the size, the shape, and the interactive relationship (intergrowths) of the constituent minerals (e.g. grain size, grain shape, grain size distribution, etc.). Fabric deals with the crystallographic- and shape-preferred orientation, distribution, state and orientation of microfractures, shape and size of grains, their spatial distribution, relations between grains, etc., i.e. the structural elements of a rock.

2.6 Rock-Forming Minerals

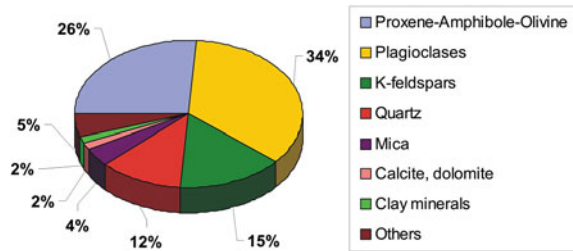
Minerals are solid substances of natural origin. As a rule, minerals have a given chemical composition; therefore, each mineral can be described by a chemical formula. Due to the differences in internal structure, one chemical formula can be attributed to more than one mineral. One example is CaCO_3 , which can have two very distinct internal structures, and, thus, it is the formula of a mineral called calcite and another mineral named aragonite. In reality, all mineral specimens have individual appearances with some containing impurities. Minerals can be further subdivided according to their internal structure. Crystalline varieties have characteristically regular internal arrangements of atoms, ions, or other compounds and form a structure called the unit cell. In contrast, amorphous mineraloids have no regular internal structure, but they are also solid. Opal is an amorphous form of silica-dioxide. Rock-forming minerals are the most widespread minerals and are the major constituents of rocks. The systematic subdivision of minerals is based on their chemical composition. Accordingly, ten major groups are known (see [Sect. 2.6.1](#)). The most common rock-forming minerals are silicates, which are compounds of silicon, oxygen, and other cations. Additional elements, such as iron, magnesium, calcium, potassium, sodium, aluminum, etc. can also form a part of silicate minerals. Besides chemical composition, minerals can also be subdivided based on their physical properties and external look, or appearance.

2.6.1 Mineral Chemistry and Classification

The distribution of minerals is controlled by the chemical composition of the Earth's crust. Only eight elements contribute approximately 99 % of the weight of the Earth's upper zones. These elements, in decreasing abundance, are oxygen (47 %), silicon (31 %), aluminum (8 %), iron (4 %), calcium (3 %), potassium (3 %), sodium (3 %), and magnesium (1 %). It is necessary to note that carbon is not in this list, although, in the processes of life, it plays a key role. The remaining other 90 elements that occur in nature are also found in minerals.

The scientific classification of minerals relies on chemical composition as well as on internal structure. Consequently, mineralogists subdivide all existing

Fig. 2.13 Frequency of the most important rock-forming minerals of the Earth's crust down to 16 km (data from Peschel 1983)



minerals into 10 groups. Many of these groups are of subordinate importance in terms of their rock-forming ability, since these also include rare or exotic minerals. The 10 groups are as follows:

1. Native elements
2. Sulphides
3. Halogenides
4. Oxides and hydroxides
5. Carbonates and nitrates
6. Borates
7. Sulphates
8. Phosphates
9. Silicates
10. Organic compounds

Of these groups, silicates are by far the most common with contributions of more than 95 % to the Earth's crust. Silicates are the major rock-forming minerals of igneous, metamorphic, and many sedimentary rocks (Fig. 2.13). The native elements are rare, and minerals such as gold or native copper belong to that group. Sulphides are minerals in which sulphur forms the major anion, while mostly metallic and submetallic minerals such as iron, zinc, copper, antimony, and lead provide the cation. Pyrite (FeS_2), galena (PbS), and sphalerite (ZnS) are probably the most common varieties from this group. Halides are minerals containing the halogen anions of chlorine, fluorine, etc. Halite (NaCl) and sylvite (KCl) are well known from this group. Fluorite (CaF_2) also belongs to this group and forms cubic crystals.

Oxides and hydroxides are not rock-forming minerals, but their importance is related to their ability to stain rocks. Iron-oxide (hematite), even if it occurs in ppm (one part per million concentration), can stain rocks red, and the same applies for iron-oxy-hydroxides (goethite, limonite) with their ability to stain rocks brown. Carbonates are key rock-forming minerals for limestones (calcite) and dolomites (dolomite) as well as marbles (calcitic or dolomitic marbles). The carbonate (CO_3^{2-}) anion can form complexes not only with Ca and Mg but also with other elements such as Mn and Fe. Calcium carbonate is known as calcite (trigonal) or aragonite (orthorhombic). Calcite has the greatest number of crystal forms of all existing minerals. Green patinas on copper or bronze structures are also related to a

copper carbonate mineral that is called malachite. For sulphates, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the most common one, but anhydrite (CaSO_4) and barite (BaSO_4) are also known.

Minerals belonging to silicates contain a basic structural unit cell, which is called the silica tetrahedron. It consists of four oxygen anions on the corners of the tetrahedron and a central silicon cation. The silicates are further subdivided according to the geometric arrangement of silica tetrahedrons. Accordingly, there are isolated tetrahedrons, linked tetrahedrons, ring-silicates, single- and double-chain silicates, sheet silicates, and framework silicates. Framework silicates are the most common ones. Quartz (SiO_2) is an oxide but, due to its structural similarity, is frequently considered together with the true silicates. Rock-forming minerals like feldspars form parts of this latter group. Feldspars are further divided into plagioclases (anorthite $\text{CaAl}_2\text{Si}_2\text{O}_8$ to albite $\text{NaAlSi}_3\text{O}_8$) and K-feldspars (e.g. orthoclase KAlSi_3O_8).

2.6.2 Mineral Physics

Physical properties play a significant role in the recognition of minerals. The most important ones are shape, color and luster, cleavage or fracture, hardness, specific gravity, and other properties such as magnetic and thermal properties, etc.

The shapes of minerals depend on the internal structure and symmetry of the minerals as well as on the available space where these minerals grow. In most rocks, we can identify idiomorphic and xenomorphic minerals. The first ones have regular shapes, while the latter ones are difficult to identify based on their irregular shapes. When a mineral grows freely, it develops special crystal forms that can be grouped into crystal systems according to their external symmetry. The seven crystal systems, in increasing symmetry, are:

- Triclinic
- Monoclinic
- Orthorhombic
- Trigonal
- Tetragonal
- Hexagonal
- Cubic

Each crystalline mineral belongs to one crystal system and, within the system, one crystal class. Within the system, there can be several morpho-types, whereby one mineral can have different crystal forms of the same symmetry. Pyrite (FeS_2), which belongs to the cubic system, can have tetrahedron, cubic, octahedron, or other crystal forms. The most common rock-forming minerals of igneous rocks are the plagioclases, which belong to the triclinic crystal system, whereas quartz and calcite reside in the trigonal crystal system.

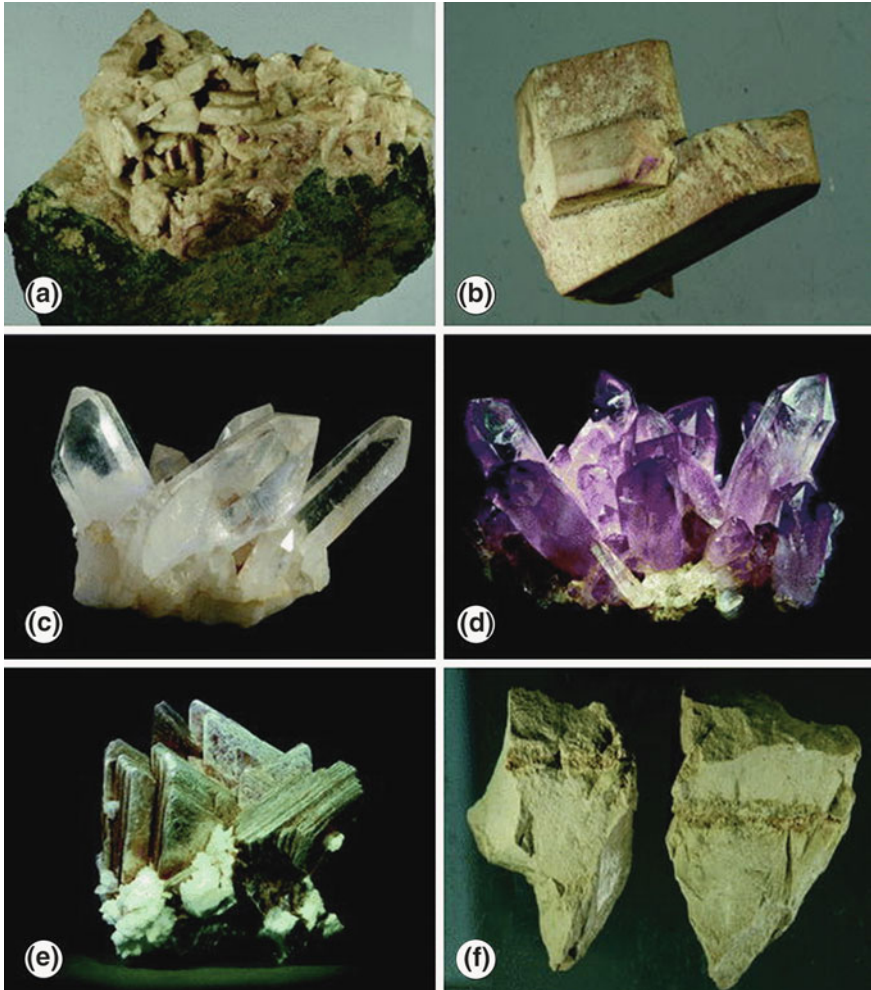


Fig. 2.14 The most common light-colored rock-forming silicate minerals are **a** Plagioclase (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **b** K-feldspar (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **c** Quartz (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **d** Amethyst, a colored gemstone variety of quartz (Figure by A. Massanek/Geowissenschaftliche Sammlungen of TU Freiberg), **e** Light-colored mica (muscovite) (Figure by A. Massanek/Geowissenschaftliche Sammlungen of TU Freiberg), and **f** Kaolinite (clay mineral) (Figure by Geowissenschaftliche Sammlung of GZG Göttingen)

The color of minerals includes all varieties of the color spectrum, but, for simplicity, minerals are named as light-colored (felsic) (Figs. 2.14 and 2.15) and dark-colored (mafic) (Fig. 2.16). Opaque minerals with a metallic luster generally have a high ability for absorbing light. These are usually ore minerals with industrial importance (Fig. 2.17a–c). Other types of light reflectance (luster)

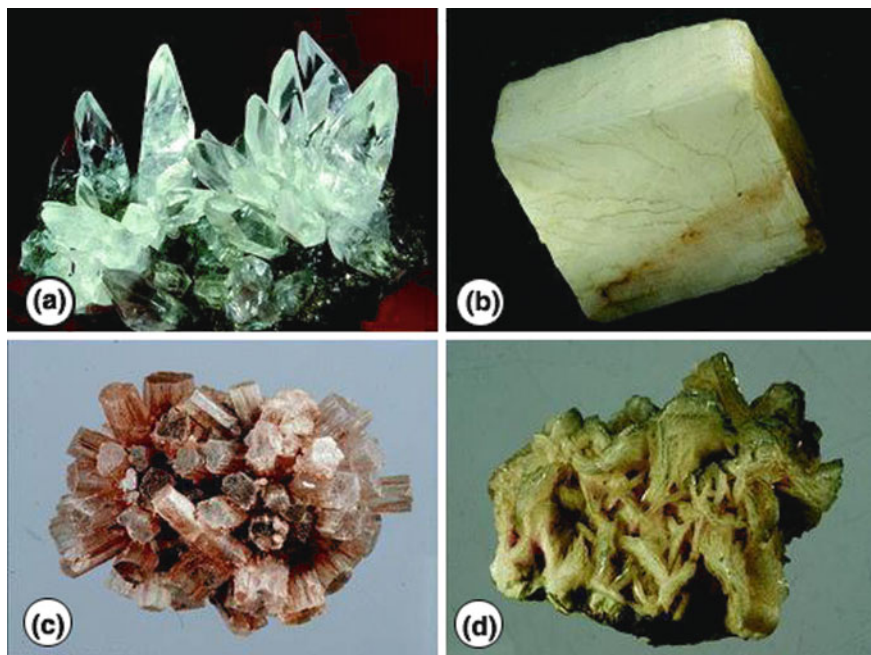


Fig. 2.15 The most common light-colored rock-forming non-silicate minerals are **a** Calcite (scalenohedral) (Figure by A. Massanek/Geowissenschaftliche Sammlungen of TU Freiberg), **b** Calcite (rhombohedral) (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **c** Aragonite (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), and **d** Dolomite

includes vitreous, greasy, pearly, earthy, etc. For some minerals, the color of the very fine powder (called streak) is also important; this is different from the color of the bulk specimen. The best example is hematite (iron oxide), which has a reddish streak, whereby the mineral is very commonly metallic black (Fig. 2.17b). A mineral can either break along an irregular surface, which is called a fracture, or it can break along a smooth plane, which is called cleavage. The cleavage plane can be smooth and shiny (perfect cleavage) or less smooth and less light reflecting (moderate cleavage). Micas, such as muscovite, exhibit perfect cleavage, whereas calcite or feldspars have good cleavage. The internal structure of the mineral influences the cleavage, since cleavage planes represent the weakest zones. As a consequence, one crystal can have several cleavage planes depending on the internal structure of the mineral. The fracture surface can also be partly regular—for example, the conchoidal fracture (smooth concentric depressions) in opal.

Hardness of minerals is generally described as scratching hardness. The measure of the scratching hardness is the Mohs scale, which is a relative scale with 10 grades. Minerals that have a Mohs hardness of 1 (e.g. graphite) are the weakest ones, whereas grade 10 (e.g. diamond) is considered to be the strongest. All grades are represented by a common mineral. Grade 2 can be scratched by a fingernail,

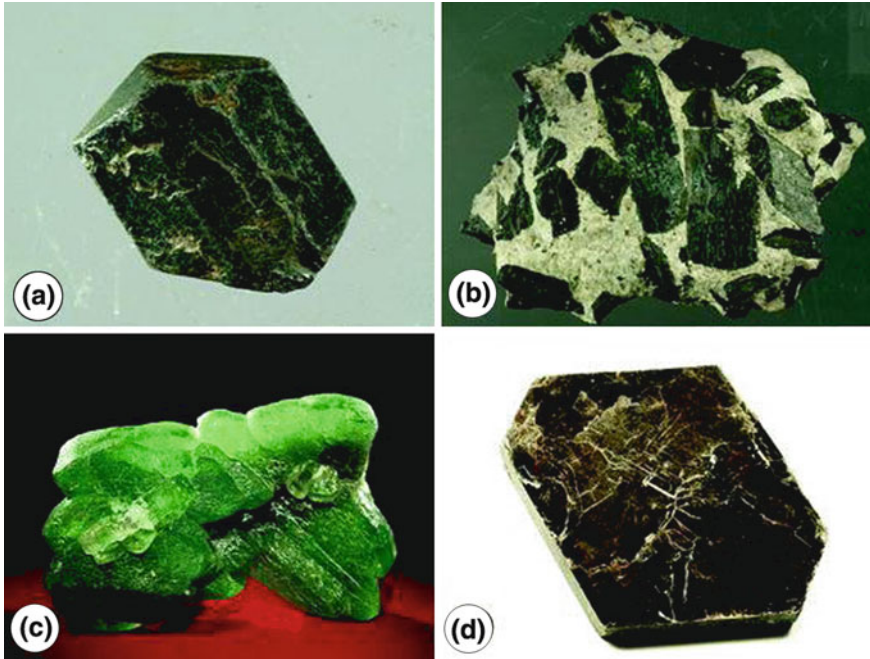


Fig. 2.16 The most common dark colored rock-forming silicate minerals are **a** Orthopyroxene (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **b** Amphibole (hornblende) (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **c** Olivine (Figure by A. Massanek/Geowissenschaftliche Sammlungen of TU Freiberg), and **d** Dark mica (biotite) (Figure by A. Massanek/Geowissenschaftliche Sammlungen of TU Freiberg)

whereas a steel knife has a hardness of 5–6. The minerals that have a Mohs hardness of 7 (e.g. quartz) or more can scratch glass.

Precious minerals are ones which are very rare and have a high aesthetic value. These can be used either in their original forms, such as gemstones (usually with high resistance and scratching hardness), or they need to be extracted and concentrated by metallurgic processing (Fig. 2.18).

The specific gravity or density of minerals is an important parameter, since it determines the weight of the rock. Dark igneous rocks with lots of heavy minerals are much heavier than a quartz sandstone or limestone.

Special properties include the magnetic ability of minerals or thermal or electrical conductivity. The optical properties of minerals are important parameters which are normally studied by using microscopic techniques. The petrographic microscope is the common tool for studying thin sections, whereas ore microscopy utilizes reflected light and can help to distinguish between non-transparent so-called opaque minerals. Transparent minerals have several key optical properties that can be used for identification. Shape, color, birefringence, and cleavage are visible under polarized light and help in the recognition of minerals.

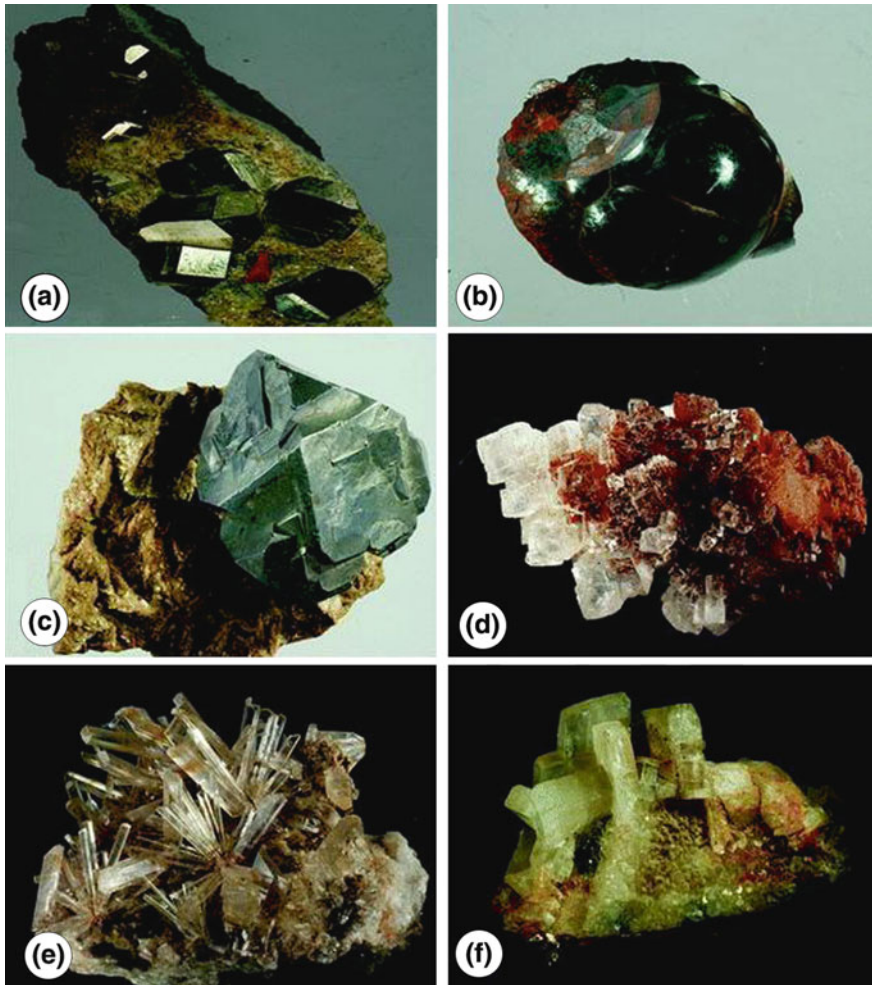


Fig. 2.17 Ore and industrial minerals. Commonly found iron minerals include **a** Pyrite and **b** Hematite. The main lead mineral is **c** Galena. Industrial use of **d** Rock salt (halite), **e** Gypsum, and **f** Barite is also important (Figure by Geowissenschaftliche Sammlung of GZG Göttingen)

2.7 Definition and Origin of Rocks

Three main rock types can be differentiated which develop under different conditions. Igneous rocks form from the cooling and solidification of magma deep in the Earth's crust, in the mantle, or at or near the surface. Thus, igneous rocks can be subdivided into plutonic (intrusive) and volcanic (extrusive) types. Small-scale intrusive bodies like dikes and sills are generally not as relevant in the exploitation of natural building stones as mountain-forming large plutonic bodies.

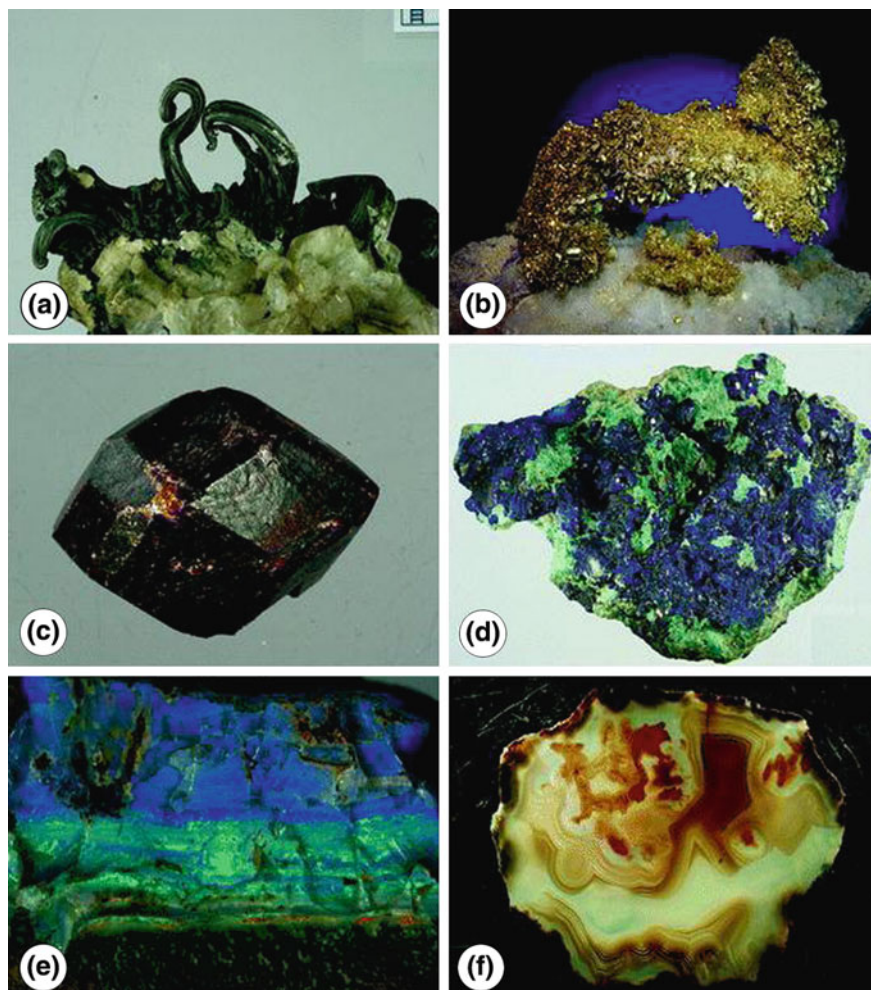
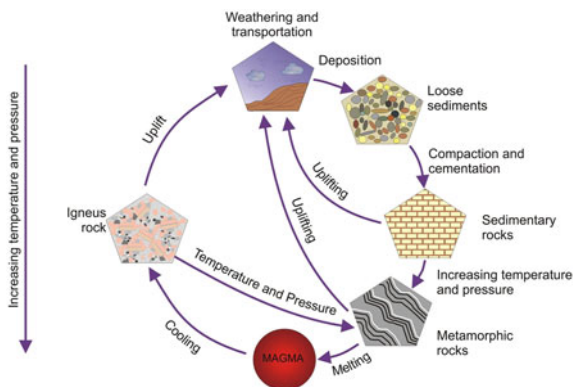


Fig. 2.18 Precious minerals or gemstones of very high value: **a** Silver (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **b** Native gold (Figure by A. Massanek/Geowissenschaftliche Sammlungen of TU Freiberg), **c** Garnet (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **d** Malachite (Figure by Geowissenschaftliche Sammlung of GZG Göttingen), **e** Opal and **f** Agate (Figure by Geowissenschaftliche Sammlung of GZG Göttingen)

Sediments and sedimentary rocks are the product of mechanical and chemical fractionation processes on a large scale. In this case, mechanical weathering or the disintegration of the original rock into smaller fragments is often the prerequisite for a deep and intense chemical segregation. Alternatively, sedimentary rocks can be formed via chemical and biological processes and can be precipitated from water (marine or freshwater, see [Sect. 2.11](#)).

Fig. 2.19 The geologic rock cycle describes the relationship of the various rock groups to each other and shows the possible pathways of the different rock types



Metamorphic rocks are formed from previously existing rock types under pressure and temperature. Metamorphism is a process whereby the mineralogical and/or structural and/or chemical composition of the rock changes under “solid state” conditions. These changes are caused by physical and/or chemical processes, which differ from weathering, cementation, and diagenesis of sedimentary rocks. Sedimentary, igneous, and even metamorphic rocks can be the source rocks which undergo metamorphism.

Different statistical calculations have been made showing the distribution of the major rock groups. In general, the major rock groups, in decreasing percentage, are: 65 % igneous, 27 % metamorphic, and 8 % sedimentary. These rock types form an interconnected geologic rock cycle (Fig. 2.19). The rocks do not last forever, and there is a cyclical development and transformation between the various rock types. The processes include the uplift of regions and exposure of igneous or metamorphic rocks, which then become prone to surface erosion and provide particles for sediments and sedimentary rocks. When sedimentary rocks are subjected to higher pressures and temperatures, they shift into the metamorphic realm, and mineral transformations begin. At greater depth, melting occurs, and both metamorphic and sedimentary rocks become parts of the magma system and the igneous province.

2.8 Rock Fabrics

In surface exposures, rocks show planar and linear structures (different types of foliation, bandings, bedding, lineations, etc.), which are often related to structures ranging from the microscopic to the macroscopic scale.

The anisotropy of rocks is produced by compositional differences as well as structural factors. In sediments, changing layers with different compositions are macroscopically easy to recognize and are generally defined as the bedding (e.g. Fig. 2.20a and b). Other important anisotropic elements are dictated by the

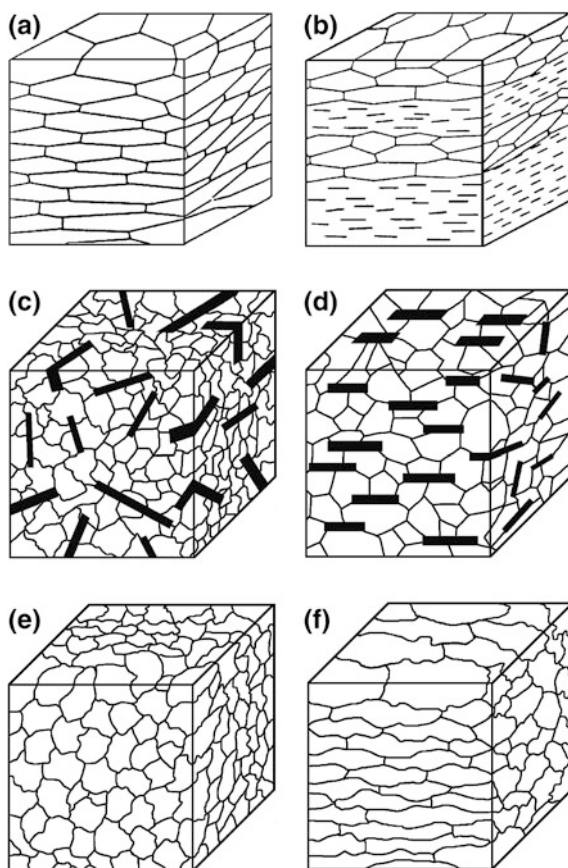


Fig. 2.20 Schematic representation of various rock fabrics: **a** Planar layering caused by shape-preferred anisotropic minerals, **b** Material-structural fabric anisotropy created by shape-preferred anisotropic minerals connected with the intercalation of different layers, and **c** Polymineralic rocks (e.g. granites) without and **d** With an arrangement of shape-anisotropic minerals (e.g. mica); monomineralic rocks (e.g. marbles) **e** Without and **f** With a shape-preferred orientation. In contrast to the equi-dimensional grains in **(e)**, the grains in **(f)** are distinctly elongated in a cigar-like way (modified from Passchier and Trouw 1996)

microfabric and are only observable in part through microscopic or physical analyses. These include the preferred orientation of mineral grains or their grain boundaries (Fig. 2.20f), in contrast to statistical grain shape orientations (Fig. 2.20e), the arrangement of microcracks, or the crystallographic preferred orientation of mineral grains, known as LPO or texture. Crystallographic preferred orientations are especially important when the arranged crystals themselves show distinct properties of anisotropy. This is the case in many rock-forming minerals.

Borradaile et al. (1982) defined foliation, whether it is spaced or continuous (s-surface in Sander's terminology), based on morphological features such as

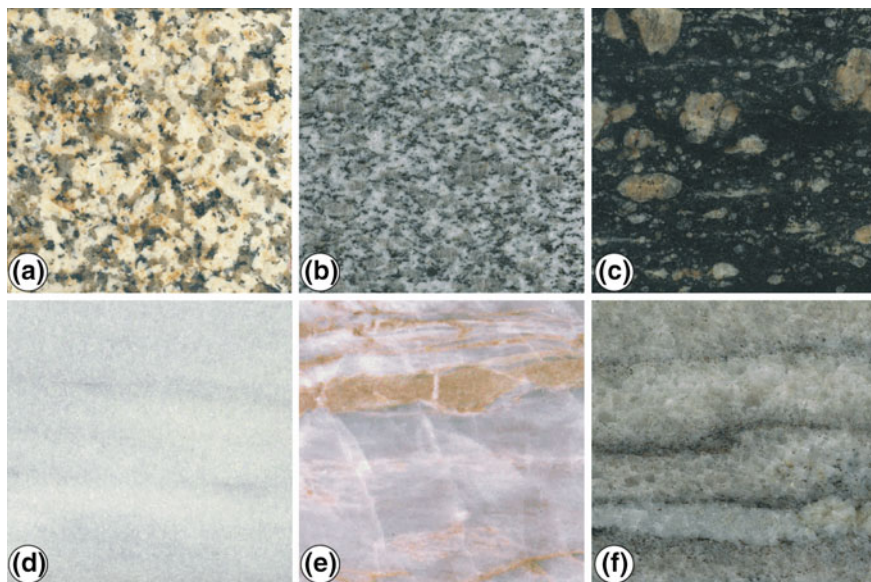


Fig. 2.21 Macroscopic fabric of various rock types with different anisotropies: **a** Waldstein Granite, **b** Riesenferner Granite, **c** Benin Granite, **d** Laas Marble, **e** Kaufinger Marble, and **f** Grosskunzendorf Marble (see explanation in text)

elongated or platy grains, compositional layers, or planar discontinuities (Fig. 2.20). A lineation is a homogeneously distributed linear structure (intersection lineation, crenulation lineation, stretching lineation, mineral lineation, groove casts in a bedding plane, etc.).

From the anisotropic elements mentioned above, the following material properties exhibit a distinct directional dependence, which is very important for the practical application of natural building stones. These include the tensile, compressive, and flexural strength, the abrasion strength, thermal properties, susceptibility to weathering, and many more (see Chap. 3).

The causes of anisotropic fabrics are complex rock-forming processes that occur over long geological time periods and are, in part, active in many cycles (Fig. 2.20). In general, this implies that the knowledge of geologic history allows certain predictions to be made in regards to the material behavior of natural building stones. The European standards EN 1341 (2006), EN 1342 (2009), and EN 1343 (2009) require the characterization of the mineral content and the fabric properties of tested natural building stone.

The generation of igneous rocks (formed from a melt) is dictated by the primary melt composition and by the prevailing geological conditions. Low viscosity melts often rise almost to the surface, where they crystallize out very quickly and where they form fine-grained and primarily and relatively weak anisotropic rocks, the most common example being basalt. Highly viscous melts, on the other hand,

remain at great crustal depths, where they can slowly crystallize out and, thus, form coarse-grained fabrics (the most common varieties are granite and similar rocks, see Fig. 2.21). Plutonic rocks show a strong tendency to develop primary anisotropic fabrics. These fabrics can originate when minerals crystallize out early and descend by “sedimentation” in the magma chamber, where cyclical processes can lead to compositional layering. During the deposition of the individual crystals, shaped-preferred orientations and textures can develop simultaneously. However, these granitic rocks often show a macroscopic isotropic fabric, but only by microscopic observation are the distinct anisotropies recognizable.

The erosion of older rocks supplies the materials for sediments (see Sect. 2.11). For almost all sediments, the significant and typical anisotropic element is the bedding (e.g. Fig. 2.20a and b), which develops during the deposition of the supplied material or through changing (and in part cyclical) depositional conditions. In clastic sediments, these changes can be in the types of minerals, grain sizes, and alternating water current velocities at the site of deposition. Another means of generating anisotropies in sediments can take place during diagenesis. In this process, the sediments undergo change with increasing pressure and temperature, which occurs during burial at great depth. Solidification of the sediments takes place essentially through mechanical compaction, dewatering, and mineralization in the pore spaces (cementation). Thus, deposits of sand change into sandstones and calcareous particles, and calcareous muds become limestones. The anisotropy strengthens during compaction, and mineral grains become elongated. Their long axes rotate perpendicularly to the direction of pressure, leading to a shape-preferred orientation. Furthermore, the solution/precipitation of materials can lead to a compositional dissociation, whereby the primary bedding becomes more accentuated and mechanically more significant.

Igneous and sedimentary rocks can be subjected to metamorphism by high pressure and/or temperatures (see Sect. 2.10). In this situation, minerals, some of which are no longer stable in these conditions, become transformed, and a recrystallization of stable minerals can also occur. Moreover, at high temperatures, many rock-forming minerals undergo plastic deformation very easily so that a directed pressure at great crustal depths causes an elongation of the shape, and, thus, a stronger, shape-preferred orientation/anisotropy occurs. Likewise, the newly formed minerals also grow in a preferred way perpendicularly to the main stress direction. Both shape-preferred processes result in an easily recognizable planar fabric (also known as schistosity), which is typical for the important and characteristic metamorphic rocks such as gneisses and mica schists. Through the complex interactions between the plastic deformation and recrystallization that develops during metamorphism, a further anisotropic element arises leading to crystallographic-preferred orientations in the rock-forming minerals.

Rocks that have passed through great depths in the course of their geological history and have essentially received their fabric structure during this period experience extreme stress release and cooling as a result of crustal uplift and the erosion of the overlying rock. This is especially true for plutonic and metamorphic rocks. Through elastic relaxation and thermal shrinkage, these rocks develop large

internal stresses, which, as a rule, lead to pronounced microcrack formation (Vollbrecht et al. 1991, 1993). These microcracks mostly occur in different generations, which show a distinct preferred orientation and, thus, represent a further anisotropic fabric element. When some of these microcracks coalesce, a macroscopic joint pattern often develops. In rock quarries, this jointing pattern is the deciding economic factor for the exploitation of raw blocks, which, for economic reasons, should not be below a certain minimum size (Mosch et al. 2010).

2.8.1 Fabric Parameters

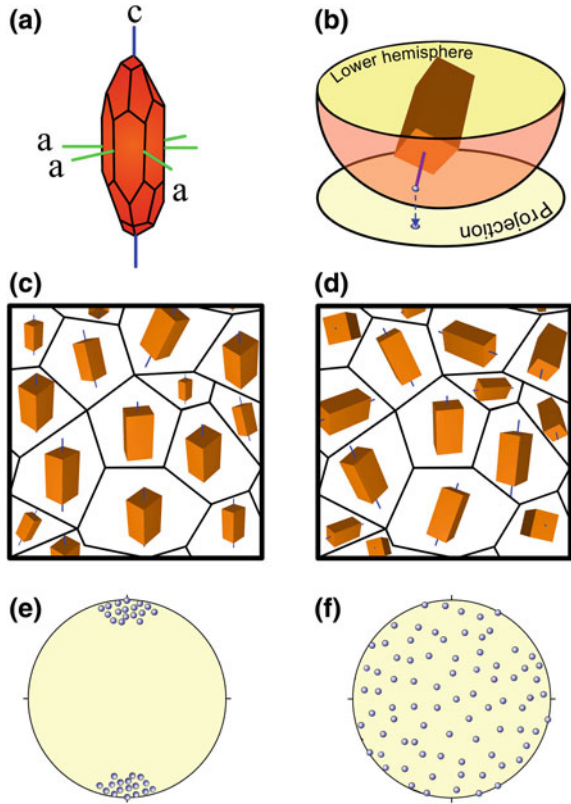
In the following section, important fabric parameters for selected natural building stones in consideration of the anisotropic elements will be presented in order to demonstrate the possible influences on the rock's mechanical properties. Examples were chosen that mostly consist of monomineralic marbles as well as polymineralic granites and gneisses (see Fig. 2.21). Marbles often exhibit a completely different layering. In contrast, granites are usually characterized as grainy with no oriented fabric. Gneisses show a macroscopic planar fabric caused by metamorphism and deformation and exhibit a mineralogical composition similar to granites.

Different anisotropic rock fabrics can be observed both in granites and in marbles. Even though Waldstein Granite shows a rather isotropic macroscopic fabric, other granitoids display increasingly strong planar fabric anisotropies. This development is schematically illustrated in Fig. 2.20c and d on a cubic rock sample. The result is a distinctly planar (gneissic) fabric with stretched crystals that are oriented parallel to the foliation, which, in strongly deformed rocks, appears mylonitic. Both examples in Fig. 2.21b and c are results of a post-magmatic deformation. Similarly diverse fabrics are also observable in marbles, which gives this rock variety an architecturally interesting decor. The Laas marble (Fig. 2.21d) only shows an indistinct foliation in the form of a gray banding. This banding can be diffusely visible throughout the rock fabric as in, for example, some Carrara Marbles (e.g. Venato). In contrast, the marble in Fig. 2.21e and f shows a distinct compositional banding with changing interbeds of calcitic to dolomitic layers, as well as biotite layers. These recognizable macroscopic features already display distinct, existing fabric anisotropies.

Next to the compositional characteristics, the following section will focus on different fabric factors. Fabric elements are essentially defined as the orientation of grain shapes and the crystal lattice (Lattice Preferred Orientation (LPO)). Under natural conditions, the LPOs in rocks are generated by a directed growth or plastic deformation in which the preferred orientation of the crystal lattice is arranged according to the external main stress directions. As a result, textures are the summation of events of geologic history, which can exhibit locally dependent variations within the rock body (areas of homogenization). When the participating mineral phases show crystal lattice anisotropies, the directionally dependent

Fig. 2.22 Diagram showing the crystallographic preferred orientation in rocks:

a Representation of a calcite single crystal with corresponding c- and a-axes, **b** Schematic representation of the position of the calcite c-axis depicting a specific orientation in a Schmidt Net projection; **c** All minerals can have similar orientations or can **d** Exhibit statistical alignment of the crystal axes. Accordingly, the pole points of the crystallographic axes (only the c-axes are shown) lie in a strong texture **e** In a well-defined area or, through a missing texture, is **f** Statically distributed over the entire pole figure (Siegesmund et al. 2002a)



physical and mechanical properties of the rock are essentially determined by the LPOs (next to the preferred orientation). The representation of the rock textures can be depicted in different ways. In geologic fabric analysis, the preferred method for representing the poles to the planes of crystal lattices or crystal lattice axes is using true planar stereo projections (i.e. pole figures). Figure 2.22 schematically depicts a calcite crystal with the main crystallographic axes (c- and a-axes). When the crystal is projected in a stereo net (lower hemisphere), a pole point is generated on the projection plane, which shows its true orientation. The interpretation of the LPO data is usually done with respect to the sample coordinate system, which is defined by macroscopic fabric elements such as bedding, schistosity, foliation, and lineation. In this case, the XY-plane corresponds to the foliation (metamorphic layering), and the Z-direction is the foliation pole. Figure 2.22 shows a schematic representation of a grain mosaic. In the sketch, single crystal orientation is given for each grain. If the orientation of the c-axes in the calcite crystals has been crystallographically and optically measured, the corresponding orientation of the pole figures can be displayed. The texture in a rock can be statistically isotropic, which means the crystallites contain all possible orientations with the same

number, or the crystallites show a more or less similar orientation (Fig. 2.22c and d). In the example on the left, the calcite crystal has more or less the same orientation. Thus, all the c-axes scatter around a very small pole point cluster in the pole figure. The right example shows a strong variation in the orientation, and, naturally, all the measurements in the pole figure are widely scattered over the entire pole figure. In extreme cases, two types of textures can develop: one with a strong preferred-lattice orientation and one that is completely random (Fig. 2.22). This can result in material behaviors wherein the physical and mechanical properties (e.g. Sect. 3.6) can be either isotropic or highly anisotropic.

2.8.2 *Shape-Preferred Orientations*

Shape-preferred orientations describe the anisotropic spatial distribution of the long and short axes of shape-anisotropic crystals (see Fig. 2.20a–f). This can be due to different geological processes: sedimentation of anisometric grains, directed longitudinal growth, and deformation. When the shape anisotropy and lattice anisotropy of crystallites are superimposed, a distinct rock fabric will result. In monomineralic polycrystals, the crystal boundaries designate the grain boundaries and are defined by the degree of lattice misorientation in the neighboring crystals. Large misorientations cause relatively high grain-boundary porosities due to the greater width of the dislocation zone. The significance of shape-preferred orientations for material behavior is, first and foremost, that the crystal boundaries represent mechanical and structural discontinuities (compare Fig. 2.20a, e, and f), which delineate the preferred directions of fracture patterns and interconnected networks for material transport (directionally-dependent permeabilities). In dense crystalline rocks, they represent a substantial part of the effective porosity.

2.8.3 *Fracture Fabrics*

In the different rock types discussed here, microcracks are a frequently occurring fabric element. They occur either along the grain boundaries (intergranular) or within the mineral grains (intragranular). With increasing density, these types of cracks can form complex networks. With continuous crack growth, macroscopic fractures can also form via the coalescence of these microcracks. Since their formation is due to directed stresses within the Earth's crust, microcracks always show a preferred orientation based on statistical measurements and are a major contributor to the anisotropy in a rock. Microcracks that formed early in the geological process and evolution of the rock often become closed by a later mineralization. Mineralized cracks can be differentiated into “healed” microcracks (filled with the same material as the host grain) or “sealed” microcracks (filled with a foreign material). As a rule, the youngest crack generations are

usually open, which makes them especially important for material behavior (Vollbrecht et al. 1993). They are a major contributor to the porosity and permeability in very dense crystalline rocks (plutonic and metamorphic rocks) and, because of their parallel orientation, often cause anisotropic fracture behavior (see Chap. 3).

In the following section, two rock types, the Waldstein Granite and Wunsiedel Marble, will be used as detailed examples to illustrate the observed rock fabrics.

The Waldstein Granite is yellow in color and shows large feldspar porphyroblasts up to 30 mm in size within a medium to coarse-grained matrix. Compositionally, the mineralogy of the rock consists of 37.5 % quartz, 29.7 % K-feldspar, 21.6 % plagioclase, 6.6 % biotite, 4.5 % muscovite, and accessories comprised of zircon, chlorite, cordierite, apatite, tourmaline, and opaque minerals. These granites were not deformed nor underwent gneissification in the mountain building processes and, thus, still exhibit their primary macroscopic and more or less isotropic fabric. Even the anisotropic processes of a developing preferred orientation, such as those mentioned above, did not occur during the early fractionation of crystals from the magma chamber. However, during the exhumation of the granite, a structural overprinting occurred that is observable in the quarry and represented by the jointing system and faults (Fig. 2.23a). Correspondingly, many microcrack generations can be observed in thin sections as additional anisotropic elements that clearly show a preferred orientation. In general, the macroscopic joints and microcracks in the Waldstein Granite exhibit the same orientation (compare Fig. 2.23a and b), whereby two systems dominate: (1) steep joint surfaces dipping northwest to southeast and (2) horizontal surfaces represented by the maxima in the center of the diagram. In both systems different crack types can be discerned at the microstructural level (Fig. 2.23c–f). For the anisotropy of the rock's mechanical properties, the open cracks shown in Fig. 2.23f are especially significant, because they exhibit a greater dilation and, thus, cut various types of minerals. The Waldstein Granite is a good example of the more or less often described isotropic character of a granite (its grains lacking any distinct orientation), but, as a result of the microcrack fabric, it does show a material behavior of anisotropy. In many cases, the macroscopic joints can give an indication of the orientation of the microcracks. However, some granitic rocks are known in which there is no strong directional relationship between microcracks and joints.

The Wunsiedel Marble shows a distinct banding macroscopically, which is defined by a gray and white fine-, medium-, and coarse-grained layering. Occasionally, local interbeds of thin, dark, graphite-rich layers are observable. Two planar fabric elements or foliation (Fig. 2.24) can be differentiated: (1) The bedding (ss) is recognizable by a change in the grain size and the graphite interbeds, as well as small, quartz grains arranged in layers and (2) a penetrative schistosity that can be discerned by the shape-preferred orientation of calcite crystals. An example of observed shape anisotropies is shown in Fig. 2.24. The Wunsiedler Marble exhibits, in all sections, a more or less strong arrangement of the shape anisotropic grains. Thin section images parallel to the three surfaces of a sample cube show different grain shapes under closer examination. In the upper corners of each

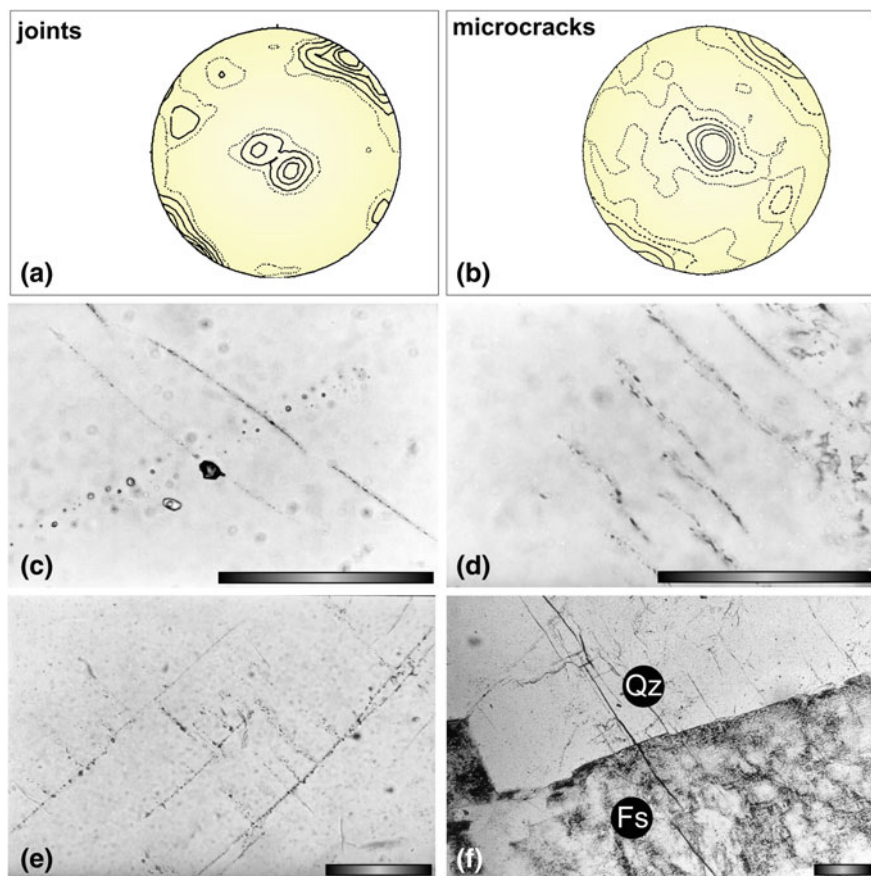


Fig. 2.23 Fabric anisotropies in granite: **a** Pole diagram of the joints in a quarry and **b** The microcrack orientation in the Waldstein Granite; **c** Healed cracks in quartz defined by fluid inclusions. In areas where younger cracks penetrate the healed ones, the fluid inclusions are empty (see *dark bubble* in the middle of the image); **d** Healed microcracks swarm with the same orientation; **e** Orthogonal crack pattern, where the older generation (*long diagonal cracks*) can be differentiated from the younger generation (*short cracks* perpendicular to the older ones); **f** Opened microcracks in quartz (Qz) grains which migrate into the feldspar (Fs) grains (*intergranular-transgranular cracks*). The scale in all thin section images is 0.1 mm (e.g. Vollbrecht et al. 1991; Siegesmund et al. 2002a)

image, a number of grains have been sketched, with a representative grain shown in color. Essentially, these are arranged as non-equidimensional grains, which can be described as triaxial, “cigar-like” ellipsoids. The larger calcite grains show twinning and are usually surrounded by small recrystallized, untwinned grains. The long axes of the grains do not necessarily dip in a similar direction to the macroscopically visible foliation. When marbles lose strength as a result of weathering along the grain boundaries, which is usually the case, the directional

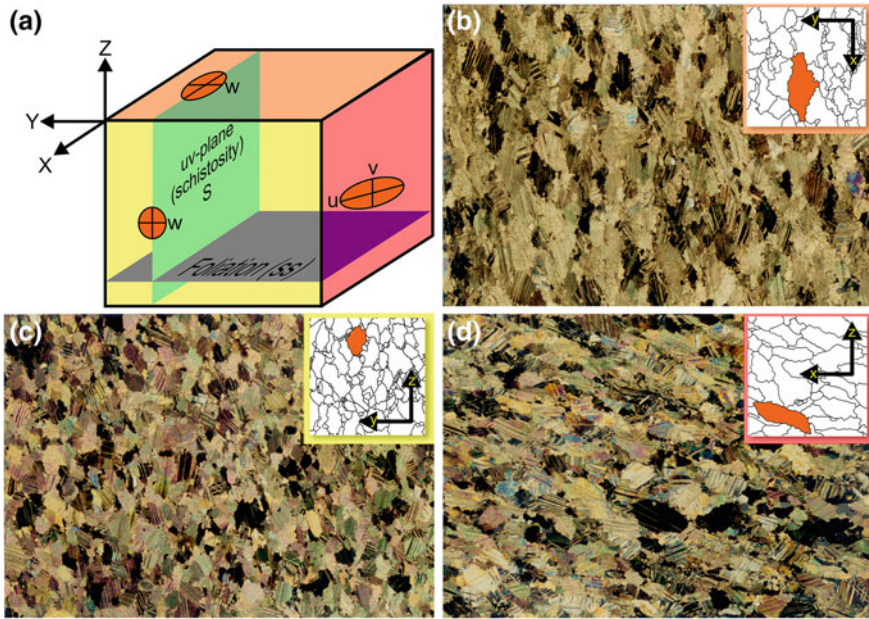
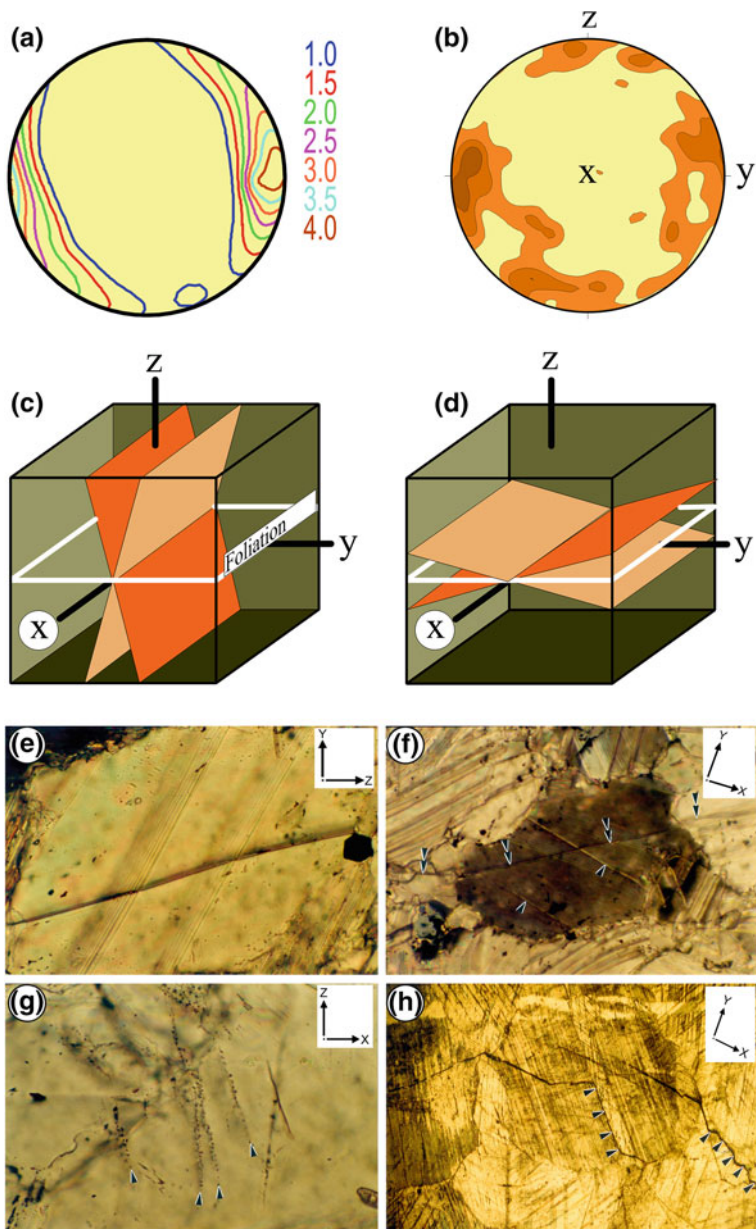


Fig. 2.24 Shape-preferred orientation in the Wunsiedel Marble: **a** Schematic representation of the grain fabric and its arrangement into subordinate structural characteristics of foliation (ss) and schistosity (s). The total fabric alignment results from the preferred orientation of non-equidimensional grains, which can be described by the triaxial ellipsoids $u > v > w$ (cigar-like grains). The u and v axes stretch the schistosity planes. **b–d** Thin section images of the grain fabric in different sections (photo length = 4 mm). The respective section is specified in the images (**b–d**) in the upper right hand corner of the image, together with a schematic representation of the typical grain shape (Siegesmund et al. 2002a)

relationships have a direct influence on the mechanical rock behavior. In surface exposures, rocks show planar and linear structures (different types of foliation, bandings, bedding, lineation, etc.), which are often related to structures ranging from the microscopic to the macroscopic scale (Fig. 2.25).

2.9 Igneous Rocks

Igneous rocks are formed by the cooling and solidification of magma, which is a hot, silicate-rich melt containing various compounds and elements. Magma is generated by the partial melting of the Earth's crust or mantle. Based on experimental investigations by Bowen (1928), a characteristic differentiation of minerals with differing composition can be crystallized from a SiO_2 -poor melt under slow cooling. This differentiation is known as Bowen's Reaction Series and is shown in Fig. 2.26. First, the Si-depleted basic fraction crystallizes from this melt as gabbro.



- ◀ **Fig. 2.25** Texture and microcracks in the Wunsiedel Marble: **a** Crystallographic preferred orientation of the c-axes with a distinct maximum parallel the Y-direction of the coordinate system; **b** Diagram of all microcracks in the Wunsiedel Marble; **c, d** Schematic representation of two orthogonal microcrack systems, which can be seen in (**b**); (**e–h**) Thin section images of different microcracks in the Wunsiedel Marble; **e** Open intragranular crack (image width = 0.25 mm); **f** An open transgranular crack and an intragranular crack. The directional change of the transgranular crack cutting the grain boundaries is probably due to crystallographic control of the crack orientation (image width = 0.4 mm); **g** Small healed cracks depicted by planes of secondary fluid inclusions (image width = 0.25 mm); **h** Transgranular-intergranular cracks and intergranular segments along the grain boundaries are marked by arrows. Dark coloration due to Fe-oxide staining (image width = 0.4 mm) (Siegesmund et al. 2002a)

Characteristic minerals are olivine, followed by pyroxene, amphibole, and biotite. The crystallization series influences the compositional changes. They determine which components are extracted from the melt. The feldspars that crystallize are the plagioclases that form a continuous solid solution series. First in the series is anorthite (a Ca-rich plagioclase), which crystallizes out in basalts. With continuous differentiation, the plagioclases become more Na-rich. The dark magnesium-iron silicates form a discontinuous reaction series. Continued fractionation in the remaining melt causes a decrease in the amount of Mg, Fe, and Ca, whereas Si, Na, and K increase. According to the model, crystallization ends with the formation of granite that is rich in Si, which means the granitic rock is acidic. Even though Bowen's Reaction Series only describes the fractionation series in an incomplete way, the model does deliver an easy means for understanding the differentiation of important minerals and rocks generated from a melt.

The classification and nomenclature of igneous rocks is typically established by considering the mineralogical and/or geochemical aspects, whereby the modal and normative mineral constituents play an important role. The internationally applied nomenclature for igneous rocks is based on quantitative modal analysis (mineralogical composition). It is used to name a rock with regards to the amount and relationship of the main mineral constituents. This name is further complemented by the secondary minerals (e.g. olivine in an olivine nephelinite or quartz in a quartz-bearing trachyte). The quantitative mineral content is given in volume-percent. According to the proposals of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks (Streckeisen 1978, 1980; Le Maitre 1989), the classification follows what is usually known as the Streckeisen Diagram (QAPF double triangle) (Fig. 2.27). The modal composition of volcanic rocks with a micro to crypto-crystalline or glassy or glass-bearing fabric is essentially impossible to determine. In this situation, the chemical composition of the rock is used to calculate the so-called normative minerals, which then helps to determine the normative mineral constituents. Using the normative mineral components, a classification system can be created that is based on the Streckeisen diagram. However, mineralogical compositions based solely on chemical analyses cannot lead to the actual minerals present. For example, the CIPW classification system (Cross et al. 1902) is based on chemical analyses. Along with the chemical composition, rocks are further subdivided into specific

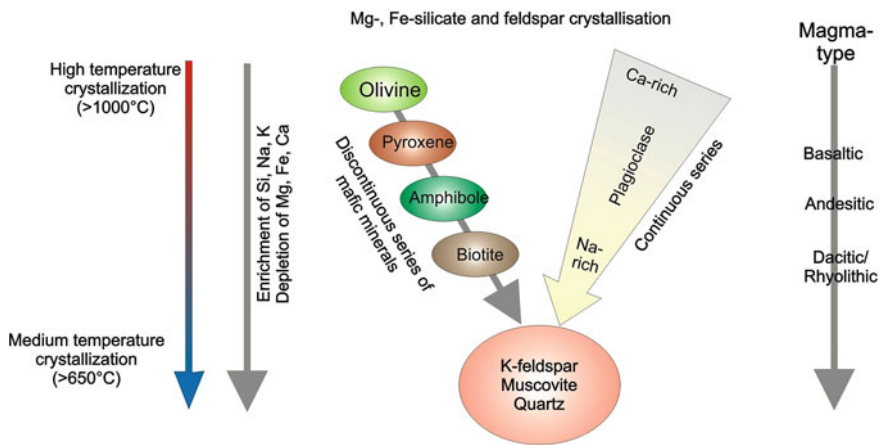
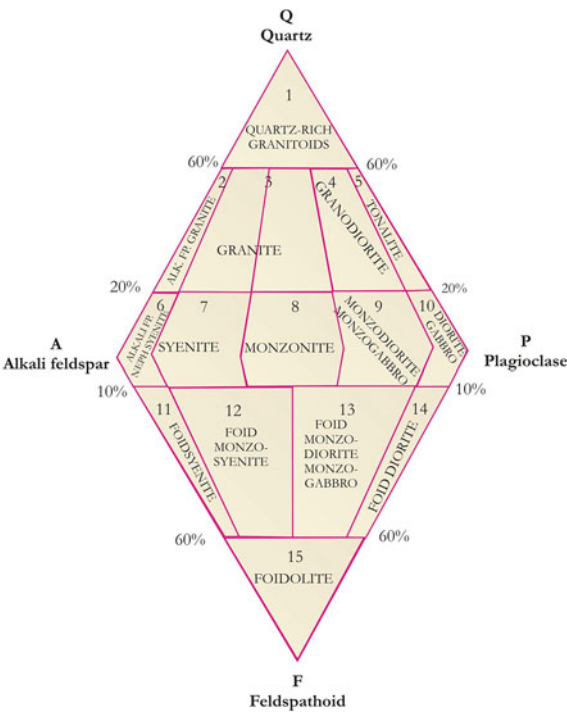


Fig. 2.26 Bowen’s discontinuous and continuous reaction series for explaining the differentiation of magma and mineral phases that are crystallized from magma at decreasing temperatures

Fig. 2.27 Simplified classification of the most common plutonic igneous rocks based on the mineralogical content (Streckeisen 1978)



rock types by being based on the SiO_2 content: acid rocks $>63\%$ SiO_2 , intermediate rocks $52\text{--}63\%$ SiO_2 , basic rocks $45\text{--}52\%$ SiO_2 , and ultrabasic rocks $<45\%$ SiO_2 .

Igneous rocks are classified according to the following minerals and mineral groups:

- Q = quartz (and the SiO_2 varieties tridymite and cristobalite), A = alkali-feldspars (orthoclase, microcline, sanidine, anorthoclase, albite with an anorthite content of <5 mol %),
- P = plagioclase with an anorthite content from An_{05} to An_{100} ,
- F = feldspar substitutes or feldspathoids (leucite, nepheline, the sodalite group, nosean, hauyne, analcime).

A color index (M) is often used for defining plutonic and volcanic rocks. This indicates the percentage of dark minerals (mafic): hololeucocratic plutonic rocks contain 0–10 % mafics, leucocratic (light) plutonics 0–35 %, mesocratic rocks 35–65 %, melanocratic (dark) rocks 65–90 %, and mafic rocks 90–100 %. Mica, amphibole, pyroxene, olivine, garnet, etc. belong to the mafic minerals.

Rocks with an $M < 90$ vol % are classified according to the amount of light minerals present and are represented in a $Q-A-P-F$ double triangle (see Fig. 2.27). The procedure is as follows: The parts of light minerals are converted into 100, which means either $Q + A + P = 100$ or $A + P = 100$.

As a rule, the darker constituents are systematically left out of consideration and are used for a rough orientation or for further nomenclature subdivision into specific rock groups.

From the natural stone industry's point of view, a modified Streckeisen diagram may be sufficient. Not only does the diagram depict the correct mineralogical composition, but it also shows the properties of the rock and how they can be applied, which is of the utmost importance. According to the European norm, e.g. the EN 12440 (2000) "Natural Stones: Criteria for the Designation", the description of the natural stone should contain the trade name, the petrographic classification, the typical color, and the location, as well as the type of surface treatment, the natural properties, the petrographic name, and, if necessary, the geologic age of the stone's origin. Thus, in the future, irritation caused by giving the stone fantasy names can be avoided (see Sect. 2.4).

2.9.1 Plutonic Igneous Rocks

In the following section, only the most important rocks will be described. According to Wedepohl (1969), the volume relationships of plutonic rocks in the lithosphere can be differentiated as follows: granite and quartz monzonite (44 vol %), granodiorite (34 vol %), diorite and quartz diorite (9 vol %), and peridotite, syenite, and alkaline anorthosite rocks (around 0.5 vol %).

Granites as well as granodiorites are the most commonly used plutonic rocks for building with regard to color, décor, and the wide range of different compositional varieties. The attempt to classify granites according to type, group, and family served the purpose of elucidating the specific conditions of formation and

defining the genetic principles. In the Archean, a very early period in the Earth's history, Na-bearing granites with a tonalitic and trondhjemitic composition occur, whereas, in the Proterozoic Ca-rich, granites are predominant (Kay and Mahlbürg Kay 1986). Besides forming from fractionated crystallization (Bowen 1928, see Fig. 2.26), the formation of granites is also possible in the melting of water-saturated metasediments through a process called anatexis (Winkler and von Platen 1961a, b). Today, granites are differentiated into S-type and I-type granites.

S-granites originate from metamorphosed sedimentary rocks, and I-granites form the original rocks of metamorphosed igneous rocks. S-granites are essentially SiO₂-rich and are felsic rocks consisting of the characteristic paragenesis of biotite ± muscovite ± cordierite ± garnet ± ilmenite. I-type granites contain hornblende ± biotite ± sphene ± magnetite. Even xenoliths (foreign inclusions) are different in both types. In addition, M- and A-type granitoids can be differentiated. A-type granitoids provide most of the dimensional stones (Fig. 2.28).

Granitoid intrusions are often formed in a structurally complex way. The Ardara Pluton in Ireland, which is an example of the ballooning model of emplacement, is a three-phase, normally-zoned pluton (Hutton and Siegesmund 2001). The outer and earliest zone is a feldspar-porphyritic tonalite/quartz diorite, an equi-granular granodiorite forms the intermediate position and age, and the youngest and central position is granodiorite. The fabric of granitic rocks is usually considered to be random and granular. This is the typical criteria used for granites discussed in the literature. Some authors, however, dismiss the observation above by proving that these rocks do show fabric anisotropy. Most of the intrusive rocks may exhibit a macroscopic planar and/or linear fabric by the arrangement of tabular shaped crystals (e.g. biotite and plagioclase). When granites exhibit a fabric with large crystals (phenocrysts) in a relatively fine-grained groundmass, the rock is considered to be porphyritic. Based on microstructural observations, a genetic interpretation may be done. Thus, former flow structures generated during the emplacement of the magma can be verified by the alignment of alkali feldspars. These crystallize out from the magma relatively early and form idiomorphic crystals that are oriented parallel to the direction of magma flow. Fabrics can form during the cooling, whereby the interstitials within the mineral framework are filled with quartz that shows a chessboard pattern, indicating temperatures above the α - β transition. This transition temperature ($\sim 573^\circ\text{C}$) is used in surface treatment when producing flamed rock surfaces. The absolute size of the individual crystals and their arrangement with each other determines the appearance of the granite. The different grain sizes of granite (e.g. fine, medium, or coarse-grained fabrics) are connected to the cooling period of a granitic melt. Other observations assume that fluid phases lead to an increase in crystal nucleation, which, in turn, is responsible for the large grain size growth.

Optical properties are primarily determined by the feldspars. The quantitative distribution and characterization of the mineral components (see Fig. 2.27) can help in the identification of the various granites. Granites with a constituent fraction of 40–60 % alkali feldspars can range from being coarse-grained to being fabrics with extreme grain sizes. They are mostly vibrant red to reddish or pink,

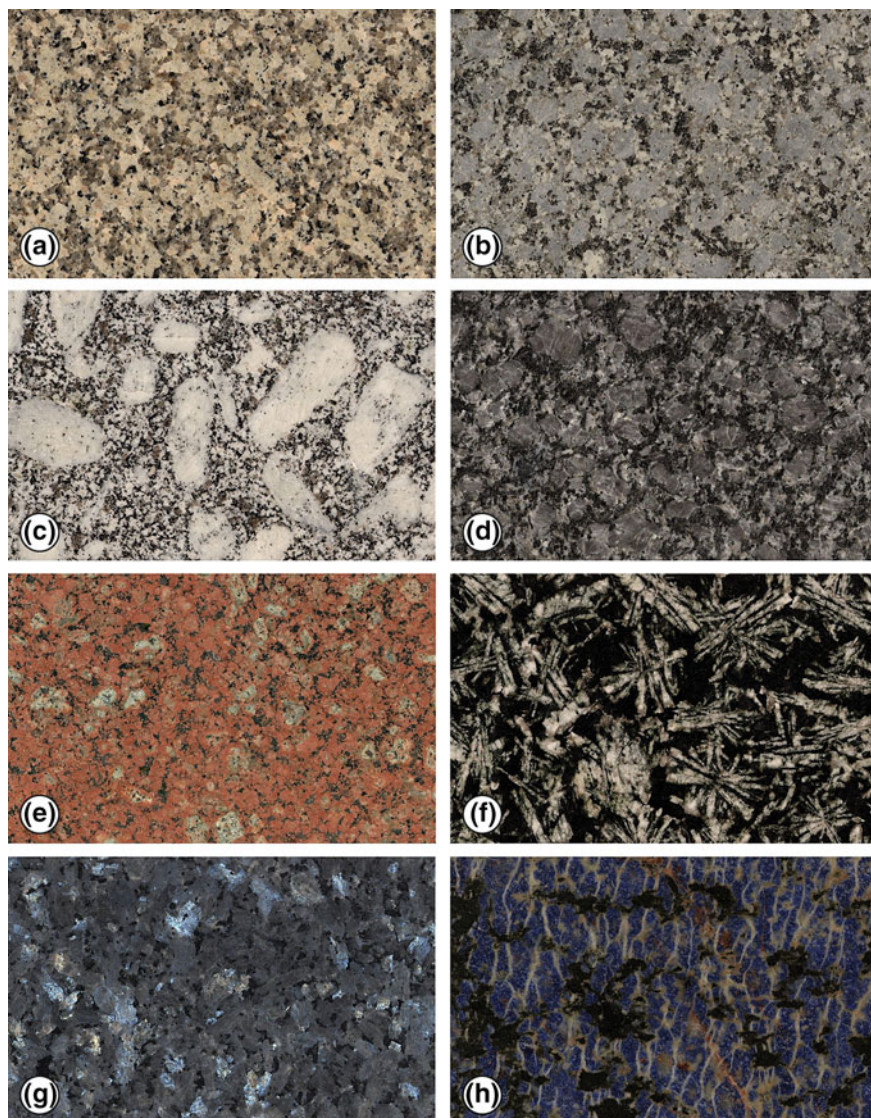


Fig. 2.28 Commonly used plutonic igneous rocks: **a** Waldstein Granite, **b** Kösseine Granite, **c** Wöllsau Porphyritic Granite, **d** Baltic Blue Monzonite, **e** Salmon Red Syenite, **f** Snowflake Gabbro, **g** Blue Pearl Larvikite, and **h** Namibian Blue Sodalite (Figure by Natursteinarchiv Wunsiedel)

and are seldom bluish, greenish, or gray (Figs. 2.28 and 2.29). When the granites consist of 0–30 % plagioclase, they are either light or white–gray and only seldom show distinct colors. Granites with 20–40 % quartz often show a greasy luster, are mostly colorless to transparent, are seldom gray, blue-gray, or pink, and are

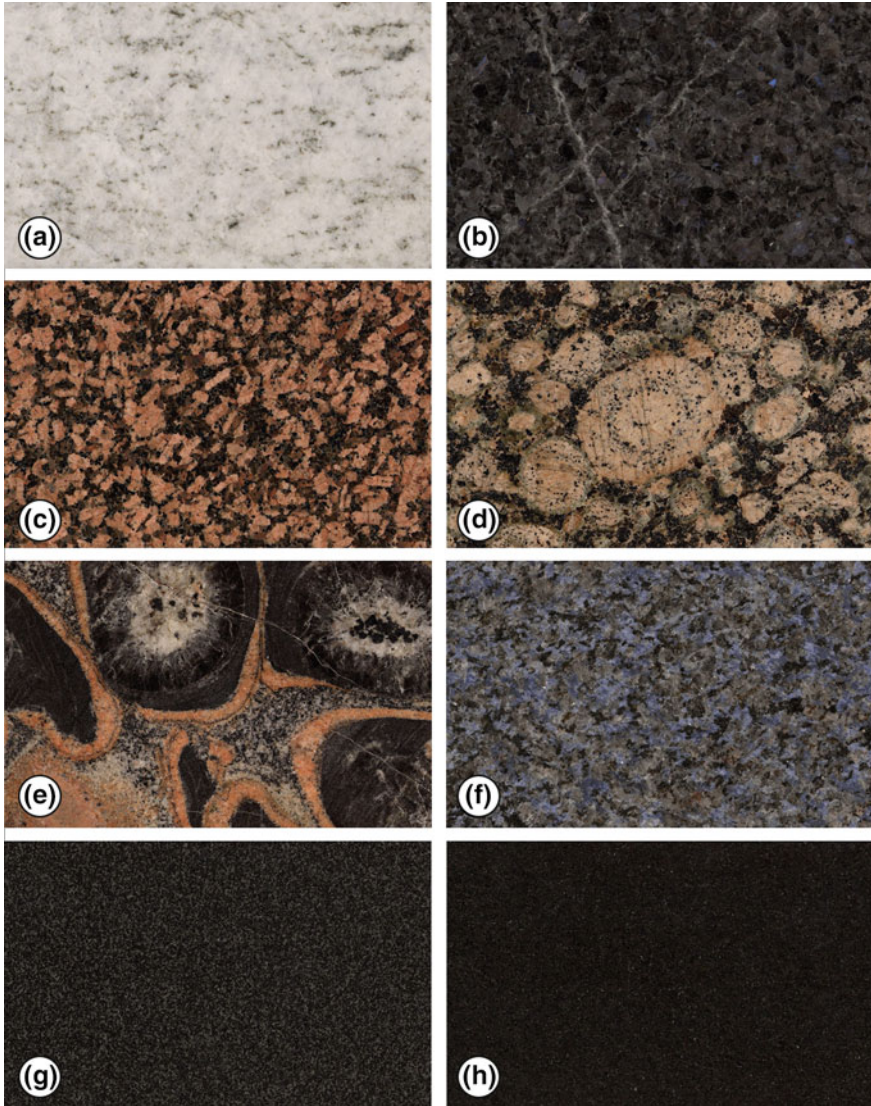


Fig. 2.29 Commonly used plutonic igneous rocks: **a** Gudvangen Anorthosite, **b** Russlabrador Anorthosite, **c** Balmoral (granite, Finland), **d** Balticrosa Rapakivi Granite, **e** Orbicular Granodiorite, **f** Malawi Blue (foyaite), **g** Negro Oriental Dolerite (Uruguay), and **h** Negro Absoluto Black Dolerite (Uruguay) (Figure by Natursteinarchiv Wunsiedel)

irregular on fractured surfaces. Higher amounts of mafic constituents that form interspersed black flakes, like biotite, for example, can impart a darker contrast to lighter colored granites. Both hornblendes and pyroxenes can be present in granites in subordinate amounts. In unweathered rocks, feldspars are more or less

colorful. Orthoclases are often pigmented predominantly by ferrous compounds (hematite), where the color ranges from a subtle to strong pink. Other granites can exhibit conspicuous yellow shading. This rock color results from alteration processes (weathering) in the deposit, which originate during the geological development of the rock. The alteration processes cause the oxidation of the rock-forming minerals like biotite or even ore minerals, e.g. iron hydroxides or pyrite. The greater the alteration, the more intense the yellow shading. Logically, the most intense yellow coloration can be found at the near-surface areas of the deposit. In the core area of the pluton, feldspars show pink coloration, which results from hematite inclusions. Plagioclases appear whitish dull to pale green. The intense white tones are caused by gas and fluid inclusions within the crystal lattice. Even quartz does not always appear colorless or transparent, but can be cloudy or occasionally show a reddish pigmentation. The color of quartz can even adopt different shades of blue. This occurs when the granite has undergone deformation, when it shows an enrichment of fluid inclusions, or when rutile (a titanium mineral) is incorporated into the quartz structure.

Syenite and monzonite are quartz-free to quartz-poor, feldspar-rich, medium to coarse-grained, deep-seated plutonic rocks. They are similar to granites in terms of structure and appearance. When orthoclase dominates the rock composition, the rocks are called syenites, and, if orthoclase and plagioclase are both present in similar amounts or only plagioclase prevails, then the rock is known as a monzonite (Fig. 2.28d, e). Syenitic-monzonitic rocks are generally reddish to red-brown because of the high potash feldspar contents. They are seldom bluish-violet or white, and never dark gray or black. The syenites shown in Fig. 2.28 are gray to pink colored and very coarse-grained. Perthitic orthoclase up to 4 cm, interstitial amphibole, pyroxene, and biotite are the main minerals. Accessory minerals include apatite and zircon. Alkali feldspar exhibits a wide palette of colors in the different intrusions (gray, deep red, brownish red, etc.). In Uruguay (Oyhantcabal et al. 2007), for example, the commercial varieties cover a broad range: Guazubirá (medium-grained and reddish pink), Artigas (coarse-grained, various shades of gray and pink colors), Bodega (medium-grained and deep red), Sara Pink (fine-grained and pink), etc. These rocks have been widely used in the cities of Buenos Aires and Montevideo and in Japan over the last several decades.

The rocks of the diorite-tonalite-trondhjemite group are characterized by the lack of reddish orthoclase, whereas the prevalent mineral is the whitish-gray plagioclase feldspar. Diorite contains plagioclase, hornblende, and biotite as the main mineral constituents. Quartz occurs with less than 5 %. Diorites never appear colored because of this mineralogical composition, but instead are dark green, black-gray, or mottled black and white. Tonalites are diorites that contain over 20 % quartz and, thus, were once designated as quartz diorites. A sub-group of the tonalites is the trondhjemites. They only contain a very small amount of dark colored silicates and appear as light-colored rock. Three types from Norway are processed and used in the natural stone industry.

Gabbros occupy the same field as diorites in the Streckeisen diagram. In gabbros, plagioclase has an anorthite content of over 50 mol percent. This makes it

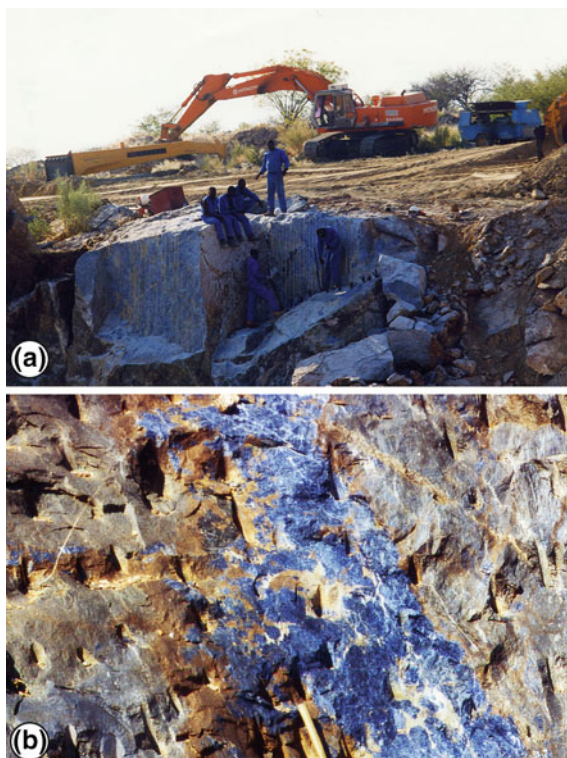
difficult to distinguish the rock from diorite in hand specimens, and mistakes in determinations are absolutely possible. Gabbros are the most frequent plutonic rocks originating from the dark basic magma type. They consist of 50–70 % plagioclase with a black-gray, dark brown, or gray-white coloration, 20–50 % pyroxene colored gray, deep black, or dark green, 0–20 % hornblende showing green to black colors, 0–20 % olivine with a dark green coloration, and 0–15 % ore minerals showing dark bright metallic coloring. From this mineralogical composition, a dark to totally black rock that has a fine to coarse-grained fabric results. Depending on the grain size, the appearance can vary from mottled to a uniform deep black color (Fig. 2.29). For gabbroic rocks, there are complementary composition diagrams which differentiate between plagioclase, pyroxene, and olivine contents, respectively, and plagioclase-olivine-clinopyroxene gabbros, olivine gabbros, gabbro norites, norite anorthosites, etc. These rock groups play a major role in modern architecture, especially because the color and décor offers many design possibilities. Gabbro rocks are designated norites where orthopyroxenes predominate over clinopyroxenes. Almost no difference to normal gabbros exists with regards to the technical and optical properties. Anorthosites are feldspar-rich gabbros where the pyroxenes show a quantitative reduction (Fig. 2.29). Zoned labradorite feldspars forming a mostly coarse crystalline fabric often show spectacular light reflections. The rock fabric also shows an intense blue shimmer. Depending on the viewing direction (incident angle = reflection angle), all the spectral colors can be observed. Its optical appeal has helped to increase the demand for anorthosites (Spectrolite, Blue Eyes, Volga Blue, or Arctic Blue), which are enormously used by building owners and architects.

Feldspathoids form a rare group of plutonic rocks and are known as the feldspathoid rocks or foyaites. They are generally medium to coarse-grained and occur in small rock bodies and veins. Silica poor melts are where they originate, which is why no quartz forms, and only little to no feldspar develops. Instead of feldspar, the so-called foid, which are feldspar substitutes, develop. This is why one refers to feldspathoid rocks as foyaites. Typical feldspar substitutes are nepheline (gray to green), sodalite (blue), leucite (white), and nosean (brown). Feldspathoid rocks have pleasing optical properties (Fig. 2.30).

2.9.2 Volcanic and Subvolcanic Igneous Rocks

Volcanic rocks not only include the extrusive lava flows but also the volcanoclastics (tuffs). Many volcanic rocks are difficult or inadequately determined macroscopically, because the mineral constituents are generally very fine-grained, whereas they can be clearly distinguished from plutonic rocks. A simplified representation in the TAS diagram (Total-Alkali-Silica) after Le Maitre (1989) is based on the work of Cox et al. (1979). This classification should only be used if the mineral mode of a fine-grained crystalline rock cannot be determined, either due to the presence of glass or to the fine-grained nature of the rock. The classification only requires the

Fig. 2.30 Photographs of **a** Sodalite opencasting (*Namibia Blue*), which is the only opencasting that is presently mined, and **b** Monomineralic layer or sodalite-rich xenoliths of deep blue sodalite (from Drüppel 2003)



values of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and SiO_2 (Fig. 2.31). Volcanic rocks have a close relationship with their plutonic counterparts, and surface morphology often reflects the origin (Fig. 2.32).

Nearly every plutonic rock can be related to an equivalent effusive rock. The nomenclature can be referenced from the Streckeisen diagram (see Fig. 2.31). Rhyolites (earlier known as porphyry or quartz porphyry) are the volcanic equivalent of granites. When an acid SiO_2 -rich magma solidifies in the lower crust, granite forms, and, as the lava reaches the Earth's surface, rhyolite develops. Rhyolites are yellowish, reddish, grayish, seldom gray-green, dense, and porous rocks in the upper parts of the flows (Fig. 2.33). The fabric is porphyritic, which means it has a fine-grained groundmass with phenocrysts. In Fig. 2.34, the use of Löbejün Rhyolite is exemplarily illustrated. The rock is characterized by a fine crystalline groundmass (ca. 66 %), where the microgranitic fabric can be recognized with the unaided eye, and phenocrysts up to 30 mm occur. Mineralogically, the rock consists of quartz (27 %), orthoclase (40 %), plagioclase (27 %), and biotite (6 %, Fig. 2.31). Accessories causing the coloration in the groundmass are hematite and magnetite. The groundmass of the rock has a characteristic and distinctive red to coral-red color. Within the groundmass, salmon pink orthoclase, yellow-green plagioclase, and pearl-like quartz occur. Biotite is not observable

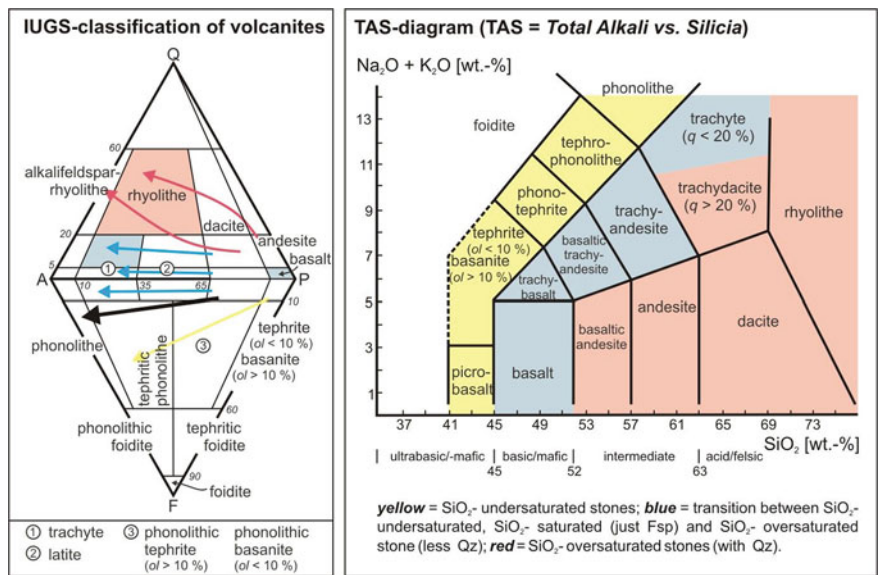


Fig. 2.31 Classification of volcanic igneous rocks according to the IUGS and TAS diagrams (based on Le Maitre et al. 2004)

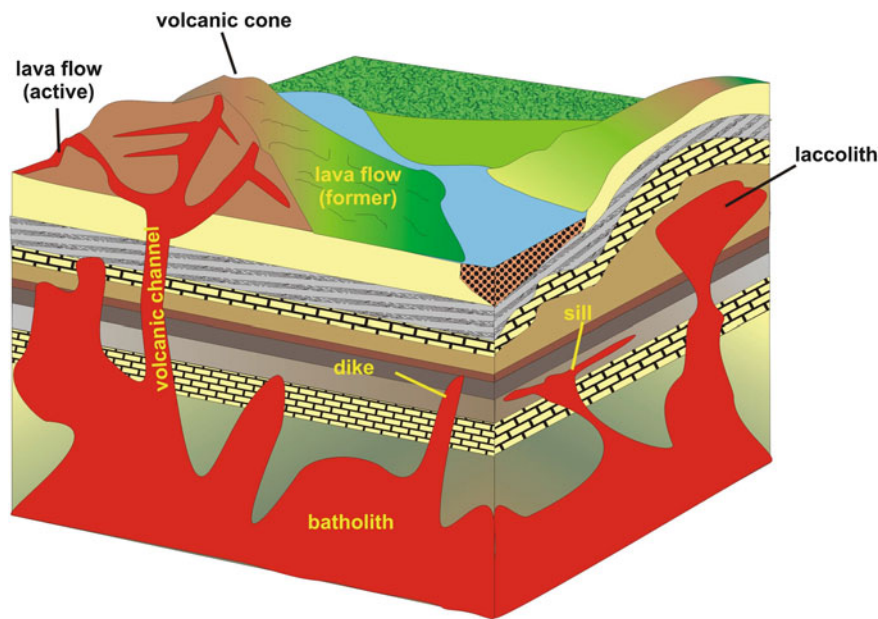


Fig. 2.32 Field occurrences of igneous rocks

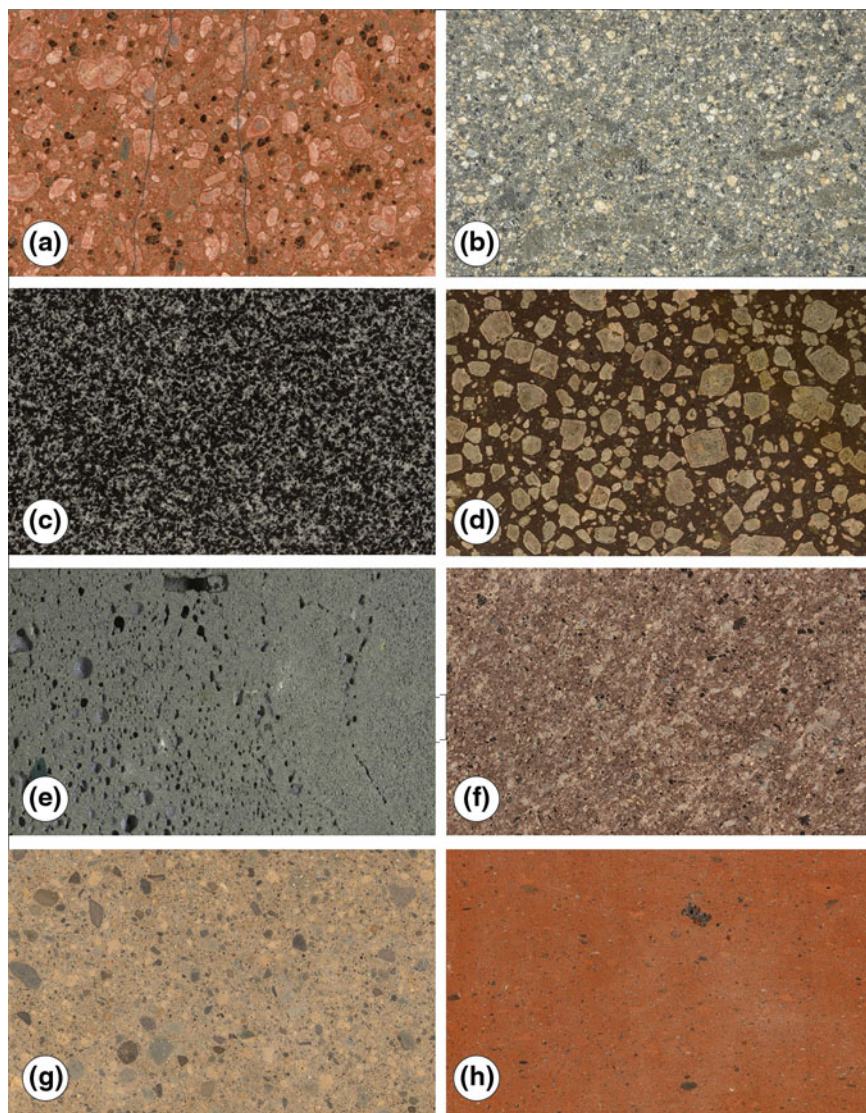


Fig. 2.33 Commonly used volcanic igneous rocks: **a** Löbejün Rhyolite, **b** Porfido Argentino Rhyolite, **c** Valtengrund Lamprophyre, **d** Trachyte, **e** Lohndorfer Basaltic Tuff, **f** Ettringen Tuff, **g** Scherwesch Andesitic Tuff, and **h** Dobraniva Andesitic Tuff (Figure by Natursteinarchiv Wunsiedel)

macroscopically. The groundmass as well as the phenocrysts only show a weak alignment, which indicates the rock essentially possesses an almost isotropic fabric property. Frequently, rhyolites show a slight directional orientation, which is represented by the solidified flow movement of the lava. The largest surface

Fig. 2.34 Dresdner Bank in Halle (Germany) cladde with the Löbejün Rhyolite (SH Naturstein, Löbejün in Germany)



exposure of rhyolite deposits in Central Europe is the Bozener Quartz Porphyry in Tyrol, Italy.

Trachytes are the volcanic equivalents of syenites. The chemical composition is intermediate to acidic. According to the Streckeisen diagram (1978, Fig. 2.31), trachytes occupy field 6 (quartz-alkali feldspar trachyte) and field 7 (quartz trachyte and trachyte in the strict sense). These rocks essentially contain little or no quartz. Trachytes frequently contain pyroxene and/or amphibole and sometimes biotite, which can be identified as mostly small, dark phenocrysts. The light phenocrysts in trachytes are predominantly sanidine. Phenocrysts can show a preferred orientation in the matrix and traces a flow fabric, which indicates the former flow direction of the magma. A famous example of where a trachyte (the Drachenfels-Trachyte) has been used is in the Cologne Cathedral. This rock comprises 50 % sanidine, 24 % plagioclase, 13 % quartz, 5 % augite, 5 % biotite, 2 % ore, and 1 % apatite, zircon, and sphene. The fabric of this trachyte is typical for volcanic rock, which is characterized by a fine-grained matrix. Feldspars and quartz comprise the groundmass (Fig. 2.33d). In some places, calcite occurs. Volcanic glass fractions can be altered to montmorillonite. More pyrite occurs in the groundmass than what generally is expected. Furthermore, in some cavities, pyrite and aggregates of pyrite-hematite (limonite?) can be found. Older trachytes frequently contain secondary chlorite, epidote, and calcite.

Basalts are the volcanic equivalents of plutonic rocks like gabbro and norite. They are dark, mostly black, blue-black, and seldom gray with a dense structure. The main mineral constituents are plagioclase, pyroxene, amphibole, olivine and iron ore. In terms of quantity, basalts are the most important volcanic rocks. Basalts are, as a rule, fine-grained and occasionally porphyritic or hyaline. In the wider sense, basaltic rocks can clearly show a distinct flow fabric, which can be applied to the matrix as well as to the phenocrysts. Petrographically, basalts can be understood as consisting of plagioclase, augite, and Fe–Ti oxides. Olivines occur frequently. Feldspar substitutes (like nepheline) are restricted to the alkali basalts. Many deposits show a very well developed columnar jointing (Fig. 2.35a).

Fig. 2.35 **a** Basalt columns from Giant Causways in Northern Ireland and **b** Use of basaltic rock as a construction material



In an ideal situation, the columns are six-sided so that they connect to each other without gaps. The columns are formed by the contraction of the rock during cooling and perpendicularly to the cooling boundary of the lava flow. Diabases are geologically old basalts from the Devonian and Carboniferous which have turned green due to chemical weathering. Original pyroxenes and amphiboles have undergone serpentinisation or have been altered to chlorite and taken on a dark green color, whereas the former feldspars have taken on shades of gray. For building purposes, basalt generally cannot be considered the most weather-resistant rock, as is often discussed in some textbooks (Fig. 2.35b). Many basaltic rocks show a characteristic gray spot formation that is indicative of the beginning stages of weathering. Later, star-like cracks form between the spots, which eventually lead to the disintegration of the rock. This process can last from many months to years. Rocks with this property are designated as “sunburnt basalt”. The cause of the sunburnt basalt is, in part, the alteration of nepheline into analcime, which leads to a volume increase of about 5.5 %.

Holocrystalline dikes consisting of fine to medium-grained basalts of varying compositions are named dolerites. Dolerites are known as important building stones in different regions of the world. The dolerites of Uruguay (Fig. 2.36) are composed of plagioclase, clinopyroxene, and opaque minerals, and the texture is

Fig. 2.36 **a** Quarry of black dolerite in Uruguay and **b** Blocks of Negro Absoluto and Oriental

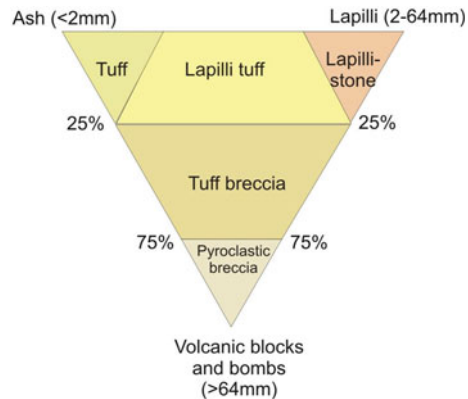


subophitic (Oyhantcabal et al. 2007; Morales et al. 2010). Biotite, apatite, and interstitial intergrowths of quartz and alkali feldspar (micropegmatite) are the main accessory phases. Rims of uralitic amphibole and chlorite are scarce. Two main varieties of dolerite are mined: one is deep black and fine-grained (Negro absoluto), whereas the other is dark gray-black and medium-grained (Negro oriental, see Fig. 2.29). The dikes show chilled margins with different thicknesses that contain a very fine-grained variety, which is highly valued economically on the international stone market. Color inhomogeneities are seldom observed and are associated with pockets of white colored quartz and alkali feldspar intergrowths.

Aplites are fine-grained igneous rocks, commonly of late igneous origin, which are found as veins in granitoid bodies. They are easy to recognize since their difference in color from the host rock is often very clear. Their smaller crystal size is strikingly different from that of granite. Their thickness ranges from the centimeter to meter scale and can even be seen at the block scale.

Pegmatite is just the opposite of aplite, since it contains coarser grained crystals than the host rock. Most pegmatites are granitic in composition and their crystal size ranges from a few centimeters to giant crystals at the meter scale. Most of the world's largest crystals are found in pegmatites (e.g. meter-scale amethysts in

Fig. 2.37 Classification of polymodal pyroclastic igneous rocks based on the proportions of blocks, lapilli and ash (after Fisher 1961)



Brazil). Aplites and pegmatites do not normally constitute building or dimensional stones, but create heterogeneities in many stones such as granites, gneisses, etc.

2.9.3 Pyroclastic Igneous Rocks

Volcaniclastic rocks include the entire spectrum of clastic materials composed in part or entirely of volcanic fragments (Fisher 1961; Fisher and Smith 1991). The designations “tuff” and “tufa” are generally used as a collective term for all the volcaniclastic rocks. The varied fragmentation processes and the type of particles within the volcaniclastic rock groups required a further subdivision into pyroclastic, hyaloclastic, autoclastic, and epiclastic rocks.

The classification of pyroclastic rocks is done by describing the attributes of grain size, composition, and fabric, as well as the origin and depositional environment. A straightforward and easy-to-use classification results from the implementation of granulometric factors (Fig. 2.37). In the strict sense, tuff describes a narrowly defined rock type, wherein the main components show a grain size of less than 64 mm. Characteristic of the rock designation is the prevalent grain size fraction (e.g. tuff). When the rock shows more than one dominant grain size, the subordinate grain size fraction is used to designate the rock type (e.g. lapilli tuff). In the classification of Le Maitre et al. (2004), only those pyroclastic deposits that have been consolidated can be considered to be a rock. Pyroclastics are essentially differentiated according to their average diameter, form, and mode of origin. For example, lapillistones show a grain size of 2–64 mm. They can be differentiated into lapilli tuff, which contains ash and a few blocks or bombs that are larger than 64 mm, and tuff or ash tuff that is dominated by fine (<2 mm) particles. An extremely coarse pyroclastic rock is the agglomerate where blocks or bombs of over 64 mm in diameter dominate. For simplicity in the construction industry and architecture, the term “tuff” is used for the most polymodal pyroclastic rock.



Fig. 2.38 **a** MUMOK Museum of Modern Art in Vienna (Austria) is clad with basaltic lava (Krings, Schmitz Naturstein GmbH & Co. KG), and **b** Moai from Easter Island in Chile is made from tuff (Figure by B. Fitzner)

Mixed pyroclastic sedimentary rocks are also known; thus, tuffaceous sandstone or tuffaceous mudstone refers to rocks with pyroclastic contents of 25–75 %.

The industrial stone classification of pyroclastic rocks preferentially contains a simplified mineralogical composition; thus, rhyolite tuff, dacite tuff, andesite tuff, and basalt tuff are used as the most common types (Fig. 2.33e–h). Additional pyroclastic rock types include lithologies such as trachite tuff, phonolite tuff, etc.

Rhyolite tuff is buff-beige to white in color, whereas pumice as lithic clasts frequently occurs. Biotite and quartz are common phenocrysts. Dacite tuff is very similar to rhyolite tuff, but often has higher strength and durability and has a variegated and often darker color than rhyolite tuff. Andesite tuffs have a wide range of color and size, and their fabric can contain lapillis or bombs and frequently forms pyroclastic agglomerates. Basalt tuff is generally somewhat different, more brownish and greenish than andesite tuff (Fig. 2.38a). The common basalt, lapillis, and the presence of olivine crystals allow the identification of this pyroclastic stone.

Most tuffs are easy to cut and work with, and, therefore, they were widely used in masonry structures and stone walls in the past. Especially large structures, such as castles or fortresses, were made of tuffs. Known examples are the Pemian rhyolite tuffs in Germany (Rochlitz) and basaltic tuffs worldwide. Besides their use in building structures, volcanic tuffs were also used in sculptures, and the best known examples are probably the basaltic tuff statues of the Moai on the Easter Islands (Figs. 2.38b).

2.10 Metamorphic Rocks

In contrast to the igneous and sedimentary rocks, a large group of metamorphic rocks are only of subordinate importance for use as natural building stones. There are, however, metamorphic rocks that are highly valued because of their exotic composition and very complex rock fabrics. These aspects are a decisive factor for creating the décor, and, thus, they are interesting stones with a high price level and should be included in the natural stone market (see Fig. 2.41).

Metamorphism is a process that leads to changes in the mineralogical and/or structural and/or chemical composition of rocks in the solid state. These changes are caused by physical and/or chemical conditions that deviate from weathering zones—cementation and diagenesis (see Winkler 1967). Metamorphism literally means transformation with respect to the mineral constituents as well as the rock fabric. Metamorphism can also take place isochemically, which means that, during the metamorphism, no chemical changes occur with the exception of introducing H_2O and CO_2 . Allochemical metamorphism occurs when there is an addition or removal of material that changes the bulk chemical composition of the rock. Sedimentary, igneous, and even metamorphic rocks can be source material for metamorphism. Sometimes, metamorphic rocks can also be designated metagranitoids, metasediments, or metavolcanics. When former igneous or sedimentary rocks are considered where a clear classification to the source rocks can be determined, the rocks can be designated ortho- or para-rocks, respectively. Metamorphic rocks make up about 15–28 vol % of the Earth's crust. With decreasing temperatures, metamorphism is replaced by diagenesis. Experimentally determined melting temperatures of different rocks provide information on the high temperature boundary of metamorphic rocks. Granites begin to melt in the region of the Earth's crust when in the presence of H_2O at temperatures ranging between 600 and 700 °C. Basalts melt at even higher temperatures. At this boundary, magma formation and metamorphism is dependent on the rock chemistry. The high temperature boundary of metamorphism is estimated to be about 700–900 °C for most rock compositions, with the assumption that a fluid phase is present. Under dry conditions, the boundary can be moved to higher temperatures.

Metamorphic rocks are essentially named after their fabric, because the rock can be characterized by this aspect in hand specimens and at the outcrop (e.g. phyllite, schist, gneiss, hornfels). Other metamorphic rocks, specifically if they are unfoliated and/or monomineralic, are named according to mineralogical criteria (e.g. quartzite, marble, serpentinite, amphibolite). Some metamorphic rocks are named in regards to their mineral constituents and metamorphic grade, e.g. greenschist, amphibolite, eclogite, and granulite (Fig. 2.39).

Metamorphic rocks are subdivided with regards to the grade of metamorphism. The deciding factors are pressure and temperature conditions. In the modern literature, this is characterized as their metamorphic facies. The rocks can be differentiated into greenschist, amphibolite, and granulite facies. The greenschist facies derives its name from metabasites, which were formed as greenschists

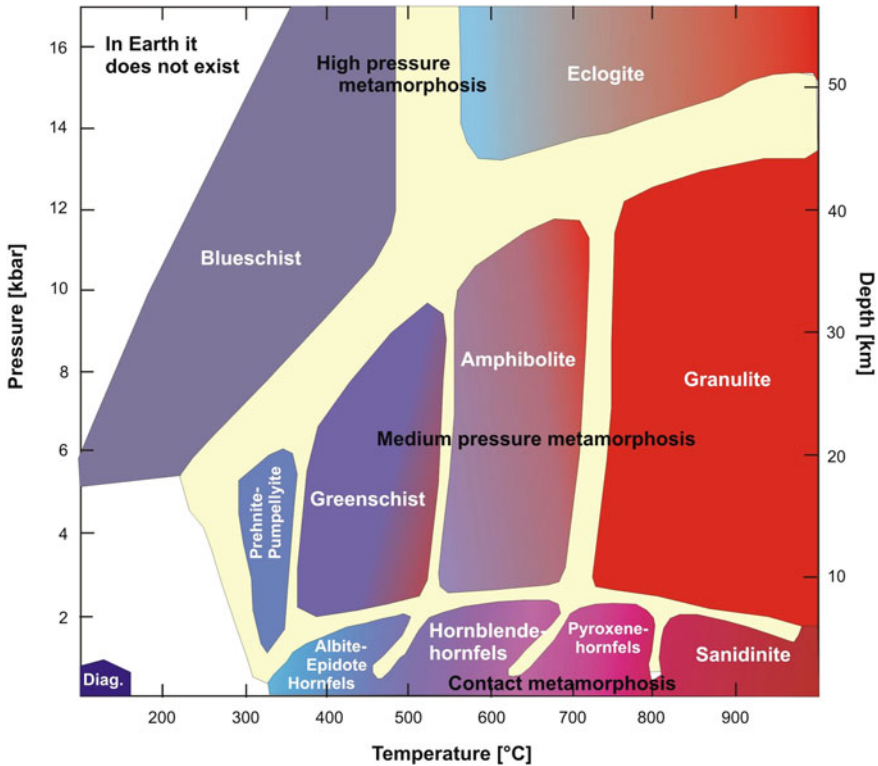


Fig. 2.39 Various metamorphic phases and the index minerals (after Winkler 1967 and Yardley 1997)

(sometimes known as prasinities) and are comprised of actinolite (a green hornblende), chlorite, epidote, albite, quartz, and sometimes garnet. Kyanite and sillimanite zones are typical for the amphibolite facies. The critical mineral in metabasites, that is, amphibolites, is intermediate-to-basic plagioclase and hornblende. In granulite facies rocks, where water-rich minerals are absent, hornblende is replaced by orthopyroxene and clinopyroxene. Garnet replaces biotite.

Metamorphic rocks that are characterized by very high pressure belong to the glaucophane schist facies or are otherwise known as the blueschist facies. The diagnostic mineral for this facies is the mineral glaucophane, which is an amphibole. The first appearance of eclogites characterizes the eclogite facies. Ocean floor metamorphism is characterized by a high geothermal gradient and material transport through circulating seawater.

Burial metamorphism is defined by Bucher and Frey (2002) as a process directly following diagenesis and, thus, could be viewed as diagenesis under

higher pressure. The zeolite facies and the prehnite-pumpellyite facies characterize this process.

Slates are very low grade metamorphic rocks that originate from fine-grained pelitic and pelitic-psammitic sediments, which are essentially shales and siltstones. The characteristic feature of slates is a well-developed cleavage, where tectonic processes have created a well-developed anisotropy or cleavage parallel to the foliation. Most of the cleavage is caused by the shape-preferred orientation of the sheet silicates (clay minerals or mica). Depending upon the metamorphic grade, the alignment is the result of a passive rotation or a recrystallization and nucleation of the sheet silicates parallel to the foliation. The term “cleavage” is used when the tectonically induced foliation cuts and overprints the bedding (slaty cleavage). Cleavage is a type of foliation consisting of a regular set of parallel or sub-parallel, closely spaced surfaces (on a scale from mineral grain up to several centimeters), which is produced by deformation along a rock body where it will usually preferentially split. More than one cleavage may be present in a rock. Slaty cleavage is used for slates, where they were mostly deformed under greenschist facies conditions. The foliation is perfectly developed and independent of bedding, resulting from the parallel arrangement of phyllosilicates, individual grains which are too small to be seen by the naked eye.

Slates consist predominantly of phyllosilicates like illite, sericite (or fine-grained muscovite), and chlorite, as well as very fine-grained quartz (see discussion in Wagner 2007 or Morales et al. 2013). Wichert (2007) calculated the following contents: muscovite/illite lies between 25 and 55 %, followed by chlorite with 10–20 %, whose proportions may also be 5 % or can be as high as 30 %. Chloritoid can be present in slates where contents generally fluctuate between 2 and 4 %. Paragonite, which represents higher pressures during metamorphism, rarely occurs and shows contents between 1 and 3 %, but some individual analyses have given values ranging from 8 to 16 %. Slates are often used as roofing tiles and wall coverings (Fig. 2.40). As a result of this specific application, roofing and wall slates are not treated as a natural building stone. If, however, slates are used as floor tiles, facades, table and billiard surfaces, or even window sills, then they should be considered a part of the resource group natural building stones. Slate was used earlier as a writing surface (chalk board) in schools. Critical assessment should be made of ore minerals (pyrite, chalcopyrite, etc.) and carbonate contents present in the rock group known as slates.

Phyllites are fine-grained, foliated crystalline schists. They represent the link between non-metamorphosed argillaceous shales and metamorphic mica schists (Fig. 2.41). At relatively small temperature increases, metamorphic minerals such as sericite/phengite and chlorite begin to form, which is also responsible for the silky sheen on the foliation surfaces. Along with these minerals, quartz and even some albite are common in these rocks.

Schist is a metamorphic rock exhibiting schistosity. The term “schistosity” is used when the minerals are coarse enough to be easily seen in hand specimens. By this definition schist is a broad term, and slates and phyllites are also a type of schist. The most frequently occurring parageneses are quartz-biotite, quartz-muscovite,

Fig. 2.40 Use of slate as cladding material: **a** The slate wall of Lotharheil and **b** Slate flooring tiles (Schieferwerk Lotharheil & Teichmann SchieferZentrum, Geroldsgrün in Germany)



quartz-muscovite-chlorite, quartz-muscovite-biotite, and quartz-biotite-chlorite. Further minerals that occur in mica schists are garnet, albite feldspar, epidote, and others. The typical fabric characterizing mica schists is a well-developed banding. Quartz forms more or less stretched lens-shaped aggregates that lie parallel to the mica and chlorite flakes. Foliation surfaces are mostly uneven in detail, and the thickness of the quartz lenses and mica layers range from a few millimeters to somewhat above that. When other minerals like garnet occur as porphyroblasts, a different fabric develops. The color impression is dependent on the main minerals: muscovite (silver-gray), biotite (dark brown to black), chlorite (green), and the pigment minerals hematite and graphite. Freshly fractured surfaces show an intense brilliance. Over geologic time periods, muscovite schists disintegrate into platy and spiky fragments as a result of weathering.

Chlorite schists consist mostly of 70–90 % chlorite, 10–25 % other silicates, and up to 10 % ore minerals. They are strongly foliated and range in color from dark green to black green (Fig. 2.41). In Italy, chlorite schists are often mistaken for serpentinites because of their similar color, even though serpentinite minerals are either present in subordinate amounts or are not.

Gneiss is a collective term for quartz-feldspar metamorphic rocks that have an acidic to intermediate chemistry, where the fabric and modal constituents can vary

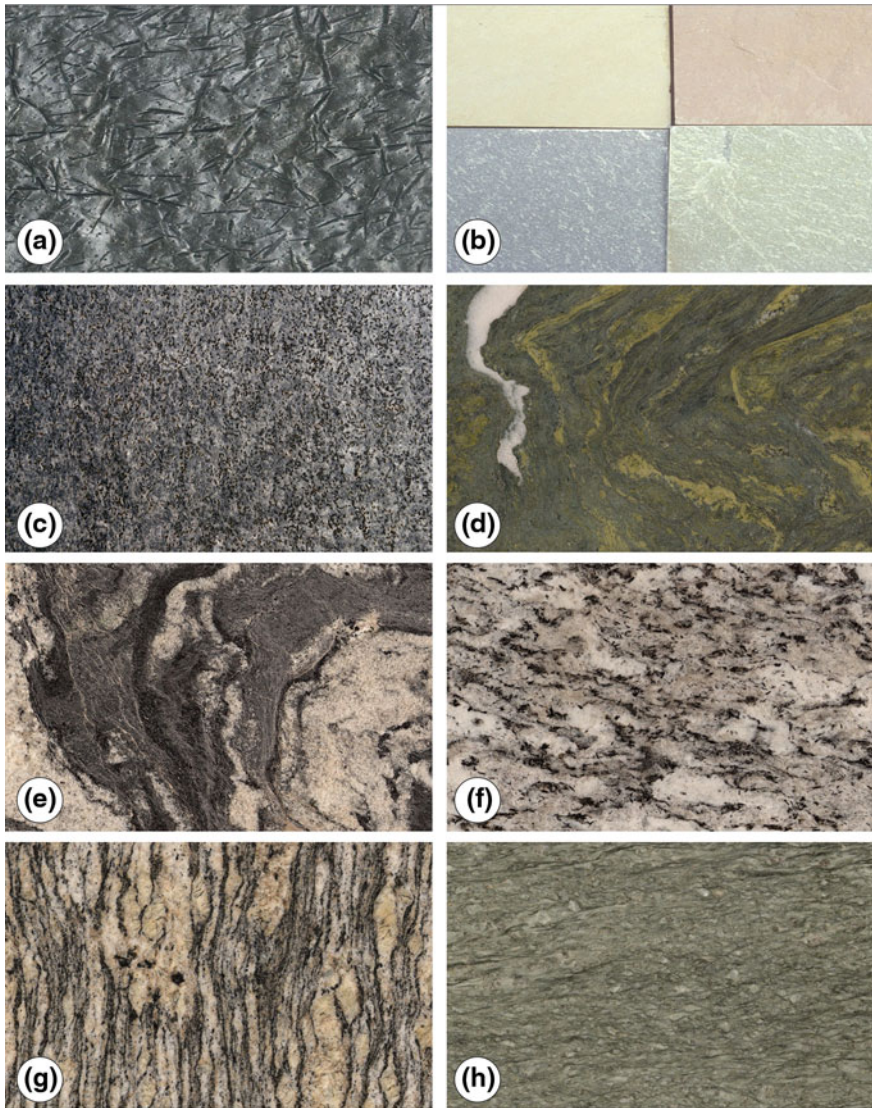


Fig. 2.41 Commonly used metamorphic rocks: **a** Otta Phyllite, **b** Camine Rufo Slate, **c** Theuma Knotted Slate, **d** Dorfergrün Chlorite Schist, **e** Mähring Biotite Gneiss, **f** Leggiuna Paragneiss, **g** Diodena Gneiss, and **h** Verde Andeer Gneiss (Figure by Natursteinarchiv Wunsiedel)

widely. Accessory minerals include biotite, muscovite, amphibole, cordierite, garnets, sillimanite, kyanite, or graphite, etc. They have a poor rock cleavage and display a gneissose structure. Gneisses are typically layered (also called banded) and often exhibit alternating felsic and darker mineral layers (Fig. 2.42). The rocks may be lineated, but also show segregations of felsic mineral-rich and

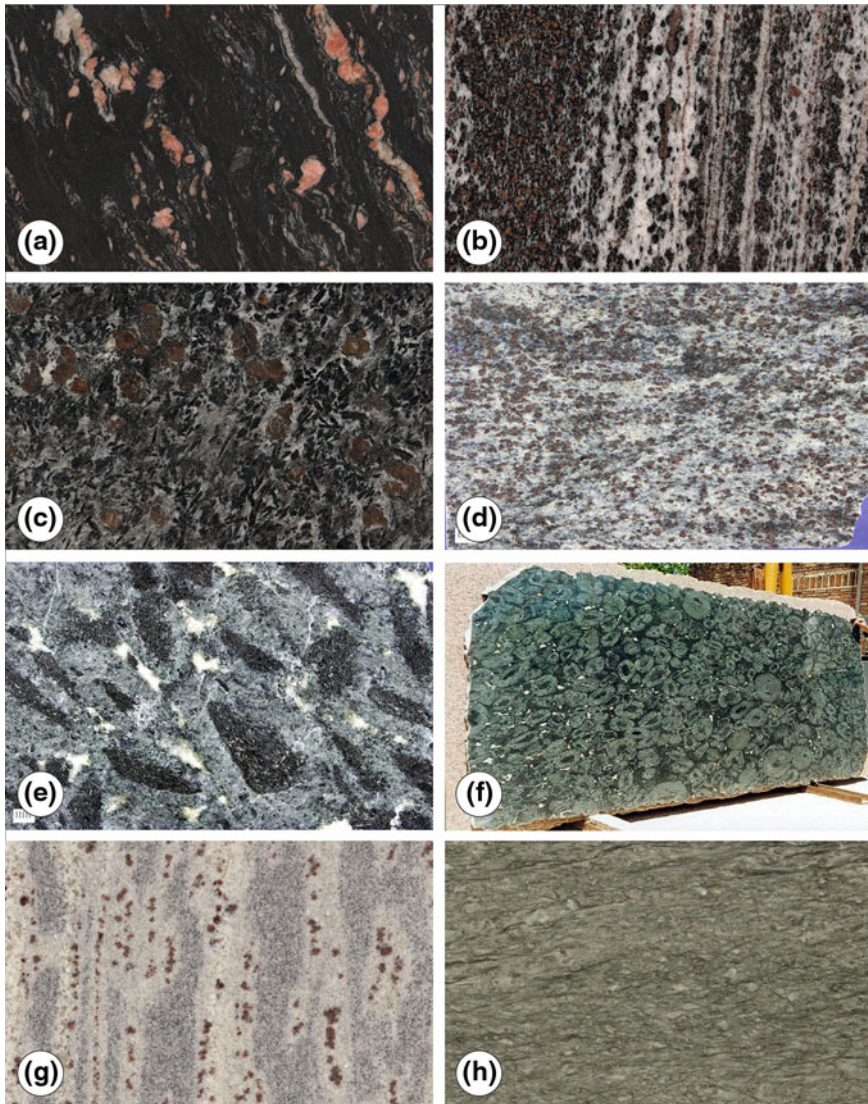


Fig. 2.42 Commonly used metamorphic rocks: **a** Pontorosa Biotite gneiss, **b** Tundra Gneiss, **c** Kendlbruck Garnet Amphibolite, **d** Azul Tango Cordierite Gneiss, **e** Verde Orcollano, **f** Verde Orcollano, **g** Keralowhite Garnet Gneiss, and **h** Silberbach Eclogite (Figure by Natursteinarchiv Wunsiedel)

dark mineral-rich concentrations (Fig. 2.43). The boundary between mica schists and gneisses is determined by the amount (20 vol %) of feldspar present. Gneisses may also be considered a medium to coarse-grained rock with a poorly developed schistosity where feldspar and quartz are characteristic components

(Brodie et al. 2007). A typical representative of this group is the Beolo Gneiss of the Beura area in Italy, which is widely used as a building stone (Cavallo et al. 2004). This rock is a black and white pencil gneiss that is composed of quartz, plagioclase, K-feldspar, muscovite, and biotite. Chlorite occurs as a retrograde product. The macroscopic appearance is characterized by a strongly developed lineation (stretched Qtz/Fsp aggregates) and rotationally arranged biotite and muscovite. Biotite and muscovite form enriched layers and, next to the flattened Qtz/Fsp aggregates, define the foliation. Since biotite traces the linear fabric, these natural building stones can be split easily. When this gneiss is cut perpendicularly to the layering, the fabric that appears is known as a “augengneiss”, because biotite is rotationally aligned around the quartz and feldspars. Starting as far back as the 12th century, this excellent property, the ability to easily split into thin slabs, has been responsible for the wide use of these stones for buildings, staircases, pavements, and roof coverings.

The term “granulite” was often used in the past to define high grade metamorphic rocks. In the literature, only those rocks which contain the minerals indicative of the granulite facies are considered granulites. In the early petrographic literature, light-colored granulites are described as leptynites. Granulite is a high-grade metamorphic rock in which Fe–Mg-silicates are dominantly hydroxyl-free. The presence of feldspar and the absence of primary muscovite are critical, while cordierite may also be present. The mineral composition is indicated by prefixing the major constituents. The rocks with >30 % mafic minerals (dominantly pyroxene) may be called mafic granulites, and those with <30 % mafic minerals (dominantly pyroxene) may be called felsic granulites. The term should not be applied to ultramafic rocks, calc-silicate rocks, marbles, ironstones, or quartzite (Coutinho et al. 2007). Such rocks are the typical representatives of the lower crust. They consist of feldspar, quartz, garnet, kyanite, sillimanite, and orthopyroxene. The protolith of these rocks are probably rhyolites or rhyolitic tuffs or granitoids. Mafic granulites are also known as pyriclasites composed of orthopyroxenes (hypersthene), clinopyroxene, plagioclase, garnet, and ilmenite. The remarkable regions of the Ivrea Zone (Italy) are excellent areas for studying these kinds of high grade metamorphic rocks. In Calabria, a mafic-dominated granulite-pyriclasite unit that is composed of pyriclasites and mafics, as well as felsic granulites, occurs. The metapelite unit consists of biotite-plagioclase gneisses, metapelitic rocks known as stromalites, and felsic granulites. Sillimanite-garnet gneisses are subordinated. Sometimes coarse-grained granulites are described as granofels. Charnockite granitoids of igneous and metamorphic origin are related to the granulites and carry the orthopyroxene hypersthene.

The upper temperature boundary of metamorphism is defined by the process of migmatization (partial melting). In typical rocks of the continental crust (metapelites, granitoids), the process begins at a temperature of around 650 °C (depending on the composition), under moderate pressure, and at a high H₂O partial pressure. Migmatites are becoming increasingly popular as a natural building stone. This is because the rock exhibits a lively decor and many different colors, opening the door for various design possibilities (Fig. 2.43). Geologically

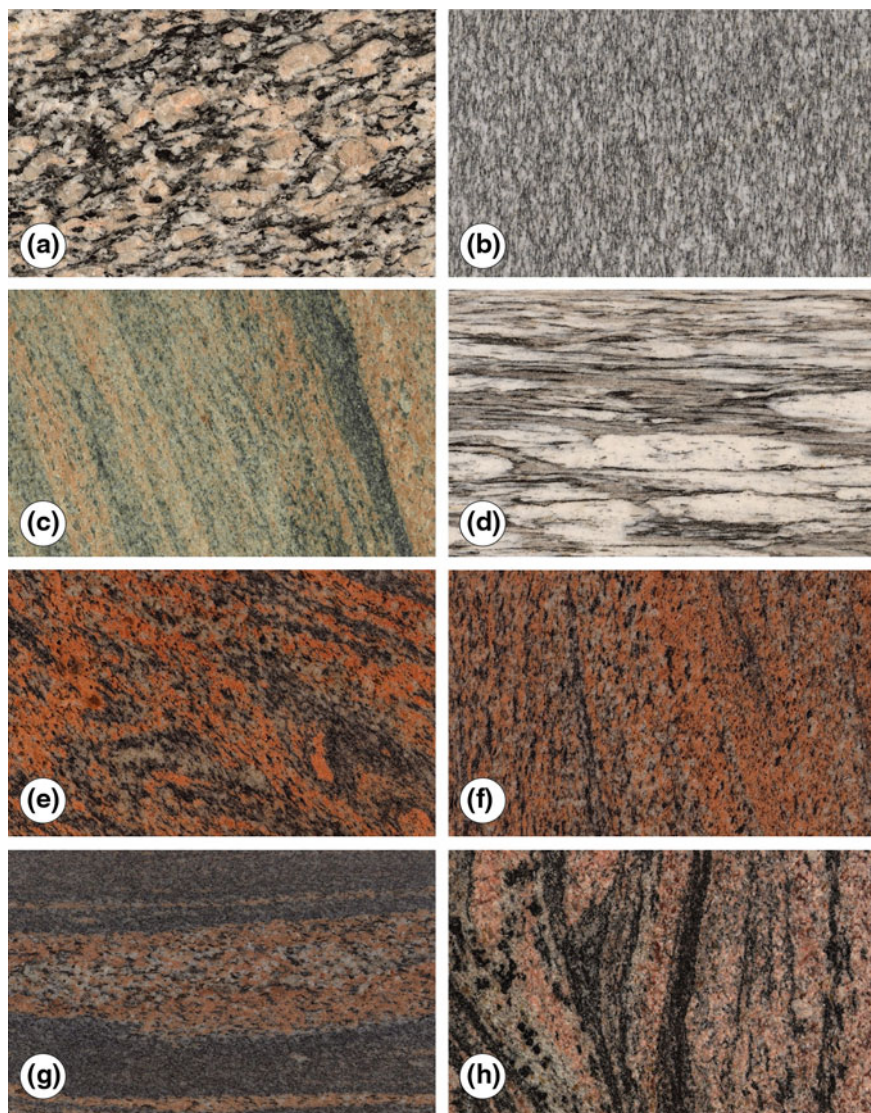


Fig. 2.43 Commonly used metamorphic rocks: **a** Pekkalan Orthogneiss, **b** Zillertal Paragneiss, **c** Indian Juparana Gneiss, **d** Kapighiandonestriato Orthogneiss, **e** Kinnasöder Migmatite, **f** Vastad Migmatite, **g** Borarp Migmatite, and **h** Rainbow Migmatite (Figure by Natursteinarchiv Wunsiedel)

migmatites can be described as very heterogeneous rocks. Migmatites form under high grade conditions and with various compositions. These aspects lead to the partial melting of the rock material. Magma formation deep in the crust can be studied when these rocks are occasionally exposed at the Earth's surface,

displaying the “frozen” melting process. The rock is characterized by the presence of dark gray to black layers (melanosome), which contain amphibole and/or biotite as the main mineral constituents, and light gray to white layers (leucosome), which are essentially composed of alkali feldspar and quartz (\pm plagioclase). Unmelted source rocks called restites can also occur. Leucosome and melanosome can also be referred to as neosome, because they both originate from the original source material. Restites can also be termed paleosome. The leucosome is the newly formed partial melt and the melanosome is the part extracted from the melt. At the outcrop scale, migmatites often show a very heterogeneous appearance. Restites can occur as long-sustained layers, or they can form isolated blocks. Migmatites can also show irregular folding of the layers. Mehnert (1968) has established a very useful classification of migmatitic fabrics. The classification utilizes a scale-orientated configurative comparison of the leucosomes and melanosomes without applying the genetic aspects as a basis.

Eclogites are former basalts, basaltic tuffs, or gabbros and, as a result of metamorphism, mainly contain the clinopyroxene omphacite, garnet, and possibly quartz or kyanite, but no plagioclase. The rocks are restricted to smaller deposits and are, therefore, used exclusively for limited building projects and the decorative arts.

Quartzites are metamorphic rocks that are dominated by the mineral quartz. According to Bucher and Frey (2002), quartzites should contain more than 80 % quartz. Associated minerals in quartzites are muscovite, feldspars, and a larger variety of heavy minerals such as magnetite, garnet, ilmenite, etc. In contrast to the orthoquartzites known from sedimentary deposits, the metamorphic ones are characterized by low porosities. Metaquartzites are very hard and stiff and popular building stones, since they are also very weather resistant. They show a widespread distribution, for example, in the Minas District (Brazil). These quartzites are used for exteriors and interiors and widely deployed in the architecture of health resorts. In this type of application, these rocks are resistant to salt damage in saline baths as well as against aggressive cleaning solutions. An interesting phenomenon is the Itacolomites, which are closely associated with the Brazilian quartzites. Itacolumites are very special rocks due to their high flexibility (Siegesmund et al. 2002b). They are composed of quartz (80–95 vol %) and muscovite (2–10 vol %), with kyanite, tourmaline, zircon, feldspar, and ore minerals being the main accessories. The observed bending and its anisotropy can be explained by the rotation of separated quartz grains between layers of mica. These act as flexural slip planes and are also responsible for the observed elastic rebound. This behavior is related to the very thin layers, characteristic higher porosity and a significant change in the pore-radii distribution. Another exotic quartzite is the Azul Macauba and related varieties, which belong to the most expensive dimensional stone in the world (Fig. 2.44a and b). The blue color is related to the mineral dumortierite (an aluminum-iron-boron silicate). The fabric of these quartzites varies strongly, which is also the case for the color. Natural quartzites occur in all colors depending on the proportion of, for example, limonite (yellow and beige varieties) or hematite (red).

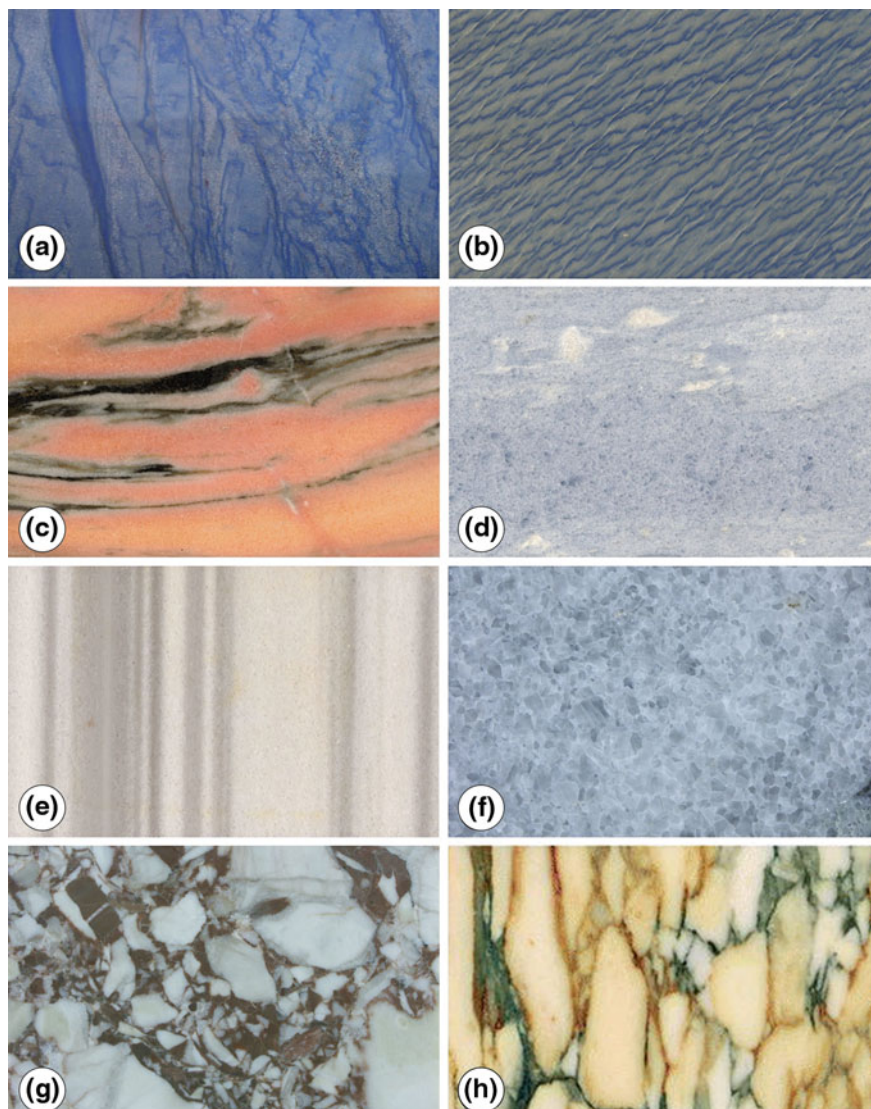


Fig. 2.44 Color and textural varieties of marbles and selected metamorphic rocks: **a** Azul do Macaubas (quartzite), **b** Azul Macanbas, **c** Artigas (calc-silicate), **d** Celeste Argentina, **e** Bantli (marble), **f** coarse crystalline marble (Thailand), **g** marble breccia, and **h** Carrara Marble (Calacatta) (Figure by Natursteinarchiv Wunsiedel)

In the natural stone industry, all types of polishable limestones are designated as marbles. However, in the petrographic literature, the term “marble” is restricted to those rocks that have undergone metamorphism. Marbles are defined in the strict sense as those rocks containing >90 % calcite or dolomite. Accordingly, the rocks

Fig. 2.45 The Oslo Opera House where the external facade is covered with Carrara Marble (Vando D'Angiolo, Campolonghi Italia Spa)



are designated as either calcite or dolomite marbles. The presence of siliceous and argillaceous mineral components as well as organic material in the original source rock can lead to the formation of new mineral phases, depending upon the grade of metamorphism (e.g. quartz, muscovite, feldspars, garnets, wollastonite, tremolite, graphite, talc, pyrite, magnetite, etc.). Marbles of this type with a carbonate proportion of 50–90 % are designated as calc-silicate rocks. In many marbles, these mineral phases also form a banding that can, in part, develop an irregularity or, as it is sometimes called, a “marbling” effect (Fig. 2.44). Furthermore, finely disseminated mineral phases can also impart a specific pigmentation, e.g. hematite creates red and chlorite, and serpentine generates green colors. Marbles can essentially be found in many different colors. The most well-known examples are from Greece (Fig. 2.9c) or Italy (Fig. 2.9d).

Grimm (1999) indicates that about 200 marble varieties are economically exploited worldwide (see also Müller 1996). In Carrara (Italy), for example (Fig. 2.3a), there is a vast amount of different marble types that are known under a variety of commercial names, such as Marmo Ordinario, Marmo Venato, Marmo Nulolato, Marmo Arabescato, Marmo Statuario, Marmo Calacata, Marmo Bardiglio, etc. Mecceri et al. (2007) determined three main general fabric types in the Carrara area, i.e. Type A, a granoblastic (polygonal) microstructure, Type B showing sutured grain boundaries, and Type C, which is characterized by a strong shape-preferred orientation including straight to interlobate grain boundaries. Müller (1996) already compiled the above-mentioned Carrara types into an arrangement according to commercial criteria (see Fig. 2.45).

The color variation in marbles shows a wide range: from light white to light yellowish-gray-beige, various shades of pink, red to yellow–brown, and different hues of green. Black and even blue shades are known, although their occurrence is much more rare. An especially impressive variety is the Azul Cielo, where the calcites exhibit a blue color. Next to calcite, a small amount of finely disseminated diopside, wollastonite, apatite, and even quartz occur as accessory minerals. Quartz is mostly recrystallized and forms very fine bands. The impressive blue coloration is probably due to physical defects in calcite. Experiments have shown

that the blue color disappears when the rock is heated to a temperature of over 200 °C (Lambergini et al. 2000). Marble can also be highly differentiated. Sections of the rock can appear without veins and streaks. Layers can occur with a light streaky fabric and without a clear development of these elements. Other areas are evident where differentiated occurrences of streaks appear with distinct colors of yellow, brown, red, and green. Variations in structure and fabric are possible in deposits where the changes develop over short distances in the quarry. Quarries also rarely produce consistent, uniform, or homogeneous rock material. This is due to the relatively deformable character of marble and the occurrence of frequent fold structures.

Serpentinites are interesting building stones and a very important rock group. They form from peridotites by hydrothermal alteration processes under specific metamorphic conditions. Serpentine minerals predominantly make up the rock. Peridotites represent mantle material directly below the oceanic crust or cumulate rocks formed by the settling of olivine and pyroxene in mafic–ultramafic layered complexes. Protoliths are either lherzolites containing olivine, ortho- and clinopyroxene, or harzburgites consisting of olivine and orthopyroxene. The serpentine minerals are alteration products of olivine and other magnesium-rich silicates and consist of fibrous chrysotile, lamellated antigorite, and sometimes a fine-grained scaly lizardite. Depending on the intensity of serpentinization, olivine, ortho- and clinopyroxene, garnet, chlorite, and talc can occur. During the alteration of olivine, iron is released and is concentrated along the grain boundaries as magnetite, since Fe cannot be incorporated into serpentine minerals. Intense red colorations are due to the alteration of magnetite to hematite.

The purest kind of serpentine generally shows a pale greenish or yellow color, is often variegated and slightly translucent, and breaks with a rather bright conchoidal fracture. Serpentinites exhibit a large spectrum of different rock fabrics. Some form massive bodies. This is seldom the case because serpentinites are easily deformed by tectonic processes. They often show a foliation with sigmoidally developed slip planes, which gives the rock a polished or lineated appearance (Fig. 2.46). Shear planes forming an interconnected system also occur frequently. Serpentinites show brecciated structures that contain more or less large amounts of carbonate in layers or streaks. Included in the carbonate matrix are serpentinite fragments. Such rocks are also known as ophicalcites and are a popular building stone because of their conspicuous decor. Occasionally, pronounced talc nests occur together with veins of chlorite. Serpentinites are relatively soft rocks, which are easily polished and have been used over time as gemstones, for monuments and architectural elements, etc. Rock surfaces exposed to the long-term stress of different weathering conditions exhibit a rapid alteration of appearance, and, thus, the use of this stone for exterior applications is not recommended.

Contact metamorphism encompasses the recrystallization of rocks within an aureole around an intrusive body due to the supply of heat, and possibly through the additional transport of materials from the magma (Fig. 2.47). The contact effect is dependent on the temperature of the intruding magma and depth of intrusion. The temperature of an intruding granitic melt ranges from 650 to

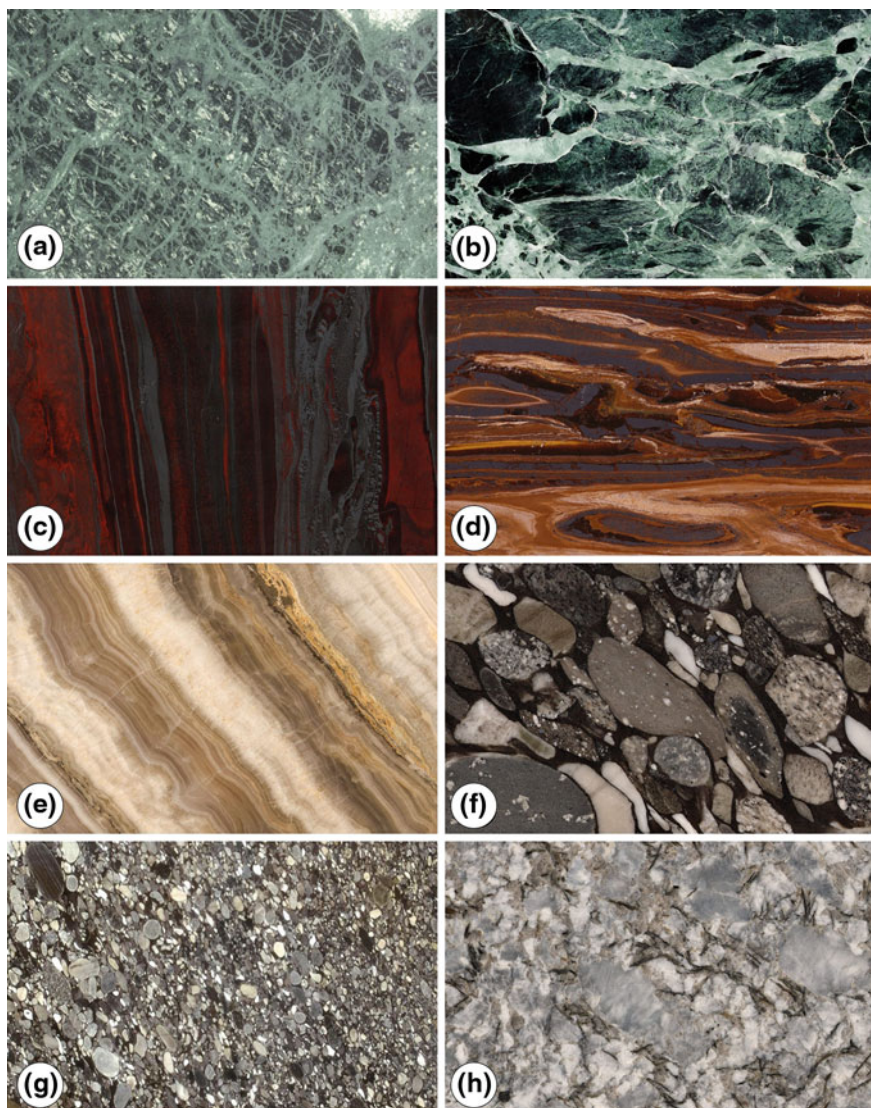


Fig. 2.46 Commonly used metamorphic rocks: **a** Verde Guatemala (serpentinite), **b** St. Denis (serpentinite), **c** Itabirite (ironstone), **d** Jaspis, **e** Cebrino (onyx), **f** deformed conglomerate, **g** Nero Marinese (deformed conglomerate) and **h** Valdarana (pegmatitic gneiss) (Figure by Natursteinarchiv Wunsiedel)

900 °C, whereas a basaltic magma is around 1,200 °C. Country rocks are relatively cold (100–300 °C) when magma intrudes into a region near the surface, which means the temperature difference between the intrusive body and the wall rock reaches a maximum value. In this case, a strong thermal gradient occurs near the intrusive contact.

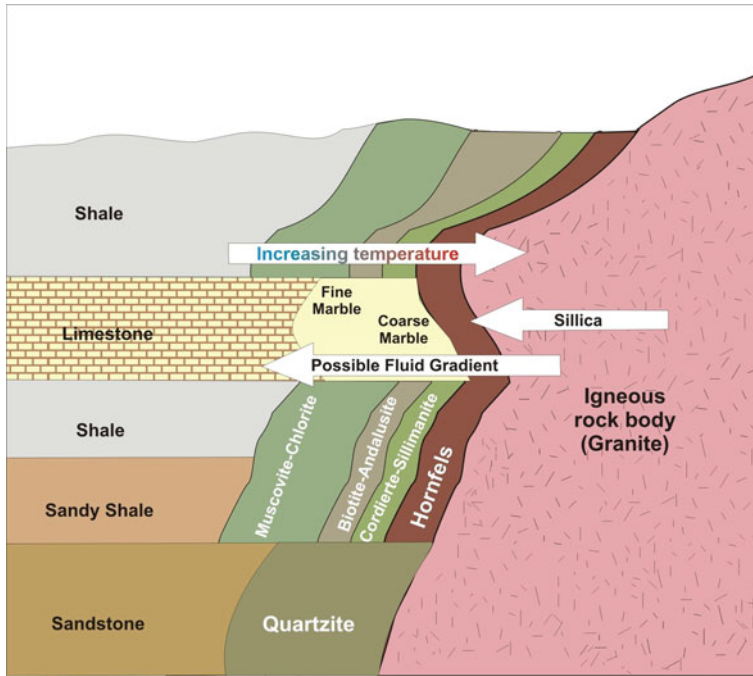


Fig. 2.47 Contact metamorphism and the most important mineral phases and metamorphic rocks formed from various sedimentary rocks such as limestone, shale and sandstone (modified after Hamblin 1989)

Directly at the contact, completely recrystallized splintered rocks with a dense random fabric, known as hornfels, occur. With increasing distance from the contact, the fabric of the rock hardly shows an overprinting. Only the type and shape of the newly formed minerals (see mineral isograds in Fig. 2.47) indicate the influence of the thermal effect. A good example of this thermal influence is the Knotenschiefer in Theuma (Germany). This schistose rock has a blue-gray, macroscopically homogeneous, and dense groundmass, where dark-gray to black, oriented columnar porphyroblasts up to 5 mm in size occur (Fig. 2.48). The cordierite minerals in the rock are typical for this building stone and give the rock its name, i.e. Knotenschiefer. The porphyroblasts have a shape similar to a seed of grain. The spindle and cigar-shaped cordierite is oriented relatively well to the schistosity, but, within the foliation plane, they lack orientation. Bedding is weakly characterized by a change from light to dark layers. The dark layers consist predominantly of ore (magnetite, ilmenite) (Peschel and Franz 1968). The macroscopic, apparently homogeneous groundmass exhibits a fine, flaky to foliated fabric consisting of sericite, chlorite, and biotite with a grain size of about 15 μm (Peschel and Franz 1968). Limestones grade into marble as a result of grain coarsening in the contact zone. Calc-silicate rocks are formed by the metasomatism between carbonates and silicate-rich rocks or fluids. These rocks are known as scarns.

Fig. 2.48 Building cladded with the Knotenschiefer (knotted slate) of Theuma. The very specific decor is due to the contact metamorphic overprint, which had produced the mineral growth (Natursteinwerk Theuma AG, Theuma in Germany)



2.11 Sedimentary Rocks

Sedimentary rocks are the most widespread rock types on the Earth's surface, especially when one considers the present day oceans as the cradle of sedimentary rocks. A continuous formation of sediments of marine origin is well documented from the very beginning of the Earth's history. Vast amounts of sedimentary rocks were produced, from which only parts have been preserved throughout geologic time. Although they represent less than 10 % of the Earth's crust, their contribution to the present day continents are approximately 70 %. The sedimentary rocks can be classified according to their origin into three major groups: (i) detrital sedimentary rocks (clastics), (ii) chemically or biologically precipitated sedimentary rocks, and (iii) organic sedimentary rocks. According to some authors, pyroclastic igneous rocks can also be classified as sedimentary rocks, but, in terms of origin and technical use, these lithotypes should be considered part of the igneous rock system.

Detrital sedimentary rocks are formed from previously existing rocks by subsequent processes, including weathering, transportation, deposition, compaction, and diagenesis. The best known examples are sand or sandstone. Chemically or biologically precipitated rocks are the ones that are mostly formed in aquatic

environments by chemical and/or biological reactions. The formation process also includes compaction and diagenesis. In this group, the most widespread lithotype is limestone. Organic rocks are normally formed from the accumulation of organic carbon-rich fossils via a complex alteration process that produces solid, liquid, or gaseous end products, such as coal, crude oil, or natural gas. This latter group is of limited importance and has no functional use in the design of architectural elements. Therefore, it will not be discussed in detail in this book.

2.11.1 Detrital Sedimentary Rocks

Detrital sedimentary rocks are formed from the disintegration of formerly existing rocks at or near the Earth's surface by means of weathering. Weathering is a complex process that includes various types of alteration, generating rock fragments or clasts. The other name of detrital sedimentary rocks, "clastic sedimentary rocks", refers to this process. Weathering can be attributed to physical/mechanical, chemical, or even biological processes (see [Chaps. 4 and 6](#)). In most cases, a combination of mechanical, chemical, and biological weathering is responsible for the decomposition of rocks and the formation of rock fragments. The ultimate weathering products of rocks are soils. The best example for chemical weathering is the dissolution of limestone and karstification, but it also includes physical and a limited range of biological decay and alteration. Under a very dry and cold climate, chemical weathering is limited, and physical weathering prevails.

Biological weathering is a combination of physical and chemical processes at the interaction surface of living organisms and stone. Tree roots can also exert pressure on stones and lift up large blocks as they grow, whereas lichens produce acid which can dissolve even the most durable stones.

After the generation of rock fragments of various sizes by weathering, the newly formed particles are transported by means of wind, water, or ice. The transportation can take place on land (by streams, wind or glaciers, etc.) or in the oceanic environment (by waves, currents, etc.). Large masses of sediments are displaced by these processes at every moment, contributing to the sediment budget of land and sea. By scrupulously studying detrital sedimentary rocks, it is possible to identify the transporting medium and the process. Internal structures of rock beds (e.g. cross bedding) and sedimentary features (e.g. grading), as well as fossils, can indicate the origin of the rock. The largest amount of sedimentary rocks are formed in marine or coastal environments (Fig. 2.49) and as river deposits (Fig. 2.50), but dry and arid settings such as desert environments also contribute significantly to clastic sedimentary systems. Water and ice can only move particles downward, whereas the wind is able to move dust/sand or, rarely, pebble-sized particles upward.

Transportation is followed by deposition, which presumes changing conditions in water or wind agitation, and, thus, the transporting medium does not have the ability to move the sediments. In terms of depositional mechanisms and environments, a wide range of facies exists both "on land and in the sea".

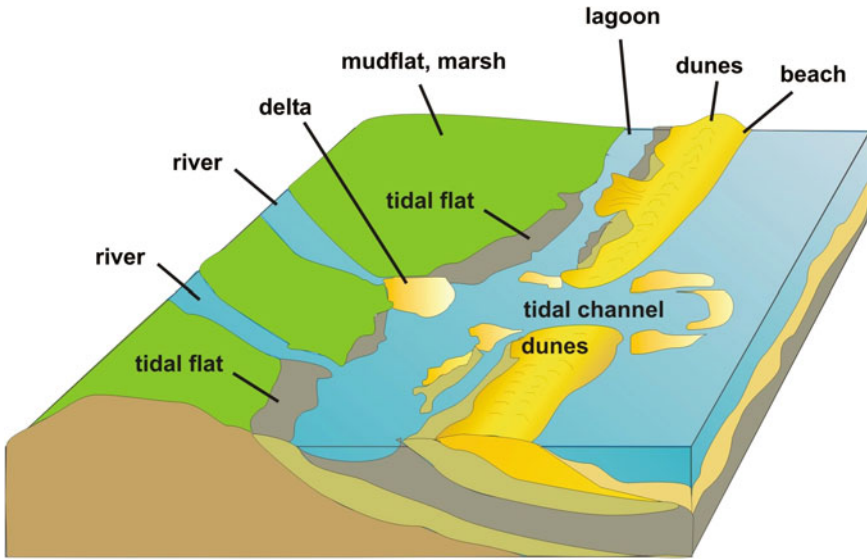
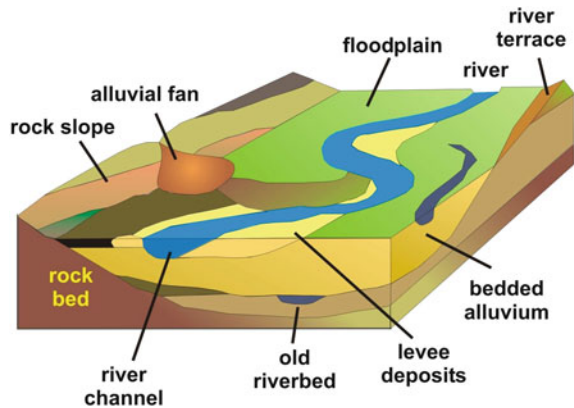


Fig. 2.49 Detrital sedimentary rock formation in coastal marine settings. Sands and coarser sediments are found at deltaic to coastal environments such as lagoons, beaches, dunes, tidal flats and marshes, etc

Fig. 2.50 River deposits of detrital sedimentary origin include clay-sized sediments from flood plains to sandy and gravelly deposits from river channels



The deposition could be rapid or slow. When slurries are formed and sediments are deposited, a typical grading is observed. This means that coarse and heavy particles are deposited first, followed by particles of decreasing grain size.

The deposition of clastic sedimentary rock layers on top of each other leads to the compaction of the sediment, which is interpreted as a decrease in volume and a denser packing of grains by the weight of the overlying layers. Cementation can be a simultaneous process with compaction, or, in some cases, it can be coeval with

Table 2.2 Classification of detrital sedimentary rocks according to grain size and cementation

Sediment	Grain-size (mm)	Consolidated/Cemented
Boulder/cobble (rounded)	63	Conglomerate (rounded)
Rock fragment (angular)		Breccia (angular)
Pebble (rounded)	2–63	Conglomerate (rounded)
Rock fragment (angular)		Breccia (angular)
Sand	2–0.063	Sandstone
Coarse	2–0.63	Coarse sandstone
Medium	0.63–0.2	Medium sandstone
Fine	0.2–0.063	Fine sandstone
Silt (Aleurite, mud)	0.063–0.002	Siltstone (Aleurolite, mudstone)
Clay	<0.002	Claystone

deposition. This causes the binding of the grains/particles by cementing minerals and provides a bridge between particles. By cementation, the loose, so-called unconsolidated sedimentary rock (e.g. sand) becomes a solid rock (e.g. sandstone). The cementation itself is only one part of the diagenesis, which is a term that refers to the processes responsible for the formation of the rock after deposition. Dissolution and the opening of new pores is also a part of the diagenetic process which acts in a way opposite to cementation. This causes a decrease in strength and durability of the rock, whereas compaction and cementation generally increases both.

Detrital sedimentary rocks are classified by two specific aspects: (i) particle size and (ii) rate of cementation. The latter one is difficult to define clearly, but, in general, the sediments that are unconsolidated and do not have any cementing mineral belong to this group (such as gravel, sand, etc.). The classification of detrital sedimentary rocks referring to particle size is a well-defined system, although the numerical values defining one special rock type might change from country to country. In this book, the nomenclatures and grain sizes described by the European Norm (EN 12670, 2001) are used. The most important detrital sedimentary rocks, according to the differences in grain size, are listed in Table 2.2.

2.11.1.1 Consolidated Detrital Sedimentary Rocks

The nomenclature of consolidated/cemented detrital sedimentary rocks reflects the differences in grain size and also relies on the visual assessment of grains. From a practical point of view, the cementing mineral is almost as important as the type of grain, since both determine the properties of the rock. Various types of cement are known, including carbonates (calcite, dolomite), iron-oxide or iron-oxi-hydroxide (limonite, goethite), siliceous (crystalline or amorphous silica, such as chalcedony), or even clay cement (e.g. kaolinite). The cementing mineral very often influences not only the mechanical properties but also the color of the detrital

sedimentary rock. Iron-oxide stains red, while iron-oxide-hydroxide gives a brownish color to the stone. Carbonates and clay minerals, as well as silica cement, are often white to colorless and, thus, do not change the visual appearance of the stone. In terms of strength and durability, silica cemented stones have higher load-bearing capacities and resistance against weathering or decay. On the other hand, hard silica-cemented sandstones are difficult to work with, and, therefore, their use for ornaments or statues requires more work.

The rock types that have particles greater than 2 mm are divided into two groups based on the roundness of the particles. Conglomerates are characterized by rounded grains, whereas breccia contains angular particles. In theory, no upper limit for grain size is given, but, in most cases, the size of the larger particles are on the order of tens of centimeters, rarely meters.

Conglomerates contain rounded pebbles of size 2 mm or larger. Some conglomerates resemble concrete, but larger varieties exist due to the differences in the lithology of the pebbles. Most conglomerates are composed of resistant quartz or quartzite pebbles, but limestone or even iron ore can be the dominant pebble type. The types that look like very coarse sandstone and are predominantly composed of quartz are used as ashlar, as cut building blocks, or in the footings of houses. On the other hand, limestone conglomerates are very often used as polished slabs or as polished decorative stones (e.g. columns, pillars, statues), especially in prestigious relics and in churches (see Fig. 2.56h).

Breccia encompasses angular grains of at least 2 mm in size. In conglomerates, quartz pebbles dominate the rock, while most breccias consist of particles other than quartz, very commonly limestone or dolomite. Brecciated marbles are also known (see Fig. 2.44g). Several types of breccias can be easily polished, and, thus, this stone type is commonly used for slabs or ornaments. Stylolitic limestone breccias with their decorative appearance are very often precious stones. The durability of the breccia often depends on the cementation and the compaction and can be determined by the presence of clayey seams. In other words, the clayey seams reduce the strength and durability of the breccia. Breccia can be formed due to tectonic activity, which results in a cataclastic fabric. Dissolution can also generate breccias.

Sandstones are by far the most common detrital sedimentary rocks that are used in architecture and in objects expressing the cultural heritage of a society. In most European countries, historic structures and monuments built from sandstones are still preserved and standing. Scotland, England, and Northern Ireland are characterized by the presence of Carboniferous and Permo-Triassic sandstones. The Permo-Triassic sandstones are generally yellowish-brownish to reddish in color and have been used not only within the UK, but have also been exported to the United States. In Germany, France, and Switzerland, Mesozoic sandstones are very common (Fig. 2.52). Significant amounts of sandstone were formed in the Late Permian to Triassic and Cretaceous periods (see Fig. 2.51). World heritage buildings such as Petra in Jordan (Fig. 6.15 in Chap. 6) are all made of sandstone.

The grain size of sandstones ranges from 0.063 to 2 mm. A further, finer subdivision is also possible according to the grain size. Fine sandstones contain

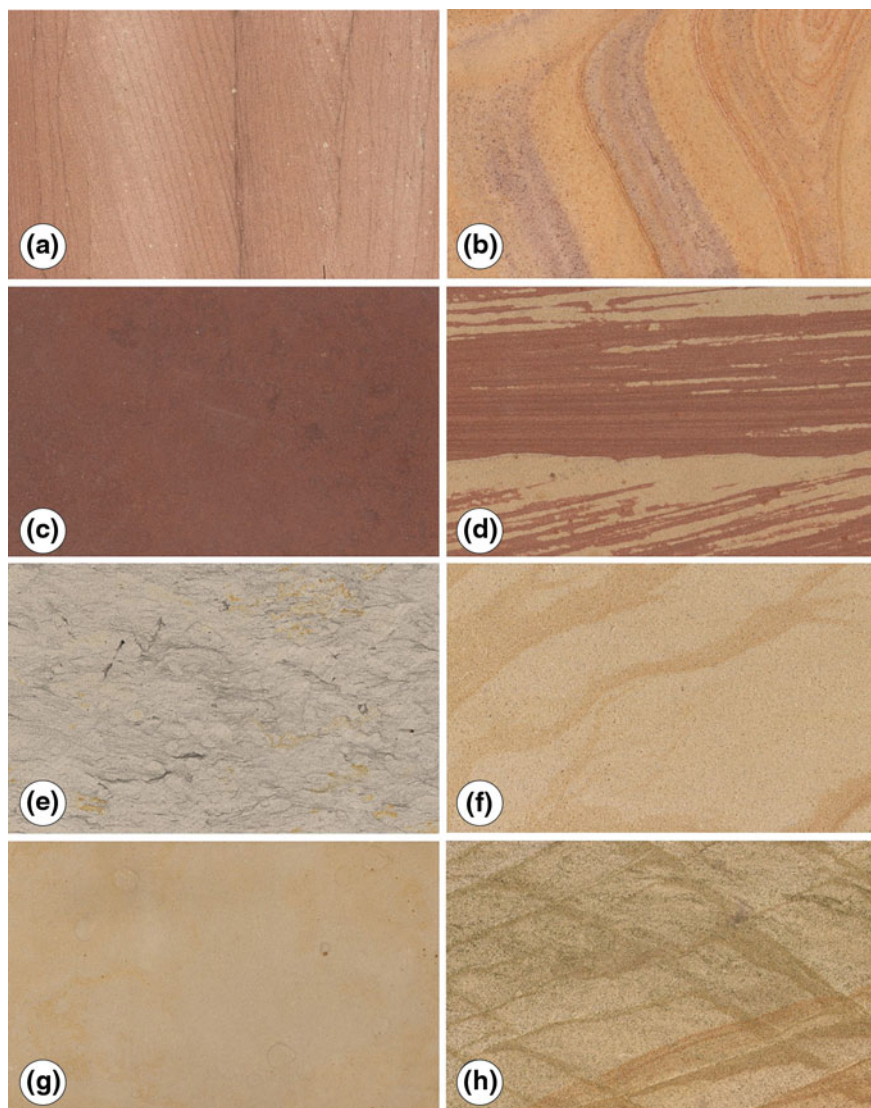


Fig. 2.51 Color and textural varieties of sandstones: **a** Crossbedded Sandstone, **b** Rainbow Sandstone, **c** Tambach Sandstone, **d** Miltenberg Sandstone, **e** Cotta Sandstone, **f** Posta Sandstone, **g** Obernkirchener Sandstone, and **h** Steinlutter Sandstone (conglomerate) (Figure by Naturstein archiv Wunsiedel)

grains ranging from 0.063 to 0.2 mm; medium-grained sandstones show particle sizes of 0.2–0.63 mm, whereas coarse sandstones with particles ranging 0.2–2 mm form a transition toward conglomerates. Sandstones exhibit great varieties in terms of appearance and properties. The color of sandstone can be white to almost black

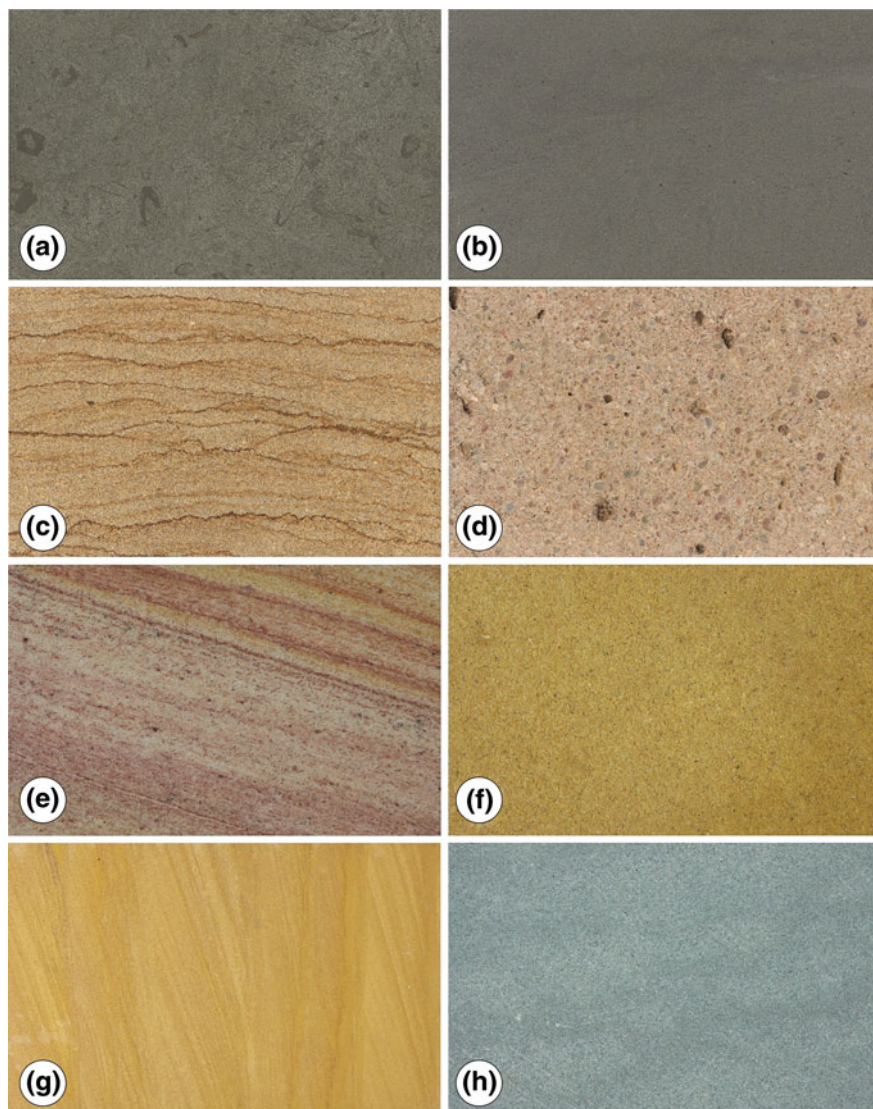


Fig. 2.52 Color and textural varieties of fine- and coarse-grained sandstones: **a** Anröchter Calcareous Sandstone, **b** Bauermährischer Sandstone, **c** Pietra Dorata Sandstone, **d** Radkow Sandstone, **e** Thailand Red, **f** Thailand Beige, **g** Crossbedded Thailand Beige, and **h** Thailand Green (Figure by Natursteinarchiv Wunsiedel)

(dark gray), but is more commonly light gray, beige, brownish, and reddish, and even greenish varieties are known (Fig. 2.52). The surface of sandstone is always rough and resembles sandpaper. The properties are mostly determined by the mineralogy of the grains, by the mineralogical composition of matrix and cement,

and by the porosity. There is a difference between the framework and the matrix. The former one includes the grains that provide the framework for the rock fabric, whereas the latter one generally includes finer particles less than 30 μm .

The most durable sandstones are the silica cemented quartz sandstones. These varieties often contain smaller amounts of other minerals such as mica or iron oxides. The presence of clay minerals can negatively influence the properties and durability of sandstones. Especially swelling clays, such as montmorillonite, can have an adverse effect on the use and long-term behavior of sandstone (Sect. 3.5). Although quartz sandstones are the most common, there are sandstones which are primarily composed of carbonate grains. This lithotype is also called calcarenite and forms a transition to limestones. In most cases, calcarenitic sandstones are less durable than quartz sandstones, although the workability of these sandstones is much better than their siliceous counterparts. Quartz sandstones often contain feldspars such as orthoclase or plagioclase. The feldspar-rich sandstones (with more than 25 % feldspar) are called arkose. Fragments of other rock types can also occur in sandstones, and these are called lithic fragments. Sandstones are grouped into three main types: quartz arenite, feldspathic arenite, and lithic arenite. With increasing clay and mud content, the stone is called muddy or argillaceous sandstone. These terms are used for sandstones that have a fine matrix consisting of at least 15 % mud and clay. One of the most well-known types is Greywacke, which is a clayey sandstone, with some feldspar content.

The porosity of sandstones shows a wide range from very low (only a few percentage points) to very high values of up to 35–40 %. The pore size is generally less than the grain size, and large open pores are very rare. Important features of sandstones are the sorting and the roundness of grains. Well sorted sandstones contain equi-dimensional grains, whereas, in poorly sorted sandstones, the sand particles show various grain sizes. Sedimentary structures are commonly visible in sandstones. Laminations (parallel to cross-lamination) are small-scale features (less than 10 mm in size), whereas bedding or cross-bedding with layers greater than 10 mm are easily observable at a block scale with the naked eye. A wide range of bedding forms occurs from tabular cross-bedding to trough cross-bedding and symmetrical to asymmetrical forms. In graded sandstones, the whole grain size distribution shows an increasingly fining upward sequence, whereas, in inverse grading or negative grading, the finer particles are found at the bottom of the bed or lamina. Other elements that are commonly seen in sandstones are ripple marks, tracks or trails of fossils, nodules, burrows, etc. Some sandstone may contain fossils that indicate the depositional environment, such as bivalve shells, snails, ammonites, etc. Sandstones are formed in a wide range of environments from marine to terrestrial settings. A large amount of sandstones was formed in fluvial environments or under arid or semi-arid conditions in desert environments. Shallow marine sandstones and sand dunes along the seashore are very common in the present, as they were in the geologic past. These provide excellent environments for the formation of thick sandstone deposits.

Mudrocks are the most widespread rock types from the entire spectrum of sedimentary rocks. They contribute nearly 50 % of all of the existing sediments.

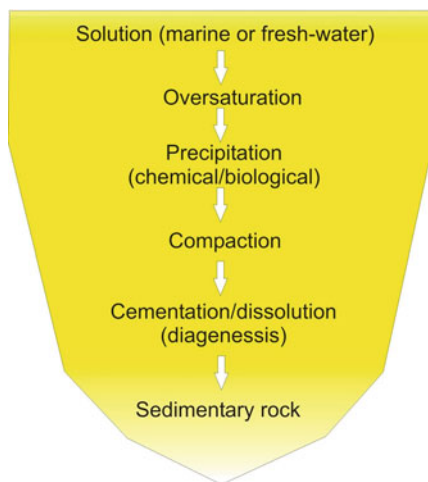
However, due to their low preservation potential and limited use as a building stone, they are under-represented in the architectural heritage of humanity's great monuments and public works. Furthermore, most mudrocks are very prone to weathering and, therefore, when exposed to the elements, very often disintegrate into smaller fragments. The term "mudrock" includes several lithologies under one common term that contains all particles smaller than 0.063 mm ($<63\ \mu\text{m}$). Mudrock encompasses names such as mudstone, siltstone, claystone, slightly metamorphosed (or diagenetically overprinted) shale, etc. Mudrocks can be differentiated based on grain size, since silt/mud has a grain size of $63\text{--}2\ \mu\text{m}$, whereas clay generally contains particles smaller than $2\ \mu\text{m}$ (or in some countries, $6\ \mu\text{m}$). Due to the very small grain size and the difficulties in identifying the particles in the field or at a building site, the terminology of mudstones is often misleading and used in an incorrect way. From a scientific point of view, two main classifications exist: one is based on the grain size (clay, silt, and sand content), and the other focuses on the mineralogical composition, whereby siliceous compounds, clay minerals, and carbonates are considered. The latter one also includes marls. Marls can also be considered carbonates, since they ideally contain 50 % clay-silt size particles and 50 % carbonates (mostly calcite).

Mudstone is the coarsest mudrock, with a prevailing grain size of $63\text{--}2\ \mu\text{m}$, but it can also contain finer grains of clay or coarser grains consisting of sand or pebbles. It appears in various colors and has a very different consistency, ranging from the soft, non-fissile rock to rigid varieties. Shale is a fissile variety of mudstone that has undergone some deformation and diagenesis. Mudstones and shales range from light gray to black or from yellowish-brown to red, depending on the mineral stain that is present. Black shales are common, and they are often enriched in organic carbon. Both mudstones and shales can show sedimentary features such as laminations or can contain pebbles and fossils. Claystones are characterized by particles of less than $2\ \mu\text{m}$ in size. Due to the very small grain size, the mineralogical composition of mudrocks is difficult to identify, and, thus, laboratory analyses (mostly XRD or DTA-DTG etc.) are needed for exact determination of the minerals present. There is no sharp boundary between the consolidated mudrocks and unconsolidated detrital sedimentary rocks, such as mud, silt, or clay. From an engineering geological point of view, mudrocks are very often considered to be unstable rocks for foundations, because they are commonly subjected to landslides and other slope movements.

2.11.2 Chemically or Biologically Precipitated Sedimentary Rocks

Chemically or biologically precipitated rocks differ from detrital sedimentary rocks, especially in their genesis. While most detrital rocks are formed from pre-existing rocks by weathering and erosional processes, chemically or biologically

Fig. 2.53 Formation process of chemically precipitated sedimentary rocks



precipitated sedimentary rocks have no prerequisites in terms of previous rocks, only an over saturation of solution or biological activity is needed. This difference in genesis between detrital and chemically/biologically precipitated sedimentary rocks generates very different properties and behavior.

The prerequisite for the formation of these rocks is the presence of a solution, in most cases either freshwater or seawater. The majority of these sediments are formed from seawater. The initial step is the supersaturation of the solution with respect to any dissolved compound. This could be the result of an increase in temperature or even the mixing of two undersaturated waters that leads to a supersaturated solution. The minerals or chemical compounds precipitated from the supersaturated solution occur by means of biological or chemical activity or both (Fig. 2.53). Moreover, organisms can also precipitate minerals from undersaturated water (e.g. marine snails and corals extract Ca and carbonate (CO_3) from seawater and build their calcite-aragonite shells). The precipitation is coeval with diagenetic processes such as cementation. The pores of the rocks are occluded by cementation or even enlarged by dissolution. Compaction is also a common phenomenon of chemically or biologically precipitated sedimentary rocks.

Unlike detrital sedimentary rocks, chemically or biologically precipitated sedimentary rocks are subdivided by their composition rather than their grain or crystal size. Consequently, four major rock groups of this origin are discussed here: (i) carbonates, (ii) siliceous sediments, (iii) evaporites, (iv) phosphates, and other sediments such as ironstones.

Carbonates are by far the most common chemically and biologically precipitated rocks and represent about one fifth of all sedimentary rocks. For simplicity, carbonates can be divided into two major rock groups, limestones and dolomites. The prevailing mineral of limestones is calcium-carbonate (calcite or aragonite), whereas for dolomites it's calcium-magnesium-carbonate (the dolomite mineral). Although they are very simple in terms of mineralogical composition compared to

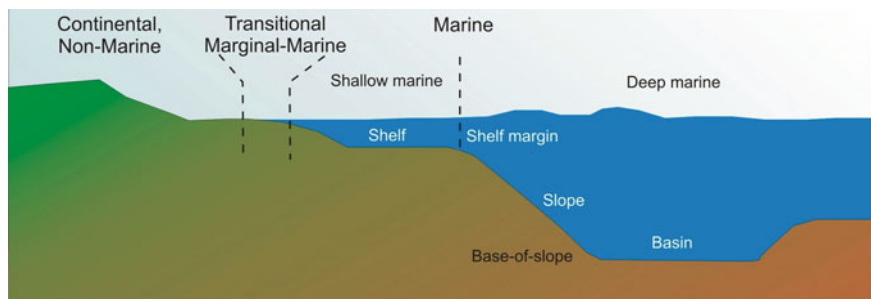


Fig. 2.54 Major carbonate depositional environments from continental settings such as streams and lakes (travertine) to marginal marine (coastal) and fully marine facies (shallow shelf to deep marine) (modified after Flügel 2004)

igneous or detrital sedimentary rocks, carbonates include very different rock types in terms of appearance and physical properties. One example is the significant difference in color, which ranges from white to black. Furthermore, there are very porous, sponge-like soft carbonates as well as non-porous, very compact and rigid lithotypes.

The formation process of carbonates requires water or biological activity with the presence of moisture. Carbonates as rocks can be either formed by the transportation and deposition of previously existing carbonate particles or in-situ by biogenic and chemical precipitation. These latter ones are often associated with the growth of carbonate skeletons (e.g. reefs, bivalves, etc.) or the trapping or binding of carbonates in organic structures, such as microbial mats. Carbonates are formed in almost all marine environments as well as in freshwater lakes or streams. Carbonate is also precipitated from springs, especially in areas where limestone is present. The greatest portion of the carbonate rocks are formed in marine environments including the coastal, shallow marine to continental slope to deep marine environments (Fig. 2.54). The major carbonate production and the so-called “carbonate factory” are found in shallow and warm marine environments, where light can illuminate the seawater (known as the photic zone), and biological activity is intense. This realm also favors the chemical precipitation from marine waters, which can be over-saturated with respect to calcium and carbonate. The depositional environment has a significant influence on the properties of carbonates, and, therefore, it is more important than in detrital sedimentary rocks. Carbonates are prone to weathering, especially since rainwater is able to dissolve most carbonates. The complex process of weathering and the resulting landforms are called karstification.

The classification of carbonates is very complex, and numerous subdivisions exist. The baseline of classifications can be the grain or crystal size, the main constituents, or the depositional fabric, as well as diagenesis. The old terminology used the grain or crystal size, and, accordingly, fine-grained (calcilutite $<63\ \mu\text{m}$), sand-sized (calcarenite, $63\ \mu\text{m}$ – $2\ \text{mm}$), and pebble or larger grain-sized (calcirudite $>2\ \text{mm}$) carbonates are known. The other classification system used the major

constituents, lime mud and cement ratio, as well as porosity, for carbonate classification. According to the system of Folk (1962), micrite is a very fine-grained calcite ($<4\ \mu\text{m}$) which is found in many limestones either as cement or as a main constituent. Sparite is a coarsely crystalline calcite (aragonite or dolomite) that has a crystal size of greater than $15\ \mu\text{m}$. Microsparite is in between micrite and sparite in terms of crystal size. The major carbonate grains that are present in the carbonates also play an important role in the designation of these limestones. Ooids are rounded carbonate grains which are formed by successive coatings of thin carbonate films around a nucleus. Ooids have a diameter between 0.2 and 2 mm, but commonly range from 0.5 to 1 mm. Oncoids are very similar to ooids, but generally larger and characterized by non-concentric coatings. Peloids are small, spherical to ovoid-shaped micritic grains that range from 0.02 to 1 mm in size. They are probably formed by biological activity and are polygenetic in origin, but many of them may be faecal in origin. Clasts are common carbonate grains found in limestones which are variable in size and considered to be reworked fragments of consolidated carbonate sediments. Intraclast is a term used for carbonate clasts from the depositional area, while extraclasts are derived from other areas or even from rocks of previous geologic periods. Skeletal grains or bioclasts are very common constituents of limestones. These biogenic grains very often provide key information on the origin of carbonates. The most common types include bivalves, gastropods, ammonoids, coral, calcareous algae, foraminifers, etc. According to one of the first classification schemes of carbonates, Folk (1962) identified various categories where names refer to the main constituent as well as to the type of cement in the rock. Among others, he identified biosparite, which is a bioclastic limestone with sparitic cement or pelmicrite, which is a limestone with peloids that are embedded in micritic cement.

The pioneering classification of carbonates (mostly limestones) according to their depositional environment was published by Dunham (1962). He subdivided limestones based on their depositional fabric, which is called microfacies. This system was later updated and extended by many authors, and it was Wilson (1975) who grouped carbonates into standard microfacies zones. Dunham's classification, which is based on the percentage of very fine (micritic) and coarser (sparitic) calcite as well as the ratio of cement to grain, was later extended by Embry and Klovan (1972), who included other categories that better describe the role of biological activity. Accordingly, there are mud-supported or grain-supported carbonate fabrics. This is probably the most widely used depositional textural classification of limestones. More recently, Tucker and Wright (1990) and Flügel (2004) gave very detailed descriptions of carbonate depositional environments and fabrics.

The porosity of carbonates are of special importance, since connected pores serve as conduits for fluids such as water and oil or provides reaction surfaces for the dissolution of carbonates. The need for a classification of the pore system in carbonates originates from research in the petroleum industry. Choquette and Pray (1970) distinguished fabric selective, non-fabric selective, and a third group that could either be fabric selective or not. This classification considers the genetics of

the pores and does not deal with the size and connectivity of the pores. Smaller sized intergranular or fenestral pores and larger fracture-related or channel-like pores are also one subclass in the pore classification system (Sect. 3.2). In the architecture and construction industry, the effective porosity (the interconnected pores) of carbonates are more important than their genetic origin, since the ratio of open pores determine the mechanical properties and durability of most carbonates.

Carbonate rocks are important, not only because of their wide use as a construction material, but also as reservoirs for hydrocarbons and groundwater. Forty percent of the world's hydrocarbon reserve is stored in carbonates.

Carbonates are divided into limestones, dolomites, and mixed siliciclastic carbonate rocks such as marl. Limestones are primarily composed of calcium-carbonate, which shows two forms according to the composition and crystal system. Calcite is the trigonal form of CaCO_3 , whereas aragonite has the same chemical composition, but structurally is classified as orthorhombic. Aragonite is commonly precipitated in marine environments and forms the skeletal part of many sea organisms. It is metastable and transforms into calcite. Besides the stoichiometric calcite, other impure calcite forms are also known, and elements such as Mg or Fe can also replace Ca ions in the crystal structure. Thus, it is possible to distinguish the so-called high Mg-calcite, low Mg-calcite, and ferroan calcite. One common method for the determination of limestone is the use of dilute hydrochloric acid, which causes a reaction (CO_2 degassing) in limestones. When the Ca-Mg ratio in the structure is 50 %, then the mineral is called dolomite (the Mg content is 40–60 % in dolomite).

Although limestones are calcite-bearing rocks, their appearance and technical properties are very different. For practical purposes, a simplified classification is proposed here that focuses on the mechanical properties and the possible uses of limestones. Accordingly, limestones are divided into: (i) non-porous or compact limestone, (ii) porous limestone, and (iii) travertine.

Compact or non-porous limestones have very limited porosity (generally less than a few percentage points) and are very well cemented. Their depositional environment, process of formation, and age show great variation, as well as their composition, but, in most cases, they are of marine origin. The key technical properties include making a sharp broken surface, producing small sharp chip fragments, and the ability to polish the surface of these limestones. In the stone industry, such limestones are very often sold as marbles due to their similarity in surface finish. They show a great range in the color spectrum and can also be pure white to black. The fabric is either micritic or sparitic, and they can contain macrofossils or microfossils. The porosity of these limestones is far less than that of the porous limestones. The compressive strength and modulus of elasticity and other rock mechanical parameters reflect higher strength compared to porous limestone or travertine (Török 2006). Their industrial uses include lime and cement production as well as filler and filter materials. The typical and easily recognizable features in many of these limestones are the stylolites or calcite veins that have different colors than the host rock. Besides their importance as a raw material for industrial processes, their use in architecture as decorative stones,

cladding, and flooring, or as ashlar, is very common (Figs. 2.55 and 2.56). Famous examples are known from all over the world. The “Belgium Granite” is a Paleozoic compact limestone that often contains visible white colored fossils (Fig. 2.55c). The German Muschelkalk is a designation that is used for a geological time period as well as a descriptive term meaning shelly limestone. The rock is also considered a compact limestone. In the United Kingdom, Portland Stone, Great Oolite, and Magnesian Limestone are also various types of compact limestones. In France, the Jaumont Limestone and many limestones in Spain belong to this type. The Istria stone is a famous building stone of Venice, which is a light-colored Mesozoic compact limestone that was quarried on the peninsula of Istria (Amoroso and Fassina 1983). Rosso di Verona is a red variety of compact limestone, as is the Adnet limestone of Austria. The streets in Portugal and most of the pedestrian zones in Lisbon and many other cities are paved with small black and white cubic blocks that are made of compact limestones. Compact or non-porous limestones are commonly used as aggregates in the construction industry, but also in smelters in the steel industry.

Porous limestones are less durable than the non-porous varieties and often are lighter in color. These sediments were formed in marine environments, and their porosity can reach 50 %, but, in most cases, it ranges from 10 to 30 %. Porous limestones are generally younger than the compact ones, and, in Europe, most of them were formed during the Tertiary to Quaternary periods and in the Mesozoic. Common examples are the Oligo-Miocene “soft limestone” that is found throughout the Mediterranean area. The globigerina limestone of Malta, which was the construction material of the prehistoric megalithic temples (Cassar 2002) (Fig. 2.9a), is one type of porous limestone. In Greece and Italy, many other monuments and structures were made of porous limestones. A French variety of porous limestone is called “Tuffeau” with extremely high porosities of nearly 50 % (Beck and Al-Mukhtar 2008). Miocene porous limestones from Central Europe are also known. The representative buildings of Vienna (St. Stephen’s Cathedral) and Budapest (St. Stephen’s Basilica) were all made from nearby quarried porous and very often oolitic limestones (Török 2002, 2004). Compared to compact limestones, porous limestones are less durable and more sensitive to weathering and decay. Many structures that are made of these stones now show severe signs of deterioration. In marine environments such as the Mediterranean, salt weathering occurs (Fitzner et al. 1996; Cassar 2002; Rothert et al. 2007), whereas in urban environments, air pollution-related soiling and blackening are observed on porous limestones (Török 2002). Porous limestones are not used in the cement industry. These stones cannot be polished; therefore, their use in construction and architecture is mainly in the form of rubble, ashlar, facing, or cladding, as well as for ornamental and artistic elements.

Freshwater limestone, or travertine, is a type of limestone that is mainly formed in freshwater aquatic environments. They include the calcareous tufas, calc-sinters from cold streams, and carbonates that are deposited from lacustrine environments or hot water such as springs or geysers. Travertines are very often creamy and beige in color and have large to small but often oriented pore systems. In recent

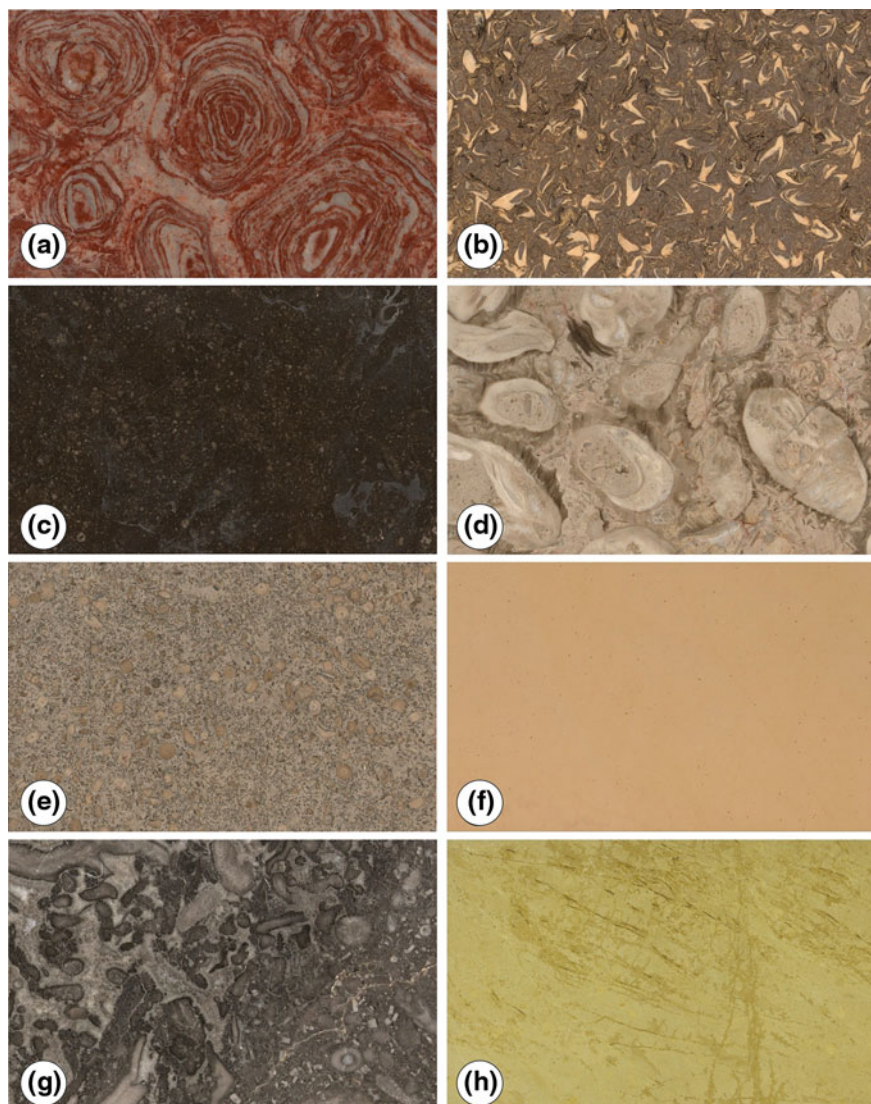


Fig. 2.55 Color and textural varieties of limestones and dolomite: **a** China (Ustromatolite), **b** Fohndorfer Muschelkalk, **c** Belgisch Granite (black limestone), **d** Fossil Columbia, **e** Crailsheimer Muschelkalk, **f** Solnhofen Limestone, **g** Wirbelau Lahnkalk (limestone), and **h** Dolomita Dorada (Figure by Natursteinarchiv Wunsiedel)

years, more travertines with various colors have been found on the market, such as pink to dark brown varieties. Plant fragments, freshwater snails, and other fossils are commonly found in travertine. Plant leaves of terrestrial origin as well as reeds or even calcified mosses indicate the rapid formation of carbonates and the

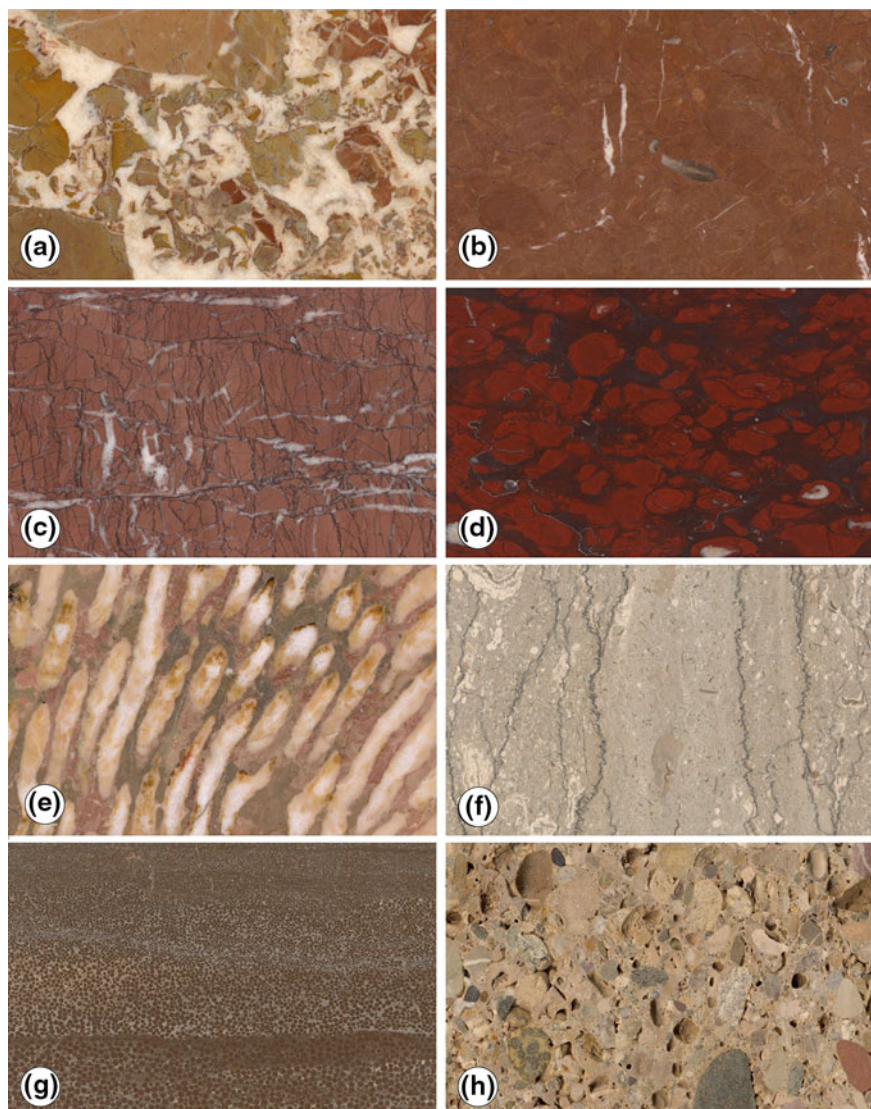
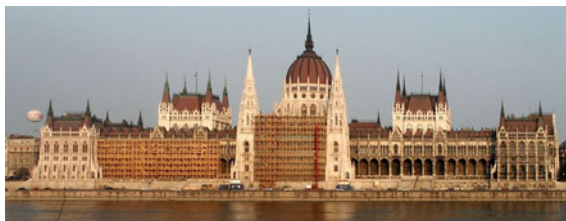


Fig. 2.56 Compilation of different limestones with different color and decor. **a** Ziller Breccia, **b** Aegea Brown, **c** Troizinarea, **d** Marbreduroi, **e** Adnet, **f** Nagelfluh, **g** Rogenstein, and **h** Perlatoroyal (conglomerate) (Figure by Natursteinarchiv Wunsiedel)

depositional mechanism of travertine (Pentecost 2005). The most durable one is a travertine from a hot or lukewarm water origin. It can be polished and used as cladding stone (Fig. 2.57). The excellent properties of this stone were even recognized by the Romans, who used travertine to build representative structures such as the Coliseum in Rome. The most famous travertine deposit is the one from

Fig. 2.57 The Parliament Building of Budapest constructed from soft, porous limestone (*gray*) and a successive restoration where this limestone is replaced by travertine (*white*)



Tivoli (near Rome), and other deposits from Turkey are also known. Many countries use travertine as a local building stone. Despite its porosity, travertine is more durable than other porous limestones and shows less severe signs of deterioration in polluted urban environments (Török et al. 2010).

Dolomite or dolostone is a carbonate rock with dolomite as the main mineral constituent. Since limestones are easy to determine by using diluted hydrochloric acid, freshly broken surfaces of dolomites do not show any reaction to HCl, due to their high magnesium content $\text{CaMg}(\text{CO}_3)_2$. Dolomite has a trigonal rhombohedral crystal structure that differs slightly from calcite. The different crystal structure also explains why dolomitic rocks have different properties than limestone. Dolomites are white to gray or even black in color, but pink, green, and other color varieties are also known. Very fine crystalline to coarsely crystalline dolomite rocks are known that are called sucrosic or saccaroidal varieties. Dolomite is more brittle than limestone; therefore, many dolomites are intersected by cracks or microcracks. This is the primary reason why it is difficult to exploit large blocks of dolomite, and most dolomites are only used as aggregates rather than ashlar or slabs. Powdered dolomite is an important constituent of many paints and plasters, and, in the past, it was also used in mortars.

Marl is a special sedimentary rock type that contains 50 % calcite and 50 % fine siliciclastic sediments consisting mostly of silt and clay. The composition can be shifted from the ideal 50–50 % content to a greater carbonate portion, (i.e. calcareous marl) and/or a more siliciclastic fraction such as clayey marl. Marl often has a slightly rough, broken surface, and its color is less variable than that of compact limestone. Bedding is a common feature of many types of marl, and the properties and possible use of marl depends on the carbonate content. Calcareous marls are very rigid and similar to compact limestones, whereas clay-rich marls can have a plastic character when they are saturated with water. Marls are formed in marine as well as in lacustrine environments. Due to the presence of carbonate and silica, marls and marly limestones are the preferable raw materials of the cement industry.

Siliceous sediments form in the oceans at great depths, especially below the zone where calcite dissolves. This zone is called the calcite compensation depth (CCD). The composition is primarily determined by the organism that forms the majority of the sediment; accordingly, there is siliceous oozing of radiolarians or diatomaceous origin. Siliceous sediments are also found in some lakes, especially in volcanic areas. Besides these siliceous sediments, silica can be found as isolated

nodules in many limestones. The best known example is flint, which is a black, nodular, very fine crystalline chert that is commonly found in Cretaceous chalk. In architecture, pure siliceous sediments of biological origin are very rare, but chert nodules of different colors are commonly visible in many limestones and marls. Limestones with low silicic content are also found.

Evaporites are sediments that have been chemically precipitated either from marine or non-marine waters and that are supersaturated with respect to one or more salt compounds. During the evaporation of water, various salts can be precipitated, although very few salts are common and occur in great quantities in nature. The most common ones are halite (rock salt), gypsum and anhydrite (two types of Ca-sulphate), and some potassium salts (mostly known as bitter salts). Dolomite may also form from the evaporation of seawater, but biological activity is very important. Evaporites are less commonly used as construction materials than other sedimentary rocks. Alabaster is a form of recrystallized gypsum, is a precious stone of evaporitic origin, and is used mainly in the decorative arts. Furthermore, many limestones of speleogenic origin and travertines are also called alabaster. The role of evaporitic minerals is more important in terms of the salt-related decay of building stones than as a material used for construction purposes. Salt weathering and the occurrence of salt minerals as efflorescence or subflorescence are discussed in detail in [Chaps. 4 and 6](#). Gypsum is a key raw material for plasters and the major constituent of many stuccos and ornaments.

Phosphates are generally formed in marine or terrestrial environments from vertebrate bone fragments, chemical precipitations, or guano. Ironstones of sedimentary origin include a great variety of stones with thick deposits of Precambrian banded iron formation (BIF) and Phanerozoic iron-rich sediments such as the Mesozoic ironoolites of Europe (United Kingdom, France, and Germany). Most ironstones are red to brown in color, depending on the prevailing mineral. Hematite, an iron-oxide mineral, creates a red stain, whereas iron-oxide-hydroxide (goethite) gives the rock a brownish color.

References

- Amoroso GG, Fassina V (1983) Stone decay and conservation. Elsevier, Amsterdam
- Beck K, Al-Mukhtar M (2008) Formulation and characterization of an appropriate lime-based mortar for use with a porous limestone. *Environ Geol* 56:715–728
- Börner K, Hill D (2007) Große Enzyklopädie der Steine: CD-ROM. Abraxas Verlag, Hasede
- Borradaile GJ, Bayly MB, Powell CMA (1982) Atlas of deformational and metamorphic rock fabrics. Springer, New York
- Bowen NL (1928) The evolution of igneous rocks. Princeton University Press, Princeton
- Brodie K, Fettes D, Harte B et al. (2007) Towards a unified nomenclature in metamorphic rocks. 3. Structural terms including fault rock terms. Recommendations by the IUGS subcommission on the systematics of metamorphic rocks. http://www.bgs.ac.uk/SCMR/docs/papers/paper_3.pdf. Accessed 20 July 2010
- Bruno R, Paspaliaris I (eds) (2004) Ornamental and dimensional stone market analysis. Osnet edition, Athen

- Bucher K, Frey M (2002) Petrogenesis of metamorphic rocks. Springer, Berlin
- Cassar J (2002) Deterioration of the globigerina limestone of the Malteses Island. In: Siegesmund S, Weiss T, Vollbrecht A (eds) Natural stone, weathering phenomena, conservation strategies and case studies. Geological Society Special Publication 205, London, pp 33–49
- Cavallo A, Bigioggero B, Colombo A et al (2004) The Beola: a dimension stone from the Ossola Valley (NW Italy). *Per Miner* 73:85–97
- Choquette PW, Pray LC (1970) Geologic nomenclature and classification of porosity in sedimentary carbonates. *AAPG Bull* 54:207–250
- Coutinho J, Kräutner H, Sassi F et al. (2007) Towards a unified nomenclature in metamorphic petrology—8. Amphibolite and granulite. Recommendations by the IUGS Subcommission on the systematics of metamorphic rocks. http://www.bgs.ac.uk/scmr/docs/papers/paper_8.pdf. Accessed 20 July 2010
- Cox KG, Bell JD, Punkhust RJ (1979) The interpretation of igneous rocks. George Allen & Unwin Publishers, London
- Cross W, Iddings JP, Pirsson LV et al (1902) A quantitative chemico–mineralogical classification and nomenclature of igneous rocks. *J Geol* 10:555–690
- Drüppel K (2003) Petrogenesis of the Mesoproterozoic anorthosite, syenite and carbonatite suites of NW Namibia and their contribution to the metasomatic formation of the Swartbooisdrif sodalite deposits. Ph.D. thesis University of Würzburg, Würzburg
- Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: Ham WE (ed) Classification of carbonate rocks. AAPG Memoir 1, Tulsa
- Embry AF, Klovan JE (1972) Absolute water depths limits of late devonian paleoecological zones. *Geol Rundschau* 61:672–686
- EN 12440:2000 Natural stone—denomination criteria
- EN 12670:2001 Natural stone—terminology
- EN 1341:2006 Slabs of natural stone for external paving. Requirements and test methods
- EN 1342:2009 Setts of natural stone for external paving. Requirements and test method
- EN 1343:2009 Kerbs of natural stone for external paving. Requirements and test methods
- European Commission (1998) European minerals yearbook 1996–1997. 2nd edn. EU, Luxemburg
- Fisher RV (1961) Proposed classification of volcanoclastic sediments and rocks. *Bull Geol Soc Amer* 72:1409–1414
- Fisher RV, Smith GA (1991) Volcanism, tectonics and sedimentation. In: Fischer RV, Smith GA (eds) Sedimentation in volcanic settings. Society for Sedimentary Geology Special Publication 45, Tulsa
- Fitzner B, Heinrichs K, Volker M (1996) Stone deterioration of monuments in Malta. In: Pancella R (ed) Proceedings of the 1995 LCP Congress ‘Preservation and restoration of cultural heritage’. Laboratoire de Conservation de la Pierre, Département des Matériaux, Ecole Polytechnique Fédérale Lausanne, Lausanne
- Flügel E (2004) Microfacies analysis. Springer, Berlin
- Folk RL (1962) Spectral subdivision of limestone types. In: Ham WE (ed) Classification of carbonate rocks. AAPG Memoir, 1, Tulsa
- Founti M (ed) (2004) Stone for construction and architecture—from extraction to the final product. Osnet editions, Athen
- Grimm WD (1999) Beobachtungen und Überlegungen zur Verformung von Marmorobjekten durch Gefügauflockerung. *Z dtsh geol Ges* 150(2):195–235
- Hamblin WK (1989) The earth’s dynamic systems—a textbook in physical geology. MacMillan, New York
- Hill D (2007) Werkstoff Naturstein aus Sicht der Architekten. *Z dtsh Ges Geowiss* 158/4:701–707
- Hoffmann A (2007) Naturwerksteine Thailands: Lagerstättenerkundung und Bewertung. Diss Univ Göttingen, Göttingen
- Hutton DHW, Siegesmund S (2001) The Ardara granite: reinflating the balloon hypothesis. *Z dtsh Geol Ges* 152:309–324

- Kay RW, Mahlburg Kay S (1986) Petrology and geochemistry of the lower continental crust: an overview. In: Dawson JB, Carswell DA, Hall J et al. (eds) *The nature of the lower continental crust*. Geological Society of London, Special Publication 24, London
- Lambergini A, Fiora L, Alciati L (2000) Il cielo dell' Argentina nel marmo Azul. *L'informatore del marmista*, 464:6–12
- Le Maitre RW (ed) (1989) *A classification of igneous rocks and glossary of terms*. Cambridge University Press, Cambridge
- Le Maitre RW, Streckeisen A, Zanettin B (eds) (2004) *Igneous rocks: a classification and glossary terms*. Cambridge University Press, Cambridge
- Lu P, Latham JP (1999) Developments in the assessment of in-situ block size distributions of rock masses. *Rock Mech Rock Eng* 32(1):29–49
- Mecceri M, Molli G, Conti P et al (2007) The carrara marbles (Alpe Apuane, Italy): a geological and economical updated review. *Z dtsh Ges Geowiss* 158(4):719–735
- Mehnert KR (1968) *Migmatites and the origin of granitic rocks*. Elsevier, Amsterdam
- Montani C (2003) *Stone 2002—world marketing handbook*. Faenza, Gruppo Editoriale Faenza Editrice, Faenza
- Montani C (2005) *Stone 2004—world marketing handbook*. Faenza, Gruppo Editoriale Faenza Editrice, Faenza
- Montani C (2008) *Stone 2008—world marketing handbook*. Faenza, Gruppo Editoriale Faenza Editrice, Faenza
- Morales M, Oyhantcabal P, Stein K-J, Siegesmund S (2010) Black dimensional stones: geology, technical properties and deposit characterization of the dolerites from Uruguay. *Environ Earth Sci* 69(4):1067–1489. doi:[10.1007/s12665-010-0827-5](https://doi.org/10.1007/s12665-010-0827-5)
- Morales M, Oyhantcabal P, Stein K-J, Siegesmund S (2013) Dolomitic states from Uruguay: petrophysical and petromechanical characterization and deposit evaluation. *Environ Earth Sci* 69:1361–1395
- Mosch S (2009) *Optimierung der exploration, gewinnung und materialcharakterisierung von naturwerksteinen*. Diss Univ Göttingen, Göttingen
- Mosch S, Nikolayev D, Ewiak O, Siegesmund S (2010) Optimized extraction of dimension stone blocks. *Environ Earth Sci*. doi:[10.1007/s12665-010-0825-7](https://doi.org/10.1007/s12665-010-0825-7)
- Müller FM (1996) *Gesteinskunde*. Ebner-Verlag, Germany
- Oyhantcabal P, Siegesmund S, Stein K-J (2007) Dimension stones in Uruguay: situation and perspectives. *Z dtsh Ges Geowiss* 158(3):417–428
- Passchier CW, Trouw RAJ (1996) *Microtectonics*. Springer, Berlin
- Pentecost A (2005) *Travertine*. Springer, Berlin
- Peschel A (1983) *Natursteine*. VEB Deutscher Verlag für Grundstoffindustrie, Leipzig
- Peschel A, Franz E (1968) *Der Fruchtschiefer von Theuma (Vogtl.). Beziehung zwischen Genese und Verwertbarkeit*. *Z Angewandte Geol* 14/9:483–488
- Primavori P (1999) *Planet stone*. Giorgio Zusi Editore S.A.S., Verona
- Rother E, Eggers T, Cassar J et al. (2007) Stone properties and weathering by salt crystallisation of Maltese Globigerina limestone. In: Prikryl R, Smith BJ (eds) *Building stone decay: from diagnosis to conservation*. Geological Society of London Special Publication 271, London
- Shadmon A (1989) *Stone: an Introduction*. Intermediate technology publications, London
- Siegesmund S, Vollbrecht A, Weiss T (2002a) Gefügeanisotropien und ihre Bedeutung für Naturwerksteine. *Naturstein* 7:76–81
- Siegesmund S, Vollbrecht A, Hulka C (2002b) The abnormal mechanical behaviour of itacolumites: fabric evidences. Geological Society of London Special Publication 205, London, pp 137–147
- Streckeisen (1978) Classification and nomenclature of volcanic rocks, lamprophyrs, carbonatites and mellilitic rocks. Recommendations and suggestions. *N Jb Mineral Abh* 134:1–14
- Streckeisen A (1980) Classification and nomenclature of igneous rocks. *Geol Rundschau* 69:194–207
- Sousa LMA (2010) Evaluation of joints in granitic outcrops for dimension stone exploitation. *Q J Eng Geol Hydrogeol* 43:85–94

- Terezopoulos N (2004) The challenge for European ornamental stones. Proceedings of the 1st OSNET Workshop. http://www.osnet.ntua.gr/Sectors/01_Quarrying/Publications/The_challenge_for_European_Ornamental_Stones.pdf. Accessed 20 July 2010
- Tomio P, Filippi F (1996) Das Porphy Handbuch. e.s.Po, Albiano Trento
- Török Á (2002) Oolitic limestone in polluted atmospheric environment in Budapest: weathering phenomena and alterations in physical properties. In: Siegesmund S, Weiss T, Vollbrecht A (eds) Natural stones, weathering phenomena, conservation strategies and case studies. Geological Society of London Special Publication 205, London, pp 363–379
- Török Á (2004) Leithakalk-type limestones in Hungary: an overview of lithologies and weathering features. In: Prikryl R, Siegel P (eds) Architectural and sculptural stone in cultural landscape. The Karolinum Press, Prague, pp 89–93
- Török Á (2006) Influence of fabric on the physical properties of limestones. In: Kourkoulis SK (ed) Fracture and failure of natural building stones. Springer, Dordrecht, pp 487–495
- Török Á, Licha T, Simon K, Siegesmund S (2010) Urban and rural limestone weathering; the contribution of dust to black crust formation. Environ Earth Sci. doi:[10.1007/s12665-010-0737-6](https://doi.org/10.1007/s12665-010-0737-6)
- Tucker ME, Wright JP (1990) Carbonate sedimentology. Blackwell Scientific Publication, Oxford
- Vollbrecht A, Dürrast H, Weber K (1993) Open microcracks: indicators for in-situ stress directions. KTB-Report 93–2:227–230
- Vollbrecht A, Rust S, Weber K (1991) Development of microcracks in granites during cooling and uplift: examples from the Variscan basement in NE Bavaria (FRG). J Struc Geol 13(7):787–799
- Wagner W (2007) Grundlagen für die Prüfung von Dach- und Wandschiefern. Z dtsh Ges Geowiss 158/4:785–805
- Wedepohl KH (1969) Composition and abundance of common igneous rocks. In: Wedepohl KH (ed) Handbook of geochemistry. Springer, Berlin
- Wichert J (2007) Schieferlexikon. <http://www.schieferlexikon.de/htm>. Accessed 20 July 2010
- Wilson JL (1975) Carbonate facies in geologic history. Springer, Berlin
- Winkler H, von Platen H (1961a) Experimentelle gesteinsmetamorphose IV. Geochim Cosmochim Acta 24:48–69
- Winkler H, von Platen H (1961b) Experimentelle gesteinsmetamorphose V. Geochim Cosmochim Acta 24:250–259
- Winkler HGF (1967) Die Genese der metamorphen Gesteine. Springer, Berlin
- Yardley BWD (1997) Einführung in die Petrologie metamorpher Gesteine. Ferdinand Enke Verlag, Stuttgart

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