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Apppendix B. Bedrock Types

Knowledge of bedrock types is fundamental to understanding fractured rock aquifer systems and the terranes in which these systems occur. Bedrock types (igneous, sedimentary, and metamorphic) and the individual lithologies that occur within these groups directly influence primary porosity, secondary porosity (such as fractures), fracture characteristics (aperture, orientation, fabric, extent), and the physiography of an area or region. Physiography consists of the physical landscape and associated hydrology. This section provides a basic description of igneous, sedimentary, and metamorphic rock types and their subclassifications that are pertinent to fractured rock hydrogeology, groundwater contamination, and remediation.

B.1 Igneous

Igneous rocks are crystalline rocks that form from the cooling of magma or lava within the earth (intrusive igneous rocks), near the earth's surface (hypabyssal), or on the earth's surface (extrusive). Crystalline igneous rocks generally have three types of textures: aphanitic, phaneritic, and porphyritic (Figure B-1). Three additional textures are used with the extrusive igneous rocks, which are: glassy, vesicular and pyroclastic. Aphanitic textures consist of equigranular, small (fine-grained) crystals; phaneritic textures consist of equigranular, larger crystals (coarse-grained); porphyritic rocks consist of coarse crystals within a fine-grained groundmass.

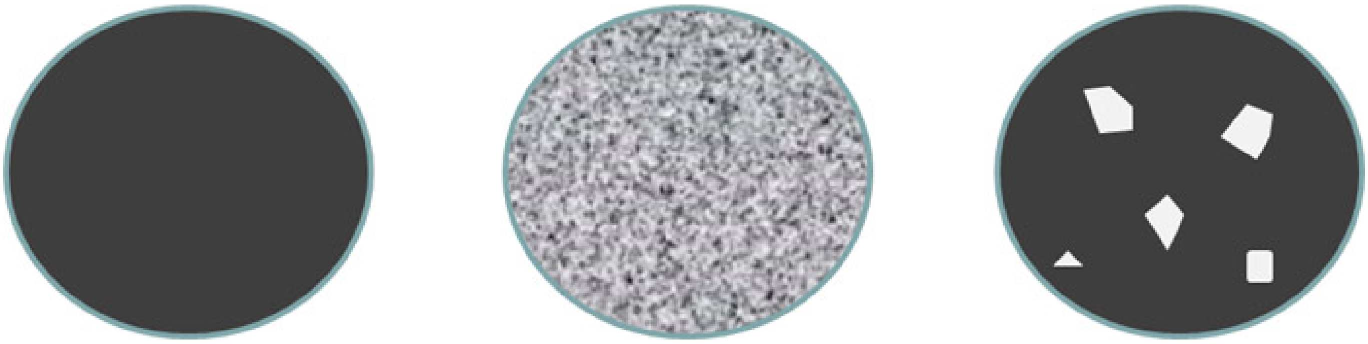

Figure B-1. Conceptual illustration of igneous textures, from left to right: aphanitic, phaneritic, porphyritic.

These equigranular or interlocking crystalline textures often result in fracture patterns that tend to be infrequent, discontinuous, nonuniform, random, or radial.

Glassy texture refers to a quick/rapid cooling lava that does not have an underlying organized mineral structure visible under a conventional polarized light microscope. Vesicular texture occurs when gases are trapped within a lava flow and minerals crystallize around the gas pocket. Pyroclastic texture results from explosive volcanic eruptions and the resulting rock is composed of a mixture of preexisting igneous rock, mineral grains, and ash particles. These three rock textures may be the most permeable of the igneous rock types, yielding zones of groundwater flow and may be the most susceptible to chemical weathering.

Igneous rocks are also characterized by their mineral and chemical composition ranging from felsic to mafic. Felsic rocks are enriched in quartz and feldspar, which consist of silicon, aluminum, sodium, and potassium. Mafic rocks are enriched in iron and magnesium-bearing minerals such as olivine and pyroxene.

Further discussion of intrusive and extrusive igneous rocks is provided below with emphasis on characteristics that influence physical and chemical hydrogeology.

B.2 Intrusive

Intrusive and hypabyssal igneous rocks are described together in this section, because they both crystallize beneath the earth's surface. These types of igneous rocks include massive intrusions such as plutons and tabular intrusions such as dikes (vertical to subvertical intrusion) and sills (horizontal to subhorizontal intrusion).

Plutonic igneous rocks derive from massive bodies of magma that have cooled slowly allowing mineral crystals to develop Figure B-2). The rate of cooling affects the size of the mineral crystals and the resulting texture. Consequently, plutonic rocks tend to have phaneritic texture with interlocking grains and little primary porosity. Plutonic rocks range in composition from felsic to mafic (for example, granite, diorite, and gabbro), which reflects the source of the magma and the timing of mineral crystallization. Mafic rocks are composed of minerals that are stable at higher temperature conditions and therefore make them more susceptible to weathering and erosion at near surface temperatures. The iron and magnesium content of mafic rocks may also make groundwater along water-bearing fractures susceptible to iron fouling of pumping and remedial systems. Conversely, a ready supply of ferric iron would be available to support microbial mediated biodegradation of some organic compounds. Felsic rock mineral assemblages tend to crystallize last under cooler temperatures and therefore are less susceptible to weathering at surface temperatures.

As erosion and uplift occurs, plutonic rocks experience decompression, which may result in radial, random, or dendritic type fracture patterns. Even at the ground surface, these plutonic igneous rocks may remain relatively massive, with few continuous fractures.

Figure B-2. Outcrop of granite pluton; generally massive with few fractures; some fractures in foreground.

Intrusive and hypabyssal rocks also include tabular intrusions such as vertical to sub-vertical dikes and horizontal to sub-horizontal sills (Figure B-3). These tabular intrusions can also range from felsic to mafic in composition (such as rhyolite, andesite, and basalt). Hypabyssal varieties of these dikes and sills experience shallow crystallization and tend to cool rapidly, resulting in an aphantic texture with the center of the intrusion being coarser grained due to slower cooling. The edge of the intrusion becomes finer grained because it cools quicker in contact with the country rock. The geometry of these intrusions has obvious implications for anisotropy and hydrogeologic boundary conditions. These dikes may be susceptible to erosion and cool in a tabular fashion, potentially resulting in planar fractures, especially in contact with country rock.

Figure B-3. Aphanitic, mafic intrusion into phaneritic pluton (granite); note thermal aureole in country rock (pink/orange discoloration surrounding mafic intrusion). Thermal aureole is susceptible to differential weathering and permeability.

B.3 Extrusive

Extrusive igneous rocks derive from the rapid cooling and crystallization of lava that has been extruded to the earth's surface (atmosphere or under a water body). The associated textures are also categorized by the chemical composition of the parent magma. Due to rapid cooling, extrusive igneous rocks tend to have an aphanitic or glassy texture. Associated with the aphanitic texture is the vesicular texture, which generally marks the top or base of a lava flow (Figure B-3). Extrusive igneous rocks tend to flow horizontally along the pre-existing ground surface and are characterized by layered stratification and textures that may include:

- tabular extrusion
- layered nonconformities (interbedded layers of extrusions and sediments)
- vesicular horizon
- weathered horizon

- weathered horizon intercepting vesicular horizon

Figure B-3 Aphanitic, mafic, extrusive igneous rock exhibiting multiple textures and porosity that may affect fluid occurrence and migration: fractures, vesicles, weathered horizon, weathered (interconnected) vesicles.

The variety of textures in extrusive igneous rocks tends to result in homogeneous permeability; however, the general horizontal nature of these extrusions can result in isotropic conditions in the horizontal plane. Columnar joints are unique to certain lava flows and hypabyssal intrusions, formed because of contraction of the lava with cooling, and the formation of polygonal joint partings perpendicular to the cooling surface. Surface water and groundwater can readily move along these joints and vesicular interflow zones. Pyroclastic textures are most like the clastic sedimentary rock type (discussed in the next section). Because they are associated with a volcanic eruption, however, the composition begins at high temperatures, so that after the rock particles and ash have deposited along low lying ground features, they may solidify together (for example, welded tuff). These rock types would not exhibit the same permeable features that a nonwelded tuff or other vesicular extrusive rock types may have.

B.4 Sedimentary Rocks

Sedimentary rocks are formed by either physical or chemical weathering of preexisting (precursor) rock formations. The sediment or dissolved matter are transported and deposited through physical, chemical, or organic processes. Once deposited, the sediment can become lithified by compaction, cementation, and recrystallization. Sedimentary rocks can be classified into textures based on the transport mechanism. Clastic textures are derived from physical weathering of the preexisting rock type and the sediment transported and deposited within a depositional environment. Clastic sedimentary rocks are further classified on the size of the resulting particles.

Nonclastic textures have undergone less transport and are formed in a depositional environment that generally contains a very small percentage of detrital silicate particles/grains. The nonclastic textures are generally subdivided by whether the main constituents are organic (organism or plant) or organically-derived (biologic or mechanical abrasion of organic material/clasts) or are inorganic mineral assemblages. The depositional environment provides a basis for initial interstitial water geochemistry and provides clues as to whether marine or fresh water conditions prevailed and whether these were aerobic or anaerobic to understand what minerals may have been more stable.

The clastic and nonclastic organic sedimentary textures include matrix-supported and grain-supported fabrics, which reflect porosity and potential permeability properties at the time of deposition. Grain-supported fabrics consist of larger grains that are in contact with one another with the potential of finer grained material in the interstitial space. Porosity and permeability can be high in this type and decrease with an increase of interstitial fine grains or cement filling in the void space. A matrix-supported fabric consists primarily of fine-grained sediments with a few coarse fragments that generally do not touch. If the grain size and composition is similar (such as a uniform sand), porosity and permeability can be high, but with compositional variety and finer grain size, permeability may decrease. According to Blatt (Blatt 1980):

The original porosity and permeability of sedimentary material changes continually through time in response to changes in subsurface stress fields, temperature and the chemical composition of underground waters.

B.4.1 Clastic

Clastic sedimentary rocks consist of rock fragments and minerals that are derived from physical and chemical weathering of other preexisting rock types (igneous, metamorphic, or sedimentary). Clastic sedimentary rocks range from fine-grained to coarse-grained depending on the size of the particles (clasts). The composition of the rock type provides some insight into the distance traveled from the parent source, with more resistant minerals remaining (for example, quartz) and less resistant minerals weathering and particle size decreasing with distance traveled.

Once deposited, the grain size and the particle shape affect the primary porosity. Smaller particles and clay minerals can be packed closer together and the resultant pore sizes are smaller and potentially more tabular, with a resultant orientation more parallel to bedding. Larger equal-sized grains exhibit a grain-supported fabric preserving the depositional porosity between these grains. Lithification of the sediments can decrease the initial porosity by either compaction affecting the finer grained sediments more or cementation of a new mineral in the existing pore space (interstitial cement). Common cements include calcium carbonate, silica, and ferric oxyhydroxide or ferrous carbonate. Many of the clastic sedimentary rocks are permeable and receive and transmit groundwater which has migrated from other rock types. Besides the process of cementation, ion-exchange may take place along a mineral surface, thus affecting the chemistry of the interstitial water. The fine grained clastic rocks, such as a siltstone or shale are characterized not only by the particle size but also by having a greater percentage of clay minerals. These rock types are porous and can hold water, which may reflect the original depositional environment, but do not transmit this water readily because the interstitial spaces are small and poorly interconnected (USGS 1992).

B.4.2 Nonclastic

Nonclastic texture indicates that the clasts or minerals that make up the rock have undergone little transport, generally were deposited in situ (within the basin of deposition). They can be subdivided into two groups based on the origin of the sediment: organic or inorganic.

Nonclastic organic rocks are formed in place within a depositional basin that is lacks an influx of detrital silicate particles and are comprised mainly of calcium carbonate minerals (calcite and dolomite) or original plant material (peat, lignite to bituminous coal). A variety of organic grains can be found in these rock types and depend on the depositional basin in which they formed. With lithification, these rocks undergo a complex series of replacement or recrystallization of the original grains or organic mud-sized particles. As with the clastic texture, the size of the grains and the mixture of grain sizes affect the primary porosity of the sediment. With lithification, the original porosity may decrease due to compaction, cementation within any void spaces or recrystallization of the original minerals.

Nonclastic inorganic rocks are formed in-place within unique depositional environments and are further classified based on the mineral present (mineralogy). These rocks tend to be composed of interlocking coarse to fine-grained crystals and generally have low primary porosities. Examples include: rock salt, rock gypsum, travertine (calcite), dolomite and chert (microcrystalline quartz).

B.4.3 Secondary Porosity

Once sediments, from both the clastic and nonclastic rock types, are lithified and have become new sedimentary rocks, they may have preserved original depositional features such as ripple marks, mud cracks, cross-beds, bedding planes and erosional discontinuities. These features, especially bedding planes, may be significant to the occurrence of and migration of groundwater and contaminants.

The nonclastic inorganic rocks are not as brittle and tend to deform (or exhibit solid-phase flow) parallel to the bedrock contacts they are adjacent to. Joints, folded or tilted bedding and fault planes can be the dominant avenue for fluid migration and interaction of the bedrock with this fluid. For some rock types, in-particular the nonclastic organic (or carbonate rocks), this interaction between groundwater and the carbonate rock may result in chemical weathering (dissolution and precipitation), enlarging the joints, fractures and bedding plane partings and result in a unique topography classified as karst.

Both clastic and nonclastic organic rocks that are exposed to tectonic forces resulting in structural deformation exhibit joints, inclined and folded bedding, and faulting.

B.4.4 Structural and Bedding Characteristics

Sedimentary rocks that are deposited in a basin and do not experience structural deformation through tectonic forces tend to be homogeneous and isotropic in the horizontal plane or parallel to bedding. Clastic sedimentary rocks that are exposed to tectonic forces, resulting in structural deformation, which results in inclined and folded bedding (Figure B-4) and faulting (Figure B-5). These structural characteristics result in significant anisotropy and hydrogeologic boundary conditions, which are often measureable and predictable at the area to regional scale.

Figure B-4. Inclined sandstone bedding on flank of NE-SW striking anticline, resulting in preferential flow direction (anisotropy) and hydrogeologic barrier condition.

Figure B-5 Vertical and thinly bedded siltstone striking N-S orthogonal to E-W potentiometric gradient.

B.5 Metamorphic

Metamorphic rocks are derived from other rock types (such as igneous, sedimentary, and older metamorphic) that are subject to heat and pressure due to tectonic forces, deep burial of sedimentary basins, and high temperatures from magma bodies or extruded flows. Like igneous rocks, metamorphic rocks are also crystalline, but exhibit growth of crystals by chemical reactions with other minerals and fluids in the parent rock of mineral suites that are more stable under the new pressure and temperature conditions. These mineral crystals can change in shape and size, and become deformed or reoriented in a different direction.

Two major textures of metamorphic rocks reflect the dominant change of either increased pressure or temperature or both from the pre-existing conditions (prior to metamorphism): foliated and nonfoliated. Foliated texture means that the rock exhibits foliation (oriented layering) that occurs orthogonal to the principal direction of compression/pressure and is most obvious with elongate mineral grains. Nonfoliated metamorphic rocks lack foliation and may have been more influenced by increased temperatures; however stretched and deformed rock and fossil fragments indicate tectonic forces may be present. Consequently, metamorphic rocks generally have low primary porosity and permeability, and exhibit physical characteristics that are similar to igneous and sedimentary rocks with regard to texture, orientated fabrics, and development of fracture patterns relevant to fluid (groundwater and contaminant) occurrence and migration.

B.5.1 Foliated

Foliated metamorphic rocks are characterized by a layered, platy, or banded orientation to the minerals that comprise the rock. This configuration imparts a foliation (directional layered fabric) to the rock, which is observed at multiple scales: microscopic, hand sample/core, outcrop, site, and regional terrane. This fabric is also referred to as schistosity. Like sedimentary bedding, foliation has a structural orientation and can exist as secondary porosity between layers, resulting in anisotropy. Foliated metamorphic rocks in order of increasing foliation include slate, phyllite, and schist. The following figures (B-6, 7 and 8) illustrate textures and foliation associated with schist, a strongly foliated metamorphic rock type.

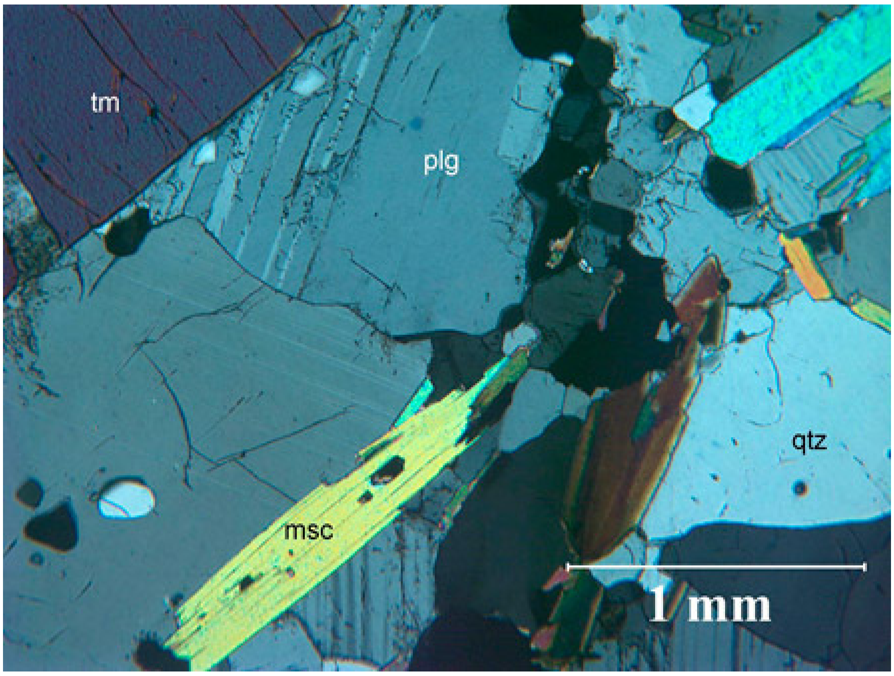

Figure B-6 Photomicrograph of schist exhibiting fused grains with little primary porosity and orientated/platy minerals (muscovite, biotite, tourmaline).

Figure B-7 Foliated schist in outcrop.

Gneiss is a foliated metamorphic rock that exhibits banding of mineral layers, but not a platy foliation that would strongly influence groundwater flow as secondary porosity and anisotropy. The texture of gneiss tends to be like that of intrusive igneous rocks, relatively large and equigranular crystals that are fused with little primary porosity.

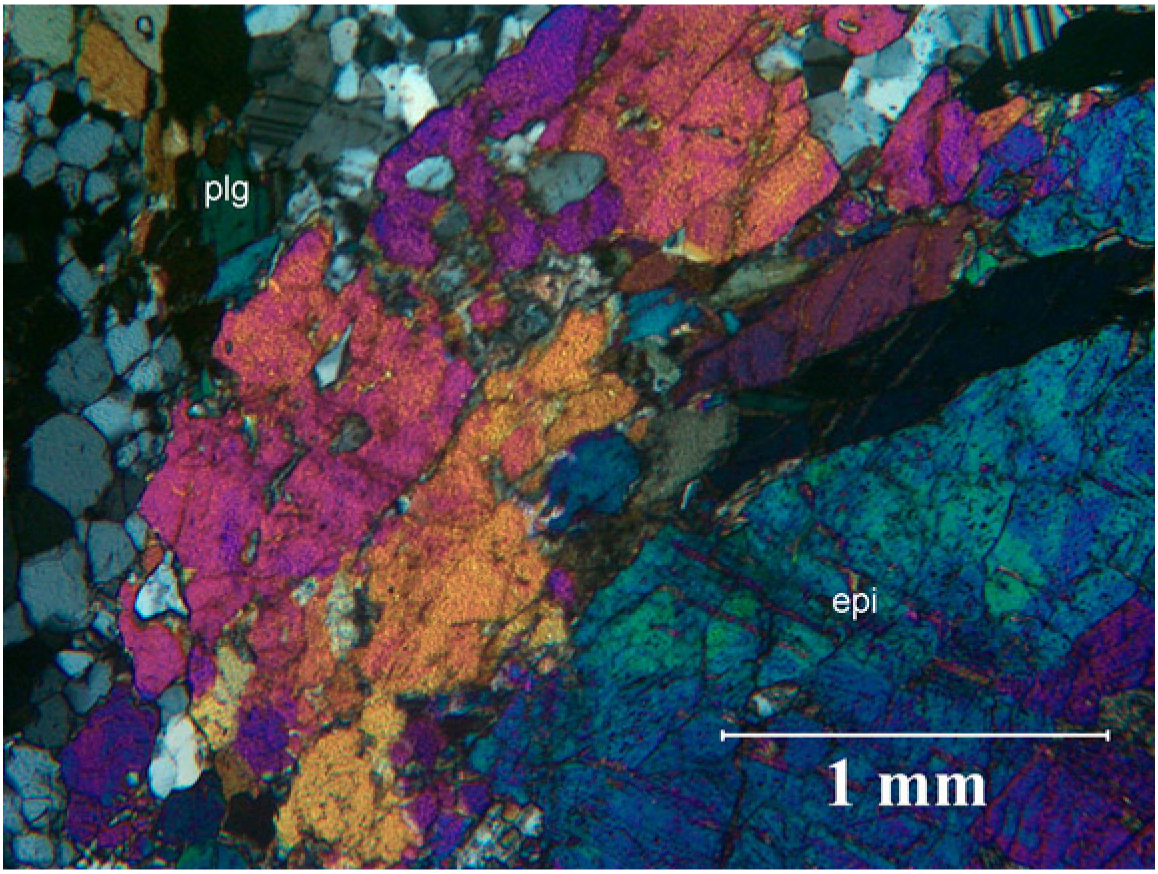

Figure B-8 Photomicrograph of gneiss exhibiting relatively large and fused grains/crystals.

B.5.2 Nonfoliated

Nonfoliated metamorphic rocks do not exhibit an oriented fabric and are subdivided on the composition of the original parent rock. These rocks include marble and anthracite coal. Marble is a metamorphosed carbonate rock and tends to be crystalline with little foliation and likewise, anthracite coal is metamorphosed bituminous coal and exhibits a conchoidal fracture. Both rock types exhibit little primary porosity.

Table B-1. Terrane analysis matrix

Click Here to view Table B-1 in Adobe Acrobat format.