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Basic Concepts in Reservoir Engineering

1.1 Rocks and Their Types

A rock is a consolidated mixture of minerals. By "consolidated," we mean hard and strong; real rocks don't fall apart in your hands! A mixture of minerals implies the presence of more than one mineral grain, but not necessarily more than one type of mineral. For example, a rock can be composed of only one type of mineral, such as limestone, which is commonly made up of only calcite. However, most rocks are composed of several different minerals. Rocks can also include nonminerals, such as fossils or organic matter within a coal bed or in some types of mudstone.

A critical point to remember is the difference between a mineral and a rock. A mineral is a naturally occurring, inorganic solid with a specific chemical composition and a crystalline structure. Minerals are the building blocks of rocks and are defined by their unique physical and chemical properties. Examples of minerals include feldspar, quartz, mica, halite, calcite, and amphibole. These minerals vary in hardness, color, luster, and crystal form, and they are often used to identify and classify different types of rocks.

On the other hand, a rock is typically a mixture of several different minerals. For instance, granite is a common rock composed of quartz, feldspar, and mica. The proportions and types of minerals present in a rock determine its characteristics and classification. Rocks are categorized into three main types based on their formation processes: igneous, sedimentary, and metamorphic.

1. *Igneous rocks*: These rocks form from the cooling and crystallization of magma, which is molten rock beneath the Earth's surface. When magma cools slowly beneath the Earth's crust, it forms intrusive igneous rocks such as granite, which have large, visible crystals. Conversely, when magma erupts onto the surface and cools quickly, it forms extrusive igneous rocks such as basalt, which have smaller crystals.
2. *Sedimentary rocks*: These rocks are formed from the accumulation and lithification of sediment. The sediments produced by weathering and erosion are eventually deposited in various environments, such as rivers, lakes, deserts, and oceans.

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Baghir A. Suleimanov and Elchin F. Veliyev.

Over time, these sediments accumulate in layers and undergo lithification—a process of compaction and cementation—to form sedimentary rocks. Sediments can be fragments of other rocks, mineral grains, or biological materials. Sedimentary rocks are often layered and can contain fossils. Common types include sandstone, formed from compacted sand grains, and limestone, formed primarily from the remains of marine organisms. Sedimentary rocks provide valuable information about Earth's history and past environments.

More than 70% of the area of all continents is covered with sedimentary rocks, and most of the mineral deposits are directly associated with them.

Depending on the forming processes, sedimentary rocks are divided into the following three groups:

- clastic (crushed stone, sand, pebbles, gravel, clay);
- chemical (various salts, silica); and
- organogenic (limestones, fossil fuels).

Common sedimentary rocks include:

- Sandstone: Formed from compacted sand grains.
- Shale: Formed from compacted clay particles.
- Limestone: Formed primarily from the remains of marine organisms.

3. *Metamorphic Rocks*: These rocks form when preexisting igneous or sedimentary rocks are subjected to high temperatures, pressures, or chemically active fluids, causing them to undergo physical and chemical changes, leading to metamorphism. Metamorphic processes can result in the formation of new minerals and the reorganization of mineral grains into a more compact, crystalline structure. Examples of metamorphic rocks include schist, which has a foliated texture, and marble, which forms from limestone.

1.1.1 The Rock Cycle

The rock cycle is a fundamental concept in geology that describes the dynamic transformations of rocks within the Earth's crust. The rock cycle is a continuous process, and rocks can be recycled through the cycle many times from one type to another through various geological processes (Figure 1.1). For example:

- Igneous to Sedimentary: Igneous rocks exposed at the surface are weathered and eroded into sediments, which are then compacted and cemented to form sedimentary rocks.
- Sedimentary to Metamorphic: Sedimentary rocks buried deep within the crust are subjected to heat and pressure, transforming them into metamorphic rocks.
- Metamorphic to Magma: Metamorphic rocks can melt under extreme conditions to become magma, restarting the cycle.

The rock cycle is a vital part of the Earth's system. It helps to recycle the Earth's materials, and it also plays a role in the formation of mineral deposits. The rock cycle is a complex process, but it is essential for understanding the Earth's geology.

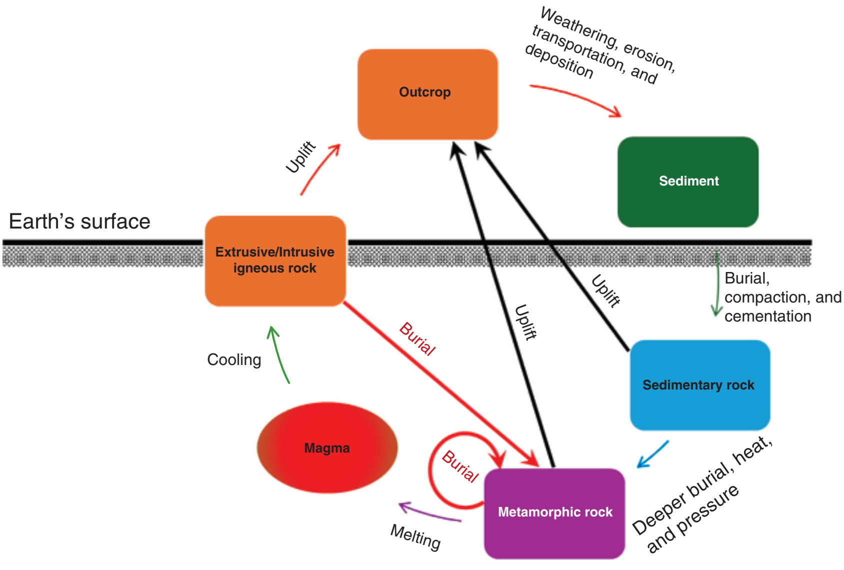

Figure 1.1 Schematics of the rock cycle.

This cycle is driven by two primary forces:

1. *Earth's internal heat engine*: The immense heat from the Earth's interior causes convection currents in the mantle, leading to the movement of tectonic plates. This movement drives processes, such as volcanic activity, mountain building, and the formation of igneous and metamorphic rocks. For example, when tectonic plates collide, they can push rocks deep into the Earth's crust, where they are subjected to high temperatures and pressures, forming metamorphic rocks (Figure 1.2).
2. *The hydrological cycle*: Powered by solar energy, the hydrological cycle involves the continuous movement of water on, above, and below the surface of the Earth. This cycle includes processes, such as weathering, erosion, transportation, deposition, and precipitation (Figure 1.3). For instance, rainwater can cause the weathering of rocks, breaking them down into smaller particles that are transported by rivers and deposited as sediment in lakes or oceans, eventually forming sedimentary rocks.

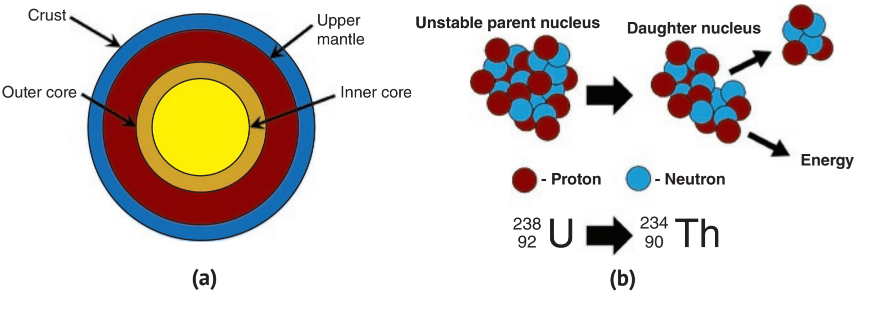

Figure 1.2 Internal structure of Earth (a) and main source of internal heat/energy (b).

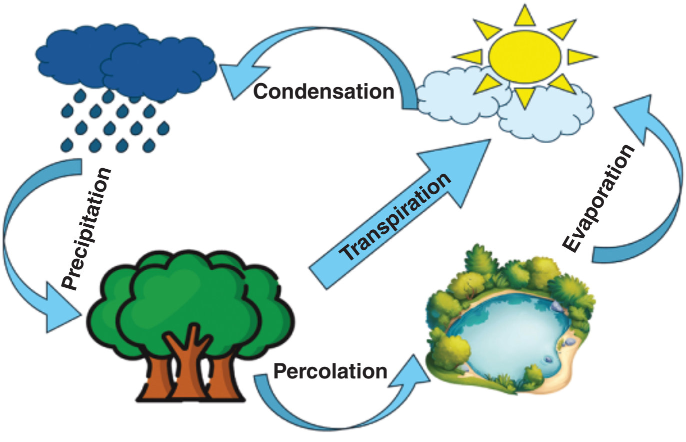

Figure 1.3 Schematics of the hydrological cycle.

To understand the rock cycle, it's convenient to start with magma, which is molten rock beneath the Earth's surface. Magma has temperatures ranging from about 800 to 1,300°C, depending on its composition and the pressure. When magma cools and solidifies, it forms igneous rocks. The location where this cooling occurs determines the type of igneous rock formed:

- *Intrusive igneous rocks*: These form when magma cools slowly beneath the Earth's surface, allowing large crystals to develop. Granite is a common example of intrusive igneous rock.
- *Extrusive igneous rocks*: These form when magma erupts onto the surface (as lava) and cools quickly, resulting in smaller crystals. Basalt is an example of extrusive igneous rock.

Weathering and erosion are critical processes in the rock cycle that break down rocks into smaller particles, which can then be transported and deposited to form sedimentary rocks. Types of weathering:

1. *Physical (mechanical) weathering*: This type of weathering breaks rocks into smaller pieces without changing their chemical composition. It includes:
   - Frost wedging: Water seeps into cracks in rocks, freezes, and expands, causing the rock to break apart.
   - Thermal expansion: Repeated heating and cooling cause rocks to expand and contract, leading to fragmentation.
   - Biological activity: Plant roots grow into cracks in rocks, and animals burrow into the ground, contributing to the mechanical breakdown of rocks.
2. *Chemical weathering*: This involves the chemical alteration of minerals within the rocks, leading to their breakdown. Key processes include:
   - Hydrolysis: Water reacts with minerals to form new minerals and soluble ions. For example, feldspar transforms into clay minerals.
   - Oxidation: Oxygen reacts with minerals, especially those containing iron, to form oxides. This process is responsible for the rusting of iron-rich rocks.
   - Dissolution: Soluble minerals, such as halite and calcite, dissolve in water, especially in acidic conditions.

3. *Biological weathering*: This type of weathering involves the contribution of living organisms. For instance, lichen and moss can produce acids that chemically weather rocks, while tree roots and burrowing animals physically break down rock.

1.1.2 Erosion

Erosion involves the transportation of weathered materials by natural agents. The primary agents of erosion include:

- Water: Rivers and streams carry sediments downstream, where they are deposited in floodplains, deltas, and oceans.
- Wind: In arid regions, wind can transport fine particles over long distances, creating features like sand dunes.
- Glaciers: Moving glaciers pick up and transport large quantities of rock debris, depositing them as glacial till when the ice melts.
- Gravity: Gravity causes rocks and sediments to move downhill through processes like landslides and rockfalls.

Understanding the rock cycle is essential for geologists as it provides insights into Earth's geological history, the formation and distribution of natural resources, and the processes that shape the planet's surface. For example:

- Natural resources: Many natural resources, such as minerals and fossil fuels, are found in specific rock types formed through the rock cycle. For instance, coal forms from buried plant material in sedimentary rock layers, while valuable minerals can be concentrated in igneous and metamorphic rocks.
- Geological hazards: Knowledge of the rock cycle helps in predicting and mitigating geological hazards, such as volcanic eruptions, earthquakes, and landslides.

The rock cycle is not unique to Earth; it can also occur on other planetary bodies, although with significant differences. For instance:

- The moon: The Moon lacks an atmosphere and liquid water, and its tectonic activity is minimal, resulting in a virtually inactive rock cycle.
- Mars: Mars shows evidence of past volcanic activity and ancient river valleys, indicating a once-active rock cycle. However, its current rock cycle is much less active than Earth's due to the absence of liquid water and significant tectonic activity.
- Studying these differences helps scientists understand the unique geological histories of other planets and the factors that influence their evolution.

1.2 Forms of Occurrence of Sedimentary Rocks

Sedimentary rocks are composed mainly of almost parallel layers (strata), differing in physical and chemical properties (Figure 1.4).

The surfaces separating the layers from each other are called the base if it is located below the layer in question and the roof if it is located on top. The line descending perpendicularly from the roof to the sole is called the thickness of the layer (or thickness of the layer); it is also the shortest distance between the roof and the base.

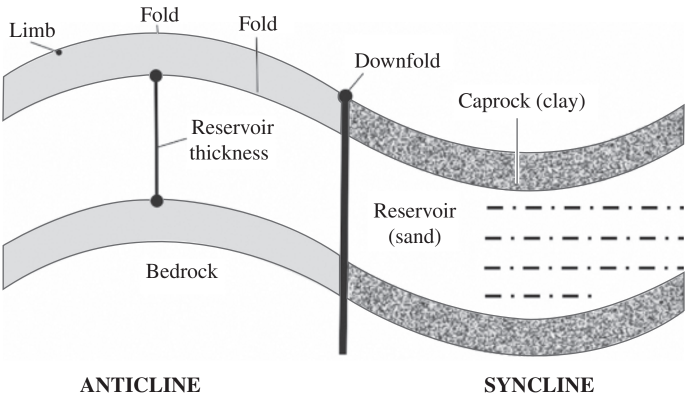

Figure 1.4 Mode of rocks occurrence.

A layer composed of impermeable rocks is called a seal, and one formed from permeable rocks is called a reservoir. In nature, ideally, horizontal occurrence of layers is rarely found; as a rule, they have a wavy (folded) occurrence. This occurrence is due to the fact that the earth's crust is not static, and various oscillatory, tectonic processes constantly occur in it.

The folds formed during these processes are called anticlines and synclines.

Anticline—an anticline is a convex bend in the Earth's crust with a core in the center, with the core composed of older rocks and the outer layers composed of younger rocks.

Syncline—a syncline is the mirror opposite of an anticline, i.e., a concave curve in the Earth's crust with ancient rocks in the outer part and young rocks in the central part. The structural elements of the anticline and syncline are shown in Figure 1.4.

Most of the oil and gas fields are confined to anticlines. Anticlines have an average length of up to 10 km and width up to 3 km. The largest oil field, Ghawar (Saudi Arabia), is located in an anticline 225 km long and 25 km wide.

1.3 Hydrocarbon Reservoirs

For a petroleum engineer, the property of rocks known as permeability is of particular interest, which will be discussed in detail below. For now, let's dwell on the fact that, depending on the permeability of rocks, they are divided into reservoirs and seals. Seals are practically impermeable rocks that act as a dividing surface between reservoir layers.

Reservoirs are rocks that have the ability to contain and release fluids. Mostly reservoir rocks are of sedimentary origin.

The following types of reservoirs are distinguished by pore void structure:

1. *Porous reservoirs*: They consist of voids formed by grain-like debris. For example: sands, sandstones, etc. This type has the best reservoir properties compared to others.

2. *Cavernous reservoirs*: They are mainly associated with carbonate strata and are composed of voids (caverns) formed as a result of leaching or dissolution of salts that make up the rock.
3. *Cracked reservoirs*: This type of reservoir is formed from impermeable rocks; however, numerous fractures of varying sizes allow them to accommodate hydrocarbons. For example, limestones.
4. *Mixed reservoirs*: They are quite common and are a combination of the above types of reservoirs, with the first word in the name indicating the type of predominant rock. For example, cavernous—porous reservoir.

The best reservoir properties. Other types of collectors may also have good abilities to contain and release liquids and gases, as well as pass them through themselves.

It should be noted that there is also a classification of reservoirs by lithological composition:

- terrigenous (silts, sands, etc.),
- carbonate (dolomite, chalk),
- siliceous rocks,
- volcanogenic-sedimentary.

Hydrocarbon deposits are most often found in terrigenous and carbonate reservoirs.

1.4 Oil and Gas Traps

A trap is a part of a reservoir, the conditions of which provide for the accumulation of hydrocarbon reserves. A trap, in essence, is a permeable rock bounded by impermeable layers (seals) in which fluids are in static conditions and distributed according to the law of gravity. This distribution forms the classic structure of an oil field (Figure 1.5).

The fluid interface is named according to the fluids bordering it:

- GWC—gas-water contact,
- WOC—water-oil contact,
- GOC—gas-oil contact.

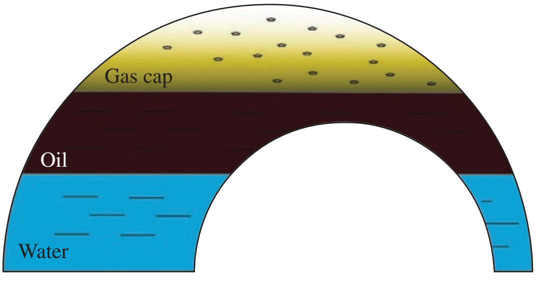

Figure 1.5 Oil field schematic.

There are two main types of traps:

- structural,
- nonstructural.

Nonstructural traps, in turn, are divided into two types:

- stratigraphic,
- lithological.

1.4.1 Structural Traps

This type of trap, formed due to the migration of hydrocarbons into the fold of the anticline, is called *Anticline (fold) traps* (Figure 1.6). Hydrocarbon migration occurs either along the limbs of anticlines or along tectonic faults.

During tectonic movements of the earth's crust, disturbances in the form of rock formations are often formed. If such a disturbance results in an overlap of the reservoir layer with an impermeable screen (seal), such a trap is called a fault trap (Figure 1.7).

The types of structural traps described above generally have the greatest industrial significance in terms of the availability of potential hydrocarbon reserves.

1.4.2 Lithological Traps

This type of traps is formed due to the lithological dynamics of reservoir rocks, that is, the replacement of permeable rocks with impermeable. The reasons for this process are different, but among the most common of them are the following: pinchout, fracturing and changes in the permeability of reservoir rocks (Figure 1.8). Such traps are formed in the form of sand lenses in clayey deposits (Figure 1.8a) or in reef bodies (limestones) covered by poorly permeable rocks (Figure 1.8b).

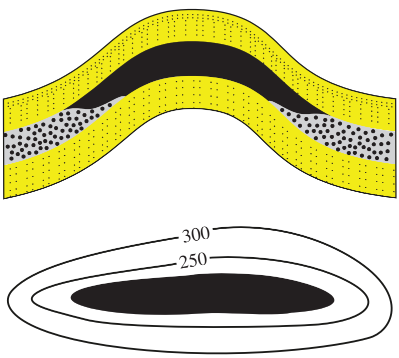

Figure 1.6 Anticline (fold) trap.

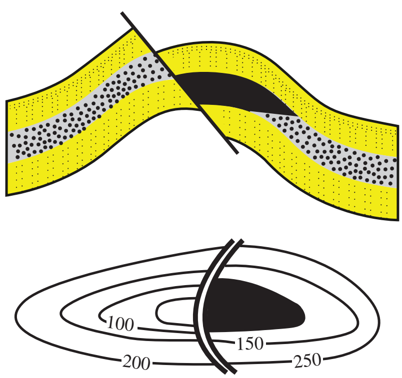

Figure 1.7 Fault trap.

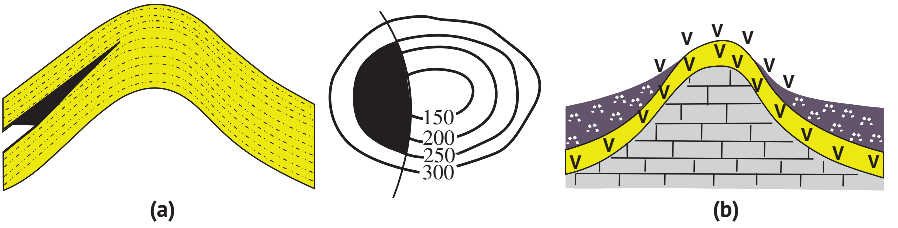

Figure 1.8 (a) Pinch-out trap; (b) a trap confined to a reef massif.

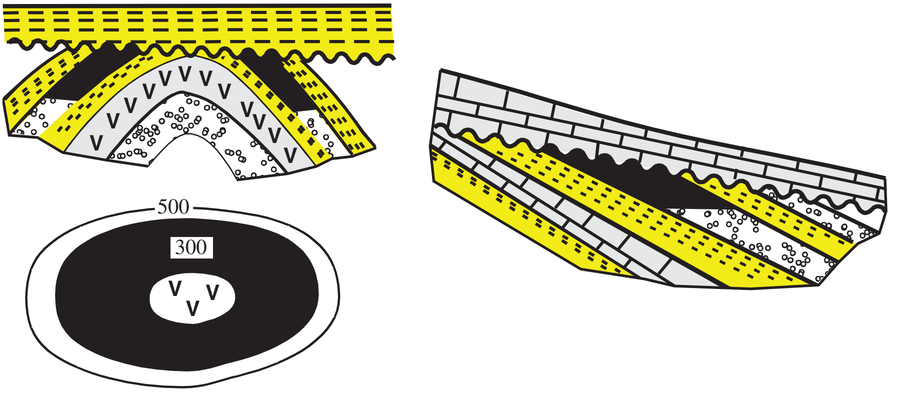

Figure 1.9 Stratigraphic traps.

1.4.3 Stratigraphic Traps

This type of trap is formed by the unconformable overlapping of reservoir rocks with fluid seals (poorly permeable layers). Sometimes a hydrodynamic seal created by formation waters (associated with high-pressure horizons) during filtration along tectonic disturbances can serve as a similar overlapping seal (Figure 1.9).

Quite often, the formation of traps is influenced by several factors, and combined structural and lithological traps are formed.

1.5 Rock Porosity

Porosity is a critical property of reservoir rocks, defined as the ratio of the void space (pores) volume to the bulk volume of the rock, usually expressed as a percentage. This property is fundamental in determining the storage capacity of reservoir rocks for fluids, such as oil, gas, and water. Porosity indicates how much fluid a rock can hold and influences the movement of these fluids through the rock.

1.5.1 Primary and Secondary Porosity

Primary porosity develops during the initial deposition of the rock material. As sediment is deposited and buried, the spaces between the grains form the primary porosity.

Over time, processes like compaction (where grains are pressed closer together under the weight of overlying materials) and cementation (where minerals precipitate from groundwater and fill the spaces between grains) reduce this primary porosity.

Secondary or induced porosity develops after the rock has formed. This type of porosity results from various geological processes, such as fracturing, dissolution, or recrystallization. For example, fractures in shales and limestones or solution cavities known as karsts are forms of secondary porosity. These secondary features can significantly enhance the ability of rocks to store and transmit fluids.

1.5.2 Effective and Total Porosity

From a reservoir engineering perspective, it is essential to distinguish between connected porosity and nonconnected pores (Figure 1.10). Effective porosity refers to the ratio of interconnected void spaces to the bulk volume of the rock, which is crucial for fluid flow within the reservoir. In contrast, total porosity is the sum of both connected and nonconnected porosities. Typically, in sandstones, the total porosity equals the effective porosity, as most pores are interconnected. However, in carbonates such as dolomites and limestones, nonconnected vuggy porosity may occur, where some pores do not contribute to fluid flow.

1.5.3 Diagenesis and Its Impact

Diagenesis refers to the physical and chemical changes that occur in sediment after its deposition, transforming it into sedimentary rock. This process can significantly affect both porosity and permeability. Diagenesis includes various processes, such as mechanical compaction (which reduces pore space by pressing grains closer together), mineralogical changes (altering the mineral composition of the rock), cement precipitation (filling pores with new mineral growth), and mineral dissolution (enlarging pores by dissolving existing minerals) (Figure 1.11). These processes can either enhance or reduce the porosity and permeability of the rock.

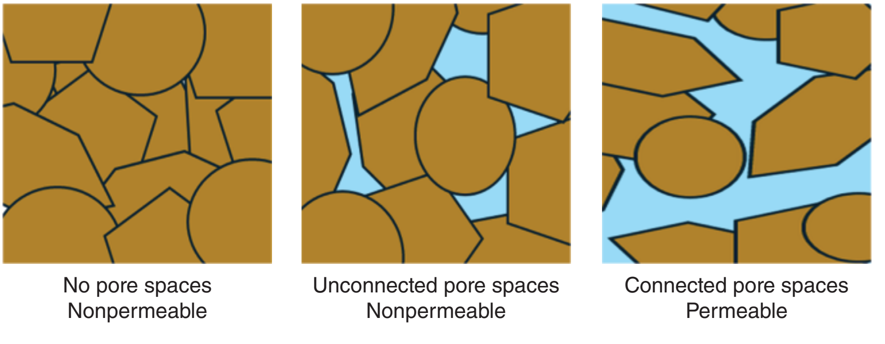

Figure 1.10 Connected/nonconnected pores.