Anniversaries

Pentti Eelis Eskola died 60 years ago

METAMORPHIC FACIES: THE BIRTH OF A CONCEPT

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Berndt Eelis Eskola (Fig. 1) was born on January 8th, 1883, in Lellainen (near Turku, in southwest Finland). He changed his given first name to Pentti during his childhood in honor of his ancestor who established the family farm in 1640. He began studying ancient Greek at the Alexander University of Helsinki in 1901, but later changed to follow courses in zoology. After failing the zoology exam, he went on to study chemistry and, after completing a study on solid-state pressure-dependent reactions, he graduated in 1906.

Fig. 1. Pentti Eelis Eskola (1883–1964). Source: Wikimedia commons.

He subsequently obtained a position as a lecturer in geology at the Department of Agricultural Economics at the University of Helsinki in 1910 and became an assistant at the Institute of Geology and Mineralogy there in 1913. In 1928, he was appointed professor at the same institute, where he carried out his research and teaching activities until his retirement in 1953.

The premise of the concept of metamorphic facies can be found in Eskola's 1914 publication. Eskola describes the parageneses (i.e., the mineral equilibrium assemblages in a rock) of the metamorphic rocks from the Orijärvi region (Finland) as being ruled by simple laws related to the bulk rock chemistry (Eskola, 1914). Although this idea may seem trivial today, it was a finding of great significance. The formal concept of metamorphic facies was introduced one year later (Eskola, 1915) and defined as follows:

> *"In any rock of a metamorphic formation which has reached a chemical equilibrium through metamorphism under constant temperature and pressure conditions, the mineral composition is controlled solely by the chemical composition [of the rock]."*

A key point is that Eskola's concept is independent of the type of metamorphism (e.g., contact and regional metamorphisms), in contrast to the depth zone classification that was applied exclusively to regional metamorphism (Barrow, 1897; Grubenmann, 1910). Even before defining metamorphic facies, Eskola emphasized the need to revise Grubenmann’s classification (epi-, meso- and cata-zones), suggesting that the number of facies should be greater than the number of depth zones. In this publication, Eskola only briefly introduced the concept of facies without proposing a comprehensive classification. He only discussed the facies of the Orijärvi rocks, which he would later classify as amphibolite facies.

In a 1920 publication entitled *“The Mineral Facies of Rocks”*, Eskola generalized the idea presented in 1915. Five years elapsed before Eskola refined his ideas on mineral facies, during which time he met Goldschmidt at the University of Christiana (Oslo, Norway) during his visit between 1919 and 1920. Eskola and Goldschmidt engaged in extensive discussions, and it was reportedly after an entire night of conversations in the laboratory corridors that Eskola conceived the idea of generalizing the concept of mineral facies.

In 1915, Eskola introduced the term *metamorphic facies* to refer to a group of rocks characterized by a mineral assemblage formed under specific conditions (pressure and temperature), in which the minerals are at equilibrium (Eskola, 1915). It is important to note that at this stage, Eskola (1920) reiterated that the composition of the minerals varies gradually with the bulk rock composition. Eskola also emphasized that, regardless of the type of crystallization, there is a tendency toward achieving a state of equilibrium. Therefore, the concept of metamorphic facies can be generalized into a broader concept, known as *mineral facies*.

A mineral facies corresponds to all rocks formed under similar pressure and temperature conditions, regardless of the formation mechanism. Eskola mentions the following mechanisms: crystallization from magma, from an aqueous or gaseous solution, direct crystallization from a solution (e.g., hydrothermal processes), or gradual changes in mineral composition (e.g., metamorphic recrystallization).

Prior to Eskola, Grubenmann (1910) had defined zones of metamorphism correlated with paleodepth (epi-, meso- and cata-zones) without distinguishing between pressure and temperature. With the concept of mineral facies, Eskola dissociates pressure and temperature as two independent variables, some facies corresponding to high-temperature conditions (e.g., hornfels facies) and others to high-pressure metamorphism (e.g., eclogite facies). In the absence of experimental petrology, the role of pressure could only be appreciated through the relative densities of the mineral assemblages, since thermodynamics indicate that an increase in pressure should lead to the formation of minerals of higher density. In 1903, Becke had used this concept, often referred to as the *volume law*, to demonstrate that eclogites were the high-pressure equivalent of gabbros.

Eskola (1920) suggested that classification should be based on mineral assemblages only, and proposed a description based on facies and characteristic minerals. This type of classification had already been applied by Goldschmidt (1911) to the hornfelses (e.g., *pyroxene-hornfels*, where *hornfels* represented the facies name). However, Eskola considered it premature to propose a precise nomenclature and defined only five main metamorphic facies (and their magmatic equivalents):

- **Greenschist Facies** (*Helsinkite* facies);
- **Amphibolite Facies** (*Hornblende Gabbro* facies);
- **Eclogite Facies** (*Magmatic Eclogite* facies);
- **Hornfels Facies** (*Gabbro* facies);
- **Sanidinite Facies** (*Diabase* facies).

Of these five facies, the first three were defined using rocks of gabbroic composition, which he considered preferable (Fig. 2), in order to simplify his analysis as much as possible. This allowed him to define critical mineral assemblages that are representative of facies, which, in turn, are characteristic of pressure and temperature conditions.

Before providing a detailed description of the different facies, Eskola (1920) reviewed some key definitions (see also, Plunder, 2013). *Critical minerals or associations* are those whose presence defines a rock as belonging to a specific facies. *Typical minerals* are those that are stable within a facies, whether they formed in those facies or crystallized in another facies and remained stable (i.e., Eskola's "*stable relics*", a concept he valued highly; for example, quartz is typical of many metamorphic facies).

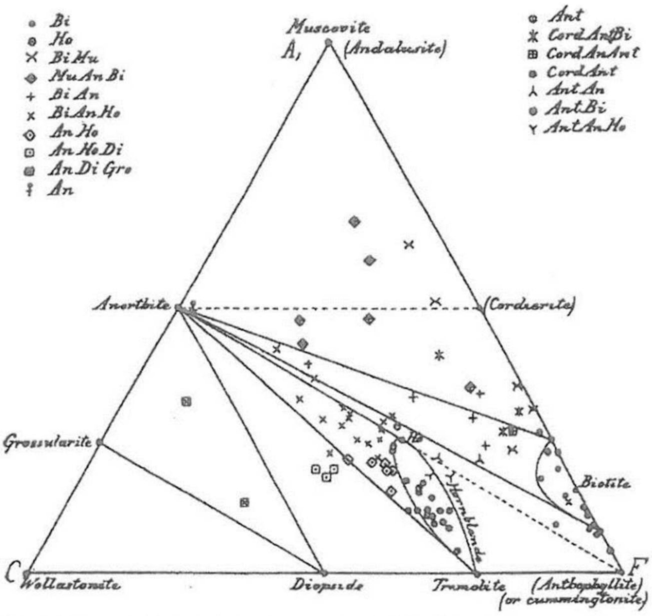

Fig. 2. Illustration of the whole-rock analyses presented by Eskola (1920), who emphasized that these rocks are similar in composition except for their water content (from Figure 4 of the original publication).

After this introduction, Eskola defined the facies more formally:

- **The Sanidinite Facies** includes all pyrometamorphic rocks that, if silicate-bearing, contain associations with: sanidine, plagioclase, sillimanite, cordierite, jadeite-free clinopyroxene, wollastonite, and olivine. Sanidine and clinopyroxene are critical minerals.
- **The Hornfels Facies** (from the German: Hornfels) includes contact metamorphism rocks that show the same mineral assemblages as the rocks from the inner zone of contact metamorphism in the Christiania [Oslo] region, regardless of their pre-metamorphic history, and excluding all rocks labeled *hornfels* that show a different mineral assemblage. Typical minerals are: orthoclase, plagioclase, andalusite, cordierite, biotite, orthopyroxene, diopside, wollastonite, grossular-andradite garnet, and olivine. The critical association is ortho- and clino-pyroxenes.
- **The Amphibolite Facies** includes rocks with the same mineral assemblages as those found in the Orijärvi region (Eskola, 1914, 1915). These rocks consistently contain amphiboles, which are considered critical for this facies. Other minerals include: microcline, plagioclase, muscovite, andalusite, almandine, anthophyllite, cummingtonite, diopside, wollastonite and Ca-bearing garnet.
- **The Greenschist Facies** rocks contain the following minerals: albite, sericite, chlorite, talc, serpentine, epidote, calcite and dolomite. The characteristic associations are sericite-chlorite and epidote-albite.
- **The Eclogite Facies** is described as follows: the critical assemblage is garnet and jadeite-rich clinopyroxene (a solid solution of diopside, jadeite and "*pseudo-jadeite*"). The possible presence of small amounts of orthopyroxene, olivine or kyanite is mentioned. Rutile is described as common but minor. It should be remembered that the following year Eskola (1921) published an important study on the eclogites of Norway, where he (erroneously) supported a magmatic origin for these rocks, thus applying his concept of mineral facies to magmatic as well as to metamorphic rocks. In fact, he shared the idea of Fermor and Goldschmidt, who had deduced from the volume law the existence of a

> deep "eclogite layer" in the SIMA (i.e., in the mantle) beneath a "gabbroic layer", both made of magmatic rocks (Eskola, 1936; Godard, 2001).

Eskola's subsequent work further refined his classification, introducing new facies: **glaucophane-schist facies** (Eskola, 1929); **granulite facies**; **zeolite facies**; **epidote-amphibolite facies** (Eskola, 1939), or the revision of some others (Fig. 3) (Plunder, 2013). In the 1920s and 1930s, however, it became clear that magmatic rocks could not crystallize over a wide range of temperatures. For example, there are no magmatic rocks in the low-temperature greenschist and zeolite facies. Eskola would also have changed his mind about the magmatic origin of the eclogites, favoring the metamorphic origin proposed by German and French petrologists, especially Yvonne Brière (Godard, 2001). Therefore, the concept of mineral facies (Eskola, 1920) reverts to that of metamorphic facies (Eskola, 1929, 1939) for a large part of the *P*-*T* diagram (Fig. 3).

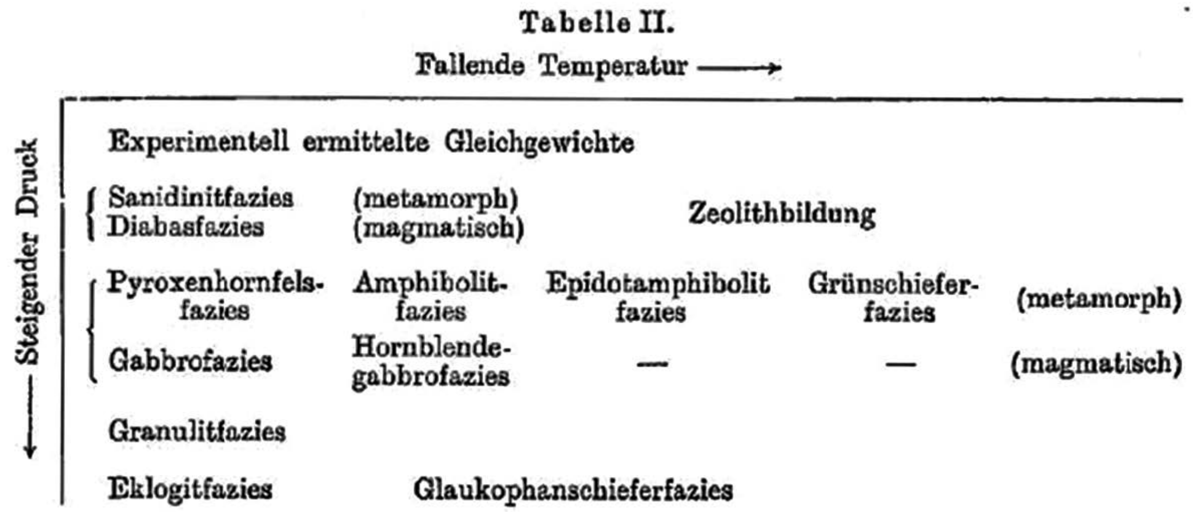

Tabelle II.

Fallende Temperatur ⟶

⟵ Steigender Druck

Experimentell ermittelte Gleichgewichte				
Sanidinitfazies	**(metamorph)**	**Zeolithbildung**		
Diabasfazies	**(magmatisch)**			
Pyroxenhornfelsfazies	**Amphibolitfazies**	**Epidotamphibolitfazies**	**Grünschieferfazies**	**(metamorph)**
Gabbrofazies	**Hornblendegabbrofazies**	—	—	**(magmatisch)**
Granulitfazies				
Eklogitfazies	**Glaukophanschieferfazies**			

Fig. 3. Table of the mineral facies from Eskola (1939). Horizontal axis: falling temperature; vertical axis: increasing pressure. Note that the name of some facies can refer to metamorphic ("metamorph") or magmatic ("magmatisch") facies.

Eskola retired from the University of Helsinki in 1953. During his career, he received several awards, some of which are briefly mentioned here. He received the Penrose Medal in 1951 (Geological Society of America), the Wollaston Medal in 1958 (Geological Society of London), the Vetlesen Prize in 1963 (Lamont-Doherty Earth Observatory). The Geological Society of Finland created the Eskola Medal, of which he was the first recipient, in 1963, on the day of his 80th birthday. Another notable tribute to Eskola is the description of a new mineral with the formula Cr_2O_3, named Eskolaite (Kouvo and Vuorelainen, 1958). Eskola passed away in 1964 on December the 6th, the National Independence Day of Finland. He was honored with a state funeral on December 14th in Gamla Kyrkan, the oldest church in Helsinki. More details about his life and work can be found in Barth (1965), Marmo (1965), Mikkola (1968) and Amstutz (2008).

What should we remember about Eskola's work? His concept of mineral facies basically assumes that the mineralogical composition of a rock (i.e., the abundance and composition of its minerals) is a *state function*. In thermodynamics, a state function depends on the state of the system, not on how that state was reached. In the case of a rock, the state is defined by pressure, temperature and bulk chemical composition; a particular state, whether reached by crystallization of a magma, prograde metamorphism, retrograde metamorphism, metasomatism, etc., results in the same mineral assemblage (for a given bulk-rock composition) when equilibrium is attained. This principle is still valid in modern petrology. Eskola could only have had a rudimentary understanding of the effects of temperature and pressure, which led him to conceive of his facies as ill-defined pressure and temperature domains. Today, thermodynamics based on experimental petrology allows the modeling of *P-T pseudosections*, where the mineralogical evolution of a rock as a function of pressure and temperature is assessed with great precision. These new techniques are, in a sense, the culmination of the concepts developed by Eskola to define the conditions of rock formation. Paradoxically, they have largely rendered obsolete the concept of facies, which is now used only to describe the first-order conditions of metamorphism.

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