This is a non-peer reviewed preprint submitted to EarthArXiv. Please feel free to contact the author to suggest improvements at crw59@cam.ac.uk.

Dr Craig Robert Walton

Trinity College, Institute of Astronomy and Department of Earth Sciences, University of Cambridge.

Universal techniques for mineral identification in thin-section

Abstract

Mineral identification using an optical microscope forms a key part of every introductory course in Earth Sciences. The presence or absence of particular minerals and their textural relationships to one another - that is, the visual impression of the size, shape, and arrangement of grains/crystals/particles in a rock - act as keys to the origin and evolution of the Earth system. Indeed, many would claim that the best geologists have simply seen the most rocks (/minerals). Whilst this is no longer strictly true in an age of increasingly abstracted geochemical and statistical approaches, optical microscope studies will (or at least should) remain at the heart of geology for the foreseeable future.
So we come to colour-blindness and visual impairment in optical microscopy. A reasonable percentage of the population are colour-blind or visually impaired. Nowadays, plenty of tools exist to level the playing field and help both tutors and students to see eye-to-eye. This document attempts to make systematic use of those tools.
In Chapter 1, I briefly review some essential points to bear in mind when approaching rock forming mineral classification, which together

help to shrink a complicated problem (whether colour blind or not) down to something more tractable. In Chapter 2, I lay out several systematic approaches for mineral and rock classification. In Chapter 3, I present collected optical microscope images of common rock-forming minerals in plane polarised light (PPL) and cross polarised light (XPL). Using the Color Oracle software, I try to capture how the same images would appear to individuals with differing types of colour blindness. Throughout, the goal is to develop a framework of 'universal' diagnostic mineral features in thin section, i.e., features that should be both possible to identify for a broad range of individuals, and possible to describe using language that translates directly from one person to another.

1 Rock-forming minerals and where to find them

Minerals are thermodynamically and/or kinetically favoured crystalline solids formed in a chemical system at a given set of pressure-temperature (PT) conditions. This reality gives helpful context to the specific minerals we observe in rocks, indicating something about their bulk chemical composition and history of residence either in the Earth's crust/mantle or at the surface.

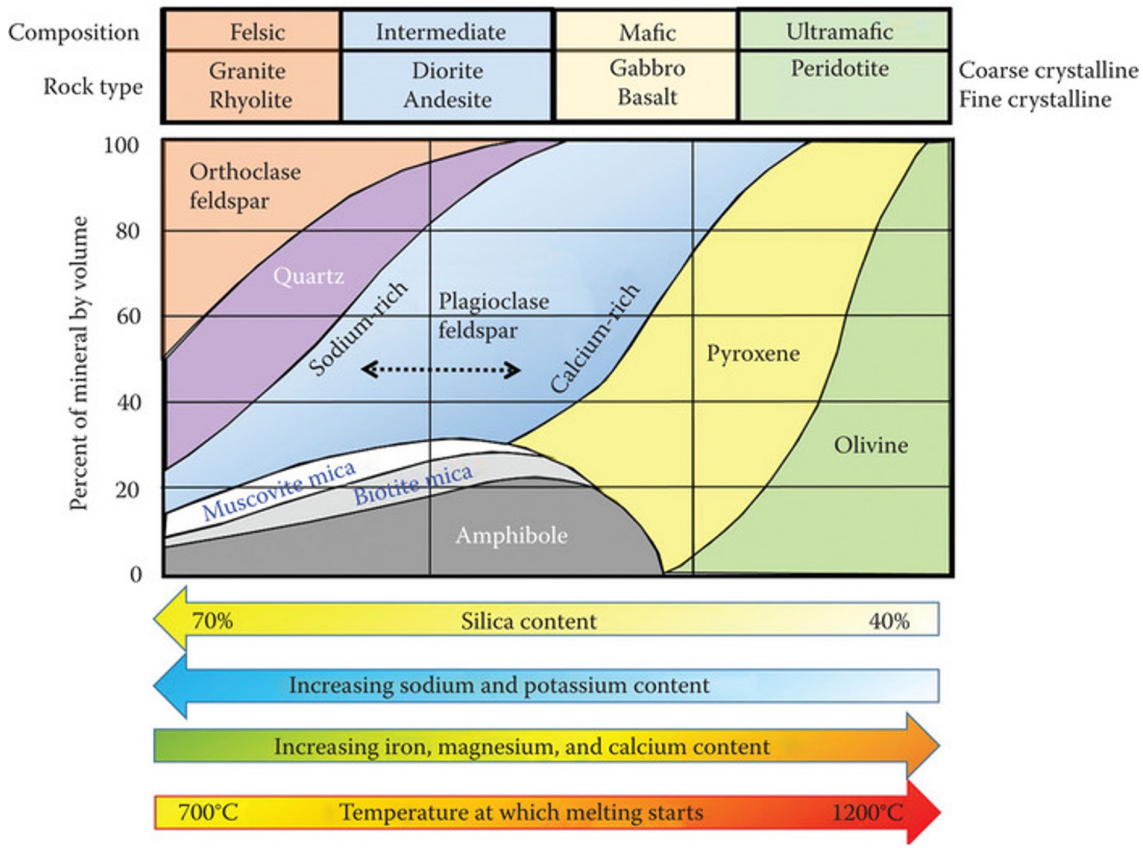
With regard to the challenge of mineral identification, we can expect there to be families of minerals that often co-exist, and those that rarely or never co-exist. That is: once you identify one mineral, you can start to rule out others and speed up the hunt for the rest. Some examples:

a) Muscovite — $(KAl)_2(Si_3Al)O_{10}(OH)_2$. This Al silicate often forms during the metamorphism of Al-rich clays. Therefore, depending on PT conditions reached, we may have formed other Al-rich silicates, like garnet.

b) Olivine — $(Mg, Fe)_2SiO_4$. This is a mafic Fe-Mg-silicate. Olivine forms in high T melts with relatively low Si content. It is unlikely to coexist with quartz, which forms in high Si systems at lower T.

c) In other cases, we might not learn very much at all from one phase – plagioclase feldspar ($(NaAl)Si_3O_8 - (CaAl)_2Si_2O_8$) is present in a wide range of rocks.

Examine Figure 1. Here, the above examples are put into the context of volume abundance in common igneous rocks as a function of silica content, melting temperature, and several other indices. As above, we can see that olivine occupies a very different region of parameter space to quartz. Co-existing with olivine, we can expect pyroxene and plagioclase feldspar. Coexisting with quartz, we can expect orthoclase feldspar, muscovite, biotite, and amphibole. In between, we can expect various intermediate mineral assemblages. In each case, identifying just one phase stands to inform us on what else we should be looking for. The logic behind these associations can be quickly established by looking at Figure 33. Olivine and quartz form at different temperatures and crystallise from liquids of different chemical composition to one another (olivine being relatively poor in Si and quartz being relatively Si-rich), as constrained by the processes of fractionation that take place during ascent and cooling of mantle-derived melts. Mineral assemblages therefore represent the result of fundamental thermodynamic constraints imposed on the physicochemical processes taking place in the Earth System. This information is critical, as it places what would otherwise be a series of obscure mineral names into a rigorous scientific context. A degree of memorisation is still needed, but the point stands: a remarkable amount of detail about the relationship between rock mineral assemblages and the processes that form them - and define the world around us - is encoded by a relatively small number of key phases. There are thousands of minerals, but we can go a long way towards understanding volcanoes, plate tectonics, and subduction zones with an



1.png

Figure 1: Relative volume abundance of rock-forming minerals in common igneous rocks as a function of bulk composition and incipient melting temperatures. Image credit: Prost and Prost (2017).

understanding of the chemical formulae, density, and mineral identification criteria of only a few dozen!

Table 1 presents a simplified guide to the common rock forming minerals and their associations to one another. Guides to the identification of these phases individually will follow in Chapters 2 to 3.

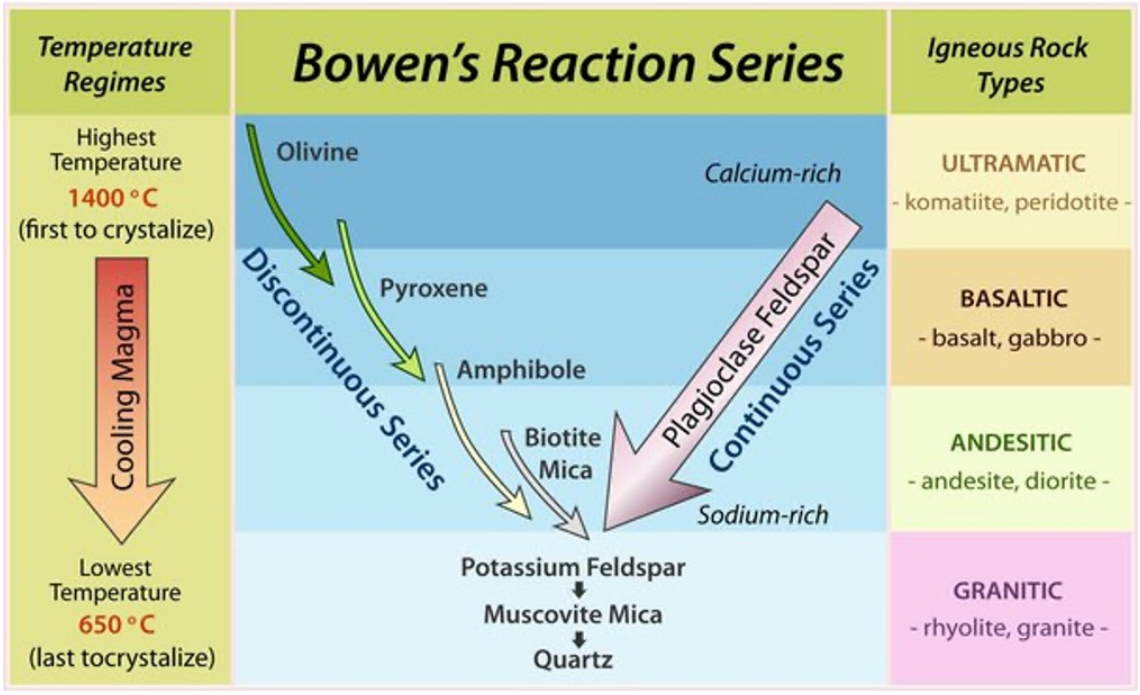
2.png 

Figure 2: The sequence and range over which particular rock-forming minerals will crystallise, explaining their possible co-occurrence or lack thereof. Image credit: Zavadska, CK-12 Foundation, CC BY-NC 4.0.

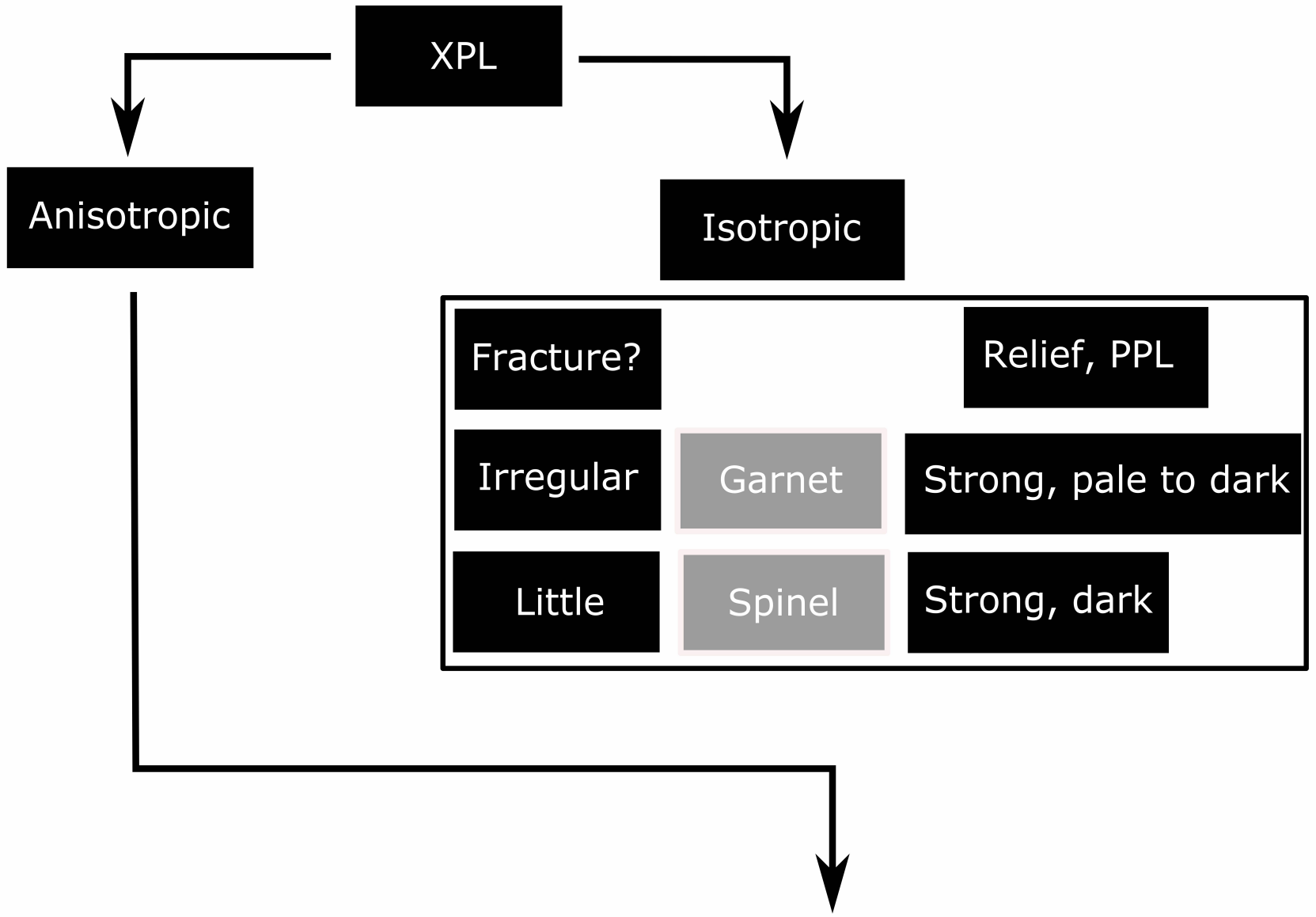
2 Systematic approaches to mineral identification

The various universal identification features of minerals outlined in Chapter 2 will be now brought together in systematic form. Table 1 provides a succinct summary of the key features of each phase. Figs. 2—3 present the same information in the form of a flow-chart, intended to help the reader leverage the identification criteria in a time-efficient manner.

The images, tables, and flow-charts in this guide should be used in conjunction with the figures presented right at the beginning, in Chapter 1 (Figs. 1—2). In doing so, the geochemical logic behind mineral associations will help to efficiently establish the range of possible rock types in which the most easily identified phases in a given sample (often the largest single crystals) may occur, aiding with the next steps of identifying more texturally awkward – fine grained, inter-grown, etc. – or otherwise obscure phases. All credit for microscopy images goes to Microckscopic.com.

Mineral	**XPL**	**PPL**	**Cleavage/fracture**
Olivine	Anisotropic (straight)	High relief, pale	Conchoidal fracture
Orthopyroxene	Anisotropic (straight)	High relief, pale	1 set
Clinopyroxene	Anisotropic (inclined)	High relief	1 set
Amphibole	Anisotropic (inclined)	High relief, pale	2 sets (120 degrees)
Biotite	Anisotropic (straight)	High relief, dark, pleochroic	1 set
Muscovite	Anisotropic (straight), banded	Low relief, pale, banded	1 set
Plagioclase	Anisotropic (banded)	Low relief	None
Orthoclase	Anisotropic, simple twinning	Low relief	None
Microcline	Anisotropic (tartan)	Low relief	None
Spinel	Isotropic	High relief, dark	None
Garnet	Isotropic	High relief, pale-to-dark	Irregular fractures

Table 1: Universal identification features of common rock-forming minerals.


XPL
Anisotropic
Isotropic
Fracture?
Relief, PPL
Irregular
Garnet
Strong, pale to dark
Little
Spinel
Strong, dark

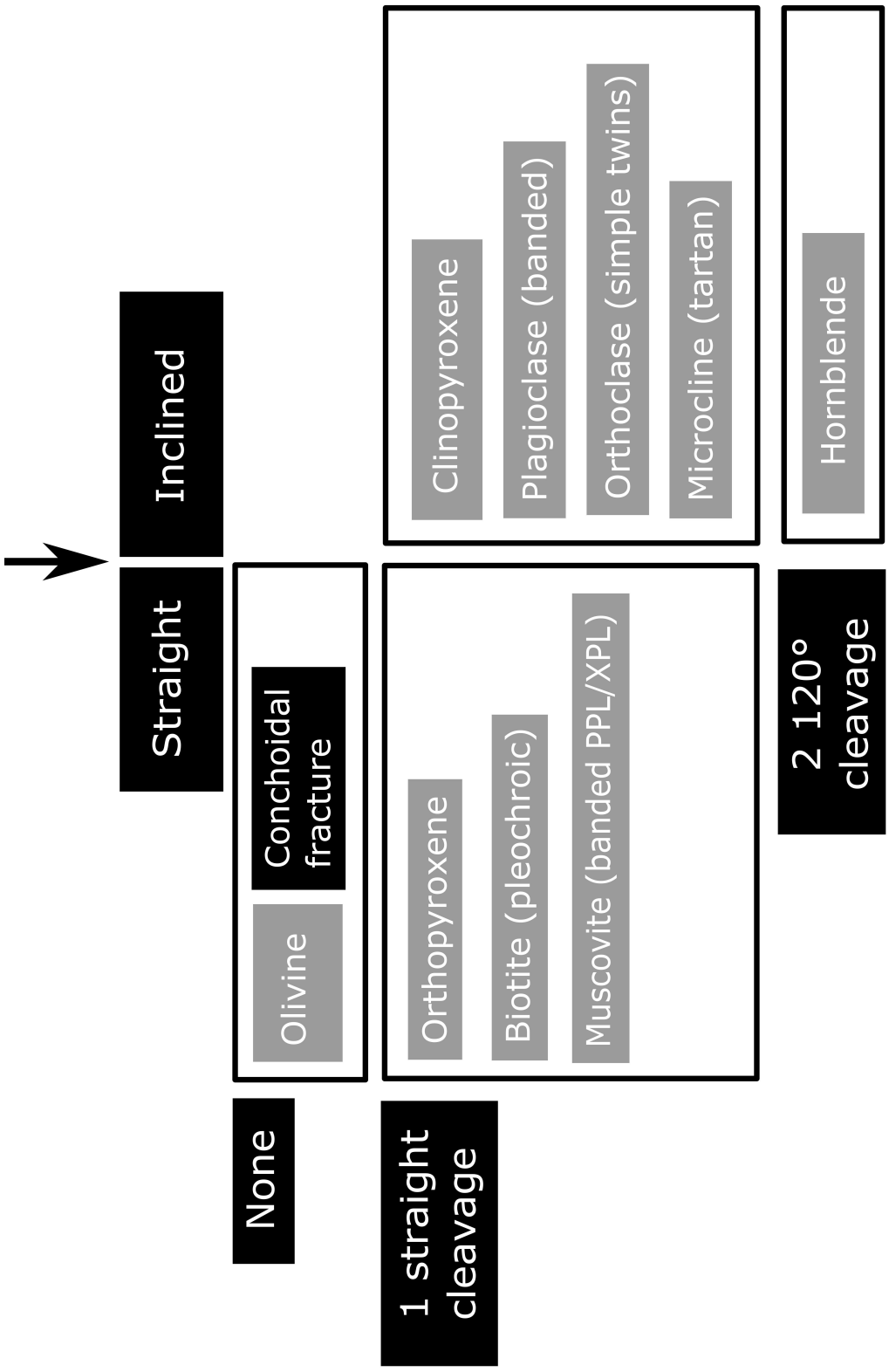


Figure 3: Flow chart for universal mineral ID of common phases.

3 Optical microscopy mineral identification

Anisotropic phases:

Olivine

Olivine — $(Mg, Fe)_2SiO_4$ — is an anisotropic rock-forming silicate mineral, distinguished by high order interference colours in XPL (Fig. 4). More universally, olivine is marked out by its characteristic irregular fracture networks and very high relief in PPL.
1A reference series sections: L141 Gabbro (*) L162 Basalt porphyritic, L172 Ultramafic cumulate.

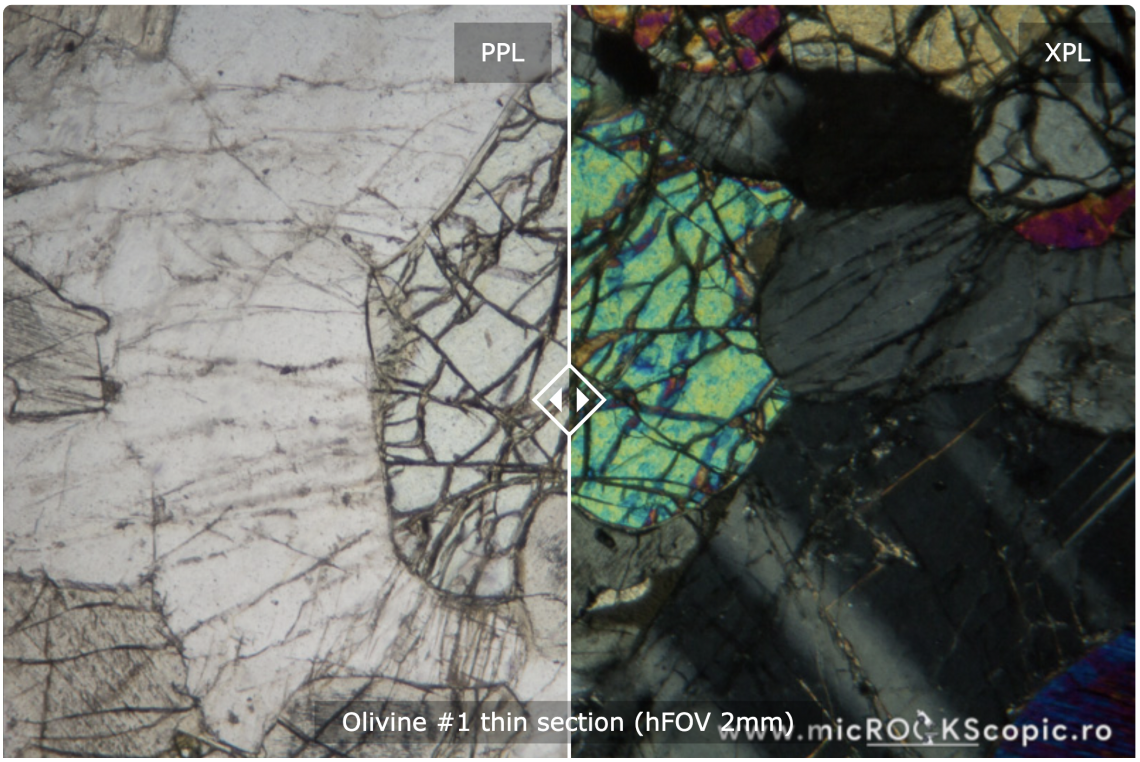


Figure 4: Olivine PPL-XPL. Full colour view.

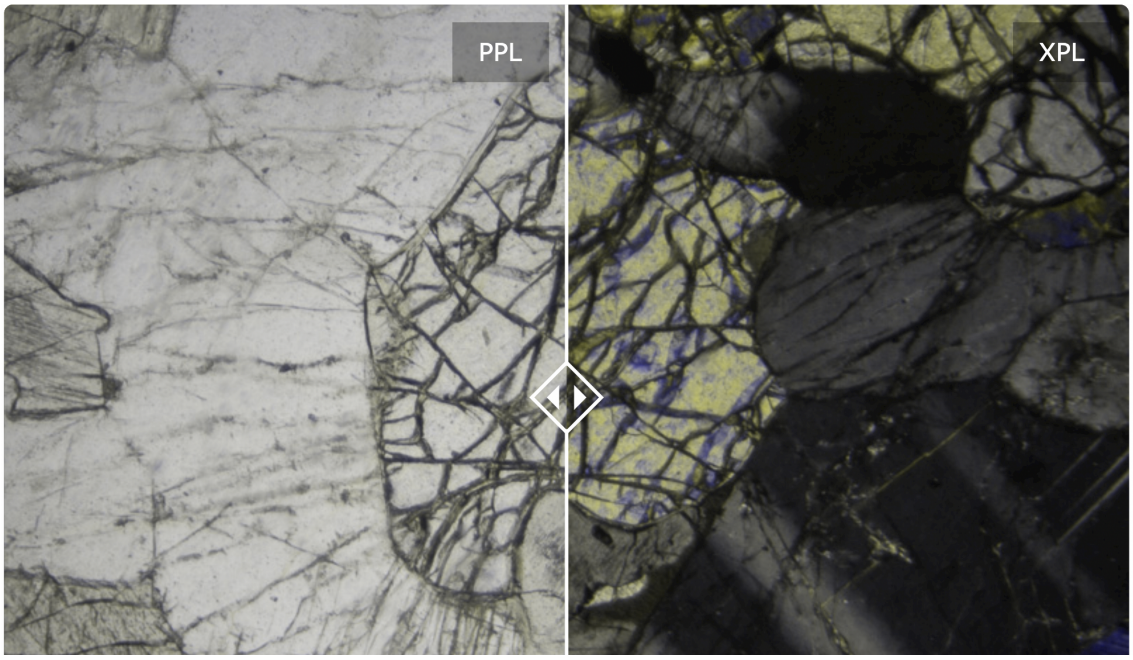


Figure 5: Olivine PPL-XPL. Deuteranopia view.

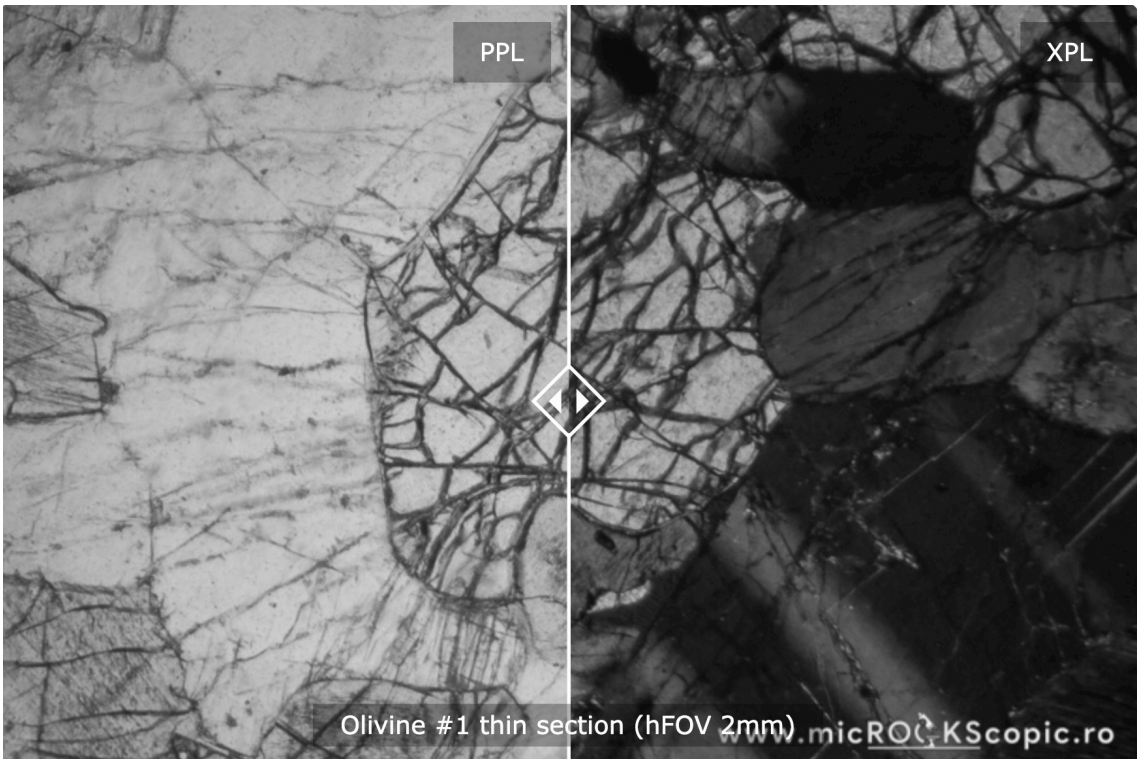


Figure 6: Olivine PPL-XPL. Greyscale view.

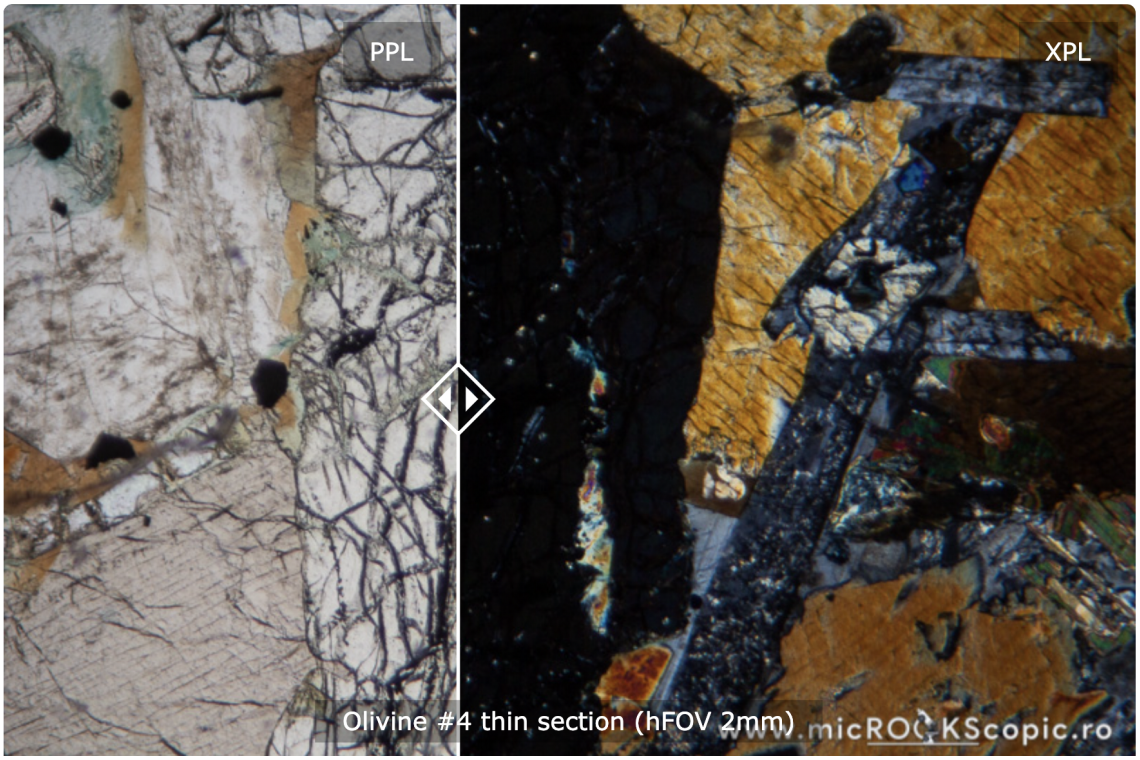


Figure 7: Olivine PPL-XPL. Full colour view.

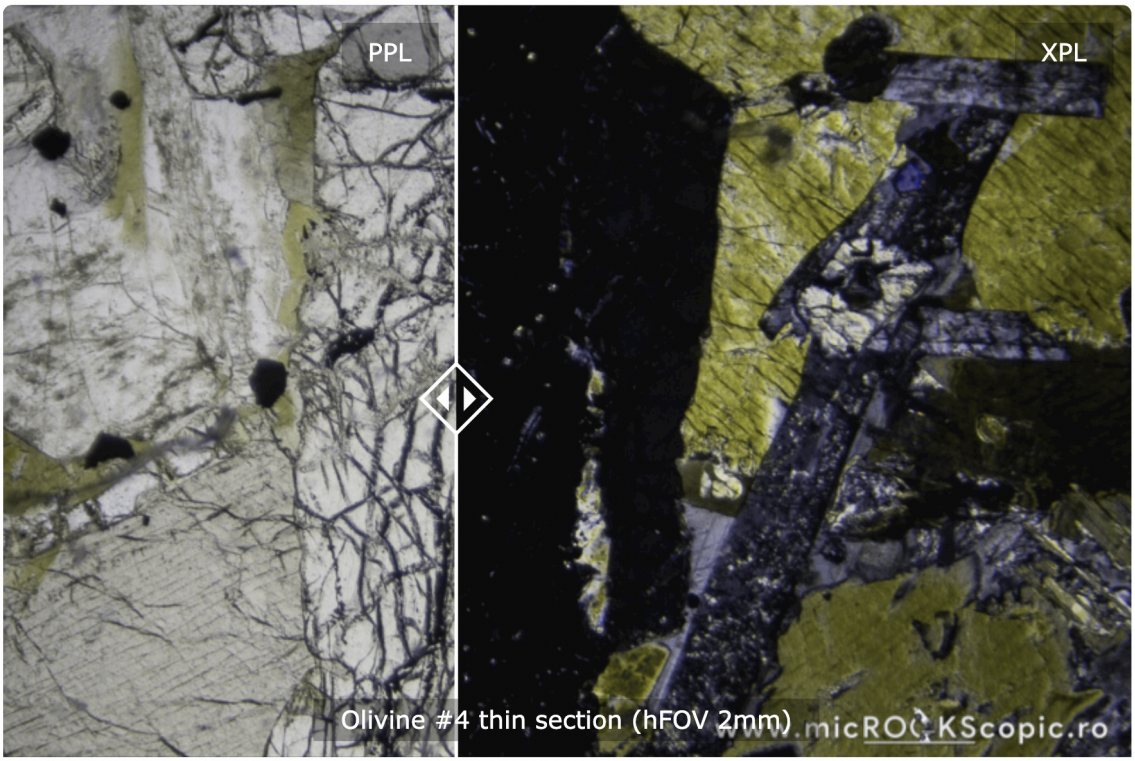


Figure 8: Olivine PPL-XPL. Deuteranopia view.

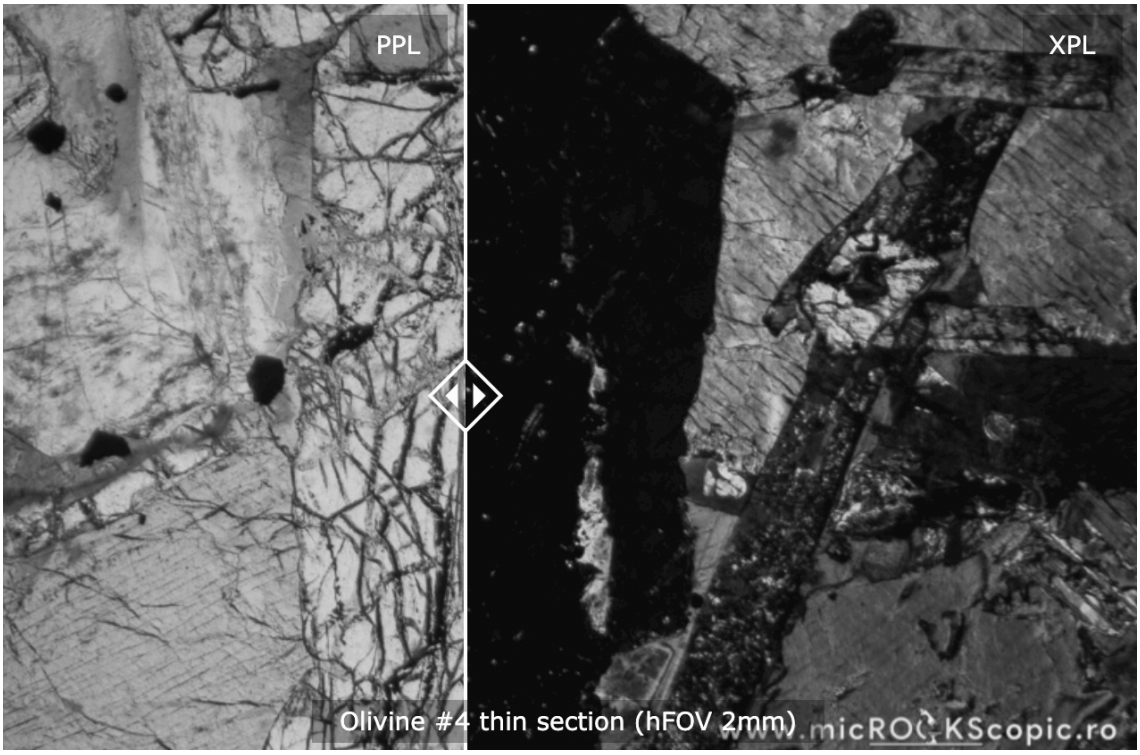


Figure 9: Olivine PPL-XPL. Greyscale view.

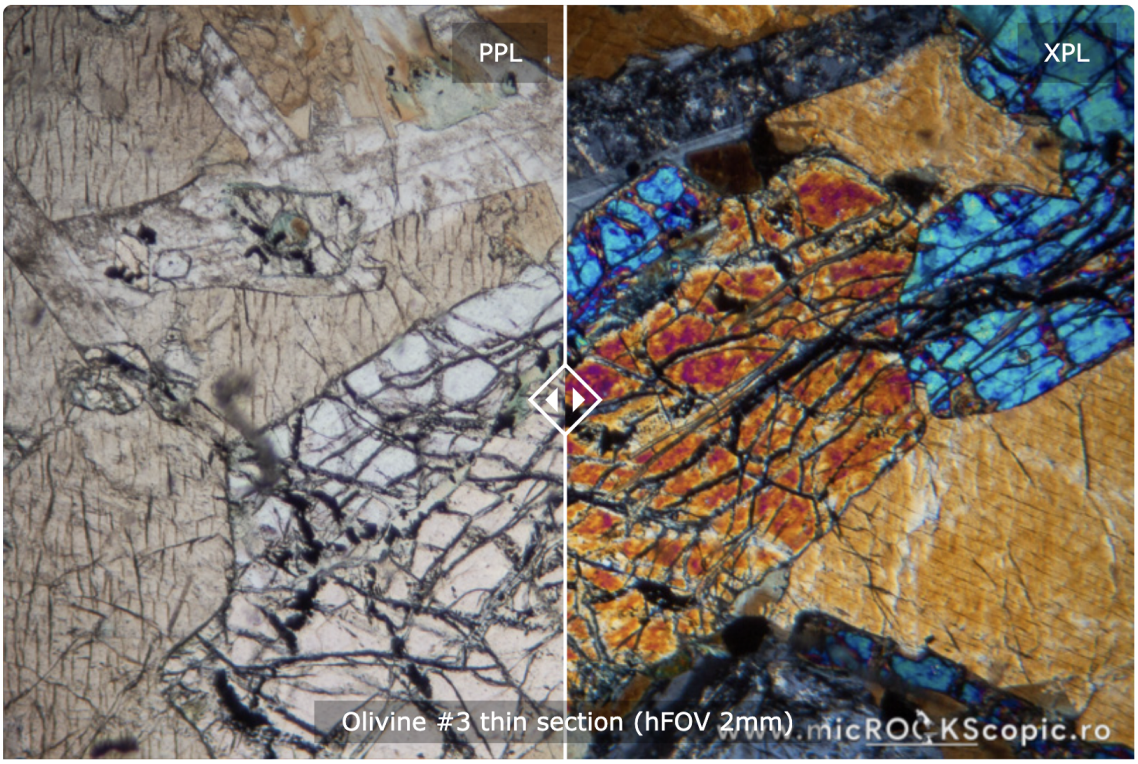


Figure 10: Olivine PPL-XPL. Full colour view.

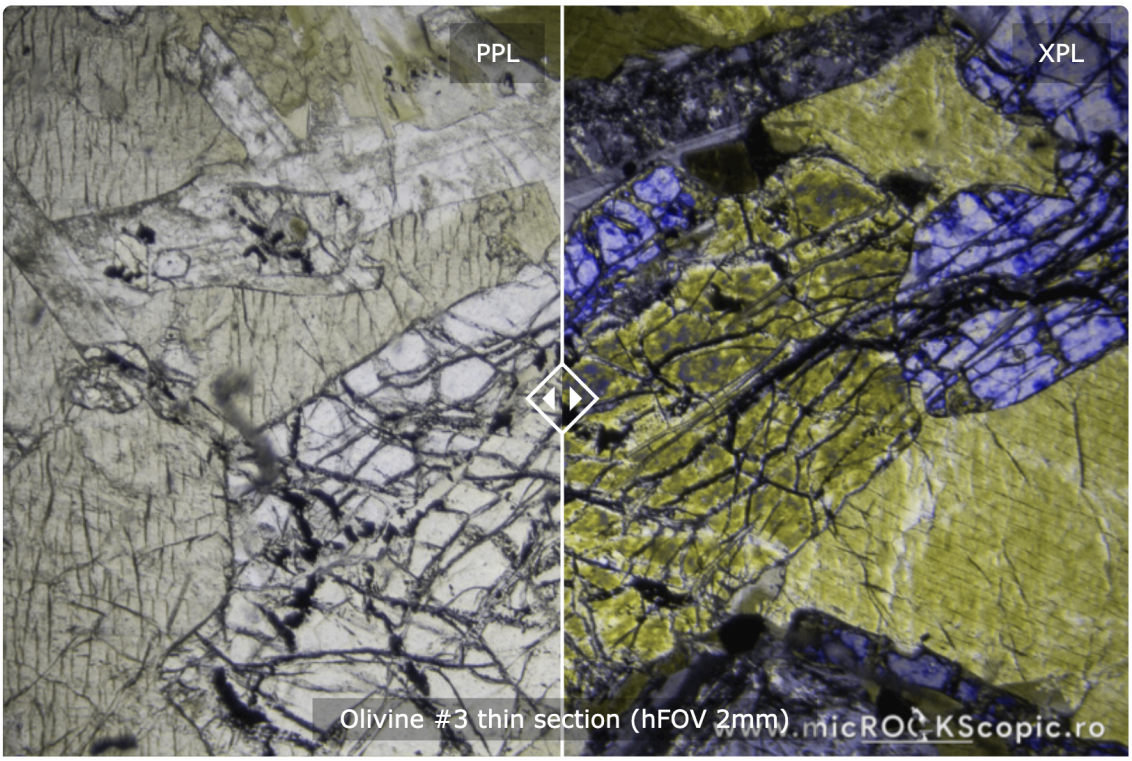


Figure 11: Olivine PPL-XPL. Deuteranopia view.

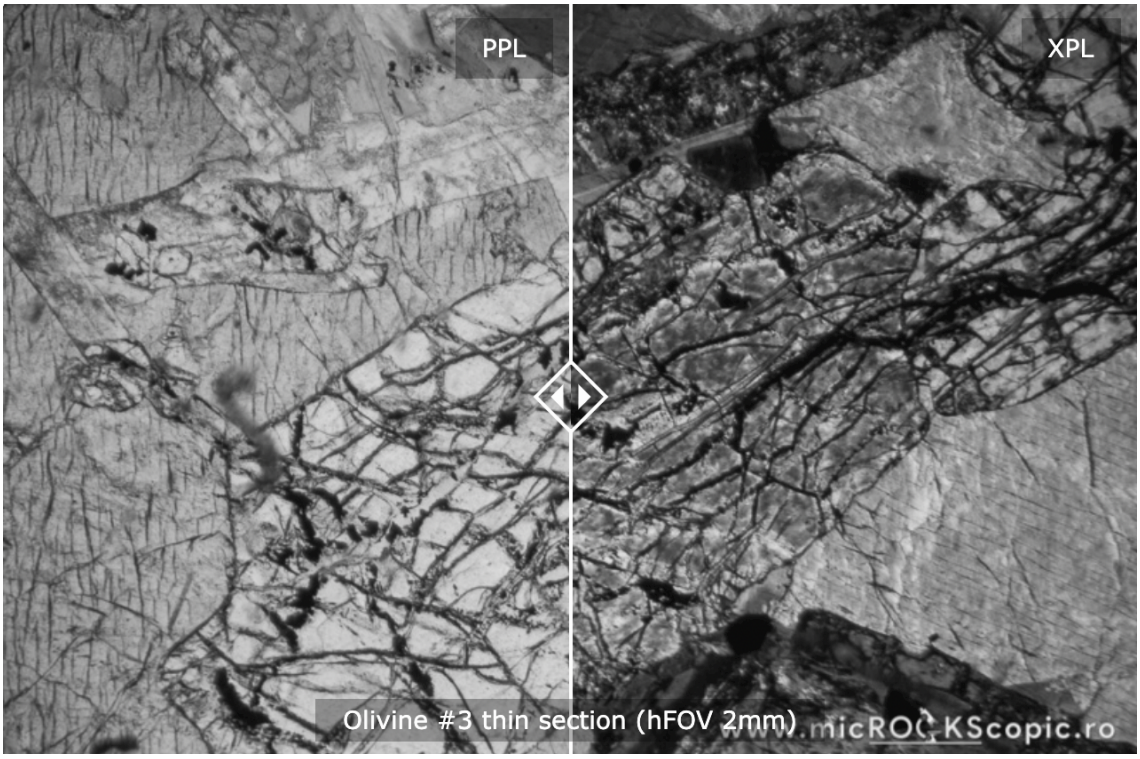


Figure 12: Olivine PPL-XPL. Greyscale view.

Pyroxene

Pyroxenes are ferromagnesian single chain inosilicates, having a general formula of $(XY)Si_2O_6$.
There are a number of pyroxenes that can be distinguished using optical microscopy. The two most important categories are clino- and ortho-pyroxene, of which two key members are augite $((Ca, Mg, Fe)_2Si_2O_6)$ and diopside $((CaMg)Si_2O_6)$.
Both have low order interference colours. Universally, a helpful feature is the presence of a single set of cleavage planes along the length of a grain. In XPL, orthopyroxene will go into extinction occurs when the cross hairs are aligned with cleavage planes. Oppositely, clinopyroxene will go into extinction when the cross hairs are positioned at an angle to the cleavage planes.
Orthopyroxene:
1A reference series sections: n/a.

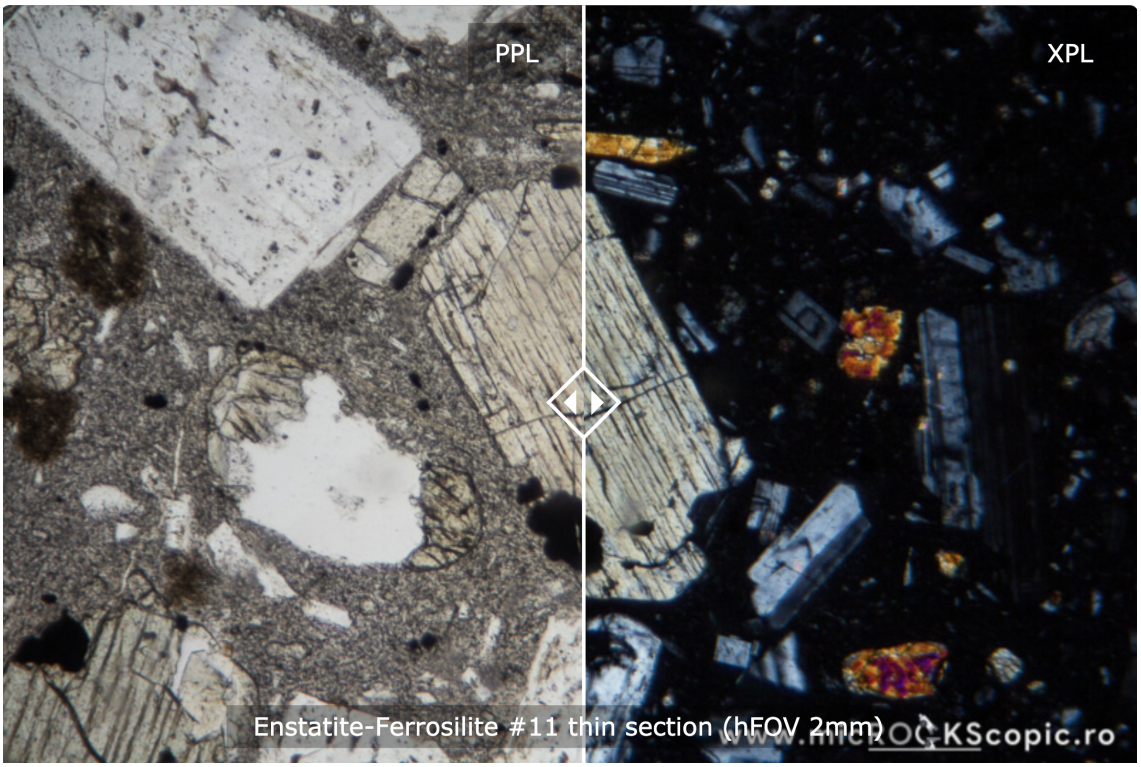


Figure 13: Orthopyroxene PPL-XPL. Full colour view.

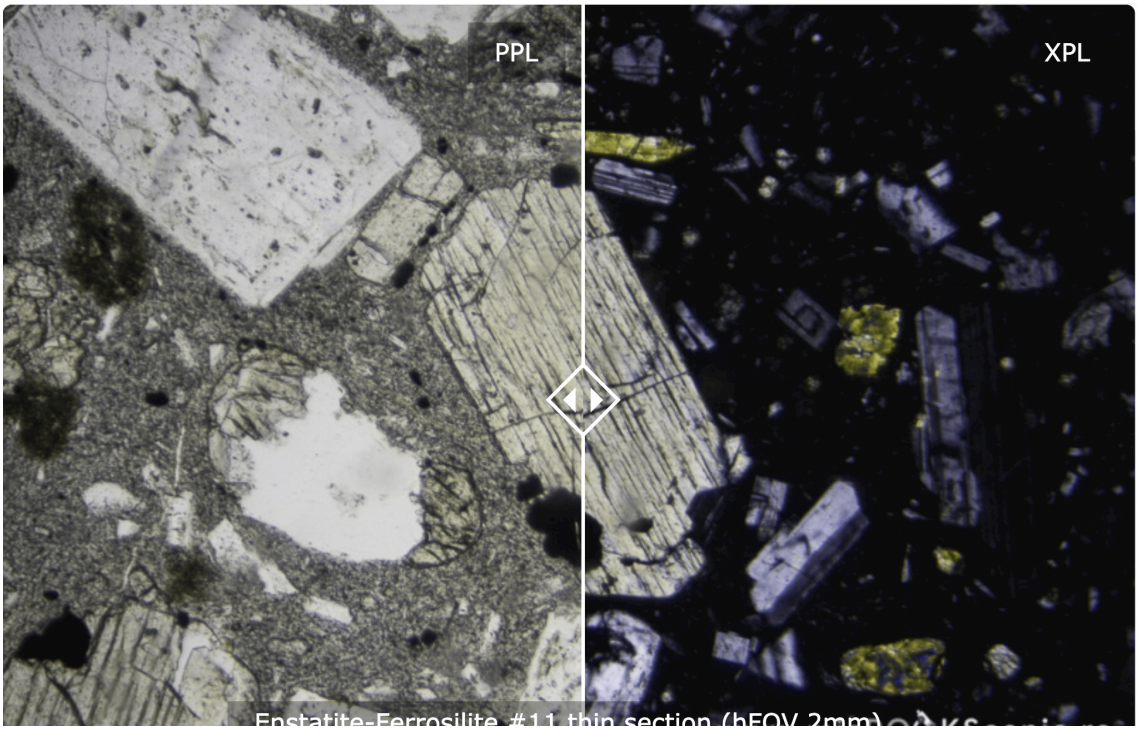


Figure 14: Orthopyroxene PPL-XPL. Deuteranopia view.

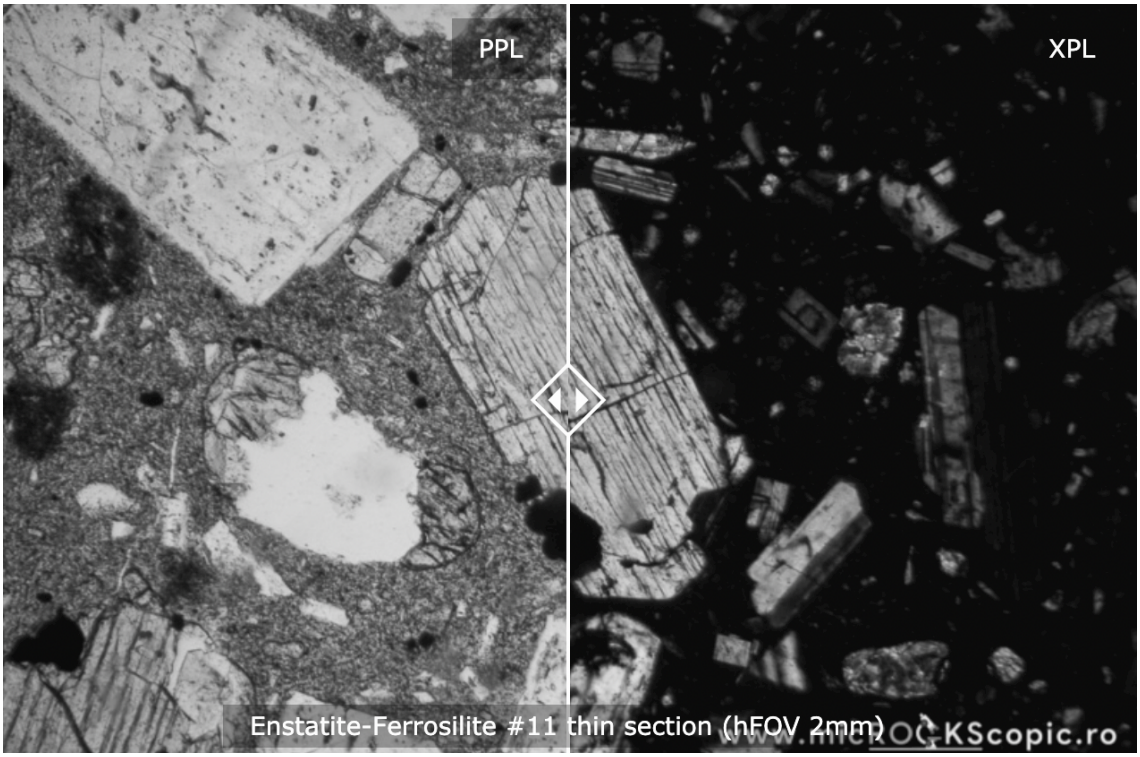


Figure 15: Orthopyroxene PPL-XPL. Greyscale view.

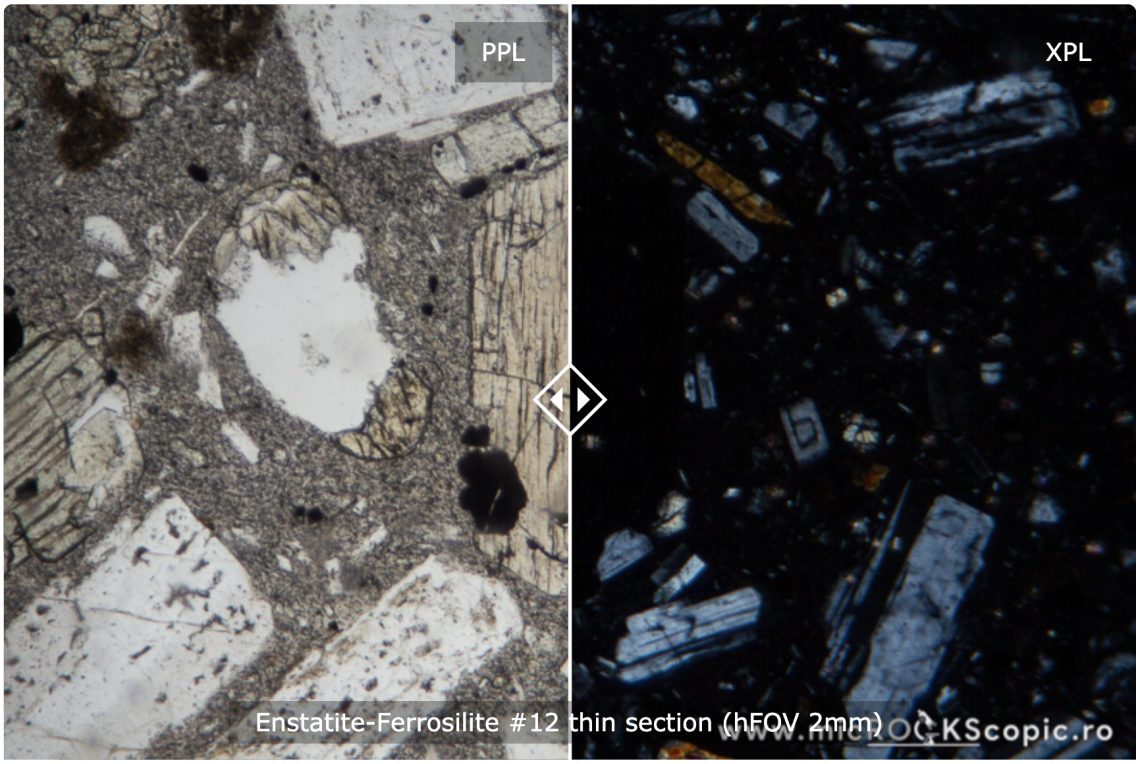


Figure 16: Orthopyroxene PPL-XPL. Full colour view.

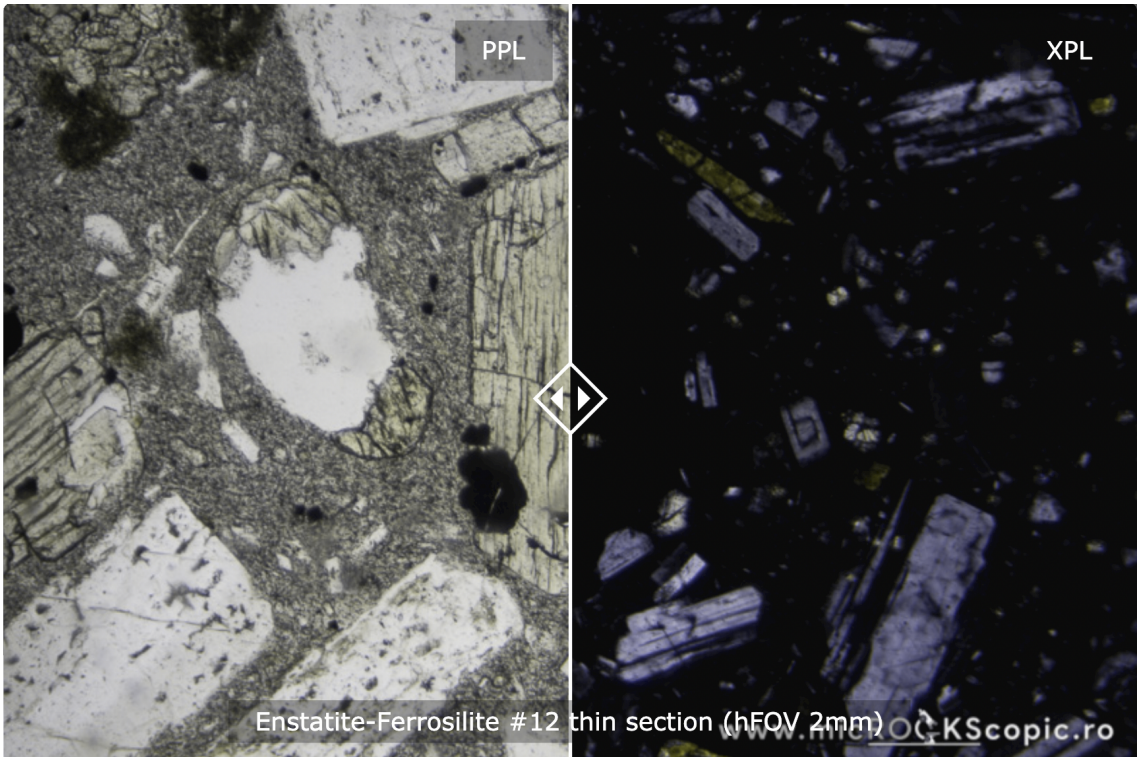


Figure 17: Orthopyroxene PPL-XPL. Deuteranopia view.

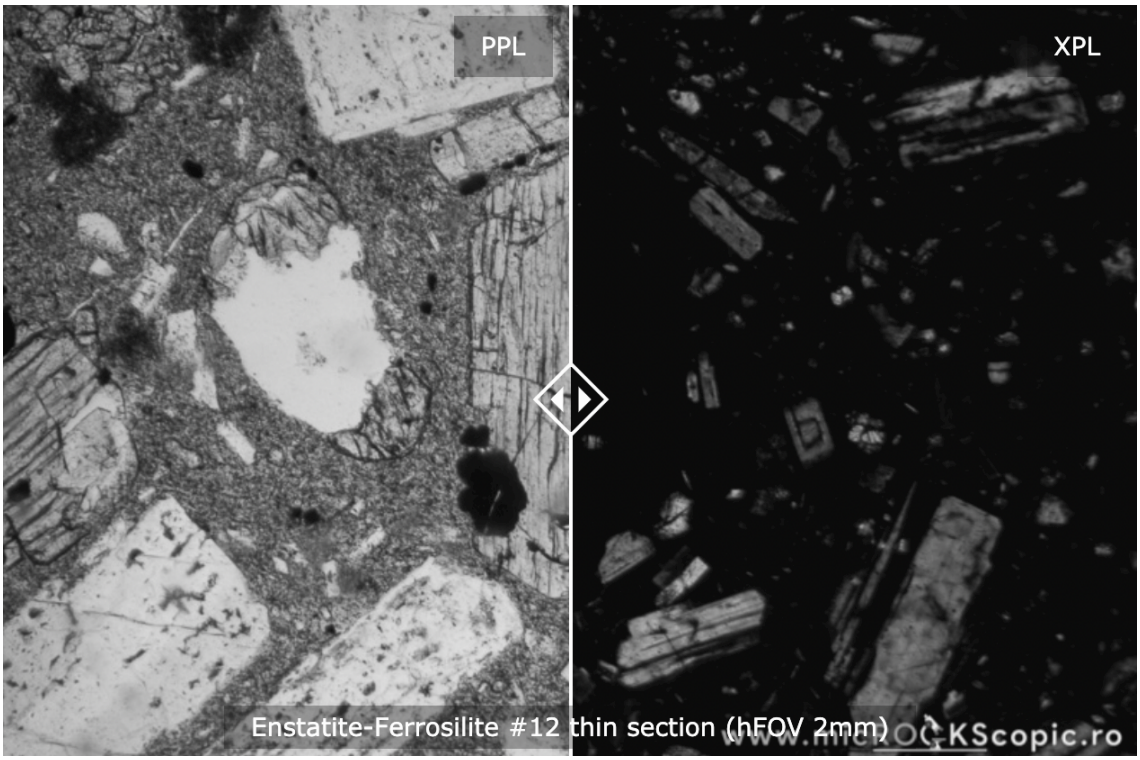


Figure 18: Orthopyroxene PPL-XPL. Greyscale view.

Clinopyroxene:

1A reference series sections: L141 Gabbro (*), L161 Basalt amygdaloidal, L162 Basalt porphyritic, L172 Ultramafic cumulate.

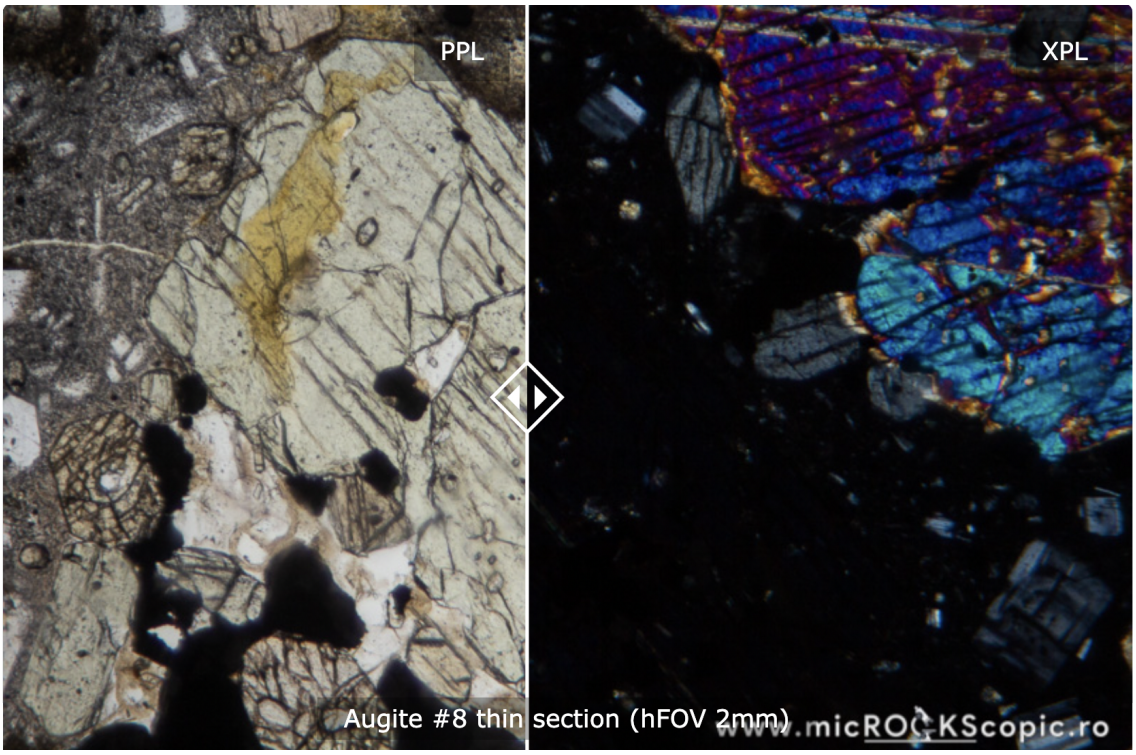


Figure 19: Clinopyroxene PPL-XPL. Full colour view.

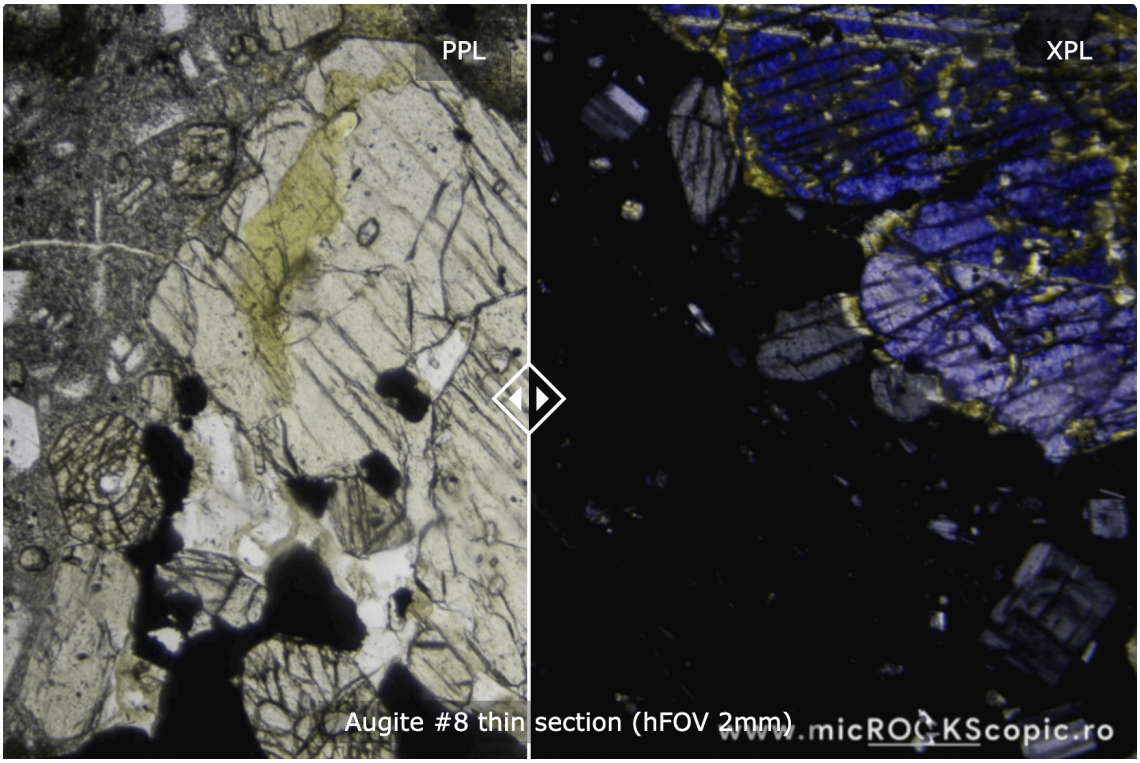


Figure 20: Clinopyroxene PPL-XPL. Deuteranopia view.

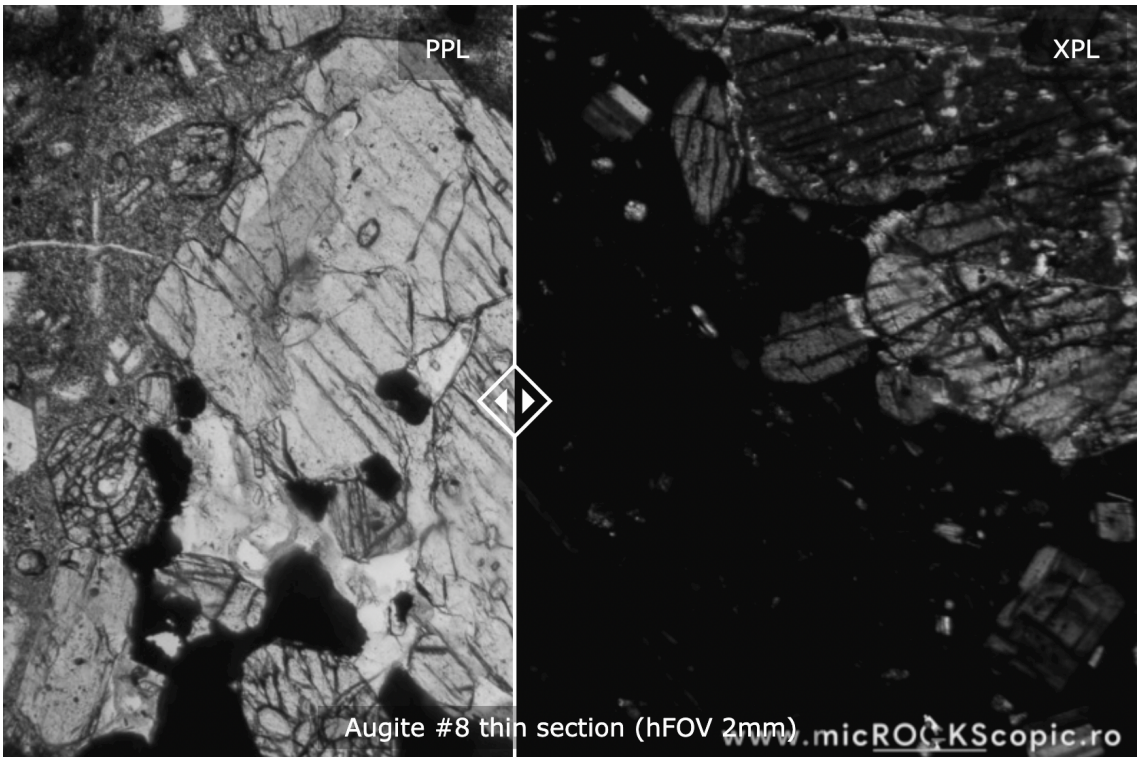


Figure 21: Clinopyroxene PPL-XPL. Greyscale view.

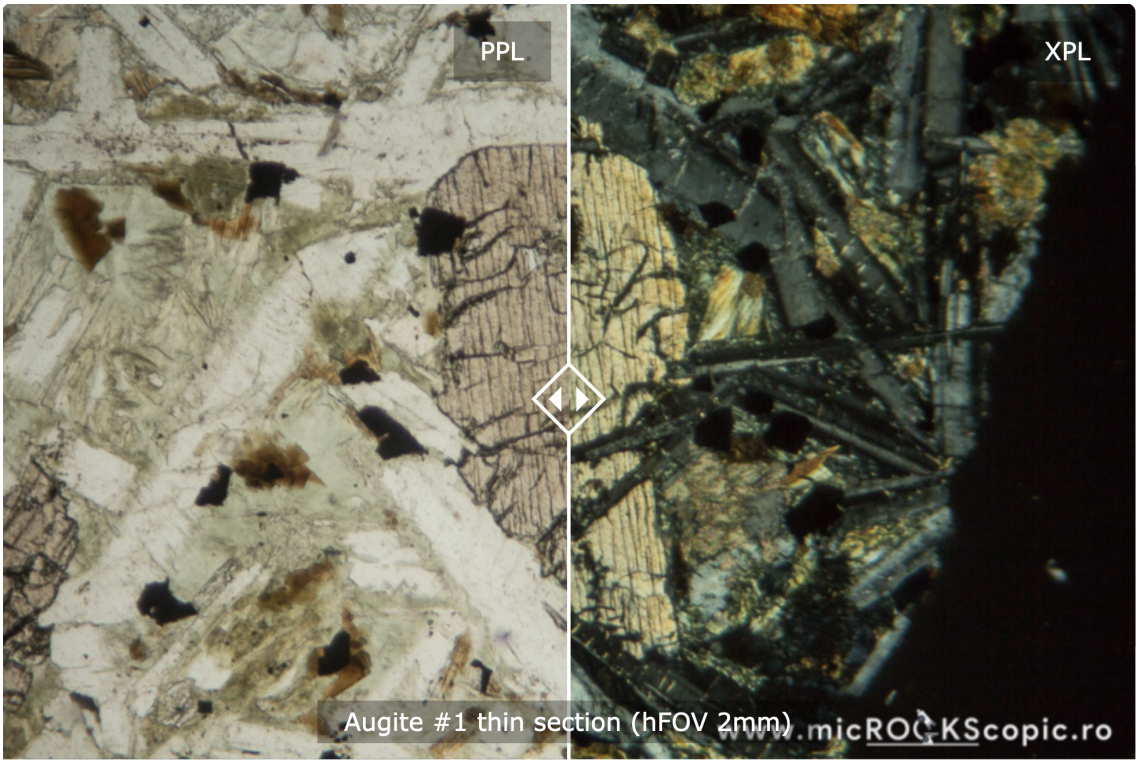


Figure 22: Clinopyroxene PPL-XPL. Full colour view.

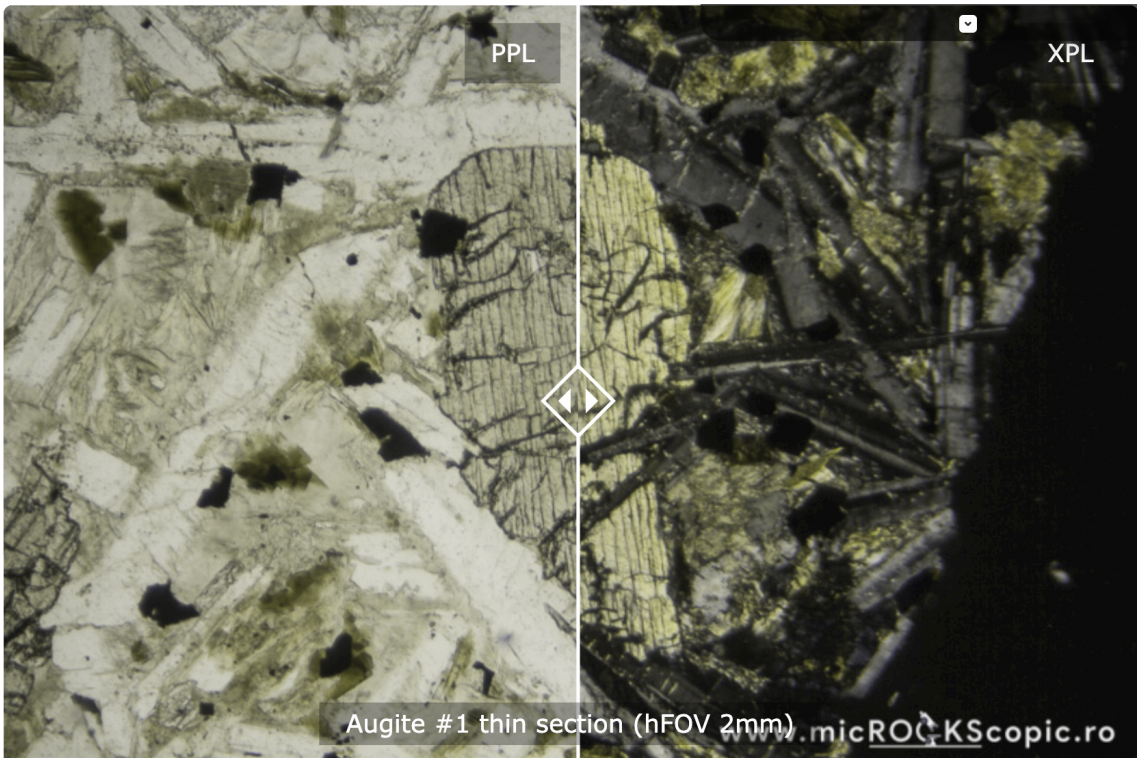


Figure 23: Clinopyroxene PPL-XPL. Deuteranopia view.

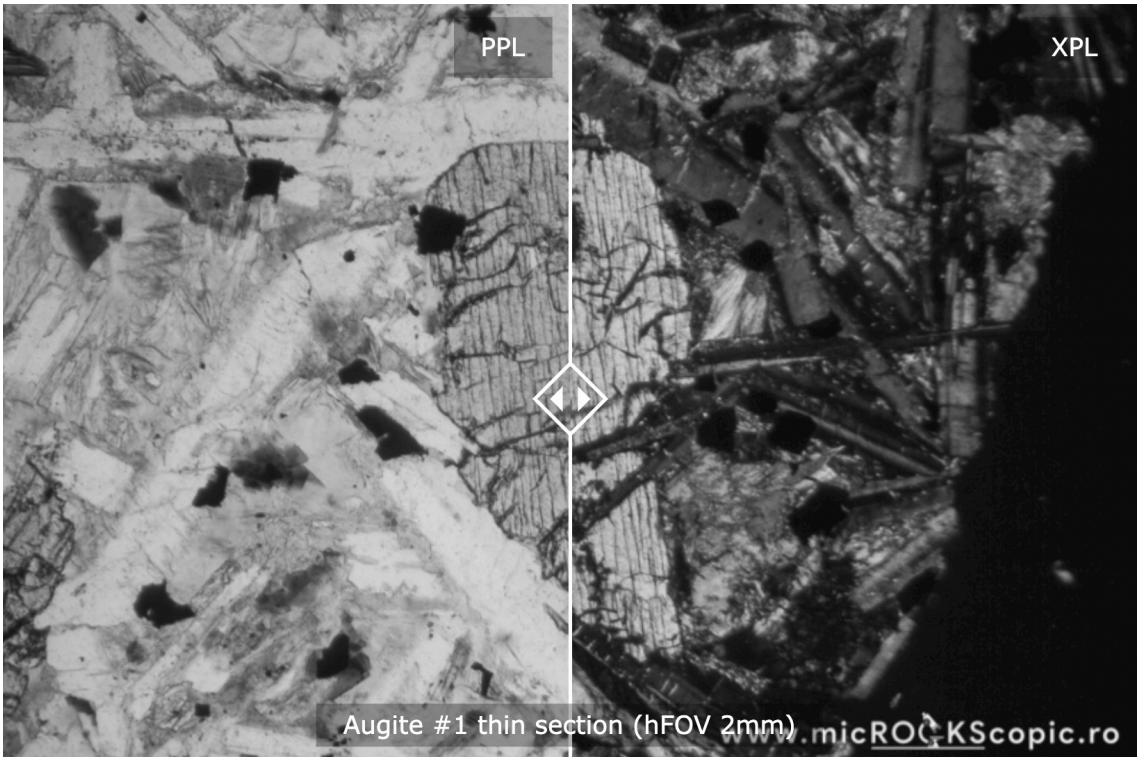


Figure 24: Clinopyroxene PPL-XPL. Greyscale view.

Amphibole

Amphiboles are a group of double chain inosilicates, of which a key member is hornblende $(Ca, Na, K)_{2-3}(Mg, Fe, Al)_5(Al, Si)_8O_{22}(OH, F)_2$. Universal features for amphiboles include a diamond patterning resulting from cleavage planes intersecting at 120 degrees.
1A reference series sections: L102 Hornblende biotite granite (*), L120 Granodiorite.

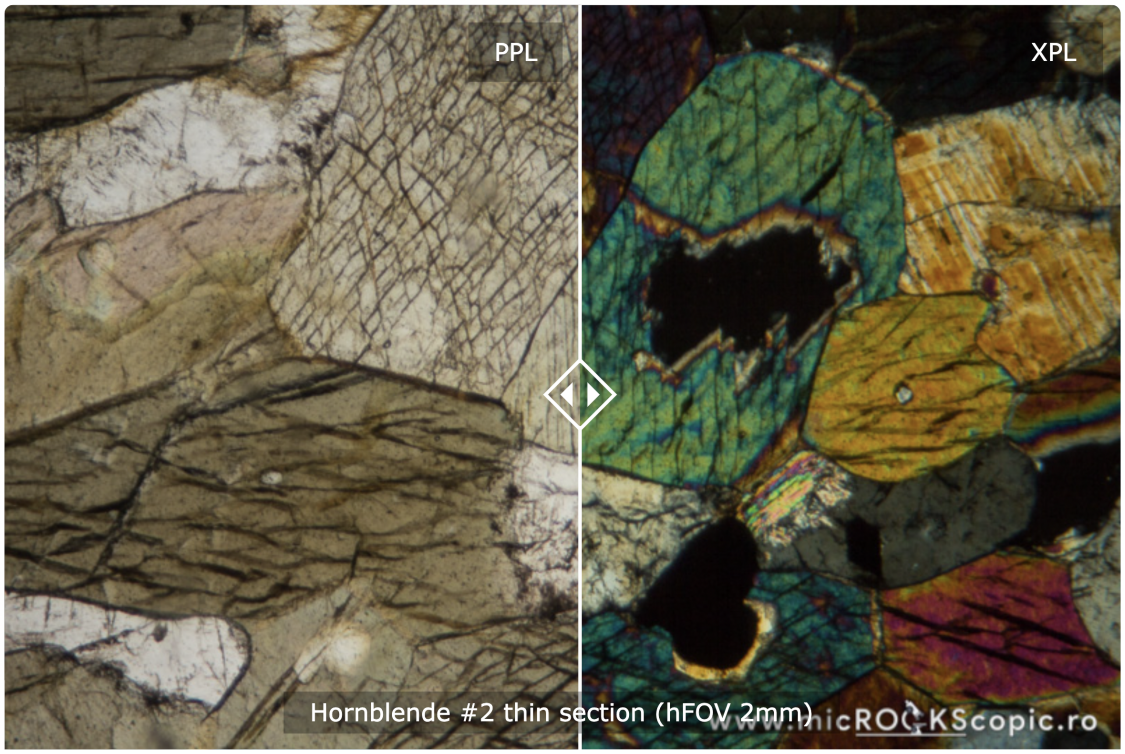


Figure 25: Amphibole PPL-XPL. Full colour view.

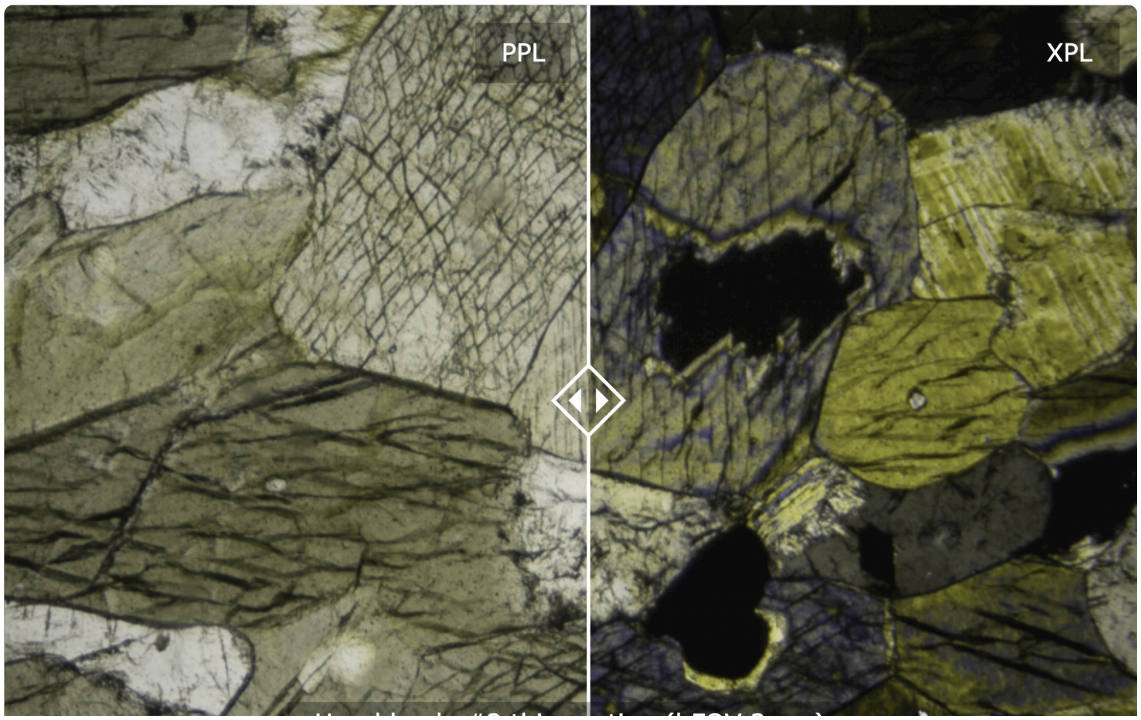


Figure 26: Amphibole PPL-XPL. Deuteranopia view.

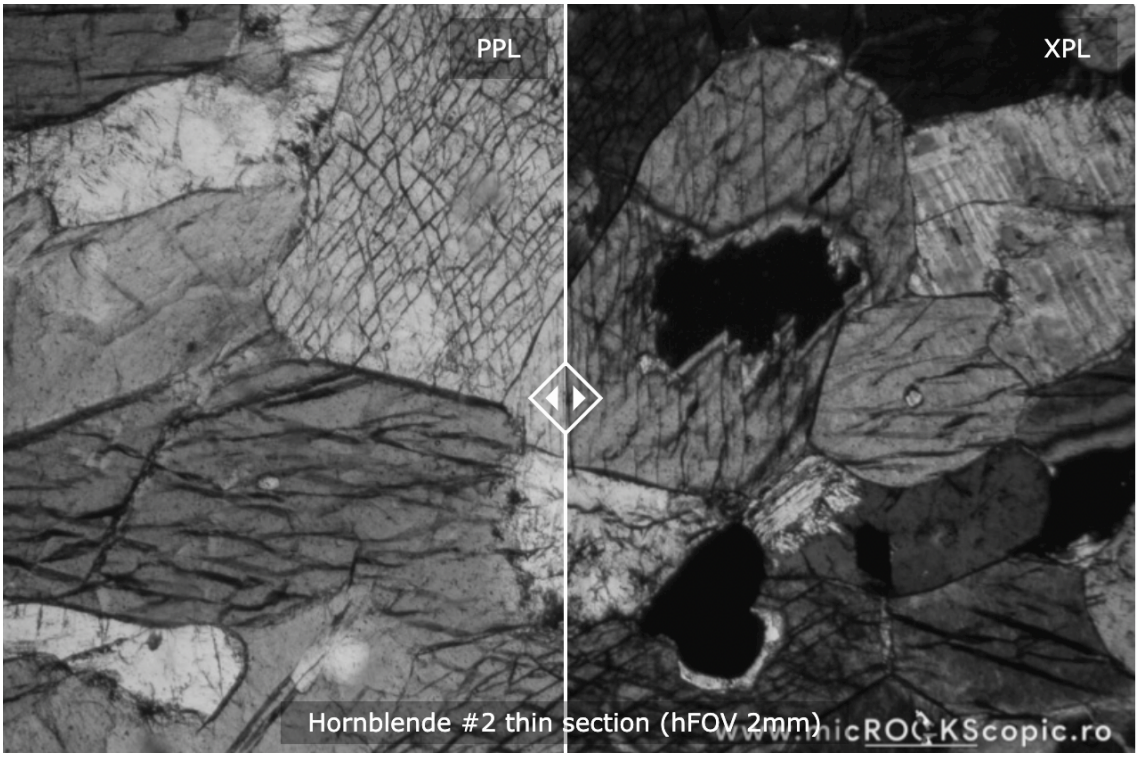


Figure 27: Amphibole PPL-XPL. Greyscale view.

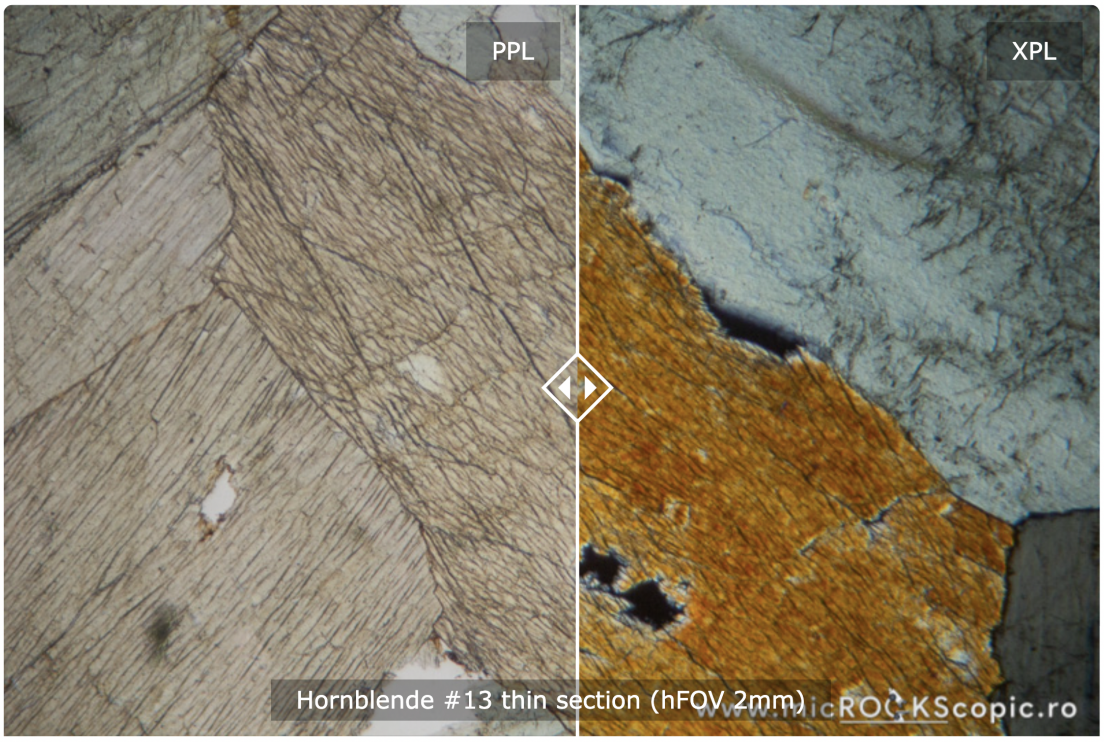


Figure 28: Amphibole PPL-XPL. Full colour view.

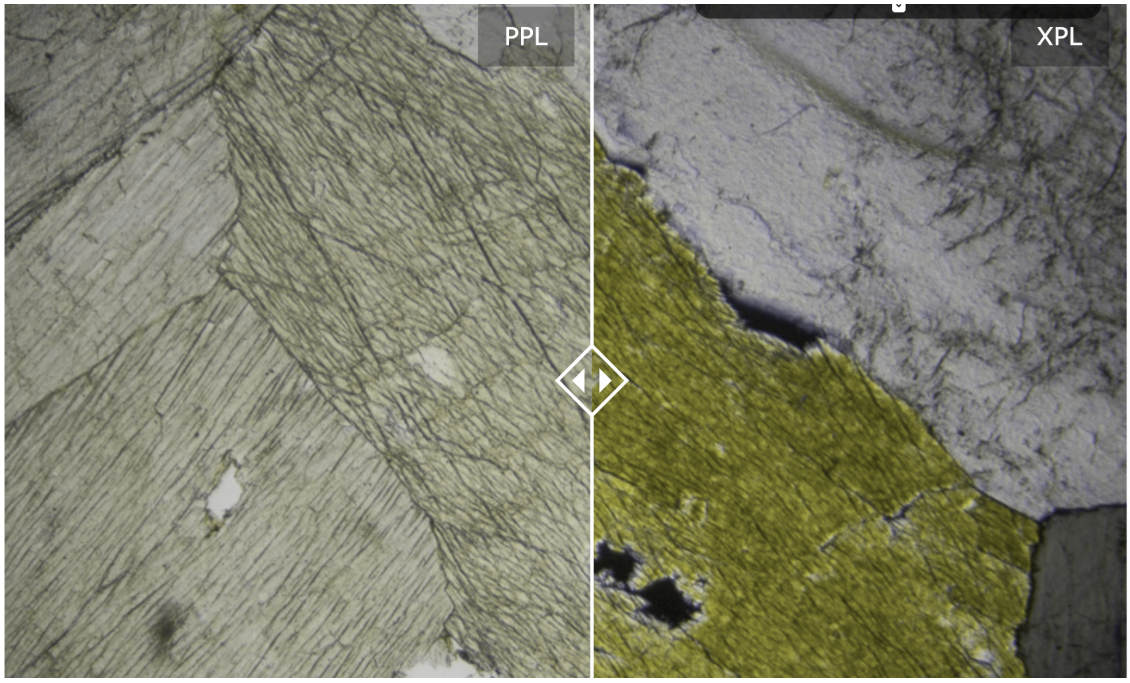


Figure 29: Amphibole PPL-XPL. Deuteranopia view.

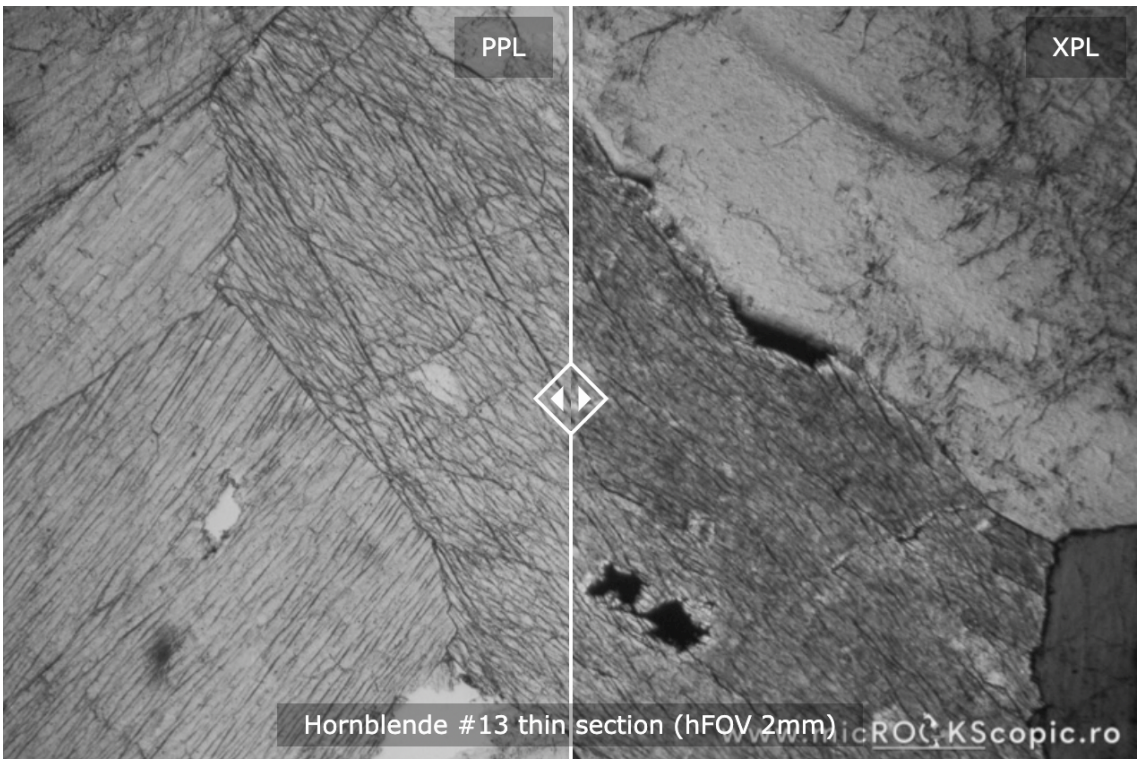


Figure 30: Amphibole PPL-XPL. Greyscale view.

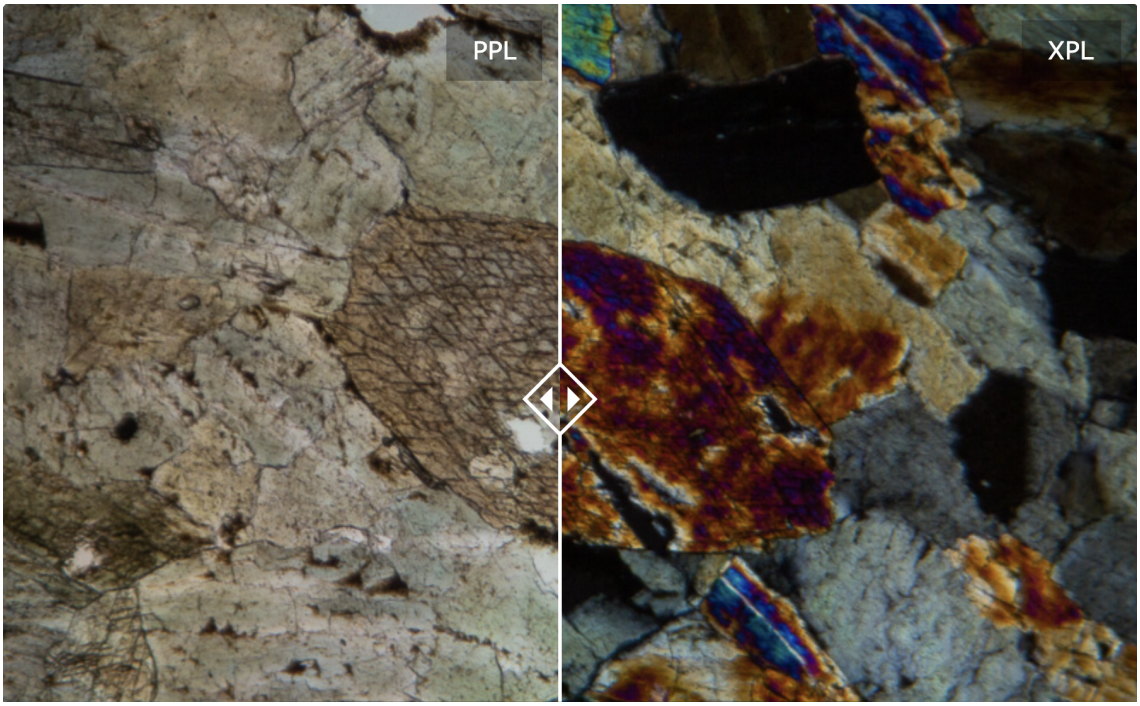


Figure 31: Amphibole PPL-XPL. Full colour view.

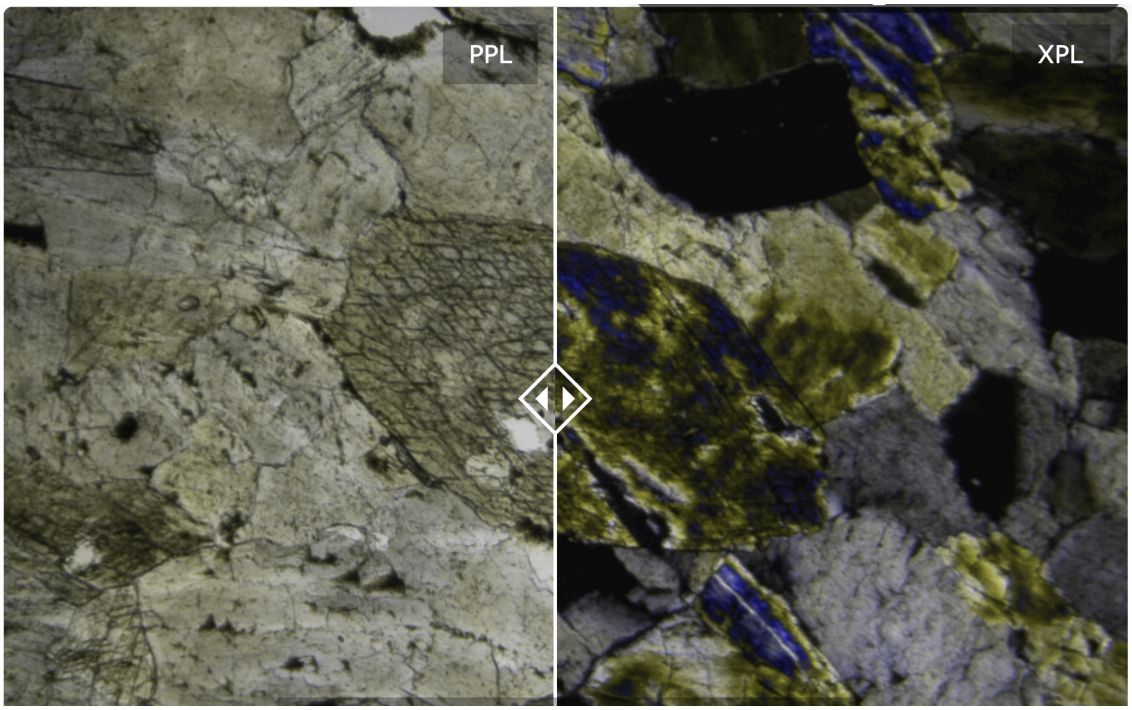


Figure 32: Amphibole PPL-XPL. Deuteranopia view.

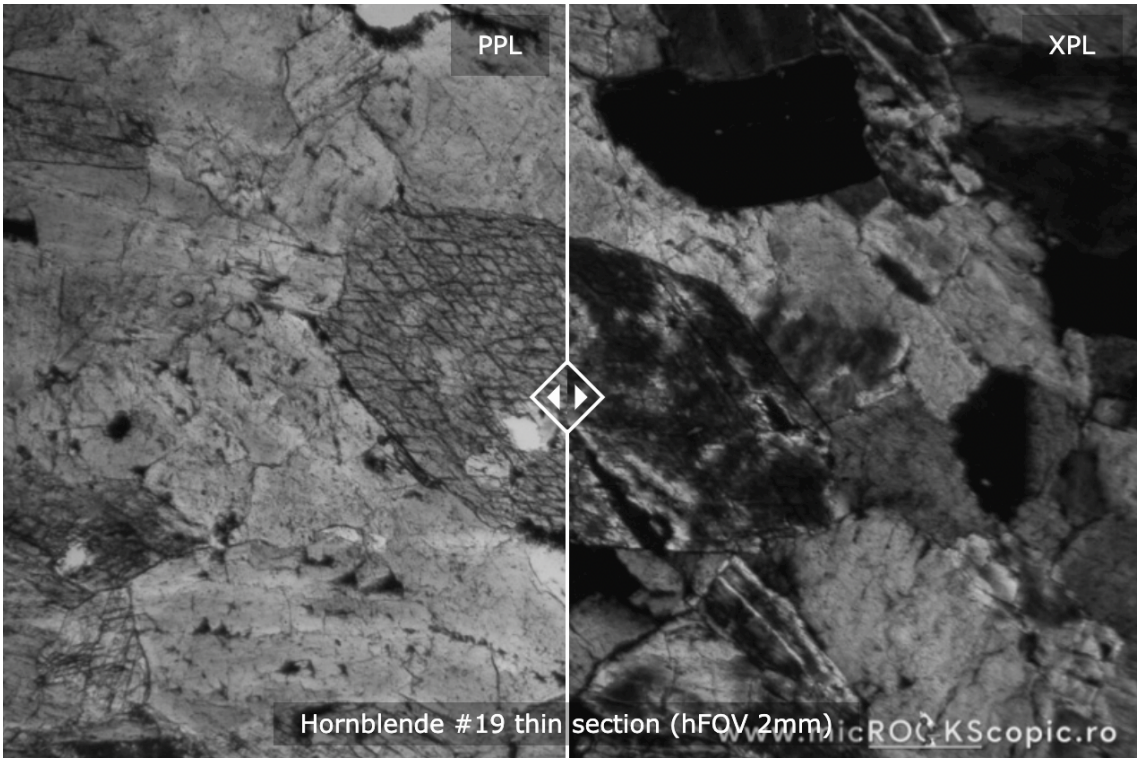


Figure 33: Amphibole PPL-XPL. Greyscale view.

Biotite

Biotite is a member of the phyllosilicates, with general formula $K(Mg, Fe)_3(AlSi_3O_{10})(F, OH)_2$.
Universal features for biotite include dark PPL, pleochroism, incomplete extinction, and one cleavage plane parallel to the long axis of grains.
1A reference series sections: L100 Alkali granite, L101 Granite, L102 Hornblende biotite granite (*), L120 Granodiorite (*), L130 Andesite, porphyritic (porphyrite), L504 Garnet schist.

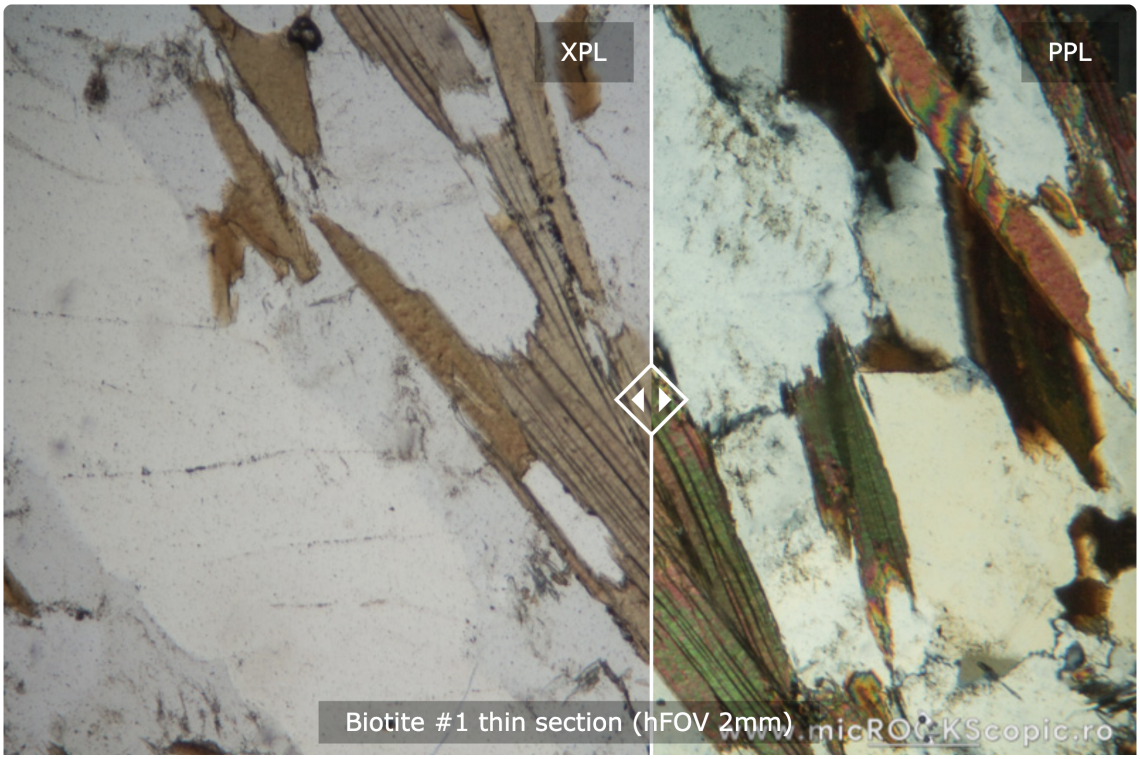


Figure 34: Biotite PPL-XPL. Full colour view.

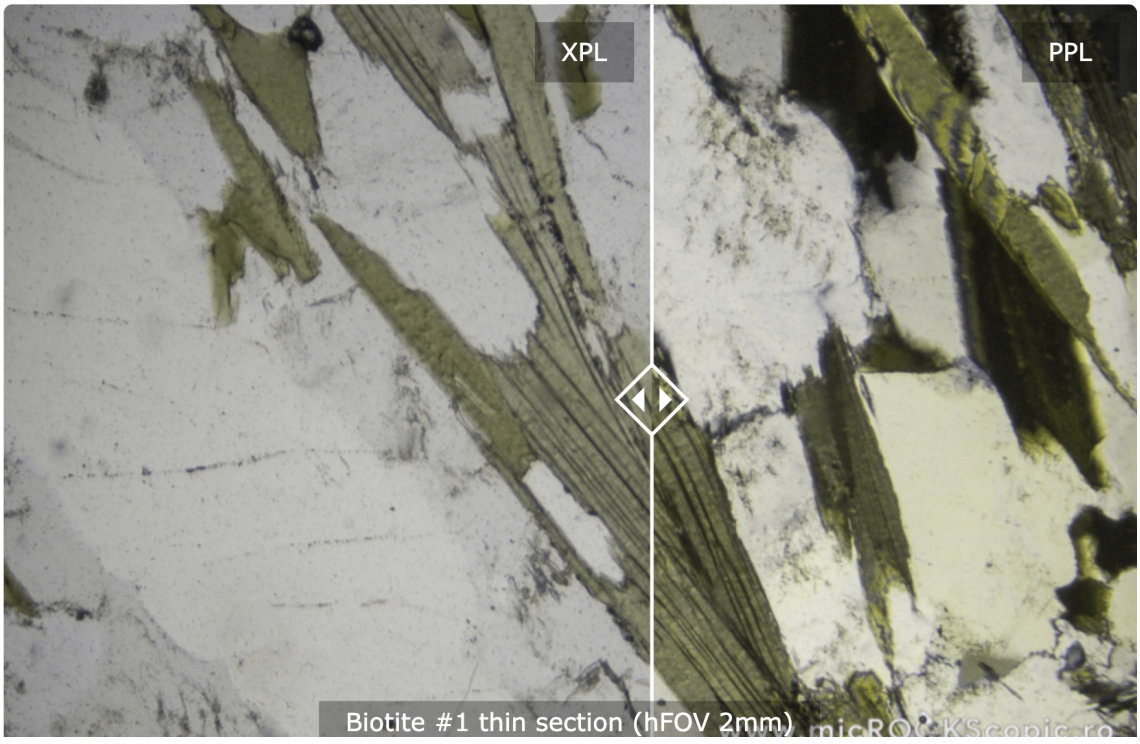


Figure 35: Biotite PPL-XPL. Deuteranopia view.

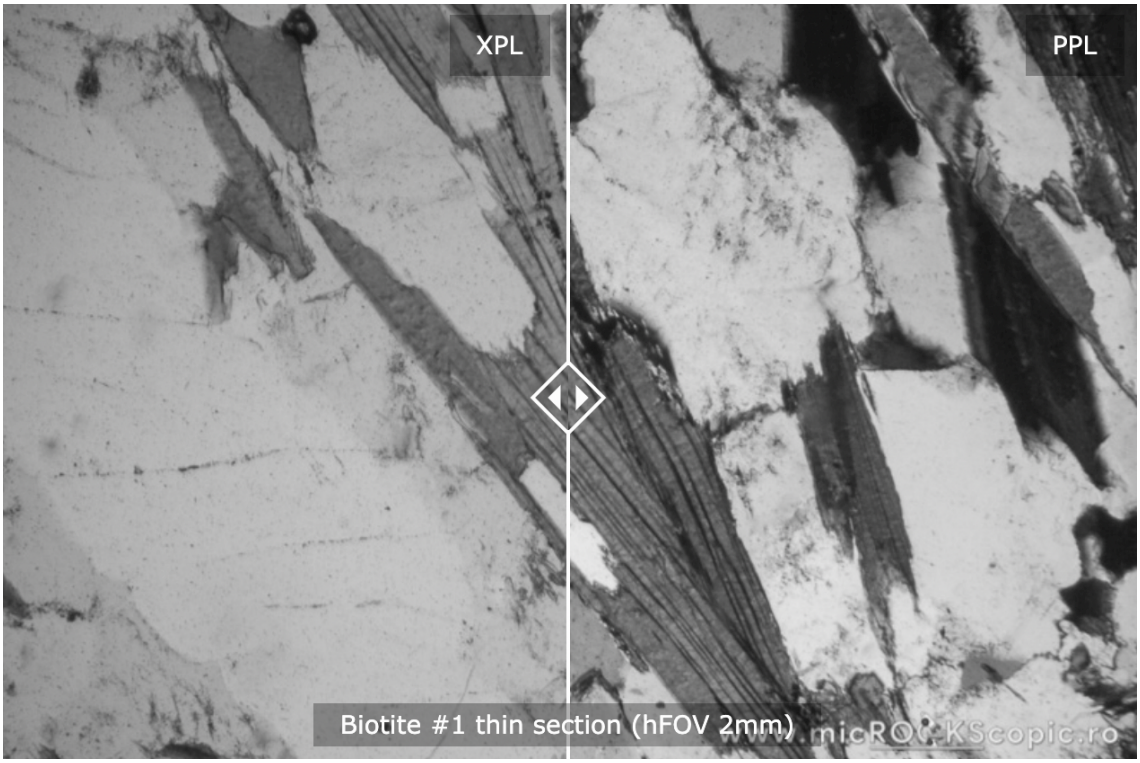


Figure 36: Biotite PPL-XPL. Greyscale view.

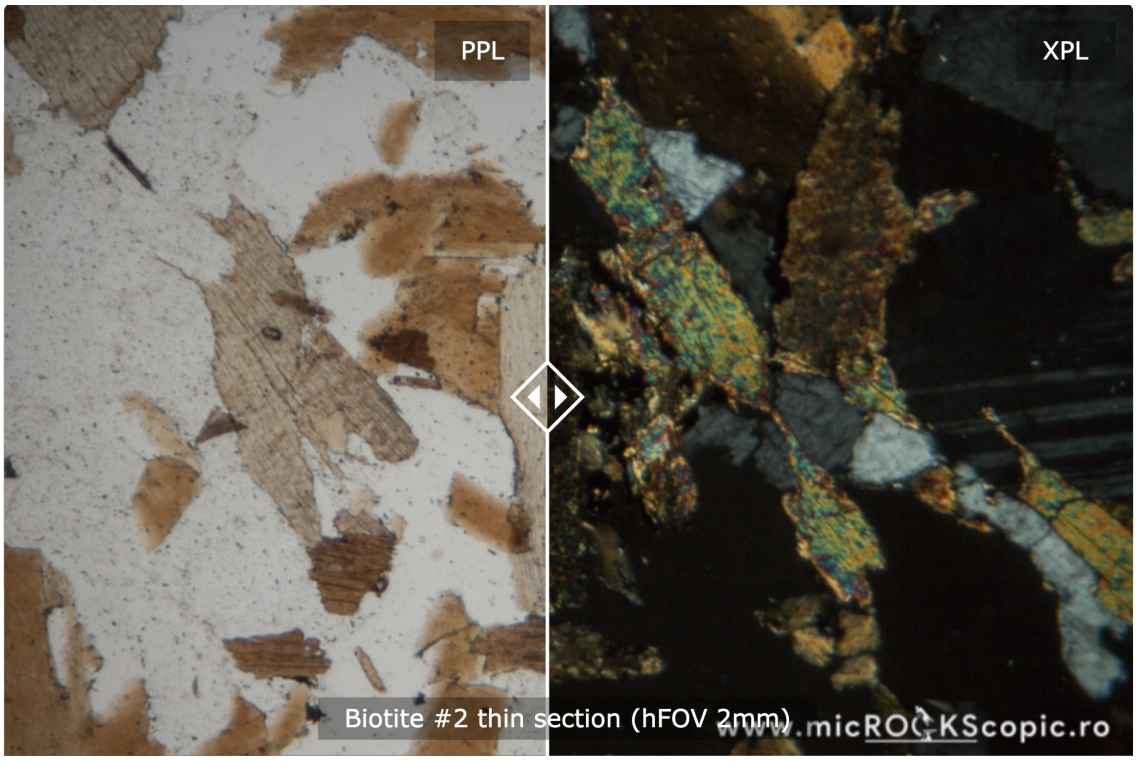


Figure 37: Biotite PPL-XPL. Full colour view.

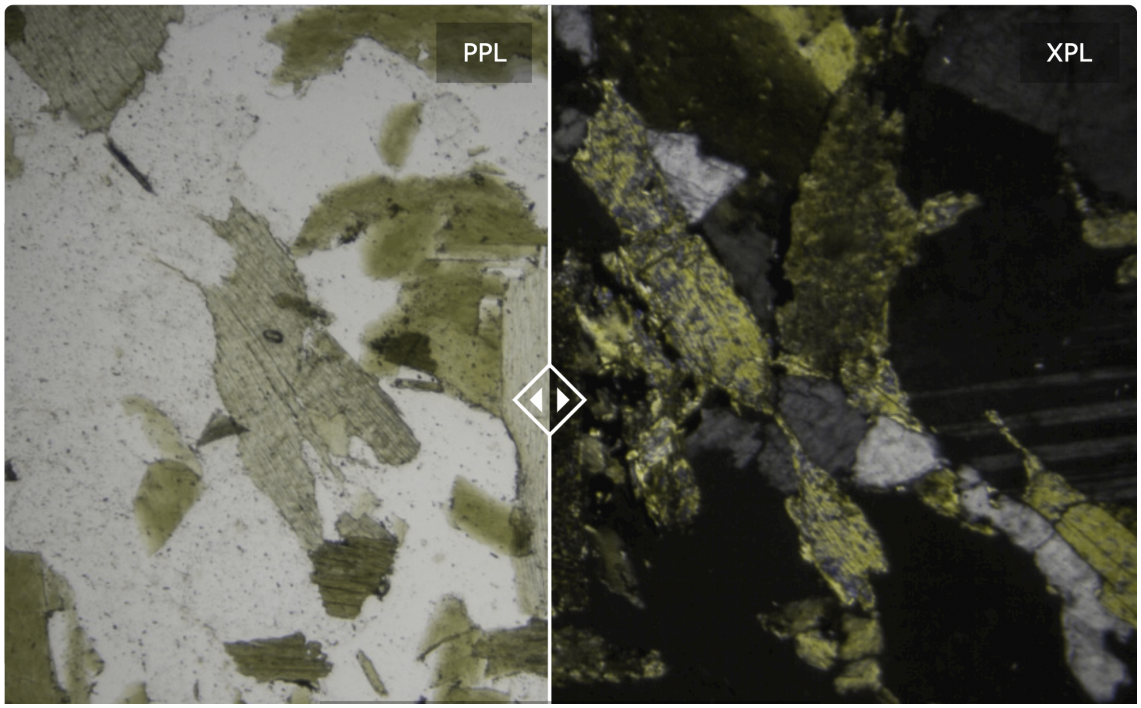


Figure 38: Biotite PPL-XPL. Deuteranopia view.

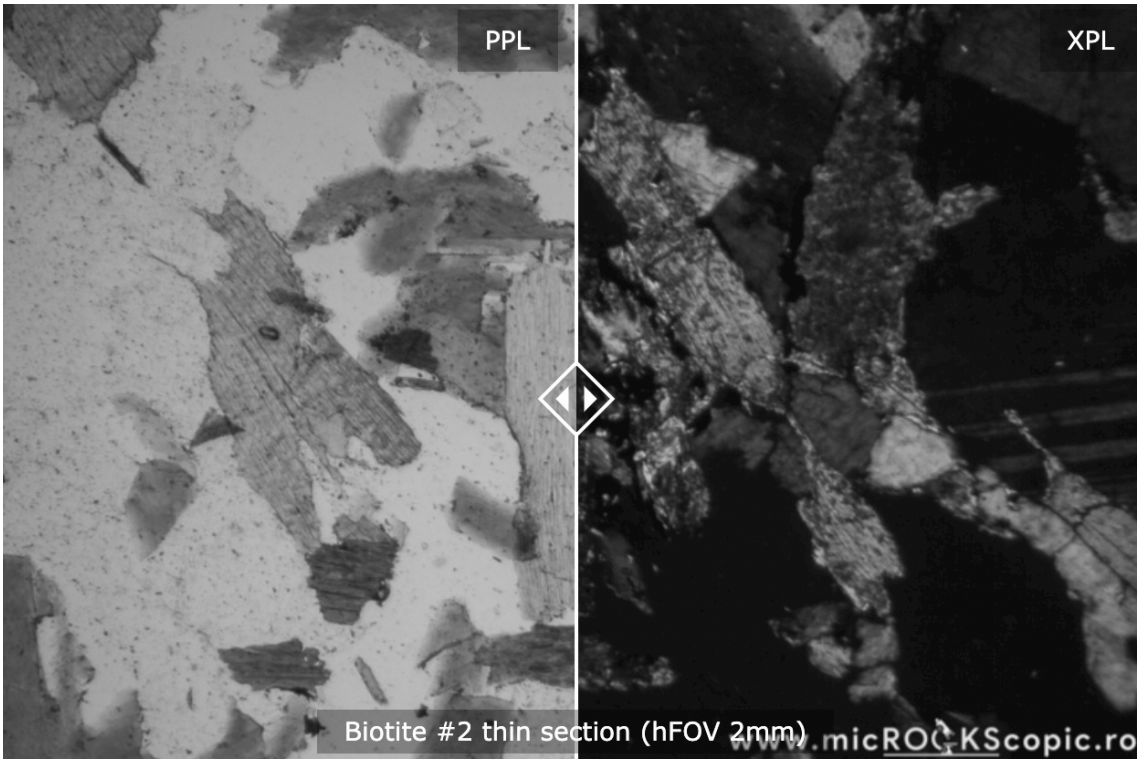


Figure 39: Biotite PPL-XPL. Greyscale view.

Muscovite

Muscovite is a member of the phyllosilicates, with general formula $(KAl_2(Si_3Al)O_{10}(OH)_2)$.
Universal features for muscovite include faint PPL, one cleavage plane parallel to the long axis of grains, and banding in XPL when not in extinction, which may be superimposed with variation in band intensity along each band.
1A reference series sections: L110 Rhyolite porphyritic (quartz porphyry), L201 Tuff, L504 Garnet schist, L506 Garnet biotite gneiss (*).

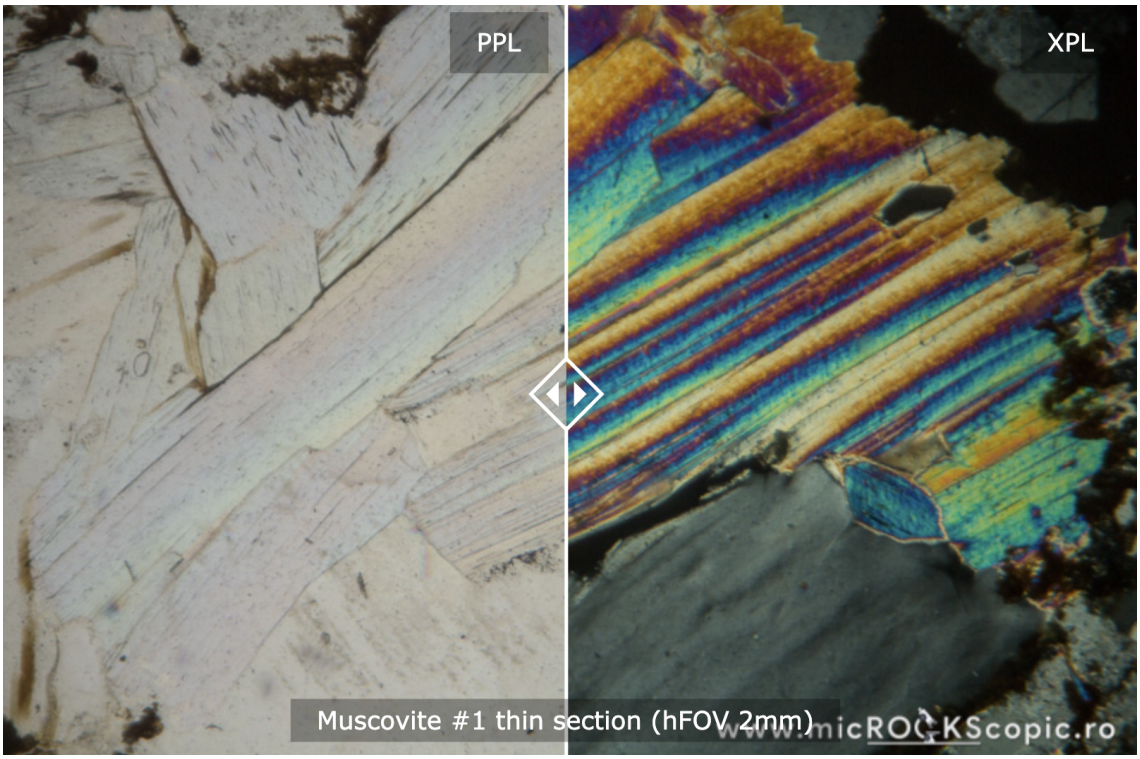


Figure 40: Muscovite PPL-XPL. Full colour view.

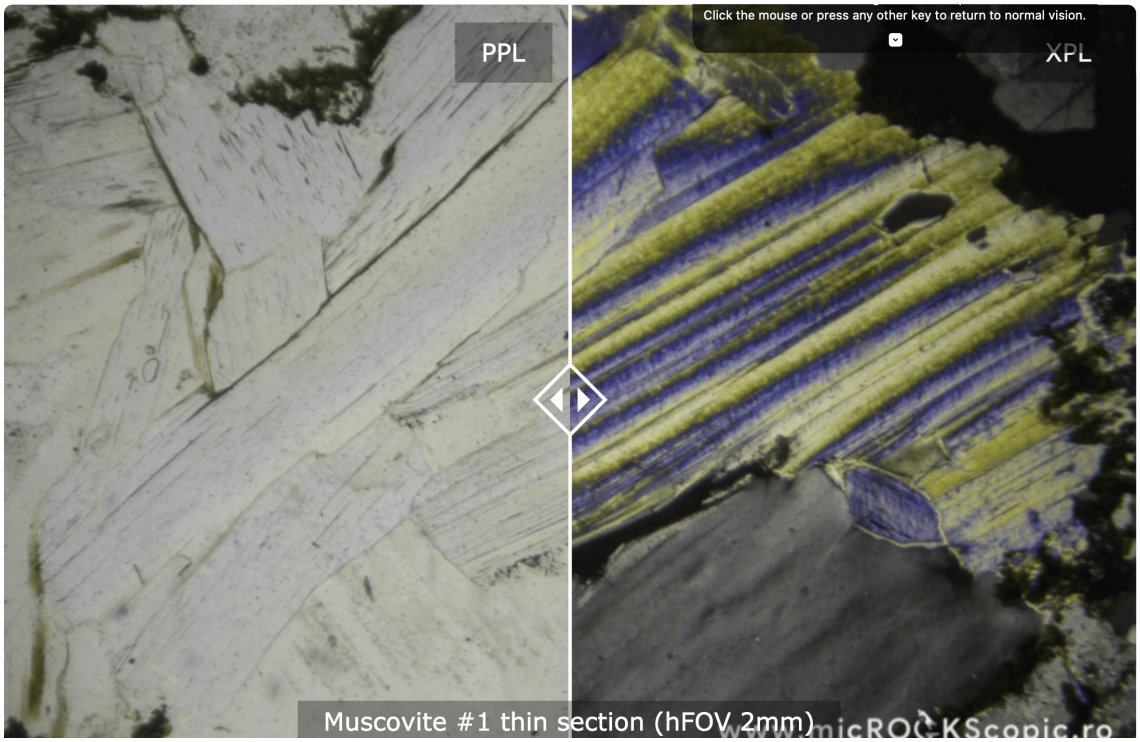


Figure 41: Muscovite PPL-XPL. Deuteranopia view.

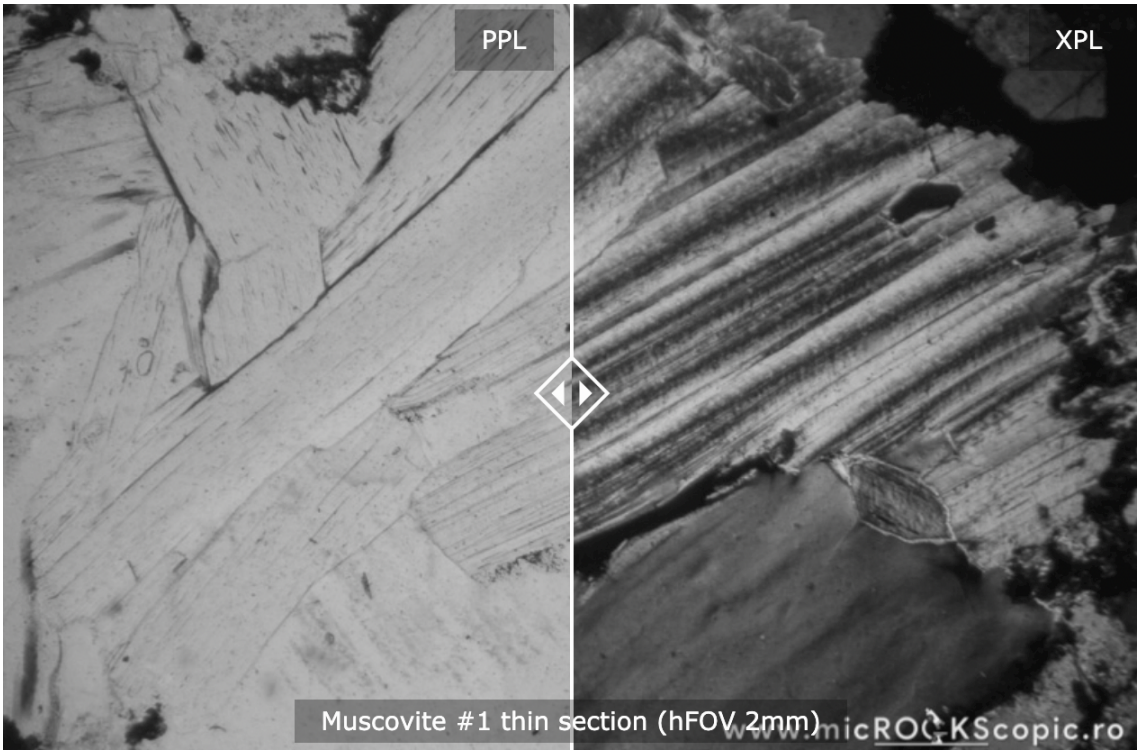


Figure 42: Muscovite PPL-XPL. Greyscale view.

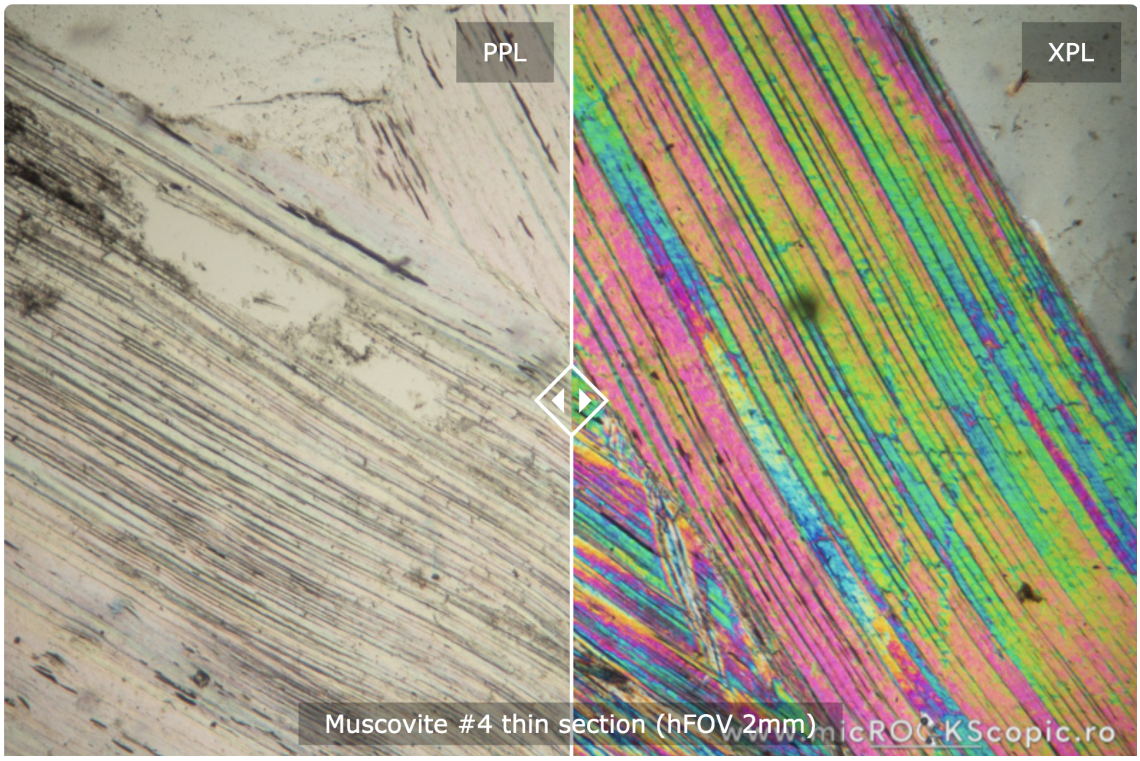


Figure 43: Muscovite PPL-XPL. Full colour view.

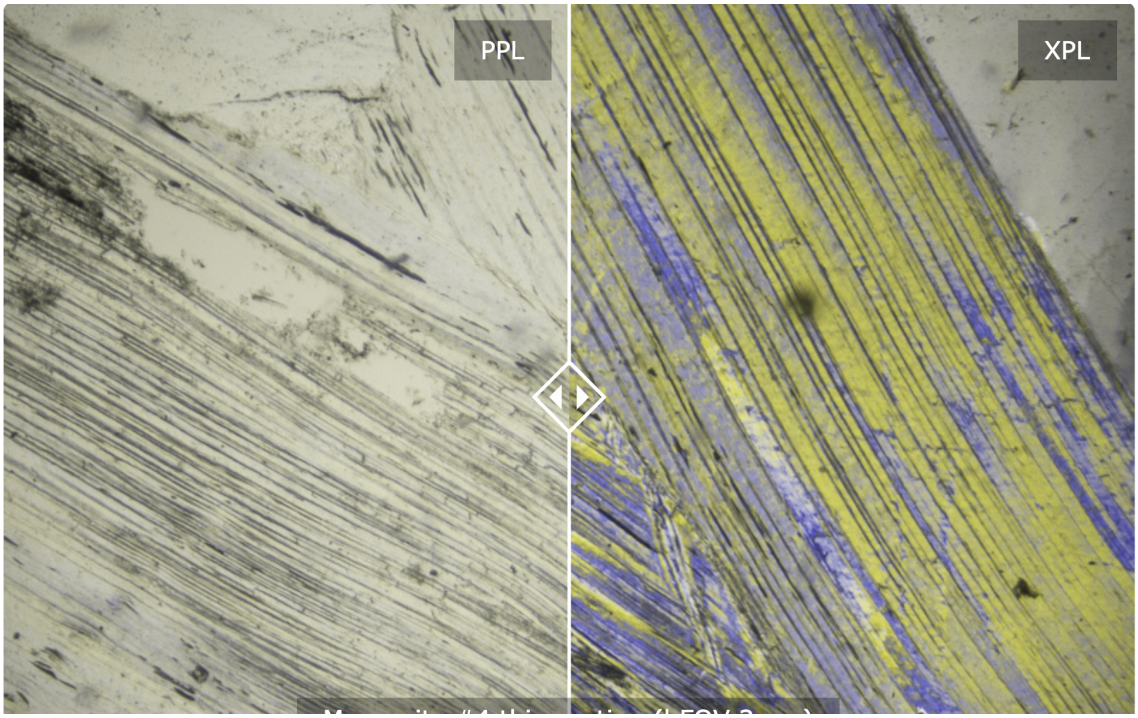


Figure 44: Muscovite PPL-XPL. Deuteranopia view.

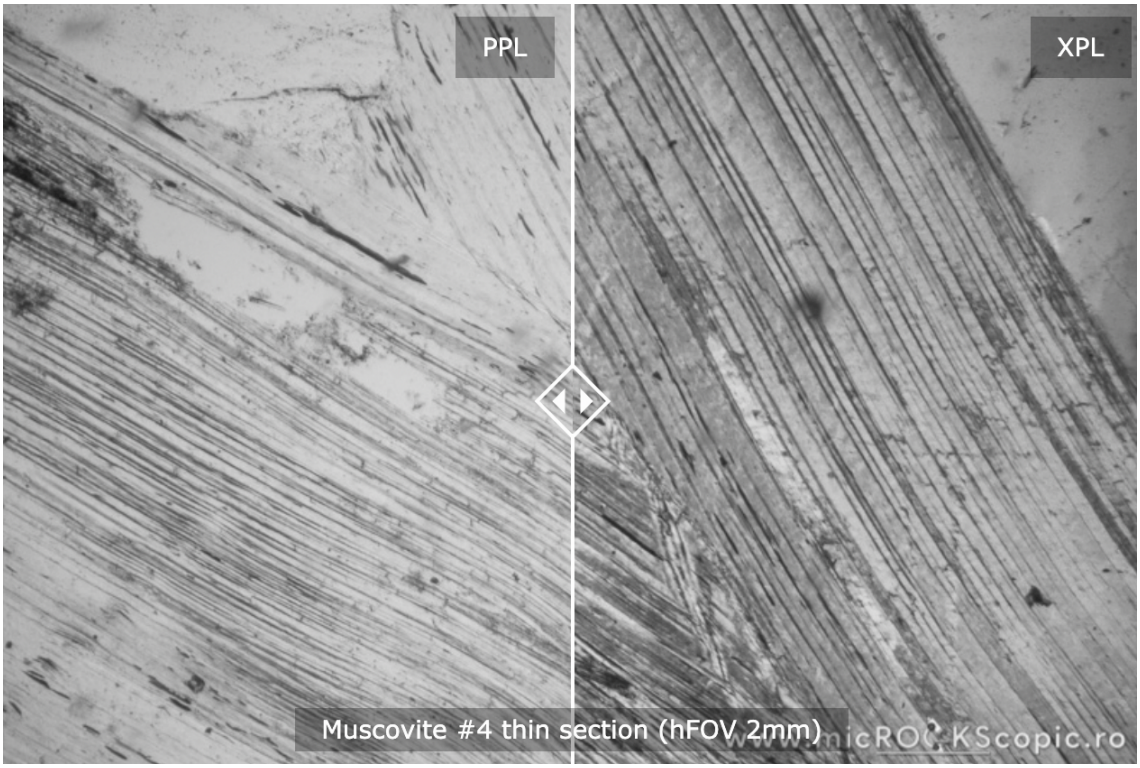


Figure 45: Muscovite PPL-XPL. Greyscale view.

Plagioclase feldspar

Plagioclase feldspar is a framework silicate or tectosilicate with general formula $(NaAl)Si_3O_8 \; - - - \; (CaAl)_2Si_2O_8$.
Universal features for plagioclase feldspar include extinction-driven 'jail-bar-like' banding effect in XPL, fainly in PPL. No obvious cleavage along bands.
1A reference series sections: L100 Alkali granite, L101 Granite, L102 Hornblende biotite granite (*), L112 Rhyolite, L120 Granodiorite (*), L130 Andesite porphyritic (porphyrite), L141 Gabbro, L162 Basalt, porphyritic, L172 Ultramafic cumulate, L504 Garnet schist.

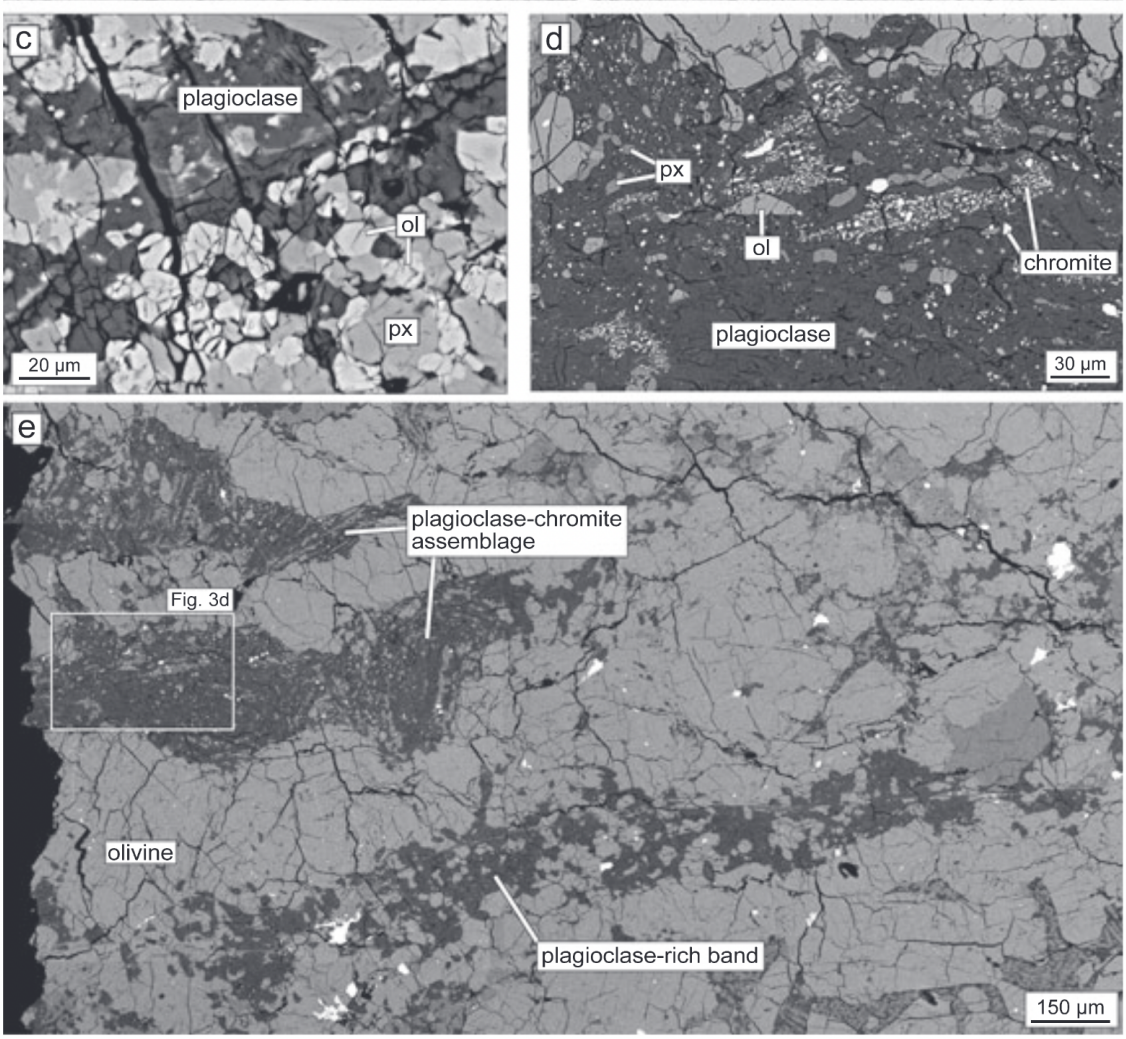


Figure 46: Plagioclase feldspar PPL-XPL. Full colour view.

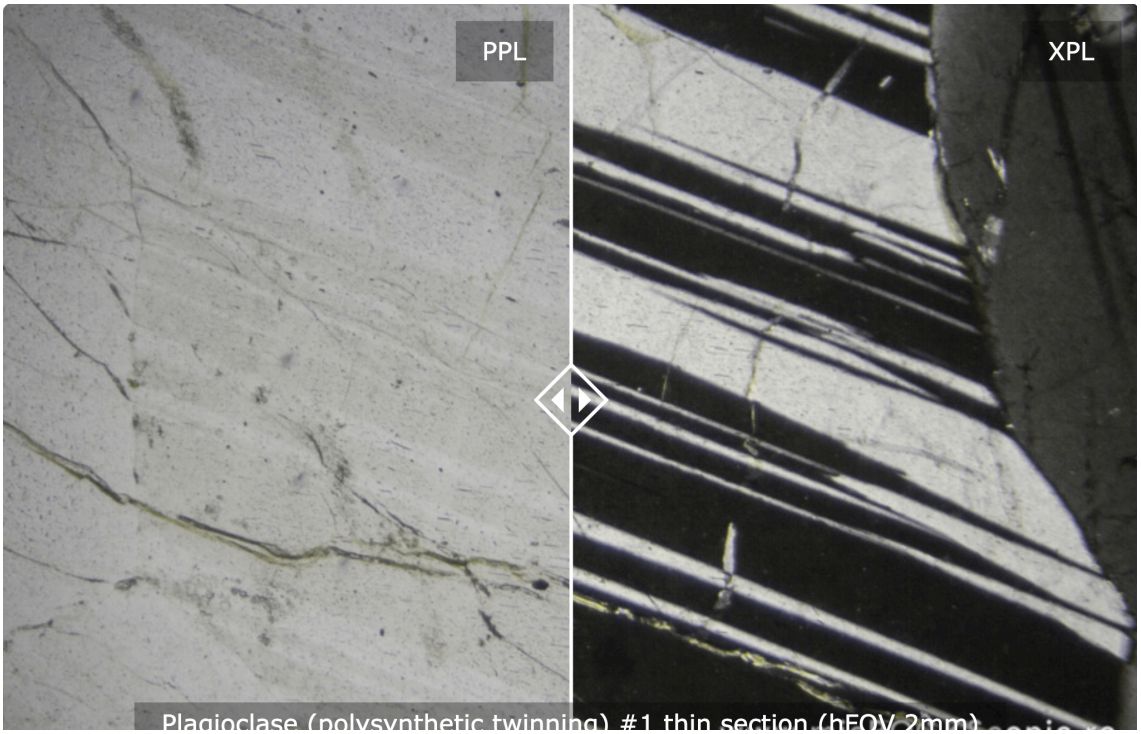


Figure 47: Plagioclase feldspar PPL-XPL. Deuteranopia view.

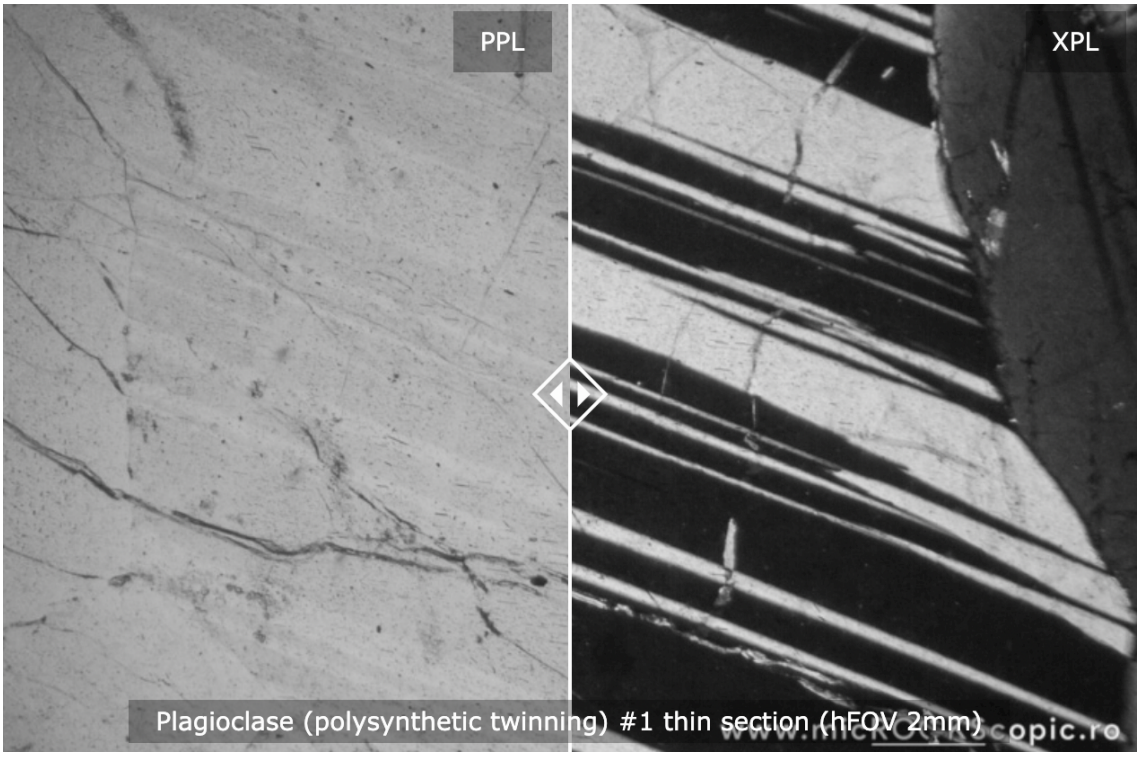


Figure 48: Plagioclase feldspar PPL-XPL. Greyscale view.

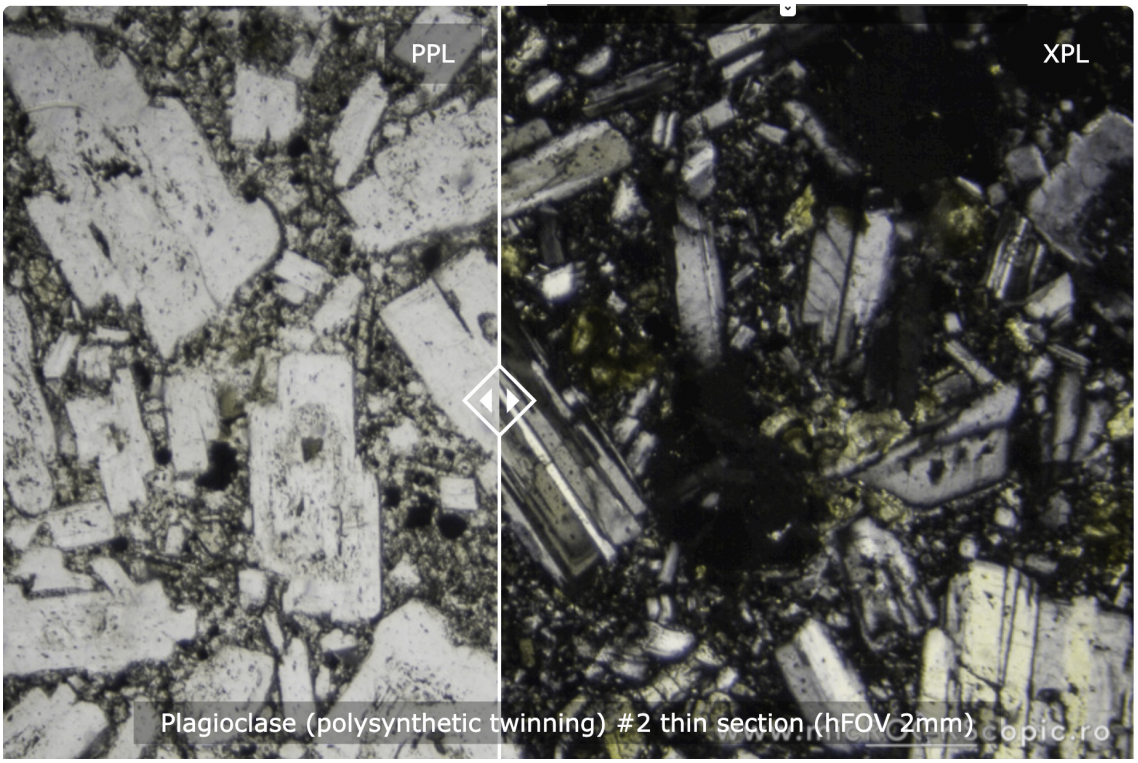


Figure 49: Plagioclase feldspar PPL-XPL. Full colour view.

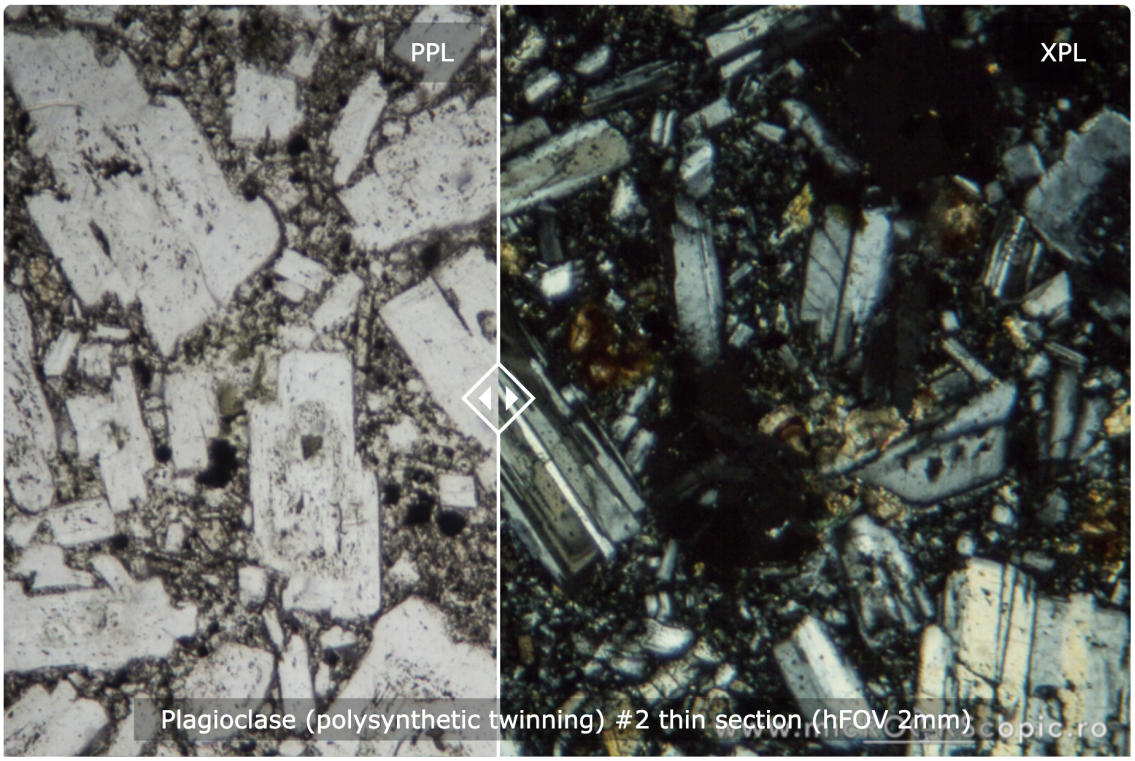


Figure 50: Plagioclase feldspar PPL-XPL. Deuteranopia view.

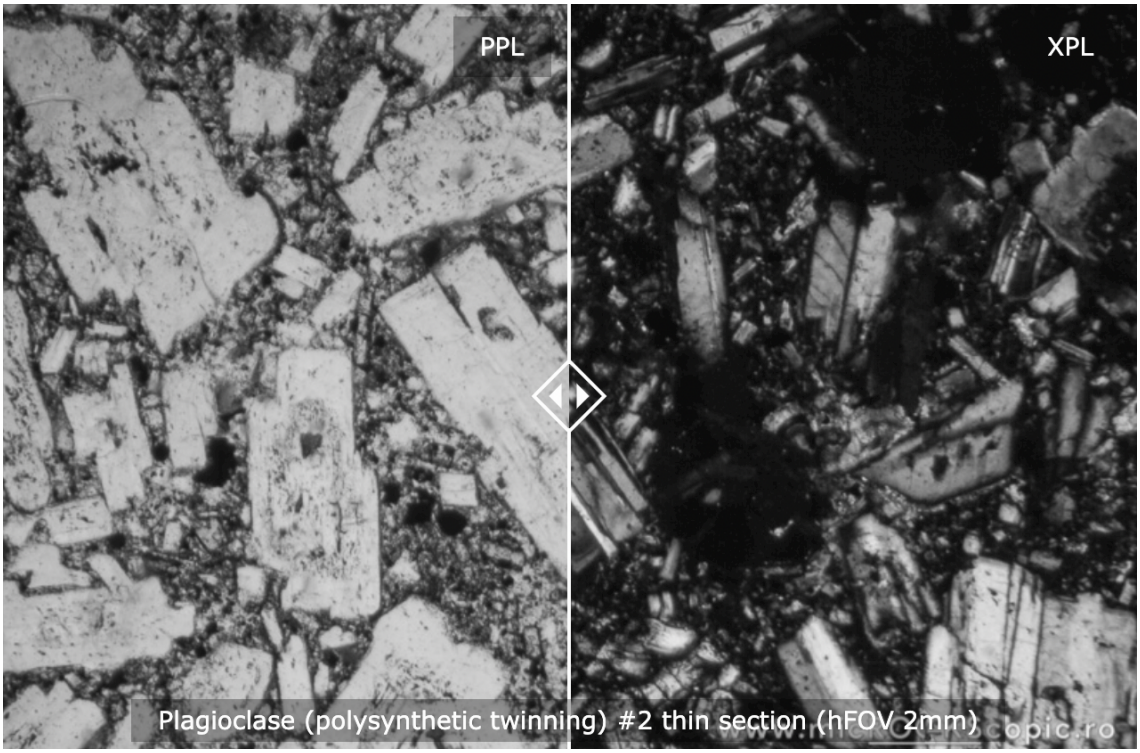


Figure 51: Plagioclase feldspar PPL-XPL. Greyscale view.

Orthoclase feldspar

Orthoclase feldspar is a framework silicate or tectosilicate with general formula $(KAl)Si_3O_8$.
Universal features for orthoclase feldspar include simple twinning in XPL, disappears in PPL. If slow-cooled, will manifest as microcline, whcih has a tartan effect in XPL.
1A reference series sections: L100 Alkali granite, L101 Granite (*), L102 Hornblende biotite granite, L110 Rhyolite porphyritic (quartz porphyry).

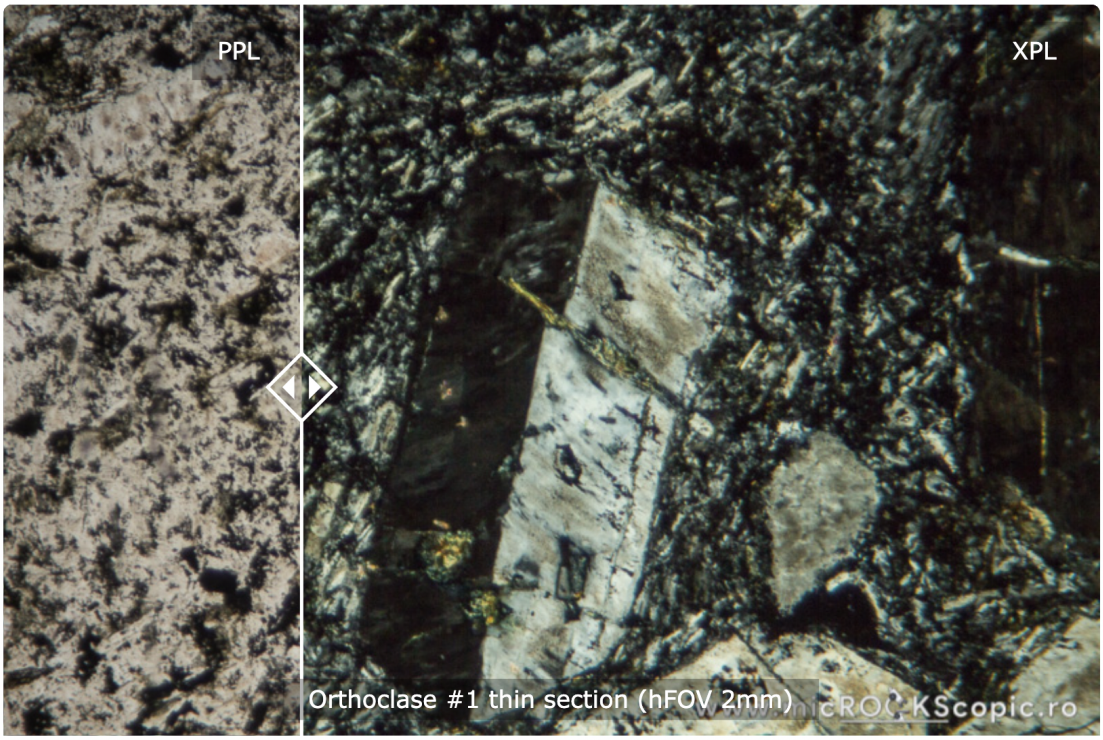


Figure 52: Orthoclase feldspar PPL-XPL. Deuteranopia view.

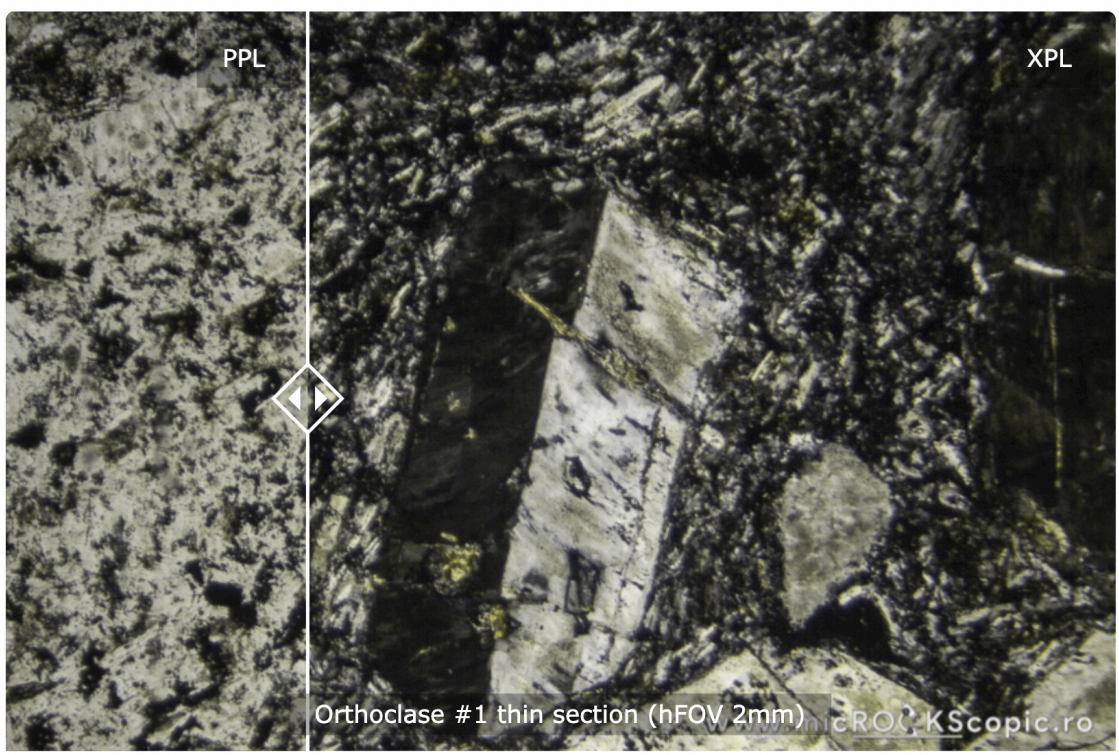


Figure 53: Orthoclase feldspar PPL-XPL. Deuteranopia view.

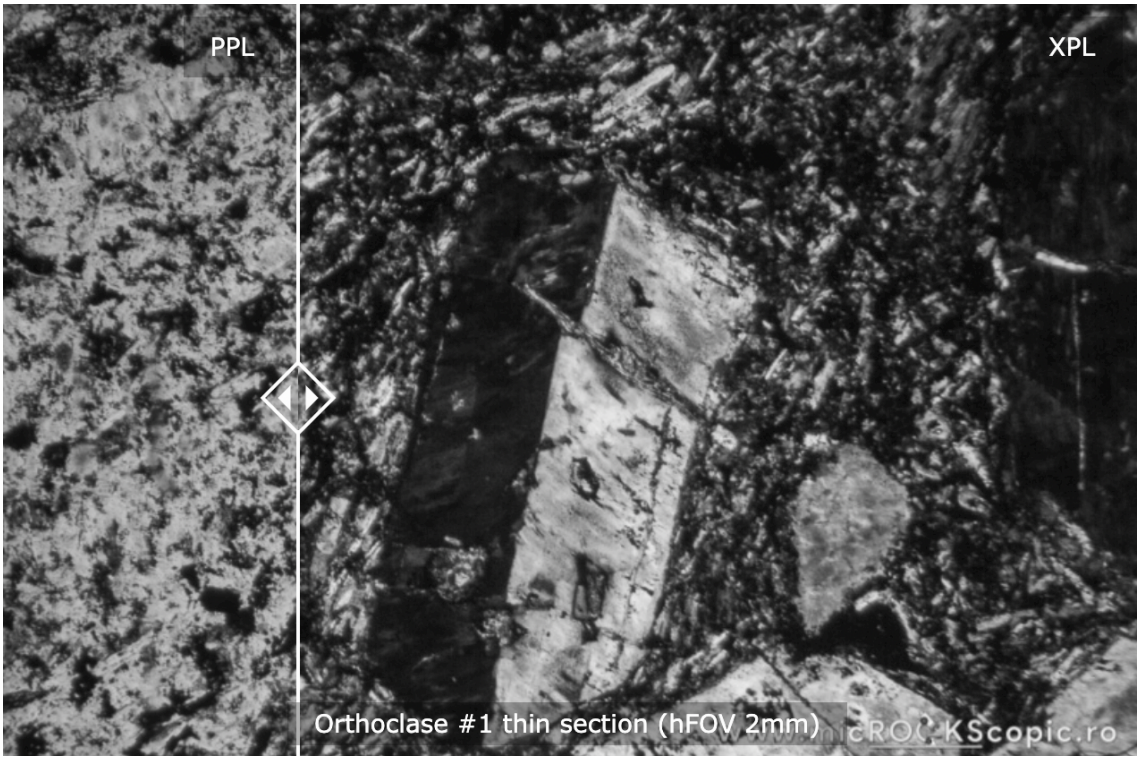


Figure 54: Orthoclase feldspar PPL-XPL. Greyscale view.

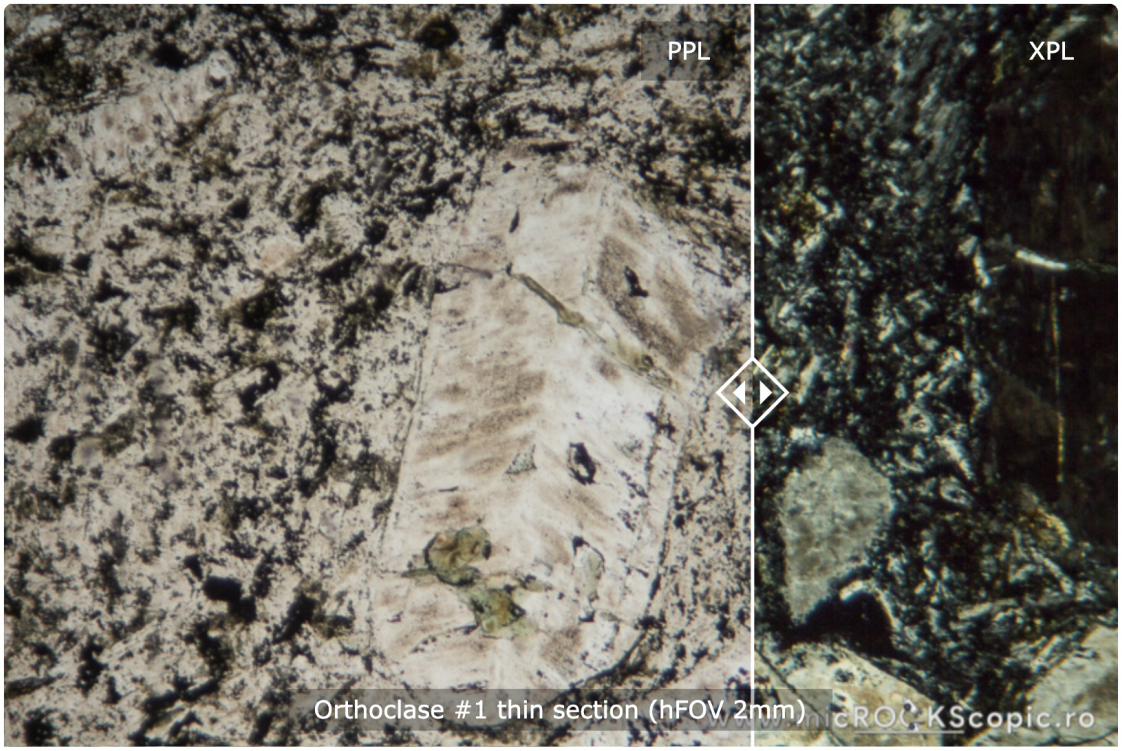


Figure 55: Orthoclase feldspar PPL-XPL. Deuteranopia view.

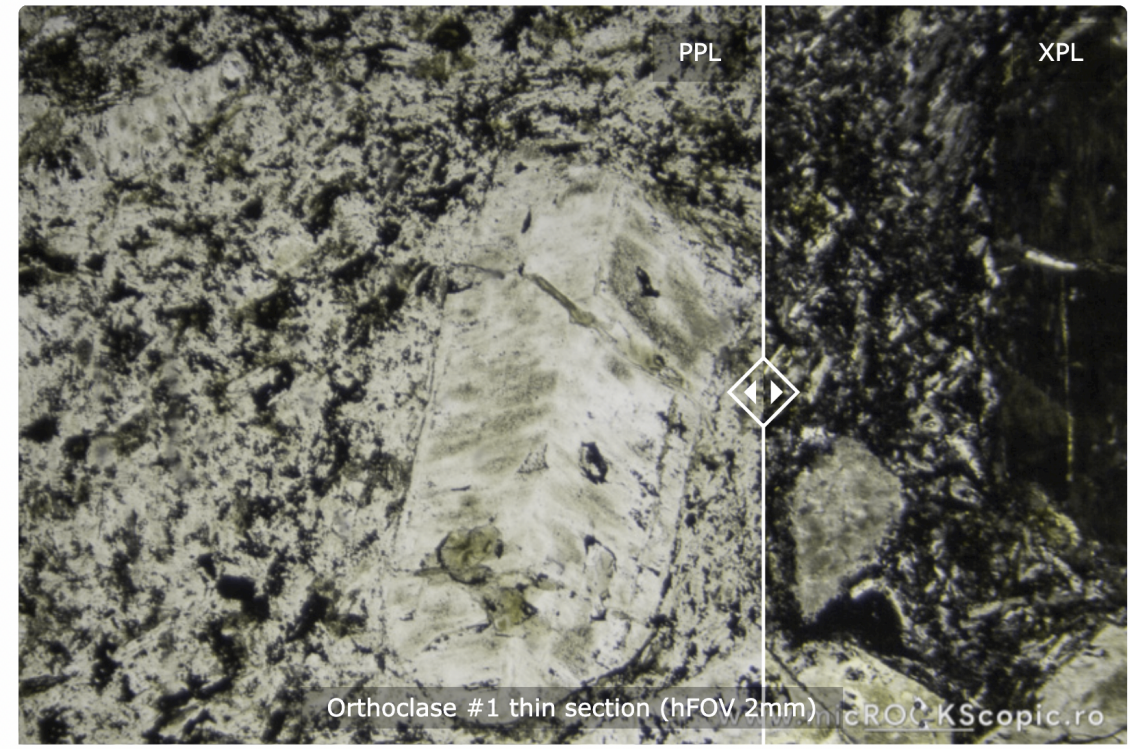


Figure 56: Orthoclase feldspar PPL-XPL. Deuteranopia view.

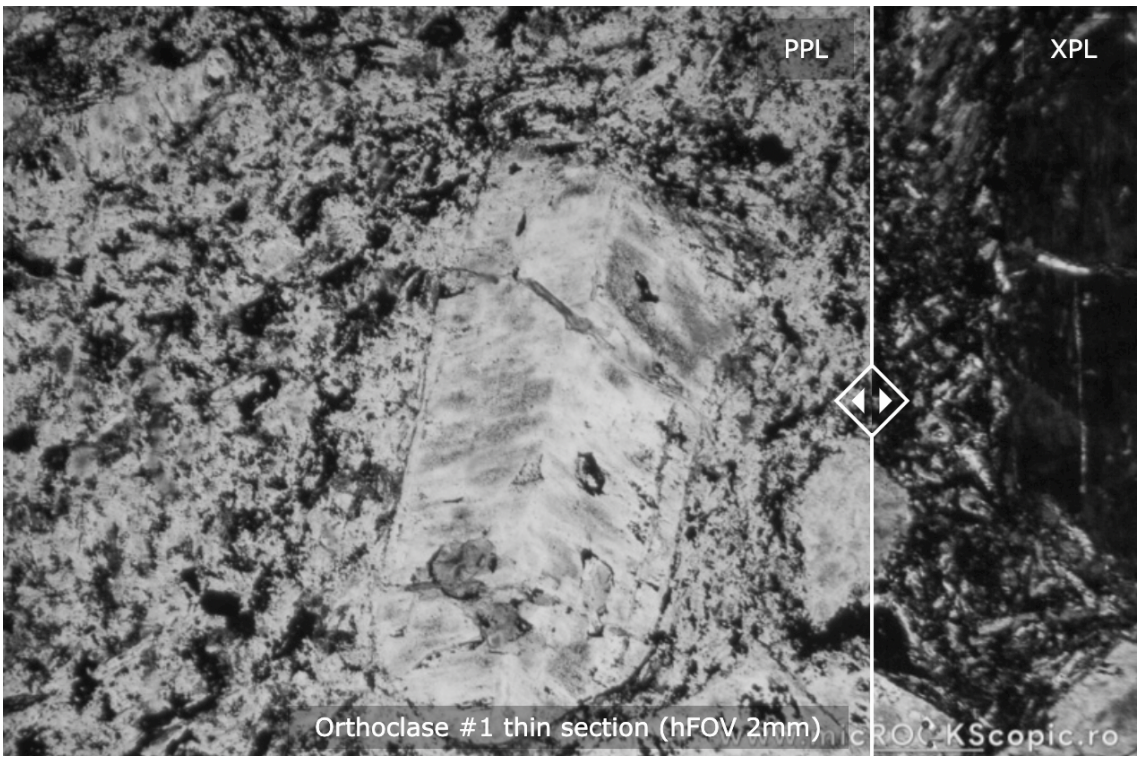


Figure 57: Orthoclase feldspar PPL-XPL. Greyscale view.

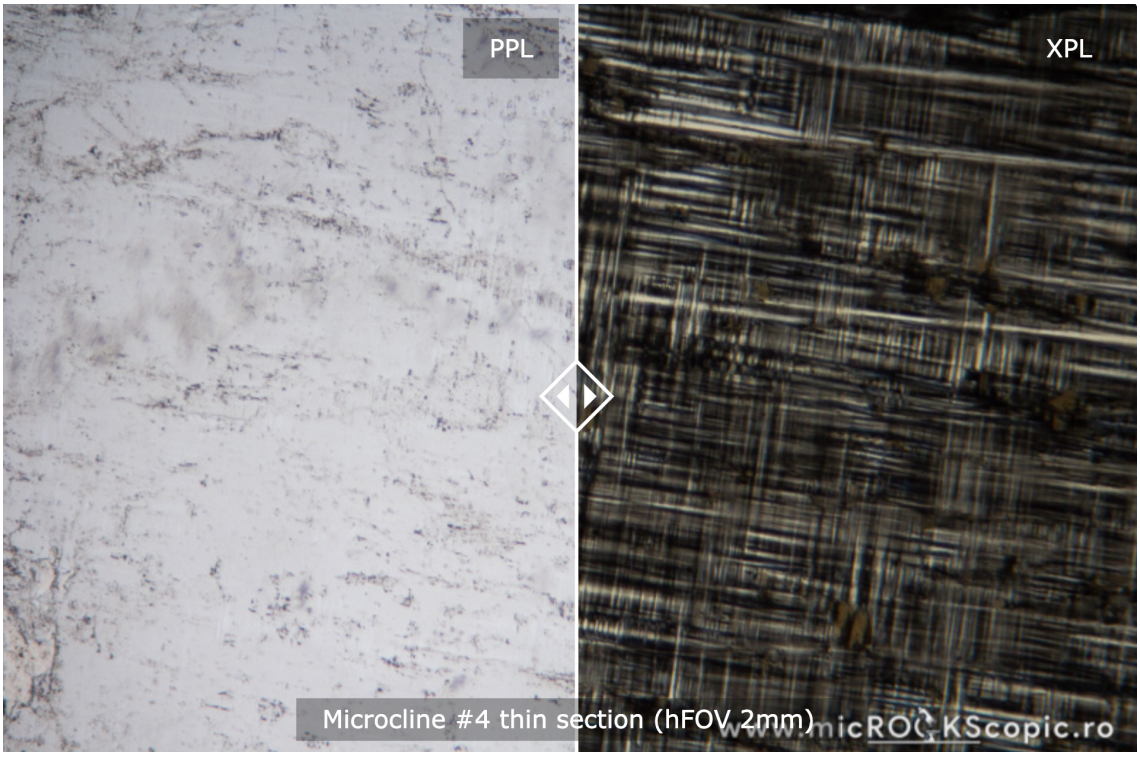


Figure 58: Microcline PPL-XPL. Full colour view.

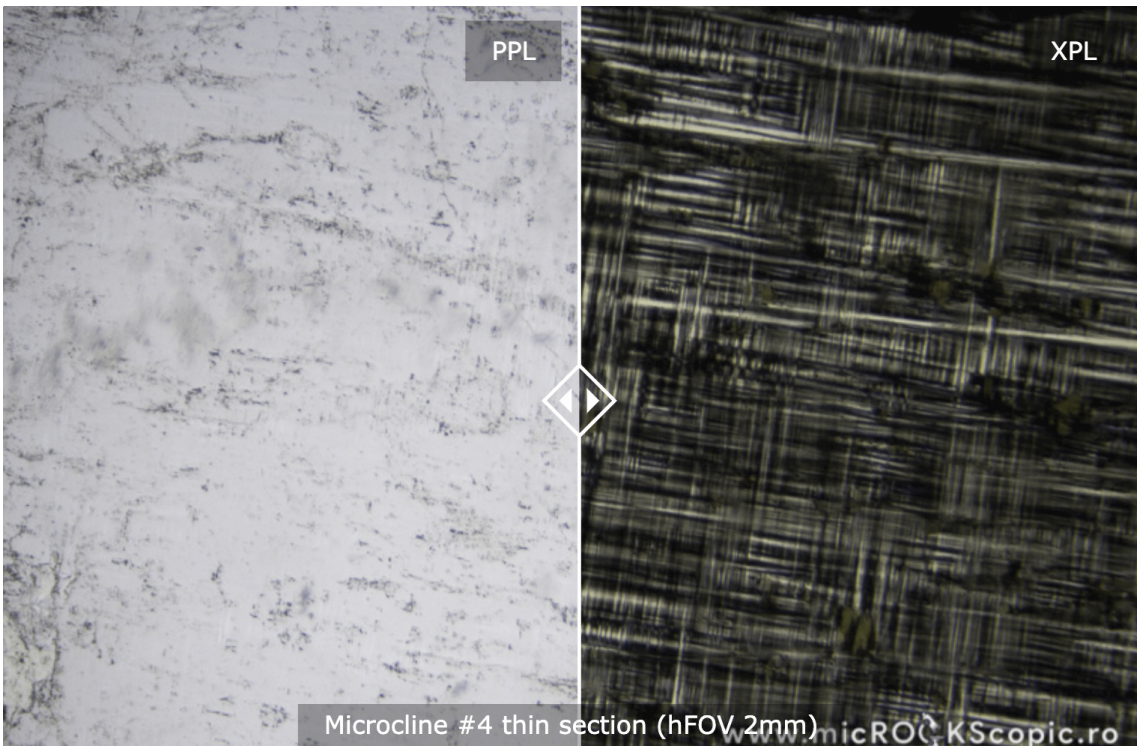


Figure 59: Microcline PPL-XPL. Deuteranopia view.

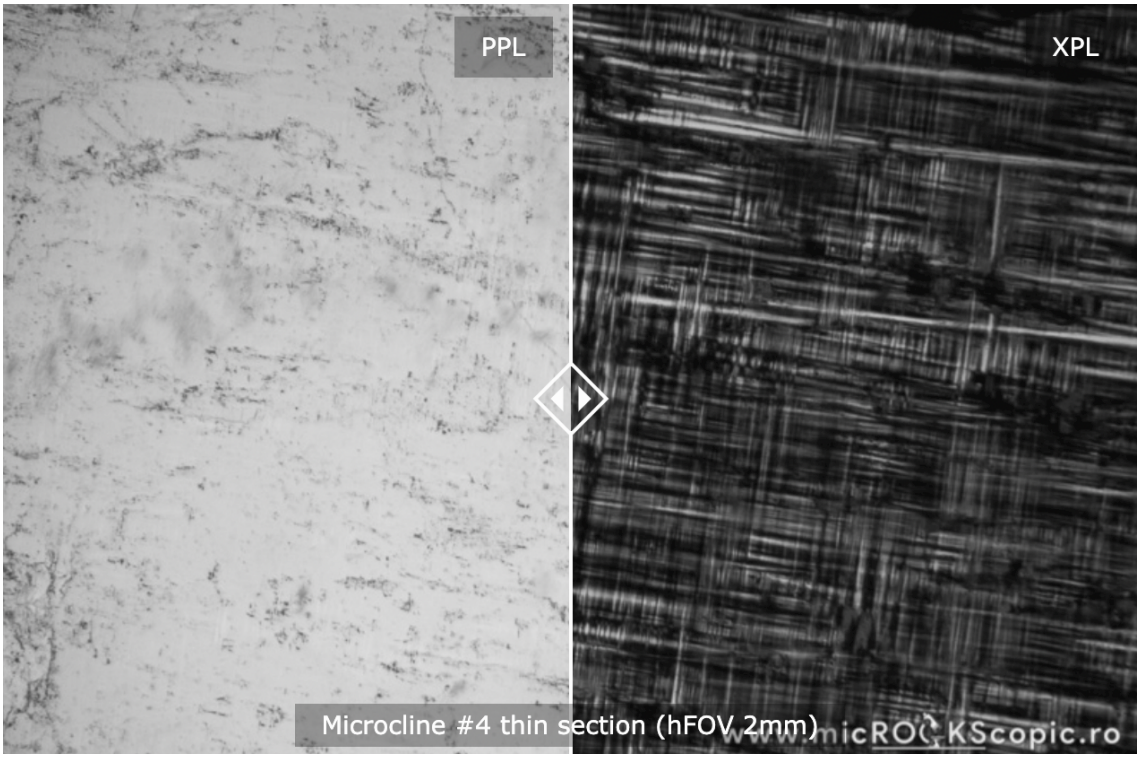


Figure 60: Microcline PPL-XPL. Greyscale view.

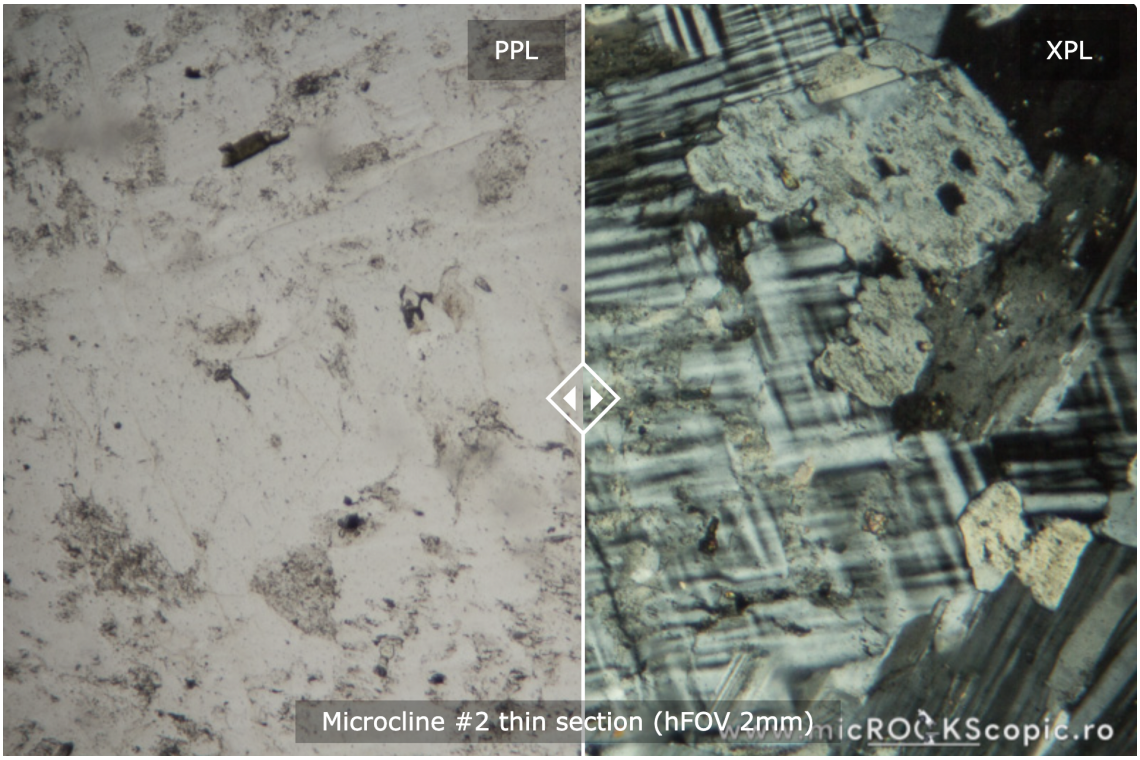


Figure 61: Microcline PPL-XPL. Deuteranopia view.

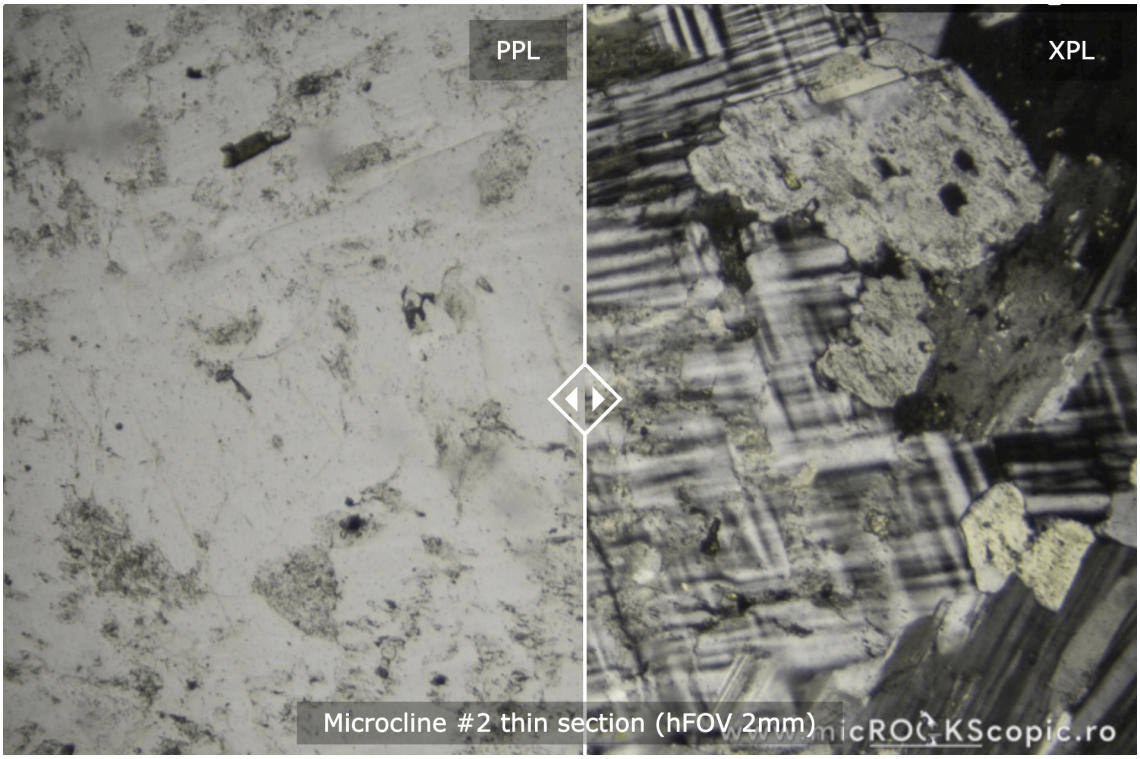


Figure 62: Microcline PPL-XPL. Deuteranopia view.

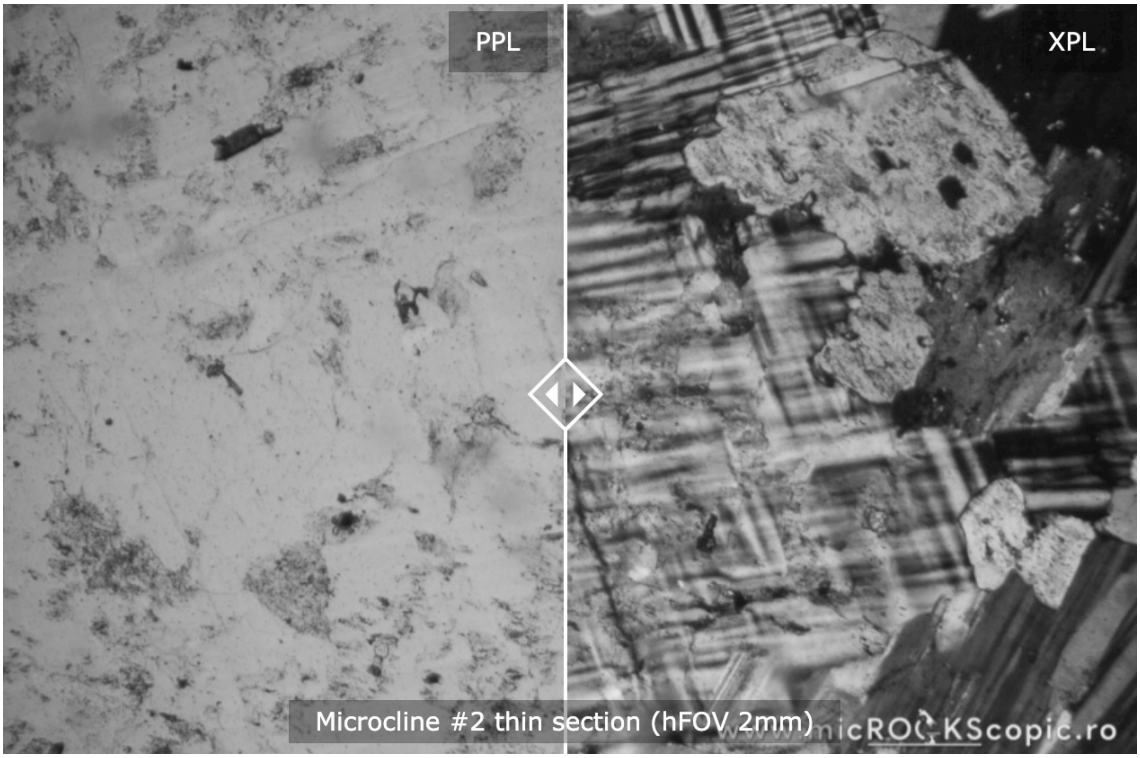


Figure 63: Microcline PPL-XPL. Greyscale view.

Quartz

Quartz is a framework silicate or tectosilicate with general formula SiO_2. Universal features for quartz include speckled texture that varies in XPL.

1A reference series sections: L101 Granite, L110 Rhyolite porphyritic (quartz porphyry) (*), L120 Granodiorite, L311 Conglomerate, matrix, L323 Sandstone, arenite, L370 Chert, flint nodule, cryptocrystalline, L504 Garnet schist, L521 Quartzite.

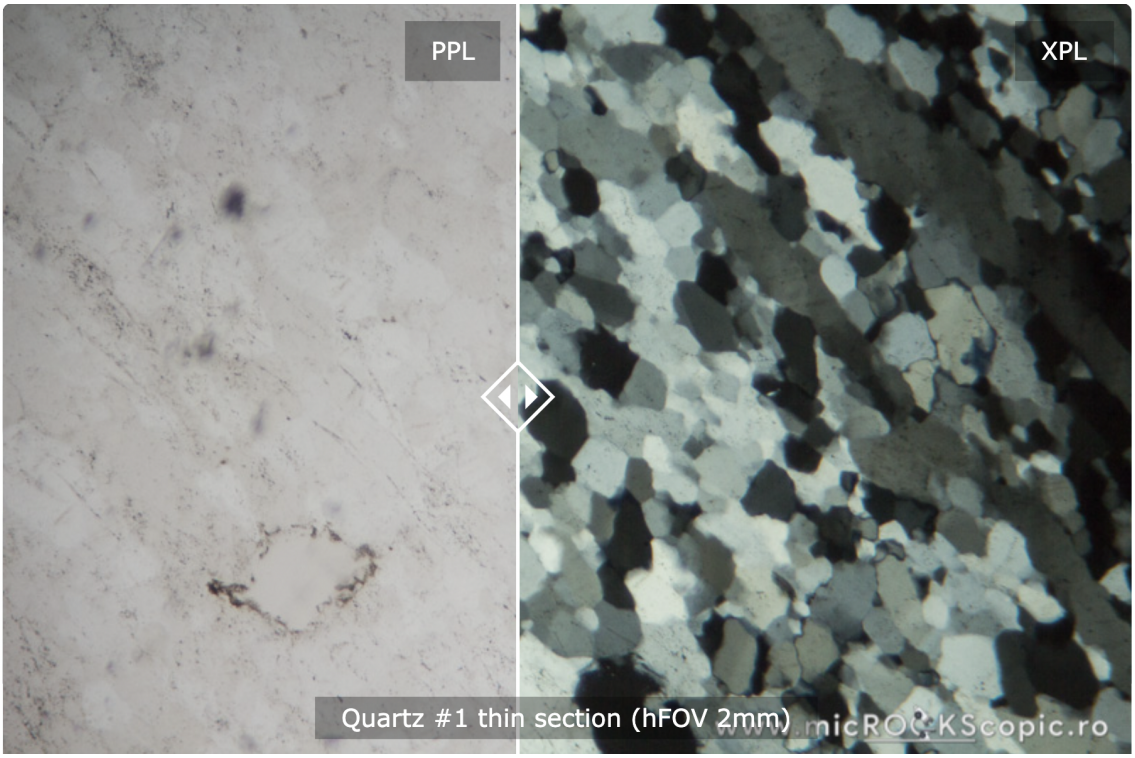


Figure 64: Quartz PPL-XPL. Full colour view.

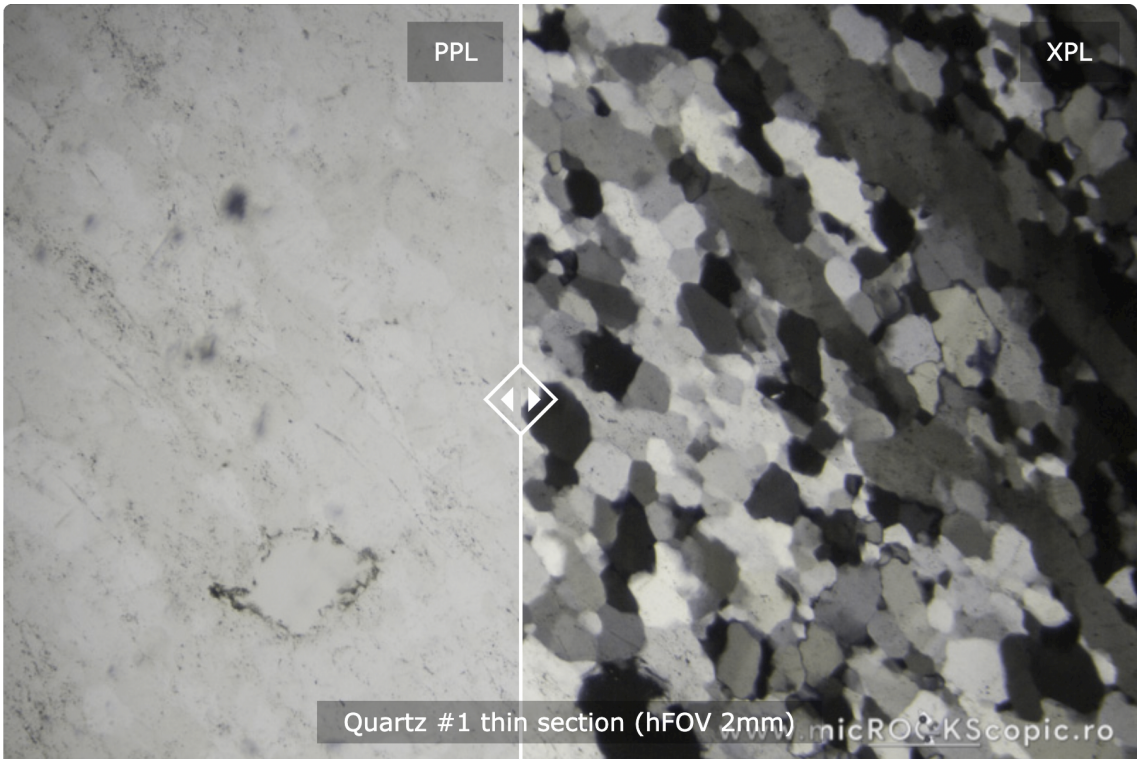


Figure 65: Quartz PPL-XPL. Deuteranopia view.

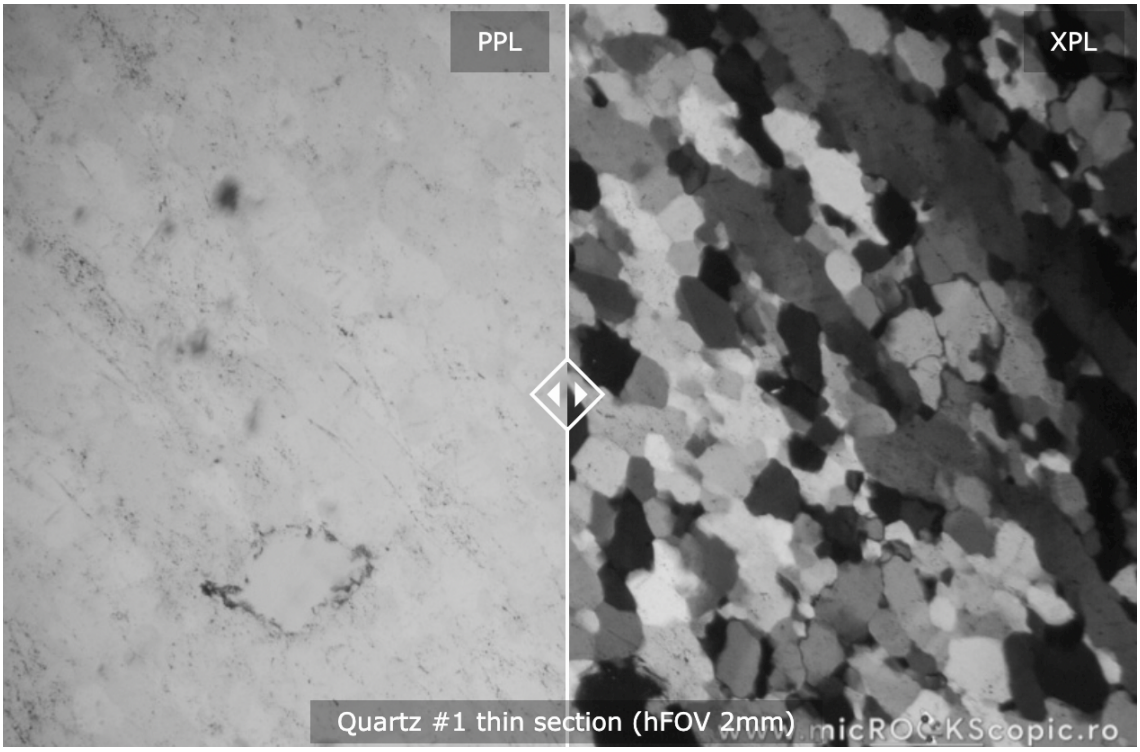


Figure 66: Quartz PPL-XPL. Greyscale view.

Calcite

Calcite is a common non-silciate mineral with a general formula of $CaCO_3$.
Universal features for calcite include hexagonal texture in XPL with thick isotropic bands. Bands are also visible as distinct regions cutting at 120 degrees in PPL.
1A reference series sections: L110 Rhyolite porphyritic (quartz porphyry) (*), L130 Andesite, porphyritic (porphyrite), L161 Basalt amygdaloidal, L325 Sandstone, calcareous cement, L341 Mudstone calcareous, L350 Limestone argillaceous, L353 Limestone oolitic packstone, L371 Chert bedded.

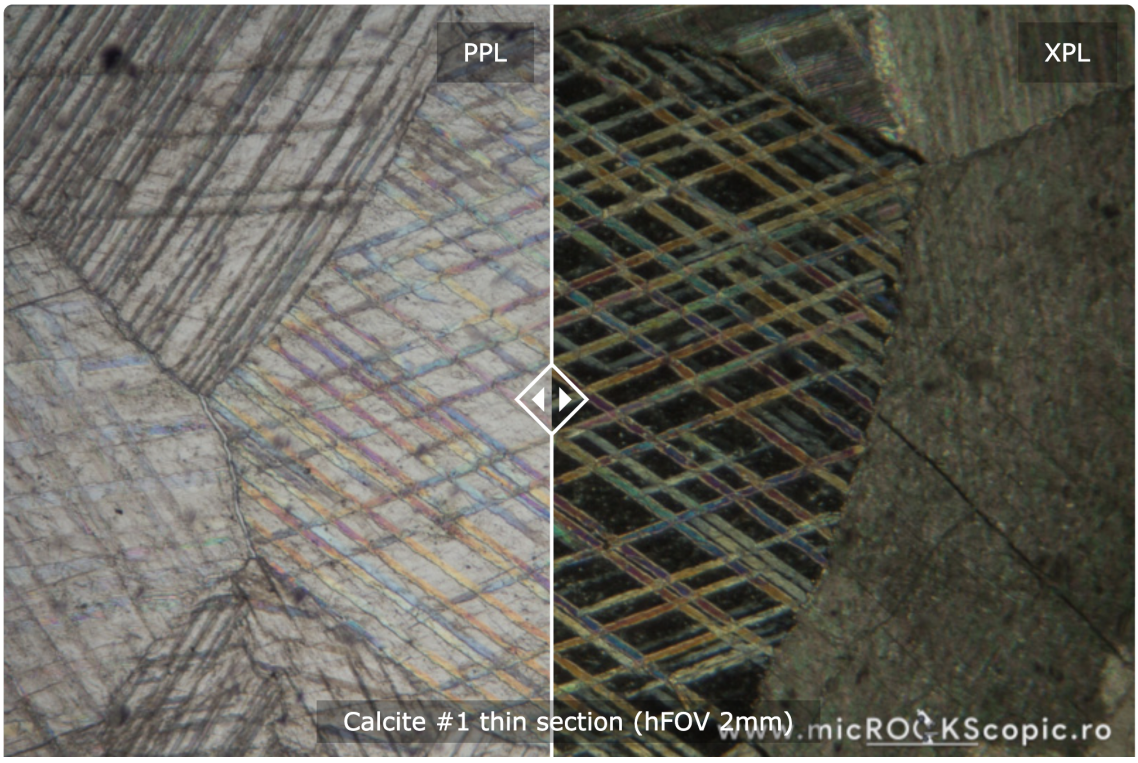


Figure 67: Calcite PPL-XPL. Full colour view.

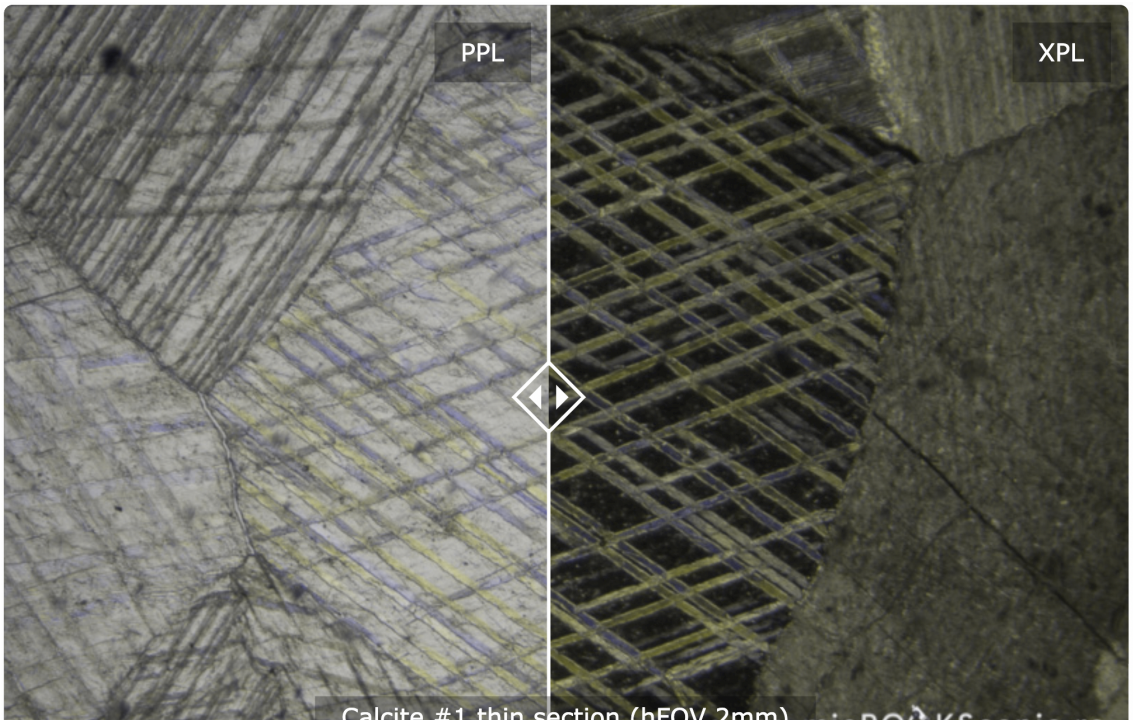


Figure 68: Calcite PPL-XPL. Deuteranopia view.

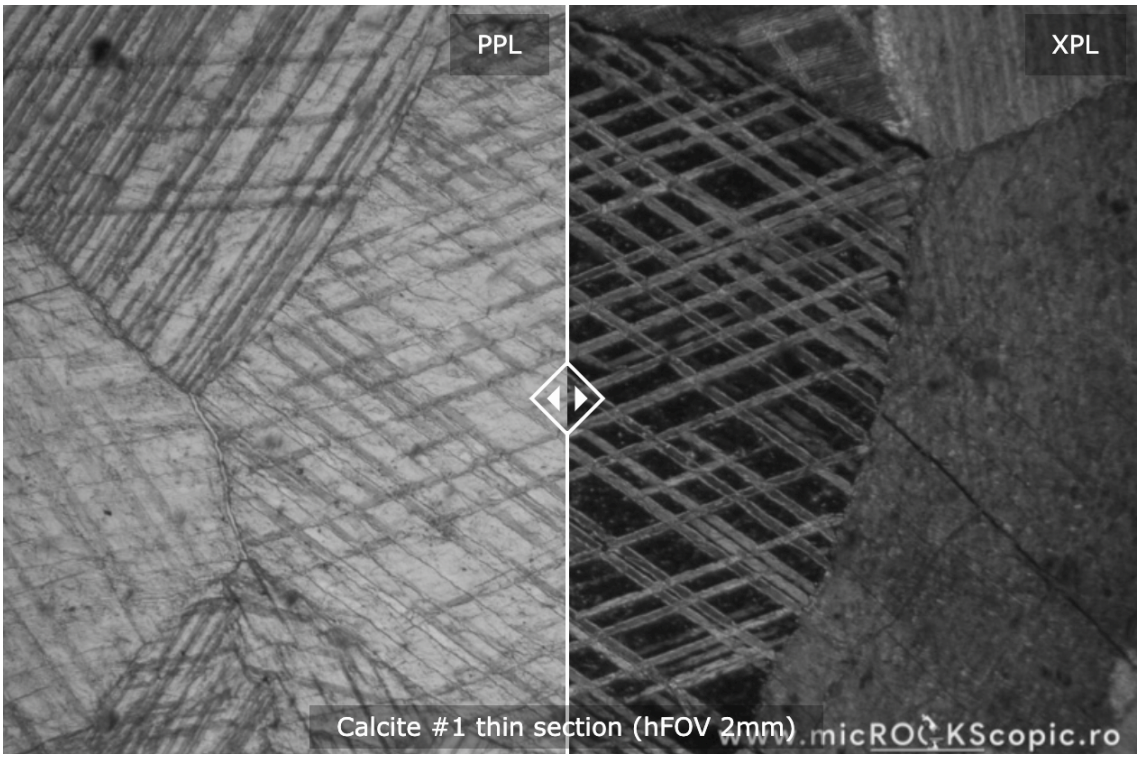


Figure 69: Calcite PPL-XPL. Greyscale view.

Anisotropic phases:

Garnet

Garnets are neosilicates with the general formula
$X_3Y_2(SiO_4)_3$ X = Mg, Ca, Fe^{2+}, Mn^{2+}, etc. Y = Al, Fe^{3+}, Cr^{3+}, V^{3+}.
Universal features for garnet include high relief in PPL, isotropic in XPL, often forming euhedral isolated grains or fractured masses of grains with anisotropic interstices.
1A reference series sections: Rhyolite porphyritic (quartz porphyry) (*), L504 Garnet schist, L506 Garnet biotite gneiss (*).

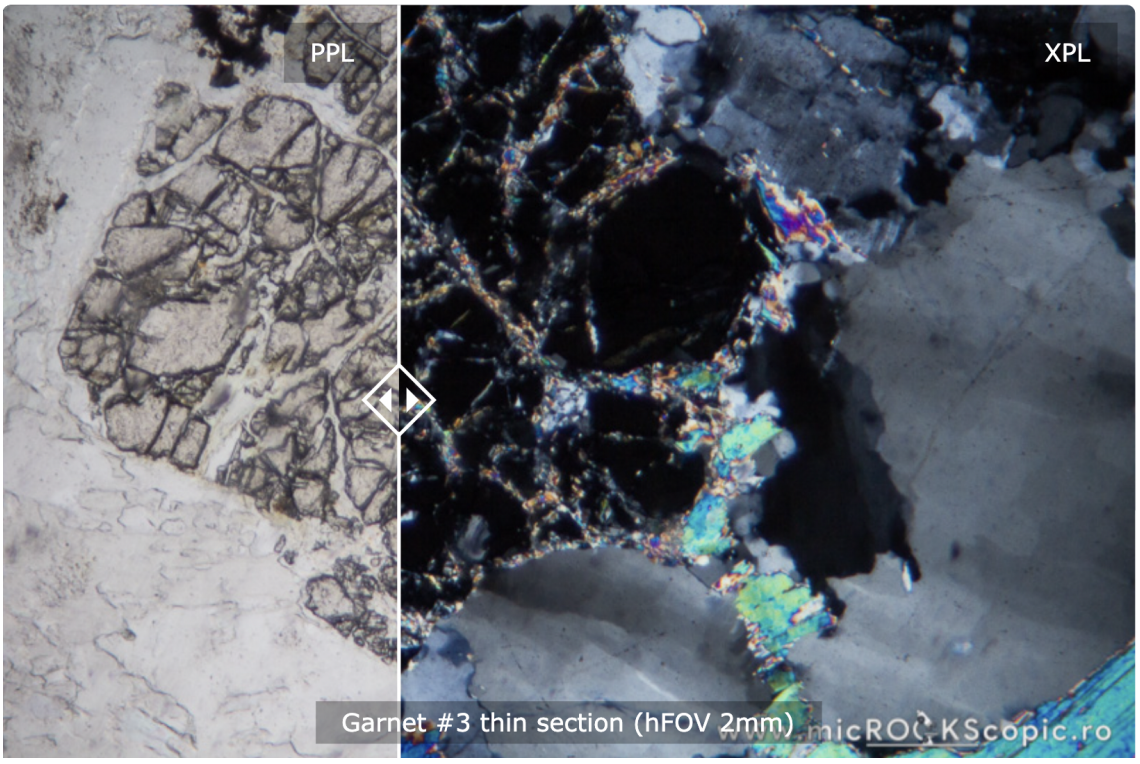


Figure 70: Garnet PPL-XPL. Full colour view.

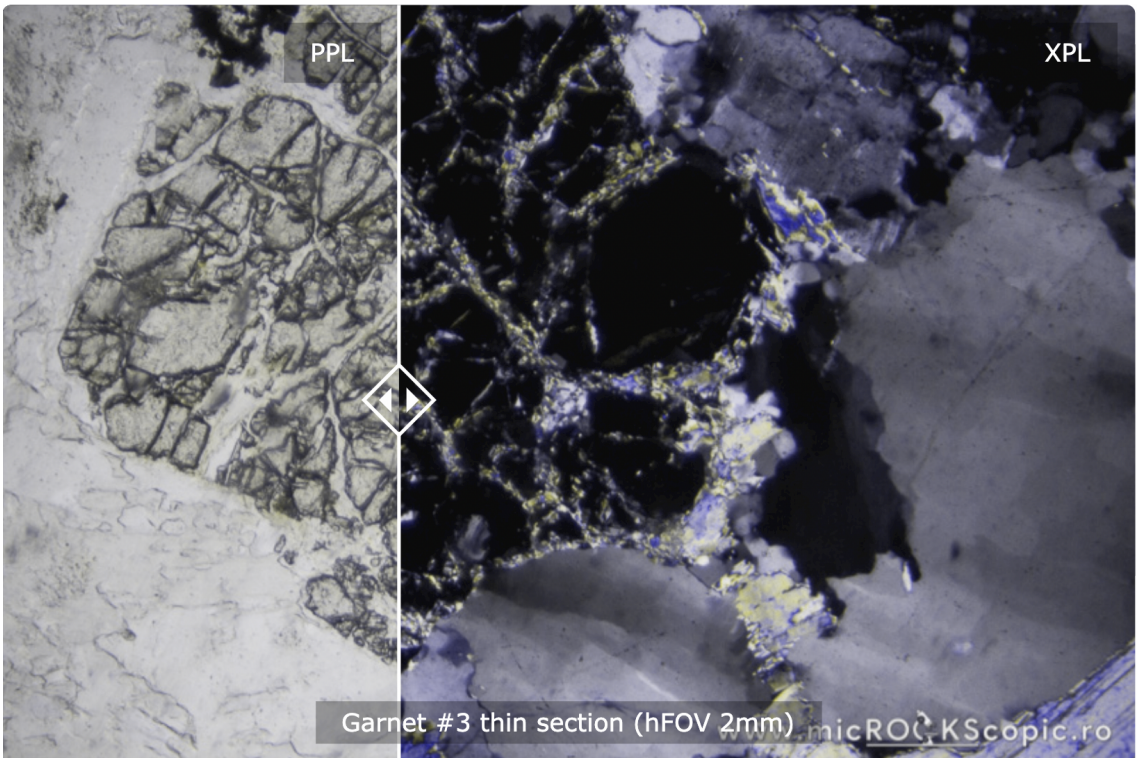


Figure 71: Garnet PPL-XPL. Deuteranopia view.

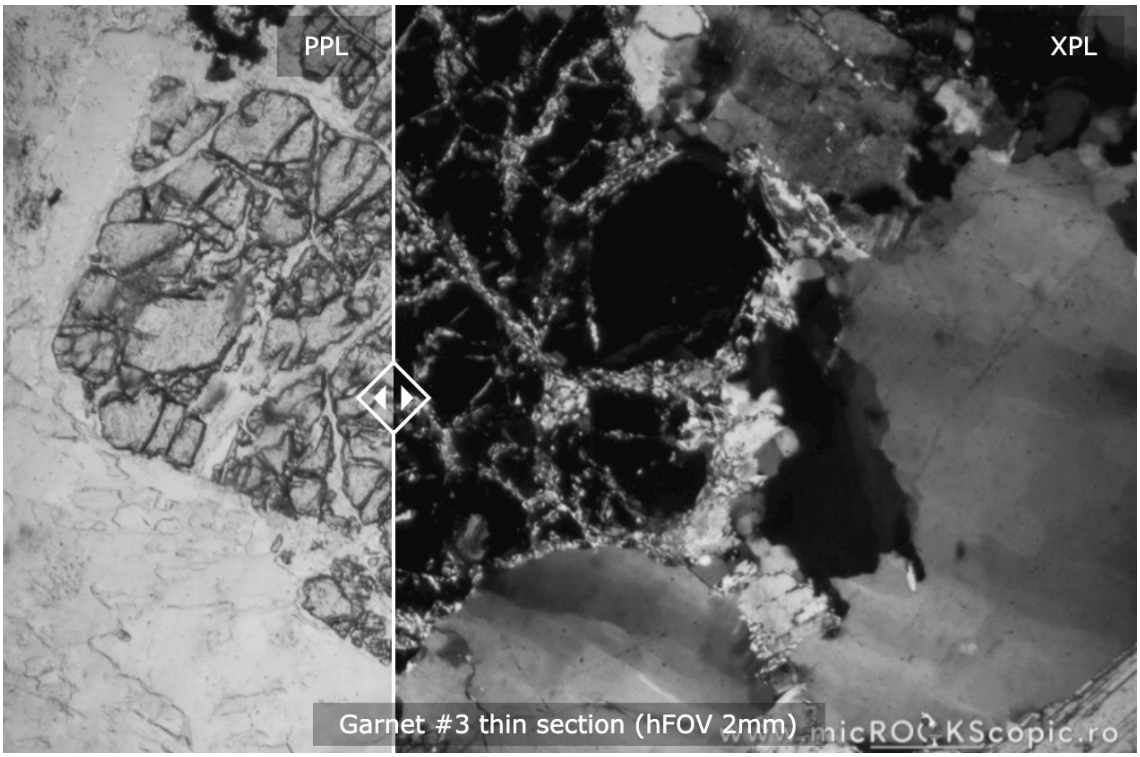


Figure 72: Garnet PPL-XPL. Greyscale view.

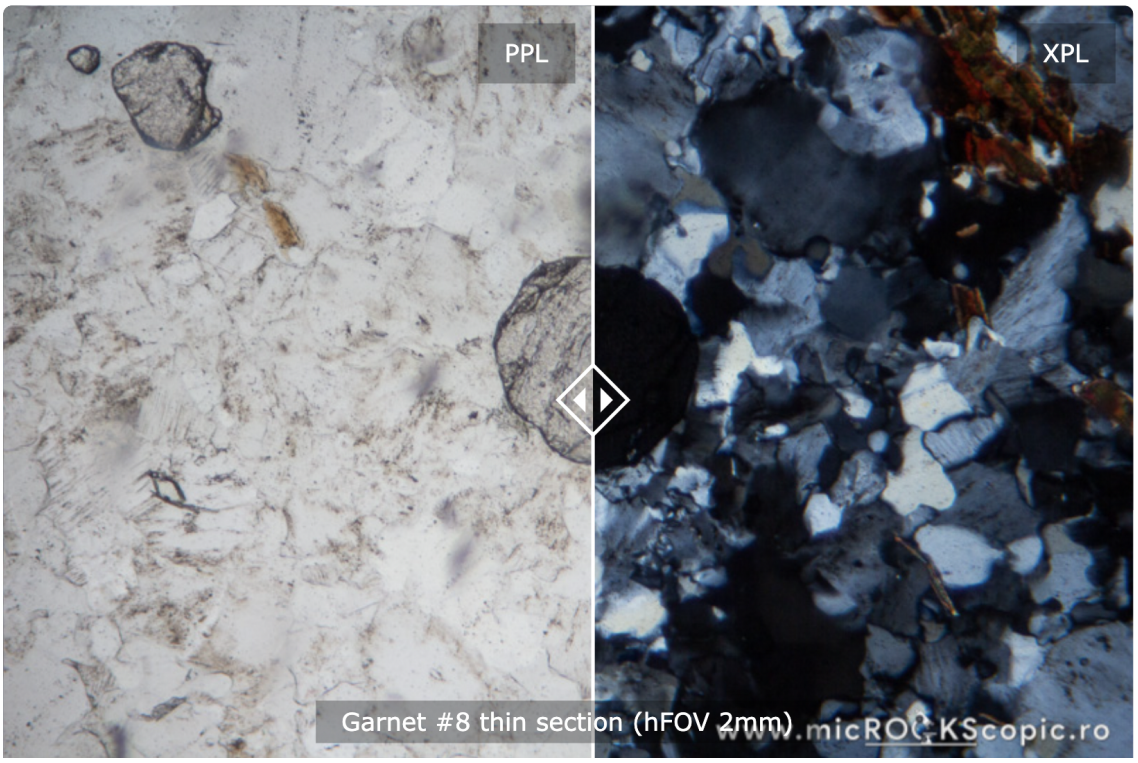


Figure 73: Garnet PPL-XPL. Full colour view.

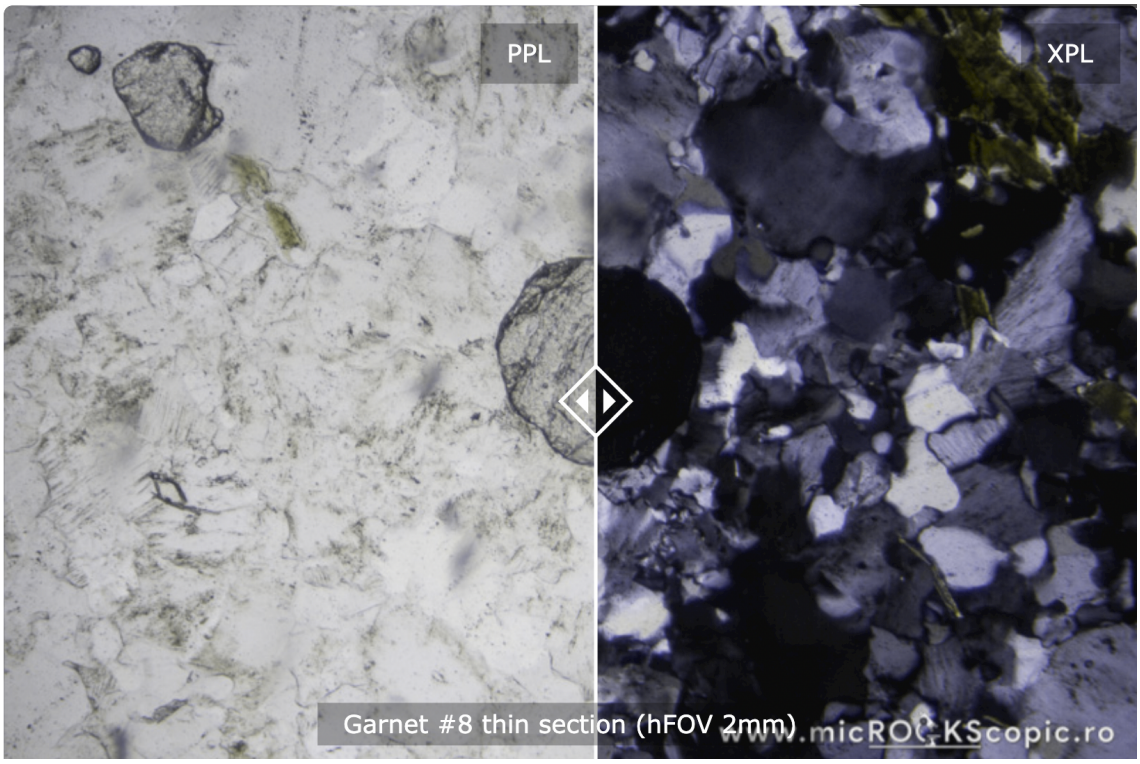


Figure 74: Garnet PPL-XPL. Deuteranopia view.

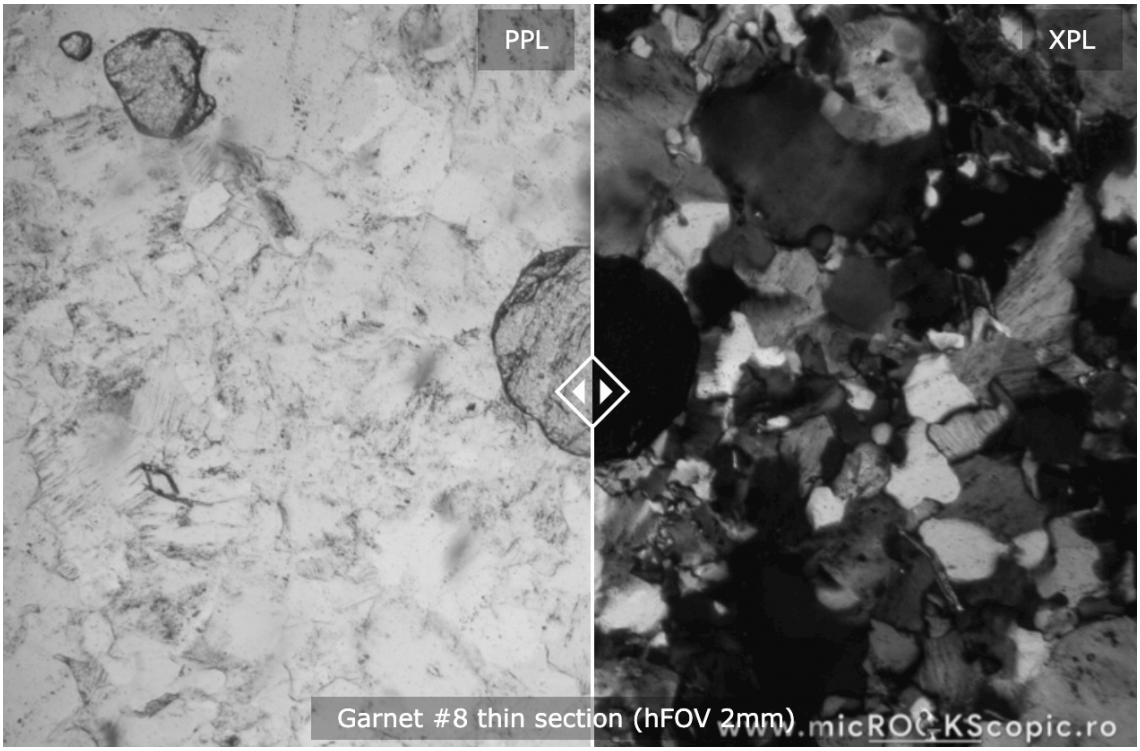


Figure 75: Garnet PPL-XPL. Greyscale view.

Spinel

Spinel is the Mg-Al end-member of the broader spinel group. It has the formula $MgAl_2O_4$.
Universal features for spinel include its dark PPL tone, being isotropic in XPL, and no cleavage or pleochroism. Grain shape differs from biotite. Most similar phase optically is garnet, but spinel looks much darker in PPL.
1A reference series sections: n/a.

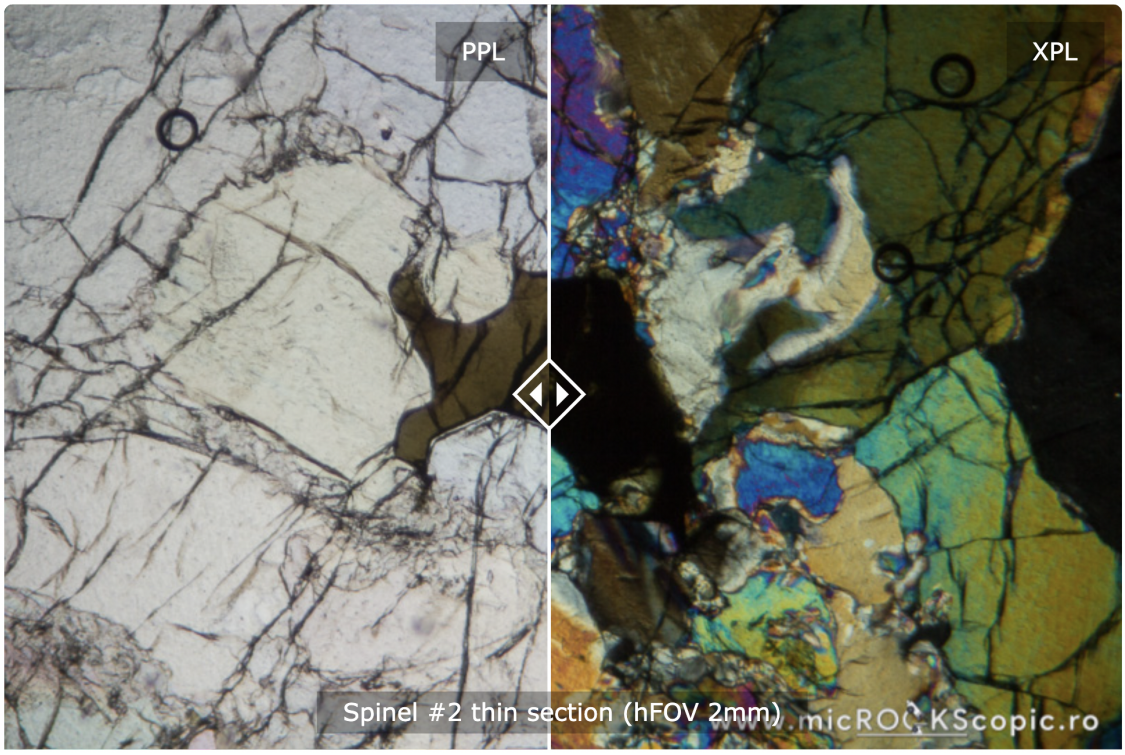


Figure 76: Spinel PPL-XPL. Full colour view.

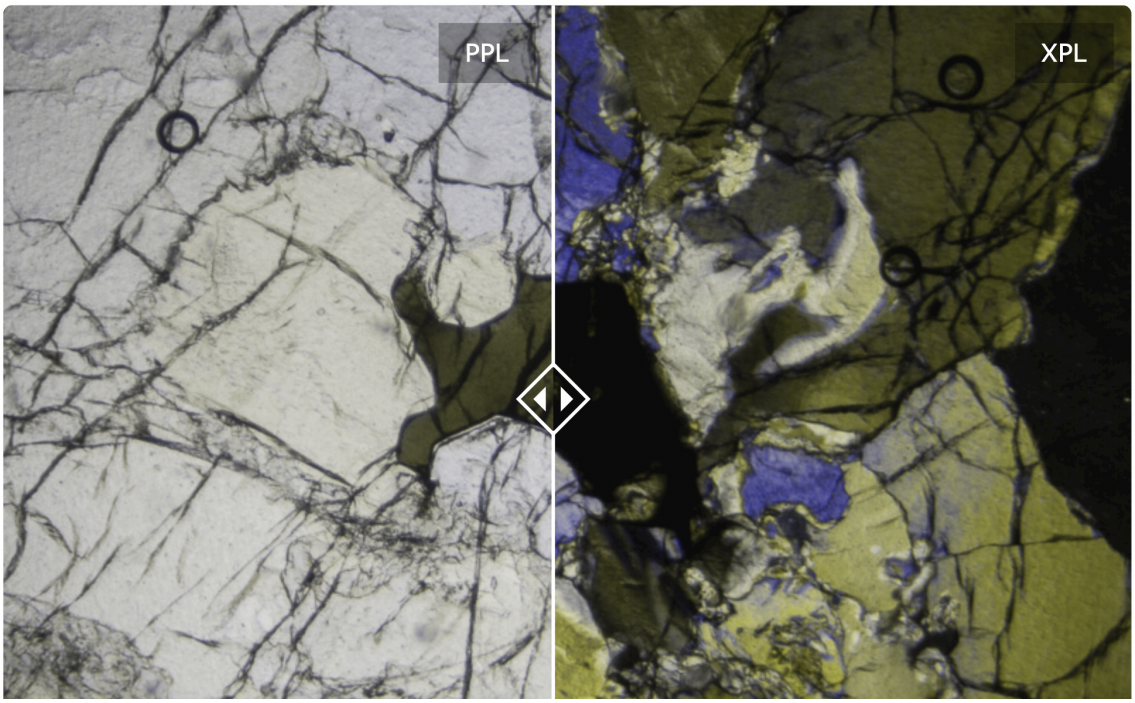


Figure 77: Spinel PPL-XPL. Deuteranopia view.

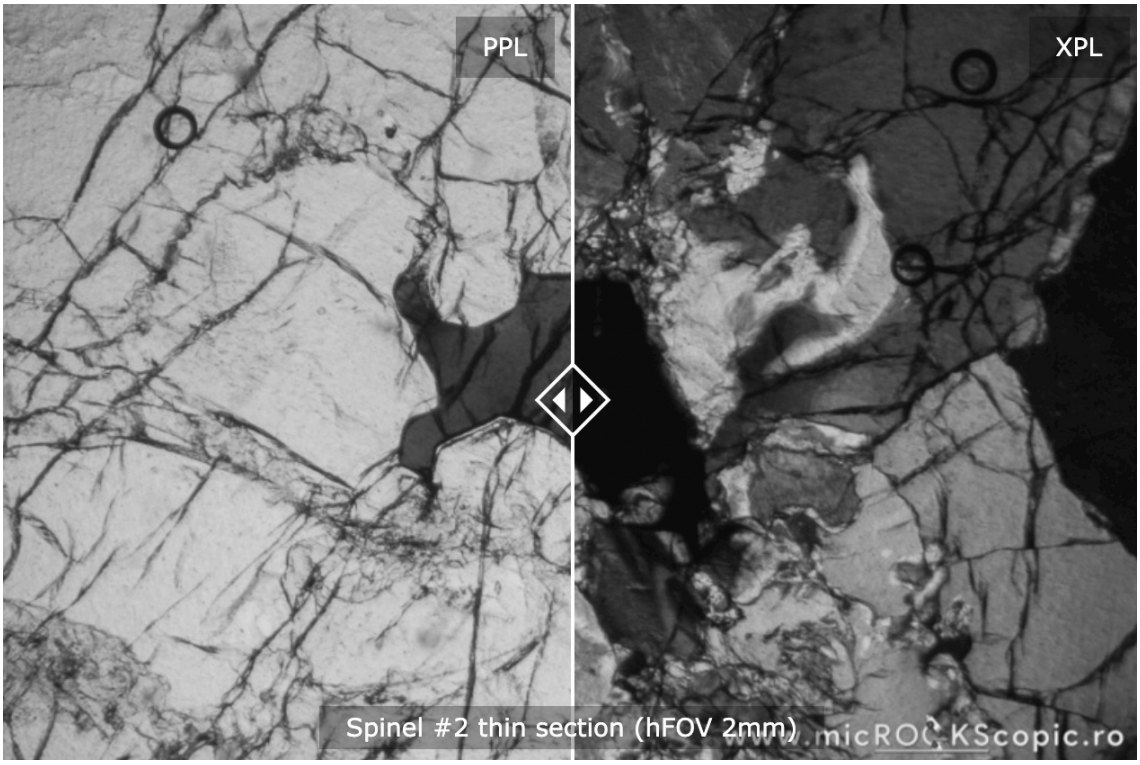


Figure 78: Spinel PPL-XPL. Greyscale view.

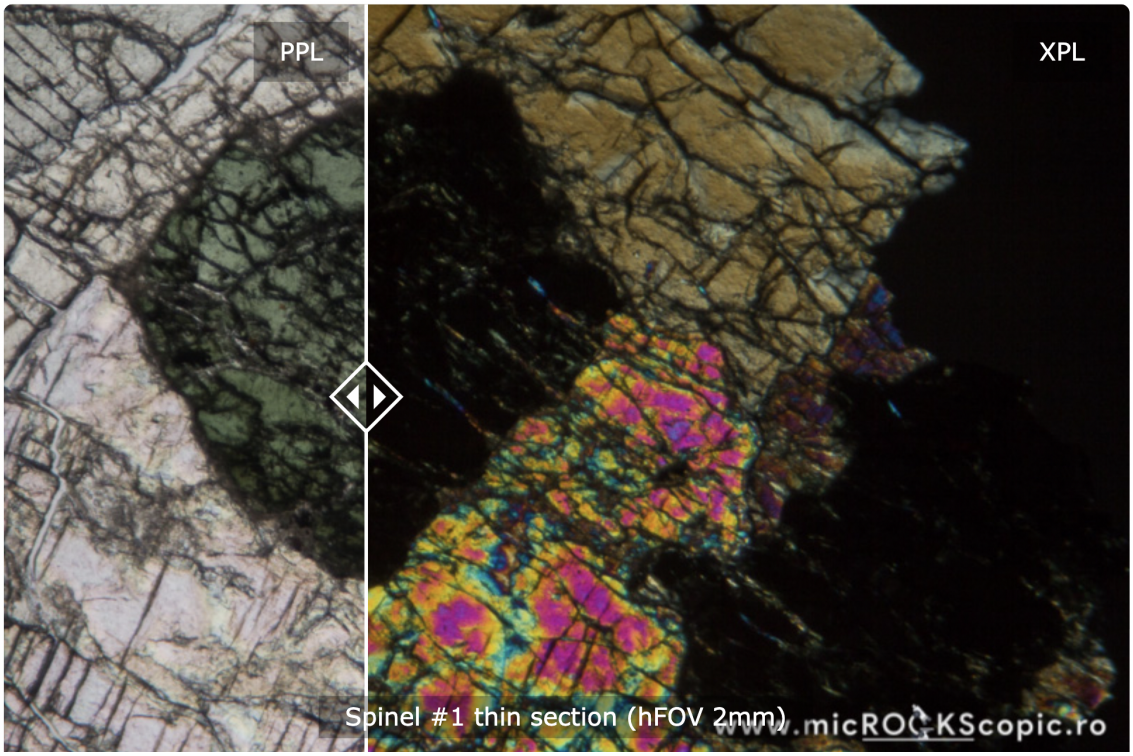


Figure 79: Spinel PPL-XPL. Full colour view.

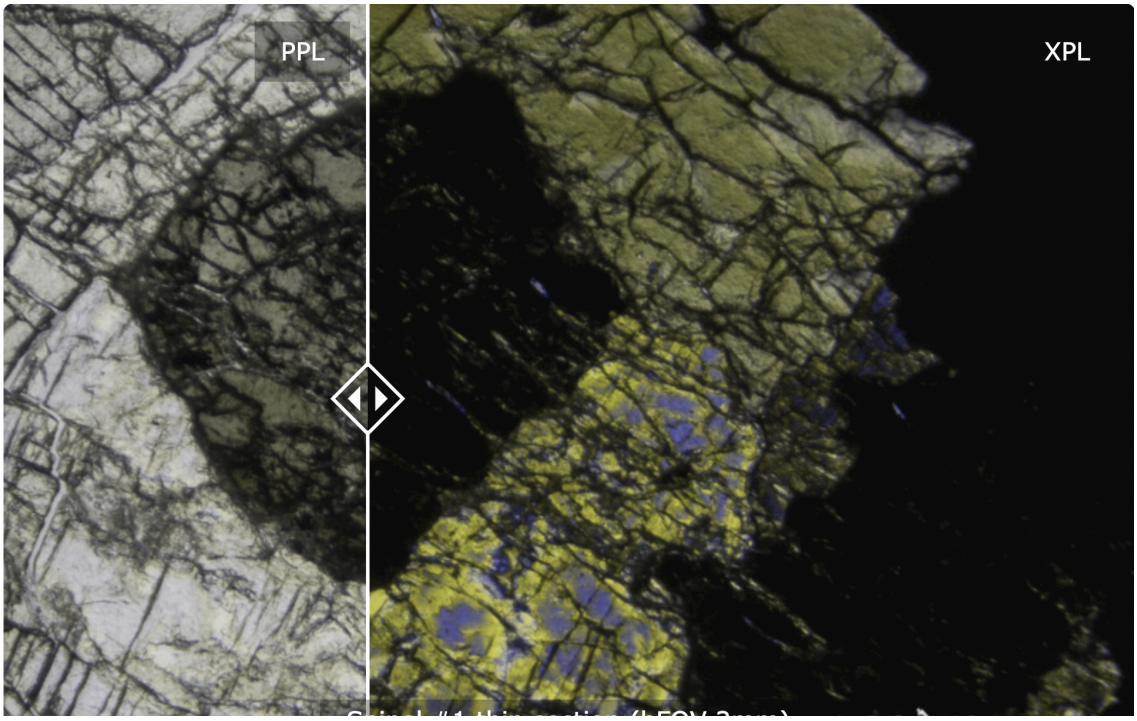


Figure 80: Spinel PPL-XPL. Deuteranopia view.

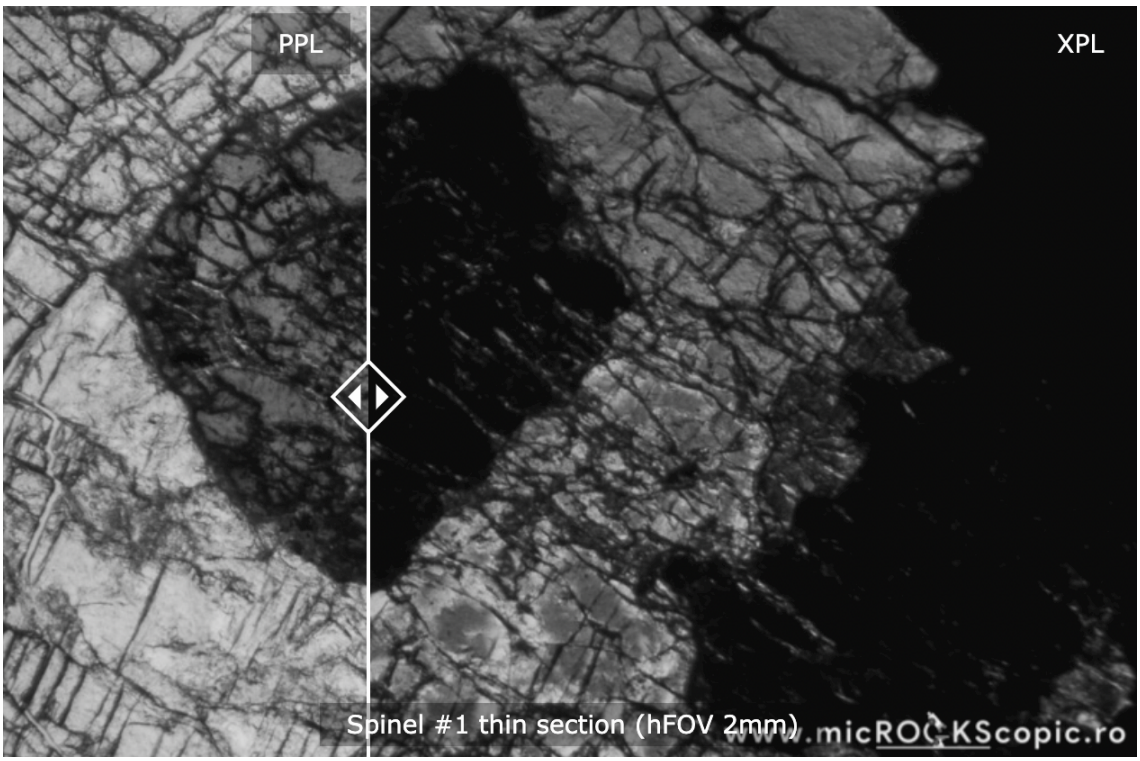


Figure 81: Spinel PPL-XPL. Greyscale view.