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Petrographic and microprobe study of nephrites from Lower Silesia (SW Poland)

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Lower Silesia hosts important European nephrite deposits of Jordanów and less-known of Złoty Stok. Nephrite artifacts were discovered in archaeological sites dated back to the Neolithic period, across Eurasia. Especially artifacts found in Poland, Italy and Bulgaria may originate from Polish nephrites. Nowadays, only one artifact is precisely linked to Jordanów. Petrographic study of nephrites and chemical analyses of constituents by means of EMPA allow accurate identification of the nephrites. The characteristic phases of Jordanów tremolite nephrite are rotated and cataclased diopside porphyroblasts with pressure shadows, chlorite layers and nests with interlocking non-pseudomorphic texture and prehnite veins. The presence of hydrogrossular, grossular, titanite, apatite with monazite inclusions, and zircon with pleochroic haloe is typical. Chlorites are usually represented by penninite, and minor clinochlore and diabantite. The characteristic features of Złoty Stok actinolite nephrite are löllingite and diopside crystals usually visible by the naked eye, with the presence of quartz and carbonates. Löllingite is chemically inhomogeneous and gold bearing. Most of the mineralogical-petrological features can be obtained using non-destructive methods.

Key words: nephrite, Jordanów, Złoty Stok, Lower Silesia, electron microprobe, mineral identification.

INTRODUCTION

Nephrite is well-known raw material for carvings, tools and low-priced jewellery. However, due to a limited number of occurrences and economic insignificance, it has drawn little scientific attention. Nephrite is a variety of jade, composed predominantly of fibrous Ca-amphiboles (tremolite and/or actinolite). Archaeologists use the term jade to implements formed mostly of monomineral rocks: monomineral amphibole rock or pyroxenite. The other variety is jadeitite composed of jadeite pyroxene. Because of ultimate toughness caused by fibrous fabric (Bradt et al., 1973) – therefore called the toughest natural stone (Makepeace and Simandl, 2001), and relatively low hardness (about 5.5–6.5 in Mohs' scale), nephrite is one of the raw materials mostly preferred by the carvers since the Early Neolithic period. Significant world deposits are restricted to tens of locations. Major nephrite deposits are located in Canada – British Columbia (e.g., Simandl et al., 2000; Makepeace and Simandl, 2001), Russian Federation – Siberia (Harlow and Sorensen, 2001, 2005; Łapot, 2004), China (Sax et al., 2004; Liu et al., 2011a, b), Korea (e.g., Yui and Kwon, 2002), Taiwan (e.g., Wan and Yeh, 1984; Hung et al., 2007), South Australia (Harlow and Sorensen, 2001, 2005 and references therein), New Zealand – South Island (e.g., Root, 1994; Middleton, 2006), and in the USA – Wyoming, Alaska and California (e.g., Sinkankas, 1959; Middleton, 2006). Despite limited number of deposits, nephrite artifacts were found in numerous archaeological sites, dated back to the Neolithic age. Limited nephrite sources together with wide distribution in archaeological sites, gives unusual opportunities in reconstruction of ancient trade and migration routes.

Europe and Asia are among the areas where nephrite artifacts were discovered in many sites, e.g., in Italy, including Sicily and especially Sardinia (D'Amico et al., 2003), Bodensee Lake in Switzerland (Maślankiewicz, 1982; Middleton, 2006; Heflik, 2010), SW Poland (Heflik, 2010), Bulgaria (Kostov, 2005; Kostov et al., 2012), Baikal Lake in Siberia, Russia (Losey et al., 2011), Gobi Altai in Mongolia (Derevianko et al., 2008), Pakistan (Fournelle et al., 2010), China (Cheng et al., 2004; Sax et al., 2004; Hung et al., 2007), Taiwan, Vietnam, Philippines, Malaysia, Cambodia, Thailand (Hung et al., 2007). Especially interesting are artifacts from Polish, Swiss, Italian and Bulgarian sites (Fig. 1) because some of them are probably made of Polish nephrites. Moreover, the sources of nephrite artifacts in numerous archaeological sites remain unknown, including those in central and southern Italy, especially Sardinia (D'Amico et al., 2003), and in South Bulgaria (Kostov, 2005). Furthermore, recent studies allowed distinguishing at least two different types of nephrite raw material used to carve objects from sites in south-west Bulgaria (Kostov et al., 2012). The Polish source of these artifacts is probable due to a relatively short distance. At present, only one artifact is identified to be carved from Polish nephrite of Jordanów – an axe from Gniechowice near Wrocław (Heflik, 2010). Detailed petrographic study of Lower Silesian (SW Poland) nephrites, applicable especially in archaeometric studies and allowing simple and precise host-deposit identification, was the

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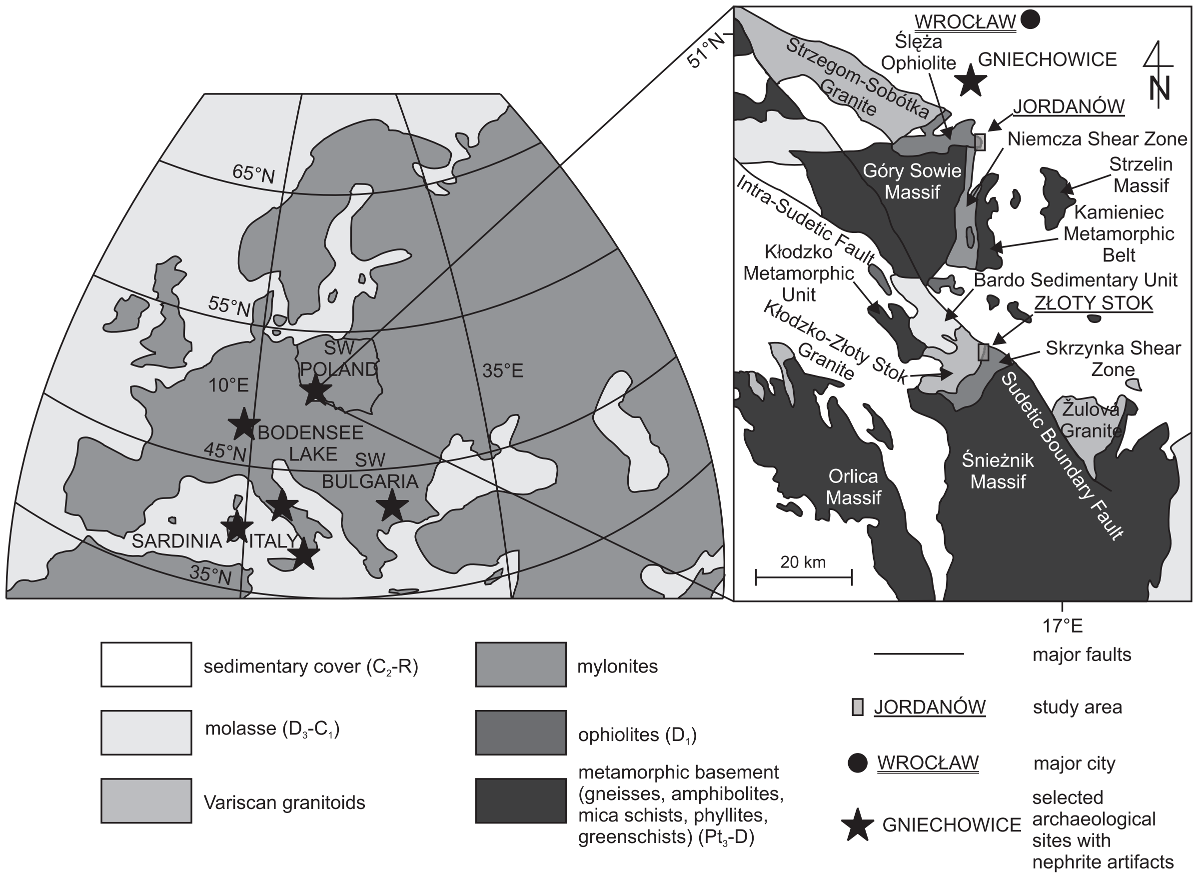

Fig. 1. Simplified geological map of the Sudetes with indicated Jordanów and Złoty Stok nephrite deposits, mountainous part of Sudetes lies SW from Sudetic Boundary Fault, NE from fault is Fore-Sudetic Block, and marked location of the study area and selected archaeological sites where nephrite artifacts were found in Europe, modified after Aleksandrowski et al. (1997, *fide* Mazur et al., 2006) and Google Earth® 2012

Detailed location of nephrite artifacts and references are given in text

major goal of the present research. In order to emphasize the characteristic features of the nephrites, a comparison with some Asian nephrite minerals is given.

Jordanów (Jordanów Śląski) and Złoty Stok are the two oldest-known nephrite deposits in Europe. Before their discovery in the 1880s, all nephrite artifacts were interpreted as raw material imported from distant Asia (Maślankiewicz, 1982; Heflik, 2010). Nephrite was commercially exploited in Jordanów in the 1900s, mostly for small carvings, decorative items (Fig. 2A) and low-valued jewellery, especially cabochon cut (Fig. 2B). However, larger blocks of nephrite were also obtained, e.g., over a two-ton block acquired in 1899 is stored in the Metropolitan Museum, New York (Walendowski, 2008); another block, which weights a few hundred kilograms is exposed in front of the Mineralogical Museum at the University of Wrocław. While Jordanów is among the most important nephrite occurrences in Europe (e.g., Middleton, 2006), the small occurrence at Złoty Stok remains rather less known. Distribution of modern carvings is much narrower. Besides those above, nephrite boulders in Lower Silesia have been found in glacial deposits (Scandinavian provenance), e.g., in the Wrocław city area (Heflik, 1974).

Jordanów (former Jordansmühl) nephrite is found in several localities scattered over a distance of 20 km, especially in the serpentinite quarry in Nasławice and the historical (now abandoned) quarry in Jordanów, where most of nephrite was mined (Traube, 1888; Sachs, 1902; Heflik, 1974, 2010; Maślankiewicz, 1982; Majerowicz, 2006; Middleton, 2006; Łobos et al., 2008; Walendowski, 2008). In Złoty Stok (former Reichenstein) nephrite was discovered in an underground gold and arsenic mine (Traube, 1888; Beutell and Heinze, 1914; Heflik, 1974; Maślankiewicz, 1982), in a gallery named Książęca (Fürstenstollen; Traube, 1888; Beutell and Heinze, 1914), known also as the Piastowska gallery (Heflik, 1974). In the 1400s, the Złoty Stok mine supplied ~8% of total gold production in Europe (Cwojdziński and Kozdrój, 2007). Recent field studies conducted by the author suggest that nephrite distribution is wider and limited not only to the mine gallery.

GEOLOGIC SETTING

Jordanów lies between Wrocław and the border with the Czech Republic, and Złoty Stok is located further south, close to the border. Geologically, the two localities are situated in the NE edge of the Bohemian Massif. Złoty Stok lies in the mountainous part of the Sudetes, while Jordanów – in the strongly peneplained Fore-Sudetic Block (Fig. 1). The Sudetes and the Fore-Sudetic Block are composed of tectono-stratigraphic units, tectonically juxtaposed during the Variscan Orogeny (Mazur et al., 2006). These areas extend between the NW–SE-trending Odra Fault Zone in the north and the Elbe Fault Zone in the south (Kryza et al., 2004). The Sudetic Boundary Fault, parallel to the Odra and Elbe fault zones, separates the Sudetes from the Fore-Sudetic Block.

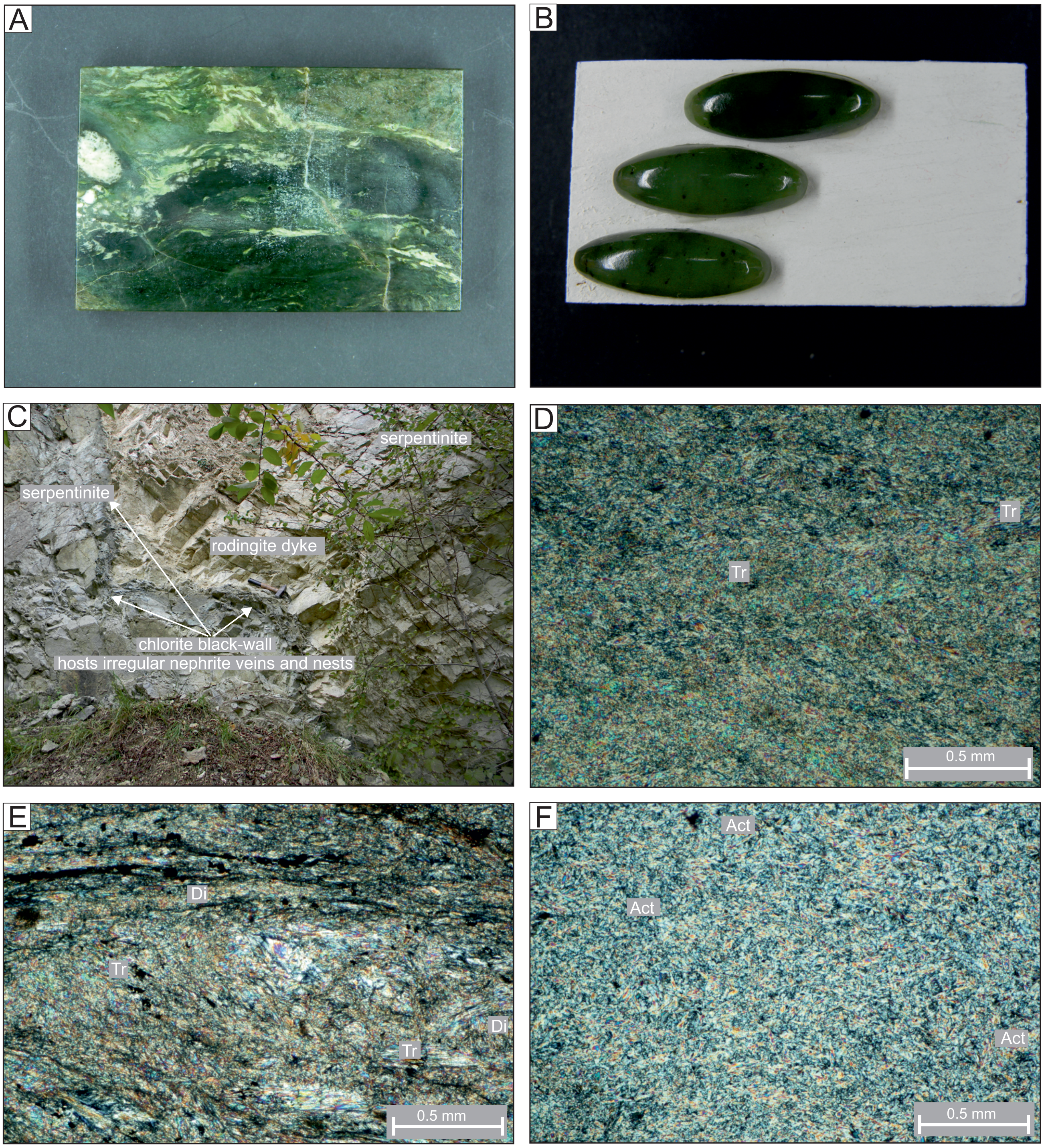

Fig. 2. Nephrite implements (A, B), field photographs (C) and thin-section photomicrographs with crossed polars (D–F)

A – modern decorative soap holder made of Jordanów nephrite (object size ~12 cm); **B** – modern cabochons made of Jordanów nephrite (longest dimension of each cabochon is ~3 cm); **C** – chlorite black wall hosts irregular nephrite veins and nests at the contact of rodingite dyke and serpentinite in the Jordanów Quarry (hammer for scale in the middle of the photograph); **D** – Jordanów nephrite; **E** – Jordanów nephrite schist; **F** – Złoty Stok nephrite; Tr – tremolite, Act – actinolite, Di – diopside

Jordanów and Złoty Stok lie in the Central Sudetes *sensu* Mazur et al. (2006). The Central Sudetes are composed of Neoproterozoic–Early Paleozoic medium- to high-grade metamorphic massifs and units of the Góry Sowie, Orlica, Śnieżnik and Kłodzko, the Silurian-Carboniferous Bardo Sedimentary Unit, the Early Devonian? Central Sudetic Ophiolite, the Niemcza and Skrzynka shear zones, and several small units. The Ślęża Ophiolite is a part of the Central Sudetic Ophiolite – a dismembered unit located at the N, E, S and SW boundary of the Góry Sowie Massif (Mazur et al., 2006; Kryza, 2011). The Niemcza Shear Zone (trending N–S), interpreted as mylonitised Góry Sowie gneisses, and their continuation – the Skrzynka Shear Zone, separates the Góry Sowie and Kłodzko massifs from the Kamieniec Metamorphic Belt and the Śnieżnik Massif

(Mazur et al., 2006). The shear zones, composed predominantly of mylonites, host basic and ultrabasic parts of the Central Sudetic Ophiolite, gneiss, mica schist and marble lenses, and Variscan granitoid dykes.

The Jordanów Quarry (Fig. 3A) is located within serpentinites of the SE margin of the Ślęża Ophiolite, close to the Niemcza Shear Zone in the south and Paleozoic metasediments in the east (e.g., Majerowicz, 2006; Kryza, 2011). Nephrite occurs within chlorite black-wall, at the contact of rodingite dykes and host-serpentinites (Fig. 2C). The orientation of rodingite dykes is from nearly vertical to ~45° dip. Black-wall thickness varies from a few centimetres to about one metre. Nephrite occurs in the form of irregular veins and nests with variable direction and strike. Over a distance of a couple of metres, the dip of the nephrite-bearing zone may change from nearly vertical to horizontal. At present, the exposed nephrite bodies are from a few to ca. 50 cm thick. In the past, elongated bodies were excavated, up to 1.5 m long and about 0.5 m thick. Similar specimens might be found if the quarry is reactivated. Within serpentinites, NW–SE-trending leucogranite veins of variable strike are also present. U-Pb zircon age of serpentinisation is 400 + 4/–3 Ma (Dubińska et al., 2004) and leucogranite veins were dated at 337 ± 4 Ma (zircon U-Pb; Kryza, 2011). The age of leucogranite veins corresponds to that of granitoid veins of the Niemcza Shear Zone (338 +2/–3 Ma) rather than of the Strzegom-Sobótka Granite (~310–294 Ma), NW of Jordanów (Kryza, 2011).

The Złoty Stok mine is located at the NW edge of the Skrzynka Shear Zone, close to the contact with the Kłodzko-Złoty Stok Granite and the Sudetic Boundary Fault (e.g., Cwojdziński and Kozdrój, 2007). Nephrite forms veins between serpentinite and pyroxenite nests within blastomylonites (Beutell and Heinze, 1914; Heflik, 1974, 2010). Adjacent serpentinites are composed of lizardite and chrysotile (e.g., Cwojdziński and Kozdrój, 2007). Unfortunately, the gallery where nephrite was mined collapsed in half way (Fig. 3B), making a detailed field-relations study impossible. K-Ar biotite age of the Kłodzko-Złoty Stok Granite (ca. 298 Ma) probably represents a final stage of consolidation (Bachliński and Bagiński, 2007). Pluton emplacement age is estimated to be 340–310 Ma; granite thermally overprints the Skrzynka Shear Zone blastomylonites, although is postdated by the latest stages of shearing (Mazur et al., 2006).

MATERIALS AND METHODS

Detailed field studies were performed in the Jordanów Quarry and in still accessible part of the Książęca gallery, which was penetrated up to the collapse site. In Jordanów, samples

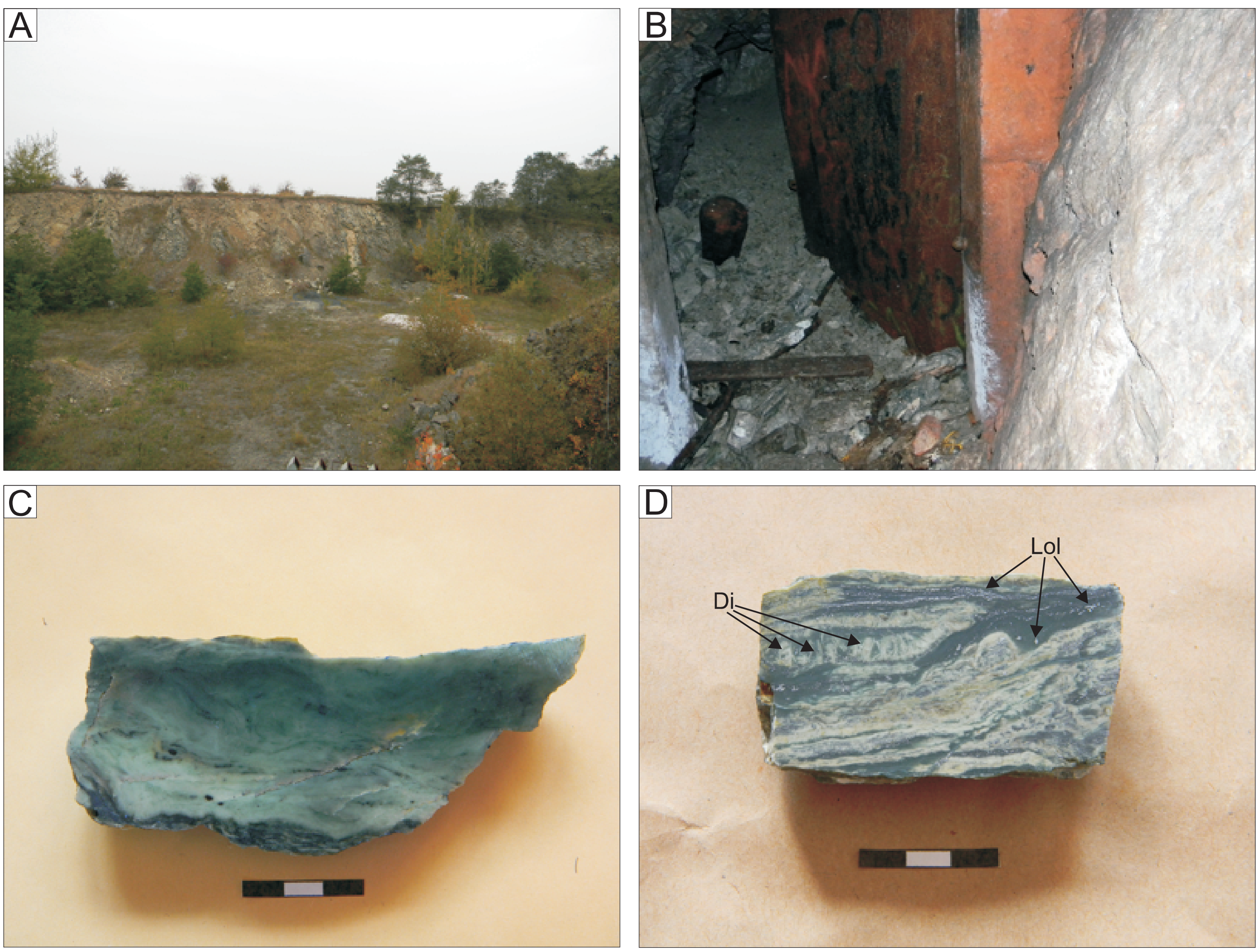

Fig. 3. Field and hand-specimen photographs: A – quarry in Jordanów, B – collapsed Książęca gallery in Złoty Stok (area of photography width is approximately 3 m), C – polished nephrite from Jordanów, D – polished nephrite from Złoty Stok

Scale bar 3 cm, Di – diopside, Lol – löllingite were collected directly from the wall, in Złoty Stok, samples were taken from closed mine dumps and nearby streams. In addition to field-collected samples, nephrite carvings from the collection of Wrocław University Mineralogical Museum were macroscopically examined. Samples were cut and polished to exhibit decorative properties.

Geochemical methods enable identification of the nephrite source area with a high certainty. Recent studies on European nephrite artifacts give opportunities for distinguishing raw material on the basis of whole-rock geochemistry (cf., Kostov et al., 2012). In the present study, chemistry of rock-forming minerals and minor constituents was examined because nephrite museum artifacts are usually valuable and usage of destructive methods is impermissible – there is a possibility to make non-invasive chemical analyses of some minerals using the environmental (ESEM) or low-vacuum (LVSEM) scanning electron microscope with energy-dispersive spectrometer (EDS) (e.g., Hung et al., 2007). Modern electron microscopes allow sample as large as 300 mm in diameter and 110 mm high, and are usually equipped with EDS and wavelength dispersive spectrometer (WDS). However, if the artifact or raw material is large enough and small piece removal is permitted, thin sections can be prepared and studied under petrographic microscope and standard electron microprobe.

Samples collected in the field were thin-sectioned and examined under the *Nikon Eclipse E600 POL* standard petrographic microscope. Mineral chemical composition was obtained under the *Cameca SX 100* (EMPA) electron microprobe with EDS and WDS, at the Microscopy and Microprobe Laboratory of the University of Warsaw (Poland). Analyses were performed at 15.0 kV acceleration voltage, and with 10.0 and 20.0 nA beam current. In case when thin-sectioning is impermissible, a similar analysis can be performed using ESEM/LVSEM. From the obtained results, 96 representative analyses were selected: 18 rock-forming amphiboles and 78 other constituents (29 pyroxenes, 18 chlorites, 18 löllingites, 6 garnets, 3 apatites, 2 Cr-spinels, 1 prehnite and 1 titanite; see Appendices 1 and 2 *). Microprobe analyses were recalculated from oxides in weight percent (wt.%) to atoms per formula unit, following e.g., Leake et al. (1997), or to atomic percent (at.%).

RESULTS

PETROGRAPHY

General appearance of the nephrites is similar to typical nephrites. Jordanów nephrite in hand-specimen reveals a wide spectrum of green colours – from greenish-creamy, through bright green, to dark green. Minor white (Sachs, 1902; Heflik, 1974), pink (Heflik, 1974) and bluish-green (Traube, 1888) zones were also reported. Transparency varies from semitranslucent to opaque. The rock fabric is chaotic or foliated (flat parallel or wavy), usually with green to black chlorite schist (Fig. 3C) and serpentinite, creamy rodingite nests and layers, visible to the naked eye. On polished surface, numerous black spots (mostly opaque spinel) are present, in some parts of rock, they are rare and scattered, in others, they form a nearly spotted texture.

Złoty Stok nephrite is bright to dark green, mostly greyish-green and translucent. Reddish weathering rims were also reported (Beutell and Heinze, 1914). The fabric is chaotic or layered – directional texture being caused by creamy, mostly opaque, clinopyroxenite layers. The unique feature is the presence of large (up to ~2 mm in diameter), silver löllingite crystals with metallic luster (Fig. 3D). Löllingite is scattered in the rock matrix or concentrated in layers. Several specimens reveal another characteristic feature – layers composed of diopside megacrysts aggregates, each crystal up to ~1 cm long.

Jordanów nephrite shows usually a typical, non-directional fabric, i.e., close intergrowths of fine and very fine tremolite fibers (Figs. 2D and 4A, B). However, larger tremolite porphyroblasts also occur (Fig. 4A). Foliated zones are also present, with flat parallel (Fig. 4C) or folded layers (Fig. 4D). Prehnite veins (Fig. 4D) with pink and blue interference colours are the diagnostic textural (and mineralogical) feature. Characteristic chlorite nests with an interlocking non-pseudomorphic texture (Fig. 4B) *sensu* Wicks and Whittaker (1977), and rotated and cataclased diopside porphyroblasts with chlorite-amphibole pressure shadows (Fig. 4C) are observed as well. Some chlorite layers contain zircon crystals with pleochroic haloe (Fig. 4E). Apatite crystals containing monazite inclusions can be identified (Fig. 4G).

The major constituents are tremolite, diopside and chlorite group minerals – mostly penninite, minor clinochlore and diabantite. Minor constituents include grossular, prehnite and opaque spinel (chromite-magnetite solid solution). Accessory phases are antigorite, hydrogrossular, titanite, zircon, apatite and monazite. Altered zones are rich in clay minerals and opaque oxides. Grossular and hydrogrossular show no clear spatial relations; both occur as single isometric or elongated grains or are concentrated in aggregates. Their intergrowths are also present, and hydrogrossular seems to have formed at the expense of grossular. In the sense of Simandl et al. (2000), Jordanów nephrite can be divided into nephrite *sensu stricto* (Fig. 2D) and nephrite schist (Fig. 2E). Nephrite is composed of tremolite (87.2–89.8 vol.%), diopside (4.7–5.7 vol.%), chlorite (3.8–8.1 vol.%), spinel (from trace to 0.2 vol.%) and grossular (from absent to 0.5 vol.%). Nephrite schist (foliated zones, petrographically corresponding to semi-nephrite) is composed of tremolite (33.5–79.7 vol.%, in transition to rodingite and chlorite schist dropping to 11.4 vol.%), diopside (7.4–55.1 vol.%), chlorite (5.0–38.9 vol.%), Cr-spinel (from trace to 4.2 vol.%), grossular (from trace to 10.8 vol.%), prehnite (from absent to 0.5 vol.%), titanite (from trace to 0.8 vol.%) and clay minerals-oxides aggregates (from trace to 9.7 vol.%). The most common is a transition from nephrite to nephrite schist in single specimens, which decreases stone's gem quality.

Złoty Stok nephrite also shows typical internal, non-directional fabric, although is composed of actinolite (Fig. 2F). However, larger actinolite porphyroblasts, euhedral diopside megacrysts (Fig. 4F), and granular clinopyroxenite nests (some cut by thin nephrite veins, similar to whole rock) are also present.

The major constituents are actinolite and diopside, minor constituent is löllingite – iron arsenide (Fig. 4F, H, I). Accessory phases were detected in some samples only; these are carbonates (dolomite and calcite) and quartz. Small number of constituents is characteristic to this deposit. In the sense of Simandl et al. (2000), Złoty Stok nephrite represents nephrite *sensu stricto* (Fig. 2F), with the amount of actinolite above 90 vol.%. However, if considered together with clinopyroxenite layers – the thickness of nephrite layers is up to ~7 cm (e.g., Traube, 1888), usually less (separation is often impossible) – composition is similar to semi-nephrite. The term nephrite schist cannot be used due to lack of schist fabric. Nephrite/clinopyroxenite inter-

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1101

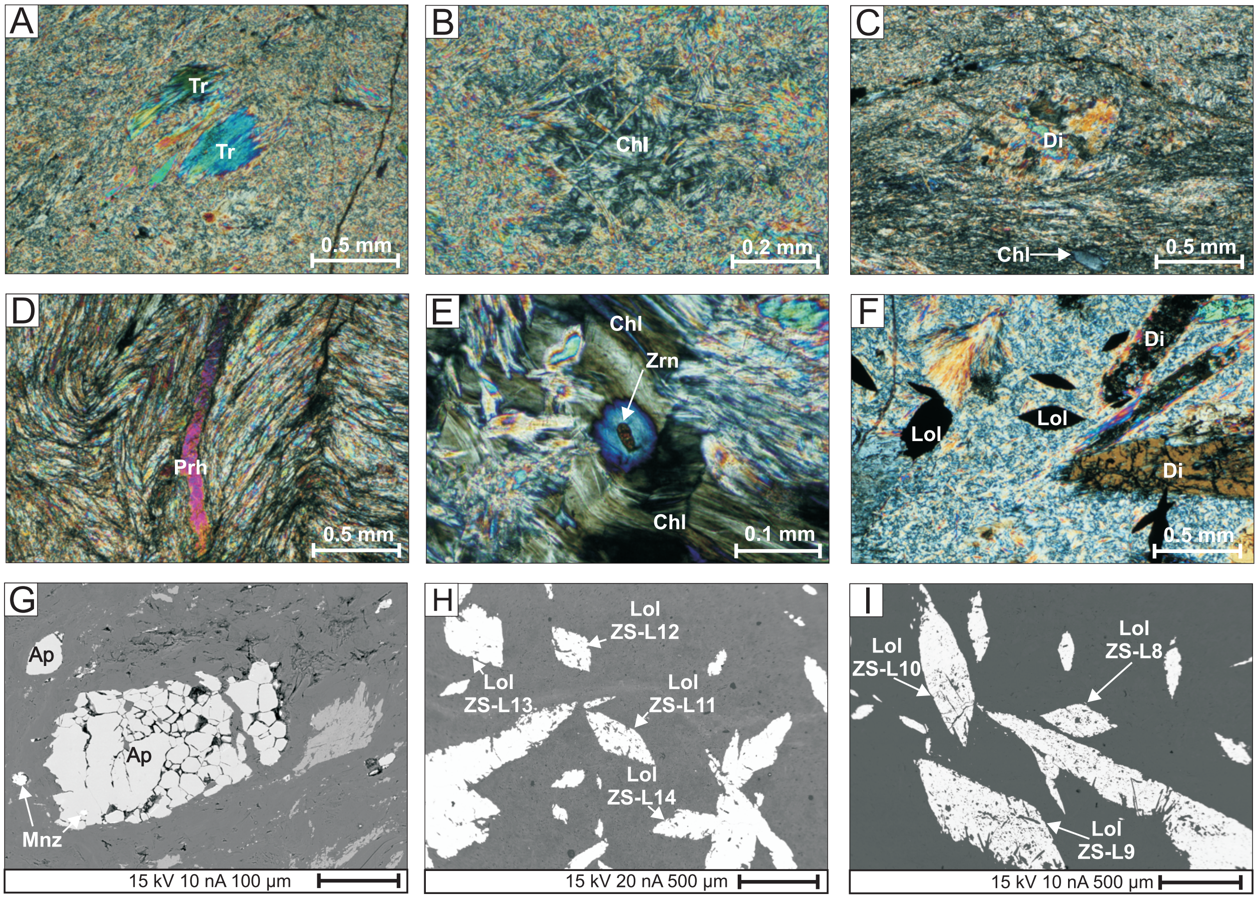

Fig. 4. Thin-section photomicrographs with crossed polars (A–F) and back-scattered electron (BSE) images (G–I) of studied nephrites

A – Jordanów (JR) – tremolite porphyroblasts in fine-grained tremolite groundmass; **B** – (JR) chlorite nest with interlocking texture; **C** – (JR) rotated and cataclased diopside porphyroblast with chlorite-amphibole pressure shadows and a single chlorite grain; **D** – (JR) prehnite vein cutting folded, layered nephrite; **E** – (JR) chlorite with zircon inclusion surrounded by pleochroic haloe; **F** – Złoty Stok (ZS) löllingite grains and euhedral diopside megacrysts; **G** – (JR) apatite with minor monazite inclusion; **H**, **I** – (ZS) löllingite grains; Ap – apatite, Chl – chlorite, Di – diopside, Lol – löllingite, Mnz – monazite, Prh – prehnite, Tr – tremolite, Zrn – zircon; löllingite crystal numbers correspond with Appendix 2

layers are composed of actinolite (54.6–58.0 vol.%), diopside (30.5–37.3 vol.%) and löllingite (8.1–11.5 vol.%).

MINERAL CHEMISTRY

Amphibole. The composition of amphibole (Leake et al., 1997) from Jordanów nephrite classifies it as tremolite. The chemical composition is as follows: SiO_2 (55.8–58.8 wt.%), CaO (13.2–13.7 wt.%), MgO (20.4–23.1 wt.%), total Fe as FeO (2.5–3.8 wt.%) and significant Al_2O_3 (0.1–3.3 wt.%) (Appendix 1), Si from above 7.7 to near 8.0 apfu (atoms per formula unit), and Mg/(Mg + Fe^{2+}) from 0.90 to 0.95. In contrast, the composition of amphibole (Leake et al., 1997) from Złoty Stok nephrite classifies it as actinolite (Fig. 7) composed of SiO_2 (56.6–57.7 wt.%), CaO (11.5–13.1 wt.%), MgO (19.1–21.9 wt.%), total Fe as FeO (4.4–8.4 wt.%) (Appendix 2), Si ca. 8 apfu. and Mg/(Mg + Fe^{2+}) from 0.8 to 0.9.

Clinopyroxene. The composition of clinopyroxene from Jordanów classifies it as diopside (Morimoto et al., 1988) composed of SiO_2 (53.6–56.5 wt.%), CaO (23.6–26.2 wt.%), MgO (14.9–17.8 wt.%), total Fe as FeO (1.6–5.7 wt.%), Al_2O_3

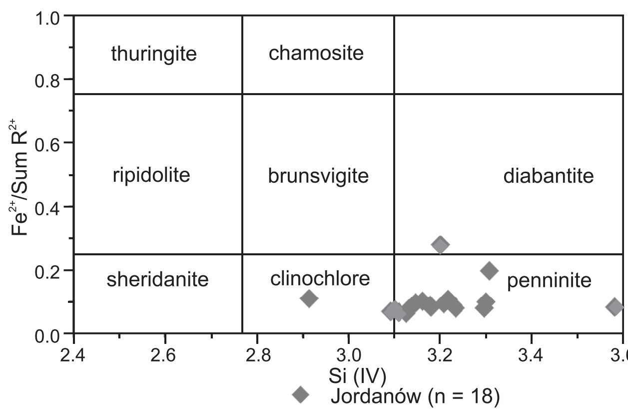

Fig. 5. Chlorites from Jordanów nephrite plotted on Foster's diagram (1962, *fide* Esteban et al., 2007)

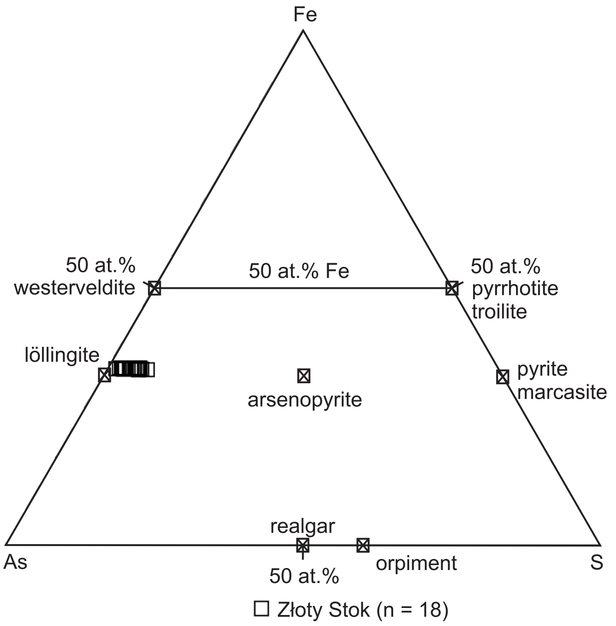

Fig. 6. Opaque minerals from Złoty Stok nephrite plotted on classification diagram after Fleet and Mumin (1997)

(0.01–2.0 wt.%) (Appendix 1), wollastonite component (47–51% $Ca_2Si_2O_6$), clinoenstatite (41–48% $Mg_2Si_2O_6$) and clinoferrosilite (3–9% $Fe_2Si_2O_6$). The composition of the least calcic clinopyroxenes is still diopsidic, although close to augite. The most calcic ones plots slightly above the diopside field (Fig. 8). However, these are diopsides rather than pyroxenoids (cf. Morimoto et al., 1988). The composition of clinopyroxene from Złoty Stok classifies it also as diopside (Morimoto et al., 1988) composed of SiO_2 (54.5–55.1 wt.%), CaO (25.1–25.4 wt.%), MgO (15.7–16.4 wt.%), total Fe as FeO (1.7–3.0 wt.%) (Appendix 2), wollastonite component (~51%), clinoenstatite (44–46%) and clinoferrosilite (3–5%). The sample plots slightly above the diopside field (Fig. 8), similar to some analyses from Jordanów.

Chlorite. According to Foster's diagram (1962, *fide* Esteban et al., 2007), majority of chlorite plot as penninite, only two samples plot as clinochlore and one sample – as diabantite (Fig. 5). Chlorites are composed of SiO_2 (30.9–38.6 wt.%), Al_2O_3 (13.4–20.4 wt.%), MgO (24.4–33.9 wt.%), total Fe as FeO (4.0–17.1 wt.%), CaO from below detection limit to 2.6 wt.% (Appendix 1), Si (IV) from 2.9 to near 3.6, and Fe^{2+}/Sum R^{2+} from 0.05 to 0.3.

Spinel, grossular, apatite, titanite, prehnite. The chemical composition of minor constituents and accessory phases of Jordanów nephrite is presented in Appendix 1. Spinel (chromite-magnetite solid-solution) is composed of Cr_2O_3 (46.7–47.0 wt.%), Fe_2O_3 (14.9–16.5 wt.%), FeO (25.9–27.5 wt.%), Al_2O_3 (3.5–4.1 wt.%), ZnO (0.8–1.0 wt.%), with Cr/(Cr + Al) ratio about 0.9. The FeO and Fe_2O_3 contents were calculated by charge balance, assuming the ideal stoichiometry, using the *Cameca SX 100* routine. Grossular garnet is composed of SiO_2 (38.6–40.8 wt.%), Al_2O_3 (21.2–22.3 wt.%), Fe_2O_3 (0.5–1.2 wt.%), CaO (35.6–38.0 wt.%), other components are below 1 wt.%, with Mg/(Mg + Fe) ratio from 0.05 to 0.65, and Ca/(Ca + Mg) close to 1. Apatite is composed of CaO (54.9–56.5 wt.%), P_2O_5 (41.8–43.4 wt.%), and F (2.0–2.1 wt.%). From a single titanite analysis, the following composition was obtained: SiO_2 (31.2 wt.%), TiO_2 (40.2 wt.%), CaO (27.5 wt.%), and FeO (1.1 wt.%). Single prehnite analysis resulted in the following composition: SiO_2 (43.9 wt.%), Al_2O_3 (24.7 wt.%), and CaO (27.8 wt.%).

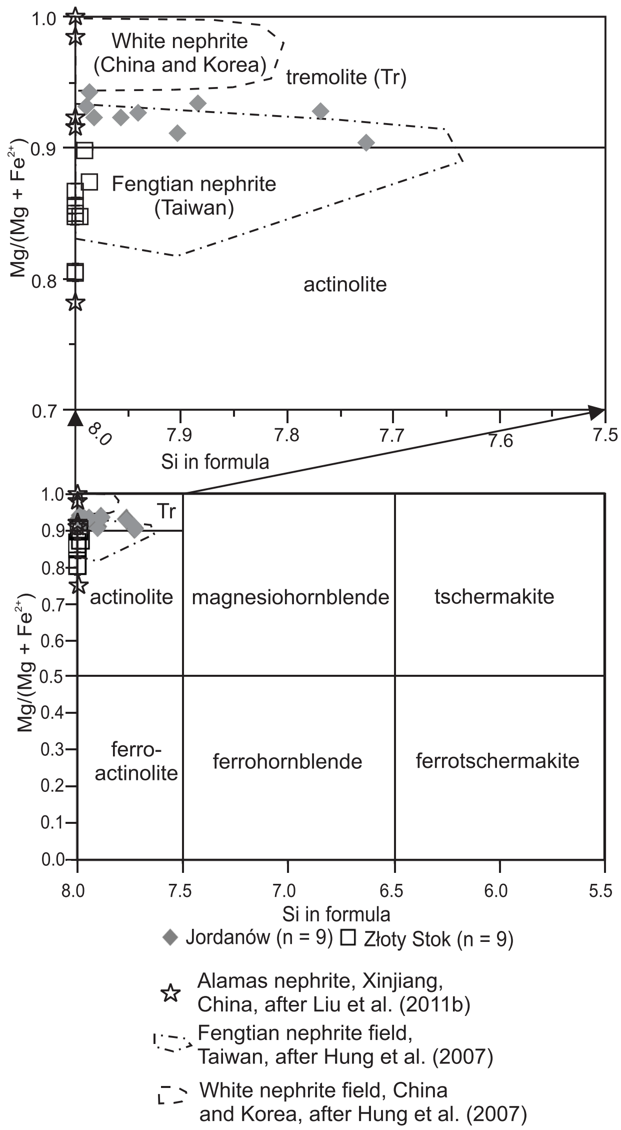

Fig. 7. Comparison of amphiboles from Jordanów and Złoty Stok, and from Taiwan, Chinese and Korean nephrites, presented on diagram after Leake et al. (1997)

Alamas nephrite (Xinjiang, China) after Liu et al. (2011b); Fengtian nephrite (Taiwan) and white nephrites from China and Korea after Hung et al. (2007)

Löllingite. Opaque minerals from Złoty Stok nephrite, following Fleet and Mumin (1997), are classified as löllingite (Fig. 6), although the composition varies from nearly pure löllingite to löllingite with a noticeable marcasite admixture, which has the same structure (O'Day, 2006). Löllingite is composed of Fe (28.0–29.0 wt.%), As (67.6–70.5 wt.%), S (0.7–3.4 wt.%) and trace elements. It is interesting that löllingite analyses reveal Au from below detection limit to 0.2 wt.% (Appendix 2). However, gold is sparse, this is the so-called invisible gold (Bark and Weihed, 2007; Kovalev et al., 2011).

DISCUSSION

Compared to the fabric of Złoty Stok nephrite, which is non-directional (chaotic), the fabric of Jordanów nephrite is chaotic or foliated (flat-parallel or folded). In Jordanów, veins composed of prehnite are characteristic. In Złoty Stok, the most characteristic is löllingite, distinguishable by the naked eye, and diopside megacrysts aggregates. In Jordanów, both nephrite and nephrite schist are present, in Złoty Stok only nephrite is found. Jordanów nephrite contains a wider spectrum of minor constituents and accessory phases – chlorites, antigorite, grossular, hydrogrossular, prehnite, opaque spinel, titanite, apatite, monazite and zircon, in contrast to Złoty Stok, where only löllingite, carbonates and quartz were identified.

Jordanów nephrite is composed of tremolite, in contrast to Złoty Stok nephrite built of actinolite. Si apfu in the formula unit in Złoty Stok is higher (ca. 8) as compared to Jordanów (7.7–8.0). Amphiboles from Jordanów are similar to tremolite from Fengtian nephrite, Taiwan (Hung et al., 2007), whereas Złoty Stok amphiboles are comparable with Alamas nephrite actinolite (Xinjiang, China; see Fig. 7) due to the similar Si apfu. Moreover, the Mg/(Mg + Fe^{2+}) ratio in Złoty Stok is intermediate between Alamas actinolite nephrite (after metasomatized serpentinite) and tremolite nephrite (after dolomite) presented by Liu et al. (2011b). Both studied amphiboles also clearly differ from the so-called white nephrite (dolomite-related deposits) from China and Korea (Hung et al., 2007; Liu et al., 2011b).

Clinopyroxenes from both occurrences belongs to diopside, typical to majority of deposits, e.g., Hetian (Xinjiang, NW China; Liu et al., 2011a) and Alamas, Xinjiang (Liu et al., 2011b). However, some of Jordanów samples shown in Figure 8 are slightly enriched in $Mg_2Si_2O_6$ (up to 48 vs. 46% in Złoty Stok) and $Fe_2Si_2O_6$ (up to 9 vs. 5% in Złoty Stok). Jordanów nephrite is characterized by the presence of rotated and cataclased diopside porphyroblasts with pressure shadows, whereas in Złoty Stok, euhedral diopside megacrysts and fine, granular pyroxenite nests are typical.

Chlorites were identified only in Jordanów nephrite, their composition corresponds to penninite, sporadically to clinochlore and diabantite. The chlorites show higher Si contents than clinochlore from Chuncheon nephrite, Korea (Yui and Kwon, 2002). Chlorites from Jordanów also show lower Fe and higher Si contents than chlorites from a similar geologic setting

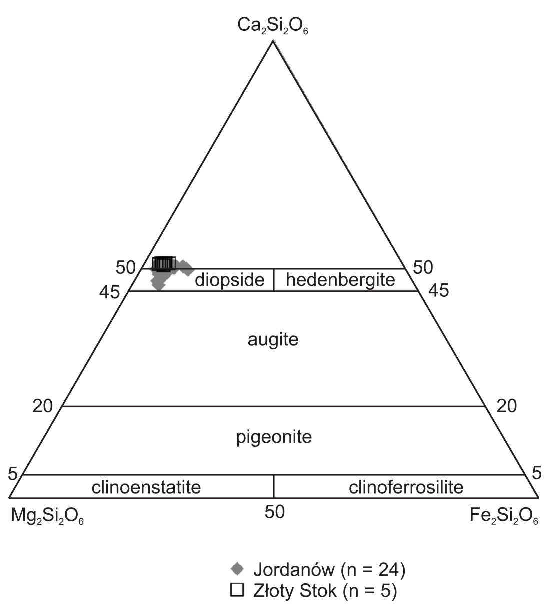

Fig. 8. Clinopyroxenes composition from Jordanów and Złoty Stok nephrites, presented on diagram after Morimoto et al. (1988)

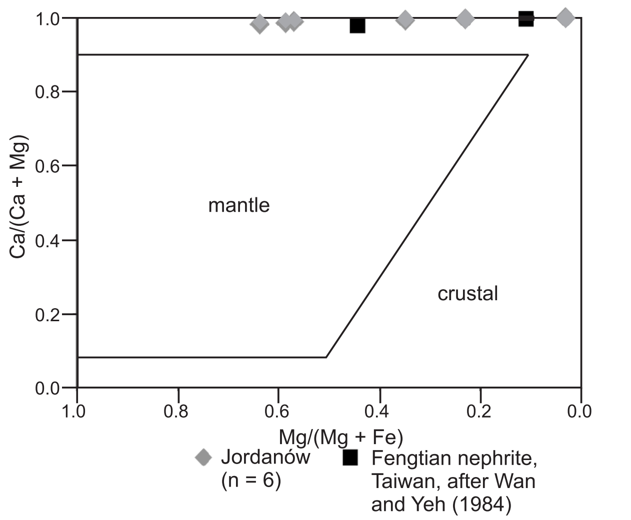

Fig. 9. Comparison of garnets from Jordanów and Taiwan nephrites presented on Schulze's (2003) diagram

Fengtian nephrite (Taiwan) after Wan and Yeh (1984)

in Southern Spain – mostly ripidolite, brunsvigite and clinochlore (Esteban et al., 2007).

Grossular from Jordanów nephrite, presented on a discrimination diagram after Schulze (2003), plots in the typical crustal-derived garnets field (Fig. 9). It indicates its genetic relations with rodingitization and serpentinization rather than with a host-rock mantle protolith. The calculated Ca/(Ca + Mg) (close to 1) and Mg/(Mg + Fe) (0.05–0.65) ratios correspond to garnets from Fengtian nephritan, Taiwan, given by Wan and Yeh (1984), with values close to 1 and from 0.1 to 0.5, respectively.

Opaque spinel from Jordanów represents a chromite-magnetite solid solution. Figure 10 shows a plot of Cr/(Cr + Al) vs. ZnO (Hung et al., 2007), hereafter spinel from Jordanów is similar to Nanshan nephrite (China), and comparable to Chara Jelgra nephrite (Siberia, Russia) and Fengtian nephrite (Taiwan). However, a larger number of analyses are required to use this method more precisely.

Złoty Stok is probably the only one nephrite deposit worldwide with significant amounts of löllingite, and probably among a few (maybe even two) gold-bearing nephrites – the other is in Siskiyou County, California (Sinkankas, 1959). The absence of pyrite and arsenopyrite, which are common in the surrounding rocks (e.g., Muszer, 1988; Niśkiewicz, 1988), in conjunction with the presence of löllingite, suggests ore minerals (and perhaps whole nephrite) formation at the temperature of 500–650°C (Gil, 2011).

CONCLUSIONS

The present description of Polish nephrites allows their identification by means of petrographic and chemical analyses of constituting minerals. It can be complementary when applied with a method of nephrite identification based on whole-rock geochemistry given by Kostov et al. (2012), or other methods.

Accurate identification of Jordanów nephrite can be managed based on the combination of features given below. Fabric and composition assign it to nephrite *sensu stricto* or nephrite schist. Chlorite schist, rodingite and serpentinite intercalations are visible by the naked eye, although are not always present.

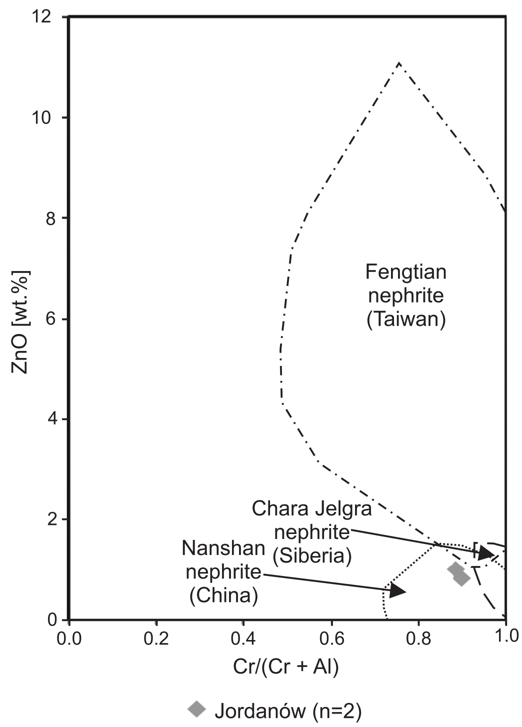

Fig. 10. Variation of Cr/(Cr + Al) vs. ZnO in spinels from Jordanów, and from Fengtian (Taiwan), Chara Jelgra (Siberia, Russia) and Nanshan (China) nephrites

Diagram and data for comparison after Hung et al. (2007)

The nephrite is composed of tremolite, similar to Fengtian nephrite tremolite (Taiwan), with the Si content from 7.7 to 8.0 apfu. Other major constituents are diopside and chlorites. Minor and accessory phases include grossular, hydrogrossular, prehnite, antigorite, opaque spinel (chromite-magnetite solid solution), titanite, apatite, monazite and zircon. Grossular and hydrogrossular occur as single isometric or elongated grains or aggregates, or intergrowths of both, and show no clear spatial relations. Hydrogrossular seems to be formed at the expense of grossular. A typical form is diopside represented by rotated and cataclased porphyroblasts with chlorite-amphibole pressure shadows, prehnite veins, and layers and nests composed of chlorite group minerals. Chlorite corresponds to penninite, sporadically to clinochlore and diabantite. Some chlorite nests show an interlocking non-pseudomorphic texture. Chlorite often contains zircon inclusions with pleochroic haloe. Moreover, apatite contains monazite inclusions. Crustal-derived grossular garnet is present, likewise in Fengtian nephrite (Taiwan). The spinel composition is similar to that of Nanshan nephrite (China).

Złoty Stok nephrite can be identified with high plausibility during careful macroscopic examination, based on the occurrence of löllingite distinguishable by the naked eye. However, löllingite is not always present. To allow distinguishing less characteristic samples, other additional features are used. Fabric and composition assign the specimen to nephrite *sensu stricto*, although if nephrite piece is removed together with clinopyroxenite, average compositon refers to semi-nephrite. The nephrite is composed of actinolite, comparable with Alamas nephrite actinolite (Xinjiang, China), with the Si content of ca. 8.0 apfu. Other major and minor constituents are diopside and löllingite. Accessory phases are carbonates and quartz. Diopside forms granular clinopyroxenite nests (some cut by actinolite veins similar to whole nephrite) and euhedral megacrysts. Some of megacrysts are visible by the naked eye. The löllingite composition varies from nearly pure phase to a löllingite-marcasite solid solution. This is one of few gold-bearing nephrites worldwide.

It is probable that nephrite artifacts found in archaeological sites in Europe, e.g. in Poland, Bulgaria, Switzerland and Italy, originate from the Polish source of raw material. In particular, features of artifacts from Poland, SW Bulgaria, Sardinia and S Italy should be compared with characteristic features of nephrites presented in this paper, because the source area of all artifacts is still unknown. The analytical methods presented herein should be applied to other European and, if possible, Western Eurasian nephrite deposits, which gives new capabilities in archaeometric studies.

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