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Joints and mineral veins during structural evolution: case study from the Outer Carpathians (Poland)

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This paper focuses on mineral veins hosted in small-scale fractures within the Tertiary sandstones of the Magura nappe (Outer Carpathians). Joints, faults and tension gashes record three successive stages of the nappe structural evolution: (1) synsedimentary folding and thrusting, (2) regional rotation and (3) late-orogenic collapse. The flow of mineral-bearing fluids was channelized by small-scale fractures resulting in calcite and quartz-calcite veins. Folding: columnar calcite formed the most common filling of early joints and the joints-related tension gashes and strike-slip faults. The mineralisation was restricted to sandstones containing primary carbonates. Rotation: precipitation of columnar and fibrous calcite was largely restricted to joints reactivated as strike-slip faults. Collapse: the collapse-related mineralisation is the most abundant. Wide-spread fluid flow was channelized by normal faults resulting in fibrous calcite and quartz-calcite along these faults whereas several blocky and drusy calcite generation and single high temperature quartz-calcite assemblage precipitated in numerous adjoining joints.

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Key words: Outer Carpathians, mineral veins, joints, fluid inclusions, fold-and-thrust belts.

INTRODUCTION

Joints are the most common tectonic structures. In some areas, they are early features recording the stress arrangement which occurred during sedimentation. Furthermore, joints can be transformed into faults or tension gashes, thus recording complete structural evolution. In addition, the flow of fluids is largely channelized by joints and other fractures into which joints were transformed. Resulting mineral veins record fluid composition, their pressure-temperature condition as well as stress arrangement during their formation. We will document development of these veins during structural evolution of fold-and-thrust belts, using Polish segment of the Outer Carpathians as an example. Moreover, we will show, that the early synsedimentary joints had overwhelming control on distribution of the veins during subsequent structural evolution.

This paper presents results of the first regional study of fracture mineralisation undertaken in the Polish segment of the Outer Carpathians. The pilot results of this study have been already published elsewhere (Świerczewska *et al.*, 1998, 1999; Tokarski *et al.*, 1999).

REGIONAL SETTING

The Polish segment of the Outer Carpathians is a north-verging fold-and-thrust belt composed largely of Lower Cretaceous to Lower Miocene flysch arranged into several nappes. This paper is focussed on origin of calcite and quartz-calcite veins hosted in joints and small-scale faults within the Tertiary sandstones of the central part of the Magura nappe — innermost nappe of the Polish segment of the Outer Carpathians (Fig. 1).

During the Tertiary times, this nappe underwent three successive stages of deformation. At the onset, the nappe was formed at an accretionary prism related to southward directed subduction (Tomek and Hall, 1993) resulting in north-verging synsedimentary folding and thrusting (Świerczewska and Tokarski, 1998; Tokarski and Świerczewska, 1998). This stage was followed either by major clockwise rotation of the regional stress field (Aleksandrowski, 1985; Decker *et al.*, 1997) or major anticlockwise rotation of the belt (*cf.* Marton *et al.*, 1999) resulting in wide-spread fold-parallel strike-slip faulting (*cf.* Decker *et al.*, 1997). The tectonic development was accom-

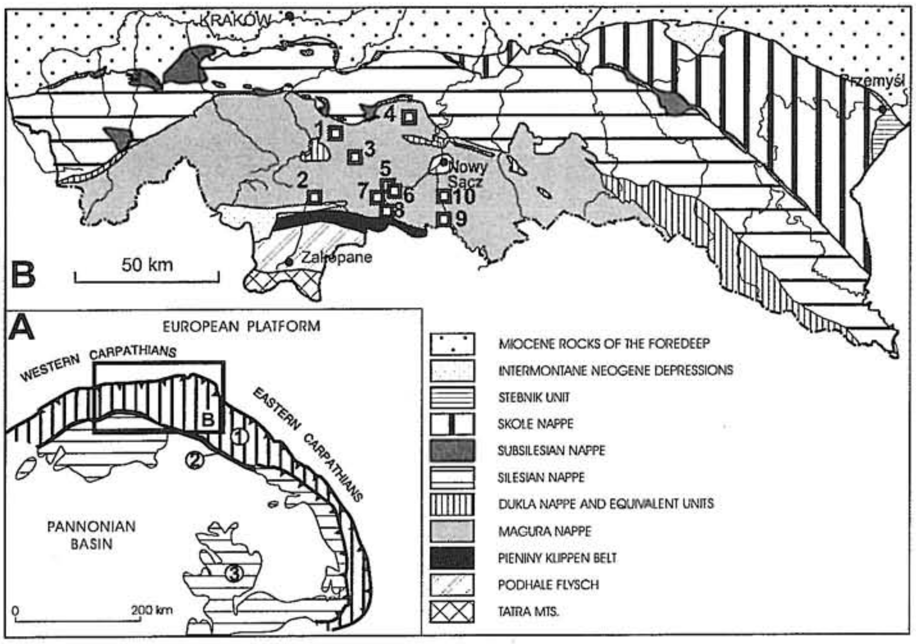

Fig. 1. Geological map of the Polish segment of the Carpathians (after Książkiewicz, 1972)

A: 1 — Outer Carpathians, 2 — Pieniny Klippen Belt, 3 — Inner Carpathians; B: studied exposures marked by squares

plished by regional collapse of the nappe marked by normal faulting (Decker *et al.*, 1997).

DATA AND METHODS

Field observations in 10 exposures (Fig. 1B) were combined with optical microscopy analysis comprising cathodoluminescence and study of fluid inclusions. Field work comprised standard structural analysis of joints, faults and tension gashes, and sampling. Special emphasis was put on collection of oriented samples of veins with different successions of mineralisation.

Standard petrographic studies of veins comprised analysis and microstructural analysis in 151 thin sections. Thin sections were cut out perpendicular to walls of joints and tension gashes and to limbs of minor faults. The latter are oriented also parallel to direction of movement along the faults. Two kinds of kinematic indicators in veins were studied: (1) strain increment patterns (*cf.* Durney and Ramsay, 1973; Beach, 1977; Cox, 1987; Petit, 1987; Fisher and Byrne, 1990; Wilson 1994) and (2) orientation of host rock inclusions (Urai *et al.*, 1991; Dunne and Hancock, 1994). Cathodoluminescence analyses were undertaken for 35 thin sections to determine scenarios of fracture filling. For 21 samples fluid inclusion analyses were done to ascertain composition, temperature, salinity and pressure of fluids during mineral formation.

EXPOSURE-SCALE PATTERNS OF JOINTS

In this paper we define joint as a fracture on which we have not observed any offset. In the study area, in particular exposures we have observed 2–5 sets of joints (Fig. 2) comprising cross-fold joints (T and two sets of D joints: D_1 and D_2) and fold-parallel joints (L and L'). The cross-fold joints are early, synsedimentary features (Tokarski and Świerczewska, 1998). In the study area, architecture of the cross-fold joints is controlled by thickness of the host sandstones. Within thin-bedded sandstones only D joints occur or predominate (Fig. 2B: 3, 4, 8–10), whereas in thick-bedded sandstones only T joints occur or predominate (Fig. 2B: 1, 2, 6). The cross-cutting relationships indicate that the fold-parallel joints usually post-date the cross-fold joints.

FRACTURE MINERALISATION

Joints are filled by columnar (CC), blocky (BC) and drusy (DC) calcites as well as by calcite-quartz (CQ) resulting in simple or composite veins (Fig. 3). The simple veins are composed of CC (Figs. 3A and C), BC (Figs. 3A and B) or DC (Fig. 3B). In composite veins, the following succession of the mineralisation can be observed: from CC to BC to CQ to DC or BC (Figs. 3C and 4A). Quartz overgrowths (QO) are developed around

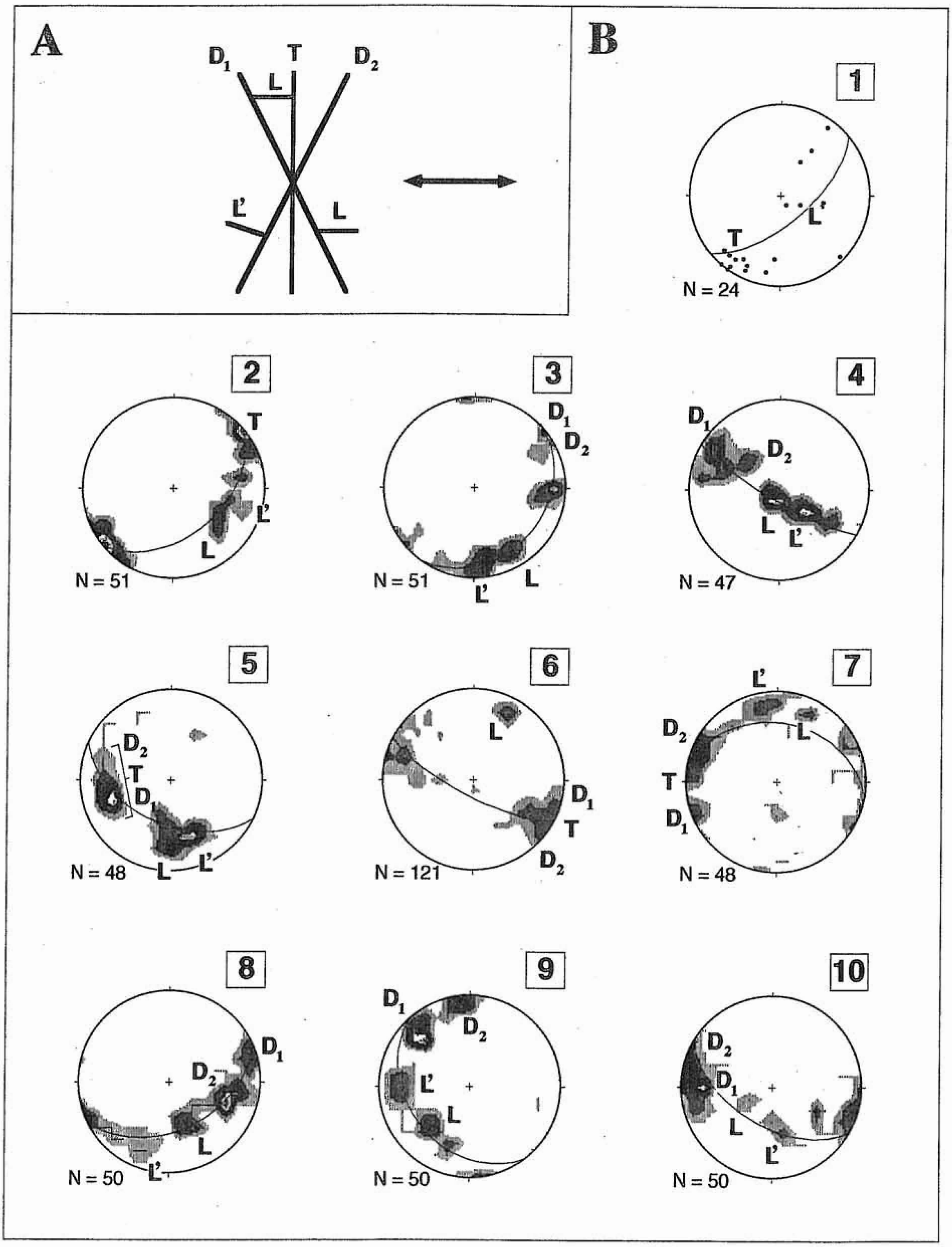

Fig. 2. **A.** Spatial relationships between joints, cartoon drawn in the plane of bedding; **B.** Joints in studied exposures, lower hemisphere plots

T, D$_1$, D$_2$ — cross-fold joints; L, L' — fold-parallel jonts; double arrow mark orientation of fold axis; for location see Fig. 1

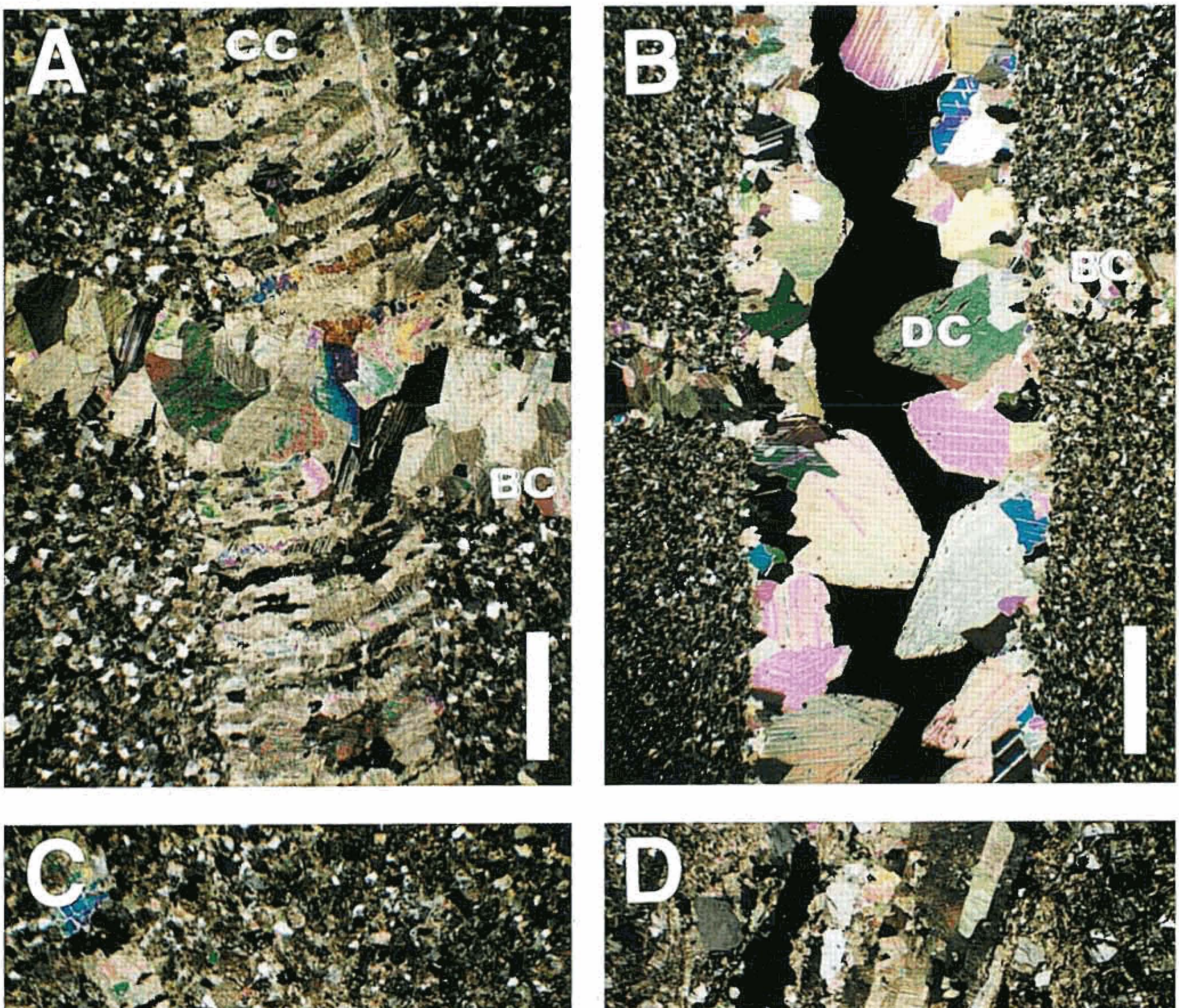

Fig. 3. Microstructures in mineral veins; photomicrographs, nicols crossed, scale bars are 1 mm long

A — simple veins; horizontal vein following D_2 joint and composed of blocky calcite (BC) cuts vertical vein following L joint and composed of columnar calcite (CC); exposure 8; **B** — simple veins; vertical tension gash following D_2 joint and filled by drusy calcite (DC) cuts horizontal vein following L joint and composed of blocky calcite (BC); exposure 3; **C** — transformation of D_2 joint into tension gash, horizontal asymmetric composite vein following D_2 joint and filled by columnar calcite with crystals perpendicular to walls of the vein (CCP) (external part), columnar calcite with crystals oblique to walls of the vein (CCO) (internal part) and blocky calcite and quartz (CQ) (innermost part) and inclined simple vein following L' joint and filled by columnar calcite (CC); the simple vein penetrates the CCP of the composite vein (arrow), however, the simple vein is cut by the CCO and CQ of the composite vein; exposure 8; **D** — fibrous quartz and calcite (FCQ) in microfault following D_1 joint, exposure 7; for location see Fig. 1

detrital grains exposed in walls of some joints. The QO are superimposed by BC (Fig. 4B). Fibrous calcite (FC) and fibrous quartz and calcite (FCQ) (Fig. 3D) are observed in small-scale faults. CC occurs only in veins hosted in the sandstones containing primary carbonate cement while the QO have been recorded only in sandstones devoid of this cement. Remaining textural types of calcite and quartz occur in both types of sandstones.

SUCCESSION OF MINERALISATION AND TRANSFORMATION OF JOINTS

Columnar calcite with crystals oriented either perpendicular (CCP) or oblique (CCO) to walls of the veins was observed in joints of all sets, in fault-related riedel shears and in tension gashes related to T and D_2 joints (Fig. 2). In veins, the inclusion trails of the host sandstone are parallel, subparallel or oblique to the vein margins. The orientation of oblique trails and curved in shape crystals show following senses of the strike-slip movement during growth of crystals (*cf.* Cox, 1987; Urai *et al.*, 1991): (I) conjugated coeval dextral and sinistral movement on D_1 and D_2 joints respectively, sinistral movement on L and L' joints and, (III) dextral movement on D_2 joints.

Cross-cutting relationships indicate that: (I) CCP in D_1 joints is coeval to that in the D_2 joints, (II) CCP in L and L' joints is younger than that in D joints (Fig. 3C), (III) CCO in L, L' and D_2 is younger then CCP (Fig. 3C), (IV) CCO in D_1 joints is coeval to that in the D_2 joints, (V) CCO related to riedel shears cuts CCP in joints.

BC, DC and CQ have been observed in joints of all sets. Some BC contains infrequent inclusion trails of host sandstone. The trails are oriented under low angle to vein walls, showing oblique opening of the joints during BC precipitation. Cross-cutting relationships indicate that: (I) single BC and CQ veins cut CC veins (Fig. 3A) and (II) simple DC veins cut veins of all other types (Fig. 3B).

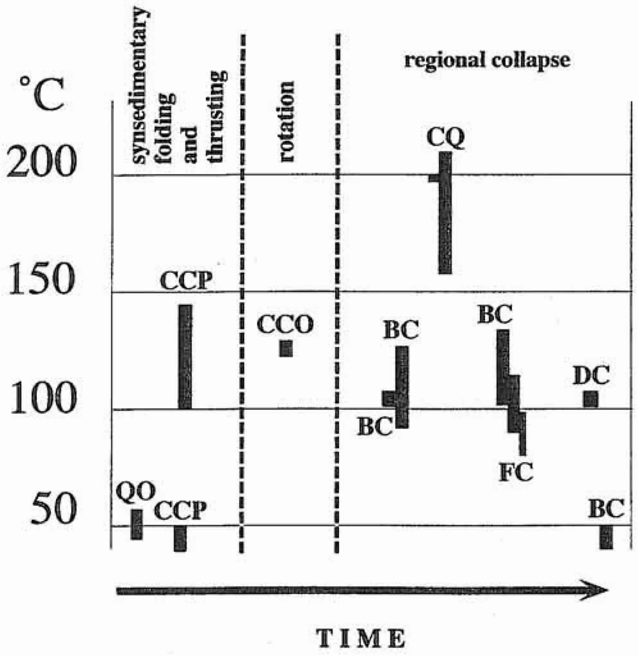

Fig. 5. Thermal data derived from homogenisation temperatures of fluid inclusions

Explanations as for Figs. 3 and 4

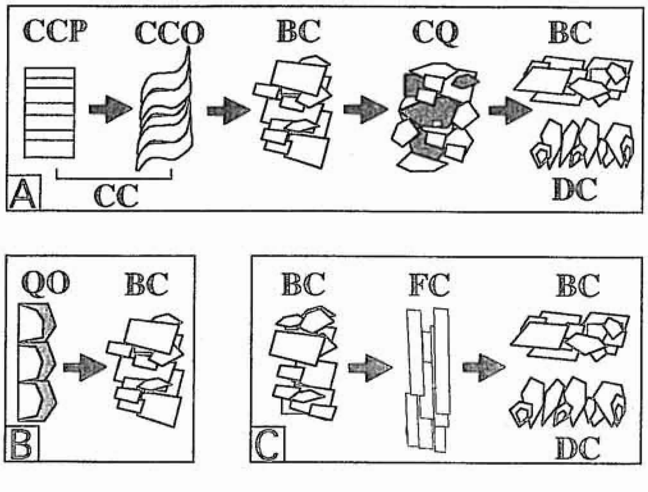

Fig. 4. Sketch of mineral successions (A–C) in fractures

QO — quartz overgrowth, CQ — blocky calcite and quartz, FC — fibrous calcite; for other explanations see Fig. 3 and text

Synkinematic FC and FCQ have been observed in small-scale faults. Some of these faults were transformed from mineralised D and T joints. In these settings (Fig. 4C), we have observed that during the transformation, BC fillings of the joints have been crushed and overprinted by FC. On some faults, FC is overgrown by BC and/or DC. The FCQ is coeval with CQ mineralisation of joints.

FLUID INCLUSION DATA

Aqueous fluid inclusions have been observed in quartz overgrowths (QO) in calcite (CC, BC and DC) and in calcite-quartz (CQ). Some calcites coexisting with quartz (CQ) contain also methane inclusions. Quartz (CQ)-hosted fluid inclusions have trapped a heterogeneous immiscible methane-water mixture.

Monophase aqueous inclusions in CCP must have been trapped at temperatures lower than 50°C, while two-phase aqueous inclusions with small vapour bubble in CCP homogenised between 100 and 145°C (Fig. 5). CCO only rarely contains aqueous inclusions with homogenisation temperatures from 124 to 133°C. Quartz overgrowths (QO) originated from low temperature fluids (< 60°C) with salinity 1.2–5.1% NaCl. Aqueous inclusions in BC homogenised between 92–137°C and at less than 50°C. These values correspond to decrease of salinity from 0.9–1.2 to 0% NaCl. In DC temperature of homogenisation was 100–110°C. In sequence BC–FC we observed decrease of homogenisation temperature from 102–133 to 91–115°C and later, to 79–98°C.

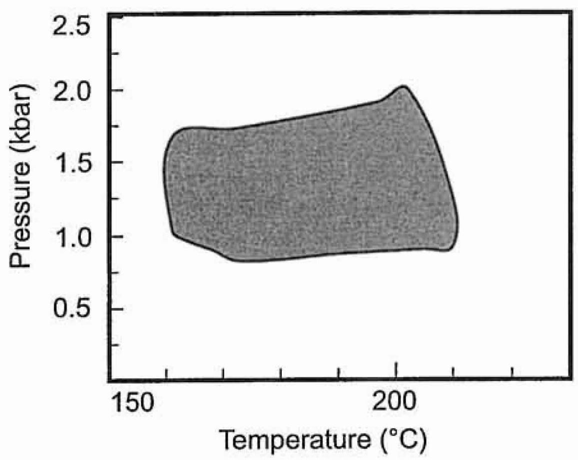

Fig. 6. Pressure-temperature conditions of CQ mineralisation, derived from homogenisation temperatures and densities of coexisting methane and aqueous fluid inclusions

Strong fluctuations of pressure (Fig. 6) and salinity occurred during crystallisation of CQ. Densities of methane-rich gaseous inclusions indicate pressure fluctuation between 0.8 and 2.0 kbar. The pressure fluctuation was accompanied by cooling from 210 to 160°C. Salinity of aqueous phases ranged from 0 to 3.1 wt. % NaCl.

INTERPRETATION — JOINTS AND MINERALISATION DURING STRUCTURAL EVOLUTION

SUBDUCTION-RELATED, SYNSEDIMENTARY FOLDING AND THRUSTING

Sedimentation of the Tertiary strata occurred in a stress regime in which the maximum stress axis was horizontal and normal to the present-day map-scale fold axes (Tokarski and Świerczewska, 1998). In this stress arrangement, T and D joints were formed (Fig. 7A). They were cemented by CCP. Numerous D joints were transformed into strike-slip faults of two conjugated sets (Fig. 7B). CCO crystals were formed at these faults whereas associated riedel shears were filled by CCP and CCO. No strike-slip faulting occurred in thick-bedded sandstones devoid of D joints. Some of T joints were transformed into tension gashes filled by CCP and probably by BC. The fold-parallel joints filled by CCP are believed to have formed during the folding.

Precipitation of CC and QO in fractures has started at low temperatures (< 50°C) and continued to at least 145°C (Fig. 5). The mineralisation during the folding was largely restricted to the sandstones containing primary carbonate cement.

ROTATION

During rotation (Fig. 7C), some T joints have been reactivated as strike-slip faults while numerous D_2 joints have been transformed into tension gashes. After that (Fig. 7D), some D_2 joints have been reactivated as strike-slip faults. The fold-parallel joints (L and L') have been reactivated close before completion of the rotation as strike-slip faults with synkinematic CCO and FC.

The newly-formed structures served as new pathways for fluids, precipitating fibrous calcite. This mineralisation was largely restricted to the sandstones containing primary carbonate cement. Temperature of fluids have been comparable with higher temperature limit during synsedimentary folding (Fig. 5).

REGIONAL COLLAPSE

A regional collapse marked by normal faulting has occurred after rotation. At that time, numerous preexisting joints and faults have been reactivated as normal faults (Fig. 7E) with FC mineralisation superimposed by BC and DC whereas some subvertical fractures have been transformed into tension gashes filled by BC and DC.

During the collapse, extensive fluid flow resulted in abundant mineralisation, which has formed in the sandstones containing primary carbonate cement and in those devoid of this cement. Faults and joints were mineralised repeatedly by several calcite generations and once by quartz-calcite assemblage. The most of calcite has crystallised at minimum temperatures of 90–140°C (Fig. 5). The calcite precipitation has been interrupted by high temperature, CQ producing episode. This event is marked also in Cretaceous rocks of the Magura nappe and in the Oligocene rocks of underlying Dukla nappe (Świerczewska *et al.*, 1999). It seams likely, that the latest BC were formed from cold, meteoric water.

CONCLUSIONS

1. Structural evolution of fold-and-thrust belt can be largely controlled by early synsedimentary joints.

2. In the studied portion of the Magura nappe mineralisation is restricted to the early joints and the brittle structures into which the joints were transformed.

3. Lithology of host rocks control abundance and distribution of mineralisation.

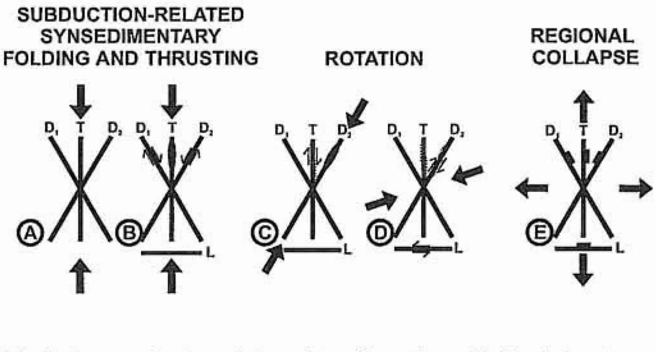

Fig. 7. Cartoon showing origin and transformations of joints during structural evolution of the Magura nappe (after Tokarski *et al.*, 1999); for explanations see text

4. Mineral filling of joints records conditions of structural evolution.

5. The bulk of mineralisation was introduced along normal faults during the regional collapse.

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