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# Cavitation erosion – a possible cause of the mass loss within thrust zones in the Tatra Mts., Poland

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ABSTRACT:

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In the Tatra Mts., thrust-napping and shearing were multi-stage re-activated processes. Their cyclic character was determined by increases and decreases in pore fluid pressure. During each cycle, new parts of the rheologically heterogeneous wall-rock were selectively destroyed due to hydraulic fracturing, brecciation and mylonitization, and moved out as a solution and/or suspension. As a result of these processes, including pressure solution, considerable mass loss could have taken place. All these processes took place under the considerable influence of fluids. In this paper we consider the possible contribution of cavitation erosion to mass loss processes. Displacement along an uneven thrust surface could create chambers filled with fluid and sudden falls in local pressure promoting the inception of cavitation. Cavitation damage, mainly mechanical in nature, could act synergistically with slurry abrasion and pressure solution processes.

Our work is of a hypothetical character. To prove the possibility of cavitation erosion within shear zones in the Tatra Mts. we conducted an experiment to show the low resistance of rock samples to cavitation erosion. We also discuss and characterize the conditions essential to induce cavitation within thrust zones at the base of nappes.

**Key words:** Cavitation erosion, Hydrotectonic pump, Fault slurry, Shear zone, Tatra Mts.

## INTRODUCTION

The presence of fluids plays a key role during shearing processes. A shear zone could be a pathway of fluid migration, with the direction of fluid flow governed by the maximum hydraulic gradient (SIBSON 1996). Fluids could be released to the shear zone due to fracturing of country rocks. Other processes, such as the dehydration of gypsum, could also be a source of water. Fluidised rocks at the base of nappes act as a low-viscosity tectonic lubricant consisting of a suspension comprising salt solutions, dissolved gases, rock fragments and matrix. Fluids may cause a change in the predominant mechanism of deformation due to hydrolytic weakening or crack-seal-slip (Petit & *al.* 1999). Gases can be released from solution as a result of a temporary decrease in pressure or an increase in temperature.

In the upper crust, fluid pressure is typically normal and equal to hydrostatic pressure. Hubbert & Rubey (1959) and Secor (1965) indicated the importance of pore-fluid pressure in the mechanics of sliding of large rock masses, especially in the case of low-angle overthrusts. According to Sibson (2004), high fluid overpressures are easier to sustain in compressional regimes that also allow the highest amplitude fluid-pressure cycling.

In the Tatra Mts., nappe structures and nappe-thrust surfaces are unique because of their geometric irregularity. Many investigations questioned the cause of these geometric peculiarities. Earlier works indicated that the morphology of the shear zone was conditioned by anisotropy of the sedimentary rocks and that the geometry of nappe structures was connected with large-scale mass-loss processes (Jurewicz 2003, 2006; Jurewicz & Słaby 2004).

Shear zones in the Tatra Mts. connected with Alpine nappe-thrusting processes cut layers of sedimentary rocks as well as the crystalline core. Only within shear zones originating in the sedimentary cover of the Tatra Mts. could processes of intense brecciation, mylonitization and pres-

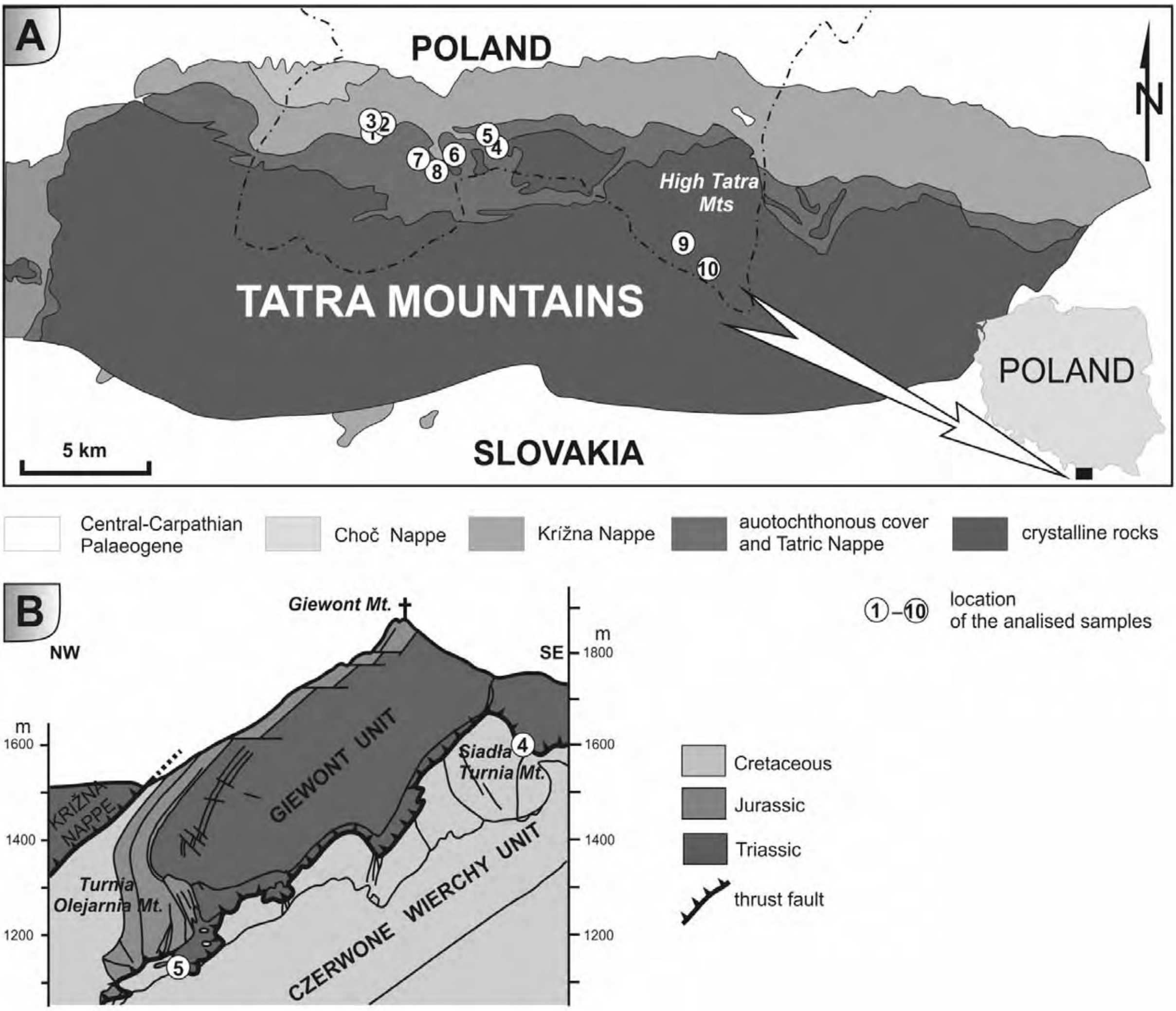

Fig. 1. A – Main tectonic units of the Tatra Mts. and sampling points (after Bac-Moszaszwili & *al.* 1979). B – Tectonic contact of two units (Giewont and Czerwone Wierchy) of the Tatric Nappe with clearly visible geometrical irregularity of the thrust surface; SW slope of Giewont Mt. (geological interpretation after Gąsienica-Szostak 1973)

sure solution leading to mass-loss be observed (JUREWICZ 2006). The surfaces of thrusts are usually corrugated and rough. From tectonically deformed rocks uniquely preserved in dilation fissures, we were able to reconstruct the shearing processes resulting from repeated fault nucleation by reactivation of pre-existing mechanical discontinuities due to cyclic changes in pore-fluid pressure (JUREWICZ 2003). The petrophysical properties of the rocks and associated liquid spots play an important role in the shearing processes. In comparison with the sedimentary cover, the main component of the crystalline core, a granitoid, shows low porosity and low solubility; the shear surfaces dip typically at a low-angle and are smooth and planar. This difference in petrophysical properties results in the lack of comparable processes within the granitoid core and in the sedimentary cover (JUREWICZ 2006).

The significant extent of mass loss associated with thrust-napping surfaces within the Tatra Mts. is difficult to explain by damage resulting from fracturing and pressure solution processes alone. We try to show below that cavitation erosion could have been equally responsible for the wall rock mass loss along the thrusts in the Tatra Mts. as the above processes. Cavitation is a phenomenon commonly associated with hydraulic equipment; it is well known to mechanical and civil engineers as a powerful erosive mechanism leading to severe damage to hydraulic equipment and civil engineering structures (KNAPP & *al.* 1970, GALPERIN & *al.* 1977, KENN 1983). Practical implementations of cavitation include drilling rocks in boreholes and cutting rocks in quarries. Even if most geologists know cavitation, this knowledge is of little use in explaining tectonic processes. The difficulty is that we are looking for something that does not exist now: the mass lost and the inferred process or mechanism resulting in the mass loss, i.e. cavitation erosion. Within the shear zones there is no preserved record of cavitation bubbles, but we can indicate the possibility of the occurrence of cavitation during thrusting in the Tatra Mts. and we are able to prove the low resistance to cavitation of rocks from shear zones and their vicinity. The authors are aware that, at this stage in the investigation, their idea is only "a working hypothesis", and that further work is required to substantiate it.

## GEOLOGICAL SETTING

The Tatra Mountains are composed of a crystalline core, overlain by a Mesozoic sedimentary cover and the Tatric, Krížna and Choč nappes, which comprise many minor tectonic units (Text-figs 1A, B). They represent the most northern massif of the Inner Carpathians. Nappe-folding proceeded from the south, gradually incorporating increasingly northerly located sedimentary zones. Thrusting of the Choč onto the Krížna Nappe started after the Early Albian in the south, and after the Early Cenomanian in the north (RAKÚS & MARSCHALKO 1997). The nappe-thrusting in the Tatric took place during the Cenomanian and Early Turonian (MIŠIK & *al.* 1985). As a final stage, the autochthonous sedimentary cover of the crystalline core underwent folding. At the base of the thrust nappes Middle Triassic dolomites and rocks known as Rauhwacke or Zellendolomite usually appeared (KOTAŃSKI 1956, PLAŠIENKA & SOTÁK 1996, JUREWICZ 2003). According to WARREN (1999), evaporite-lubricated protoliths of Rauhwacke acted as detachment horizons during thrusting and folding.

### Pressure and temperature during thrusting

Processes of tectonic transport probably took place in underwater conditions at full saturation of rocks with seawater. Studies of fluid inclusions in synkinematic quartz on slickensided low-angle fault surfaces from the granitoid core (connected with nappe-thrusting) proved that they originated at a pressure of 145-170 MPa and a temperature of 212-254°C (JUREWICZ & KOZŁOWSKI 2003). Nappe-thrusting processes of the Tatric Nappe took place at a depth about 2 km nearer the surface (6-7 km for the upper part of granitoid rocks minus the thickness of autochthonous High-Tatric sedimentary cover c. 1.1 to 2.4 km by KOTAŃSKI 1959) and hence temperatures and pressures could have been lower; however temperatures determined from chlorite and feldspar thermometers obtained from the shear zone within the Tatric Nappe varied in the range 300-350°C (JUREWICZ & SŁABY 2004).

In a very similar situation, much higher temperatures (213-471°C) and pressures (20-540 MPa) were obtained by MILOVSKÝ & *al.* (2003) from investigation of fluid inclusions in the basal cataclasites of the Muráň Nappe belonging to the

Silicicum cover nappe system (southern part of the Central Western Carpathians). The wide range of pressure values was interpreted by those authors as a reflection of locally supralithostatic overpressures. Such large amplitude fluid pressure fluctuations determined on the basis of fluid inclusion studies have also been noted by ROBERTS & *al.* (1996) on fault-fracture veins associated with steep reverse faults.

## Character of the thrust zones

In many cases, rocks within the shear zones and at the bases of the nappes do not show any features which could indicate such high temperatures. There is no evidence of metamorphism in the wall-rocks. The surfaces of the thrusts are not planar. Their complex course is clearly visible in the cross-section (Text-fig. 1B) and directly in the field (Text-fig. 2A). Structures appearing within the thrust zones are diverse and complicated (Text-fig. 3). On the Stoły Hill, the contact between the Tatric and Krížna nappes is locally stylolitic (BAC-MOSZASZWILI & *al.* 1981). The shear fissure is closed. Triassic dolomites of the Krížna Nappe and Urgonian limestones of the Tatric Nappe stick closely to each other, without any damage zone or cementing material, as if glued together (BAC-MOSZASZWILI & *al.* 1981, JAROSZEWSKI 1982, JUREWICZ 2003, JUREWICZ & SŁABY 2004). In some places a number of isolated megaclasts of Urgonian limestones, belonging to the Tatric Nappe, and tectonically incorporated into the Triassic dolomite of the Krížna nappe, were noted in the hanging wall. There is no tectonic deformation connected with this incorporation. The thrust surface lacks the slickensides that would enable kinematic analysis of tectonic transport and reconstruction of the stress field. Rocks in the vicinity of the stylolitic contact show no evidence of strong deformation, with the

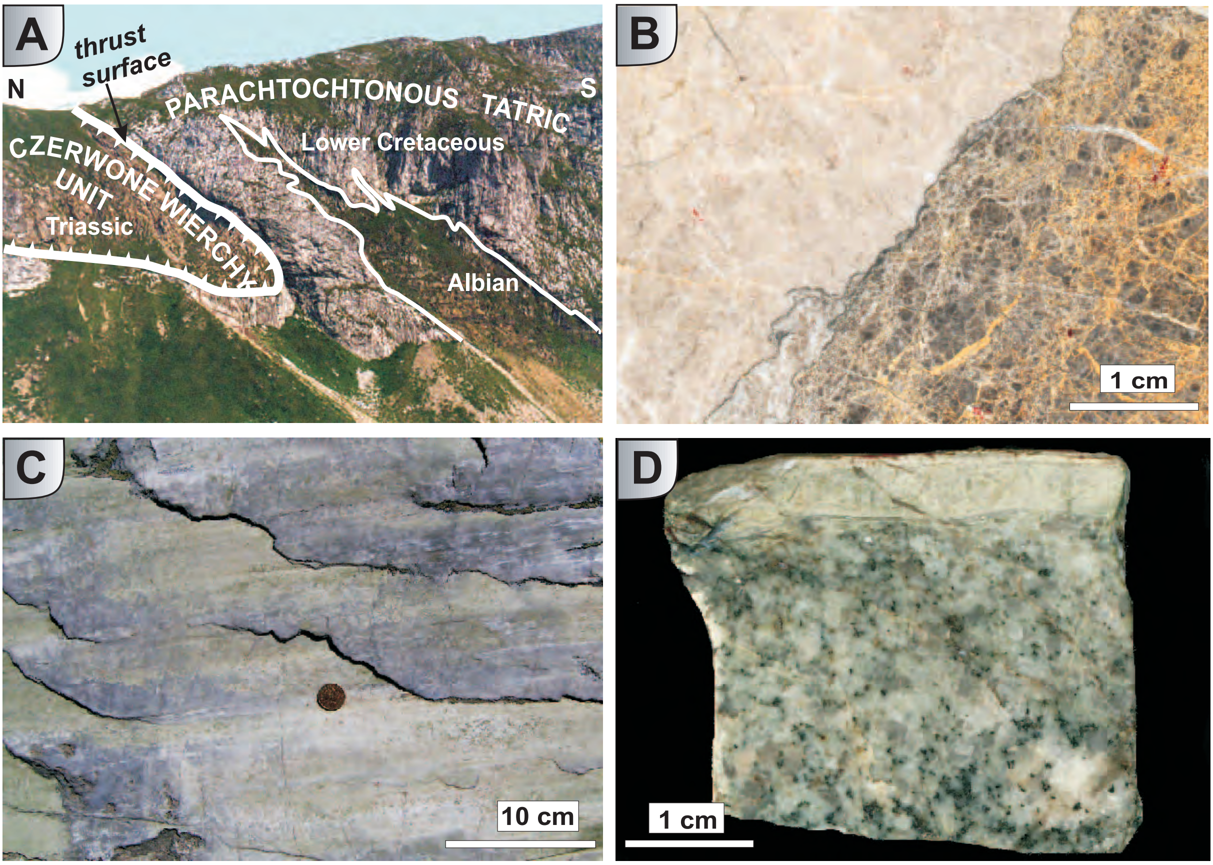

Fig. 2. A – Complicated course of the thrust zone at the base of the Czerwone Wierchy unit (Kozi Grzbiet Ridge). B – Tectonic contact between Urgonian limestone of the Tatric Nappe (light) and Anisian dolomite of the Krížna Nappe (dark); Stoły Hill. C – Typical slickensided fault plane, mineralized with quartz and epidote, originated within granitoid core of the Tatra Mts. D – Fragment of the granitoid rock with fault plane coated with synkinematically-grown quartz and epidote

exception of pressure solution within the limestone and of hydraulic fractures within the dolomite (Text-fig. 2B). This is connected with the radically different mechanical behaviour of the limestone and dolomite, which makes the dolomite less susceptible to dissolution and more prone to brittle disintegration (PASSCHIER & TROUW 1996, KENNEDY & LOGAN 1997). To sum up, there is a lack of evidence that this is the base of the nappe or that this is the shear zone.

A different situation occurs e.g. at the base of the Giewont Unit or in the Zadnie Kamienne shear zone (JUREWICZ 2003, JUREWICZ & SŁABY 2004), where typical dynamometamorphic structures such as foliation, stretching lineation and veining, associated with pressure solution, strain shadow and neoformed minerals, can be found (Text-figs 3D-F). In some cases (e.g. in the base of the Czerwone Wierchy Unit), these structures show signs of folding (Text-fig. 3F). Different characters of the shear zones in the Tatra Mts. are inseperably linked to the anisotropy of the rocks and the concomitant anisotropy of the shear surfaces. Such variability of tectonic structures appeared in the sedimentary cover only. The main cause for the lack of a comparable structures within the granitoid core is the planar character of the fault surfaces (Text-figs 2C, D) and tightened fissures preventing fluid migration (JUREWICZ 2006). The above-mentioned fluid inclusion investigation revealed rather narrow ranges of pressure and temperature values, which indicate rather uniform conditions of quartz formation and deformation. This is connected with the relatively isotropic character of the granites in comparison to the lithologically diverse sedimentary rocks, and with the fact that in many cases the activation took place only once. Due to the low solubility and low porosity of granite, as well as the lack of sources of fluids, hydrotectonic phenomena and associated cavitation erosion could not appear in the crystalline core of the Tatra Mts.

## Mechanism of tectonic transport and shearing-related processes

The character and mechanism of deformations within the shear zone at the base of the Tatric nappes could be established from the investigation of dilation fissures associated with the thrust surface (JUREWICZ 2003, JUREWICZ & SŁABY 2004). The preserved rocks are tectonically deformed in various ways. The multistage character of rocks deformations are connected with multiply activation of tectonic displacement depended on cyclical changes in pore fluid pressure. The build-up of pore fluid pressure leads to a decrease in stress to an effective value (HUBBERT & RUBEY 1959) and to rupturing by faulting associated with hydraulic fracturing. A model of fault development in carbonate rocks based on repeated crack-seal-slip cycles was described by PETIT & *al.* (1999) and RENARD & *al.* (2000). Processes of such a kind, in which fluid pressure plays a key role, were termed hydrotectonic phenomena by JAROSZEWSKI (1982) and KOPF (1982, 2003). In the Tatra Mts., the cyclical character of nappe movement was described by JUREWICZ (2003).

Newly-formed shear zones associated with a fault-related fracture net provide a drainage path for fluid migration (SIBSON 1996, 2004; GUDMUNDSSON & *al*. 2001). In the case of the Tatra Mts., the source of fluids could have been pores (which appeared due to solution of salt crystals and filled with meteoric water) or fluids could have originated from, for example, the dehydration of gypsum, occurring in the so-called Anisian “cellular dolomites” (KASIŃSKI 1981) and in sediments of Rauhwacke type (PLAŠIENKA & SOTÁK 1996, MILOVSKÝ & *al.* 2003). It cannot be excluded that the shear zone was a passageway for hydrothermal solutions, this being supported by the presence of hydrothermal feldspar crystallizing at a temperature of ~350°C (JUREWICZ & SŁABY 2004). Fluids and rock fragments filling the shear zone formed a suspension circulating along the hydraulic gradient (SIBSON 1996).

The presence of such a suspension, described by KOPF (2003) as a “fault slurry”, causes a decrease in friction, with the angle of internal friction decreasing to values close to zero (JUREWICZ 2003). According to BRODSKY & KANAMORI (2001), the lubrication effect of the fluid in all fluid-filled faults facilitates tectonic transport and reduces the friction stress by as much as 30% relative to the hydrostatic value or 50% to the dry rock friction. MARON (2004) stated that friction at the interface between the fault walls may additionally fall dramatically due to high rates of slip, e.g. seismic in nature.

After displacement, the shear zone was gradually veined, cemented and immobilised. During this time, ductile folding took place of material filling the shear zone, comprising brecciated, mylonitized

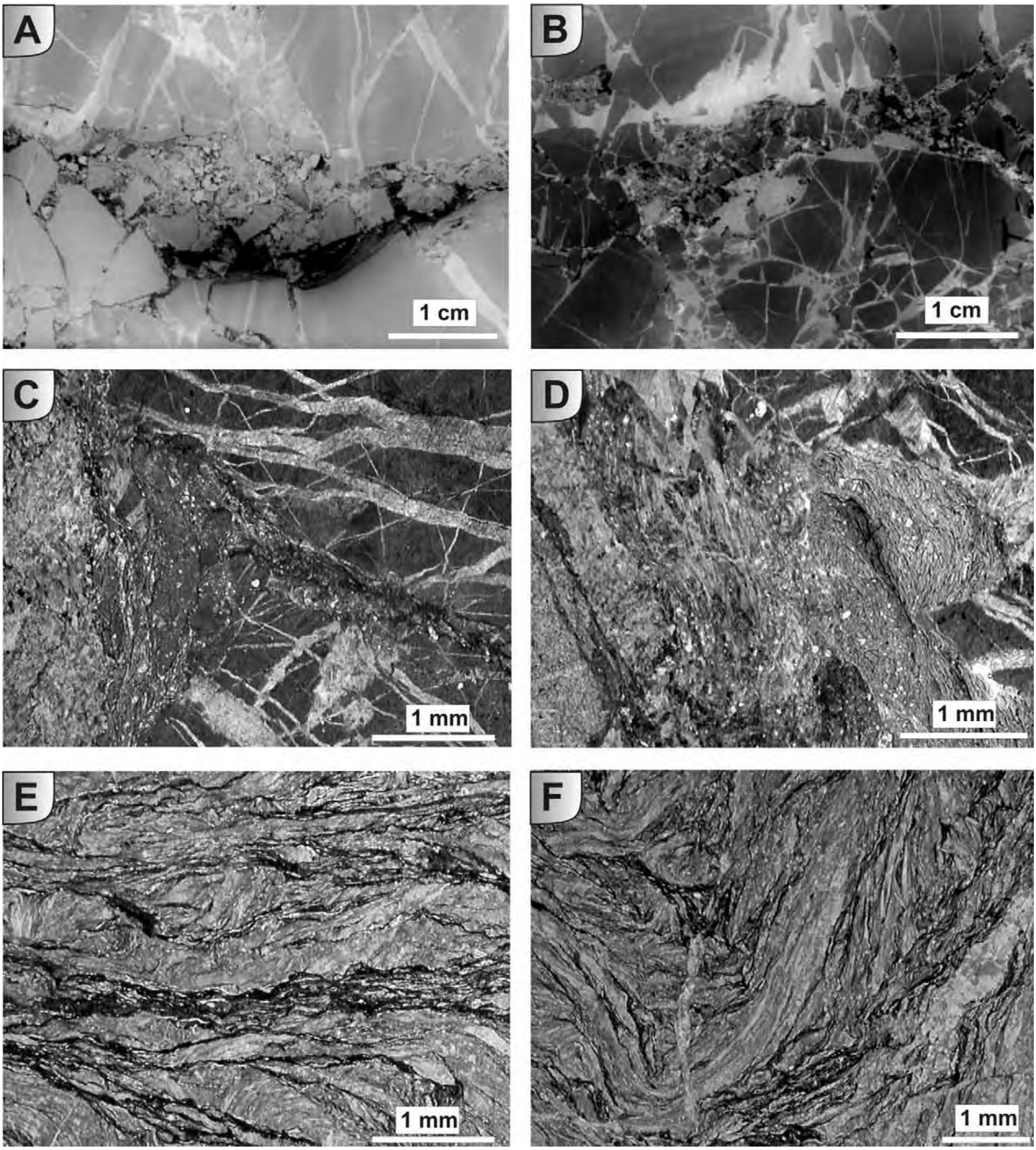

Fig. 3. Structures from the shear zones in the Tatra Mts. A – Strongly fractured and partly cataclased dolomite from the base of the Giewont Unit. Mylonitic matrix composed of detrital material and clay minerals aggraded due to fluid flow can be seen in the central lower part. Slightly zoning and gradation within matrix could have originated due to injection of suspension (fault slurry) from the shear zone into the fractured country rocks. B – Fracture network in the Anisian dolomite at the base of the Giewont Unit, partly filled with detrital material (dark) and mineralized with calcite (light). C – Fracture network (mineralized with calcite) in the Anisian dolomite at the base of the Giewont Unit (Tatric Nappe). Space between fractured clasts filled with mylonitic matrix composed mainly of insoluble residues. D – Foliated and folded mylonitic matrix incorporated into irregular spaces within fractured dolomites. E – Well developed foliation, stretching lineation and stylolites within repeatedly mylonitized and mineralized rocks at the base of the Giewont Unit (Tatric Nappe). F – Strongly folded mylonitized rocks from the Zadnie Kamienne shear zone with well-developed foliation crossed by veins of calcite

and veined rocks. Before the next stage of shearing, both the stress and the pore-fluid pressure increased, causing a decrease in the normal stress to an effective value (see HUBBERT & RUBEY 1959) so that the rock cohesion was ruptured by brittle failure and the cycle started again (JUREWICZ 2003). The cyclical character of this process, during which multiple episodes of cementation and renewed shearing took place, could be related to the successive build up and drop in fluid pressure (SIBSON 2004). In each cycle, brittle failure and ductile deformation may have occurred (see JAEGER & COOK 1969, KENNEDY & LOGAN 1997).

During each cycle new parts of the wall-rock were selectively destroyed due to hydraulic fracturing (Text-figs 3A, B). The fractured rocks underwent brecciation and mylonitization (Text-figs 3C, D), and then moved out as a suspension (fault slurry). Such a suspension could be injected from the shear zone into the fractured country rocks (Text-fig. 3A). Each next stage of tectonic activity resulted in a more complex topography of the damage zone – Text-figs 1B, 2A (see JOONG-JEEK & BRUHN 1996). Fluids, released to the shear zone and forming, together with the brecciated rocks, a suspension with low friction values, could have acted as a “water pillow” facilitating the movement of the nappe mass (JUREWICZ 2003). In contrast to the extensionally open fissure of normal faults, along which fluids can migrate freely, fluids within low-angle shear zones can accumulate more easily and migrate more slowly due to a low hydraulic gradient (SIBSON 1996). The existence of such a water pillow may be related to the over-pressured fluid within the shear zone (GUDMUNDSSON 2001). The effect of reversing fluid pressure in highly permeable rocks separating water from water-saturated fault breccia and fault slurry was described by KOPF (2003) on the basis of an experiment conducted in 1979 (Text-fig. 4). The author of the experiment concluded that the water-saturated-fault slurry “restricts flow through a porous rock, essentially acting as a one-way valve”. It means that the water could flow freely from pores and fractures into the fault fissure (Text-fig. 4B) but it could not leave the closed fault fissure because the water-saturated fault-breccia and fault slurry acted as a diaphragm (Text-fig. 4C).

## Problem of mass loss

The nappe structures of the Tatra Mts. do not resemble the classic duplexes described by BOYER & ELLIOT (1982). Cross-section analysis and field investigations revealed considerable damage to and complication of the geometry of the nappe structures (Text-fig. 1B, 2A) which could have been the result of selective destruction and mass loss based on their lithological and rheological heterogeneity (JUREWICZ 2006). The character of processes within thrust zones and the rheology of

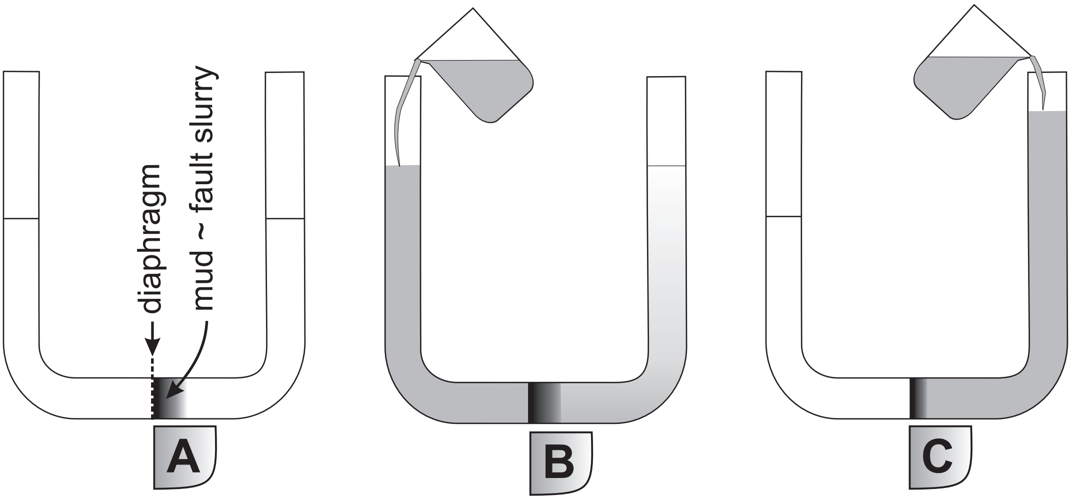

Fig. 4. Experiment of KOPF (2003) conducted Oct 21, 1979. Experiment to determine the effect of reversing fluid pressure on highly permeable rocks separating water (left tube) from aqueous slurry (right tube): about 10 cc of mud representing water-saturated fault slurry (A). If the coloured water was added to the left tube, the fluid level in both tubes quickly equalized (B). When the same volume of water is added instead to the right tube, the water has not equalized (C)

fault-zone materials could be established from the investigation of damage products preserved within dilation fissures associated with shear zones (see Cowan 1999, Kim & *al.* 2004). Detailed analysis of structures associated with shear zones in the Tatra Mts. indicated that apart from cyclical brecciation of the wall-rocks due to hydraulic fracturing and moving out of the floating rock fragments, pressure solution may have been equally responsible for mass loss (Jurewicz 2003). Analysis of thin sections indicates that significant mass has been lost due to pressure solution under the hydrothermal conditions responsible for dissolution creep (Jurewicz & Słaby 2004). In particular cases, erosion within the tectonic zone lead to "eating" of the wall-rock and caused stress relaxation due to mass loss, without dislocation. Such a kind of shear zone was described as "ravenous" in the Zadnie Kamienne shear zone (Jurewicz & Słaby 2004), where the damage zone and the character of meso- and microstructures is incommensurate with fault displacement. It is very difficult to estimate the value of the mass decrease in such complex processes. The reduction in mass caused only by chemical compaction of the condensed Middle Jurassic deposits in the Tatric series was assessed by Łuczyński (2001) at about 20-70%. In the shear zone, estimation of the mass loss value based on the residuum is difficult because of the high lithological variability and the possible removal beyond the tectonic zone of a large volume of rocks in the form of suspension and solution.

## Role of the shear surface topography

In the displacement processes, a kye role could be played by a complex topography of the damage zones (Power & Tullis 1991, Di Toro & *al.* 2004). In the Tatra Mts., the geometry of the thrust-related shear zones was determined by the bedding anisotropy of the sedimentary rocks. Rheological heterogeneity of the sedimentary rocks conditioned their selective damage and controlled the morphology of the shear zones (Jurewicz 2006). Since shear zones in the Tatra Mts. were repeatedly reactivated, they became geometrically more and more irregular. The surfaces of the shear zones are rough and corrugate, additionally deformed by small associated faults.

Displacement along the non-planar thrust surface and non-congruent walls of the shear zone could create bottlenecks and chambers (Kopf 2003) accompanied by restraining and releasing bands (Davis & Reynolds 1996). Pull-apart arrays (Ahlgren 2001) could be produced under brittle conditions of failure due to shearing processes (Text-figs 5A-C).

During the rapid movement along undulatory fault-walls, the volume of the newly opened chambers alternately increased and decreased (Text-figs 5C, D), mimicking a rotary engine or hydraulic pump, and for this reason was named by Kopf (2003) as a "hydrotectonic pump" (cf. "seismic pump" of Sibson & *al.* 1975). The pumping

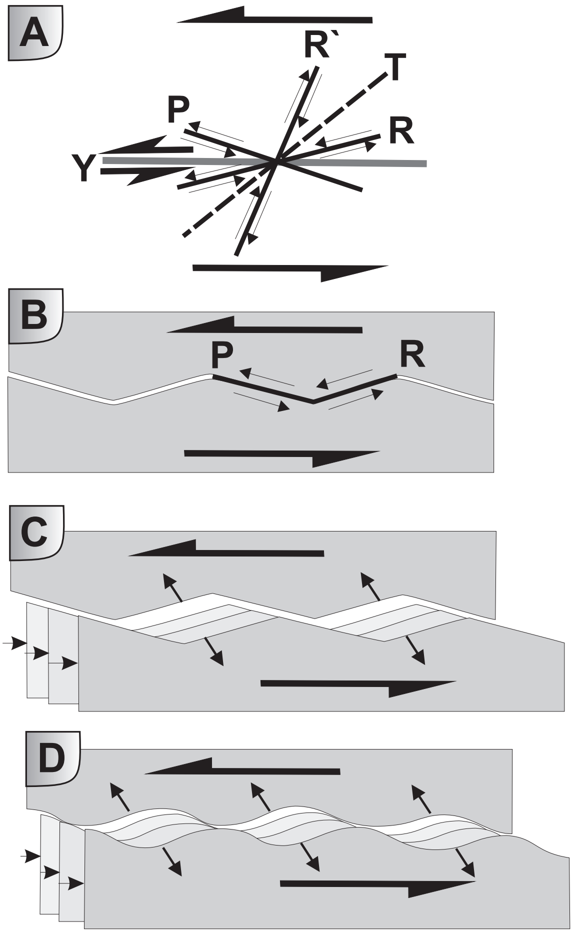

Fig. 5. Scheme of origin of fault fissures and undulatory fault-walls favourable to cavitation phenomenon. A – Idealized geometry of a Riedel shear zone system (see Ahlgren 2001); B, C – Under brittle conditions, pull-apart arrays, linked with "P-shears", could develop as a result of Riedel shearing; D – Under ductile conditions, lens-shaped chambers, separated by bottlenecks, may develop as a result of shear displacement along undulatory fault-walls.

processes could suck in fluids from the porous system of the country rock, as well as from other parts of the shear zone. It could be possible that squeezing the liquid in some chambers caused local but significant anomalies of pressure and induced liquid jets flowing out through the slots into chambers of lower internal pressure. Furthermore, short and narrow slots or bottlenecks between the chambers created conditions under which very high flow velocities could occur locally. This could have resulted in an effect similar to that in hydraulic rock-cutting devices and when the dynamic depression was high enough to decrease the local static pressure to the value below the saturated vapour pressure, the phenomenon of cavitation might have been triggered.

In the next part of this paper we consider the possible contribution of cavitation erosion to the mass loss process within the shear zones in the Tatra Mts.

## CAVITATION PHENOMENON AND CAVITATION EROSION

Vapour-gas bubbles develop in a liquid as a result of the supply of mechanical or thermal energy; either by subjecting it to tensile stress or by raising its temperature to boiling point. After the appropriate strength level of the liquid is exceeded, local rupture occurs at numerous points in the liquid volume. The theoretical tensile strength of ideal water is in the range 3-30 GPa (FRENKEL 1955). In fact, nucleation of cavitation bubbles is facilitated by the presence of objects belonging to another phase, such as impurities (contaminations) or bubbles of undissolved gas. This dramatically reduces the threshold at which cavitation appears. The essentials of the phenomenon are explained comprehensively in the following description taken from PREECE (1979): “Cavitation refers to the repeated growth and collapse of bubbles (or cavities) in a fluid due to local pressure fluctuations. If the pressure of a flowing liquid falls below its vapor pressure, for example, because of sharp changes in geometry of the flow, cavities are nucleated. These are transported downstream and, when they reach a region of higher pressure, they collapse violently and may cause erosion of any solid in their vicinity. (...) Cavitation can also occur in fluids which are subjected to cyclic pressure pulses. (...) In these cases, there is a temporal rather than a spatial variation in the fluid pressure”.

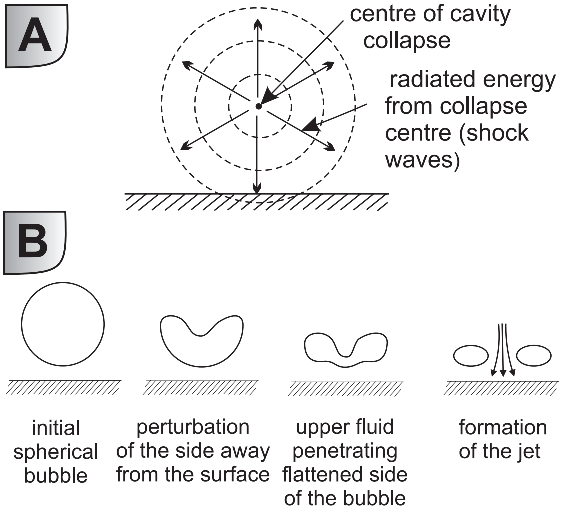

Fig. 6. The shock-wave mechanism (A) and micro-jet mechanism (B) of cavitation erosion (after KNAPP *et al.* 1970, LAMB 1987 and KOIVULA 2000)

A cavitation nucleus is transformed into a cavitation bubble after local pressure has fallen below a certain critical value (dependent on temperature, surface tension and gas content in the nucleus). This triggers a non-equilibrium, explosive increase in size of the cavity, which can be stopped only by an increase in ambient pressure or an encounter with liquid phase boundaries. An increase in ambient pressure results in another non-equilibrium process – cavity implosion (collapse). During the collapse of cavitation bubbles, large stress pulses are generated due to the shock wave (Text-fig. 6A) and/or high velocity micro-jet of liquid that impinges the solid surface in contact with the liquid (Text-fig. 6B). According to the evaluation of LAUTERBORN (1974), the velocity of a micro-jet could reach about 100 m/s. More recent data indicate even higher values. The resulting local pressure amplitudes are known to reach the level of several GPa. Rapid repetition of the stress pulses induces localized fatigue failure and subsequent material removal (KWOK & *al.* 2000).

Various types of cavitation are known. Flow cavitation “is common in hydraulic turbines, ship propellers, hydrofoils, pipelines etc.” whereas vibratory cavitation occurs “in the working liquid of hydraulic pumps and valves and in the lubricating or cooling fluid of a vibrating machine such a diesel engine” (PREECE 1979). Furthermore, the phenomenon is also detected in submerged jets (LICHTAROWICZ 1972). Cavitation associated with a liquid jet is usually generated deliberately and used in cutting or drilling technology.

The flow system of a hydrotectonic pump, as shown in Text-figs 5C, D, resembles closely that of a cavitation tunnel with a slot cavitator created by a barricade/counter-barricade system (Text-fig. 7). Cavitating vortex structures are shed from both barricade and counter-barricade and collapse in the test chamber downstream. Slot cavitator tunnels are used extensively by various researchers for testing the resistance to cavitation of structural materials and for studying the mechanism of cavitation erosion (PIGHINI & BENANTI 1972, ERDMANN-JESNITZER & LOUIS 1973, KIREJCZYK 1979). Test samples are usually inlaid in the test chamber wall (Text-fig. 7).

Vortex cavitation is generally considered to be the most aggressive type of cavitation. High cavitation loads are to be expected, especially at the solid surface perpendicular to the vortex axis, downstream cylindrical body. A situation like this is known to have been responsible for the collapse of the water intake at the Tarbela dam spillway in Pakistan (KENN 1983) the several meters deep damage to other concrete structures. This kind of cavitation is produced in cavitation tunnels with cylindrical bolt cavitators (Text-fig. 7) and in some rotating disk test facilities (Text-fig. 8).

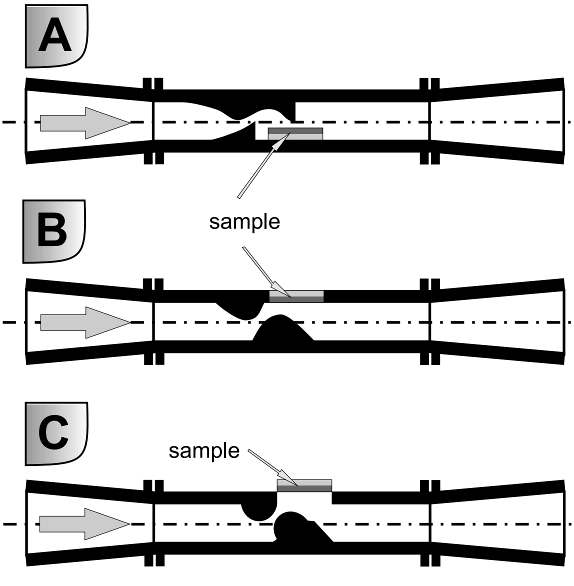

Fig. 7. A-C – Schematics of typical double-wear cavitation channels

Another form of cavitation occurs in high speed jets formed in narrow nozzles between two chambers with different pressures. In typical laboratory installations pressure differences as high as 15±2.5 MPa are applied (ASTM G134). Cavitation bubbles in ring vortex structures collapse at the target (tested specimen) situated in the plane perpendicular to the jet axis.

Under geological conditions described in the previous section, cavitating vortex structures emerging out of the slots between chambers created in the shear zone between moving rock masses are the most likely form of cavitation, if any. The formation of cavitating jets emerging out of "bottlenecks" is also possible. However, some special conditions are required for this phenomenon to occur and the resulting erosive effect is highly localised in this case.

The physical conditions in the shear zone between moving wall-rocks are characterized by high pressures and temperatures. In this connection, it should be noted that temperature plays a significant role as a factor influencing such variables as viscosity, vapour pressure, surface tension and density of the liquid. Thermodynamic effects in cavitation bubble dynamics are generally known to be essentially dependent on the temperature of the ambient liquid. According to PREECE (1979), "reported studies show that the rate of erosion initially increases as the temperature is raised (…), passes through a maximum, and decreases to zero at the boiling point".

Another factor influencing fluid properties is its saturation with diffused gas. The eroding effect decreases as the density of the diffused gas increases. It has been also pointed out by some authors (CECCIO & BRENNEN 1991) that the highest cavitation aggressivity is typical of loadings of unsteady nature, e.g. those due to the collapse of cavitating vortex structures.

Cavitation impingement generates shocks in the stress fields within the material. In reality, stresses either do not relax fully or their relaxation is completely non-elastic. As a result, residual stresses (TERAUCHI *et al.* 1973) and/or cracks or persistent deformations appear. Initiation of microcracks or voids is most probable at the boundariesof any discontinuities present. In fatigue processes, the creation of large cracks is due to the development of a network of microcracks that join each other. In brittle materials, cracks are usually initiated at the body surface. A liquid grout in the crack prevents its closure and forces its further propagation (WADE & PREECE 1978).

The density of the discernible indentations is a measure of the damage to the surface layer of the material in the initial (incubation) stage of the erosion. The depressions and indentations are the result of local plastic deformations of the microstructure of the impinged solid. In the case of brittle materials (e.g. rocks), the major damage process consists of multiplication of cracks and blocks, followed by the extraction of small pieces of eroded material. In the latter case, the amount of energy required to induce the process is obviously much less.

The kinetics of the mass loss of the material under cavitation conditions are represented by cumulative erosion curves. These reflect specific stages of the erosion, especially the stages of the accumulation of energy, acceleration of mass loss and stabilization of erosion. With the exception of very brittle materials, cavitation erosion is a fatigue process, as shown by RICHMAN & NAUGHTON (1990).

It has been found that resistance to cavitation depends mainly on the crystal structure of the material, the binding energy, the deformation strength and the ability to undergo phase transformations (FELLER & KHARRAZI 1984). In multiphase solids, the erosion kinetics of any single element of the microstructure is not the same (ENDO & NISHIMURA 1973). This is the reason for the selective destruction observed in heterogeneous materials. The weaker phase is removed first. Initiation and violent development of the damage at the phase boundaries are due to differences in the elasticity and plasticity of the adjoined grains (HEATHCOCK & *al.* 1982). Cracking of the material under mechanical load is linked to its heterogeneity (MOGI 1995).

One can distinguish between several regimes of fatigue crumbling of material under cavitation loading conditions. They are linked to various rates of increase in crack length, which are related to different levels of the loading forces (RITCHIE 1999). Rough partition of the impinged solid surface involves simultaneous extraction of small and large particles at rates related to their size and cavitation load conditions.

In order to demonstrate the effect of wall-rock impingement by a cavitating vortex structure, tests of rock samples collected at localities shown in Table 1 were conducted at the rotating disk facility shown in Text-fig. 8.

## EXPERIMENTAL PROCEDURE

### Specimen preparation and cavitation testing

The rock samples were inserted into hollows (Text-fig. 8) drilled in duralumin disks 30 mm in diameter and fixed to the metal with a resin-based glue. The rock surfaces were polished with diamond powder of $^1/_4$ $\mu$m Ø. The lithologies, localities and structural characteristics of the rock samples are presented in Table.1. Most of the rocks are heterogeneous due to their petrology, fractures

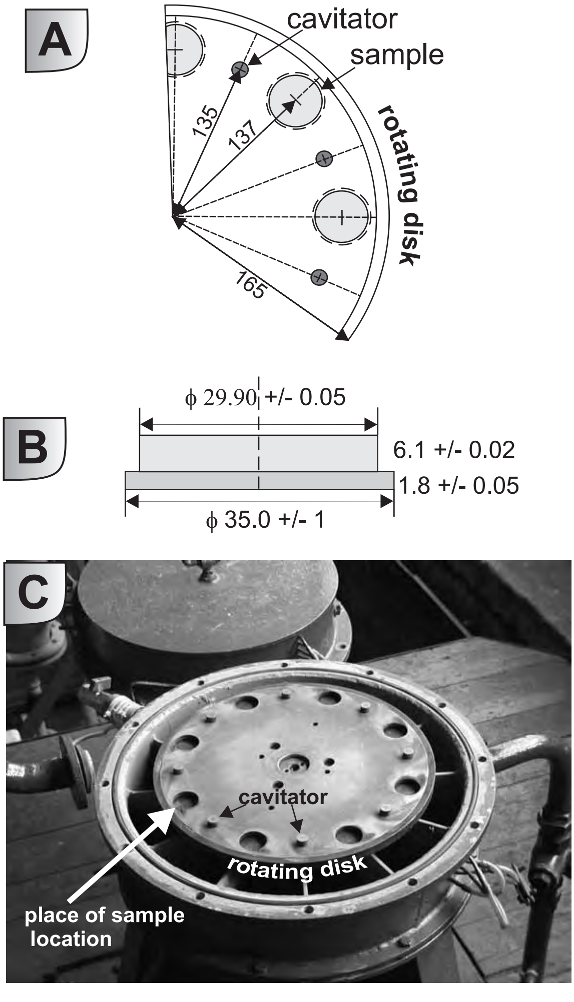

Fig. 8. Schematic diagram of rotating test disk (A) and specimen (B). C – Photograph of the IMP PAN rotating disk facility with visible cavitators and the braking vanes

| Sample | locality | litology | structures | age/unit |
|---|---|---|---|---|
| 1 | Stoły Hill | limestone | stylolites, mineralized fractures | Cretaceous (High-Tatric) |
| 2 | Stoły Hill | tectonic contact of dolomite and limestone | stylolites, mineralized fractures | Triassic (Krížna)/ Cretaceous (High-Tatric) |
| 3 | Stoły Hill | dolomite | mineralized fractures | Triassic (Krížna) |
| 4 | Olejarnia Mt | limestone | stylolites, mineralized fractures | Jurassic (High-Tatric) |
| 5 | Siadła Turnia Mt | mylonite from shear zone within sedimentary rocks (shale and carbonate) | mylonitic textures; porphyroclasts of dolomite and limestone, veins | post-Turonian, pre-Eocene (High-Tatric) |
| 6 | Twardy Upłaz | dolomite | several fractures | Triassic |
| 7 | Zadnie Kamienne Stream | tectonic contact of dolomite and limestone | stylolites,calcite veins | Triassic/Cretaceous (Tatric) |
| 8 | Chuda Turnia Mt | brecciated dolomite | clasts of dolomite within recrystallized dolomite cement | Traissic (Tatric) |
| 9 | Męguszowiecki Szczyt Mt | mylonite from shear zone within granitoid core | mylonitic textures; quartz porphyroclasts, quartz veins | post-Carboniferous (crystalline core) |
| 10 | Galeria Cubryńska Range | quartz vein from shear zone | fractures with Fe-dolomite mineralization | post-Carboniferous (crystalline core) |

Tab. 1. Characteristics of the rock samples tested at the rotating disk rig

filled with mineral veins (mainly calcite or dolomite) and the presence of stylolites.

Cavitation testing of samples 3-10 (Text-fig. 9) was carried out using the rotating disk rig (Text-fig. 8) in the laboratory of the Institute of Fluid-Flow Machinery, Polish Academy of Sciences, in Gdansk (STELLER & *al.* 1975). The rig is a typical facility used to determine cavitation resistance of structural materials applied in hydraulic machinery and equipment. The cavitation intensity attained exceeds substantially (up to 2000 times) that encountered in hydraulic machines. Cavitation is generated by cylindrical bolts (cavitators) situated on a disk surface on a circle 274 mm in diameter (Text-figs 8A, C). The rotation speed of the disk is 3000 rpm. Liquid rotation is prevented by braking vanes situated above and below the disk. The distribution of loading over the sample is not uniform, and the loading intensity varies over the surface from zero to its maximum value. Test specimens are inlaid in the disk downstream of the respective cavitators. Typically, tap water at temperature of 20°C is used as a working medium. The mean gauge pressure is kept at 150 kPa.

The tests of rock samples nos 3-10 were performed in one run lasting three minutes (Text-fig. 9). The duration of the run was less than the time needed to achieve the steady-state test conditions with nearly constant cavitation intensity.

Prolongation of the experiment was unjustified due to the very high susceptibility of the samples to erosive impingement, which could result in disaggregation of the entire test specimen. Investigation of lithologically diverse rock samples indicated that a relatively higher resistance to cavitation was shown by homogeneous samples, e.g. non-fractured limestone (Text-fig. 9.6). The most severe damage was observed within fractured and mineralized dolomite (Text-fig. 9.3), mylonitized and stylolitized limestone (Text-figs 9.5, 9.7) and mylonitized granitoid rocks (Text-fig. 9.9)

Investigation into concrete – an artificial material that best resembles the natural rock samples – has revealed that even a very brief exposure to cavitation (2-10 sec) is sufficient to produce measurable mass loss (MOMBER 2000).

## Mass loss evaluation

Experiments with samples 1 and 2 (Text-fig. 10) consisted in measuring their mass loss after specified intervals of exposure to cavitation loading as shown by cumulative mass loss curves obtained for both samples (Text-fig. 11A). Rapid removal of material was observed only 80 seconds after the beginning of the test. For the purpose of comparison, a sample made of carbon steel (0.45%C) was subjected to cavitation load under the same conditions (Text-fig. 11B). A striking difference in the erosion rates of the materials is observed.

## Results of the cavitation test

The cavitation test results from observation of the tested surfaces with the naked eye and using scanning electron microscopy, and from evaluation of the weight loss curve, were used to characterize the failure mechanisms.

The rock samples were not homogeneous with respect to mineral composition and crystal structure, and the individual constituents showed different resistances to cavitation. Observations confirmed that the weaker the phase of the material, the higher was its rate of extraction. The rock samples appeared to be extremely brittle and non-resistant to cavitation impingement. No evidence of plastic deformation on the sample surfaces could be found. Instead, the development of brittle cracking was readily observed with the naked eye. The damage appeared as a fragmentation of surfaces. Nucleation of the cracks and holes was mostly at boundaries between different phases

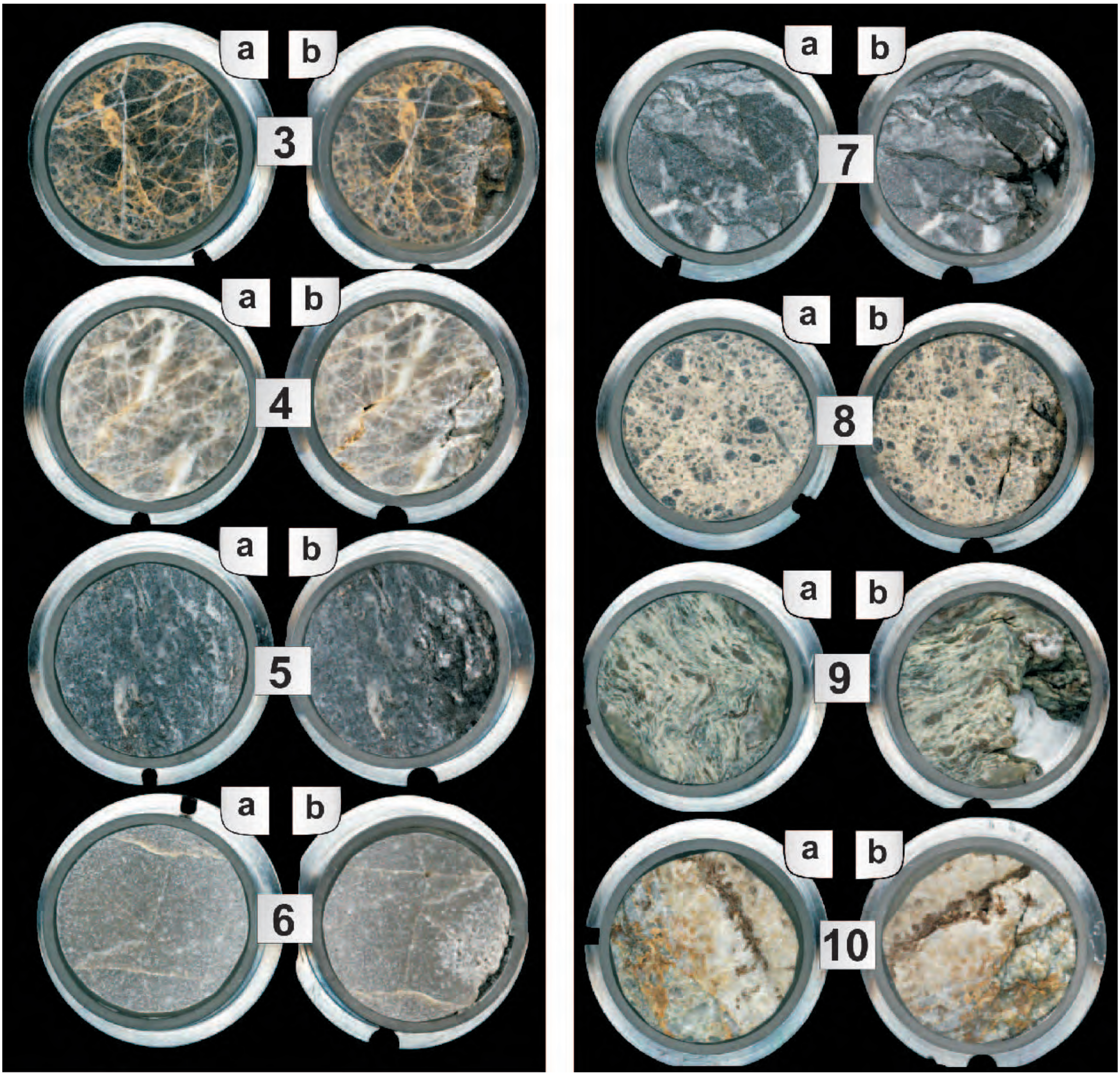

Fig. 9. Macroscopic view of specimen surfaces (nos 3-10) before (a) and after (b) 3 minutes exposure to cavitation impingements (see Table 1 for sample location and lithology); samples diameter ~ 35 mm

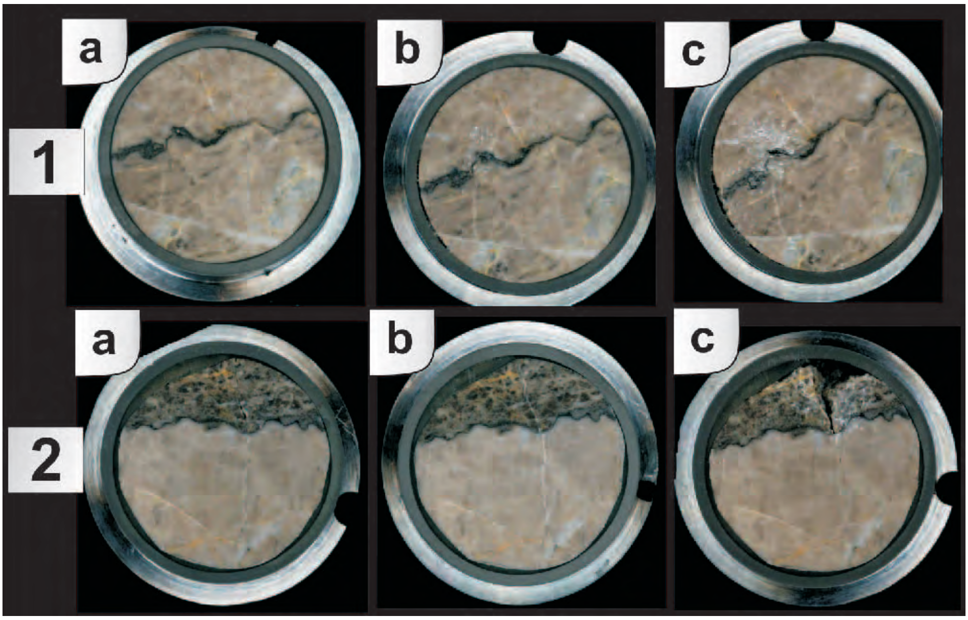

Fig. 10. Macroscopic view of specimen surfaces (nos 1 and 2) before (a), after exposure to cavitation impingement for 1 min 30 sec (b) and for 3 min 20 sec (c); samples diameter ~ 35 mm

and at weak sites in the rock structure: fractures, veins and stylolites (Text-fig. 9). In SEM images (Text-fig. 12), some of the microcracks originated from the bulk of the matrix (Text-fig. 12A), others started from grain boundaries (Text-fig. 12D, F). Within carbonate samples, dissolution processes could be observed along the surface of microcracks. Having produced a microhole at the surface, erosion accelerated inside the sample, which led to the holes generated becoming deeper and deeper (Text-fig. 12A, F). Eventually, large amounts of rock fragments were removed from each sample. Apart from the deep holes, there were scarcely any discernible indentations in the surface. A sample of mylonite, which had the most diverse mineral composition of all the samples tested, showed the least resistance to erosion (Text-fig. 12F). Grain boundaries between minerals of different hardness and the presence of mica sheets with perfect cleavage favoured extraction (Text-fig. 12E, F).

Analysis of the results has led to the conclusion that the fatigue crumbling and removal of the rock fragments was accompanied by large-scale cleavage-type cracking. The latter was probably a decisive mechanism in the destruction of the material. Holes within carbonate samples could originate as a result of dissolution processes (Text-fig. 12A-C).

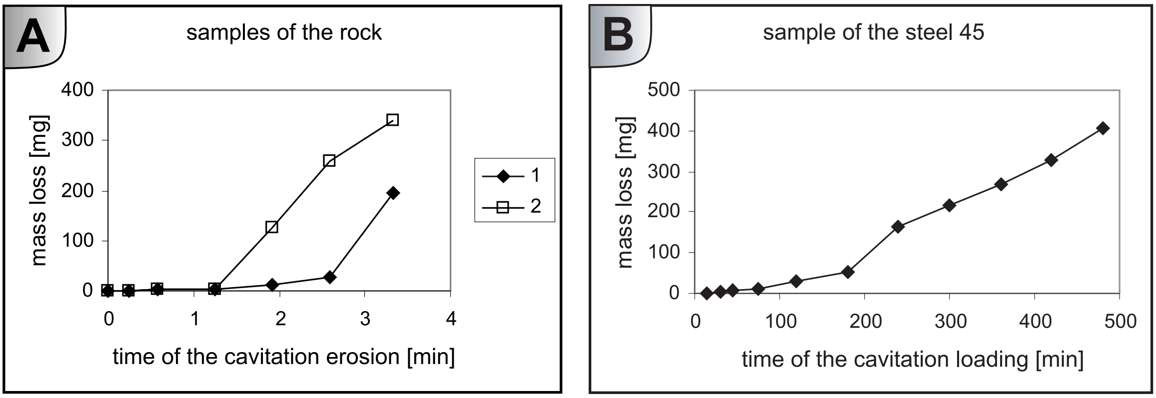

Fig. 11. A – Mass loss of samples 1 and 2 subjected to cavitation loading at the rotating disk rig; B – Mass loss of the sample made of steel 45 subjected to cavitation loading at the rotating disk

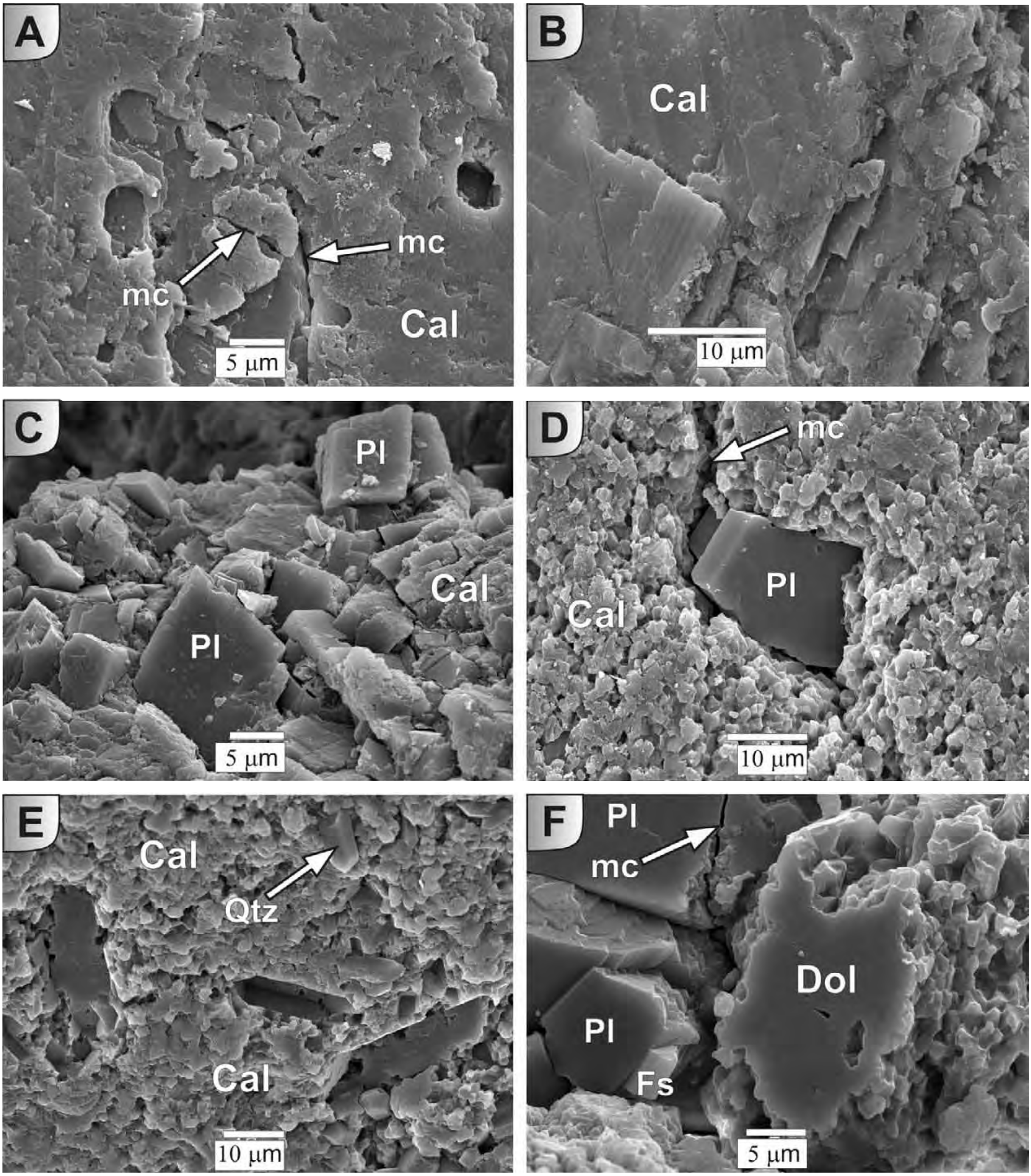

Fig. 12. SEM micrograph of specimen surface after exposure to cavitation field illustrating the damage mechanisms (Scanning Electron Microscope JSM-6380LA, JOEL, Japan) A-C – sample no 1, A – surface of the limestone with holes in the solution; B – traces of chemical and mechanical erosion appearing along growth zones in calcite (Cal); C, D – authigenic grains of plagioclase (Pl) isolated due to selective solution and destruction of calcite background; D – increased etching of calcite (Cal) along microcrack (mc) originates from the grain of plagioclase (Pl) D-E – sample no 3, F – sample no 10. E – 3 holes generating due to extraction of authigenic quartz grains; isolated crystal of quartz (Qtz) saved from damage is clearly visible in upper part of the photograph; F - authigenic grains of plagioclase (Pl) and Ca-feldspar (Fs) isolated due to selective solution and erosion of Fe-dolomite (Dol); in upper part clearly visible microcrack (*mc*) within grain of plagioclase

## FURTHER DISCUSSION ON THE POSSIBILITY OF THE OCCURRENCE OF CAVITATION RELATED PHENOMENA WITHIN A FAULT FISSURE

In the Tatra Mts., the pressures and temperatures of the order of ~85-120 MPa and 150-200°C respectively that obtain at a depth of 4-5 km would tend to inhibit the inception of cavitation. One could expect suppression of cavitation nuclei. However, in the case of the conditions described, additional circumstances should be taken into account. The pressure of water released by means of the "hydrotectonic pump" mechanism could be locally substantially lower than the above-mentioned values (immediately after the onset of fault-wall displacement). This phenomenon can be easily explained by the appearance of huge empty spaces during wall-rock rapid movement and their subsequent filling with water. Such rapid displacement with a high slip velocity could have originated due to an earthquake. For example, for the 1995 Kobe earthquake (M=7.2), IDE & TAKEO (1997) cited a 0.8 m/s slip velocity at the southern part of the fault. SHIMADA & *al.* (1996) estimated that the maximum slip velocity for the 1984 Western Nagano earthquake (M=6.8) was greater than 2 m/s. During fault motion, the speed of fluid migration within a fault fissure could be presumably much higher. The fluid pressure field depends essentially on the flow geometry. It is reasonable to expect a local decrease in pressure down to the critical (cavitation inception) value in the slots and nozzles formed between subsequent cavities in the shear zone, as well as on numerous, randomly distributed surface irregularities. In particular, one can expect inception of cavitation in the vortex structures resulting from turbulent flow and flow separation from a solid surface. The significant pressure drop in the cores of vortices developing in the flow separation zone promotes development of the so-called vortex cavitation, which is usually considered to be the most destructive form of this phenomenon. Additional factors promoting bubble nucleation in the fault fissure are: (a) increased contamination of water with solid particles or non-water molecules; however, an excessive density of such contaminants leads to suppression of cavitation; and (b) size effect. It is worthwhile to notice that large dimensions of chambers originating from shearing processes lead to higher cavitation susceptibility of the flow system than in the case of geometrically similar lab installations. This well-known cavitation inception scaling effect is due to an increase in the time available for the development of cavitation nuclei up to their critical size. Increasing the number of critical cavitation nuclei and the size of collapsing cavities is mechanism of cavitation damage scaling effect responsible for the non-linear intensification of the material destruction process in case the geometrical scale of the flow system is increased.

Moreover, the generation of cavitating jets at the onset of displacement of the wall-rocks is very likely. One could expect the cavitating jets to have parameters resembling those commonly met in laboratory rigs, where, as a rule, the pressure reaches 20 MPa and the flow velocity 100 m/s.

Last but not least, one should mention the synergistic effect of cavitation and slurry erosion, quite common in the case of intense fragmentation of the wall-rock. This phenomenon has been the subject of intense studies by some researchers in the past (eg. KOUTNY 1989) who proved the existence of such an effect in hydraulic equipment.

## CONCLUSIONS

Cavitation is a phenomenon associated not only with hydraulic equipment; it could originate within a shear zone and play a key role in the mass loss processes.

In the Tatra Mts., the geometric complexity of the nappe structures and the morphology of the shear surfaces resulted from selective damage of the rheologically heterogeneous wall-rock. During cyclical shearing and tectonic transport processes, a key role was played by fluids and associated hydrotectonic phenomena. Repeated reactivation of these processes could have been responsible for the increasing mass loss and could have caused the morphology of the shear zones to become increasingly complex. Hitherto, a large scale of the mass loss was explained mainly by mechanical disintegration and pressure solution. In addition to these processes, cavitation erosion supported by the hydro-abrasive wear could have been responsible for substantial mass loss along shear surfaces. The phenomenon of cavitation, which is related to repeated growth and collapse of bubbles in liquids due to local pressure fluctuation, could also have been responsible for the unstable P-T conditions (as well the hydrothermal effects) at the sole of the nappes that have been repeatedly documented. The main factors promoting the occurrence of cavitation and cavitation erosion within a shear zone include: a) a compressional regime in which high fluid overpressures are easier to sustain and in which the highest amplitude fluid-pressure cycling is enabled; b) high porosity of country rocks which could be a source of liquid; c) rapid fault movement resulting in high and variable speed of fluid flow, squeezed through the shear zone; d) lithological and rheological variability which determine the structural anisotropy of the shear surface, and narrowing and widening of the shear fissure during fault movement, resulting in a rapid drop in fluid-pressure, thereby favouring the development of cavities.

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