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Jerzy BALWIERZ, Stanisław DŻUŁYŃSKI

EXPERIMENTS ON ROCK DEFORMATIONS PRODUCED BY UNDERGROUND KARST PROCESSES

(Pl. I—II and 7 Figs)

Doświadczalne deformacje krasowe

(Tabl. I—II i 7 fig.)

Abstract: This paper presents the results of model experiments on rock deformations, produced by underground karst processes. The passage of water through plaster-of-paris models of fractured and bedded strata gave rise to solution collapse breccias, gravity faults and related deformations, similar to those known from nature.

INTRODUCTION

This paper presents the results of simple experiments on karst deformations, resulting from dissolution of rocks by underground waters. Such deformations include solution collapse breccias, gravity faults and other disturbances consequent upon the solution removal of minerals („karst microtectonic" of Rodionov 1971, „karst tectonics" of Dżułyński 1976).

The experiments discussed were made on small-scale models. Like many other experiments in geology, those here described are based upon the assumption that „Nature on the small scale and on the great acts always by the same laws and is ever analogous to herself" (Paul Frizi, 1762, quotation after Mavis et al. 1935). The results of our experiments do not represent complete reproductions of larger scale natural processes but simulate some of the principles involved in such processes. It will be shown, however, that the geometry of experimental structures and sequence of forms, observed in the experiments, conform to the geometry and sequential development of the much larger structures, occurring in nature (for example, see Meistrel, 1966).

The experimental investigations on karst features have already a long history (Saint Vincent, 1819, Stanislaus Meunier, 1875, 1899 —

fide Watson 1965). The earlier experiments, however, were chiefly concerned with the geometry of cave passages (e.g. Lange, 1959; Mowat, 1962, Reams 1965; Evers, 1966), the rates of dissolution (e. g. Kaye, 1957; Roques and Eck, 1973) and minor features revealed by the walls af cave (Rudnicki, 1958; Curl, 1974). Little experimental work has been done on karst deformations and only passing remarks to this subject have come to our attention (e. g. Beales and Oldershaw, 1969).

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APARATUS AND MODEL MATERIALS

The experiments were conducted in glass — and plastic — walled tanks provided with input and discharge orfices to ensure the flow of water (Fig. 1). The water was supplied to the tanks through rubber pipes connected to a constant level tank. The discharge orfices were also provided with rubber pipes to regulate the positions of water table and to

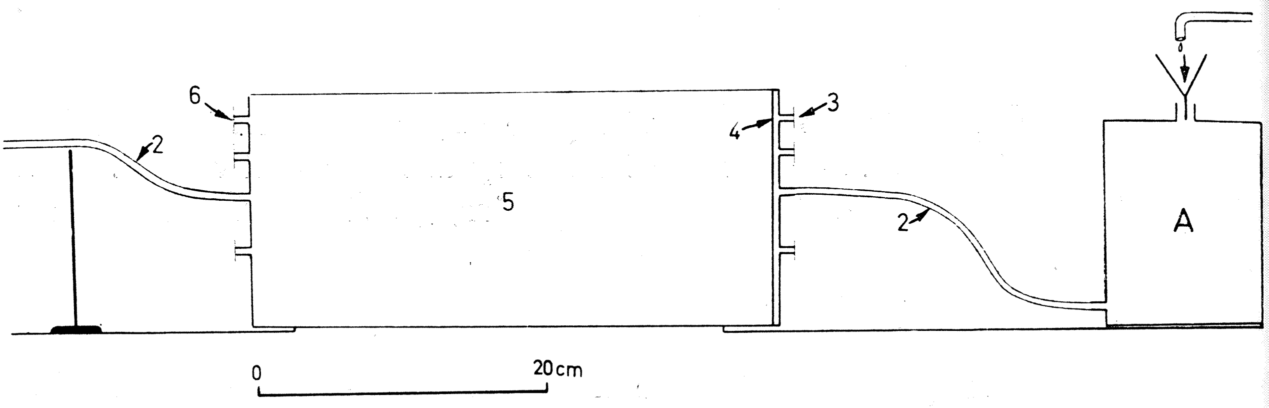


Fig. 1. Sketch showing arrangement of apparatus. 1 — constant level tank; 2 — rubber pipe; 3 — input orfices; 4 — diverting screen; 5 — main tank; 6 — discharge orfices

Fig. 1. Schemat urządzenia doświadczalnego. 1 — zbiornik wyrównawczy; 2 — przewody gumowe; 3 — otwory wlotowe (wprowadzające); 4 — przesłona odchylająca strumień; 5 — główny zbiornik modelowy; 6 — otwory odprowadzające wodę

keep the models under conditions of complete saturation, if necessary.

The model materials used were; plaster-of-paris and commercial „drawing chalk" made up of the crushed plaster-of-paris. Such model materials, are susceptible to dissolution (corrosion) and mechanical removal of particles (corrasion) by circulating water.

The model materials were sawed into slabs of convenient size. The slabs were then fitted and clamped together into tanks to produce simple models of fractured and stratified rocks. The major requirement for karst deformation is fracturing of the rock and/or the presence of bedding discontinuities. The models produced were not intended to simulate the karst aquifers, but sets of fractured strata whereby the fitted surfaces of slabs were meant to simulate the transmissive joint and bedding planes.

PROCEDURE

Water was introduced into the tanks from one of the inlet valves and a continuous flow established over time periods of suitable length. The rates of flow ranged from 2 to about 30 liters per hour. The stages of progressive dissolution and resulting changes were observed and photographed at time intervals from 5 to 10 hours. No attempt was made to record the rates of dissolution.

The water was introduced into the tanks as an intergrated jet and diverted round the corners of the tanks by special screens (Fig. 1). The water then flowed laterally, downwards and upwards along transmissive fractures of the model structure. Caverns and related deformations were formed simultaneosly at various levels and at random depth below the water table.

In some of the experiments, the breaking down of caverns was speeded up by slight shocks inflicted by tapping the walls of tanks. By this our experiments have not been made less realistic. It should be borne in mind that earthquake shocks are among the impulses triggering collapse (see e. g. Maksimovich, 1969; White and White 1964 and others).

MODEL EXPERIMENTS

The model experiments discussed below fall into two groups. 1. experiments on models, simulating horizontal strata and, 2. experiments on models simulating steeply dipping beds.

In each of the experiment conducted the initial configuration of slabs went through a succession of changes. The selected and representative stages of such changes are shown in Figs. 1—7, and Pl. I, II. The figures are largely self-explanatory and text explanations are kept to the minimum, necessary for the clarity of the discussion.

The experiments were conducted in open tanks with a free water table and in closed containers under a confinement, simulating artesian conditions. In both instances the results were essentially similar.

Experiment I

The first experiment to be discussed is that shown in Fig. 2. It concerns the model simulating a set of horizontally disposed and jointed layers of varying thickness.

The Figs. 2A-F show progressive stages of dissolution and deforma-

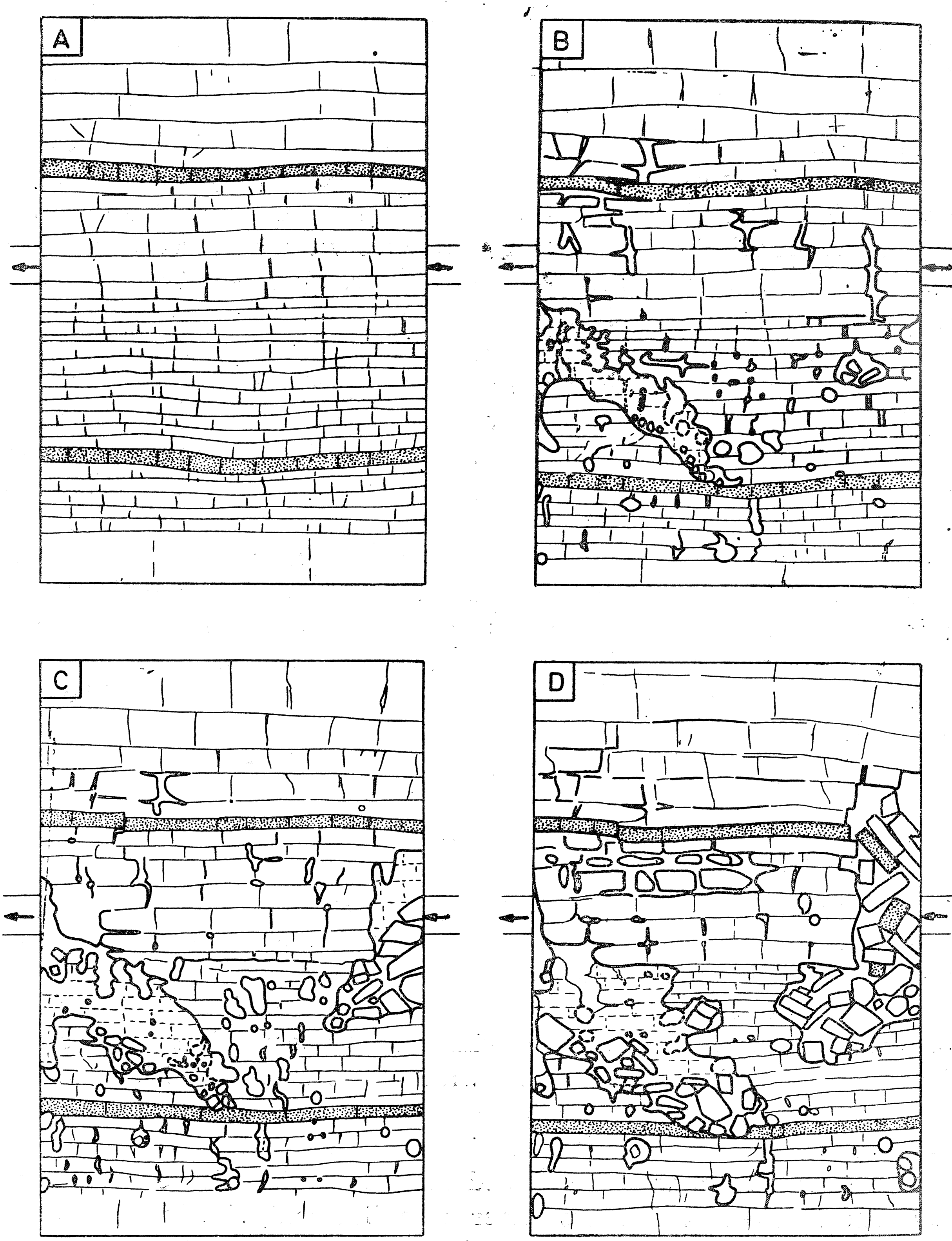


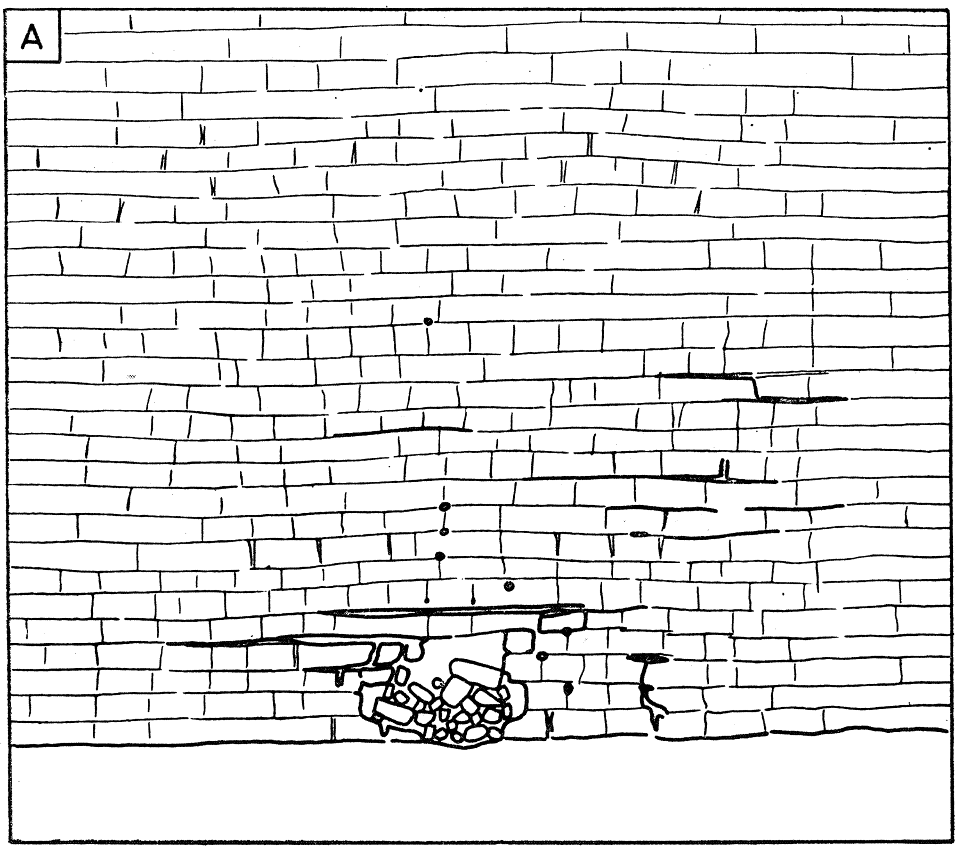
Fig. 2. Experimental effects of dissolution in horizontal and fractured layers under constant phreatic conditions. Flow of water from right to left (arrow). „A" ... „F" successive stages of dissolution and deformation. Progressive (down-current) and retrogressive (up-current) development of longitudinal caves is initiated from input and discharge sides of the main tank. Note transverse solution caverns fixed along fractures and intersections of fractures. Transverse caverns are produced by water diverted from main flow towards observer. „F" shows final collapse breccia with solutionally obscured lower boundary. Detached and broken fragments of upper stippled layer indicate extent of vertical displacement of fragments. Note solutional roundening of fragments close to lower boundary of breccia

Fig. 2. Zmiany i zaburzenia w układzie spękanych i poziomych warstw przy przepływie wody od prawej ku lewej w warunkach freatycznych. Kawerny rozwijają się równocześnie od strony otworów wprowadzających i wyprowadzających wodę. Pierwsze rozprzestrzeniają się zgodnie z prądem, drugie pod prąd. Obok podłużnych kawern tworzą się kanały poprzeczne o kolistych przekrojach. W miarę powiększania, kawerny ulegają zawałom. Rys. „F" przedstawia końcowy etap takiego procesu

tions, effected by the flow of water, directed from right to left, chiefly in the plane of the section depicted.

In the first stages of dissolution, minor tubular channels are formed. Such channels display a braided and winding pattern, and are very similar to natural bedding-plane anastomoses. The tubular channels tend to form along the tightly fitted slabs. With progressing dissolution, some of the tubular channels become enlarged into irregular cave passages. More commonly, however, the experimental caves, like natural ones, tend to develop along the fractures and their intersections.

Because of the intergration imposed by the orfices, the formation of larger solution channels is initiated simultaneously from both the input and output ends of the tanks (Fig. 2C). The caverns that form near the input end are being enlarged and propagated in the direction of flow. Those forming near the outlet spread headwards, that is, in the upcurrent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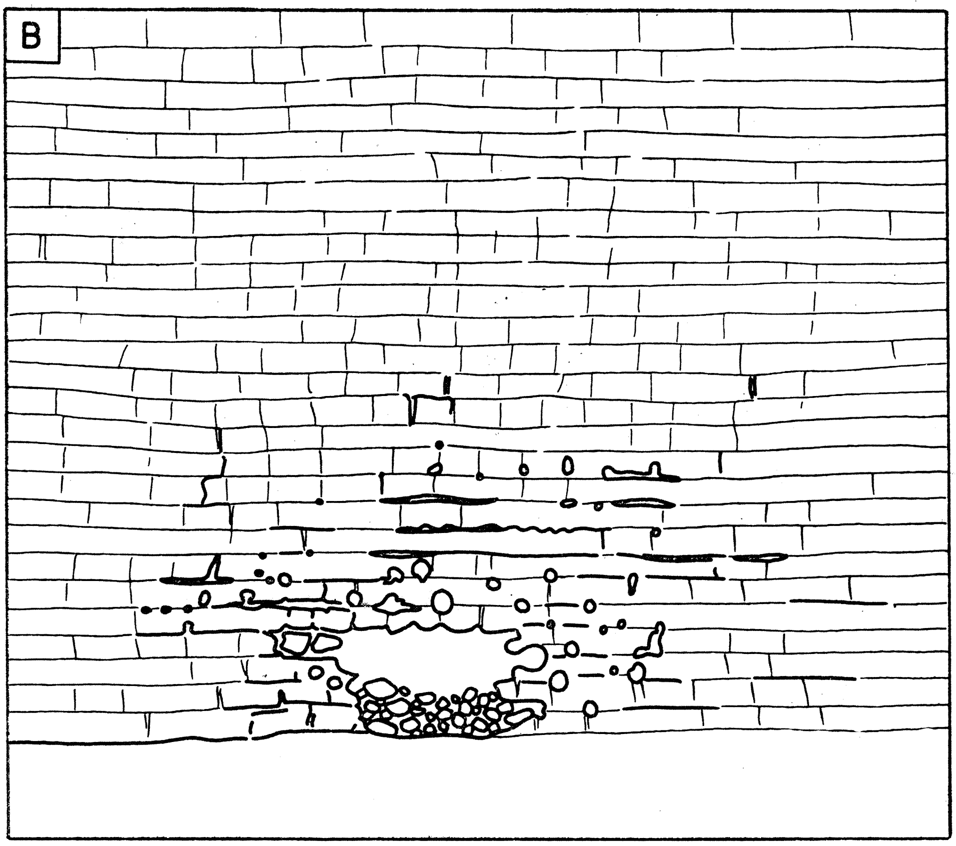
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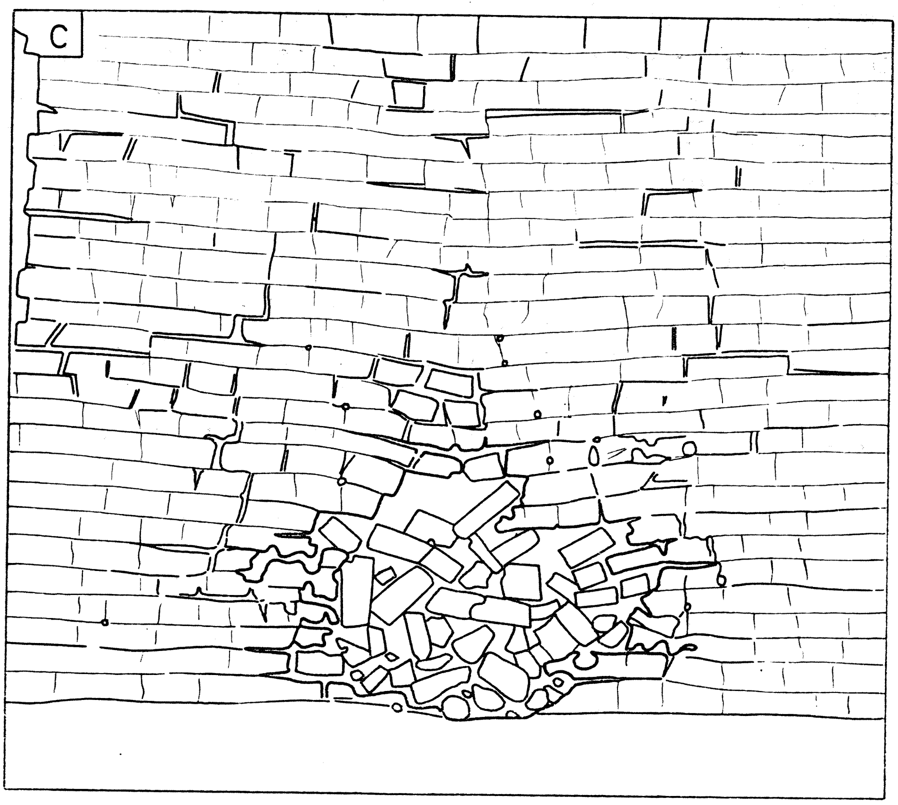

Fig. 3. Dissolution and deformation under constant phreatic conditions by water jet flowing towards observer. „A", „B" and „C" show selected stages of dissolution and collapse. „A" illustrates partly collapsed cavern with angular profile. „B" shows more advanced stage of dissolution of same cavern. Note formation of satellite solution channels around master conduit and solutionally rounded fragments on floor of cave. „C" shows same cave after collapse. Tumbled and rotated fragments in central part pass laterally and upwards into crackle breccia. Lower boundary sharply defined

Fig. 3. Powstawanie kawerny i zawałów w warunkach freatycznych w przekroju prostopadłym do kierunku strumienia (w stronę czytelnika) „A", „B" i „C" wybrane stadia zmian w modelu. „A" przedstawia przekrój kawerny o łamanym zarysie. „B" ta sama kawerna po dalszym rozpuszczaniu. Zwrócić uwagę na mniejsze kanały utworzone równolegle do kierunku głównej jaskini oraz na zaokrąglone przez rozpuszczanie fragmentów na dnie tej jaskini. „C" jaskinia po zawale. Bezładna brekcja w części środkowej przechodzi w górę i na boki w brekcję mozaikową i system rozwartych szczelin

direction, like natural meteoric caves which develop retrogressively from the springs.

As it is to be expected, with further enlargement, the caves produced suffer from roof failure and solution collapse. In very advanced stages of dissolution, the whole set of layers, is transformed into an irregular array of angular and solutionally rounded fragments (Fig. 2F and Pl. I).

Experiment II

Fig. 3 illustrates three selected stages of dissolution and brecciation as seen at right angles to the direction of flow. „A" shows an already advanced stage of development with a partly collapsed cave displaying a rectangular profile. „B" illustrates the same cave after more dissolution has taken place. The profile of the cave is here less angular and fallen fragments exhibit solutional rounding. Of particular interest are here the newly formed tubular solution channels, localized around the „master" conduit and trending parallel to it. „C" shows the breccia body that originated from further solutional enlargement and collapse of the cavern depicted in „B" (see Pl. II).

Experiment III

Fig. 4 shows two selected stages of dissolution and brecciation, consequent upon the flow of water through a model made up of horizontally disposed layers. „A" shows joint-controlled solutional caverns oriented at right angle to the main flow direction (from right to left). „B" shows

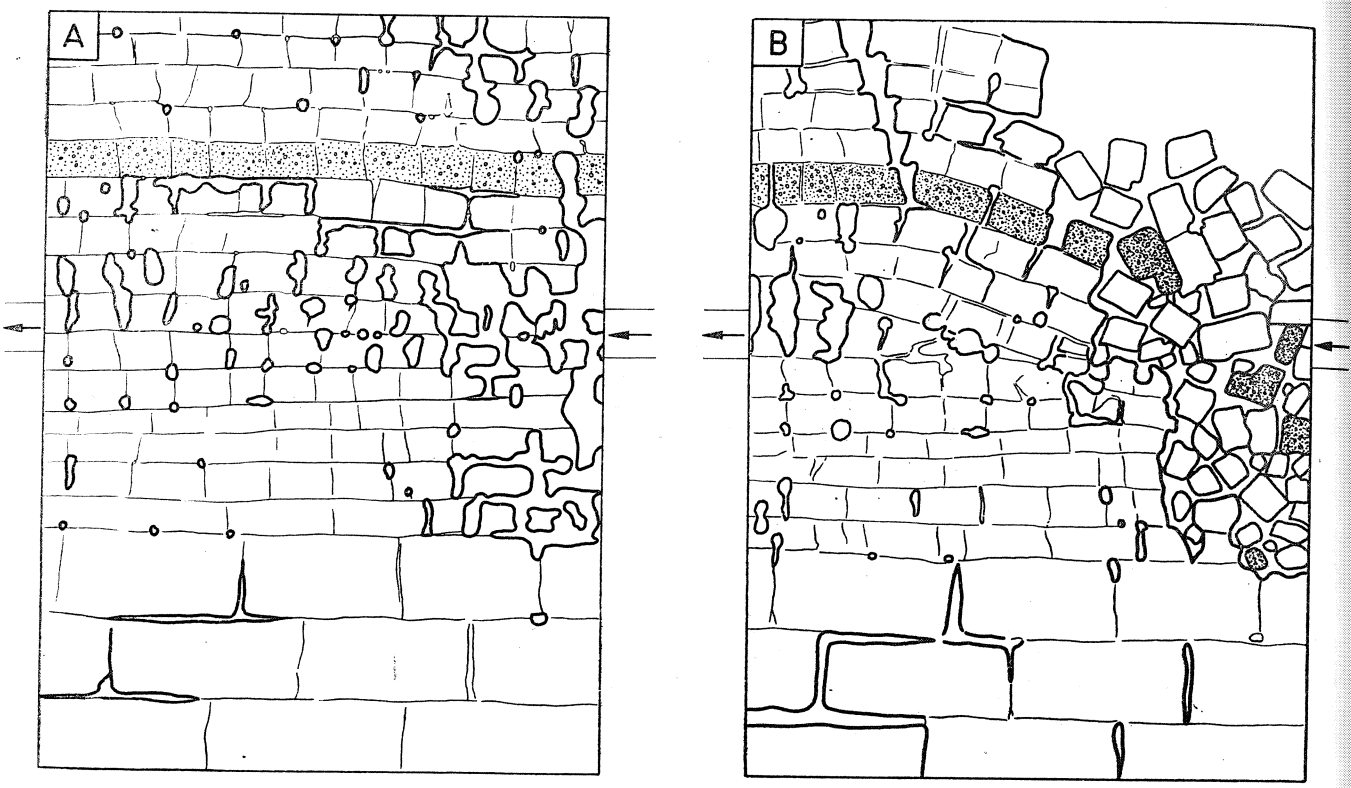

Fig. 4. Two selected stages of dissolution and brecciation under phreatic conditions. Flow direction from right to left. Caverns seen in „A" are produced by transverse currents diverted from main flow towards observer. Note bending of layers and solution thinning close to area of maximum brecciation (B)

Fig. 4. Wybrane stadia rozpuszczania i zaburzeń w warunkach freatycznych. Główny kierunek przepływu z prawej ku lewej. Jaskinie rozwinięte wzdłuż szczelin i na ich przecięciu (A) powstały w wyniku rozszczepienia strumienia głównego na przepływy boczne skierowane prostopadle do kierunku strumienia. Zwróć uwagę na ugięcie warstewek w pobliżu strefy brekcjowej (B)

a further stage of development with a solution collapse breccia, formed close to the inlet valve. Of particular interest here is the bending of layers, adjacent to the area of maximum dissolution and brecciation. Such downward bending is due to solutional thinning and solutional removal of part of the layers, affected by the flow of water.

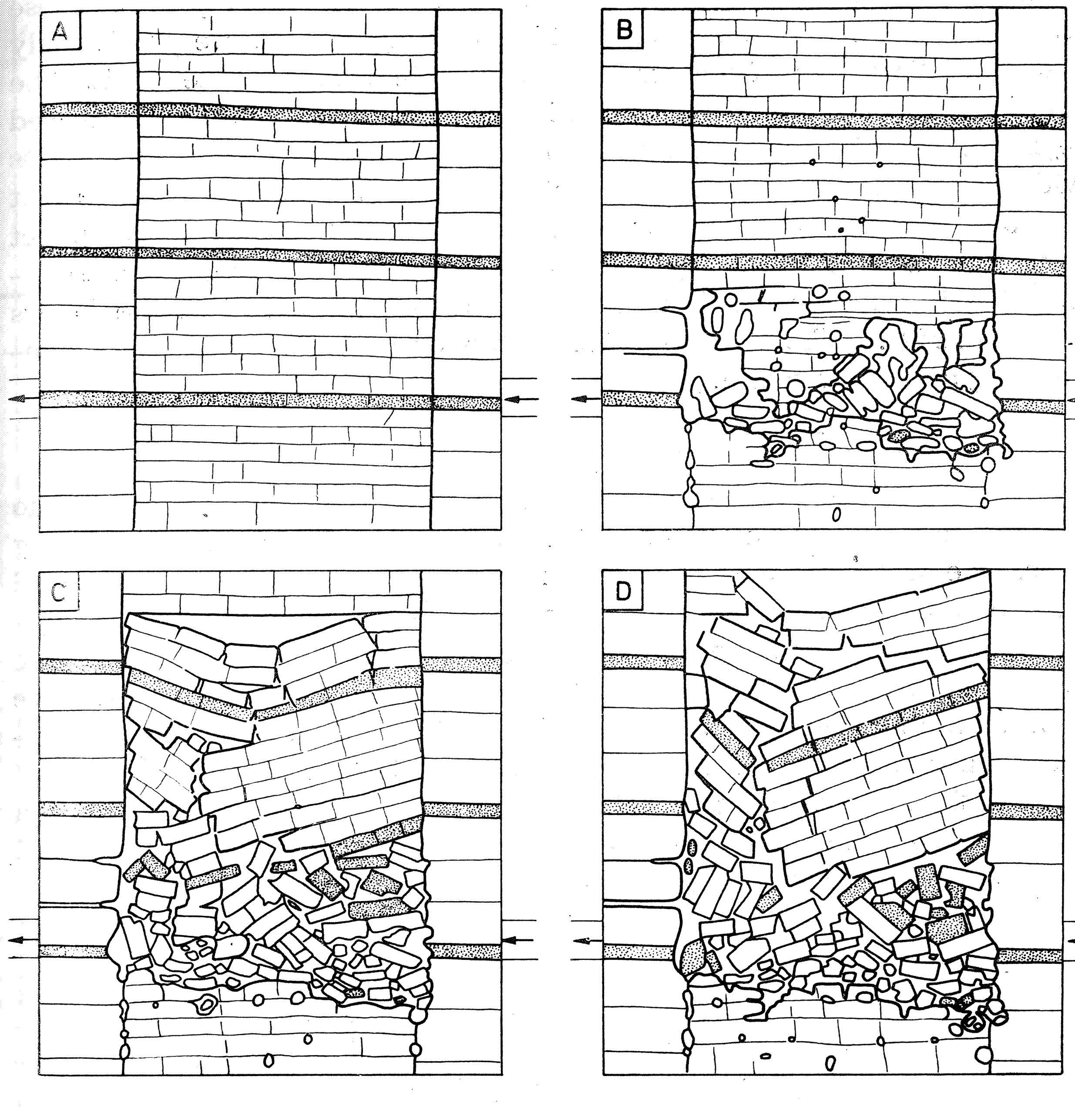

Fig. 5. Selected stages of dissolution and deformation in horizontal layers differing in thickness and cut by two vertical discontinuities simulating fault planes. Experiment carried under constant phreatic conditions. Main flow from right to left. Flow concentrated at level with orfices. Solution caverns seen in figures represent chiefly transverse deviations from main flow. Note uneven settling and tilting of layers overlying zone of maximum dissolution and collapse. Note formation of open sag fractures and displacement along vertical discontinuities

Fig. 5. Wybrane stadia rozwojowe w modelu, w którym dwie prostopadłe powierzchnie nieciągłości pozorują powierzchnie uskokowe. Główny przepływ skierowany od prawej ku lewej, lecz formy krasowe widoczne w przekroju rysunku powstały głównie przez prądy poprzeczne odchylone od zasadniczego kierunku przepływu. Kawerny rozwijają się również wzdłuż prostopadłych powierzchni nieciągłości tworząc otwarte szczeliny, wzdłuż których ma miejsce osiadanie zespołu cienkowarstwowanego. Zwróć uwagę na pochylenie i łamanie warstw osiadających w wyniku walenia się stropu kawerny oraz tworzenie się rozwartych szczelin wzdłuż poziomych powierzchni nieciągłości

Experiment IV

Fig. 5 shows selected stages of dissolution and deformations in a model in which the two vertical discontinuities simulate fault planes. These discontinuities separate the highly fractured layers that are particularly prone to dissolution from those that are less susceptible to it. The caverns are preferentially localized in the lower part of the thin-layered segment. The dissolution works its way also along vertical discontinuities widening them into open fissures. Consequently, with further enlargement and collapse of caverns, the whole set of the overlying layers is subject to unequal settling along the above mentioned discontinuities. The down--settling is combined with tilting and further fracturing of the layers involved. Figs. „B", „C" and „D" show the successive stages of the down--settling and deformation.

Experiment V

The model depicted in Fig. 6 differs from those discussed hitherto in that the layers are disposed obliquely to simulate steeply dipping beds. The water table is here in a relatively low position as compared with that in previous experiments, and the main dissolution is concentrated near the top of the phreatic zone. Fig. 6 „B" shows the structure after collapse of the „water table cave". The former floor of the cave is seen as a sharply defined, irregular solution surface. The layers overlying the solution surface have settled differentially with a distinct offset toward the right with respect to undisturbed layers below the solution surface. The differential settling of layers resulted in a number of small „reversed" faults along steeply dipping „bedding" surfaces.

DISCUSSION OF THE RESULTS

Although our considerations are primarily concerned with deformational structures, a few comments needed on the geometry and progressive changes in the shape of incipient voids, subjected to dissolution under phreatic conditions.

The observed progressive changes are in agreement with those predicted theoretically (Lange, 1959) and obtained experimentally by earlier workers (e. g. Lange, 1959; Mowat, 1962). Thus, the interior sharp edges of small voids become rounded and the voids themselves enlarged into circular conduits (Figs. 1, 2) by the erosive action of cross-currents. Wider linear openings, however, may be enlarged by parallel retreat of walls and may retain their initial contours. The exterior sharp edges, inherited from a primary configuration of fractures or produced by partial coalescence of adjacent conduits, tend to be preserved in form of sharp protuberances similar to the so-called „rock

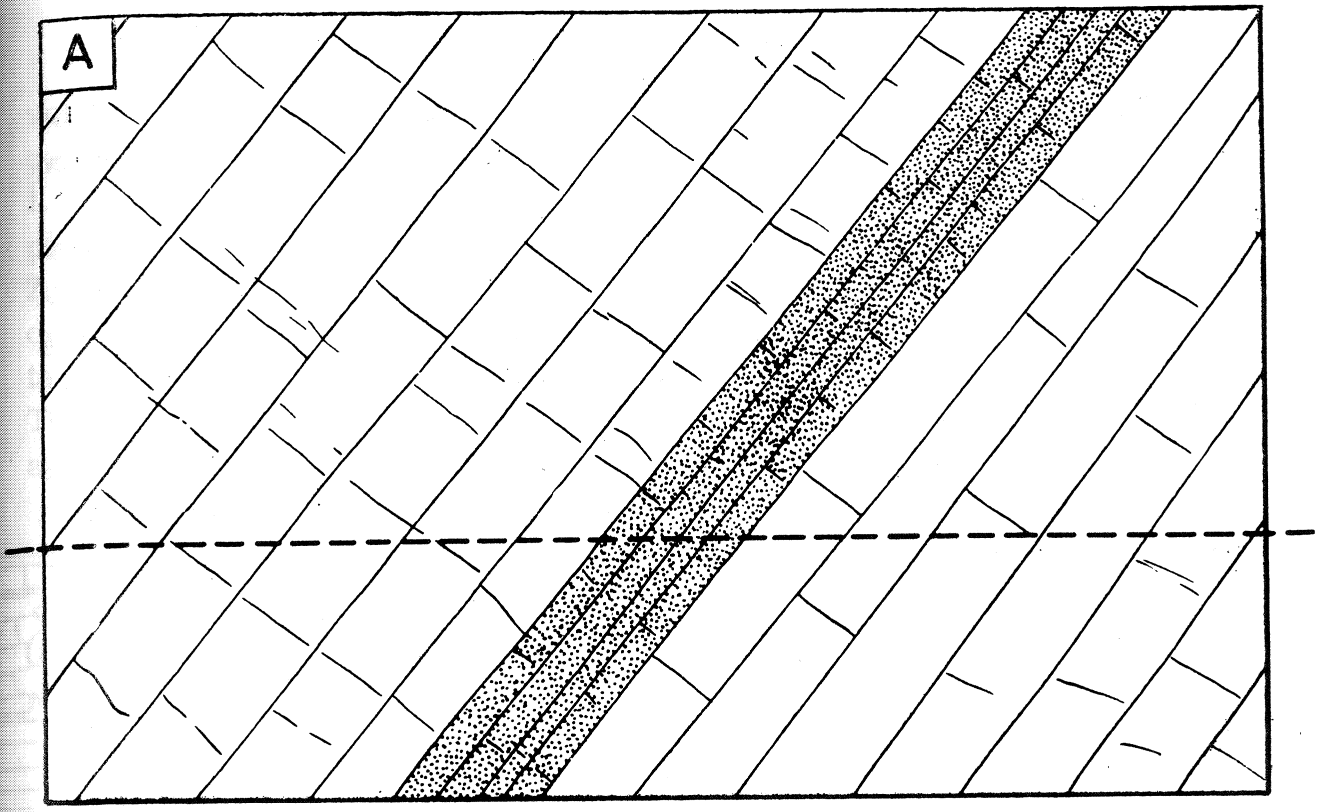

Fig. 6. Effects of dissolution in steeply dipping layers. Direction of flow from right to left. Water table indicated by dashed line in „A". „B" shows structure after collapse of longitudinal water-table cavern. Note irregular sharp solution surface at base of settled and brecciated rocks (false unconformity), gravity dip faults showing reverse orientation (x) and offset of layers overlying solution surface

Fig. 6. Wynik zawalenia się kawerny powstałej w pobliżu swobodnego zwierciadła wody (linia kreskowana w „A") w modelu przedstawiającym zespół pochylonych warstw. Kierunek przepływu z prawej ku lewej. „B" struktura po zawale jaskini. Zwróć uwagę na „odwrócone" uskoki grawitacyjne (x) wzdłuż pochylonych powierzchni oraz pozorny „odstęp uskokowy" widoczny w zespole warstw cienkich

pendents", known from natural caves. In this connection, it may well be recalled that the rock pendents are held to be indicative of the dominance of corrasion over corrosion (M o v a t, 1962).

As in the case of natural braided tubes, minute surface irregularities influence the localization of winding anastomoses (see also E v e r s, 1966). The fractures, however, are the most important factors controlling the development of caves (compare: W a l d h a m, 1971; F o r d, 1971), whereby the more transmissive fractures may be preferentially enlarged.

The formation of „master conduits" does not prevent the simultaneous development and enlargement of minor satellite passages in the nearest vicinity of the master caves. Such satellite passages may be located concentrically with respect to the main passage (Fig. 3B).

In models, composed of tilted slabs, the caverns show a „jagged", vertical, longitudinal profile (fig. 6). This confirms both theoretical expectations and observations, made in natural caves (F o r d, 1971).

With further enlargement, the experimental caverns suffer from roof failure and collapse in the same way as do the natural caves developed in fractured rocks. The mechanism of cave breakdown has been dealt with by several authors (e. g. D a v i e s, 1951; W h i t e and W h i t e, 1964). The results of our experiments confirm much of what has been said on this subject and there is no need to dwell on it in details. Instead, we shall concentrate on same controversial and less exploited questions.

In the presence of flowing water, the cave breakdown as observed in experiments, occurs repeatedly under phreatic conditions. Piecemeal or massive collapse begins as soon as the cave becoms sufficiently large and/or the enclosing „rock" is weakened by the appearance of satellite channels. In such situations mechanical impulses are among important factors triggering collapse. A siphonage effect, manifested in periodic draining and inundation of caves may be important in promoting cavern collapse. The rapid return of water into a temporarily emptied cave system is particularly effective in this regard. Significantly, however, the more loss of buoyant support by draining of water-filled experimental caverns appears to be of minor significance.

Cavern collapse produces characteristic solution collapse breccias. By jamming of broken fragments the further collapse may be temporarily arrested. If, however, the rock fragments are subject to dissolution the process of cave breakdown is reactivated. With prolonged flow of aggressive waters through the breccia body, the processes of down--settling, brecciation and faulting spread upwards, involving successively higher layers and may extend into the vadose zone.

The cavern collapse is one of the most important factors promoting the formation of breccias. Such breccias may, however, originate in the absence of large caves. In general, depending on the size of incipient voids and the integration of flow, the breccias produced by karst processes may be divided into two groups:

1. Monocentric cave collapse breccias originating from massive and/or piecemeal roof failure of larger caverns (Fig. 3).
2. Polycentric, solution derangement breccias, resulting from piecemeal derangement of fractured rocks (or model materials), subject to simultaneous dissolution along a great number of transmissive fissures (Fig. 7).

The distinction, indicated just above, has already been implied by several authors, but seldom, if ever, definitely stated.

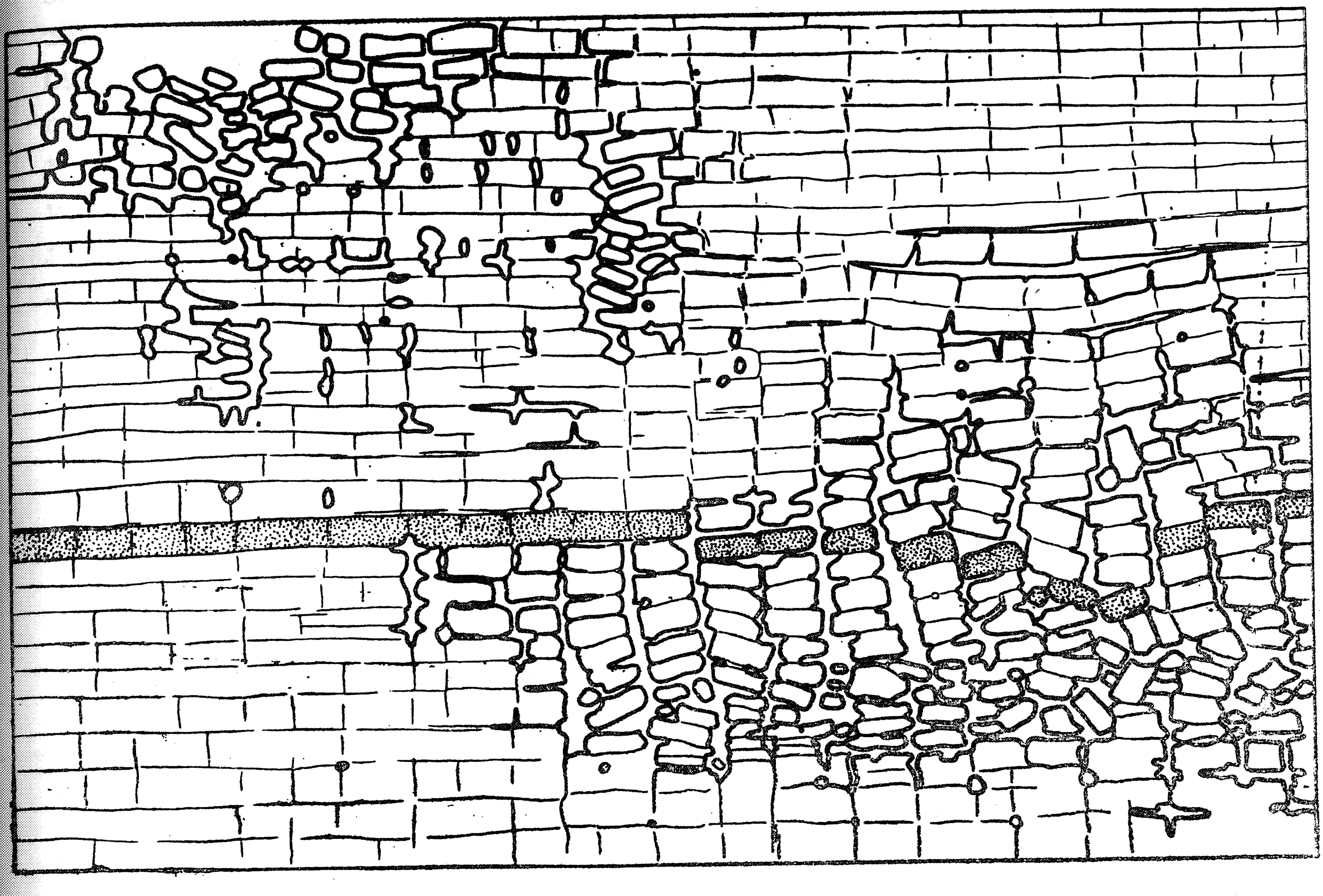

Fig. 7. Solution derangement breccias produced experimentally under phreatic conditions in horizontal layers

Fig. 7. Brekcje krasowe powstałe w warunkach freatycznych bez uprzedniego wytworzenia się większych pustek. Brekcje takie powstają przez równoczesne poszerzanie większej ilości spękań w następstwie przepływu agresywnych wód

The monocentric cavern collapse breccias are characterized by the presence of sharply defined solution surfaces at the base of the breccia bodies. Such surfaces represent the floors of collapsed caverns. The solution derangement breccias are devoid of such surfaces. It should be borne in mind, however, that the solution surfaces discussed may be blurred and masked by the development of satellite conduits and dissolution along fractures (Fig. 2F). This is particularly apparent in breccias, underlain by thin and closely fractured layers (Pl. I).

No attempt will be made to animadvert on various natural deformations, resulting from dissolution. There are many references to such deformations in the existing literature. The reader is here specifically referred to publications, concerning the Mississippi Valley and Silesian type of Zn—Pb deposits, inasmuch as this work has been designed to produce the esperimental analogues of the solution collapse breccias, characteristic of such deposits (see B o g a c z et al. 1970, M c C o r m i c k et al. 1971, S a s s - G u s t k i e w i c z 1974).

Although karst deformations are familiar to geologists their implications have not always been fully appreciated. The experiments make us aware of the importance of such deformations and are instructive for the light they may throw on the origin of some of the faults in karstified rocks. Such faults and notably hose observed in recent caves are often indiscriminately attributed to tectonic processes. From the foregoing, it appears that in studying such faults we must not overlook the possibility that some of them resulted from cavern collapse and/or that subsequent karst processes might have rejuvenated the true tectonic faults by solutional removal of soluble rocks.

Polish Academy of Sciences, Department of Geology. Mailing adress:
Jagellonian University, Institute of Geological Sciences
30-063 Kraków, ul. Oleandry 2a

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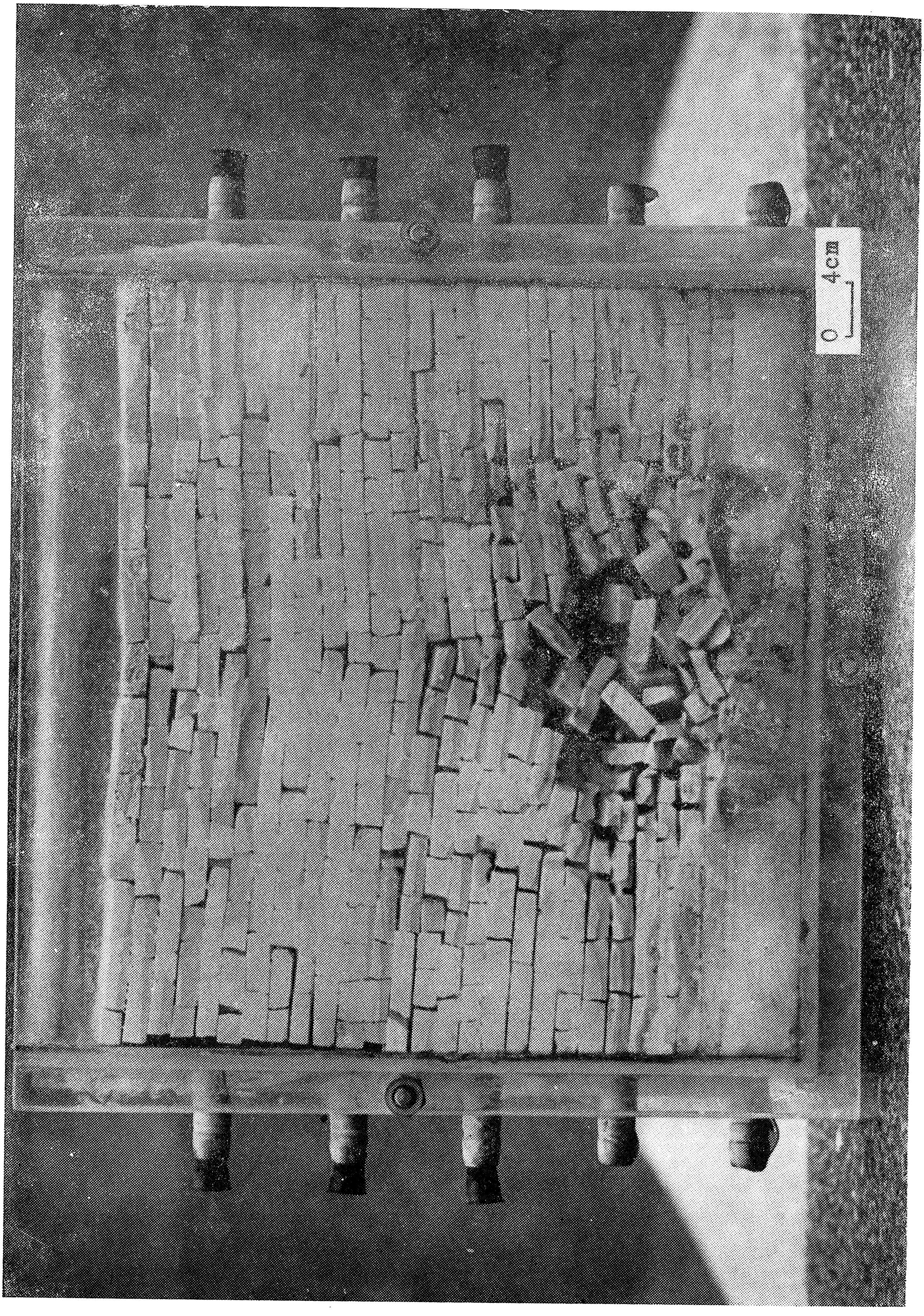
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STRESZCZENIE

Jednym z przejawów zjawisk krasowych zachodzących pod powierzchnią ziemi są mechaniczne zaburzenia skał podlegających rozpuszczeniu. Zaburzenia takie przypominają deformacje tektoniczne w ścisłym słowa tego znaczeniu i za takie bywają niekiedy uważane. Najpospolitszymi formami zaburzeń krasowych są okruchowce zawałowe (brekcje zawałowe), spękania i uskoki związane z waleniem się stropów jaskiń i nierównomiernym osiadaniem. Dla uzyskania bezpośredniego wglądu w zaburzenia tego rodzaju przeprowadzono szereg prostych jakościowych doświadczeń nad modelami sporządzonymi z płytek gipsowych lub tak zwanej „kredy tablicowej", która również składa się z gipsu. Modele przedstawiały najprostsze układy spękanych i warstwowych skał. Zostały one zbudowane w odpowiednio do tego celu sporządzonych zbiornikach (ryc.

1) i poddawane rozpuszczeniu w warunkach freatycznego przepływu. Załączone w tekście ryciny przedstawiają kolejne stadia tworzenia się kawern oraz deformacji związanych z zawalaniem się pustek powstałych przez rozpuszczanie.

Zakład Nauk Geologicznych PAN. Adres pocztowy:
Instytut Nauk Geologicznych UJ, 30-063 Kraków
ul. Oleandry 2a

EXPLANATION OF PLATES
OBJAŚNIENIA TABLIC

Plate — Tablica I

Final stage of deformations in experiment I. Compare Fig. 2 F in the text
Końcowa faza zaburzeń w doświadczeniu I. Porównaj fig. 2 F w tekście

Plate — Tablica II

Cavern collapse breccia formed in experiment II. Compare Fig. 3 C in the text
Brekcja zawałowa utworzona w doświadczeniu II. Porównaj fig. 3 C w tekście