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TRIASSIC CARBONATES AS THE HOST ROCK FOR KARSTIFICATION: TENGLONG CAVE AND THE LICHUAN KARST (WEST HUBEI, CHINA)[1]

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(5 figures and 3 plates)

ABSTRACT.- Triassic carbonates deposited on the Yangtze Paraplatform in the Tethyan realm were studied petrographically during a karst research project in West Hubei (China). The carbonates form part of a 1000m thick Triassic sequence divided in a lower Daye Formation (T1d) and an upper Jialinjiang Formation (T1j). The Tenglong cave developed along a morphological break occurring at the transition between the T1d and T1j Formations. These consist of intensively recrystallised wackestones and subordinate grainstones deposited in a shallow epicontinental sea with oscillating depths moving frequently into supratidal conditions. The use of cathodoluminescence techniques enabled the refinement of the diagenetic succession during progressive burial until present exposure. Peculiar units such as solution collapse breccias, pseudobreccias and primary dolomites correspond to regressive phases in the sedimentary sequence, allowing a more detailed elucidation of the diagenetic history in the otherwise monotonous neomorphosed limestone succession.

KEY WORDS.- Triassic, Hubei, China, carbonates, diagenesis, cathodoluminescence, karst.

RESUME.- **Les roches carbonatées triasiques dans le karst de Lichuan et la Grotte de Tenglong (Hubei occidental, Chine)**. Des roches carbonatées se sont déposées au Trias sur la Paraplatforme du Yangtse à la bordure du Paléotéthys. Elles ont été étudiées sous l'angle pétrographique dans le cadre d'un projet de recherche sur le karst de la partie occidentale de la province de Hubei (Chine). Les carbonates font partie d'une séquence triasique de 1000 m de puissance, composée, à sa partie inférieure, de la Formation de Daye (T1d) et, pour la partie supérieure, de la Formation de Jialinjiang (T1j). Ces formations très recristallisées, qui sont atteintes d'une néomorphose d'apparence monotone, consistent en wackestones et en grainstones subordonnées, déposées dans une mer épicontinentale peu profonde que des oscillations du niveau marin ont souvent portée dans la zone supratidale. Des unités particulières sont distinguées: brèches d'effondrement-dissolution, pseudo-brèches et dolomies primaires correspondant, dans la séquence sédimentaire, à des phases de régression. L'emploi de techniques de cathodoluminescence a permis de reconstituer en détail leur évolution diagenétique depuis le dépôt jusqu'aujourd'hui.

MOTS-CLES.- Trias, Hubei, Chine, carbonates, diagenèse, cathodoluminescence, karstification.

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1.- INTRODUCTION

A karstified Triassic carbonate sequence situated in the western part of the Hubei province, close to the border with the Sichuan province (coordinates 30°20'N and 109°E) was studied in conjunction with a karst research and cave exploration project (Fig.1). Field studies were carried out in August - September 1988, as a cooperation between the Belgian - Chinese Karst and Caves Association and the Institute of Geology, Karst and Groundwater Research Division of Academia Sinica. This resulted in the recognition and mapping of the sofar longest cave in China, the Tenglong Cave (Masschelein & Zhang Shouyue, 1990).

The area covered in the present study is situated within Lichuan county (Fig.2). It coincides with the upper catchment area of the Qing Jiang or Clear River, an 800 km long tributary of the Chang Jiang or Yangtze. Outcrops of carbonate rocks are very abundant in this region as a result of the pronounced topography and the active karst features but also as a result of the frequent roadcuts and small quarries. Field observations and sampling were mostly concentrated on four areas, namely 1) the karst exploration zone around the Tenglong dry valley which reaches a length of 9.5 km, 2)inside the cave which entrance is situated at 7 km to the NE of Lichuan, 3) road sections on the Qiyue Anticline along the Lichuan - Wanxian road, 4) the north slope of the Jinzishan Synclinorium along the Lichuan - Enshi road (Fig.2). For this reason no complete stratigraphic sections could be measured nor was it possible to establish any detailed stratigraphic correlations with the type areas.

The objectives of the present sediment petrographical study were twofold : firstly to provide an insight in the depositional environment and diagenetic evolution of the Triassic carbonate sequence, and secondly to clarify its control on the karstification and cave development.

2.- GEOLOGICAL FRAMEWORK OF THE LICHUAN KARST

2.1.- STRUCTURAL OUTLINE

Lichuan county which contains the Tenglong cave system, forms part of the folded Sichuan block or Yangtze Paraplatform developed on the Precambrian Yangtze craton. The thick sedimentary cover of this craton is composed of marine siliciclastics and intercalated carbonates (Cambrian to Permian), grading into marine carbonates (Lower and Middle Triassic) and finally into Upper Triassic to Jurassic molasse deposits with coal (Hsieh & Chao, 1925; Zhang, Liou & Coleman, 1984)-(Fig.3). The Triassic carbonates

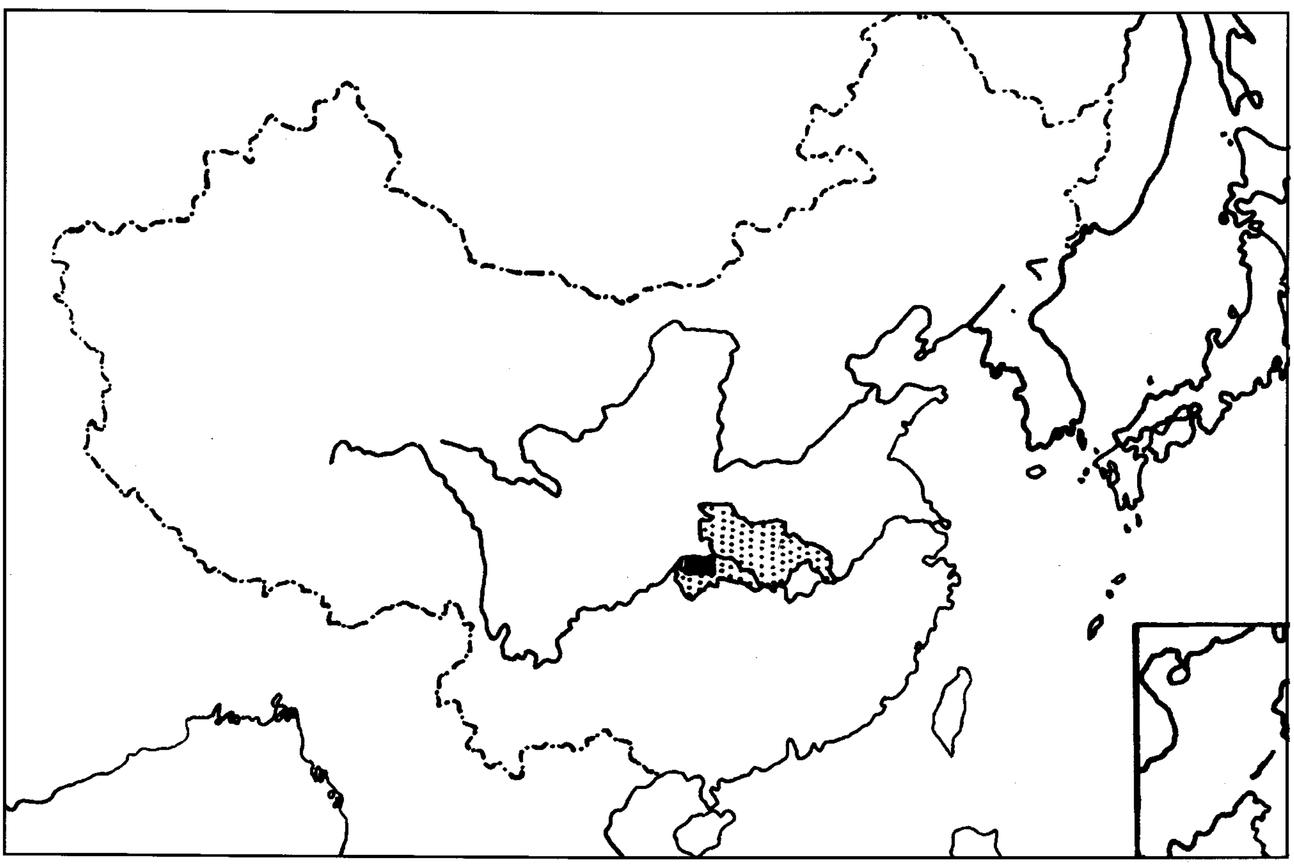

Fig.1.- Location map of the Lichuan area (west Hubei province)

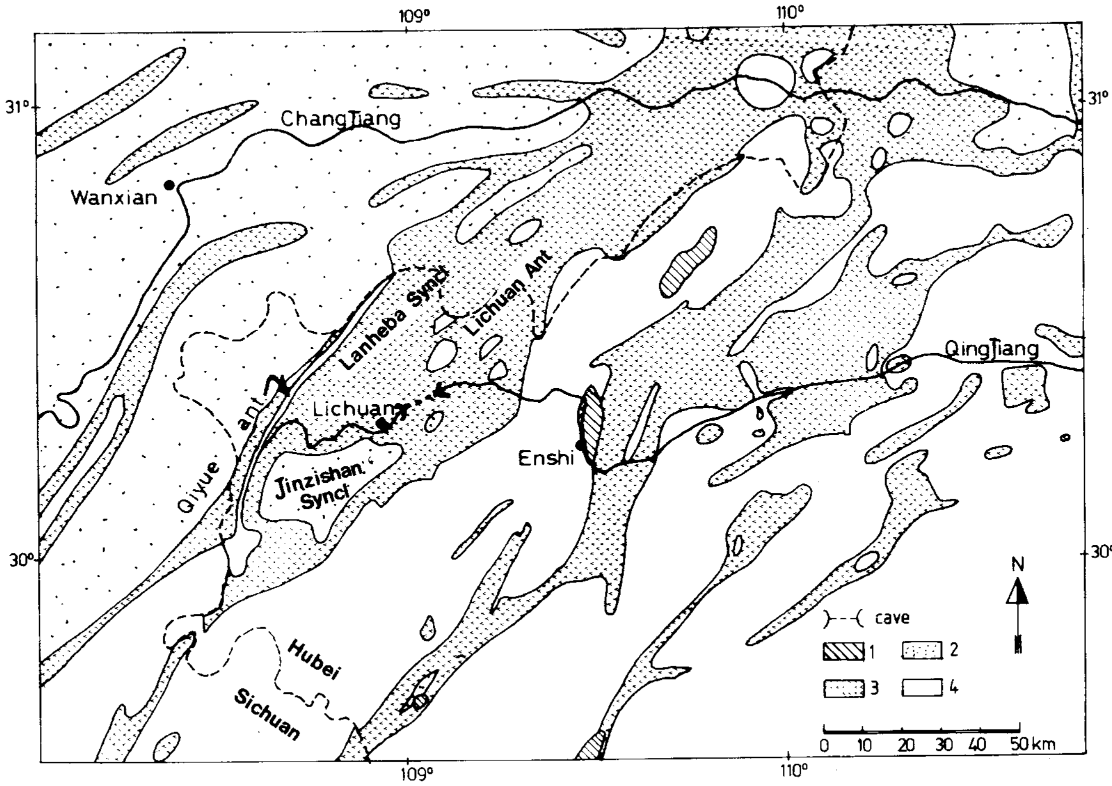

Fig.2.- Geological outline of the Lichuan area, after the Geological Atlas of China (cave: Qing Jiang dry valley and Tenglong Cave, West of Lichuan; 1: Tertiary Donghu Formation, unconformably overlying Yanshanian sequences; 2: Upper Triassic - Lower Cretaceous sequences, overlying Triassic carbonates; 3: Triassic Jialinjiang and Daye carbonate Formations; 4: Permian and Pre-Permian Formations underlying Triassic carbonates)

form the host rocks for the investigated karst system.

These Triassic sediments were deposited in a Paleotethys basin stretching westward to the Carpathians in central Europe, and accreted to the northern Laurasian continent during the Jurassic Yanshanian deformation, time equivalent of the Cimmeride deformation (Sengör & Hsü, 1984; Sengör, 1987). This sedimentary basin - fill sequence is well comparable to the earlier Hercynian sequence known in Europe.

The Yanshanian structural deformation has generated a range of large box folds, trending NW - SE, with large and rather flat synclines (average dip 5-25°) separated by narrow and steep anticlines (average dip 50-75°). These form part of the Daloushan Mountains, stretching from west Guizhou province in the south to east Sichuan province in the north. They constitute the major support for the mountain land, including the Lichuan area along the middle Chang Jiang (Yangtze) course (elevation between 1500 m and 2000 m). The renowned Gorges occur at the intersection of the Chang Jiang with the Daloushan fold belt. The longitudinal fold axes striking N30E in the Lichuan region, such as the Qiyue anticline, separate zones with eastwards plunging open folds striking N60E, such as the Lichuan anticlinorium and the Jinzishan synclinorium, suggesting the presence of dextral shear along the major fold axes (Fig.2).

An important peneplanation developed after the Yanshanian deformation. The abrasion surface was covered by clastic red beds of aeolian, alluvial and lacustrine origin assigned to the Donghu Formation of presumed Eocene age. These are best preserved near Enshi (Fig.2). This abrasion surface was subsequently tectonised. In the Lichuan area uplift and erosion has completely removed all traces of the Tertiary cover and cut down at least 1000m in the Yanshanian sequence. This is associated with a strong late Tertiary uplift due to the Himalayan orogeny. It also led to the spectacular karst phenomena observed in Lichuan. The topographic expression and the development of the karst landscape on the carbonate rocks of the Lichuan area are described by Antrop & Zhang Dachang (this volume).

2.2.- STRATIGRAPHY

The oldest beds exposed in the study area are Permian chert -bearing limestones outcropping in the Qiyue anticline and assigned to the Yangxin Formation, which may reach a thickness of +/- 500m. In the Yangtze Gorges area both Permian and succeeding Triassic limestones are combined into a single huge carbonate mass, also known as the Wushan limestone, reaching 1800m in thickness and responsible for the highest cliffs. Towards the east and southeast

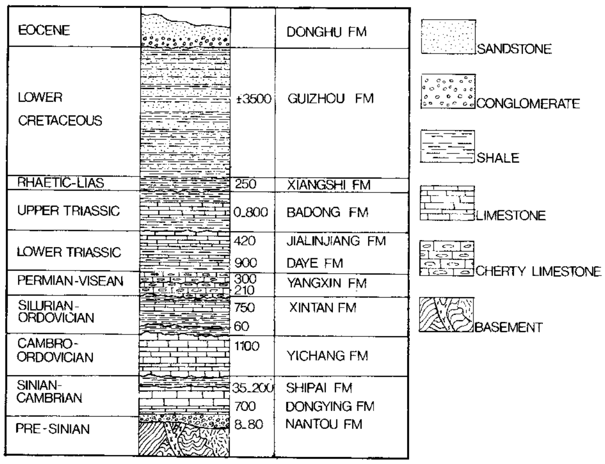

Fig.3.- Generalised stratigraphic section in western Hubei (after Hsieh & Chao, 1925)

of the Yangtze Gorges the Tanshanwan coal series intervenes at the top of the Yangxin Formation. In southwestern Hubei this member is also known as the Maochuang coal series, composed of black shale and siliceous shale, chert-bearing limestone, yellow sandstone and shale, attaining a thickness of several tens of meters. The thin coal seams of inferior quality which occur within this member are mined on the Qiyue anticline, west of Lichuan; they are suited for local consumption only (Hsieh & Liu, 1927).

The Permian is covered by a huge carbonate sequence, of presumed Lower Triassic age, subdivided into a lower "T1d" unit or Daye Formation and an upper "T1j" unit or Jialinjiang Formation. The former unit attains an estimated thickness of 700m, and is composed of mostly thinly bedded (decimetric scale) carbonates with shale partings. The latter unit attains an estimated thickness of 300m, and is composed of mostly thickly bedded (metric scale) carbonates with less impurities (Fig.4). The Daye (T1d) and Jialinjiang (T1j) Formations were originally defined in the Yangtze valley, as all other formations mentioned (Hsieh & Chao, 1925) (Conventional Chinese stratigraphy uses symbols for lithostratigraphic units consisting of a chronostratigraphic component followed by the abbreviation of the formation name.

Tenglong cave developed in the transition beds between the Daye Formation and the Jialinjiang Formation at the south slope of the Lichuan anticlinorium. To the north T1d beds and even Permian are updoming in several secondary anticlines near the anticlinorium core (Fig.2). The T1d - T1j transition also has a marked impact on the regional karst morphology by defining a morphological break between a plateau - mountainland preserved on the T1d Daye Formation, and a depressed cone karst on the more deeply corroded T1j Jialinjiang Formation (Antrop & Zhang, this volume). The top of the T1j Formation is strongly dolomitised (Hsieh & Chao, 1925).

The Jialinjiang Formation is disconformably overlain by the Middle - Upper Triassic ("T2") Badong Formation, reaching a thickness of +/-200m. This formation is composed of purple shales and grey limestones in which a threefold subdivision can be made. Purple shales predominate in the lower and upper parts whereas thin bedded grey limestones and calcareous shales mark the middle part. The basal contact with the Jialinjiang Formation is often disturbed by karstic dissolution and collapse of the underlying carbonates. Hsieh & Chao (1925) already noticed paleokarst features when mentioning "exposure and solution, caused by a retreat of the shoreline" for the T1j carbonates along the Yangtze gorges. This "T2" unit is easily erodable, leaving a large polje in the Lanheba syncline, west of Lichuan.

The Xiangshi Coal Measures disconformably overlying the Badong Formation and assigned to the Lower Jurassic, form the major coal bearing unit in the Yangtze Gorges. The Xiangshi Formation reaches a maximal thickness of 250m and contains up to 13 seams with maximal thickness for the individual seams of 1.5m. Coal quality is variable; the rank ranges from coking coal to steam coal. In the Lichuan area this formation is greatly reduced in thickness and hence in coal content (Fig.3).

Jurassic sandstones and shales assigned to the Guizhou Formation and conformably overlying the Xiangshi Formation complete the Yanshanian sequence in the study area. This formation may reach impressive thicknesses (up to 3500m) and consists of alluvial to lacustrine deposits. These form a positive relief and are partly preserved in the elevated and non - karstic Jinzishan synclinorium found to the southwest of Lichuan (Fig.2).

3.- CARBONATE HOST ROCK OF THE TENGLONG CAVE

3.1.- GENERAL CHARACTERISTICS OF THE T1D/T1J SEQUENCE

The T1d / T1j Triassic carbonates form a thick monotonous series, originally covering a large part of the Yangtze Paraplatform and now outcropping over several provinces. They consist of mostly bluegrey occasionally violet limestones which - due to intensive microsparitic recrystallisation - generally have the appearance of wackestones. The strong recrystallisation which affected both formations, has obliterated many original sedimentary features. This certainly contributes to the remarkably uniform composition of these limestones.

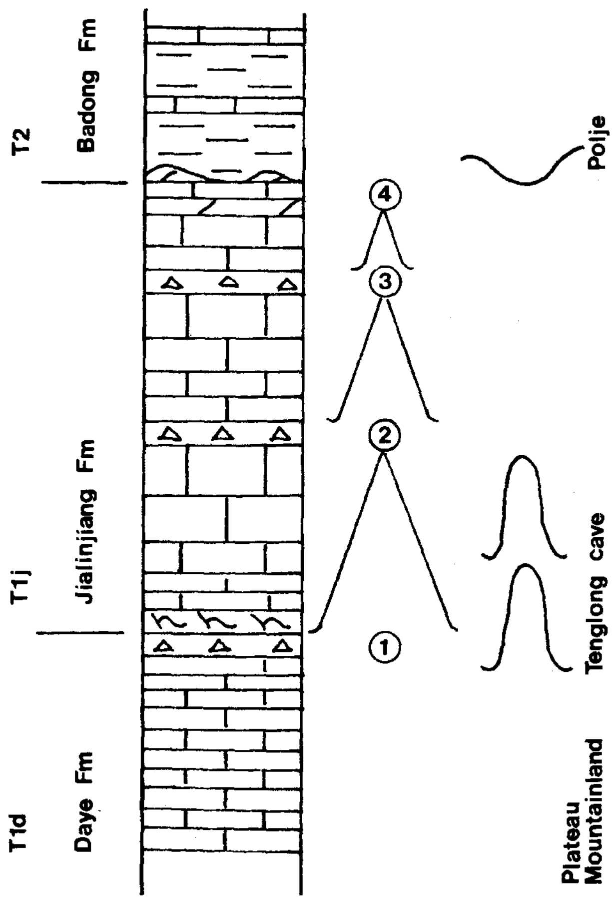

Fig.4.- Schematic lithostratigraphic column of the Triassic Jialinjiang Formation, showing major sedimentary sequences, associated landforms and the relative position of the rock types studied (1: pseudobreccia horizon at the T1d/T1j transition with overlying synsedimentary deformation features; 2: pseudobreccia horizon in T1j; 3: solution collapse breccia horizon; 4: top T1j dolomite); vertical scale 1:6000

The T1j beds studied in the Qing Jiang dry valley above Tenglong cave (Fig.2), show a cyclic deposition with major sequences attaining 70 m to 150 m in thickness (Fig.4). They start with thinly bedded units enriched in silt and shale partings, which are intersected by a dense set of joints (already present in the T1d), and quickly grade into more massive pure - carbonate units with discontinuous joints (more typically for the T1j). These units which correspond to sequences of a lesser order normally show a progradational increase in thickness from 5 - 15 m at the base to 15 - 25 m towards the top of the major sequences. Unfortunately no detailed sedimentological log could be established over this interval.

Lenticular breccia beds up to 5 m thick, occurring at the top of the major sequences, constitute the best marker horizons in the upper T1j formation (Fig.4). One bed at the top of the T1d formation could be traced continuously over 3 km in the dry valley. The breccia beds possess a massive appearance, unlike the surrounding beds which are clearly stratified. They form horizontal karren in the dry valley canyon or attractive polished marble - like surfaces in erosion dominated underground river sections. A strong internal microstylolitisation surrounding the breccia clasts nevertheless prevents their use as polished stones. The thinly bedded strata directly overlying this breccia horizon were frequently affected by small thrusts accomodated by parallel folding or by imbrication which never extended into the next unit. These synsedimentary features are best explained by basal detachments on a weak layer, now represented by the breccia beds. It therefore seems likely that the latter beds originally consisted of other dissolvable rock types.

3.2.- DEPOSITIONAL ENVIRONMENT

Despite the fact that most carbonate rocks are extremely neomorphosed, it is occasionally possible to recognise their original textures and thus to infer the original depositional environment. Lithology types vary from pelletoidal to bioclastic mudstone to wackestone.

Characteristic sedimentary features of these beds are the occurrence of :

- rare current marks such as ripple beds
- occasional lenticular bedding and scouring features
- mudstones with birdseyes
- green to red shale laminae
- detrital quartz and K-feldspar grains, which never exceed 3% of bulk volume. They occur more frequently in T1d strata
- bioturbations and few trace fossils ("bamboo leaves")
- bioclasts; mainly ostracodes and crinoid ossicles have been recognised. In general bioclasts are scarce.
- some oolite relicts
- evaporite pseudomorphs
- algal laminites
- rare pelletoidal grainstones
- pseudonodular aggregates in T1d beds

Lithology features indicative of paleokarst are formed by:

- dolomite beds, with typical brown alteration
- several breccia horizons

These features indicate deposition in a shallow epicontinental sea. Water depths varied from subtidal to intertidal and periodically even supratidal. Restricted water circulation in an intertidal to supratidal setting is indicated by the presence of evaporite pseudomorphs, algal laminites and mudstones with birdseyes. Porous dolomite beds with fenestrae, occurring towards the top of the Jialinjiang (T1j) Formation probably formed in a similar environment and evolved into a paleokarst as can be inferred from regional paleogeographic reconstructions (Hsieh &

Chao, 1925) - (Fig.4). There is an apparent increase of restricted facies conditions towards the top of the Jialinjiang (T1j) Formation. The contact with the overlying Batong Formation (T2) is strongly marked by karstic dissolution, leading to local angular unconformities in the Lanheba syncline. In the southern part of the adjoining Sichuan basin Lower Triassic evaporites are still present; a halite intercalation in the T1j Formation, reaching a thickness of +/- 12 m is even mined there. In the Lichuan area only traces of former evaporites are preserved.

4.- DIAGENETIC HISTORY OF SOME MARKER HORIZONS

The intensive recrystallisation and compaction witnessed by the Triassic carbonates and observed at different stratigraphic intervals throughout the sequence testifies of a deep burial diagenesis which probably terminated by the Yanshanian deformation and uplift of late Jurassic age. Cathodoluminescence techniques are especially applicable in deciphering the diagenetic history of such recrystallised sediments. This history is illustrated best by the sediment-petrographic study of some peculiar rock types in an otherwise monotonous series, such as breccias and dolomites. These rock types also seem to exert a major control on karst development. Remarkable crystal growth structures in cement and in calcite veins are also worth illustrating before a general succession of the diagenetic events is proposed. The relative stratigraphic position of the studied intervals is shown on Fig.4.

4.1.- SOLUTION COLLAPSE BRECCIAS

4.1.1.- Macroscopic description

Different breccia horizons occur in the Jialinjiang Formation. A crackle breccia zone of only 4m thick was sampled on the northwest slope of the Qiyue anticlinal ridge along the Lichuan - Wanxian road (Fig.2). The stratigraphic relationship of this breccia with the Tenglong dong sequences to the east of Lichuan is not exactly known (Fig.4). The Qiyue crackle breccia consists of intensively fractured limestone. The cemented crackle breccia is of post-depositional origin. It has been tentatively interpreted as a solution collapse breccia. Similar breccia types are indeed encountered over large areas at the same stratigraphic position and seem to be associated with intercalated evaporites in the adjacent Sichuan basin.

Different diagenetic phases transformed the originally bluegrey wackestone into a variegated vuggy and/or veined crystalline limestone. Superficial weathering processes completed the diagenetic evolution. Two zones can be distinguished in this breccia, whereby the upper zone can be characterised as a moderately veined cemented crackle breccia, and the lower zone as a strongly veined cemented crackle to mosaic packbreccia (after the descriptive field classification by Morrow, 1982).

4.1.2.- Microscopic description of the upper crackle breccia

The neomorphosed microsparitic limestone fragments are composed of a crystal mesh, 10 to 40 micron in diameter. In the less neomorphosed beds, original microfacies types are vaguely discernable. They consist of bioclastic peloidal wackestone, occasionally with algal relicts, of laminated wackestone, or of wackestone with birdseyes or burrows, at present filled with blocky calcite cement. Bioclasts (mainly crinoid relicts) are surrounded by syntaxial rimcement. Dispersed dolomite rhombs are often dedolomitised.

Different vein generations can be distinguished, some of which developed after dolomitisation. Locally lath shaped calcite crystals are arranged in clusters. They could correspond to anhydrite pseudomorphs. Laminations are only inferred by the presence of more residue - rich fine crystalline interlayers occurring in an otherwise homogenous microsparite. Within the residu - rich layers coarse carbonate grains occur. They seem to have replaced quartz or feldspar detritals. The absence of increased amounts of organic matter and the presence of some detrital relicts make it less likely that the laminations are of algal origin. Dispersed within the matrix, silt sized K-feldspar grains (less than 0.5 % of the bulk volume) are present.

Under cathodoluminescence (C.L.) these neomorphosed limestones possess a dull to orange luminescence. Dull to dark brown spots alternate with nicely zoned dark brown to yellow luminescing calcite crystals (Pl.1A). The former correspond to the recrystallised matrix, while the latter, which is often more coarsely crystalline, probably reflect cemented cavities. In fact similar zoned crystals also occur in burrows and birdseye - like cavities. Generally these crystals are composed of three zones, namely by (I) a brown to orange central zone, (II) a bright yellow orange zone consisting of different very bright yellow luminescing subzones, and (III) a brown luminescing outer rim, characterised by different very thin yellow luminescing subzones. Sector zonation may be present within each of these zones as far as the zonation within this cement corresponds to variations of Fe and Mn content, which respectively are regarded as the major luminescence quenching and activating centres in calcite cementation (Sommer, 1972; Fairchild, 1983).

Cementation occurred under varying redox-conditions. Furthermore it is important to notice that these textures were not erased during recrystallisation, which could either mean that recrystallisation preceeded or was concomitant with cementation.

The zoned crystals are crosscut by stylolites and different vein generations. The most prominent veins are bright yellow orange luminescent. This most likely relates to Mn-rich calcites, which would point to a very late diagenetic origin. Several of these calcite vein - infills are also characterised by a complex zonation pattern and by sector zonation. This zonation pattern however is different from the one recognised in the birdseye - like cavities. The yellow orange luminescent veins are themselves crosscut by dull brown to non-luminescing veinlets.

4.1.3.- Microscopic description of the lower crackle to mosaic packbreccia

Towards the base of the brecciated zone, intensively fractured and veined yellowish to reddish fine crystalline limestone prevails. Nearly all primary sedimentary structures within the fragments have been obliterated by the microsparitic recrystallisation. Only locally a pelletoidal / oolitic texture vaguely appears. Variation in microspar size reflects the brecciation. Veins and cavities are filled with a sucrous calcite phase which is symmetrically oriented and develop perpendicular to their substrate. It is however sometimes difficult to differentiate the veins from the host rock (Pl.1B). Under transmitted light microscopy they are characterised by well developed crystal twins. Crystal length is mainly controlled by the available space; crystals may reach 2mm in length. Another vein type is characterised by the development of a brown coloured aureole (halo) around the vein infill. Subsequent fracturing may give rise to a cataclastic texture as well.

Under C.L. the microsparite also displays a dull to uniform orange luminescence. Larger microspar crystals are zoned. In that case crystals display a brown orange luminescence with one or several non - luminescing subzones. The zonation pattern, however, differs within the different samples studied.

Two important vein types have been differentiated, namely :

1 - yellow to brown luminescing calcite veins, characterised by different growth zones and a sucrous macroscopic appearance. Renewed cementation of the different zones is often preceeded by a fracturation event. Also the different growth zones are separated from each other by a truncation or corrosion surface (Pl.3). These features point to formation fluids which alternatively were $CaCO_3$- saturated and undersaturated. Renewed cementation was initiated after the reopening of the system allowing fluids to be channeled along these fractures.

2 - dull brown to non - luminescing calcite veins (comparable to the veins observed in the lower sequence and shown in Pl.1B). The central part of these veins locally consists of a bright yellow luminescing phase. This vein type is represented by veins displaying a halo. Based on the crosscutting relationships of both vein types the second vein type is diagenetically younger.

4.1.4.- Serrated micronodules in marly limestones

Some peculiar textures exist in a marly limestone displaying synsedimentary deformation (fracture infill). Luminescence features of the microspar grade from brown to bright orange (Pl.1C,D). Within the matrix irregular concentric serrated zonal micronodules develop, especially next to the veined intervals. Brown finely zoned fractures locally occur. The origin of these textures is yet unknown. They resemble microbial alteration clusters also observed in calcretes and possibly may be linked to paleosol development during the Triassic. A temporary supratidal environment in these solution collapse zones seems plausible. Furthermore a regionally important paleokarst phase marked the end of the Jialinjiang Formation and the transition to the overlying Badong Formation. Nevertheless recent or subrecent corrosion has affected these beds as well and has led to recent karst development. Since the formation of these nodules cannot be dated their interpretation is difficult.

4.2.- THE PSEUDOBRECCIA HORIZONS

4.2.1.- Macroscopic description

Breccia beds may occur at the top of major sedimentation sequences and thus constitute important marker horizons in the carbonate succession. A particular breccia horizon marking the T1d - T1j transition has apparently guided the development of Tenglong cave over a distance of more than 6 km between Xiang Shui Dong and Shun Tan Dong, encompassing the canyon part of the dry valley (Masschelein & Zhang, 1990). It therefore was studied in some detail. Other pseudobreccias present in the sequence display similar features. The breccia is always preserved in lenticular beds, up to 2.5 m thick in Xiang Shui Dong. It is overlying a massive bluish fine-grained limestone bed without apparent internal stratification but almost always presenting vertical fissures and/or veins. The latter unit is usually thinner as the breccia but may reach 5 to 6 m in thickness where the breccia is absent. The breccia horizon itself is often overlain by a folded unit (see **3.1**).

The texture of this breccia is quite variable. Sometimes it appears as a cemented polymictic rubble packbreccia, containing white, light grey and brown fragments. However, lithologic variability in the composition of the fragments is not observed everywhere. Their average diameter attains 2.5 cm but may become finer towards the top and the base. Some larger clasts consisting of brown laminated dolomite, may reach a thickness of 5 cm and a length of 25 cm. This breccia type usually presents some stratification and thus should be qualified as a resedimented 'debris flow' pseudobreccia. More often the breccia has the morphological appearance of a cemented oligomictic mosaic packbreccia (Morrow, 1982) with rounded clasts. Although recrystallisation and stylolitised contacts between the clasts prevent an unequivocal recognition of their original setting, all these exposures are described here as pseudobreccias, modified after burial by strong diagenesis.

4.2.2.- Microscopic description

The whole pseudobreccia is intensively recrystallised and compacted. Only a variation in homogenity and crystal size (from 3 to 50 micron) could be observed in the thin sections studied. Vague allochems (intraclasts) and bioclasts (crinoid relicts,...) are sometimes present. Stylolites generally mark the contact between the different fragment types. Their outline is accentuated by the presence of iron-oxides. Pyrite crystals locally occur in clusters or are dispersed over matrix and fragments. Silt - sized quartz and K-feldspars are concentrated along stylolites. Brown coloured (Fe-rich) dolomite and dedolomite spots, which mainly are found next to stylolites make up the wispy beige brown spots, as is especially the case with a second breccia horizon within the T1j Formation at +/- 140m above the T1d/T1j boundary breccia.

Under C.L. the microspar (matrix and fragments alike) display a uniform orange to brown luminescence. Larger microspar crystals possess a brown core and a light brown luminescing rim. The matrix locally seems to be altered along stylolites. Individual dolomite crystals and dolomitised intervals occur. These dolomites are often intensively dedolomitised, especially in the vicinity of stylolites. The dedolomites display a bright yellow luminescence comparable to the luminescence of the calcite type 1 vein generation described from the lower sequence in the collapse breccia zone.

Furthermore, rectangular to rhombic spots, at present consisting of bright orange yellow luminescing dedolomite, are scattered within certain intervals (Pl. 1E). The crystal size in these spots is larger than in the matrix. It is unclear whether these rectangular to rhombic spots correspond to former evaporites or if they are simply altered dolomite rhombs (i.e. dedolomite). However non - luminescing dolosparitic crystals also have been observed in these spots, making the first assumption less likely.

Within the grainstone fragments which were recognised in the second pseudobreccia horizon (Fig.4) it can be observed that allochems and some of the fragments have been completely dissolved. The resulting cavities subsequently became cemented by circumgranular equant calcite (Pl.1F). Remaining cavities finally were filled by blocky orange brown luminescing calcite which later was preferentially dolomitised and subsequently dedolomitised. Noteworthy is that not all fragments have been dissolved pointing towards fragments with different initial mineralogical compositions, of which some were susceptible for dissolution. Possibly these phases originally consisted of evaporites.

Within these pseudobreccias different vein generations have been recognised :

-bright yellow luminescing veins, found close to stylolites
-brown luminescing satinspar type veins with crystals developing perpendicular to the vein wall
-brown luminescing blocky calcite veins often characterised by an irregular outline and the presence of saddle dolomite. This vein type locally gives the rock a cataclastic fabric. It preferentially develops along stylolites and is itself crosscut by stylolites. Most of the calcite crystals are twinned.

4.3.- THE UPPERMOST T1J DOLOMITIC SEQUENCE

4.3.1.- Macroscopic description

The road Lichuan - Enshi runs approximatively west - east along the karst plain with small cones developed on the T1j - T2 transitional beds, occurring on the north flank of the Jinzishan Synclinorium (Fig.2). A small road quarry in one of these cones at 3 km east of the Qing Jiang river crossing exposed recrystallised bluegrey wackestone to packstone beds with small birdseye - like cavities, filled with blocky calcite. Within this sequence which corresponds to the topmost beds of the Jialinjiang Formation, a brown- grey fine crystalline porous dolomite bed, 0.5m thick, was really outstanding (Fig.4). The contact with the overlying Badong

Formation ('T2') is generally not exposed. The T1j/T2 transition normally is associated with a shoreline retreat and a paleokarst phase (Hsieh & Chao, 1925).

4.3.2.- Microscopic description

The thin dolomite beds nearly entirely consist of a porous (idiotopic) dolomite with fenestrae. The latter are filled by calcite. The dark - grey massive limestone, underlying the dolomite bed, consists of neomorphosed grainstone. Allochems which were still recognisable, consisted of coated grains, micritised bioclasts, irregularly shaped intraclasts and peloids (Pl.2B). Stylolites locally start to develop. Veining by Fe-rich dolomicrosparite postdates stylolitisation. Dispersed lath - shaped pores display a cross-cutting relationship with the allochems, stylolites and veins. Originally they probably consisted of replacive late - diagenetic anhydrite.

Under C.L. the dolomite displays a uniformly brown - reddish luminescence. The birdseye - like cavities are cemented by calcite spar with beige luminescing centre and a non - luminescing rim. Thin bright luminescing phases are present in the calcite spar.

The grainstone matrix displays a brown orange uniform luminescence (Pl.2A). Some of the allochems - bioclasts were dissolved before a fringing dark brown calcite cement precipitated (Pl.2B). This cement resembles the circumgranular equant calcite fringe described in the topzone of the pseudobreccias. The remaining cavities subsequently were cemented by equant calcite yielding a brown luminescing core and sometimes a yellow - brown rim. It seems likely that during this cementation stage the first fringing calcites were altered or recrystallised. This could explain why those fringing calcites possess a brown core which is irregularly surrounded by a brown orange luminescing fringe (Pl.2A).

The veins testify of a complex fracturation history. The following vein types occur :

- non - luminescing veins with dispersed rhombs. The latter are zoned; they possess a black core and a dark brown fringe
- bright yellow luminescing veinlets
- veins filled by equant calcite which is non - luminescent with thin bright luminescing subzones (Pl.2A).

4.4.- SEQUENCE OF DIAGENETIC EVENTS

Unraveling a sequence of diagenetic events was hindered by the intensive recrystallisation of the limestones. Furthermore no systematic sampling could be performed which should relativate the deduced sequence. Nevertheless different important diagenetic periods could be differentiated (Fig.5):

I. Very early (synsedimentary) to rather early diagenetic events (pre-compactional). The early diagenetic dolomitisation of the top T1j strata (see **4.3**), as well as the breccia development (see **4.2**) can be assigned to this category. This interpretation is partly supported by the development of synsedimentary deformation features above the breccias (see **3.1**). Also the selective dissolution of fragments in the pseudobreccia (see **4.2**) and the cementation (circumgranular equant calcite and blocky orange brown luminescent calcite = BCI on Fig.5) can be considered as pre-compactional in origin. Whether the coarse crystalline zoned calcite crystals in the collapse breccias should also be placed in this category is less clear.

II. Neomorphism under burial conditions. Most limestones are intensively recrystallised. The timing for this phase could correspond to the period of

	TRIAS → RECENT	
sedimentation	---	
micronodule formation	-	
dolomitisation	-- (locally developed on top T1j)	
breccia development	?----?	PRE-COMPACTIONAL
selective dissolution pseudo breccia	?----?	
equant calcite cement pseudobreccia	----	
blocky orange brown lum. calcite (BCI)	---	
neomorphism (phase A)	----	
calcite cement (phase B) in neomorphosed limestone	--	
stylolitisation	?-?-?-?	
fracturation		BURIAL
BV	--	
YV	--	
BB	--	
NV	--	
Fe-dolomite	?--?	
dedolomite	?--?	
sec. porosity development	--	
authigenic quartz, chalcedony, pyrite	?-?-?-?	

Fig.5.- Sequence of diagenetic events

maximal burial extending into the Jurassic. Within the neomorphosed phases two major luminescing patterns can be distinguished, namely:

A: uniform brown to dark brown luminescing matrix. Silt - sized K-feldspar, plagioclase and quartz grains are dispersed in this matrix. Skalenohedral crystals compose the coarser crystalline parts of this phase (Pl.1E, 2C,E). The latter sometimes are zoned.

B: beige brown phase without detritals (Pl.1E, 2C,E). Locally this phase is vaguely zoned and resembles the BCI cement phase (Pl.2A). Whether they are really equivalent is yet unknown. At other places this beige brown phase could correspond to a recrystallisation phase of A.

III. Fracturation. Different vein generations crosscut these strata. It is yet impossible to correlate the successive vein generations in detail. Some of the fractures are filled by one specific calcite generation, whereas others, such as those encountered in the lower zone of the solution collapse breccia consist of several calcite growth generations, each separated by a truncation or corrosion surface, and sometimes even fractured again. Nevertheless a relative timing of some of the most frequent fractures is possible. Notice however that several other fracture types have been recognised :

-Thin brown to dark brown luminescent veinlets (BV on Fig.5), occur in all samples as a first fracture infill (Pl.2E).
-Thin bright yellow luminescent calcite veinlets (YV on Fig.5) are omnipresent (Pl.2E). They postdate some of the stylolites (Pl.2F); however at other places they are crosscut by high amplitude stylolites. Their luminescence is comparable to the yellow luminescent dedolomite phases (Pl.1E, 2E) with which they are often interconnected. Where these veinlets crosscut the non-luminescent to dark reddish luminescent dolomite crystals a bright reddish luminescent phase develops (Pl.2C). This probably represents an intermediate reaction product of the dedolomitisation process. It is also possible that these bright yellow luminescent calcite veinlets correspond to the second fracture system recognised in the type 1 vein infill in the lower zone of the solution collapse breccia.
-Beige brown luminescent calcite (BB on Fig.5)
-Non - luminescent calcite veins (NV on Fig.5) which display a crosscutting relationship with all other vein types (Pl.1B).

IV. Stylolitisation. Several episodes of pressure solution have been recognised giving rise to different generations of stylolites.

V. Other late-diagenetic products have been recognised such as late-diagenetic (Fe-rich) dolomite and dedolomite. Both mainly occur in the recrystallised matrix B described above. The dolomite crystals are dark reddish to non-luminescent. The dedolomite spots possess a bright yellow luminescent pattern (Pl.2C). Under transmitted light they often show a brown colour due to development of Fe-oxides. Similar brown coloured dedolomite also occurs in rectangular spots (Pl.1E). Whether these spots originally correspond to evaporites is doubtful. Of importance in the context of karst development is the observation that dissolution cavities (enhanced secondary porosity development) often occur next to dedolomitised spots (Pl.2C). Furthermore minor occurrences of authigenic quartz, chalcedony and pyrite formed in a late diagenetic phase after stylolitisation.

5.- REMARKS ON THE KARST DEVELOPMENT IN THE TENGLONG CAVE AREA

As stated before, Tenglong cave developed at the morphological break between the Daye (T1d) and Jialinjiang (T1j) Formations. Dissolution by groundwater in these intensely recrystallised (neomorphosed) low-permeability carbonates most likely occurred by conduit flow through fractures and along bedding planes. Especially the omnipresence of small cemented fractures is worth mentioning. Several fracture generations have been recognised. Initial penetration by solvent water also may have occurred along stylolites and/or along the now bright green coloured clay laminae which resemble bentonites. Penetration via pores is considered insignificant in this type of rock.

Dissolution thus was mainly controlled by the saturation state of the circulating waters ("water controlled alteration" of James & Choquette, 1984) rather than by the relative solubilities of the minerals involved ("mineral controlled alteration" of James & Choquette, 1984). The latter process could have happened within originally evaporitic beds which today are inferred only.

Other processes which may have enhanced karst development are dedolomitisation and oxidation of pyrite. Everywhere where these processes were documented in the studied Triassic carbonates, a limited secondary porosity enhancement occurred.

The position of Tenglong cave and a fortiori of the morphological break between T1d and T1j beds could depend on the regional morphological evolution (Masschelein & Zhang, 1990). Nevertheless lithology plays an important role in controlling the actual development of the cave system. Although lithological differences between T1d and T1j beds are not really impressive, a combination of their lithological characteristics and tectonic structure will favour cave development in T1j beds which tend to be more pure and more coherent. At places where cave galleries entered strongly fractured, thinly bedded T1d beds, passages generally became narrower and obstructed by mechanical breakdown which are rapidly silting up.

The pseudobreccia horizon at the base of the T1j beds also guides the ongoing evolution of the underground river. The canyon section of the dry valley and large stretches of the underground river follow this horizon. Further incision of the underground river as well as the junction with the canyon is deflected downdip along this horizon. Such an affinity is truely remarkable in a carbonate sequence 1000 m thick.

Different karst phases have affected the Triassic carbonates. Paleokarst development associated with the Cretaceous and Early Tertiary peneplanations cannot be distinguished anymore because of the deep erosion after the Late Tertiary Himalayan uplift. Triassic paleokarst is inferred from the study of some marker horizons in the Jialinjiang Formation, interpreted within their regional context. Dolomitisation associated with the development of evaporites at the top of this formation are the best known regional paleokarst indication. The pseudobreccia beds testify of different synsedimentary to early diagenetic dissolution phases. The solution collapse breccias possibly contain indications for paleosol development, as suggested by the presence of microbial nodules. However, the dating of these nodules is still enigmatic.

6.- CONCLUSIONS

A karstified Triassic succession, situated near the city of Lichuan in the western part of the province of Hubei (China) contains the sofar longest cave in China, Tenglong Dong. This succession consists of a 1000 m thick carbonate series, organised in major sequences of approx. 140 m thickness, deposited in a shallow epicontinental sea covering the Sichuan block or Yangtze Paraplatform in south - central China. The Yanshanian deformation, time - equivalent of the Cimmeride tectonic phase, marked the closure of this Paleotethys basin and produced a range of large box folds with gentle sloping synclines and steep anticlines. An initial Cretaceous to Eocene peneplanation was reactivated by the Himalayan uplift during the Neogene. The subsequent erosion went at least 1000 m deep in the Lichuan area and laid bare the Triassic carbonates. These developed into the spectacular karst landscape now contributing to the scenic beauty of this region.

The limestones are strongly neomorphosed with obliteration of most of the original sedimentary structures. The few relict textures indicate a transitional environment ranging from shallow subtidal to supratidal. Evaporite beds are not preserved but indications for their dissolution or pseudomorphosis cannot be neglected.

Slight differences in lithological composition and structural behaviour between the upper T1j Jialinjiang Formation and the lower T1d Daye Formation have influenced the position of a morphological break and the development of the Tenglong cave in the transition zone between both formations. Otherwise karst dissolution of the carbonate rocks is controlled by the saturation state of the circulating waters. In the low - permeability carbonates, this was induced by conduit flow through fractures and along bedding planes.

The diagenetic history started very early in synsedimentary to shallow burial (pre-compaction) conditions. Neomorphism probably occurred under deep burial conditions realised at the onset of the Yanshanian deformation of essentially Jurassic age. Frequent stylolites, which often host silicification and pyritisation testify of important pressure solution. Several calcite vein generations have been differentiated and reflect a complex fracture cementation history.

Cathodoluminescence petrography of a T1j solution collapse breccia zone allowed a further specification of these diagenetic phases by the recognition of different cement growth zones and their separation by truncation or corrosion surfaces. Unique textures resembling microbial clusters in paleosols developed in this collapse breccia zone. They are tentatively interpreted as an indication for a late Triassic paleokarst development on top of the T1j formation.

Resedimented debris flows or pseudobreccias constitute the best marker beds in the studied carbonate sequence. The position of these horizons also influences the actual development of the cave. A peculiar characteristic of the pseudobreccias is that the clasts have also been dissolved and recrystallised in different phases. Accompanying tectonic deformation structures explained as basal detachments on a weak layer also support the evaporitic origin of the pseudobreccia horizons.

PLATE 1

A: sample CHMD1 (RS/B/50/1A); top of solution collapse breccia along Wanxian - Lichuan road on northflank of Qiyue anticline.
Cathodoluminescence microphotograph of dull to orange luminescent neomorphosed limestone. The dull to dark brown areas (**A**) correspond to recrystallised matrix, while the dark brown to yellow zoned calcite crystals (**B**) reflect cemented areas.
Scale 220 m

B: sample CHMD7 (RS/B/50/17A); base of solution collapse breccia along Wanxian - Lichuan road on northflank of Qiyue anticline.
Cathodoluminescence microphotograph of contact between neomorphosed limestone (**L**) and vein interval. The neomorphosed interval consists of zoned brown luminescent crystals, whose luminescence is comparable to the first brown zoned luminescent calcite growth generation (**1**) of the vein. A second bright yellow zoned growth generation (**2**) is also discernable. These textures are crosscut by a second non-luminescent vein generation (the so-called **NV** type).
Scale 220 m

C: sample CHMD8 (RS/B/50/19A); base of solution collapse breccia along Wanxian - Lichuan road on northflank of Qiyue anticline.
Cathodoluminescence microphotograph of marly limestone with occurrence of irregular concentric serrated zonal micronodules. These structures resemble microbial alteration clusters similar to structures occurring in calcretes. These structures thus may be associated with paleokarst development during the Triassic. However it cannot be excluded that they relate to more recent karst development.
Scale 85 m

D: sample CHMD8 (RS/B/50/20A); same area of view as Pl. 1C.
Photomicrograph of marly limestone with micronodules.
Scale 85 m

E: sample CHMD14 (RS/B/51/20); lower pseudobreccia horizon in Tenglong Dong dry valley, 200m upstream of Shun Tan Dong.
Cathodoluminescence microphotograph of neomorphosed limestone with bright yellow spots. Within the recrystallised matrix two phases can be distinguished, namely:

A: dispersed and locally clustered skalenohedral crystals characterised by a uniform brown to dark brown luminescence. Within these crystals few blue luminescing K-feldspar grains occur (**K**).

B: beige brown phase surrounding A without detritals.

The rhombic to rectangular yellow spots (**R**) occur within phase B. In the centre of these dedolomitised spots a non-luminescent dolomite phase occurs (**D**), which suggests that these rhombic to rectangular structures originally consisted of dolomite rather than of anhydrite.
Scale 220 m

F: sample CHMD52 (RS/B/54/28A); upper pseudobreccia horizon in small quarry for grinding stones on the south flank of the Tenglong Dong dry valley overlooking Rainbow Gorge Lake.
Cathodoluminescence microphotograph of grainstone fragment of this pseudobreccia. Different allochems and fragments have been dissolved prior to circumgranular equant calcite cementation (**C**). The remaining cavity subsequently was cemented by a blocky orange brown luminescent calcite (**B**). In the latter phase different Fe-rich dolomite rhombs occur (**F**).
Scale 220 m

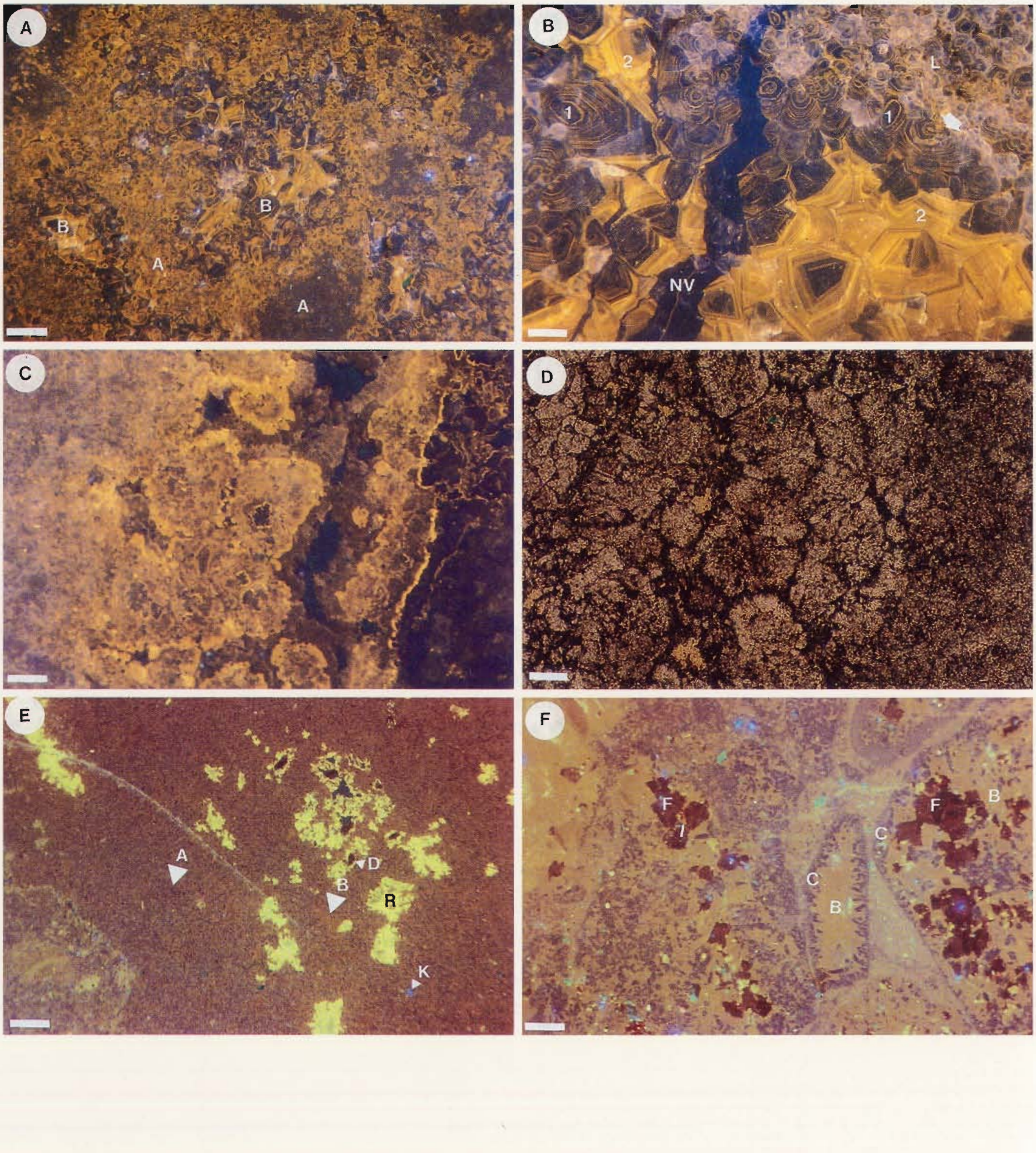
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PLATE 2

A: sample CHMD19 (RS/B/54/3A); top dolomite sequence of T1j Jialinjiang Formation: bluish packstone intercalation, Lichuan road quarry in direction of Enshi.
Cathodoluminescence microphotograph of grainstone matrix in contact with calcite vein. The latter is composed of equant calcite which is mainly non-luminescent, possessing thin bright luminescing subzones. The grainstone matrix displays a uniform brown orange luminescence. Some of the allochems were probably dissolved and subsequently cemented by dark brown luminescing calcite (**DB**). Remaining cavities were finally cemented by brown orange luminescent blocky calcite (**BO**). Apparently the first cement generation was altered and partly became recrys-tallised (**arrows**) during the second cementation stage.
Scale 85 m

B: sample CHMD19 (RS/B/54/4A); same area of view as Pl. 2A.
Microphotograph of grainstone matrix (**G**) in contact with calcite vein (**V**).
Scale 85 m

C: sample CHMD23 (RS/B/54/8A); massive limestone bed at the base of the lower pseudobreccia horizon exposed in the Third Arch of Tenglong Dong dry valley.
Cathodoluminescence microphotograph of intensively recrystallised limestone. Different luminescing patterns can be distinguished, namely:
- uniform brown to dark brown luminescing crystals (**arrows**) occurring next to blue luminescing K-feldspar crystals (**K**).
- beige brown luminescing detrital free phase (**B**) surrounding the above described crystals.
- dark reddish to non-luminescent dolomite (**D**).
- bright yellow luminescing dedolomite (**DD**).
- thin bright yellow luminescing veinlets (**YV** type).
- voids (secondary porosity) - (**V**).

Scale 85 m

D: sample CHMD23 (RS/B/54/9A); same area of view as Pl. 2C.
Microphotograph of intensively recrystallised limestone.
Scale 85 m

E: sample CHMD23 (RS/B/54/12A); same location as Pl. 2C.
Cathodoluminescence microphotograph of intensively recrystallised limestone (for description see Pl. 2C).
Scale 220 m

F: sample CHMD39 (RS/B/54/36A); polymictic rubble packbreccia, in cobble at entrance of Yen He Dong in Tenglong Dong dry valley, assigned to lower pseudobreccia horizon at T1d/T1j transition.
Cathodoluminescence microphotograph of intensively recrystallised limestone with low amplitude stylolites (**S**). Within these stylolites detritals (non-luminescent quartz and blue luminescent K-feldspar) are concentrated. Bright yellow luminescent calcite veinlets (**YV** type) display a crosscutting relationship with the stylolites.
Scale 220 m

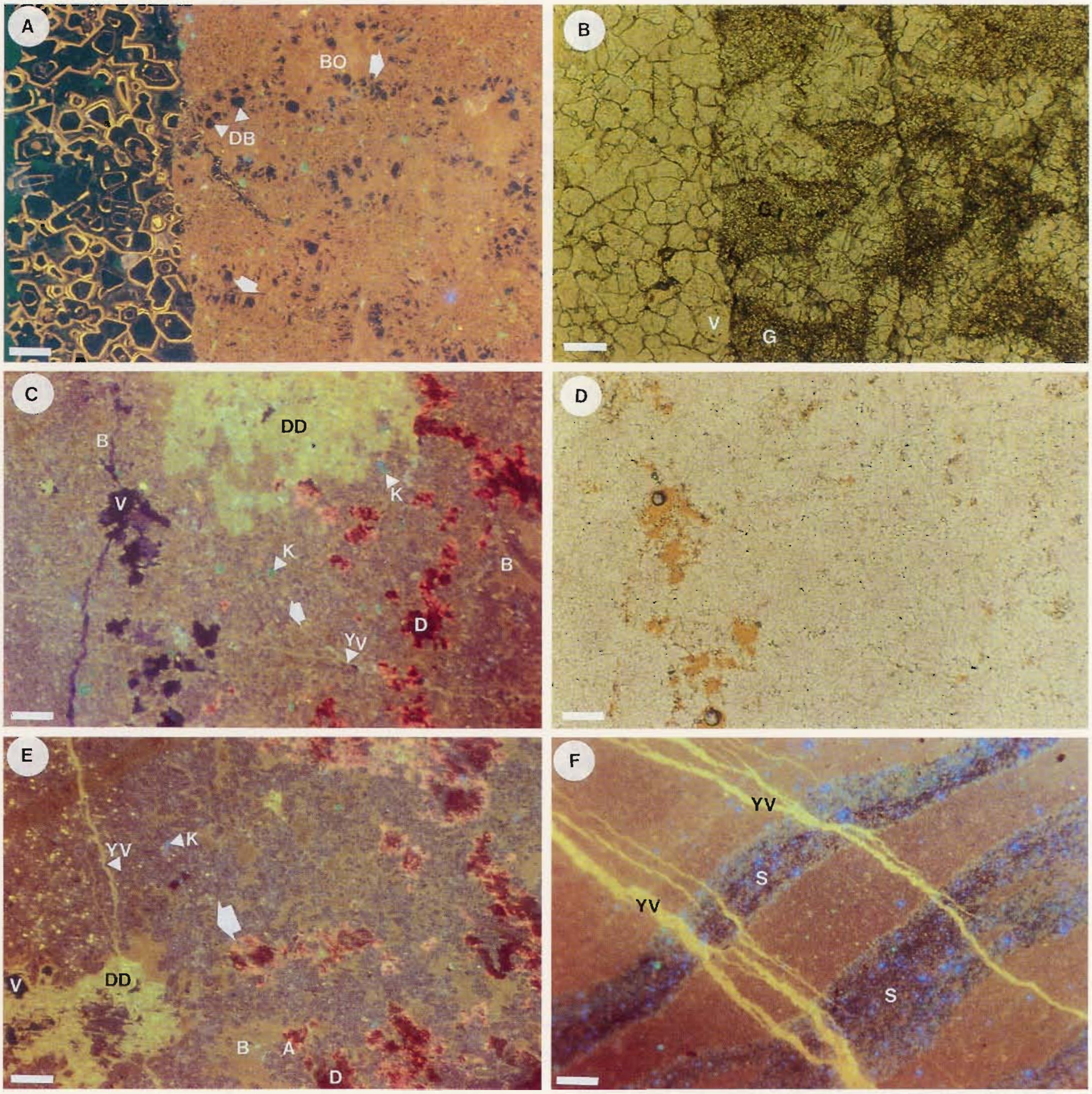
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PLATE 3

Photomosaic of sample CHMD9. Detail of yellow to brown luminescing calcite vein of the lower breccia. The breccia fragments are completely recrystallised (**BR**). Different growth zones, separated from each other by a truncation or corrosion surface (**arrows**) can be recognised in the vein. They are:

A: brown luminescing calcite characterised by different thin bright yellow subzones. The frequency of these subzones varies. At the outer edge of this zone the yellow luminescent subzones predominate. Notice that the aspect of the first subzones resembles to some degree the zoned aspect of the microspar crystals (Pl. 1A).

B: beige to orange luminescing calcite characterised by broad growth zones and sector zonation. A dark brown subzone characterises the outer edge of this zone. The latter clearly is truncated.

C: yellow to brown luminescent calcite characterised by a rhytmic subzonation pattern. The first subzone is bright yellow luminescent.

It is also interesting to notice that crystal growth follows fracturation. A first fracturation phase (**F1**) occurred after growth zone A development and before growth zone B precipitation. This is inferred from the fact that these fractures are filled by the initial phases of the beige to orange luminescing calcite B. A second fracture system (**F2**) which crosscuts the first one (see **X**), is filled by bright yellow luminescent calcite. This fracture fill resembles the terminating bright yellow subzone of calcite B. If these phases are indeed identical then the second fracturation event occurred after growth zone B developed and before growth zone C precipitated.

Cementation thus seems to have followed a fracturation event. As far as the luminescence pattern directly can be related to fluid composition, the latter clearly evolved through time.

Field of view 1 x 0.7 cm

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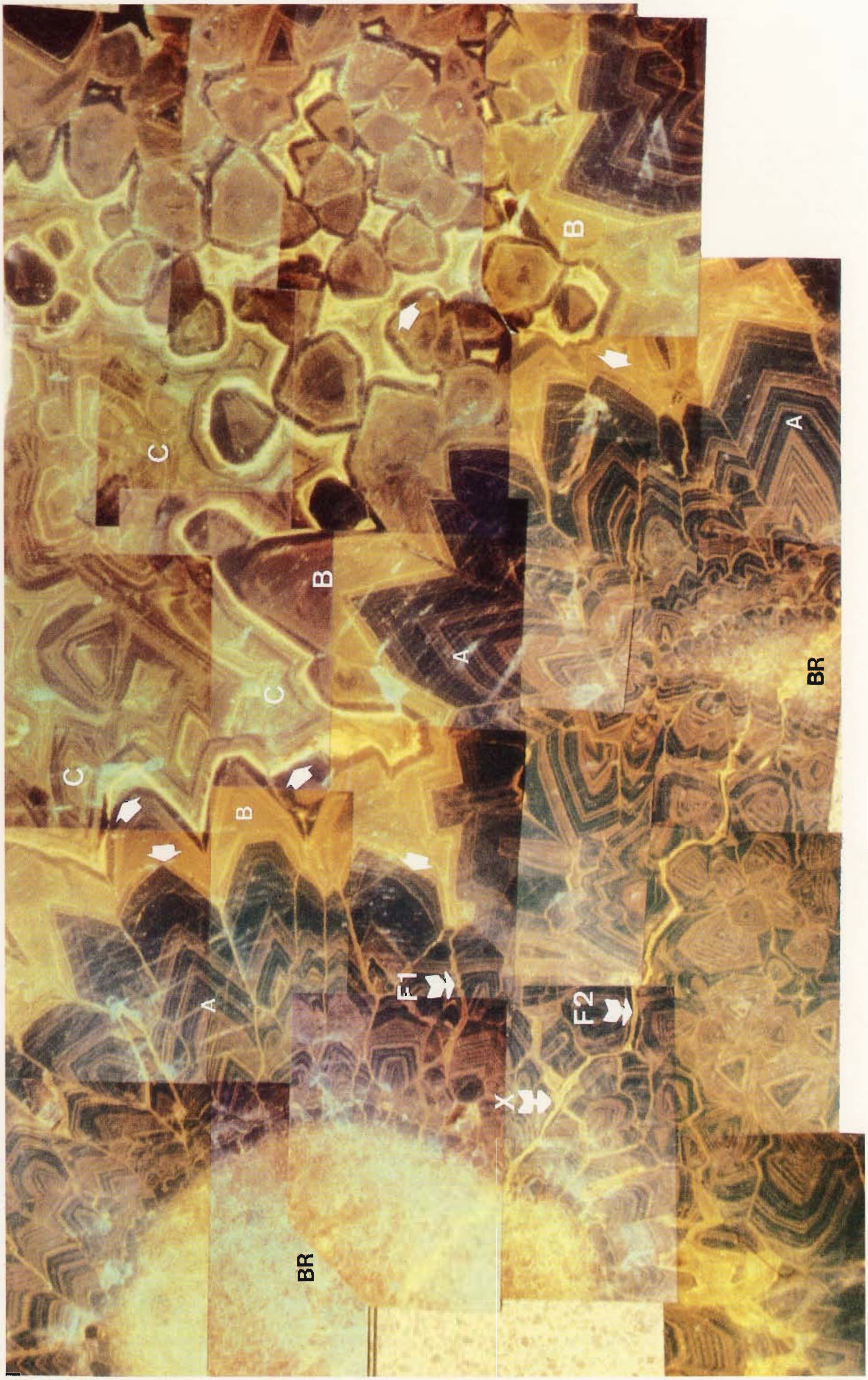
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