Chapter I.10

BREAKDOWN DEVELOPMENT IN COVER BEDS, AND LANDSCAPE FEATURES INDUCED BY INTRASTRATAL GYPSUM KARST

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It is shown in Chapter I.4 and elsewhere in Part II of this volume that intrastratal karst is by far the predominant gypsum karst type. Its development may begin in deep-seated settings within rocks already buried by younger strata, and it proceeds increasingly rapidly as uplift brings gypsum sequences into progressively shallower positions. Such development commonly occurs under confined (artesian) hydrogeological conditions, that subsequently change to open conditions (phreatic-water table-vadose). The general evolutionary line of intrastratal karst is typified by progressive emergence of a sequence into a shallower position, activation of groundwater circulation and development of cave systems within karst units, commencement of gravitational breakdown and its upward propagation through overlying beds, and development of a karst landscape. These processes and phenomena progress through the directed evolution of karst types as follows: deep-seated intrastratal karst (IK) $\Rightarrow$ subjacent IK $\Rightarrow$ entrenched IK $\Rightarrow$ denuded karst (see Chapter I.4).

One of the main characteristics of intrastratal karst is that it induces gravitational breakdown in cover beds. With the aid of processes other then simple breakdown, such effects may propagate upwards and may, or may not, reach the surface, depending upon the thickness and structure of the overburden. A karst landscape evolves when such features reach the surface. This paper considers the conditions and mechanisms of such development.

1. Vertical through structures

Among the most characteristic features of intrastratal gypsum karst are vertical through structures (VTS). The term VTS is used here to designate and encompass various complex phenomena known from gypsum karst regions all over the world and referred to as breccia pipes, vertical pipes, collapse columns, geological organ pipes, and so on. They are commonly believed to be breakdown structures, induced by dissolution of gypsum beds, propagated upwards through stratified overburden and filled with in-fallen clasts. Closer examination reveals that VTS are also hydrogeological structures, whose development is triggered by gravitational breakdown. However, sequential upward-stoping breakdown is maintained by active groundwater circulation accompanied by dissolution and suffosion. When mature, VTS drain any intercepted aquifers and serve as pathways facilitating and focusing cross-formational hydraulic communication. VTS location is commonly guided by fracture zones, so that any pre-existing hydrogeological function is normally inherited by the VTS. Groundwater circulation can be directed upwards, driven by artesian head, or downwards, in cases of gravitational percolation (leakage from perched aquifers) in

entrenched and drained situations. Progressive upward stoping depends upon a continuing crea-
tion of space in the VTS occurring due to dissolution of soluble material in the breccia clasts.
Open space tends to "concentrate" at the top of VTS, because infill generally subsides during the
course of dissolution. Removal of unconsolidated material from VTS by suffosion processes also
operates under certain conditions. The complex VTS formational mechanism (along with fracture
zone guidance) explains their commonly disproportionately large vertical extent, relative to their
diameter. Such a relationship would be impossible if mere gravitational breakdown alone was
involved.

Vertical through structures are very characteristic, but not diagnostic, features of gypsum and
salt karst areas. Similar phenomena are known, but are less common, within carbonate karsts
developed under artesian conditions. Outstanding examples are breccia pipes within the
Phanerozoic sedimentary succession of the Grand Canyon region, Arizona. These are believed to
originate through the above mechanism (Hoffman, 1977; Huntoon, 1996) but their development
was triggered by the collapse of dissolutional cavities in the deep-seated Mississippian Redwall
Limestone, not gypsum. These pipes extend upwards for as much as 900m above the limestone
and they are typically about 90m in diameter. Huntoon (1996) stressed that groundwater circula-
tion through pipes (upward in this case) is vital to the stoping process, because it facilitates disso-
lution and removal of soluble materials (infallen carbonate blocks and soluble cements or clasts
within infallen clastic blocks) in the pipe structure.

VTS probably occur more commonly in gypsum karst than in carbonate karst because the
significant cavities that are required to induce initial breakdown form more readily in gypsum
beds under deep-seated conditions than they do in carbonate sequences. Also, the rapid forma-
tion of vertical *dissolution* pipes, specific to entrenched gypsum karst, commonly triggers VTS
development due to the effects of descending percolation (see below).The vertical extent of VTS
in gypsum karst areas ranges widely, from a few tens of metres to more than 1000m, as exempli-
fied by many observations in North America, England, Germany, the Eastern-European platform,
the Urals, Siberia and China (see chapters II.2, II.3, II.9, II.11, II.14, and references therein).
Quinlan (1978) noted some 5000 VTS up to 500m in depth throughout the gypsum and salt karst
areas of the United States. Some 2875 VTS are recorded in coal mine areas of China (Yaory &
Cooper, 1997), most of them being caused by gypsum karst, through some are triggered by disso-
lution in limestones. The greatest concentration of VTS is within the Xishan mine area, where
1300 VTS are recorded in 70km². Ford & Williams (1989) refer to the VTS that propagate from
depths as great as 1200m after being induced by potash mines in Saskatchewan in Canada. Vertical
through structures of great vertical extent provide one of the strongest strands of evidence in sup-
port of the wide occurrence of deep-seated karst. The widespread view that all breccia pipes are
palaeokarst features is partially misleading, as they become fossilized only if their hydrogeological
function ceases.

The development of vertical through structures is the most important mechanism by which
surface features begin to evolve in all sub-types of intrastratal gypsum karst.

2. Factors that govern breakdown and VTS development

Breakdown mechanisms in gypsum sequences and their cover beds, and of the development mechanisms of vertical through structures in overburden are conditioned by many factors, of which the following are the most important:

1) the origin and structure of cavities in the gypsum;
2) the overall structure of a gypsum bed or sequence;
3) the structure, lithology and thickness of the overburden;
4) the hydrogeological conditions.

Most of these factors will change during the course of the geological/geomorphological evolution of a karst terrain. They are considered individually below, with references to appropriate examples.

Origin and structure of cavities in gypsum. Caves in deep-seated intrastratal karst develop under confined conditions. Gypsum beds are not good aquifers before speleogenesis begins; groundwaters commonly come into the contact with gypsum beds from underlying aquifer formations. If few or no fissures pass through the gypsum, dissolution remains localized along the base of a gypsum bed, or is focused along rare major tectonic faults that penetrate the gypsum. This can produce large cavities (such as caves described in the Zechstein gypsum of the South Hartz; see Chapter II.5). Breakdown of such cavities may trigger VTS development by means of upward stoping and continuing dissolution of infallen clasts, especially if the cavity is guided by a tectonic fault or fracture zone, facilitating upward groundwater circulation through a low permeability stratified cover.

Where lithogenetic and/or tectonic fissuring in a gypsum sequence is relatively dense and uniform, speleogenetic development is "dispersed" along many paths. This results in the formation of maze cave systems comprising relatively small conduits with no large chambers. This type of speleogenesis does not normally trigger significant breakdown, and sporadic local collapse cavities are commonly filled with clasts, being unable to propagate upwards significantly through the overburden. This reflects a failure to focus hydraulic communication through the gypsum to connect surrounding aquifers (which would create additional space) and signifies that the cavities do not coincide with pre-existing (initial) circulation paths in the cover beds. Breakdowns of this type cannot ramify to the surface from a deep-seated karst, and they receive surface expression only if they are brought into the fairly shallow sub-surface (subjacent, entrenched or denuded types of karst).

When incising valleys have established a water table within a gypsum sequence, inherited caves continue their active development due to widening of conduits at the water table. This process is particularly effective close to major surface streams, where annual fluctuations in river level periodically cause water to flood back into caves. Occasional breakdown is enhanced by the increasing widths of cavities, and old breakdowns are reactivated due to dissolution of infallen blocks and washing out of unconsolidated material. This situation is exemplified by Kungurskaya Cave, in the Pre-Urals region, where the Sylva river enters the cave during times of high flow (Fig. 1). In contrast, in most parts of the Western Ukraine valleys have incised rapidly to a level far
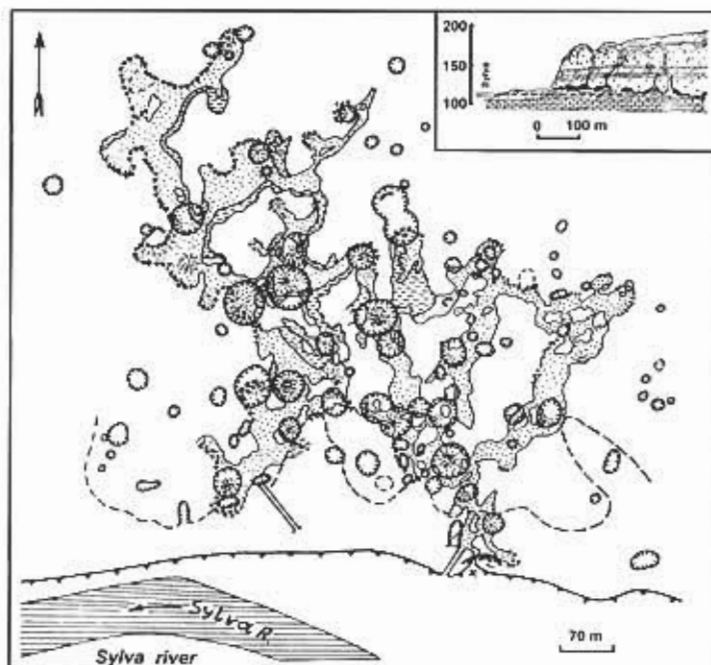
Fig. 1. Plan of Kungurskaya Cave in the Pre-Urals region, Russia, with breakdown features expressed at the surface as collapse and subsidence dolines.

below the gypsum due to intense uplift. In many of the maze cave systems there has been no significant widening of conduits due to dissolution at the water table, and simple breakdowns are uncommon. However, there are some exceptions, as exemplified by the Kryvsky quarry area in Bukovina, where during the Holocene the standing water table in the upper part of the gypsum bed was controlled by the nearby Prut river valley. This caused significant widening of conduits in the maze cave system (Zolushka Cave), and these have triggered many simple breakdowns that have propagated to the surface by upward stoping (Fig.2). Breakdown development was greatly enhanced by lowering of the water table in response to quarry operation (see Chapter I.10).

In entrenched karsts, where vadose conditions encompass all, or most, of a gypsum sequence, *vertical dissolution pipes* are a very common feature. They develop downwards from the gypsum's upper contact with a suitable protective layer (commonly limestone or dolomite), due to focused dissolution by groundwater that percolates through the overburden or leaks from an aquifer perched above the gypsum. Vertical pipes in gypsum have a diameter up to some meters. Relict lateral caves that pre-exist in gypsum sequences are commonly intersected by pipes as they cut down, even if the pipes are initially unrelated to the caves (for details see Chapter I.5). At some stage, dissolution pipe enlargement will induce breakdown of the overlying protective bed, leading to VTS development by the mechanism described above (Fig. 3). Ongoing downward percolation through such structures is vital to the upward stoping process. VTS of this type can propagate upwards through an overburden up to several tens of metres, ultimately reaching the surface while remaining disproportionately small in diameter (commonly 1 to 5m). In the Urals region (Dorofeev, 1970; Andrejchuk, Dorofeev & Lukin, 1990) and the Western Ukraine
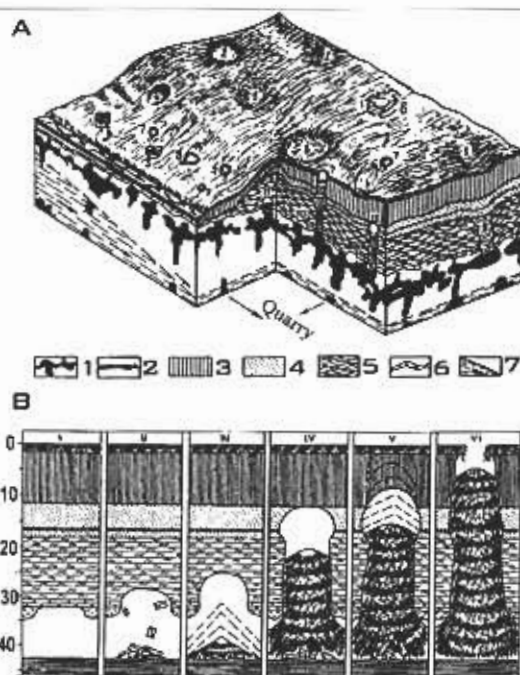
Fig. 2. Element of the karst landscape (A) in the vicinity of Kryvsky quarry above Zolushka Cave, Western Ukraine, and (B) the successive stages of breakdown formation (After Andrejchuk, 1991). 1 = cavities, 2 = soil, 3 = loam, 4 = sand, 5 = clay, 6 = limestone, 7 = water table drawdown cone. Numbers 1-13 on diagram A indicate various styles and genera of surface karst landforms induced by cave breakdown. Numbers I - VI on diagram B specify different stages of breakdown propagation at the surface.

(Klimchouk, 1984) it has been shown that most surface dolines in intrastratal entrenched karst settings evolve by means of the VTS mechanism being initiated by dissolution pipes in gypsum. A good example is shown in Fig.1, where most of the small- and medium-sized dolines above the cave are related to dissolution pipes in gypsum rather than to simple breakdown. VTS can easily be mapped in caves by observation of their characteristic breakdown talus piles, which contain sediments derived from the overburden and commonly show signs of continuing water percolation.

Dolines that evolve from VTS commonly become swallow-holes (ponors), transmitting some localized surface run-off underground. They support development of vadose caves, which are commonly represented by linear conduits. Such caves rarely achieve growth to significant volumes to give rise to breakdown that can propagate through the cover beds in entrenched karst. They normally develop a surface expression only at the denuded karst stage.

Structure of a gypsum bed or sequence. Single gypsum beds rarely exceed a few tens of metres in thickness, but gypsiferous sequences many tens to a few hundred metres thick are common, comprising gypsum beds intercalated with limestone, dolomite and/or other sediments.

Within a single gypsum bed, variations in rock structure and texture greatly influence the style of fissuring that is imposed by both lithogenetic and tectonic forces, thus helping to determine the potential structures of karst-generated voids. This aspect is discussed in detail by Klimchouk et al, 1995; see also Chapter I.1.

There is a great difference in the tolerance to cave breakdown exhibited by massive gypsum and layered (laminated) gypsum. The latter commonly contains clay as minor layers or impurities,
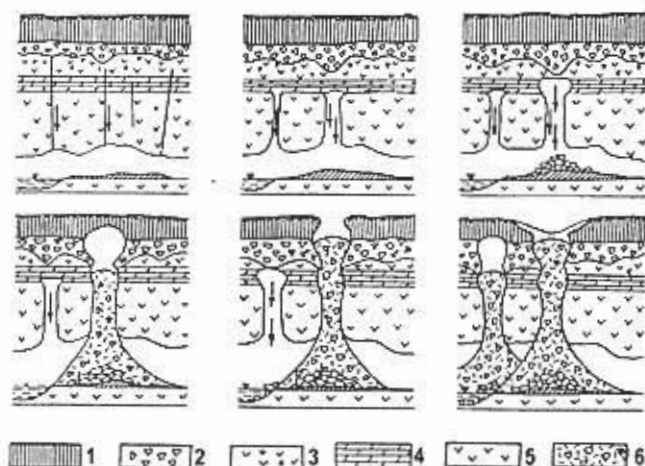
Fig.3. The successive stages of dissolution pipe development in gypsum, and VTS development in the overburden, with the final appearance of a doline at the surface (based on the example of Kungurskaya Cave). 1 = loams, 2 = breakdown slabs, 3 = gypsum, 4 = dolomite, 5 = gypsum-anhydrite, 6 = mixed breakdown clasts that form the body of the VTS and talus piles in the cave

dramatically reducing the strength of the rock. Within some of the vast cave systems in the Western Ukraine there are zones where the host rock changes from the more common massive gypsum to thinly-bedded or laminated varieties. Such zones are especially prone to breakdown. In the Urals and adjacent regions, Permian sulphates have experienced a complicated history that included several major episodes of tectonic disturbance and karstification. As a result the gypsum here is closely fractured, or even brecciated, in places, and cave breakdown is much more common than in the younger (Miocene) and less broken gypsum succession of the Western Ukraine.

In the case of multiple sulphate sequences, it is of particular importance whether or not the other, intercalated, lithologies provide initial (pre-karst) aquifers. This factor can significantly influence the cave-generating flow architecture in an artesian system, in determining which gypsum horizons will be preferentially cavernous. This point is considered further below.

Structure, lithology and thickness of the overburden. The set of factors that includes the composition, structure and thickness of the sequence overlying a gypsum formation, is crucial both to the development of caves within a karstifiable unit and to mechanisms of breakdown formation and their propagation to the surface.

For cave development under confined conditions the hydro-stratigraphical aspect of whether a gypsum unit is surrounded below and above by aquifers or by low-permeability beds is important. This aspect is considered in the next sub-section below.

For VTS development in cover beds, regardless of whether an ascending or descending circulation operates, the presence of a fractured zone or major fissure that provides an initial path for cross-formational hydraulic communication is crucial.

In many areas gypsum sequences have some carbonate beds at the top, separating them from overlying poorly consolidated sediments such as clays, loams or sands. Such carbonate beds are important for the formation of vertical dissolution pipes, as they protect the evolving pipe from early infilling by unconsolidated sediments, and allow pipe growth to reach several metres in diameter. In this way a large enough void is created to trigger a VTS mechanism when initial break-
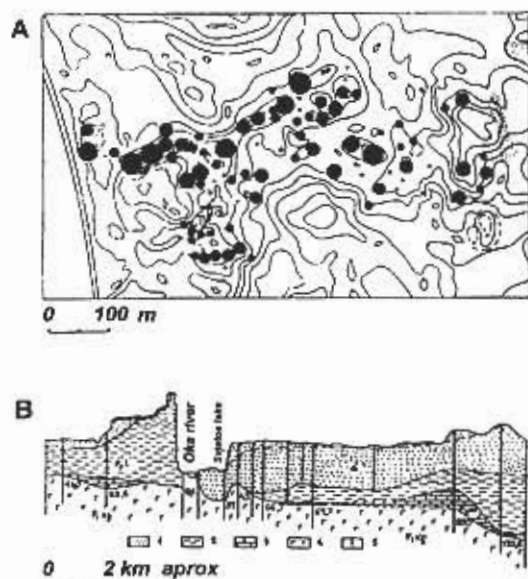
Fig. 4. A = Typical karst landscape near Dzerzhynsky city, Volga-Kamsky region, Russia. Recent dolines are indicated as black circles. B = geological profile through the area (After Karst Phenomena..., 1960).

down occurs.

Properties of sediments in the overlying sequence help to determine stoping mechanisms. In unconsolidated sandy materials VTS propagate rapidly and relatively uniformly in time. In loams, argillaceous sediments, clays and laminated shales stoping proceeds less uniformly (cyclic), and generally more slowly, by chip breakdown or small "block" breakdown. In cemented bedded rocks stoping occur during relatively long time spans, usually as block breakdown events. The shape and dimensions of the open space developed at the top of VTS can also vary between these lithologies.

Overburden composition (as well as hydrogeological activity within a VTS) determine the "void-transmissivity" of cover beds, i.e. their ability to transmit a void of given initial dimensions through a significant vertical extent of overburden. If the overburden consists largely of sandy sediments, even a relatively small breakdown cavity at the top of a karst unit may induce VTS propagation up to 80-100m upwards, providing the active groundwater circulation supports a suffosion (piping) process. When readily soluble rocks comprise a significant proportion of the overlying stratified sequence, and ascending artesian discharge occurs via VTS, the latter may extend upwards for up to 400-500m, as exemplified by cases in the Hebei Province of China (see Chapter II.13). If clayey sediments dominate in the overburden, VTS can normally reach the surface only where the overburden thickness is less than 45-60m. Where massive solid rocks overlie the gypsum, the VTS mechanism does not operate, except in cases where the massive cover beds consist largely of soluble rocks. For simple breakdown to achieve surface expression, large void volumes must be created within the gypsum, and the thickness of the cover beds must be relatively small. The void-transmissivity of cover beds determines a critical overburden thickness, above which intrastratal karst will receive no surface expression at all.

Fig.4 illustrates a typical surface karst landform assemblage in the Sredneje Povolzhje region, where Lower Permian gypsum occurs immediately below the floor of the Oka river valley. In most of the region it is overlain by Upper Permian porous carbonates and low permeability clays, but locally it is overlain directly by Quaternary fluvial sands (Karst phenomena..., 1960; see Fig. 4-B). Several generations of dolines are recognized. Recent dolines (shown as black circles) have formed most readily where the overburden comprises only sand, and they have evolved mainly where the thickness of sands is less than 80m.

The Western Ukraine presents a characteristic example of intrastratal gypsum karst (various sub-types), developed under a cover of predominantly clayey sediments. Argillaceous clays here vary in thickness from 5 to 100m or more. Karst landforms evolve when their thickness is less than 45-60m mainly due to the VTS mechanism, which starts after the roof of a vertical solution pipe has been breached. Detailed study and survey of breakdown talus piles through the maze of the Zolushka Cave system has allowed recognition of VTS that represent various stages of upward propagation (see Chapter I.10).

Examples of gypsum karst where a karstified unit is overlain mainly by (commonly soluble) solid rocks are numerous throughout many regions of Europe, Siberia and China. Settings of entrenched intrastratal karst with varying thicknesses of rocks above the intensely karstified horizon are represented in Fig. 5. The Ledjanaja Mount massif in the pre-Urals region is composed mainly by sulphates, with some carbonate beds (up to 3m thick), and a few metres of unconsolidated sediments at the top. The major river Sylva has incised to a depth of 70-90m. An intensely karstified horizon lies at, and immediately above, the present water table, some 60-80m below the surface of the massif, where Kungurskaya Cave is an explored part of the system (see Fig.1). The map below shows that the areas of highest density of surface karst features coincides with II-IV terraces, where the thickness of rock above the top of the karstified horizon does not exceed 25-40m. There is also a line of karst features at the edge of the plateau, along the steep escarpment that faces towards the river. In the latter case the dolines are related to suffosion processes induced by dissolution along unloading fissures. This is a common cause of high doline density along escarpment edges (see also karst trenches in sub-chapter 3 below). However, dolines also exist on the interior plateau areas, 60-80m above the "cave level". Detailed mapping on the surface and in the caves has proved that most such dolines have evolved via the VTS mechanism, after development of vertical dissolution pipes.

Hydrogeological conditions. Different types of caves that induce breakdown processes, are developed under a variety of hydrogeological conditions; these aspects are considered briefly above and, in more detail, in Chapters I.5 & I.6. For cave development under confined settings the most important criterion is whether a gypsum unit is immediately underlain and overlain by aquifers or by low permeability beds. In the latter case speleogenesis in gypsum might not advance until a unit has been exposed by denudation. If the gypsum is underlain by an aquifer but is overlain by low permeability rocks, cavities can develop mainly along the gypsum base, though some breakdown can be induced if large enough voids are created. The VTS mechanism can commence only where fracture zones exist, breaching the upper confining bed and providing paths for upward discharge from a particular aquifer. The most favourable configuration for speleogenetic
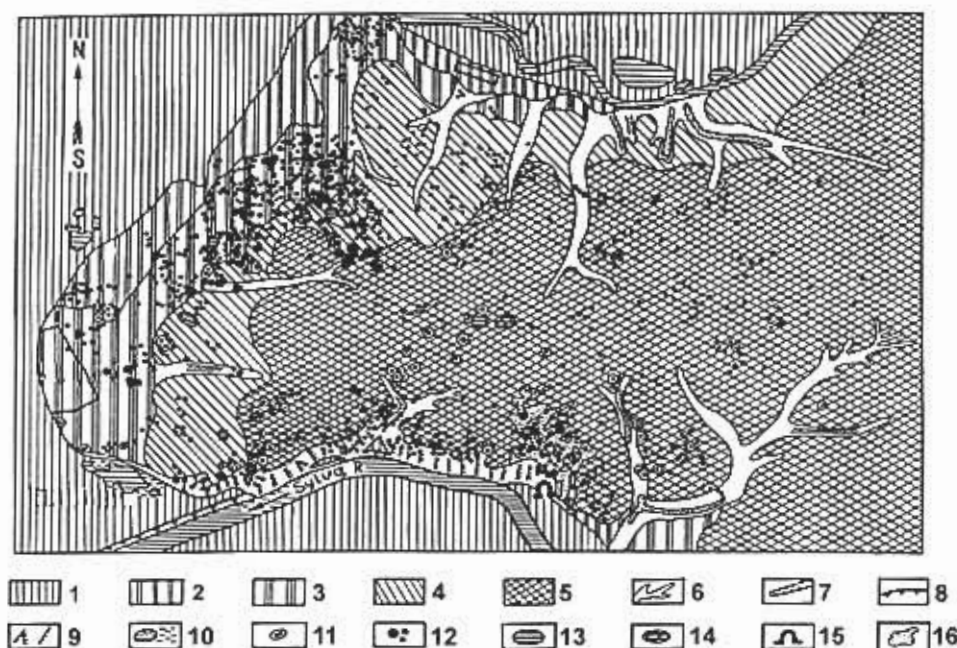
Fig. 5. Geomorphological map of the Ledja-naja Mount massif. 1-5 = terraces: 1 = I terrace (4-12m above the river), 2 = II terrace (15-25m), 3 = III terrace (30-40m), 4 = IV terrace (55-60m), 5 = higher terraces (>75m); 6 - 10 = erosional forms: 6 = ravines, 7 = steep-sided ravines, 8 = lip of the lowermost terrace, 9 = gypsum outcrops at the main escarpment of the Sylva valley, 10 = "mort" lakes; 11-16 = karst forms: 11 = cap-shaped dolines, 12 = cone-shaped dolines, 13 = lakes in dolines, 14 = swamps in dolines, 15 = caves, 16 = area of the Kungurskaya Cave.

development is where gypsum has aquifer beds below and above. Hydraulic communication through the gypsum bed (which acts initially as a low permeability bed) will be the main driving mechanism for cave development (for details see Chapter I.5). Depending upon the fissure structure within the gypsum, dissolution can be either uniformly dispersed or focused along sporadic fracture zones. Again, the VTS mechanism is only likely to start where fracture zones initially breach an upper low permeability bed that confines an aquifer system.

In complex stratified sequences, where a number of gypsum beds are intercalated with limestones, dolomites and clastic sediments, lithologies other than gypsum can provide lateral flow paths. Conditions similar to those already noted determine which gypsum beds will be preferred for cave formation. If the VTS development is triggered from a lower gypsum bed, then upward VTS propagation will be greatly facilitated by the fact that many of the infallen clasts, and the VTS walls, are composed of readily soluble gypsum from the upper beds.

Deep-seated (artesian) gypsum karst can achieve surface expression only via the VTS mechanism. This is possible where a significant hydraulic head gradients exists between a confined aquifer system comprising a karstifiable unit, and an upper unconfined aquifer. Yaoru & Cooper (Chapter

II.13) describe an active VTS that has propagated about 400m upwards from Ordovician gypsum in Hebei Province, China. Although this particular structure has not yet reached the surface, collapses known elsewhere in the area demonstrate such a possibility. When intersected by a coal mine at a depth of over 300m, this structure was discharging up to 12 m^3/s, flooding the mine with about 46km3 of water. A prominent example of large collapse dolines occupied by lakes was described by Quinlan (1967) in the Roswell area of New Mexico. The steep- to vertically-walled dolines, 50-100m wide, aligned along the Pecos valley, have formed in a zone of upward discharge from the Roswell aquifer, caused by collapses that were triggered by gypsum and salt dissolution at depths of several hundred metres. This VTS development was facilitated by the overburden of the Artesia Formation being composed of intercalated soluble and clastic rocks. Other impressive examples of VTS that discharge water from deep-seated confined aquifers, are know from the Urals foredeep.

Surface expression of subjacent intrastratal gypsum karst is more common, notably where gypsum lies at shallow enough depths to allow incision by major valleys to partially breach artesian confinement. A good example is the Sredneje Povolzhje region in the Russian Plain, where the Oka river has eroded a confining bed and deposited thick sands over the gypsum in some areas, while elsewhere the flow in the gypsum remains confined (see Fig.4-B). With overburden thicknesses varying from 10 to 130m, numerous dolines are forming at the surface, via the VTS mechanism, in areas where the gypsum lies at depths less than 80-90m. These VTS develop as upward circulation (discharge) paths.

Water table lowering within the upper aquifer, due to continuing valley incision, and particularly water table fluctuations within an unconsolidated overburden, result in activation of VTS development by suffosion processes.

When the entrenched karst stage is achieved, and the water table lowers below a cave horizon, breakdown development is greatly accelerated due to removal of buoyant support. White (1988) estimated that limestone buoyancy in water contributes 40% of the ceiling support; a similar figure for gypsum is about 44%. Removal of buoyant support is commonly followed by a stage of intense dissolutional widening of passages and erosion of cave sediments (including breakdown talus piles) due to water table and backflooding water activity. Thus, this stage is highly effective in terms both of triggering/VTS development new breakdown and activating pre-existing, but still "hidden", VTS. In other words, these hydrogeological conditions are most favourable for supporting collapse and subsidence formation at the surface. In gypsum karst areas where these conditions are active now, the rate of recent collapse occurrences can be as high as several collapses a year per km^2.

Under vadose conditions, breakdowns in relict caves are commonly stabilized. Previously formed VTS may continue to develop (upward stoping) if they drain perched aquifers within the overburden. New VTS originate only along vertical dissolution pipes, which develop readily where leakage paths in cover beds allow water to reach the top of a gypsum stratum (see Fig. 3). Continuing downward percolation through such structures is vital to the progress of upward stoping. This view is supported by observations that all successive perched aquifers in a stratified sequence, and eventually the uppermost aquifer, will leak into a VTS, dissolving soluble infallen

clasts and washing out unconsolidated material, creating voids within the structure and allowing further stoping to occur.

Most maze caves in the Western Ukraine contain numerous pipes superimposed upon relict passages, as the upper aquifer is normally within Quaternary sediments, perched on thick clays within intervalley massifs. This aquifer drains mainly downslope, but leakage occurs along tectonically weakened zones through the clays, giving rise to dissolution pipes in the gypsum. However, some caves contain no vertical pipes at all, because they lie beneath areas that lack an upper aquifer, where no porous sediment is present above the clays.

3. Superficial features of intrastratal karst

Superficial features of intrastratal gypsum karst display many similarities, but also some differences, to carbonate karst. The most important characteristic of intrastratal karst, common to all lithological karst types, is that superficial forms evolve almost exclusively as a reflection of pre-existing underground karst features.

Dissolutional sculpting micro- and meso-forms. A wide variety of dissolutionally sculpted karst landforms, such as different karren types occurs in intrastratal karst, but only on very limited areas of rocks that crop out locally along valley slopes and escarpments or in collapse dolines. They are discussed in Chapter I.9.

Dolines. Dolines are by far the most common superficial feature of intrastratal gypsum karst. They evolve as collapse or subsidence forms. Their shape and size when they first appear depends mainly upon the type of initial breakdown in the gypsum and on the thickness and composition of the overlying cover beds.

VTS that develop from deep-seated karst appear on the surface mainly as collapse dolines. The collapse is commonly catastrophic. Many such dolines have a pit-like (cylindrical) shape and appreciable size (diameters and depths of 40-50m are common, and locally they can be larger still). This is because VTS in deep-seated karst can propagate successfully through many tens or several hundred metres of overburden only if they develop along large tectonic fracture zones, and if groundwater circulation is sufficiently active to support creation of additional voids.

When a karst horizon lies at relatively shallow depths, increasingly diverse shapes and sizes of dolines appear. Vertical lithological heterogeneity in the upper part of cover beds determines how VTS affect the surface. If denser or better-consolidated deposits lie at the top, above sandy sediments, sudden collapse dolines are more likely to appear. Newly-formed features are commonly cylindrical (pit-like), pitcher-like, or bowl-like in shape. Similar shapes result where cover beds are elastic and collapse en masse. Where sandy sediments or light loams cap a succession, dolines tend to evolve by gentle subsidence or as smoothly-shaped collapse forms, although cone-shaped ones are also common if suffosion processes operate. The latter shapes are also typical within other poorly consolidated lithologies if active ponors open up at the bottom of dolines. Regardless of the initial doline shape formed in loose sediments, they tend to grade towards smoother profiles quickly, in spans of only months or a few years, except where well consolidated rocks cap a sequence or where suffosion and active ponors operate. Gorbunova (1979) described

two remarkable examples of the rapid evolution of recent dolines. The Brekhovsky collapse in the Perm region appeared in 1953 as a 40m-deep shaft. In 1954 its depth was 28m and its diameter was about 25m at the surface and 3 to 5m near the bottom. In 1961 it was a bowl-shaped doline about 30m in diameter and only 15m in depth. The other example is from the Angara region in Siberia, where a 56m-deep collapse shaft half-filled with water appeared suddenly in 1949. Its upper diameter was only about 4m, but the shaft had a pitcher-like shape. In 1951 it was a pit 15m deep, and by 1957 the form had turned into a doline 15m in diameter and 16m deep.

With increased variation in cave formation and changing hydrogeological conditions from arte-sian through phreatic and water table to vadose, the full range of possible VTS triggering and development mechanisms is realised. Finally, when a thickness of cover beds is lowered sufficien-tly within a particular geomechanical setting, simple breakdowns can also evolve into collapse dolines, and purely suffosion features can form by cover sediments being washed into open fissu-res at the top of a karst unit.

An example of a deeply entrenched intrastratal karst landscape, where the cover is relatively thick and largely impermeable, is provided by the Podol'sky sub-region in the Western Ukraine. Maze caves here are relict, having developed under earlier artesian conditions, and there are no large voids to trigger significant breakdown. Major valleys have entrenched deeply below the gypsum, but thick clay cover remains largely intact within wide intervalley massifs. Dolines com-monly evolve in response to VTS stoping, or as sporadic simple breakdowns, in the floors of minor perched valleys that approach the gypsum. They become ponors that intercept the surface run-off, so the valleys become dry and commonly separated into several closed basins. Outside such valleys, dolines form almost exclusively due to VTS stoping. Doline density in the area is commonly relatively low, though it increases dramatically where erosion has removed most of the overburden, as for instance on the extensive upper terraces of the major rivers.

A typical example of an entrenched karst landscape with thin and permeable cover is illustra-ted in Fig. 6. Dolines here have evolved through different mechanisms: as simple cave break-downs, as VTS, and as suffosion features. Older dolines are fossilized and stabilized. Some dolines are rejuvenated, and new forms appear commonly superimposed upon the older features. The resulting doline fields are polygenetic and may became very complex. Dolines can cover up to 30% of the total area.

A still more diverse karst landscape is observed in some areas of the Pinego-Severodvinsky karst region, where the thickness of permeable cover beds above the Permian gypsum is relatively low (ranging from few metres to a few tens of metres). Major rivers have incised only slightly below the Permian gypsum and many tributaries operate within the gypsum horizon. Large cave passages have developed during this stage, transmitting significantly large active streams, perched upon the underlying non-karstifiable bed. Many of the trunk passages have been partially destroyed by collapses, which have produced an intermittent karst hydrology, dry karst valleys and canyons, bridges, and so on (Caves..., 1974). Vertical dissolution pipes are common, being formed beneath thin unconsolidated sediments and a minor bed of dolomite at the top of gypsum. This bed collapses readily, and the pipes become pits. There are some areas where the density of such pits is many hundreds per km^2. Being complicated by superimposition of larger
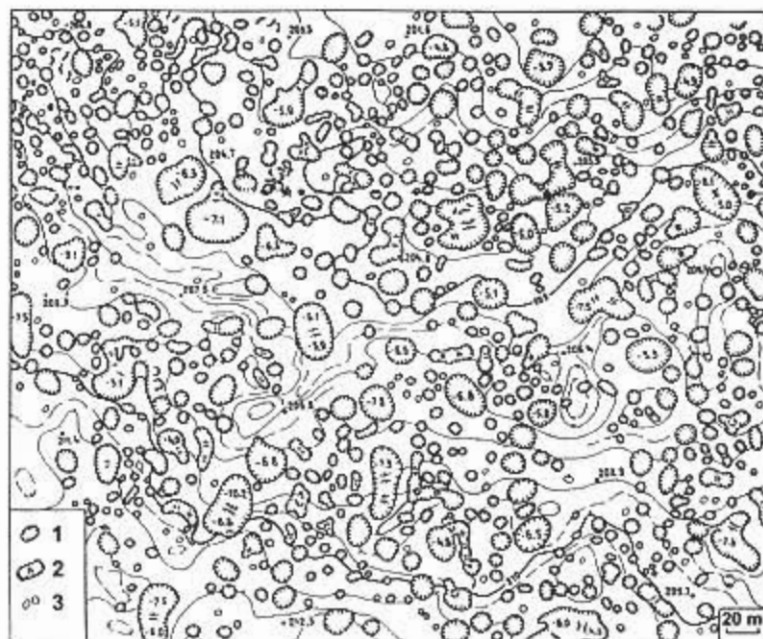
Fig. 6. Typical landscape of a gypsum karst area in the Iren river basin, Pre-Urals, Russia.

collapses formed in response to cave breakdowns, such areas represent a kind of "karst badland", known locally as "shelopnjak". This karst landscape has almost passed into the category of denuded karst.

Data describing the parameters of about 2800 dolines in intrastratal gypsum karsts have been summarized by Gorbunova (1979). Fig. 7 illustrates the frequency distribution of dolines according to their diameter (A) and depth (B) . Most of the dolines have a diameter between 5 - 25m (10-15m is the most typical diameter) and depths ranging between 1-3m. However, it must be noted that the data set includes measurements reflecting a variety of cover bed thicknesses and compositions, though overall the area can be viewed as an entrenched karst.

Other important surface karstification characteristics are the density of dolines (expressed as number per km2), index of surface karstification (expressed as the ratio of area of dolines to total area, %), and rate of doline appearance (expressed as the number of new dolines appearing per year per km²). These parameters are meaningful if determined for limited areas that are characterized by a relatively homogenous distribution of karst forms. They have been utilized widely for local karstological mapping and engineering-geological assessment of gypsum karst terrains in the Soviet Union (Savarensky, 1967; Iljin, Savarensky & Tolmachev, 1972; Tolmachev, Troitsky & Khomenko, 1986). Characteristic figures for intrastratal gypsum karsts vary, for density, from a few tens to a few hundred dolines/km², for index of surface karstification - from a few to a few tens percent, for the rate of appearance - from 0.01 to 3.0 dolines per year per km² (Gorbunova, 1979). However, anthropogenic impact may increase the values for the latter characteristic dramatically (see Chapter I.11).

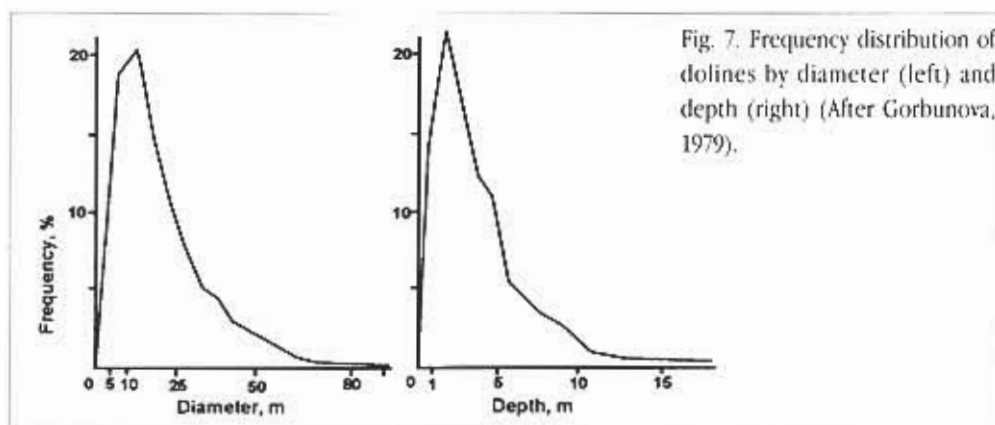Some studies suggest that collapse and subsidence processes are activated during specific

Fig. 7. Frequency distribution of dolines by diameter (left) and depth (right) (After Gorbunova, 1979).

periods. In the Kungur area of the Pre-Urals, new collapses occur most frequently in years with the highest precipitation and spring floods (Lukin & Ezhov, 1975). In the Volga region of the Russian Plain, collapses commonly coincide with periods of minimal levels in the Volga river, when it increasingly drains underground waters (Kaveev, 1967). Andrejchuk (1984) found that in the Bukovinsky sub-region of the Western Ukraine collapses occur predominantly during extremely dry or extremely wet periods. For the Bashkiria region in Russia, a cyclicity of some 11-16 years is revealed in the activation of collapses, related to climatic and karst water regime factors (Gorbunova, 1979).

In exposed gypsum karst areas (the sub-types of denuded and, particularly, barren karst) solution dolines are much more common than the collapse and subsidence features considered above. However, there may be great differences between the individual karst landscapes that represent the exposed karst type. Such differences are partially related to the various structural and geomorphic settings of exposed gypsum sequences, but probably the most important are evolutionary differences between denuded and barren karst sub-types. As defined in Chapter I.4, denuded karst is a former intrastratal karst, that has inherited structures from sub-surface karstification, whereas barren karst represents a system that has evolved largely in adjustment with the exposed geomorphic setting. Dissolutional landforms found in exposed karsts are discussed in chapters I.8 and I.9 of this volume.

Karst trenches. These typical intrastratal entrenched karst features are known from many parts of Russia, Germany and Canada. Karst trenches develop along escarpment edges and on the upper parts of steep slopes where gypsum crops out. They are markedly elongated closed depressions with irregular floors, commonly complicated by ponors and small dolines. The characteristics and mode of genesis of trenches in gypsum karst terrains have been summarized by Gorbunova (1979). Trenches vary considerably in size: from a few to 250-200m in width, from 10 to 2500m in length, from a few to 20m in depth. They form along clefts and fissures that originated due to unloading of a massif towards a side that has been opened up by erosion or other geomorphic processes. Unloading commonly enlarges pre-existing tectonic fissures. Some larger clefts can open directly to the surface and then further widened by gypsum dissolution. More commonly, extensive fissures form and then enlarge by dissolution under a still-continuous and
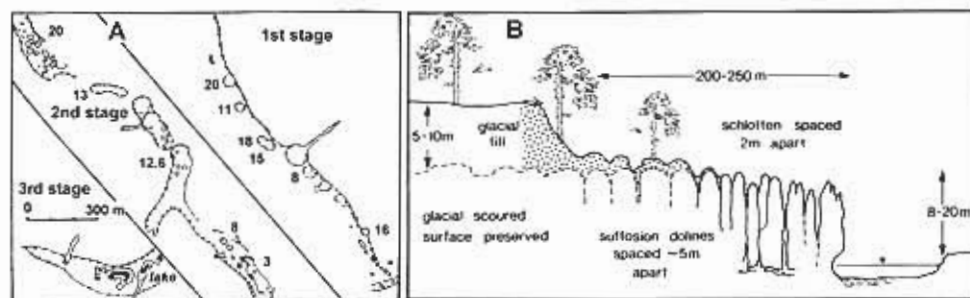
Fig. 8. A = The development of karst trenches in the Polazna area, Pre-Urals, Russia (After Butyrina, 1962). Stages are explained in the main text. Numbers indicate the depth of dolines. B = Progressive development of shlotten topography in massive gypsum near Windsor, Nova Scotia, Canada (After Ford & Williams, 1989).

poorly consolidated cover, until trenches develop in response to doline evolution (Butyrina, 1962; Lukin, 1966). Features representing different stages of such evolution (Fig.8-A) are also described under the term "shlotten depressions" or "shlotten karren" (Ford & Williams, 1989; Kempe, Chapter II.5). The first stage involves formation of separate dolines along a fissure, by suffosion and breakdown. During the second stage adjacent dolines amalgamate into a trench. Within the third stage the trench floor is smoothed and can be filled with poorly permeable alluvial deposits, allowing the formation of lakes, or a trench can be breached to one side. Several trenches can combine. Small caves are commonly associated with trenches, especially during the first development stage. Broken edges of exposed gypsum karst massifs and ridges, with deep clefts and displaced large gypsum blocks, are quite typical of some parts of Italy and Spain. In such cases dolines and trenches do not form (due to the lack of cover sediments), but the features provide clear illustrations of the unloading/gravitational phenomena that initiate development of the features described above in intrastratal karst settings.

Karst valleys. Minor stream valleys perched on a non-karstifiable cover commonly become dry and then separated into several discrete closed basins as evolving dolines and ponors pirate surface flow. A valley can be terminated by development of a single large ponor, or a group of sink points, at its downstream end. Development of such valleys in the exposed karst type is considered in Chapter I.9. Karst valleys of different sizes (up to a few kilometres in length) are very widespread in many regions of intrastratal entrenched karst (e.g. in the Western Ukraine, the Belomorsko-Kulojsky Plateau, the Volga region, the Pre-Urals and the Urals). Further incision into the gypsum commonly leads to a total breakdown of cave passages beneath a valley, so that valleys may become complicated by breakdown canyons (as for instance in the Angara region, Siberia). Canyons formed due to the destruction of cave passage roofs are also known from exposed karst areas (e.g. Sorbas in southern Spain). In areas where notable caves with underground streams existed, their breaching may result in development of a valley that inherits the course of a trunk cave passage, having been further widened after breakdown. The stream effectively becomes a surface one, although it may appear from a cave at its upstream end and disappear into a

cave at its downstream end. The Karjal valley on the Belomorsko-Kulojsky Plateau is an example of this type, about 10km long, 10 to 100m wide and up to 30m deep. It has five known caves at its upstream end, and steep gypsum outcrops along its walls. The valley floor is perched on a dolomite bed that underlies the gypsum. Karst valleys of another type, also known in this region, developed by a cliff above a large cave passage, retreating backwards from a major valley toward the interior of a plateau. Such valleys are typically 300-400m long (locally up to 1km) and 20-50m deep (Saburov, 1974).

Karst depressions. Depressions (forms that are larger than common dolines) in areas of intrastratal gypsum karst have different, commonly complex, origins and dimensions. In the most general terms, depressions represent some of the latest stages in the development of gypsum karst.

Relatively small depressions, 100-500m wide and a few tens of metres deep, form by over-enlargement of a single doline or by the fusion of several dolines. Intensely karstified areas with a high density of normal dolines can eventually evolve into depressions. In areas of temperate climate, such depressions commonly become partially filled with poorly permeable sediments, and may be occupied by lakes.

Intermediate depressions, a few to several tens of kilometres in lateral extent, commonly result from the fusion of several smaller depressions or from enlargement of karst valleys. In some respects many of these can be considered as analogous to the poljes of carbonate karsts (Gorbunova, 1979). Depending upon relationships with non-karstifiable rocks, structural and hydrogeological settings, gypsum karst analogies can be drawn with three major polje types: border, structural and baselevel poljes (Ford & Williams, 1989). Generally They may have surface flow across their floors, eventually sinking at ponors, or contain lakes that represent "windows" into the water table. Different kinds of intermediate depressions within the intrastratal karst types are widespread in the Belomorsko-Kulojsky and Pre-Urals regions of Russia. The most favourable are zones for their development are on the sides of large positive tectonic structures, where sulphates are in lateral contact with carbonate or terrigenous rocks (Gorbunova, 1979).

Large depressions, up to a few hundred kilometres in lateral extent are known in Canada, New Mexico, Texas and Russia (Ford & Williams, 1989). The term "solution subsidence troughs", also applied to such depressions, can be confusing, as it implies a gradual lowering of the surface. In fact, such depressions are commonly developed in structural situations like that mentioned above, or at the margins of large gypsum and/or salt deposits, by slow retreat of the dissolution front, with the "belt" of the karst landscape slowly shifting in the direction of retreat. The final results of intrastratal karst development within the belt are a karst breccia that replaces the karstified horizons, and a lowered surface that follows the migration of the belt. Within the karst belt the lowered surface is the result of the complex evolution and lateral migration of karst features rather then of uniform subsidence. Such depressions may have no (or only slight) topographical expression, as they are commonly infilled by terrigenous or other sediments, this being the reason that Quinlan (1978) termed them "solution-induced basins". Large depressions of this type develop during geologically lengthy time spans and are considered as palaeokarst features (Ford & Williams, 1989).

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