Solutional Landforms on Silicates; largely ignored or largely unrecognised?

Robert Wray.
Department of Geography, University of Wollongong.

Introduction.

The long held belief that the formation of karst, both the small-scale features superimposed upon a landscape, and the large scale landscapes themselves, can only develop upon relatively water soluble carbonate rocks has only recently been seriously questioned. Research into karst geomorphology has generally been restricted to the 'classic' forms developed on rocks of high carbonate content, even going as far as insisting that karst be strictly defined to carbonaceous rocks as this is where best developed karst forms are found; karst-like forms on non-carbonaceous rocks must, therefore, be "pseudo-karst" (cf. Otvos 1976). Others have discarded this circular reasoning and regard karst as a process, namely solution, the action of which is "thought to be critical (but not necessarily dominant) in the development of the landforms and drainage characteristics of karst" (Jennings 1983, p. 21).

It has further been argued that in a karst terrain not only do solutional features dominate surface landforms, but surface drainage gives way to underground water circulation (Dreybrodt 1988). However, sub-surface water flow is not definitive; a terrain may be karstic *sensu stricto* despite a lack of subsurface drainage if solution of bedrock matrix or cement has been critical in the development of the landscape (Twidale 1984; Young 1986a; Young and Young 1992). The implications of this are quite profound; if it meets this solution criterion a terrain may be karstic whatever the rock type, and even in the absence of significant subsurface flow.

Although karstic phenomena on silicate rocks have been reported for quite some time, little attention was given to their detailed study because, unlike limestone most silica rich rocks (notably quartzite and quartz sandstones) they were generally believed to be "virtually chemically inert" (Tricart and Cailleux 1972). However, the discovery of large scale solutional features, underground drainage networks, and large cave systems - possibly nowhere better displayed than on the Roraima quartzites of Southern Venezuela (White *et al.* 1966; Pouyllau and Seurin 1985; Briceño and Schubert 1990) - has shattered the classic view of karst formation being unconditionally restricted to 'soluble' rocks (Young and Young 1992).

Goldich's Scale of relative rates of chemical weathering suggest that quartz sandstone and granite are twice as resistant to chemical breakdown than volcanics and shales, nearly five times more resistant than most metamorphics, and over ten times more resistant to chemical attack than carbonates. However, if silicate karst is compared in detail with limestone karst, there is very little difference in landform morphology or in the genetic processes involved. The only significant difference between the two is that in silicates the removal of material by dissolution is restricted to about 10 to 20 percent of rock bulk, compared with the 80 percent or more generally found with carbonate rocks (Martini 1979).

Thus, silicate karst may be less common, and often less well developed than limestone karst, but given the appropriate environmental condition, almost any rock can be modelled to karst forms (Briceño and Schubert 1990).

Solubility of Silica.

Before examining the various forms and distribution of siliceous karst it is necessary to briefly examine the chemical processes, dominantly that of solution, responsible.

Whereas the chemical solution of calcium carbonate involves a multi-stage process (Bögli 1960), the solution of quartz in water can simply be written as (Henderson 1982);

$$SiO_2 + H_2O = H_4SiO_4$$

However, the breakdown of silicates is not as simple as it may at first seem. Dissolution of silicate minerals is more complex than for quartz and is often incongruent, that is, the solution process does not simply result in the formation a solute, but often leads to the formation/precipitation of new solid phases. For example, dissolution of felspar, a silicate mineral common in rocks and clays, often leads to the precipitation of aluminium hydroxide or kaolinite (Velbel 1985)

$$NaAlSi_3O_8(s) + H^+ + 7H_2O = Al(OH)_3(s) + Na^+ + 3H_4SiO_4(aq)$$

$$= 1/2Al_2Si_2O_5(OH)_4 + Na^+ + 2H_4SiO_4(aq)$$

These three processes result in uncharged monosilicic acid $Si(OH)_4$ being released into the natural environment, but this silica will not necessarily remain in solution. It may precipitate as one of the several naturally occurring forms of silica, generally either amorphous silica or opal-A, but almost never quartz. Silica in natural solutions may also be used in the neoformation of clays (Velbel 1985). These processes are themselves reversible; the clays may weather or the amorphous silica or opal-A redissolve.

The amorphous silica or opal-A thus formed may over time be transformed by diagenesis to more ordered forms of silica; to cristobalite-tridymite, thence chalcedony, and finally to the most stable form, quartz (Yariv and Cross 1979). Thus it is obvious that in any natural system, siliceous bed-rock, saprolite or soil, highly ordered quartz is not the only form of silica that can reasonably be expected to be present.

A further complicating factor in the geochemistry of silica is that the form taken by the silica greatly influences its solubility. Krauskopf (1956), Yariv and Cross (1979) and others have demonstrated significant differences in the solubility of silica. At 25°C amorphous silica is soluble in water to 100 - 140 mg/l whilst quartz is in equilibrium at 6 - 16 mg/l. At temperatures of 85-90° C, often attained on some exposed rock surfaces, the solubility of amorphous silica attains 300-380 mg/l - into the range of limestone solubility (Hedges 1969). The pH of the solvent solution has also been shown as having an influence on silica solubility. At pH below 9, silica solubilities are relatively uniform, however, above this point the solubility of amorphous silica increases very rapidly to 600-1000 mg/l (Yariv and Cross 1979), a six to ten fold increase over solutions with pH less than 9.

Although these rates of silica solubility have been widely modelled under laboratory conditions, concentrations of silica in rivers and streams suggest that similar rates may not always be found in nature. Recent studies indicate that the solubility of many silicates, especially that of quartz, may be reduced in the presence of some metallic ions, notably iron and aluminium (Yariv and Cross 1979). Conversely, rates of solution are greatly enhanced by some organic acids whilst the equilibrium solubility remains unchanged (Bennett 1991).

Thus, it is evident that the form of silica present and the environmental conditions under which the chemical attack occurs both have an important role in the breakdown of siliceous rocks. Silicate minerals and amorphous silica are potentially more than an order of magnitude more soluble than quartz. Nonetheless silica solution is an important process not only in granite, and felspathic or arkosic sandstones, but in highly quartzose sandstones and even very pure silica cemented quartzites.

Siliceous Karst.

Highly siliceous sedimentary rocks, notably sandstones and quartzites, often display karst features. Solutional forms on granite and related igneous rocks (granodiorite, syenite, etc), are common but generally at a lesser scale. Less familiar are solution features on metamorphics and even basaltic lavas.

The distribution of solution features on quartzose rocks spans an wide range of lithologic types and climatic regions. The most highly developed siliceous karst is generally found in the humid tropics (Wentworth 1944; Wall and Wilford 1966; White *et al.* 1966; Chalcraft and Pye 1984; Pouyllau and Seurin 1985; George 1989; Briceño and Schubert 1990), but excellent examples are reported from the seasonally dry tropics (Jennings 1979, 1983; Young 1986a,b), the hyper-arid tropics (Busche and Erbe 1987; Busche and Sponholz 1992), more temperate regions (Hayes 1900; Frye and Swineford 1947; Hedges 1969; Martini 1979, 1981; Battiau-Queney 1984; Cooks and Pretorious 1987; Whitlow and Shakesby 1988), continental Asia (Dzulynski and Kotarba 1979), and even sub-arctic environments (Dahl 1966).

Siliceous karst occurs over a similar range of scales and types to limestone, from towers, poljes and caves to the smaller *karren*. Indeed, almost every limestone form has been described on non-carbonaceous rocks with similar morphology and at a similar scale.

Tower Karst.

Probably the best examples of tower karst in quartz sandstone found anywhere in the world are in northern Australia. Jennings (1979,1983) describes large areas of the Arhnem Land Plateau, possibly best displayed at the 'Ruined City', the Proterozoic quartz sandstones of which have been "in parts chopped up by meshes of corridors and canyons, in parts reduced to towers jumping out of the plains" (1983, p.21). Percolation of water down and along joints during a long period of sub-aerial weathering removed much of the quartz cement which bound the rock. Later erosion of this weathered rock, dominantly along the major joints, has resulted in the formation of subsurface pipes and a general 'ruiniform' relief. Springs issuing from small tubes along bedding planes and numerous large closed depressions attest to underground drainage.

On a comparable scale, the Bungle Bungle Range in the Kimberley Region of Western Australia is also an extremely impressive example of tower karst. Solution of the quartz cement of these Devonian sandstones has been so intense that large blocks of the rock can be crushed in the hand. The interlocking network of grains has, however, resulted in the sandstone retaining a high compressive strength allowing it to stand in steep faces, turrets and sinuous arétes (Young 1986a,b, 1988).

Jennings (1983) insists the 'Ruined City', and presumably the similar landscapes in much of the Arhnem Land Plateau are attributable to solution, and thus true karst. Young (1986a) also demostrates conclusively that despite a lack of subsurface drainage, the intense etching and solution of silica that has occured in the Bungle Bungle Range has been critical in the formation of this landscape, which is thus also karstic.

Tower karst in many ways similar to those just described have also been found in the more humid Sydney Basin. In several localities south of Sydney the Permian Nowra Sandstone has been chopped up into numerous series of towers, aretes and cones, often closely resembling those of the 'Ruined City'. The best example of this 'ruiniform' relief is at Monolith Valley in the Budawang National Park. Here the sandstone is highly jointed and relatively thinly bedded. Springs often issue from small tubes along bedding planes high up on the cliffs. Preliminary analysis of the sandstone shows it has a low compression strength and is highly etched at the microscopic level

(Wray *in prep*). Other areas such as Bulee Gap exhibit a similar assemblage of rounded towers and coridors.

Tower karst and 'ruiniform' landscapes of this type are not unique to Australia and have also been reported from many parts of temperate Africa (Mainguet 1972) and the Roraima area of southern Venezuela (Pouyllau and Seurin 1985).

Caves.

Less well known but no less striking are the numerous caves and shafts formed in sandstones and quartzites around the world. Whilst none reach the sizes or lengths found in the largest limestone caves, they are in many cases comparable to limestone caves in size and length, and in themselves very impressive.

The most imposing sandstone karst landforms in the world must be those reported from Venezuela. Precipitous cliffs, often nearly a kilometre high and dense jungle surround large table mountains of Precambrian Roraima quartzites. For an excellent photographic essay on this area see George (1989). The mountain tops are areas of very high rainfall with the runoff draining through fissures, canyons, sinkholes and caves, or plunging directly over the rim to form the highest waterfalls in the world (Briceño and Schubert 1990). Angel Falls, the highest, has a single uninterrupted drop of over 986m (Pouyllau and Seurin 1985). This drainage pattern is controlled by the major fracture systems and by lithological contacts. The water that proceeds underground via the myriad of sinkholes finds its way by large and intricate cavern systems, a tiny number of which have yet been explored, to reemerge on the vertical walls of the table mountains, generally several hundred metres below the summits. An complex passage system over 400m long with tubes of up to 20m diameter has been reported within Cerro Autana, 650m up the 800m high mountain (Jennings 1983). Other cave systems are reported in this area, including active river passages over 2km long, all in quartz sandstone and quartzite (Chalcraft and Pye 1984; Pouyllau and Seurin 1985; George 1989; Briceño and Schubert 1990).

The wet tropics are not the only region with significant sandstone caves. Busch and Erbe (1987) report closed drainage depressions and phreatic caves in the hyper-arid (20 mm precipitation p.a) Sahara of northern Africa. The caves are relict and have been attributed to wetter periods during the mid-Tertiary, although the scarp-foot depressions are believed to have been active until the Pliocene. Both Mainguet (1972) and Martini (1979, 1981) also describe large and active cave systems many hundreds of metres long in South Africa, particularly in the Transvaal.

Jennings (1979, 1983) discussed several large sandstone caves in northern Australia. Yulirienji Cave excavated in the Upper Proterozoic quartzose Hodgson Sandstone south of Roper River, Arnhem Land, is a large rounded remnant of a former river cave 50m long by 8-10m wide and 1.5 to 4m high, whilst Whalemouth Cave near Turkey Creek in the East Kimberley is an active river passage about 220m long and 120m deep. The impressive exit of this cave is 60m high and 45m in width.

Many other sandstone caves are also known in the seasonally dry tropics of northern Australia. Joyce (1974) reports similar caves in Arnhem Land and southern Queensland, several of which have intermittently active streams. Galloway (1967), R.W.Young (*pers comm.*), A.R.M. Young (*pers comm.*), G. Nanson (*pers comm.*) and others, all describe dozens of caves in the Precambrian Kombolgie Sandstone of Arnhem Land, some of which exceed many tens of metres in length. This region also contains large doline fields formerly attributed to load casts (Needham 1978), but more recently reinterpreted as solutional (A. R. M. Young *pers comm.*).

Temperate Australia also has sandstone solutional caves. The Natural Tunnel at Hilltop, south of Sydney, is a large active through cave 85m long in the highly quartzose Hawkesbury Sandstone. Smaller caves are also found in this sandstone, one 60m long on Cowan Creek north of Sydney (Pavey 1975), whilst Endless Cave at Kincumber, near Gosford, is 35m long and intermittently fed from small solution tubes (Jennings 1983). The Yadbro Conglomerate below The Castle near Ulladulla is also riddled with hundreds of solution tubes many metres in length, some of which are accessible. Surface stains and drapes on the cliffs of the overlying Nowra Sandstone often originate from small solution tubes up to 30cm in diameter, also attesting to subsurface water flow.

Shafts.

Huge collapse shafts are also found, particularly in the tropics of South America. In the Roraima area (Gesner and Mehl 1977; George 1989) and in nearby Guyana (Urbani 1977) and Brazil (Brichta *et al.* 1980) huge vertically walled collapse dolines 150 to 400m wide and deep, all in sandstone and quartzite, have formed from collapse associated with chemical solution of quartzites and other siliceous rocks under the tropical climatic conditions.

Shafts of this magnitude are not unique to tropics however. Hayes (1900) describes two shafts or "solution sinks" (p.228), over 50m deep in quartzite in Alabama. Hayes proposed that the "beds in which they occur have been faulted over beds of limestone, and the material which originally occupied the depressions has fallen into underground channels through which it was carried off by flowing water" (p.229). There is, however, no evidence given for the presence of limestone below the quartzites.

This process of subjacent solution of limestone has been employed to account for many collapse features world-wide, even when no evidence for limestone has been found (Gesner and Mehl 1977; Brichta *et al.* 1980). The Big Hole near Braidwood, New South Wales, is a well known case in point. This 110m deep shaft in Devonian sandstones and conglomerates located on top of a hill has been attributed by Jennings (1967, 1983) to subjacent limestone solution and collapse into the resulting void. Although limestone is found in several locations close by, no evidence for limestone has been found in the vicinity of the shaft. Recent Scanning Electron Microscopy of the Big Hole sandstones indicates extensive etching and solution of the component detrital quartz grains and overgrowths (Wray *in prep*). In the light of this recent knowledge it is proposed that a quartz solution mechanism similar to those responsible for similar shafts worldwide may be in part responsible for the formation of this impressive and regionally uncharacteristic hole.

Small Scale Karst Features.

Notwithstanding their less impressive nature, smaller solution features are far more numerous than towers, caves or shafts. So ubiquitous are these small *karren* that they are normally passed by without a second glance or much thought as to how they originate in 'insoluble rocks'.

The study of small basins, rills and pits on siliceous rocks is one which has attracted the casual attention of numerous geographers and geologists around the world for over 130 years (Ormerod 1859; Cooks and Pretorius 1987), but during this period little detailed work has been done. German researchers have probably been the most productive in the field, and this language contains an extensive literature concerning these landforms, however, until recently few authors of other linguistic backgrounds were suitably impressed by these small solutional forms to have made more than superficial study of them.

Basins.

Solution basins, known variously as gnammas, opferkessel, rock tanks, etc., are the siliceous rock analogues of those on limestone (kamenitsa, tinajitas, etc). They are found on generally soil free, rocky outcrops of both inland and littoral areas. Their flat floors, undercut rims, and often well defined spillways are unmistakable testimony to the ability of rainwater initially impounded in small hollows to dissolve and carry away normally 'insoluble' minerals such as biotite, hornblende, feldspars, and even quartz (Hedges 1969).

These basins normally possess relatively flat to gently concave-up floors, interrupted only by occasional inclusions of material having a rate of solution different from that of the host rock. Their floors often terminate abruptly in vertical to slightly overhanging walls, and these exposed walls and floors are minutely irregular due to projecting crystals. They are often found in chains connected by shallow channels, and often coalesce to form larger, amoeboid hollows. Unlike kamenitsas, fretwork is not commonly found on the walls and rims of siliceous solution basins, possibly due to the coarse grained nature of the host rocks, but it is occasionally reported. Nested solution basins have not been found reported in the literature, but are common in the Sydney Basin sandstones (cf. Hedges 1969).

Sizes of these basins usually range from 1 or 2 cm up to a metre or two in width, and from less than 1 cm up to several tens of cm deep. They are usually much wider than they are deep. In most is retained a relatively thin regolith of fragments of the host rock, vegetation debris and organic scum. Many hold water for long periods after rain. Rarely, much larger basins are found, dimensions of which must be expressed in tens of metres (Dahl 1965; Howard and Kochell 1988; Netoff *pers comm.*).

Solution basins have been reported in numerous rock types, most commonly granite (Osmerod 1859; Hedges 1969; Dzulynski and Kotarba 1979), but also quartz sandstone containing less than 1% carbonate (Frye and Swineford 1947; Cooks and Pretorius 1987), granodiorite (Branner 1913), syenite (Branner 1913; Udden 1925), as well as certain schists, and basaltic lavas (Wentworth 1944).

Mostly described from relatively warm and humid climates, solution basins are distributed through as varied climates as those of much of the United States (Hedges 1966), western Greenland and Norway (Dahl 1966), Antarctica (Dahl 1966), Great Britain (Ormerod 1859), tropical Brazil and Venezuela (Wentworth 1944; Wall and Wilford 1966; White *et al.* 1966; Chalcraft and Pye 1984; Pouyllau and Seurin 1985; George 1989; Briceño and Schubert 1990), Hawai (Wentworth 1944), arid northern Africa (Busch and Erbe 1987), Mongolia (Dzulynski and Kotarba 1979), temperate South Africa (Mainguet 1972; Cooks and Pretorius 1987), and Southern Australia (Twidale 1984).

These basins are generally not relict forms, previously developed under more humid climatic regimes, although some exceptions to this general rule have been shown (Busch and Erbe 1987). They normally retain far too much fine surface detail to have survived been created under climatic conditions different to that of today. Smith and Albritton (1941) refused to place climatic limits on the development if limestone tinajitas in Texas because of climatic changes during the last few millenia, but in view of the wide variety of climates under which siliceous solution basins are presently found it would appear that climate *per se*, either past or present, is of little influence in their development (Hedges 1969).

Unlike solution basins on limestones which may develop beneath a soil mantle (Bögli 1980), siliceous solution basins are almost exclusively a sub-aerial form (Twidale 1984), but some currently inactive basins are found infilled with sediment. However, precursors of the basins are sometimes believed to develop at the weathering front beneath a soil layer (Twidale 1984).

Although Hedges (1966) believed that solution basins are only found in mountainous regions and other areas of high relief where weathering debris cannot accumulate to form a mantle over the parent rock, or on marine rock platforms (Wentworth 1944) this is clearly not always the case. Smith (1941) found that the largest basins were located where surfaces were flattest, finding none on slopes inclined more than 20 degrees.

Branner (1913), however, found basins developed on slopes as steep as about 45 degrees in Brazil, whilst Dahl (1965) reports large basins in Norway on slopes of over 20 degrees. Near Sydney solution basins are found on mountain tops, in valley bottoms, and at sea level. In favourable locations, basins tend to occur on level or gently sloping exposures of bare rock, such as the tops of rock bosses or boulders, the edges of clifflines, the beds of rivers and creeks incised into bed-rock, marine platforms and similar locations. The basins are most common on exposures inclined less than about 20 degrees, although in some rare instances basins on slopes as steep as about 50 degrees have been observed by the author.

Although basins are found in many different locations and a wide range of sizes, their morphology is not random. Morphometric studies, although rare, indicate there are definite relationships inherent in the gross characteristics of basins. Schipull (1978) studying 'waterpockets' in the quartz sandstone of Colorado discovered correlations between length and width ($r = 0.95$) and length and depth ($r = 0.81$) in the 80 basins examined. Similarly, Crooks and Pretorius (1987) found characteristic relationships of length, depth and width within basins in greywacke in two areas of similar lithology but markedly different climate in South Africa. Preliminary investigations of solution basins in the quartz sandstones of the Sydney Basin also suggest distinct relationships of similar correlation between basins in various locations, suggesting that "daß das Wachstum gleichzeitig in die Breite und in die Tiefe geht" (Schipull 1978, p.431) (*"that tincrease in width is simultaneous with tncrease in depth"* Translation R.Wray.)

Flutes.

Like solution basins, flutes, rilles or runnels resulting from the solvent action of flowing water are an almost ubiquitous feature of carbonate terrains. Solutional rilles have been classifed by size and supposed mode of origin (Bögli 1960), with numerous morphometric analysis conducted on these various forms (Dunkerley 1979, 1983). Solution runnels are also common on siliceous rocks, notably granite and sandstone, and are in many cases morphometrically similar to those on carbonates.

Twidale (1984) and Whitlow and Shakesby (1988) discuss various runnels and 'gutters' on granite outcrops in both Australia and Zimbabwe and demonstrate an evolution at the weathering front beneath a soil or regolith cover, with later stripping of this cover and sub-aerial exposure, in a similar manner to various limestone 'gutters'. These authors also demonstrate that these gutters are continuing to be modified by the solutional and corrosional action of running water.

Flutings that have developed sub-aerially have also been reported, but less commonly than the sub-surface 'etch' forms. Wall and Wilford (1966) report a comparison of small scale solutional features on microgranite in West Sarawak. Flutes of up to 6m length, with widths ranging from 2 to 100cm are common. These flutes are morphological similar to those on adjacent limestones. "The formation of these flutes appears to be mainly the result of solution by flowing rain water...corrasion by particles carried by the water.. is probably only of minor importance in flute formation" (Wall and Wilford 1966, p.466).

Excellent examples of flutes and runnels are also found on many sandstones. Whilst these are in general not as well defined as those on limestones, they are certainly well developed at several locations in the Sydney Basin.

Conclusions

All authors concede the influence of more or less chemical activity in the formation and enlargement of solutional forms on siliceous rocks. However, whilst chemical processes are critical, the physical processes of erosion of weathered material are paramount for continued development of siliceous karst features.

The actual focus of the chemical attack on siliceous rocks is also uncertain. Microscopic analysis suggests that alteration proceeds along mineral junctures, fractures and grain boundaries, with solution of alumino-silicates commonly leaving little residue. Klaer (1957) thought that by removal of the biotite in solution, the other mineral grains were freed and literally fell out. In similar fashion, Wilhelmy (1958) states that biotite and hornblende are the first minerals to be removed, followed by the feldspars, first oligoclase and then orthoclase, and then finally quartz.

However, in highly pure quartzites and sandstones this selective solution of silicate minerals cannot be shown. The slow chemical dissolution of quartz, 'arenisation' in the terms of Martini (1979), usually occurs along crystal boundaries with the freeing of individual grains, although it is often the case that the detrital grains are attacked more than the overgrowths which have lower surface free energies (Hurst and Bjorkum 1986). Faster rates of solution promote a general recession of surfaces and joint widening without rock disintergration (Martini 1979). This arenisation results in a rock that eventually becomes incoherent (Martini 1979; Young 1986a), and is thus highly suited to physical erosion. A plentiful supply of flowing water is then necessary for the removal of the material produced, preferably under vadose conditions (Martini 1979).

Unfortunately, the actual mechanisms of this arenisation are still unclear. White *et al* (1966) report that the spectacular Roraima orthoquartzite karst has formed from the hydration of quartz to amorphous silica under tropical weathering conditions. This conversion would enhance the solubility of the rock immensely. Chalcraft and Pye (1984) disagree, however, that this is the process responsible. They present SEM and XRD analyses and argue that this karst formed by the direct solution of quartz grains and silica cement, not involving any intermediate hydration phase. During weathering the minor feldspar and mica component is altered to kaolinite and, with other minor impurities, leached out concurrently with the removal of the quartz in solution.

The very high rainfall in this area is also important. Douglas (1969) demonstrated that the silica load of rivers is dependant on runoff, and thus rainfall. The amount of water moving through a rock will influence solution; for a given solubility regime, the higher the rate of flushing, the higher the silica loss. However, field measurements by Chalcraft and Pye (1984) showed dissolved silica to be very low, indicating that this dissected landscape must have formed by slow solution over a very long time period.

This factor of slow but very prolonged solution is one that has all too often been ignored. The slow rate of solution of the numerous forms of silica, especially quartz, was believed to preclude to formation of karstic lanforms on these 'inert' rocks. In the areas where most of the highly developed silicate karst is found, notably South America, Australia and southern Africa, slow rates of solution have been offset by long periods of sub-aerial weathering. In these areas moist temperate or tropical climatic reigimes have often been common since at least the Early Tertiary.

Thus it seems that given the right environmental conditions and the necessary geologic time periods landforms produced by silica weathering, and especially that of quartz, are not always as would be expected from that predicted from Goldich's Scale. Given a sufficiently long time period, the landforms produced by the slow dissolution of siliceous rocks can be in many respects similar to those produced by the much faster solution of carbonates. This notion challenges the classic view of karst formation being unconditionally restricted to 'soluble' rocks.

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