Lecture 13
Karst Landforms in the Humid Tropics

KEY QUESTION:

- ✓ *What landforms can be found in the humid tropics?*
- ✓ *What factors influence the formation of karst landforms in the humid tropics?*
- ✓ *What is the importance of karst landforms in the humid tropics?*

With the completion of this lecture, attached readings and tutorial, you should be able to:

- Identify the different karst landforms and describe their features
- Discuss the role of geomorphic processes in the formation of karst landforms
- Discuss the ecosystem services provided by karst landforms
- Discuss the impact of human activities on ecosystem services provided by karst landforms

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13.1 Introduction

- In geomorphology (i.e. the study of characteristics, origins and development of landforms), **karst landforms** (see **Fig. 1**) are a set of landforms mostly developed in carbonate rocks due to their ***high solubility***. Karst landforms therefore only develop in limestone under favourable conditions.

Fig. 1 Different Karst Landforms

- Characteristics of Limestone
  - Limestone is made up of **calcium carbonate**. Calcium carbonate is insoluble in water; it is highly soluble in acid.
  - The concentration of calcium carbonate may vary from area to area. Limestone which has **high concentration (80% or more) of calcium carbonate** is highly susceptible to the processes of **carbonation** and **solution** (see **Lect. 11**).
  - Limestone is a permeable rock. It has lines of weaknesses such as **joints** and **bedding planes** (see **Fig. 2**). Thus, limestone allows acidic water to pass through its lines of weaknesses, enabling weathering, fluvial erosion and mass movement to occur along these lines of weaknesses, thereby contributing to the formation of karst landforms. The **density of joints** may vary over place and time and thus so will the rate of weathering. The rate of weathering is most intense where two or more joints and bedding planes intersect (intersecting joints) or where joints and bedding planes are more dense.

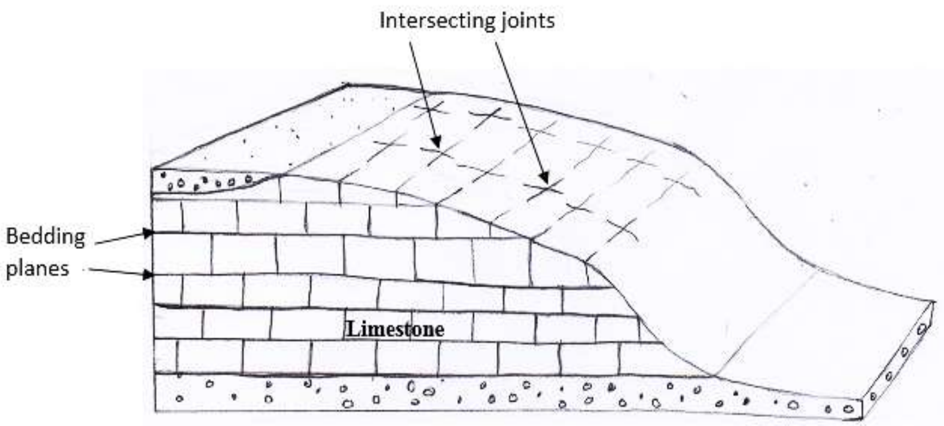

Fig. 2 Lines of weaknesses in limestone

- It has been suggested that certain karst landforms are more **common in the humid tropics**. Thus, their formation is influenced by **climatic conditions**. To understand such relationships, we need to become familiar with the characteristics of limestone, and the processes capable of **weathering** it into distinctive landforms. Also, we need to consider the role of **fluvial erosion** and **mass movements** involved. Thus, all three geomorphic processes play a role in the formation of karst landforms.

13.2 Global Distribution of Karst Landforms

- Karst landforms are common in southern China and countries of Southeast Asia such as northern Vietnam, Thailand, Indonesia, Sabah and Sarawak. Karst landforms are also found in south-eastern parts India, Central and South America, Australia and several European countries, including the UK, France and Slovenia (see **Fig. 3**). For our syllabus, we would focus on karst landforms found in the **humid tropics** mainly in parts of India, Vietnam, Thailand, Indonesia, Southern China, Malaysia etc.

Fig. 3 Global distribution of limestone regions

13.3 Features of Karst Landforms

- The karst landforms as specified in the syllabus are:
  - Cockpit karsts (Section **13.3.1**)
  - Tower karsts (Section **13.3.2**)
  - Caves (Section **13.3.3**)
- These landforms can be differentiated based on **surface** and **sub-surface location**. They can also be distinguished based on their **features** like **shape, height, slope angle** *etc*.
- These surface and sub-surface landforms are the result of **prolonged and extensive** weathering, fluvial erosion and mass movement of limestone regions.

13.3.1 Cockpit Karsts

- Cockpit karsts consist of **star-shaped depressions** called **cockpits** separated from each other by roughly equally spaced **conical/cone-shaped hills** (cone karst) (see **Fig. 4** and **5**), with local relief that is anything from **30 to 300 metres**.
    - Often been labelled as **egg-box topography** (see **Fig. 4** and **5**).
- The cones or conical hills are **generally symmetrical**, and their slopes measured between **45° and 60°**, regardless of their structure. Conical hills are **30 to 120 m tall** and occur with a density of **15 to 30 hills/km^2**. (Compare these numbers with tower karst later).
- Example of cockpit karst is **Chocolate Hills, Bohol, Philippines** (see **Fig. 6**).

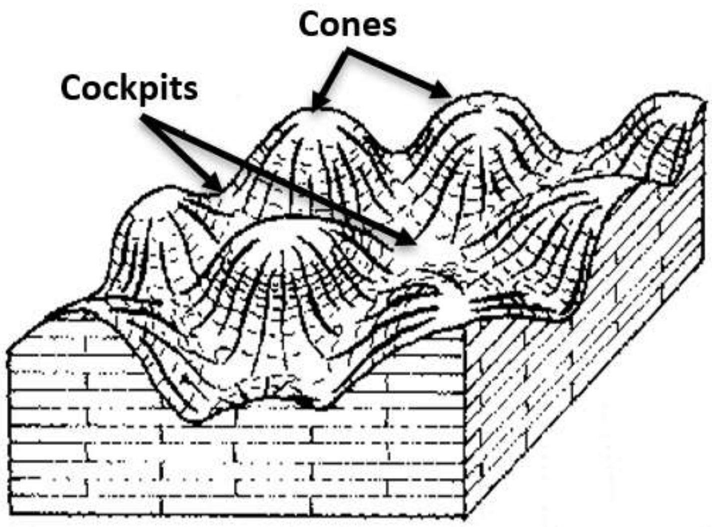

Fig. 4 Cockpit Karst

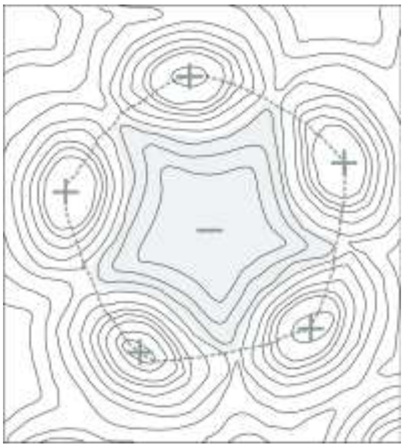

Fig. 5 Star-shaped depression

Fig. 6 Cockpit Karsts: Chocolate Hills, Bohol, Philippines

13.3.2 Tower Karsts

- Tower karsts are a steeper variety of karst risers than cone karsts. In general, towers are steeper and higher than cones and have a bigger height-diameter ratio. These residual hills come in a range of shapes, though a common dominant feature is their sharp rise from the surrounding plains.
- **Tower karsts are steep-sided limestone hills that rise above a plain, formed in humid tropics due to the further deepening of cockpits** (see **Section 13.3.1**).
    - Tower karsts are much more variable in size than the cone karst (see **Section 13.3.1**), and their heights may reach **over 150 m** in Sarawak and **even 300 m** elsewhere such as Vietnam (see **Fig. 7**) and southern China (see **Fig. 8**). They occur with **a density of 5-10 hills/km^2**, which is relatively much lower than cockpit karst.
    - Form in hard limestone with pronounced vertical jointing and almost horizontally bedded.
    - Tower karsts are characterised by **steep sides (between 60° and 90°)** with cliffs and overhangs, and with cave and solution notches at their base. Tower karsts usually occur in groups and are **separated from each other** by an alluvial plain or swamp or river.
- Thus, in general, tower karsts are steeper and higher than cones in cockpit karsts and have a bigger height-diameter ratio (less than 0.5 i.e. they are two to three times as tall as they are wide).
- For example, Halong Bay in Vietnam and Guangxi Province in southern China.

Fig. 7 Halong Bay, Vietnam, has an area of around 1500 sq km, including 1,960–2,000 tower karsts. It has been estimated that the evolution of the landscape here had taken 20 million years.

Fig. 8 Tower karst in Guangxi Province, southern China

13.3.3 Caves

- Caves are underground openings through which water in the subsurface circulates. Caves may occur as isolated openings in rock, but they usually have input and output points connected by conduits, at least 5–15 mm in diameter. Caves occur at different depths through the bedrock.
- Caves form in limestone because it is so easily dissolved by carbonation (see **Fig. 9**). Caves are the most important **subsurface features** in any limestone terrain. Caves formed in limestone are larger and more numerous than those formed in other environments.
- Caves are characterised by **solutional opening** and **speleothems**.

Fig. 9 Solutional Opening to Sub-surface Cave with Variety of Speleothems

13.4 Role of Geomorphic Processes in the Formation of Karst Landforms

- The formation of karst landforms involves the dissolution of soluble rocks both on the surface and underground.
- Chemical weathering processes like carbonation and solution breaks down limestone, resulting in the formation of karst landforms.
- Fluvial erosion and mass movements result in the removal of weathered materials down slope to form distinctive topography of cockpit and tower karsts.

13.4.1 Role of Geomorphic Processes in the Formation of Cockpit Karsts

- **Stage 1:**
  - Precipitation in the form of rain or snow melt water reaches the surface and eventually infiltrates into the soil through the lines of weakness in limestone.
  - The presence of water initiates the **carbonation** process (a form of solution) along the intersection of joints on limestone to form depressions.
  - Depressions are continually deepened by surface solution and carbonation caused by frequent episodes of rain (especially in the humid tropics).
  - The development of vegetation may also contribute to the deepening of these depressions through **bio-physical** and **bio-chemical weathering**.
  - Eventually, surface flows cut through the limestone terrain through **fluvial erosion**, eventually reaching the lowest point of the developing depressions.

- **Stage 2:**
  - Density difference of joints and bedding planes result in differential rate of weathering of limestone. Areas of more dense joints and bedding planes get weathered at a higher rate as more water can pass through forming depression. Whereas areas with less dense joints and bedding planes weather at a lower rate as less water can pass through thus forming a conical hill.
  - Over time a network of interconnected depressions forms **star shaped depression** called **cockpit** (see **Fig. 5** and **Fig. 10**). Cockpits are separated by **conical hills** called **cones** (see **Fig. 10**).

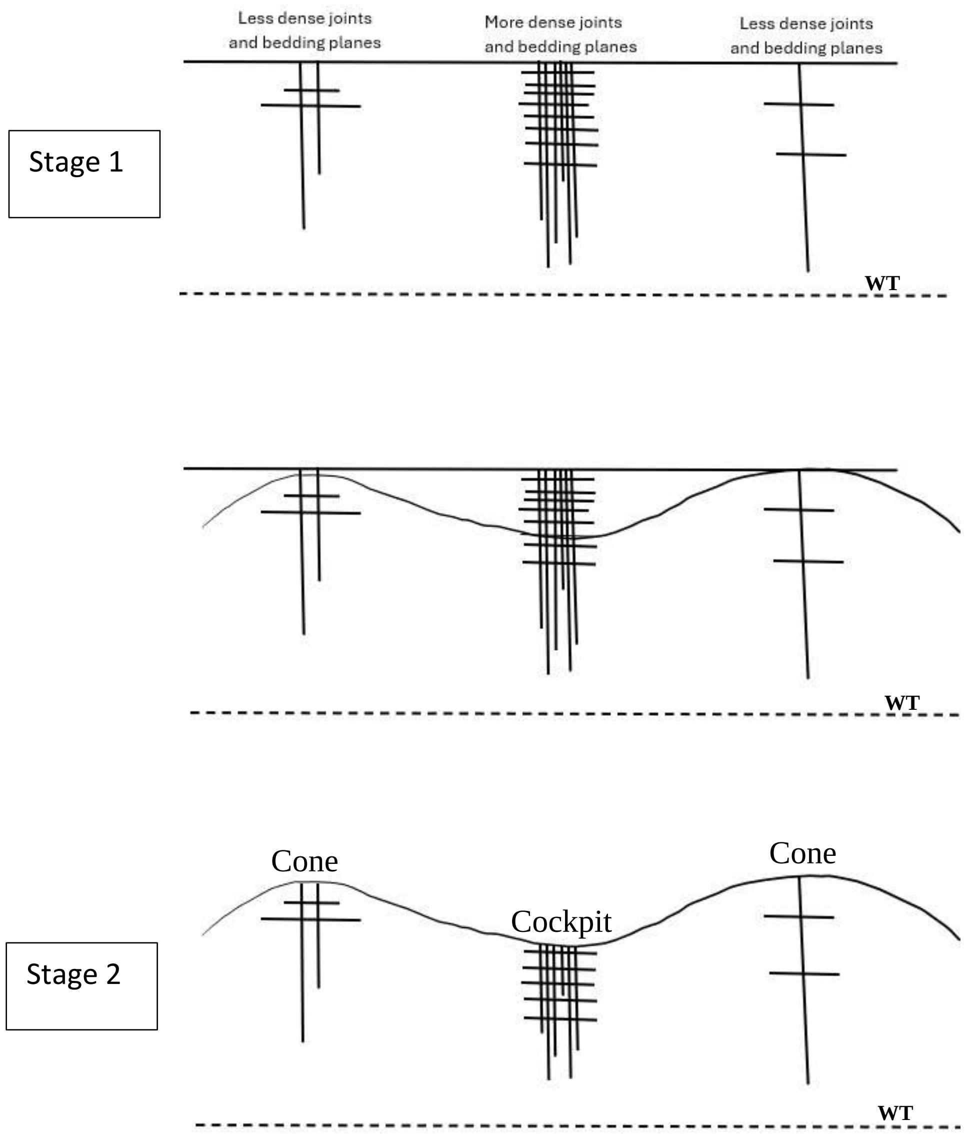

Fig. 10 Differential rate of weathering of limestone

13.4.2 Role of Geomorphic Processes in the Formation of Tower Karsts

- Over time cockpit karst turns into tower karsts (see **Fig. 11**). As the cockpit deepens, the conical hill increases in height to form a limestone tower known as tower karst. The following is a stage-by-stage formation of a tower karst from a cockpit karst:
- **Stage 3**:
  - Areas with more dense joints and bedding planes continue to get weathered by carbonation as water moves vertically downward and weathered materials get eroded by water or fluvial erosion and transportation. The vegetation on the slopes also keeps breaking down the rock by bio-physical and bio-chemical weathering processes. Thus, the cockpit gets deeper, and the cone gets taller.
- **Stage 4**:
  - As the base of the cockpit touches the water table (**WT**) or impermeable layer, water cannot move downwards and starts moving sideways or laterally. The lateral movement of water weathered and eroded the base of the slope of the conical hills forming caves. As the base gets removed, the overhang has no support at the base. This reduces the shear strength of the slope, and the slope became unstable. Also, the slope angle exceeds angle of repose, and the slope becomes unstable. Mass movement occurs thus widening the cockpit turning it into a wide, flat plain. This also turns the cone into a steep sided, tall mountain of limestone known as tower karst. Wave action and salt weathering also can erode the base of towers if these landforms rise from the sea.

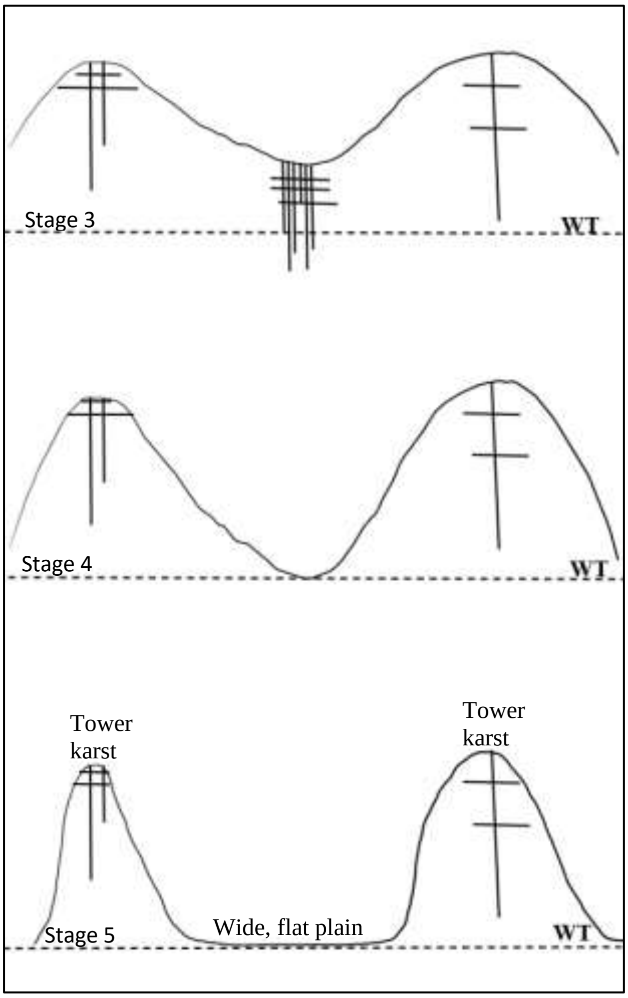

Fig. 11 Tower karst

- **Stage 5:**
  - Over time, tower karsts are formed which rises sharply from the surrounding plain, separated by flat plains, rivers or swamps (see **Fig. 11**).
  - Tectonic uplift may result in the limestone landscape to be raised above the basal surface of erosion.
  - This re-activates vertical erosion, resulting in the tower karsts becoming taller.

13.4.3 Role of Geomorphic Processes in the Formation of Caves

- **Stage 1:**
  - Throughout time, rainwater seeps into the cracks and pores of the ground (see **Fig. 12**). Rainwater either percolates or flows underground as streams or rivers. This rainwater which absorbs carbon dioxide in the atmosphere, (and takes more carbon dioxide as it drains through soil and decaying vegetation), becomes a weak carbonic acid solution.
- **Stage 2:**
  - This acidic water slowly dissolves the calcium carbonate by chemical weathering processes like **carbonation** and **solution** and carves tunnels and cavities. The weathered materials are transported by underground **fluvial processes**. The walls and ceilings of the cavities collapse by **mass movement**. The resulting network of passages become fully submerged or underwater caves in the limestone rock.
- **Stage 3:**
  - When there is climate change (ice caps form thus lowering sea level) or a tectonic uplift occurs, the water drains out of the caves, leaving dry chambers called caves.
- **Stage 4:**
  - Over time,as rainwater continues to pour, dissolved limestone drips from the roof to form into stalactites and drops to the ground becoming stalagmites.

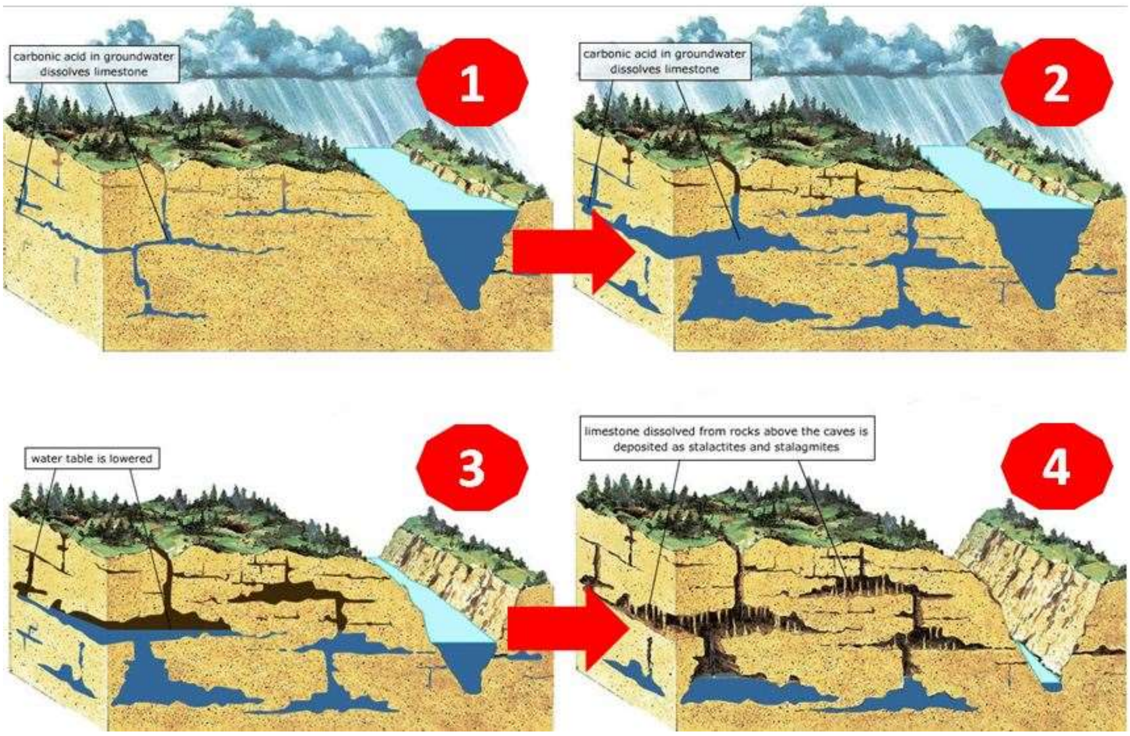

Fig. 12 Formation of limestone caves

Formation of speleothems:

- Inside the limestone caves, various formations called **speleothems** can develop. These include stalactites, stalagmites, columns (see **Fig. 9**). Speleothems form as water drips or flows through the cave, depositing minerals such as calcite.
- **Stalactites** are the formations that form on the ceilings of caves, which look like icicles. Formation of stalactite begins with a single mineral laden drop of water, i.e. the water chemically combined with carbon dioxide, calcium carbonate and calcite. The water drops squeezes between the rocks and drops to the floor leaving behind a minute deposit of the dissolved calcite in the shape of a thin ring of calcite. Each subsequent drop that forms and falls deposit another calcite-ring. Eventually, these rings form a very narrow (0.5 mm diameter) hollow tube hangs from the ceiling is commonly known as a Soda Straw stalactite (see **Fig. 13**).
- **Soda Straws** can grow quite long but are very fragile. Soda straws are initially hollow, allowing dissolved limestone to travel through the tube. Because a dissolved solid is traveling through the tube, it sometimes gets plugged up. This forces the dissolved limestone to "back up" and start flowing on the outside of the straw. Eventually, it thickens and becomes recognisable as a stalactite.

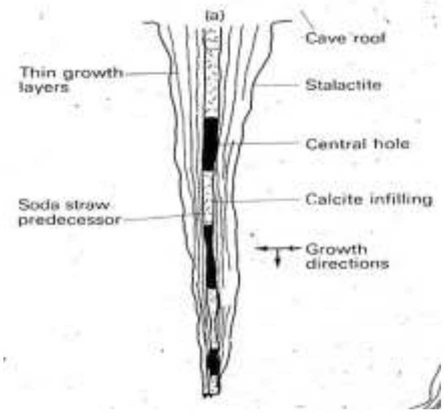

Fig. 13 Soda Straw Stalactite

- Speleothems which grow upwards from the cave floor are known as **stalagmites** (see **Fig. 14**). The water drops that fall from the tip of the parent formation, the stalactite, deposit more calcite on the floor below, eventually resulting in a rounded or cone shaped stalagmite. **Stalagmites** are the formations found on the floor of caves, reaching upward to touch the stalactites hanging above from the ceiling. Unlike stalactites, stalagmites are rounder, smoother and has no central tube.
- Straight formations of stalactite and stalagmites can meet and fuse to create **limestone pillar** or **column**.

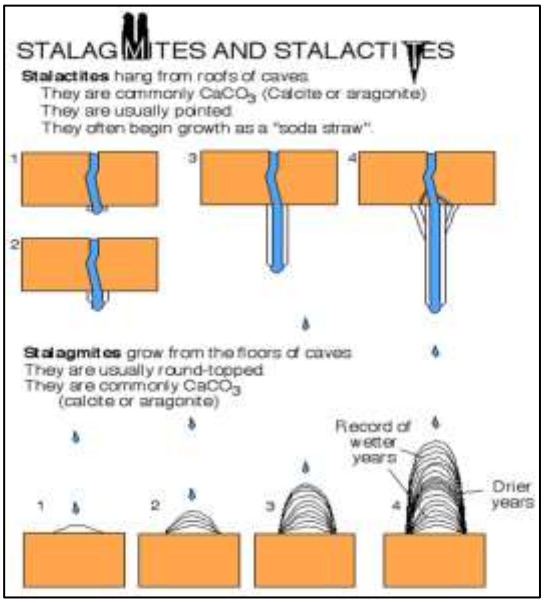

Fig. 14 Speleothems

- **Role of Weathering**
  - Groundwater moving through the limestone along the joints and bedding planes will dissolve the rock through carbonation and solution, converting the initial cracks and fissures into large cavities.
  - In massive limestone with very low primary permeability (i.e. porosity), water flow is confined to these fissures. Solution of the rock is therefore localised and cave conduits are formed. Since the opening to the caves are formed through carbonation (a form of solution), the openings are known as **solutional openings**. The removal of calcium bicarbonate (the by-product of carbonation) allows for carbonation to continue to take place, facilitating the formation of caves.
  - Speleothems are formed inside caves by the precipitation of calcium carbonate, which can only happen in subaerial environments (see **Fig. 9** and **Fig. 15**).

- **Role of Fluvial Erosion**
  - Surface streams enter through the surface solution hollows and start flowing through these caves as sub surface streams and causes erosion enlarging the caves (see **Fig. 15**).

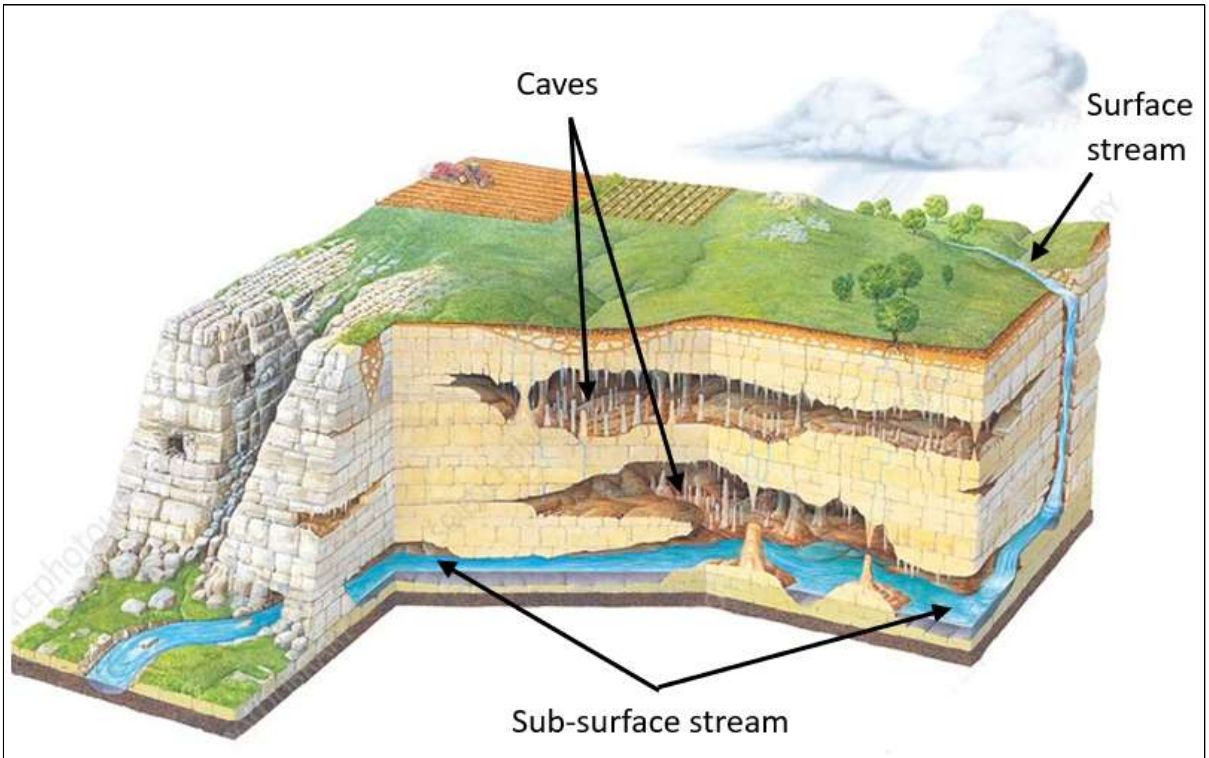

Fig. 15

- **Role of Mass Movement**
  - After limestone gets weathered by carbonation and solution, the joints and bedding planes widen making the rocks loose and thus **shear strength reduces** making the rocks to collapse forming bigger, wider and deeper caves. The walls and ceilings of the cavities collapse by **mass movement.**

13.5 Factors Influencing the Formation of Karst Landforms

- Clearly, the availability of limestone must be the first condition for karst landforms to develop, but the degree and scale of development has been observed to be much larger in the humid tropics than in cooler and drier parts of the world. Hence, the amount and distribution of rainfall is generally agreed to provide optimum conditions for karst landforms to develop.
  - In the humid tropics, the karst landforms tend to be dominated by tall and spectacular towers on the surface and extensive cave systems underground (see **Fig. 16**).

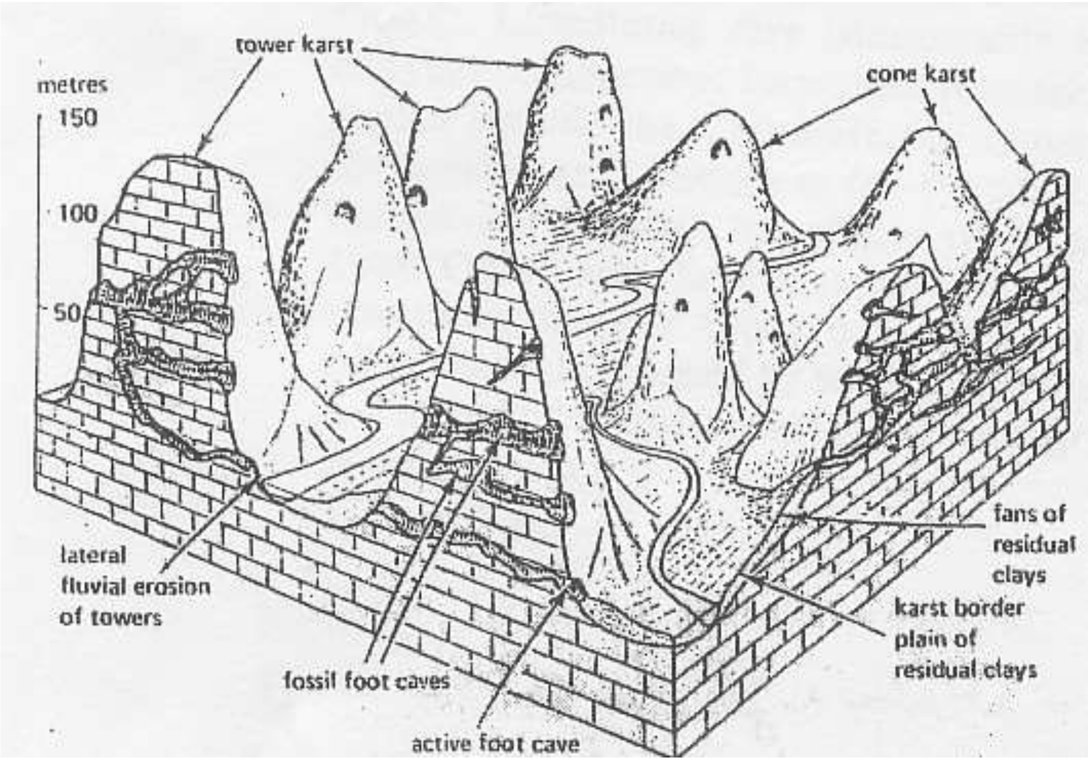

Fig. 16 Karst landforms in the humid tropics

13.5.1 Climate

- The importance of climate stems from its influence on the effectiveness of the chemical weathering processes that shape karst landforms.
- Karst landforms therefore develop best in regions with a minimum annual rainfall of 250 to 300 mm to support carbonation and solution. The A-zone climates have much more than this minimal amount of water, and as the water circulates through limestone via the joints and bedding planes, limestone becomes weathered and removed.
- Temperature is also an important factor, as it influences the rate of chemical reactions and biochemical processes. (Recall from **Lect. 11**: The rate of chemical weathering increases 2.5 times with each 10°C increase in temperature)

13.5.2 Vegetation

- As we learnt in **Lect. 11**, vegetation is capable of producing bio-chemical and bio-physical weathering processes.
- In the humid tropics, vegetation is dense, allowing much formation of humic acids, which aids in chelation.
- Bio-physical weathering such as root action would still play a role in prising apart limestone along the joints and bedding planes, increasing the surface area for water and acids to act on the rock, accelerating the rate of solution and carbonation. It could also encourage mass movement such as rock falls on the slopes of limestone cliffs or towers.

13.5.3 Rock Characteristics of Limestone

- **Purity of rock**: 80% or more of calcium carbonate
  - The limestone/soluble rock must contain at least 80% of calcium carbonate for dissolution processes to proceed effectively.
- **Permeabilit**y: Low primary permeability (pore spaces or porosity), high secondary permeability (joints/bedding planes or perviousness), low density of joints
  - Limestone has very low porosity as it is crystalline in structure with the mineral grains tightly locked in relation to each other with very miniscule gaps.
  - Complex pattern of joints in the otherwise impermeable limestone is needed for water to form routes to subsurface drainage channels.
  - Presence of joints and bedding planes (see **Fig. 17**) allow for the movement of water through the limestone which facilitates both carbonation and solution processes as it allows a greater surface area to be in contact with flowing water.
  - Secondary permeability (perviousness) is thus considered to be more crucial to the development of karst landforms.
  - Joint spacing cannot be too dense which may result in structural weakness and the likely collapse of underground karst features.

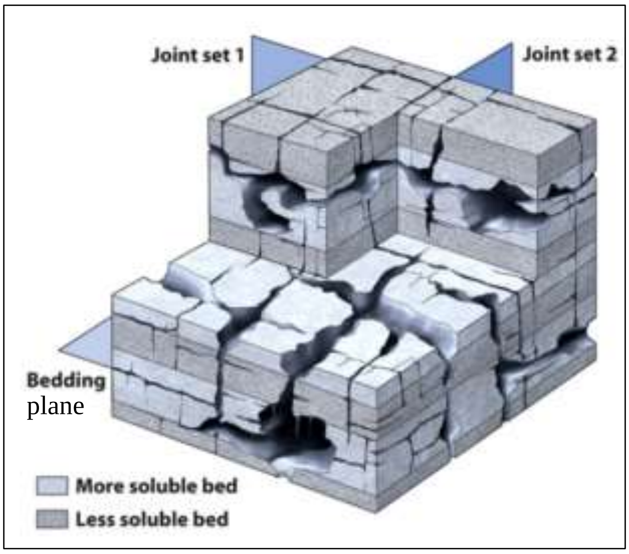

Fig. 17

- **Depth of rock**: At or near the surface
  - Rocks which are soluble by surface or groundwater must be present at or near the surface.
  - There can only be less than 15m of loose soil covering this soluble rock.

- **Thickness of rock**: Hundreds of metres
  - The soluble rocks must be of considerable thickness of up to hundreds of metres in order to be structurally strong enough to support karst features.

13.5.4 Tectonic Activity

- Tectonic activity such as earthquakes can trigger mass movements that affect karst landscapes (see **Case Study: Earthquake hits Jiuzhaigou National Park** and **Case Study: Landslides and Karst in Naga, Cebu**).

Case Study: Earthquake hits Jiuzhaigou National Park

China Focus: Scarred UNESCO World Heritage site recovers slowly after quake
08 August 2018

Over the past year, Ren Guiyuan has spent at least four hours every day touring the Jiuzhaigou National Park in the mountainous areas of southwest China's Sichuan Province.
His job is to look for any potential geohazard factors within the park -- a UNESCO World Heritage Site that was rocked by a 7.0-magnitude quake a year ago.
"It may take longer when it rains as I need to go through every corner," said Ren, who has been working at the park for two decades.
The national park, also known as the Jiuzhai Valley, contains around 20 tourist sites and is known for its spectacular waterfalls, lush forest, serene plateau lakes, and karst rock formations.
But the pristine scenery was left scarred by landslides and falling rocks triggered by the powerful earthquake last August.

RESTORED BEAUTY
The glassy waters of Wuhua Lake, or the five-flower lake, one of the most beautiful lakes in the valley, turned brown after the quake, and a total of 89 spots in the park suffered risks of geological hazards. Many people feared that the region's breathtaking scenery would be destroyed forever.

However, a year later, the five-flower lake has magically regained its original beauty and shines like a sapphire embedded among the valleys.
"The waters in Jiuzhai Valley come from underground rivers, and it can purify itself since 85.5 percent of the park is covered with forests," said Du Jie with the park's management bureau.
However, restoration of the whole park still takes time and can be very dangerous due to its unique karst landforms.
Over the past two months, Jiuzhai County was hit by continual torrential rains, which again triggered mudslides in the park. "The mud and rocks flew from ravines down to the roads under construction, we almost failed to escape," recalled Xiong Bo, a worker on the site. The second day, seven workers quit.
Now over a third of the 89 spots have been restored, but the remaining parts are more challenging to fix, as there is no precedent of how to restore a UNESCO World Heritage Site which was severely damaged by natural disasters.

Source: http://www.xinhuanet.com/english/2018-08/08/c_137376663.htm

Case Study: Landslides and Karst in Naga, Cebu

More communities could be relocated after Naga landslides — Cimatu
October 24, 2018

MORE COMMUNITIES in Naga City, Cebu are seen to be at risk of natural hazards and could be required to permanently relocate, Environment Secretary Roy A. Cimatu said on Monday during a dialogue with the victims of the Sept. 20 landslides in Barangay Tina-an.
The landslides that killed 78 and displaced more than 7,000 exposed the natural hazards in the city, according to a report prepared by state geologist Liza Soccoro J. Manzano. The disaster, she said, was a result of a "complex mass movement" in the city that is predominantly a karst terrain with numerous underground caves and sinkholes.

"Subsidence in karst is one of the most dangerous geohazards due to its extreme unpredictability," she said. Ms. Manzano explained that one of the causes of subsidence in karst is ground shaking due to earthquake, which she pointed as the main "culprit" of the tragic incident. But aside from the geology or topography of Naga and the earth tremors occurring there, other contributory factors are urbanization, industrialization, and quarrying. "Human activities, including quarry operations, that affect the change of the natural landscape are contributory factors to the complex landslide," the report said.

Barangays outside the active quarry operations that also showed signs of active subsidence are Cabungahan, Cantao-an, Upper Naalad, Mainit, Inayagan, and Inoburan it noted. With this, other households may also be recommended for evacuation, Mr. Cimatu said. In the meantime, the regional office of the Mines and Geosciences Bureau will announce by Oct. 25 who among the current evacuees can return to their homes and who needs to remain at evacuation centers while the relocation program is being worked out.

Source: https://www.bworldonline.com/more-communities-could-be-relocated-after-naga-landslides-cimatu/

13.5.5 Human Activities (see also **Section 13.6.2**)

- Humans have the potential to modify karst landscape, in this case, causing karst collapse.
- Karst collapse is a dynamic geological phenomenon, in which the rock mass or deposits overlying the karstified zone subsides down along the karst cavity, resulting in a collapse pit or sinkhole.
- Human activity plays a major role in the formation of ground collapse in karst areas.
    - Pumping for water supply and mine draining account for 64.1% of man-made causes of karst collapse (see **Case Study: Karst Collapse in South China**).
- While human activities may hasten karst collapse, humans may also undertake conservation actions to reduce their impact on karst landscapes (see **Section 13.6.2**).

Case Study: Karst Collapse in South China

Research of karst collapse has been carried out in South China provinces of Guangdong, Guangxi, Hunan, Hubei, Yunnan, Guizhou, and Jiangxi, where 738 karst ground-collapse have been found, with more than 30,000 pits or sinkholes. These include 33.6 percent natural ones and 66.4 percent caused by man (Table I).

Table 1. Type of collapse in ten provinces (autonomous regions) of South China

Type of collapse	Natural (including those caused by rain and drought)	Manmade (total = 434)					Collapse with unclear genesis
		Mine draining	Pumping for water supply	Storing water	Shock of added load	Water seeping	
Number	248	75	203	120	29	7	56
Percentage	33.6%			58.8%			7.5%
Sum total				738 (100%)			

There are many cities standing in the covered karst area including: Guangxi, Guangdong, Hunan, Hubei, Zhejiang, Jiangxi, Guizhou, Yunnan, and Jiangshu. In each city, the municipal water supply is mainly from the karst aquifer, only a few from the surface river. As the city demand for underground water from lower water bearing beds increases and the drawdown cone becomes larger, ground fracture and collapse occur.

Collapse has occurred in all "karst cities" including Kunming, Guiyang, Hangzhou, Guilin, Nanjiang, Shuicheng, Yulin, and Jioujang. Pumping groundwater in these cities is the main cause of collapse (203, accounting for 41 percent). The individual scale and affected zones of collapse from pumping are smaller from wells than those caused by mine drainage. Even though most collapses are concentrated near the pumping well, and the scale and density of pumping collapse are not large, buildings are directly impaired and destroyed, the water source is polluted, and people's normal lives are disturbed. The loss suffered by the economy is heavy because of the proximity of wells to the living area. For example, Hangzhou is a very beautiful city with attractive scenery and a pleasant climate. Since 1964, the water demand for domestic use has grown rapidly, and the volume of water extracted from underground has increased to 8870 m^3 per day. With the drop in water level to 12-30 m, ground collapse has occurred extensively. The cost has reached tens of thousands of yuan.

Source: https://link.springer.com/article/10.1007/BF02574824

13.6 Importance of Karst Landforms in the Humid Tropics

- In Southeast Asia, karsts cover an area of around 400,000 km^2. Karsts in this region, which are most extensive in Indonesia, Thailand, and Vietnam (see **Fig. 18**), possess impressive geological features, such as the world's largest cave chamber (Good Luck Cave in Sarawak, Malaysia) and one of the world's longest underground rivers (St. Paul Subterranean River in Palawan, Philippines).

Fig. 18 Distribution of Karsts (in black) throughout Southeast Asia (excluding Myanmar)

13.6.1 Ecosystem Services Provided by Karst Landforms

a) Provisioning Services

- Karsts are mainly exploited for limestone, an important mineral with over 100 industrial uses, which include the production of cement and marble products.

Background Information

The high biodiversity on karsts arises from a multitude of unique terrains (e.g., fissured cliffs and extensive caves) and variable climatic conditions. High species endemism can also occur on karsts that have gone through tectonic and sea level changes, different degrees of isolation, and incidences of random events. On karst surfaces, soil-related isolation produces a unique flora that includes many calcicoles (species adapted to growing on limestone). At the same time, such vegetation supports animal species somewhat different from those in non-karstic areas. Because of their poor dispersal capabilities, plants and some animals, such as invertebrates, have to adapt to highly alkaline conditions, thin soil layers, and desiccation on porous limestone bedrock. In caves, animals such as arthropods and fishes must evolve specializations to cope with fluctuating levels of light, water quantity, temperature, humidity, gas concentrations, and organic material.

Diversity of Cave Fauna

The relative stability and age of underground cave ecosystems enable relict faunas to persist. In Sarawak, some of the 200 cave species found in the Mulu karsts belong to ancient animal groups that have mostly disappeared from the surface. Invertebrates make up the majority of cave faunas, and as a result of their sheer diversity, surveys consistently yield new genera and species from Southeast Asian karsts. In just three hours of sampling a well-documented karst cave in Peninsular Malaysia, 28% of the 53 invertebrate species collected by Dittmar and colleagues were new records, and a further 6% were likely to be new to science. In karst caves, most invertebrates (e.g., flies, cockroaches, and snails) primarily or ultimately depend on guano for food, and several arthropods, such as certain families of millipedes (Glyphiulidae) and beetles (Aderidae), are even restricted to life on guano piles. Some invertebrates complete their life cycles entirely within caves, and most have undergone regressive evolution. For example, the troglobitic crab Cancrocaeca xenomorpha (**Fig. 19c**) from the Maros karsts in Indonesia is characterized by ocular degeneration, pale coloration, and abnormally long appendages after years of isolation in perennial darkness.

Fig. 19 *Examples of karst biodiversity. (a) Site-endemic begonia,* Begonia amphioxus, *from Sabah, Malaysia. (b) Site-endemic prosobranch land snail,* Opisthostoma (Plectostoma) obliquedentatum, *from Sabah, Malaysia. (c) Blind troglobitic crab,* Cancrocaeca xenomorpha, *genus from Sulawesi, Indonesia. (d) Cave-dwelling insectivorous bat,* Hipposideros diadema, *from Sarawak, Malaysia. Photographs: Peter Koomen (a), Menno Schilthuizen (b), Louis Deharveng (c), and Kelvin K. P. Lim (d).*

- Several karst species are commercially valuable as well. Rare slipper orchids are often sold or hybridized on a large scale in the billion-dollar orchid industry, while endemic cycads, palms, and various herbaceous plants (e.g.,Chirita and Paraboea) are sought after by horticulturalists.

- Nests built by swiftlets (e.g.,Collocalia fuciphagus and Collocalia maximus) on karst cave walls are highly prized as Asian culinary delicacies. At 15 caves in the Gomantong karsts of Sabah, nest yields of about 5 metric tons can fetch more than US$2.5 million annually.
- Guano deposited by bats and swiftlets onto cave floors is also harvested for fertilizer. At the Niah karsts, for example, the Sarawak Museum operates a cooperative that sells guano to fertilize local black pepper fields.

b) Regulating Services

- Services provided by karsts and their biodiversity are less tangible but significant, nonetheless. Karsts readily store rain, and apart from maintaining the hydrological integrity of a watershed), they also serve as sources of groundwater for consumption and irrigation. In Indonesia, quarrying has caused water shortages in human settlements because, in the absence of water storage in karsts, rain flows directly into underground streams that empty into the sea.

- Animals in karst caves are also known to perform valuable ecosystem services. Bats pollinate and disperse the seeds of many economically important plants. In the Niah karsts, resident populations of cave nectar bats are vital pollinators of the durian tree, which has a yearly market of approximately US$1.5 billion in East Asia. Around karsts, insectivorous bats, such as the Diadem roundleaf bat (see **Fig. 19(d)**), and swiftlets also help to control agricultural pests; these animal groups consume up to 7.5 and 11 metric tons, respectively, of insects at the Niah karsts each day. Karsts feature prominently in several cultures and religions within the region.

c) Cultural Services

- Caves have been used as places of worship (e.g., by the Buddhists and Hindus; see **Fig. 20(c)**) or burial sites (e.g., by the Dayak people in Borneo) for several centuries. The economies of countries such as Malaysia and Thailand ultimately benefit from cultural and religion-based tourism, especially during important festivals held at karst temples. Similarly, many countries have profited from tourism at karsts of high aesthetic value (e.g., the sea-flooded karst towers of Ha Long Bay, Vietnam). By protecting and maintaining the natural states of Niah and Mulu karsts, the state of Sarawak obtains US$80,000 from eco- and geotourism each year.

Fig. 20 *Examples of land uses around karsts. (a) A pristine tower karst in Sarawak, Malaysia. (b) Karst quarried for limestone in Perak, Malaysia. (c) Karst used as a Hindu temple in Selangor, Malaysia. (d) Karst as an aesthetic backdrop for a resort in Perak, Malaysia. Photographs: Reuben Clements.*

d) Supporting Services

- The inhabitants of one village, known as Panyee, dealt with their space limitation by building the entire village on stilts (see **Fig. 21**). Even the school "soccer field" is nothing more than a "pier" between buildings. The villagers use the rock tower next to their perched village exclusively for burial of the dead and for the siting of a mosque. Tourists can reach Panyee by boat, but tourism is changing this community. Selling cheap souvenirs has replaced fishing as the primary source of income for the people of Panyee.

Fig. 21 Koh Panyi (Koh Panyee) is a surprising village almost entirely built on stilts in Phang Nga Bay near the famous James Bond Island.

13.6.2 Impact of Human Activities on Ecosystem Services Provided by Karst Landforms

- Large-scale operations involving the mining of limestone and basement minerals (e.g., antimony, gold, and iron) are a primary threat to karst landforms because they cause irreversible ecosystem damage and extinction of endemic species. To estimate the magnitude of limestone-quarrying activities in the tropics, mineral statistics over a five-year period (1999–2003) for four regions are shown in **Fig. 22**. Southeast Asia appears to have greater mean annual increases in limestone quarrying rates (5.7% per year; see **Fig. 22(a)**) and significantly higher mean annual limestone quarrying rates (178 million metric tons per year; see **Fig. 22b**) when compared with larger tropical regions such as Africa, South America, and Central America (including the Caribbean).

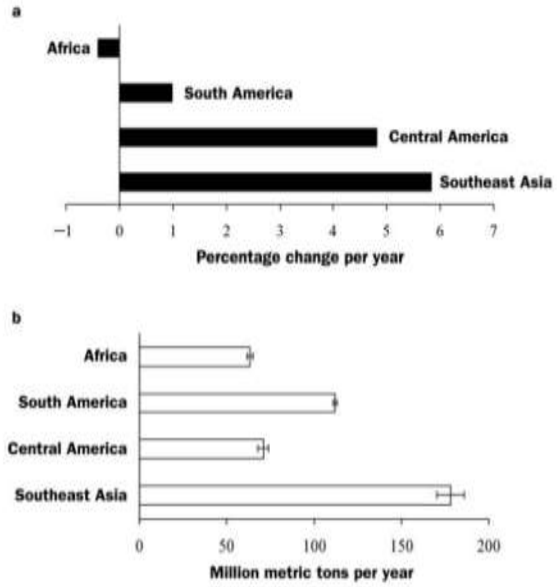

Fig. 22 *Scale of limestone quarrying in terms of (a) mean annual percentage change in quarrying rates and (b) mean (± standard error) annual quarrying rates for four major tropical regions over a five-year period (1999–2003). Quarrying rates in Southeast Asia appear to be the highest relative to other regions. Calculations excluded countries with incomplete statistics for all five years. Data are from the US Geological Survey (http://minerals.usgs.gov/minerals).*

- Furthermore, quarrying rates for each region are likely to be underestimates because they do not include statistics from village-level quarries. The gravity of these figures will become clear only when remaining limestone resources for the whole of Southeast Asia have been quantified. Nevertheless, they suggest a bleak outlook for the future of regional karst biodiversity.
- Land clearing for development is another major threat to karst biota. Logging activities around karsts (a) reduce shade and humidity and endanger sensitive plants, (b) drive away cave-visiting animals such as mammals and arthropods that supply organic matter to guano communities, (c) pollute cave streams and kill resident fauna, and (d) diminish bat populations that depend heavily on surrounding forests for foraging.
- The land surrounding karsts is sometimes burned to facilitate crop cultivation (e.g., for federal agricultural land schemes in Malaysia), but the fires resulting from such activities can easily sweep up karst slopes. Burnt karsts subsequently experience prolonged desiccation due to higher solar radiation and are more susceptible to further fires. The resulting secondary vegetation that grows on burnt karsts not only takes decades to recover but also results in population declines in plant and animal species that are sensitive to disturbance.
- Unsustainable collection of endemic plants of medicinal and ornamental value can also result in population extinctions, and the indiscriminate harvesting of swiftlet nests in Borneo has reduced swiftlet populations. Excessive nest-harvesting activities may have indirectly contributed to the decline of bat populations as well; the abundance of naked bats at the Niah karsts in Sarawak fell from approximately 30,000 to 1000 over a 42-year period. Hunting pressure can also deplete populations of certain karst-associated animals if it continues unregulated. Bats from karst caves are sold for consumption in the markets of Thailand and Indonesia, and horn trophies of the threatened serow can be purchased at markets in Laos. Other threats to karst species include the quarrying of speleothems (mineral formations in caves, such as stalactites), insecticide use, flooding caused by the damming of nearby rivers, treasure hunting, and spelunking.

Conservation Efforts

In most countries, karsts have been preserved based on anthropocentric criteria (e.g., karsts with high tourist potential or those that are inaccessible to mining companies). At times, environmental impact assessments (EIAs) of karsts are undertaken before development commences. By conserving 'valuable' or environmentally-sensitive karst landforms, humans can ensure that **human activities do not drastically compromise the ability of karst areas to provide important ecosystem services**.

In Southeast Asia, the conservation of karst areas is met with **several challenges**.

1. Firstly, about 13% of Southeast Asia's karst areas are deemed to be protected. This level of protection may appear satisfactory, given that a frequently cited goal of conservation scientists is to protect 10% of all habitat types globally. However, such **percentages do not necessarily correspond to species representation, and 'protected habitats' may be "paper parks" that are not properly managed because of insufficient resources.**

- Laws to protect karst species are severely lacking; the only known case is a cave fish from central Java, Indonesia.
- Mining companies often exploit the uncertain demarcation of legal authority arising from the involvement of too many agencies. In Indonesia, laws that necessitate EIAs prior to quarrying are often circumvented.
- For the abovementioned laws and policies to work, however, governments must clamp down on corruption, resolve conflicting jurisdictions, and provide administrators with greater incentives (e.g., income from geo-tourism and fines from offenses) to ensure better enforcement and accountability.

2. Secondly, the **lack of biological information on karsts ultimately weakens justifications for their conservation in the long run**.

- Among internationally peer-reviewed articles from the Biological Abstracts database for biodiversity-related articles over a 20-year period (1985–2004), karsts contribute just 1% of the global and regional biodiversity research output from terrestrial and freshwater ecosystems.
- Given that karsts cover around 10% of the land area in Southeast Asia, more studies need to be devoted to these ecosystems.

3. Thirdly, **poverty and resource shortages resulting from overpopulation are likely to continue to marginalize karst conservation issues**. Concepts of animal population extinctions and unsustainable extractions are usually of little concern to the poor.

- In Sarawak, a survey of 198 low-income households around the Bau karsts revealed that more than half (54%) were dependent on karst resources for subsistence, and a substantial minority (33%) were unwilling to accept conservation measures restricting their customary land rights.
- For cash-strapped governments, royalties from cement manufacture are so substantial that policies for sustainable limestone quarrying are generally overlooked.
- To alleviate poverty and resource overexploitation in karst areas, land-use planning must be improved (using a landscape-scale conservation approach) to consider the welfare of poorer communities.
  - For example, the managing agencies of the Pu Luong-Cuc Phuong karst conservation project in Vietnam allocated land to local residents for sustainable agroforestry and involved them in ecotourism projects to generate income.
  - Government officials in Gunungkidul, Indonesia are equally concerned that karst quarries will ruin the landscape and affect tourism, which generated US$57,000 more than quarrying in 2002.
  - In Malaysia, karsts that were preserved as aesthetic backdrops for a resort township have not only attracted multimillion-dollar investments but also opened up job opportunities for local residents.

13.7 Summary: Conditions Favouring the Development of Karst Landforms

- **Fig. 23** shows a possible sequential development of karst landforms, from the early depressions to cockpit karst, caves and tower karsts.
- The conditions that encourage such a sequential development are:
  - Climatic conditions play a part. There should be **sufficient rainfall** to promote carbonation and solution (see **Section 13.5.1**).
  - Limestone must be **well-bedded** and **well-jointed** to promote maximum chemical weathering (see **Section 13.5.3**).
  - The area of limestone must be large enough for a full karst landform to develop. In particular, there should be a considerable **thickness of limestone**. Otherwise, other types of rock may hinder karst development.
  - The height of the area, where weathering of limestone starts, above water table must be great enough for the progression of the stages to be complete.

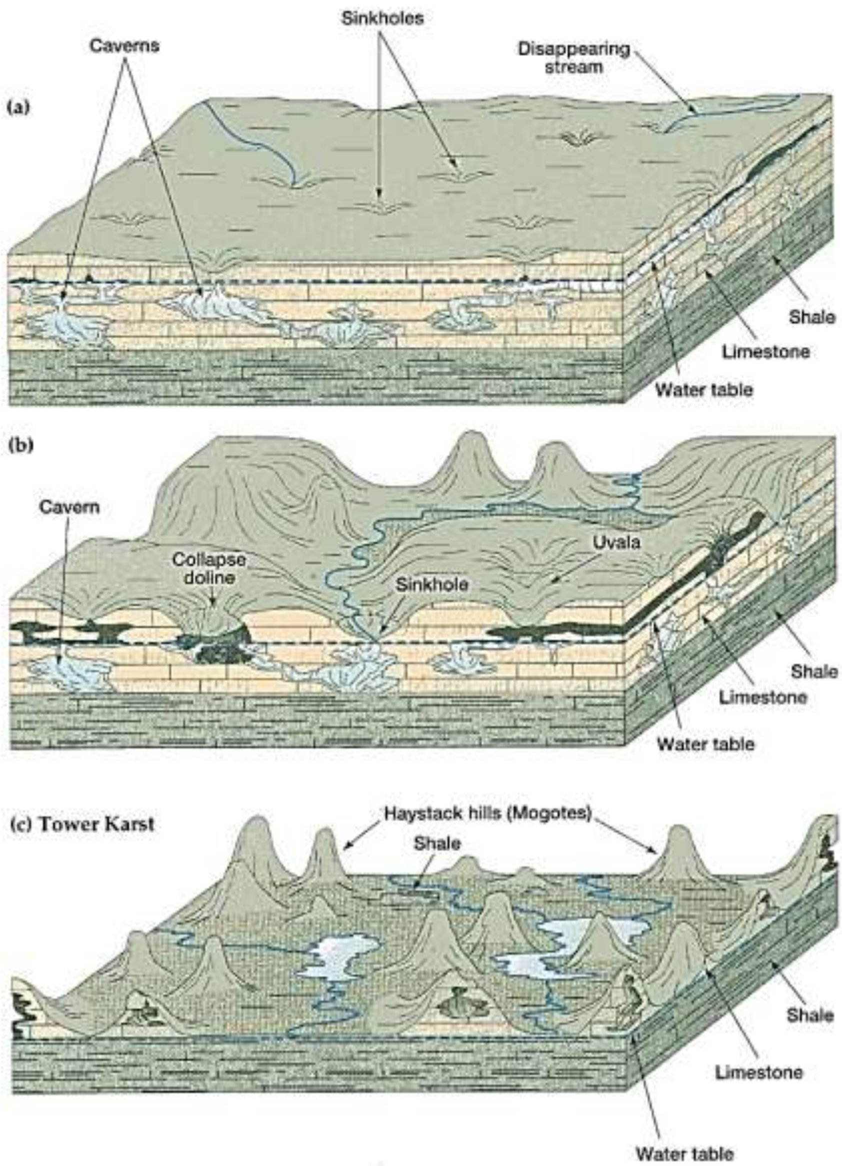

Fig. 23 A possible sequential development of karst landforms

13.8 Conclusion

- In conclusion, the study of cockpit karst, tower karst, and caves in tropical environments is crucial as these landforms are not only a testament to the dynamic processes of the Earth but also a reminder of the intricate relationship between geology and ecology. Understanding these formations provides valuable insights into environmental conservation, sustainable management, and the appreciation of the natural beauty and diversity of our planet. This exploration of limestone landforms in tropical environments underlines their significance in the broader context of physical geography. They serve as natural laboratories for understanding geomorphic processes, as well as hotspots for biodiversity and ecological research.