Characteristics and Main Controlling Factors of Karst Caves in the Tarim Basin*

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Abstract

The Tarim Basin experienced extensive lateral compression and vertical uplift during the Middle Caledonian. The Ordovician Yijianfang and Yingshan formations were exposed three times, resulting in vast karst and the forming of different types of paleocaves. Morphology and structure of 174 karst caves are studied in detail and categorized in Tarim outcrops, and as analogy, karst caves of Tarim Oilfield buried deep in Ordovician formation are analyzed using seismic attribute and seismic inversion data, and the main controlling factors of different types of karst caves were studied. The research shows that: karst caves can be divided into four types according to their morphology and structure, which are tubular and branching type, karst caverns group type, plate profile type and single isolated type. Different types have different characteristics and controlling factors. 1) Controlled by underground rivers, the tubular and branching type of karst caves are long slender pipes with circular shape in cross section, and many branches connected each other. The biggest one found in Sanjianfang outcrop is more than 100m long and has seven branches with more than 10 m length. This type of karst caves were found in Halahatang Oilfield as well with linear property in seismic amplitude gradient. 2) The karst caverns type is usually comprised of many caves with different scale and shapes, and they connected with each other, these caves distribute in several layers, which are controlled by different level of water table. Karst cavern type caves show high impedance in seismic inversion body and disorder reflection in conventional seismic section, and this type of caves are the main reservoir space of Halahatang Oilfield and Tahe Oilfield in Tarim basin. 3) The single isolated type of caves are usually small scale, scattered in the plane and vertically in geomorphic lower part in outcrops, can be funnel-shaped, inverted funnel-shaped, plate profile or combined shape, controlled by different factors (faults, fractures, or corrosion along layers). Some larger caves of single isolated type shows ball chain reflections, while most single caves less than 50m wide cannot be identified due to low resolution of seismic data. 4) Controlled by regional corrosion along layers, caves of the plate profile type show property of great width along layers and relatively small height, and mostly distribute on geomorphic lower part of the side of ravine along layers.

Geologic Overview

The study area, the Kepingtage structural zone, lies in the northwest part of the Tarim basin. It consists of five rows of thrust nappes, which strike ENE to WSW. In these thrust nappes, the southernmost one is the biggest, and wide Ordovician carbonate outcrops are found here. The

Kepingtage structural zone underwent Caledonian movement, Hercynian movement, Indosinian-Yanshan movement, and Himalayan movement, among which, Caledonian and Himalayan movements had the greatest impact to the sedimentary formations in this zone. During the early Caledonian movement, the whole Kepingtage area fell down and thick Ordovician carbonate formations, Yingshan group and Yijianfang group, were deposited. In the middle and late Caledonian movement, under the impact of South Tianshan oceanic plate subducting northward, the Kepingtage area tilted up three times, leading to the exposure of the Yijianfang and Yingshan groups, meanwhile, wide karstification developed and different types of karst caves formed at that time. In the late Miocene, Himalayan movement caused extensive lateral compression and vertical uplift, and finally the thrust nappes formed in the Kepingtage zone.

Evidence of Paleokarst

During Himalayan movement, the formations in the Kepingtage structural zone were uplifted, bent and deformed, and underwent corrosion as well. While the karst caves in this zone are paleocaves formed during the middle Caledonian, rather than the period after Himalayan movement. There is some evidence showing this point of view:

(1) Paleokarrens, paleoridges and paleokarsts are widespread phenomena in the carbonate formations of the Kepingtage outcrops. Paleokarrens are usually 5 to 8 centimeters deep and 15 to 50 centimeters long. A ferric membrane could be seen in most paleokarrens (Figure 1a and 1b). While results of paleoclimate show that the Tarim basin was in hot and dry weather during the whole Meso-Cenozoic era, karstification proceeded very slowly. Great paleokarrens and paleoridges like these findings could not form at all.
(2) Upper Ordovician and Silurian formations could be seen in the Kepingtage outcrop. It was deduced from their occurrence that the recent exposure time of the Ordovician Yingshan and Yijianfang groups was not long, and the explosion quantity is limited. Moreover, some red marl and sandstone residue of upper Ordovician formations could be seen in the outcrop (Figure 1c and 1d).
(3) Ten kinds of fillings were found in the karst caves, including calcite, breccias, anhydrite, gypsum, sulfur, fluorite, silty shale, rust upper Ordovician sandstone, yellow-green Silurian siltstone, malachite, pyrite and so on. In these fillings, gypsum, sulfur, fluorite, and malachite are hydrothermal minerals, reaction products of hot fluid and buried rock around unconformities, which could not form in the exposed earth surface (Figure 1e and 1f).

The forming mechanism and the formations of these paleocaves in the Kepingtage structural zone are similar with the Ordovician reservoir of Halahatang, Lungu west and Tahe oilfields. These paleocaves in outcrops provide direct analogues for the deeply buried reservoir, and give great value to the carbonate reservoir characterization in the Tarim basin.

Types, Characteristics and Main Controlling Factors of the Paleocaves

Karst caves in Kepingtage outcrops have various shapes and complex structures. During our time studying the Yijianfang, Liuhuanggou, Sanjianfang, Wudaoban and Xiker outcrops in the south of the Kepingtage structural zone, we have observed and described 174 karst caves, and we classify these caves into four types, according to their spatial structures, shapes, connectivity and distributions. They are tubular and branching type, single isolated type, plate profile type and karst caverns group type. Different types have different characteristics and main controlling factors.

(1) Tubular and branching type karst caves

The tubular and branching type of karst caves are long slender pipes with circular or oval shape in cross section, and usually many short branches connected to one main long pipe. The main long pipe is from tens to hundreds of meters long, up to several kilometers. Enhanced dissolution form larger caves we call halls, in some sections of the main pipe, and branches form accordingly, with the length several to tens of meters. Usually, the branches lie in different depths or formations with the main pipe. The tubular and branching type of karst caves are the most complex and largest one in those four types of karst caves.

Several tubular and branching type of karst caves are found in the Kepingtage outcrops. The biggest one is more than 100m long with circular or oval cross sections, six resolution-enhanced halls develop in the main pipe, and seven thinner branches develop from these halls, with six to 14 meters lengths (Figure 2).

The tubular and branching type of karst caves are passages of underwater channels, so, their development and distribution are controlled by underwater channels. From some recent distinguished karst caves, underwater channels could form long tubular karst caves. The water of the underwater channels could come from rainfall, vadose water and recharge of surface rivers, and enter into the paleokarrens, karst gorges or the surface rivers in the end. During this process, water corrodes and resolves carbonate rocks around the karst caves continuously, and consequently, these caves enlarge and more branches form, making the karst caves more and more complex.

This type of karst caves are found in Halahatang Oilfield as well, which are underwater channels with linear property in seismic amplitude gradient. Tens of underwater channels are identified in this oilfield; the scale is around 2.6 km wide and 8.4 km long.

(2) Single isolated type of caves

The single isolated type of caves has relatively small scales and simple shapes, with only a single and isolated cave. The shapes of this kind of caves are usually funnels or inverted funnels in the cross section. Figure 3 shows an inverted funnel, it has internal and external parts, the space of the external part is around 2.5-3.5 meters high, 2 meters wide, and 17 meters long; while the space of the internal part turns narrower obviously, around 0.2-0.6 meter wide, 3-4 meters high, and 10 meters long. There are fractures on the top of this cave, around 5-15 centimeters wide, these fractures are narrower upward and filled with limestone breccias and calcite crystalline. In addition, the inverted funnel extends upward along the fractures' strike. For the funnel (Figure 4), the top of the cave is flat, relatively wide, and narrower downward, faults and fractures develop on the bottom, and there are no other caves nearby. The amount of the funnel shaped caves is few in the outcrop, focusing on two small areas, and filled with rust siltstone.

Usually, surface fresh water infiltrates downward along faults or fractures, corrodes and resolves the rocks around the faults or fractures, making the bottom of the fractures enlarge more and more, and single and isolated inversed funnel forms at last. For funnel shaped caves, the karst water flows downward to the bottom fractures, resolves the surrounding rock, and leads to the funnel-shaped karst caves.

Faults and fractures not only control the shape of the caves, but also control the extension direction of the resolution, which is the strike direction usually.

The single isolated types of caves are usually small scale, scattered in the plane and vertically in the geomorphically lower part in outcrops. Some larger caves of single isolated type shows ball chain reflections, while most single caves with less than 50m width cannot be identified due to low resolution of seismic data.

(3) Plate profile type caves

Caves of the plate profile type show property of great width along layers and relatively small height. Several caves develop along a boundary and connect by the narrow resolved passage along boundary. In the Xiker outcrop, there are many plate profile type karst caves, the one showing in Figure 5 is 16 meters wide, 3.1 meters in height, and is filled by rust siltstone. Horizontal beddings developed and the surrounding rock is laminated marl without any faults or fractures.

Horizontal beddings develop in the surrounding rocks of the plate profile type caves; meanwhile, several caves lie in the same boundary, which means they are the results of resolution along boundary by interlayer water. When the resolution is going on, the overlying rock collapse under the overburden pressure, and then the collapsed broken limestone was corroded by interlayer water, resulting in larger karst caves.

(4) Karst caverns type caves

The karst caverns are usually comprised of many caves with different scale and shapes. They locate closely, less than five meters, and connected to each other by faults, fractures or karst passages along boundaries. In the southern outcrop of the Kepingtage area, karst caverns developed just under the unconformity, with the distance around 10-50 meters. Most of these caves are filled with calcite crystals, with layered shale or silty shale deposited on the top of some caves. The Xiker karst caverns located in the northwest of the Kepingtage outcrop consist of 22 caves. They are filled with calcite, and are distributed in three layers, which are controlled by different levels of the water table.

Conclusions

In the seismic forward models done within the shallow ground in the Tarim oilfield, single caves less than 50 meters in diameter could usually not be identified. However, multiple small caves around 20 meters in diameter within a sphere of 400 meters diameter could be identified clearly, showing bead-like reflection in seismic section. Based on these seismic forward models, we can know the strong bread-like reflections in the real seismic sections are caused by multi-cavern type caves. In other words, this type of cave is the easiest type to identify in seismic sections, and so, they are the main target reservoirs in Halahatang Oilfield, which was verified to be successful in the Tarim basin.

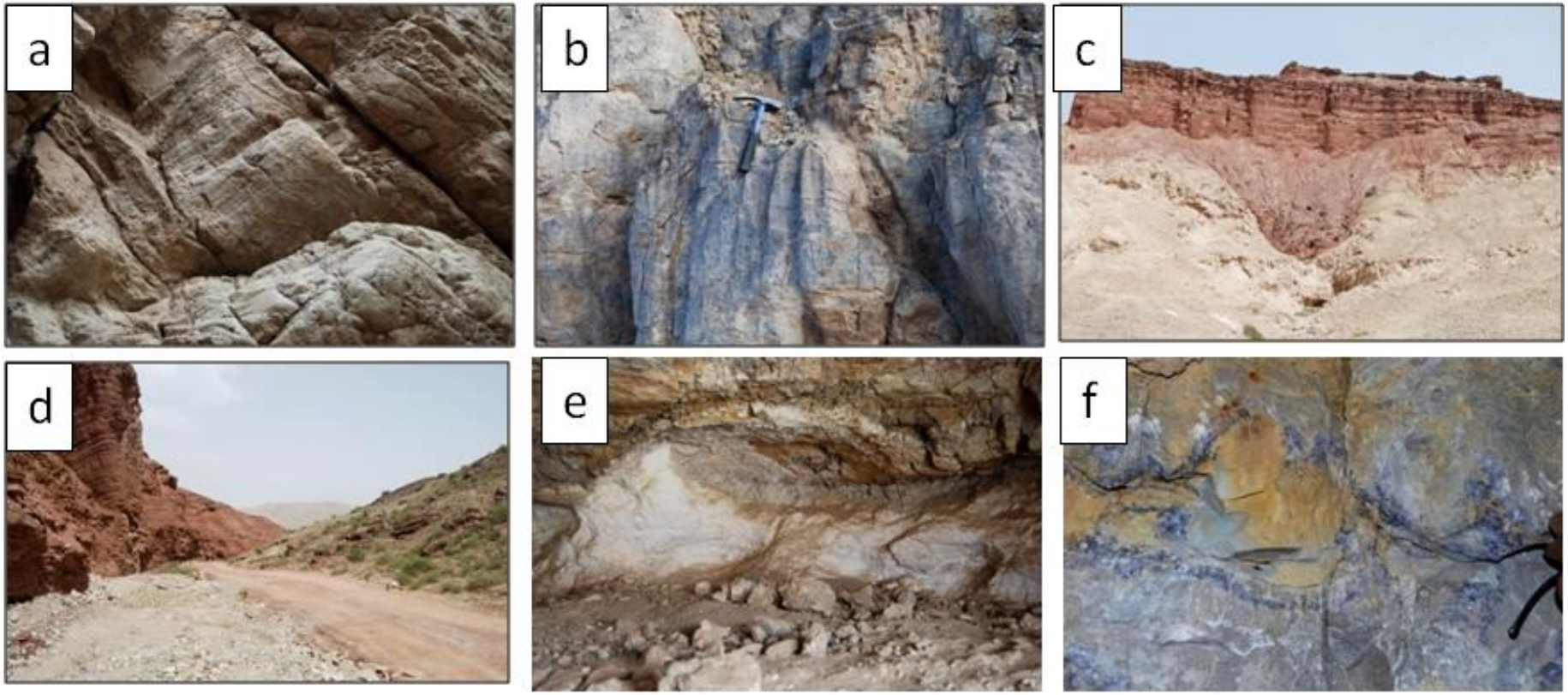

Figure 1. Evidences of paleokarst. a. Traces of paleokarst, paleokarrens and paleoridges, Wudaoban outcrop; b. Traces of paleokarst, paleokarrens, paleoridges, and ferric membrane, Xiker outcrop; c. Upper Ordovician sandstone overlies on Middle Ordovician paleokarst cave, Xiker outcrop; d. Upper Ordovician sandstone overlies on Middle Ordovician paleokarst cave, Sanjianfang outcrop; e. Gypsum in karst caves, Liuhuanggou outcrop; f. Fluorite in karstcave, Xiker outcrop).

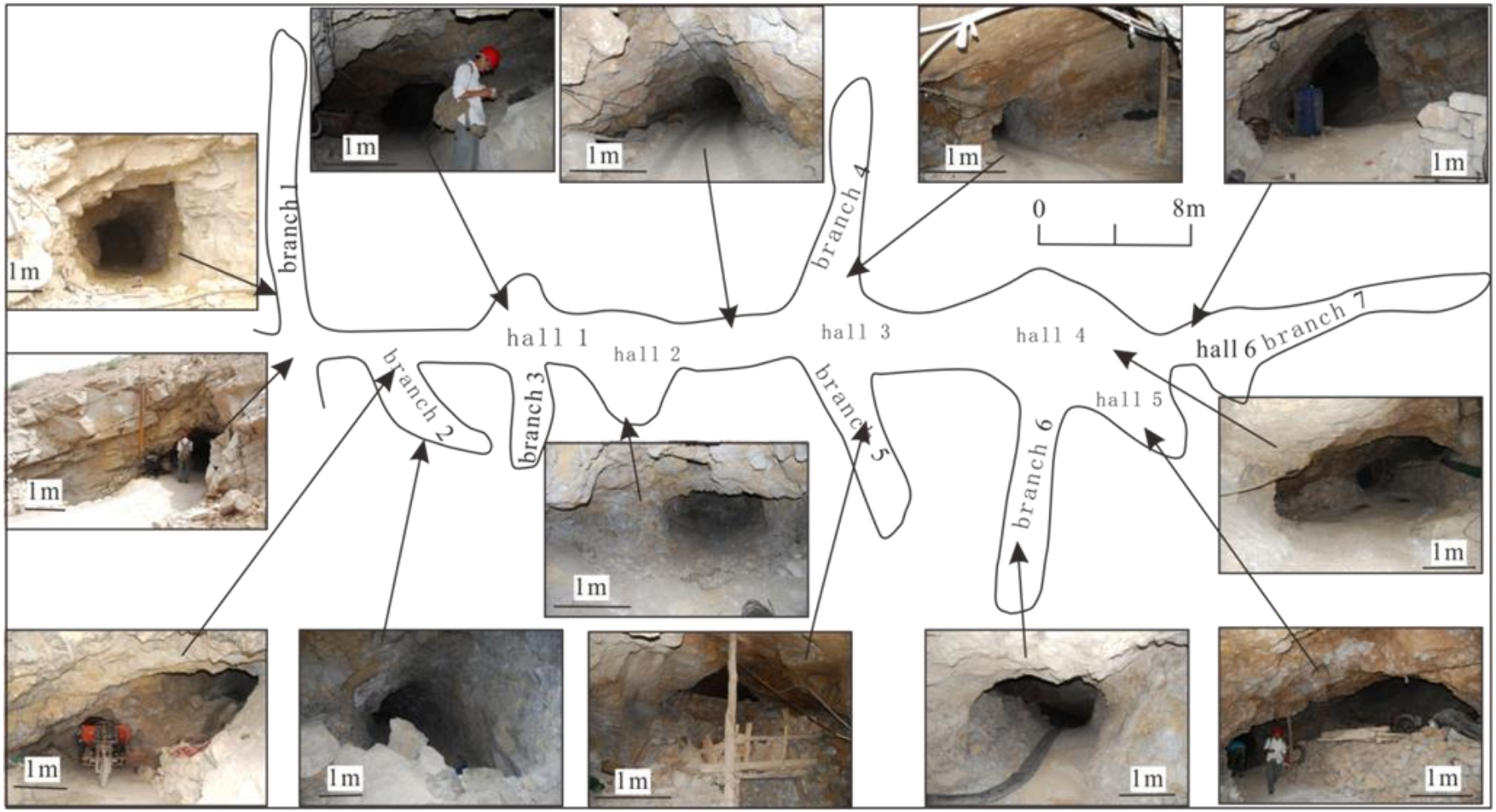

Figure 2. Structure chart of tubular and branching type of caves, Sanjianfang outcrops.

Figure 3. The inverted funnel isolated type of cave in Yijianfang outcrops.

Figure 4. The funnel isolated type of cave in Yijianfang outcrops.

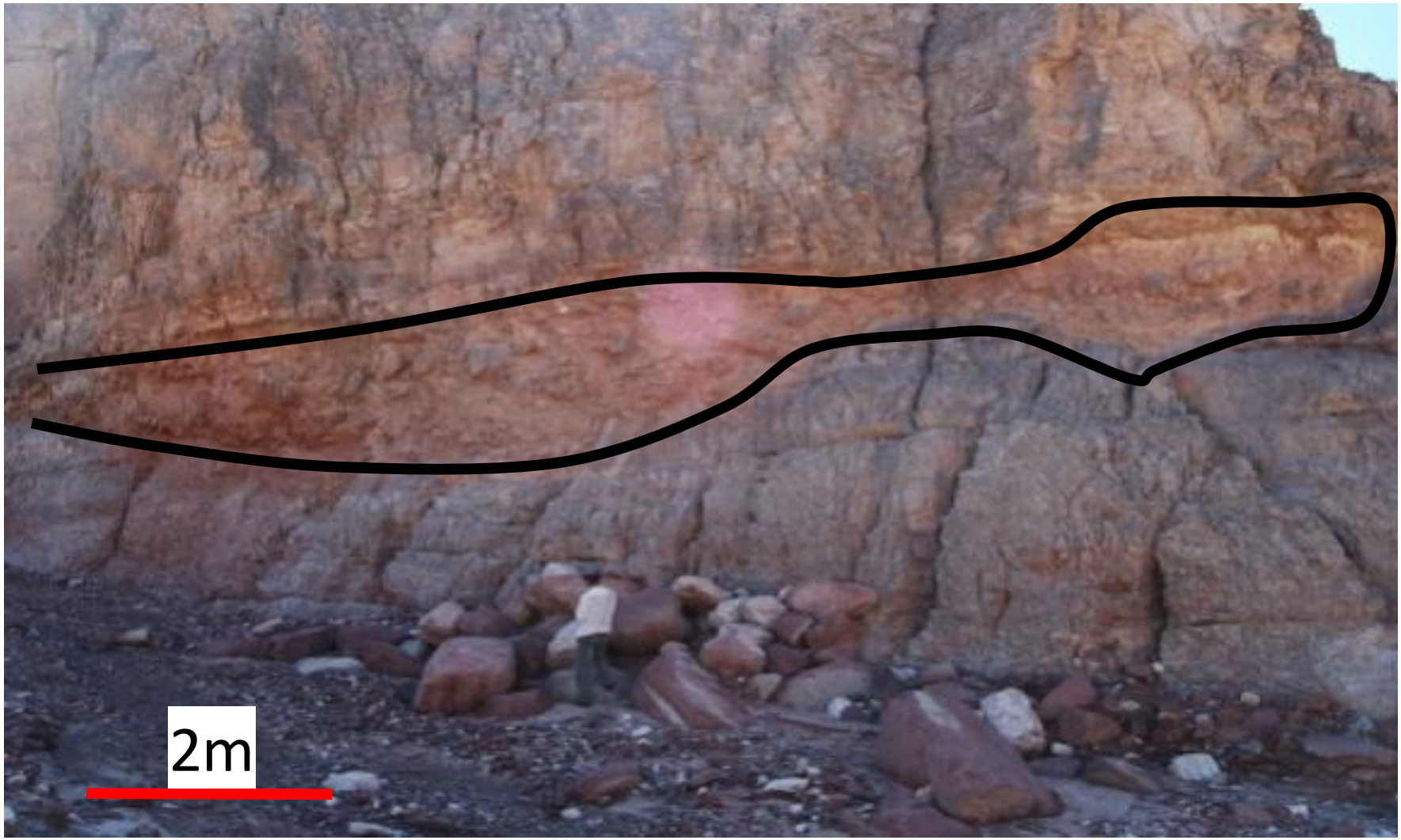

Figure 5. The plate profile type cave in Xiker outcrops.