THE FORMATION OF LARGE CHAMBERS, WITH EXAMPLES FROM LAOS AND OTHER COUNTRIES

By Claude MOURET
La Tamanie 87380 Magnac-Bourg, France

Abstract

Formation of large chambers is discussed on the basis of geological heterogeneity existing in stratigraphic successions. Given structural conditions lead to a given type of chamber. Most favourable are dipping strata forming a convex up anticline flank close to a syncline axis in a small wavelength folded section, with limestone underlain by different, erodible, rocks: this is the case of the Sarawak Chamber. Large chambers are in most of the cases sloping and this affects their stability in a good way. They are often, if not always, made up of coalescent voids, which have their own individual stability. The role of the individual voids is of paramount importance for the stability of the whole chamber. The chamber fill (boulders) also plays a role in sustaining chamber walls.

INTRODUCTION

More and more large underground chambers are becoming known in the world, though the "Number 1" Sarawak Chamber in Sarawak, Malaysia, remains unrivalled. No full explanation of their stability has been proposed so far, and it is still too often said with some exaggeration -and written- that the laws of physics cannot explain them. This may be due to the fact that, perhaps the theory is incomplete, but specially that the large chambers may have been taken for what they are commonly not: simple volumes. Instead, one can often easily recognise in them a composite shape, with several vaults which are co-existing laterally and/or vertically, though a few chambers show an apparent regular shape, salle de La Verna for instance.

The author has discovered in limestone and mapped more than nine large chambers in Laos, three in the Philippines, plus one in andesites (salle Jules Verne), located in the dome of the Soufrière active volcano, Guadeloupe (French West Indies). The related observations have brought elements of thinking, which are used in this paper. Knowledge from bibliography is added as well.

DISCUSSION

Characteristics of large chambers

The classical first approach to large chambers has been commonly oversimplified, as they are often referred to by 3 dimensions only (length, width and height), which are not by themselves indicative of the cause of the void formation and stability, except that for such a large void can form, rock export is necessary, in solution or mechanically, which requires the action of a significant underground stream.

The 3 dimensions only give the size of the -horizontally extensive- parallelepiped with the same dimensions, into which the chamber can be entered. Chambers are commonly sloping and the real height (i.e. the distance from floor to roof, perpendicularly to the slope) is often much smaller than the vertical height. A chamber would be already better described by the smallest parallelepiped into which it can be entered, which would be in most of the cases oblique instead of horizontal. Surface area is given by a number of authors, but it is usually a projected surface. Using the volume is more helpful, though it is rarely accurate.

Let us review the main characteristics of a large chamber:

- A large size, out of which it is of paramount importance to highlight the individual (coalescent) volumes,
- An irregular cave floor, largely covered with boulders, usually sloping, not always in one direction only,
- The presence of an active, temporary or fossil stream. For instance, a stream associated with a chamber, directly in it or directly underlying it, is found in the following chambers: Sarawak Chamber (Malaysia), salle des Miaos (China), Sagada Chamber (Philippines), salle de La Verna (France). In Laos, it is the case of Tham En (Fig. 1, A), another Tham En (Fig.1, E) and Tham Thon (C) for instance. Temporary flows are encountered in Tham Koun Dôn (B) and in Nam Non (J) (Laos), to a smaller extent in the Panayoran Chamber (Philippines).
  Presently dry chambers exist in Majlis Al Jinn, though its flat bottom part is covered with clay (Oman), Torca del Carlista (Spain), Nam Non (Laos, D).
  The salle Jules Verne (55x35x11 m, with a ca 30 degrees slope) is in andesite and was generated by explosions (MOURET, 1985). The Furna de Enxoffre in Graciosa Island (Açores) is in basalt and 200 m wide (C. THOMAS, 1997). It is due to the surface solidification of a lava lake, with subsequent downward removal of the molten lava.
- Cave walls (often of limited apparent height, as their base is buried below boulders) with a variable, though usually steep, inclination.
- Open passages at the ends and possibly on the sides, which ensure a minimum section to which the whole chamber envelope has to converge morphologically.
- A roof with a variable shape, which varies between a nearly flat surface in a few cases (Tham Koun Dôn, B), a half-cylinder vault in rare cases (in average size chambers which are indeed enlarged galleries), domal shapes (in Majlis Al Jinn, as a semi-dome of 4 million m3, 60000 m2, 300x200x120m, HANNA et al,

1997; in La Verna, as a dome overlying a funnel-shaped lower part, 270x230x165m, GILLI, 1984) and, more commonly, complex shapes (salle des Miaos, 700x215x100m, 120000 m2, 7 to 10 million m3 (volume twice La Verna), BARBARY et al, 1989).

Composite shape and structure of large chambers
Complex shapes of the roof are clearly formed by associated unitary volumes, which have a lateral and a vertical distribution. In the Panayoran Chamber, an elongated chamber with maximum dimensions of 275x165x80m, (MOURET, 1994b), the end part is clearly made of a gallery type vault, with an axis inclined down to the end. The main part of the chamber is larger (though still elongated) and much higher; the shape of the roof, a kind of dome, is clearly visible and this dome is bounded by the adjacent inclined gallery type vault. The intersection of the dome and the inclined vault draws a relatively regular arch. There is no doubt that the dome stability is largely ensured because of this arch. Such a setting is classical in religious architecture, where transept domes are stable because lateral vaults are present in the four perpendicular directions, for instance in Périgueux or Chartres cathedrals (France).

Thorough examination of chamber roofs show that this kind of complex setting is not rare in cave chambers. In salle des Miaos, two domes are mentioned.

Comparing the architecture of natural underground chambers and man-made structures is therefore possible and, in any case, fruitful. First of all, basic forms need to be reviewed: arches. They can be classified in no less than four main types: normal, surbased, lancet, rampant. In architecture, each type allows the stability of overlying walls or vaults. In caves, each of these shapes should allow stability of overlying rock. Normal arch may correspond to regular vaulted passages in homogeneous rocks for instance, surbased arch to large volumes largely filled up with boulders (Tham En large entrance chamber in Laos, A), lancet arches to the effect of joints or faults, rampant arches to sloping vaults following dipping beds (as in Sarawak Chamber, Fig. 2-3). A simple volume may be the result of the juxtaposition of repeated arches.
In monuments, forces which are exerted on or transmitted by arches are directed in directions which depend on the arch shape, i.e. towards the outside of the arch or onto sustaining pillars. In both cases this means that, in caves, equivalent arches and the overlying rock can be supported by the full rock masses around the chamber (i.e. the outside of the arch) and that they are stable in this way.
Additional vaults can be present on top of complex arch systems or on top of other vaults (Fig. 4), which is a building principle of cathedrals, fact also present in caves. In caves, this applies to large chambers, but also to the connection with smaller passages of different directions.
A variety of roof shapes can exist in caves if structural rock factors and cave history are favourable to arch formation. The presence of several arch lines across a chamber may allow a composite roof with two or several juxtaposed domes. Arch lines may correspond to the intersection of different vaults (groined vaults).

Structural factors favourable to large chambers formation
For a karst chamber forms, besides a stream to export the rock, the following structural factors are necessary:

- Strata or a strata complex with a favourable thickness. Thinner strata are less prone to generate large vaults than thicker ones.
- Strata with a sufficient mechanic resistance. Shaly limestone (Lias of Périgord, France) or poorly diagenitised limestone in Bali (Indonesia, author's explorations) allow only chambers of limited extent though still significant, but no real large chamber. To the opposite, an excellent combination is a resistant limestone and an underlying, erodible, usually impervious, rock: Sagada Chamber, salle de La Verna, etc. A somewhat different combination is shown by giant cave passages in West Borneo, up to 45 m wide despite they have a low height (surbased arch), which have a basalt roof and a sand/shale alternation forming the floor (MOURET, 1994a).
- A favourable dip. Horizontal or low angle dips combined with thick strata may allow large chambers, as the Panayoran Chamber. Often, dip is around 10 to 20 degrees. This is the case in the Sagada Chamber, the Tham En caves large entrance chambers (A, E), the Tham Thon Chamber (C). The inclined Sarawak Chamber is the most impressive example: the folded strata clearly form the roof and the lower wall of the chamber (GILLI, 1993; Fig. 2).
- Other settings can be exceptionally found, such as in salle Jules Verne and Furna de Enxoffre where the roof is formed by vertical prisms. The high friction along the surfaces between prisms ensures vault stability.
- Boulders against the walls also bring stability, in preventing caving in or in slowing down chamber enlargement, which would otherwise lead to roof failure. With this respect, two main cases exist:

1.The chamber is elongated in the dip direction. In the Tham En entrance chamber, one in the largest in the world (A), the dip is around 10 to 15 degrees along the longitudinal axis and sub- horizontal in the transverse direction. The cross-section is elongated in this transverse direction. The width is of ca 155 m, with a maximum extension to ca 215 m and the height is only 5 to 30 m, because of the boulders on the floor. In this case, the controlling factor of cave stability is the width, which represents the maximum vault length, because in the long axis direction of the chamber, the vault is only the result of a repetition of juxtaposed arches, with a cylindrical symmetry. The visible part of the large vault near the cave entrance is shaped as a surbased arch and the boulders against the walls ensure a better stability. This is probably why such a large entrance chamber can exist. With this respect, a sub-longitudinal low which is likely located above the underground stream which flows below the boulders, has no impact on stability but it enlarges the chamber volume. It joins the chamber wall where this one turns: the stability is preserved by this shape, which corresponds to a shorter vault width, onto which the rest of the vault can increase its stability.

2.The chamber is elongated perpendicularly to the dip direction, as in the Sarawak and Sagada Chambers. The cross-section profile is very characteristic, with a vault following the dip to a significant extent. The very specific structural context of the Sarawak Chamber, below the flank of a small wave length anticline next to a faulted narrow syncline (GILLI, 1993), likely explains the existence of the chamber. This setting creates an effect of rampant arch, as for gothic cathedrals. The force exerted by the vault is largely transferred laterally to the cave wall, because of the shape. To some extent, the vault partly acts as a wall. The lower wall of the chamber is also the lower part of the arch.
In the upper part of the chamber, the upper wall has a moderate height. Located below the limestone vault, it is inclined towards the chamber and made up of sandstone (Fig. 2). The sloping chamber floor between the lower wall and the upper wall is sandstone as well and covered with limestone boulders. The floor slope is a very important fact. The chamber would not exist if it was not inclined, because the rampant arch effect would not exist. The real vault starts at the top of the sandstone wall. In other words, the space protected by the arch is only the upper part of the distance from chamber floor to roof. The bottom part is due to sandstone removal in the “shadow” of the vault and besides the internally sloping upper wall.
The Sagada Chamber (95x59x10-20m, oblique height) shows a comparable setting, though it is not exactly the same: dipping strata, lower part close to a stream in the downdip direction, partial inward dipping upper wall. It is also an inclined chamber.

Besides these basic cases, many others exist, which are more complex. In any case, an existing dip favourable to the existence of a chamber slope is a favourable factor to stability. A number of chambers have a longitudinal low axis bordered by two slopes of boulders (Panayoran Chamber, Tham En (A), salle des Miaos, though it is less clear;) some others have such an axis in a direction perpendicular to their elongation (Tham Koun Dôn, B): such settings are favourable to wall stability and to larger volumes. The roof of Tham Koun Dôn Chamber is relatively planar, inclined, and the walls are not so high (ca 10-30 m): the central transverse low axis adds significant volume.

Domal chambers are more difficult to explain, but two critical factors already discussed can be used. First, large chambers such as salle de La Verna formed initially at the contact surface between overlying gently dipping limestones and underlying subvertical strata including limestone and largely erodible schists. The overlying limestones exactly played the role of a rigid surface below which the void developed at the contact of vertical limestones and schists. Then, progressively, after the void enlarged, the vault started collapsing and developed into a dome. The void corresponding to the vault is located only in the overlying limestones. The stability of the hollow void in the schists is mainly ensured by the funnel shape of the lower part of the chamber, with peripheral slopes limiting the height of cave walls on three sides. This lower void is in the “shadow” of the limestone vault.
In this way, we can compare the salle de La Verna with the Sarawak Chamber (and many others), with an upper part subject to given geological conditions, bearing a specific vault (evolving by successive collapses) and a lower part, mainly subject to erosion/dissolution. That is to say that the vault effect is borne by not all the chamber cross-section, but by the more resistant part above. Depending on the chambers and their geological conditions, the vault effect may be ensured by a variable proportion of the rocks encountered in the stratigraphic succession.

CONCLUSIONS

The elements discussed in this paper lead to consider large chambers as composite voids, which are made up of individual volumes with their own stability, but which also have all together a global stability. Excessive geometric changes in relation with the evolution of even one of the voids may lead to a collapse, local or of the whole chamber, depending on the existing geometric shapes.
It is also considered that a chamber best requires a rigid rock in a strata set which has an excellent mechanical resistance, which acts as a cover above less resistant rocks. The vault shape and its size are controlled by the cover rock. Dipping strata bring additional stability to chambers, by arch effect. These elements of discussion may be used as a basis for further research on the topic, which should further establish our knowledge on large chambers.

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