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BULGING PATTERNS OF COKE DRUMS

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ABSTRACT

One of the most common defects in coke drums is bulging, which is a non-uniform radial growth of the shell. Bulging often leads to cracks that occasionally result in leaks and fires. Drum bulging and cracking often cause unplanned outages, costly repairs, and premature replacement.

Bulging is commonly treated as a single phenomenon that is caused by one failure mechanism. In this study, we examine this assumption using a database of one hundred and eighty four laser scans obtained from operational coke drums that vary in location, metallurgy, age, size, and wall thickness. Based on the study, we identified nine types of bulges and related them to loading mechanisms, design features, operating practices, and fabrication processes that likely contribute to their formation. This new understanding of bulging types and causes should help design, fabricate, and operate coke drums in a more informed manner.

INTRODUCTION

Coke drums are pressure vessels that process heavy oils or oil residues to produce lighter hydrocarbons and petroleum coke. The process exposes these vessels to severe thermal and mechanical cyclic loads that, over years of operation, result in various types of mechanical and structural damage mechanisms.

One of the most common defects in coke drums is bulging, which is a non-uniform radial growth of the shell. Bulging often leads to cracks that occasionally result in leaks and fires. Drum bulging and cracking often cause unplanned outages, costly repairs, and premature replacement.

Weil and Rapasky's examined shell bulging in their classic 1958 paper (1) and described its progression stages until reaching the shape of a "constrained balloon" which was the most common pattern of bulging at that time. Since then, drum material has changed from mostly Carbon steel to 1, 1¼, and 2 ¼ Chrome alloys as well as Carbon-½ Moly. The impact of this material change on the magnitude and progression of bulging appears to be significant.

For example, the 1968 API Survey concluded that "Carbon steel drums bulged far more extensively than C-Mo drums before giving through-wall cracks (2). In the 1996 API Survey, the average reported number of cycles to first bulge for Carbon steel, Carbon-½ Moly, and Chrome Moly alloys were 3023, 2504, and 2978 cycles, respectively (2). The 1996 API Survey also found that the maximum-size bulge reported had an average radial size of 2.1 inches, a vertical length of 65 inches, and a circumferential length of 547 inches (2).

In trying to explain the severity and pervasiveness of bulging in coke drums, several studies have demonstrated that, during water quenching, coke drum shells experience extremely high plastic-regime strains that last for relatively short periods of time (3, 4). Measured strains and corresponding stresses are an order of magnitude larger than typical allowable design stresses per pressure vessel design codes. These strains appear to be caused by a combination of mechanical and thermal loads that significantly vary from cycle to cycle and from one location on the drum to another.

In all surveys and studies on this subject, bulging is treated as one phenomenon with no distinction between different types of bulges. Our experience suggests otherwise. In this study, we examine a set of operational coke drums to highlight the various types of bulges and their characteristics and discuss the likely loading mechanisms that cause them.

DATABASE

This study is based on a database of one hundred and eighty four laser scans obtained from operational coke drums in refineries and upgraders in North America, South America, Europe, and Asia. Scanned drums are made of Carbon steel, Carbon-½ Moly, and 1, 1¼, and 2 ¼ Chrome alloys and range in age from brand new to 48 years. They range in diameter from 19.7 to 32 feet, in tangent-to-tangent height from 50.5 to 102 feet, in minimum shell thickness from 0.45 to 1.54 inches, and maximum shell thickness form 0.84 to 1.89 inches.

The internal laser scans utilized in this study were originally obtained and used for assessing bulging severity using the Plastic Strain Index ^{TM} method which examines strain-based local failure (5). The experience gained from conducting these assessments, observing bulging-induced failures, and designing subsequent repairs provided the motivation for this study.

Laser scans are shown in this paper using a three-dimensional map format, such as the one shown in Figure 1. The abscissa (x-axis) is the azimuth around the circumference, in degrees, from 0 to 360. The ordinate (y-axis) is the height as measured from the bottom tangent line, in inches or meters, that typically covers the cylindrical shell from the bottom tangent line to the top tangent line of the shell. The third dimension (z-axis) is the radius of the shell shown using a magnified scale in order to make bulging shapes visually discernable. When bulge variations over height are examined, the two-dimensional side view of this three-dimensional map is shown instead.

BULGING PATTERNS

Based on our examination of the database of laser scans, we observed the following distinct bulging patterns. These patterns were neither specific to a particular metallurgy nor mutually exclusive. In most drums, many of these patterns coexist and often overlap. Axially-oriented increase and decrease of radius are not included in this treatment because they typically represent global or local out-of-roundness (ovality) that typically has negligible impact on drum integrity.

A. Uniform bulging: This type is characterized by a radius increase or decrease around most or all the circumference of the cylindrical shell as follows:

1. Seam Bulging: This is the classic coke drum bulging that was most reported in the 1950s and referred to as the “constrained balloon” phenomenon (1). As this label suggests, in most cases, adjacent plates increase in radius relative to circumferential seam welds that act as restraining belts on the expanding shell. Less frequently, however, the opposite happens and welds grow relative to plates. An example is shown in the Chrome alloy drum of Figure 1 where growth is noticeable on both sides of the third, fourth, and fifth seams counting from bottom to top. In the 3D map, these bulges look like circumferential depressions at the seams.
2. Bottom Growth: The average radius of the bottom courses of the shell is mostly uniform and larger than the top. The transition between large and small occurs over a relatively short distance above the outage level (i.e. height of maximum fill). Examples of this type of bulging are the Chrome alloy drums shown in Figure 2.
3. Tapered Growth: As with Bottom Growth, the average radius of the bottom of the drum is larger than the top but the transition occurs over most of the drum length. We mainly found this type of bulging in Carbon steel drums such as the ones in Figure 3.
4. Outage Growth: A radius increase at the outage level that is typically located between half and two thirds of shell height. Examples are the Carbon Steel drums shown in Figure 4.
5. Mid-height Growth: A radius increase at the middle of shell height. Examples are the Chrome alloy drums shown in Figure 5.
6. Band Bulging: This very common type appears as bands of outward and/ or inward axisymmetric bulging that extend most of or all the way around the circumference and is not centered at a seam weld. An example of a drum that developed both inward and outward band bulges is the Chrome alloy drum shown in Figure 6.
7. Helical Bulging: This is a special case of Band Bulging in which the band is not perfectly axisymmetric. Instead, elevation changes along the axis of the drum to form a helix, such as the one at the bottom two courses of the Chrome alloy drums of Figure 7.
8. Accordion Bulging: A zigzag variation of shell radius over the entire shell that does not correlate with circumferential seam weld locations. An example is the brand new Chrome alloy vertical-plate drum of Figure 8 that shows significant zigzag bulging and out-of-roundness (ovality).

B. Local bulging: This type is characterized by a radial increase or, less commonly, a decrease over a relatively small area of the shell. This is the classic and most prevalent type of bulging in coke drums. This type of bulging can be seen, to various degrees, in all the drums shown here. In our experience, for the same magnitude, local bulges are the most likely type to result in cracking (5).

LOADING MECHANISMS

Typically, shell distortion associated with the above types of bulging is visually discernable. For such high strains to be reached, excessive loads must be involved. Based on the examination of temperature and strain measurements as well as numerical models, we hypothesize that the following loading mechanisms are the primary cause of bulges in coke drums:

a. Axial thermal gradient: During quenching, an axial thermal gradient is formed at the rising water level that separates the hotter shell above and the cooler shell below. According to our analyses, resulting bending stresses at the water-line, sometimes referred to as the "vasing effect", are not sufficient alone to cause plastic deformations. However, these stresses, which are uniform around the circumference, increase the severity of stresses from other loading mechanisms.

b. Resistance of solid coke: During quenching, the shrinking of the cooler shell on hot solid coke results in high membrane stresses. The combination of coke resistance and axial thermal gradient is likely the cause of observed plastic deformations in Seam, Bottom, Tapered, and Outage Growth bulges. In Seam Bulging, the difference in growth between weld and plate is caused by the difference in yield strength and the stiffening effect of weld caps. Tapered growth may be explained in Carbon Steel drums by the larger hydrostatic pressure and higher temperature at the bottom and resulting creep damage that starts within typical operating temperatures of coke drums. In drums that are made out of other materials that are not susceptible to creep damage, we experience Bottom Growth which is mostly uniform from bottom to outage level. Outage growth appears to be caused by "top quenching" in which water and/or anti-foam liquids are inserted at the top of hot drums causing extremely high bending and membrane stresses in the shell at the outage level above which the wall is free to contract and below which it is not.

c. Hot spots: During quenching, the random channeling of water inside the hot body of coke results in random hot and cold spots on the shell. These thermal spots can cause extremely high local thermal stresses and plastic distortions that can lead to local outward or inward bulges.

d. Uneven quenching: The injection of cold water into a bed of solid coke often results in non-uniform cooling of the drum. Temperature differences in excess of 400°F are not uncommon across the diameter. Such large side-to-side thermal gradients can cause drum tilting, also known as the "banana effect", as well as Band Bulging on the compression side of drums. Helical Bulging may also be caused by uneven quenching from spiraling water channels.

e. Local post-weld-heat treatment: The facilities needed to perform global heat treatment of large-sized coke drums are not available in most fabrication shops. Instead of performing global treatment on entire drums, some shops conduct global heat treatment on two halves and, after welding them together, perform local treatment for the last weld in the middle of the drum. During local post-weld-heat-treatment, if temperatures are not strictly controlled, both spatially and temporally, excessive stresses can develop and can cause fabrication-induced distortions. The same process is used in field-fabricated drums which are also known to develop Mid-height Growth bulges before they are placed in service.

We currently don't fully understand all the loading mechanism(s) that cause uniform Band Bulging. It may be caused by an operating practice that results in hotter or cooler thermal conditions at particular elevations, such as abrupt changes in quench water flow rate. Alternatively, these bulges may be caused by local bulges that, with time, grow around the circumference of the drum.

Since Accordion Bulging is found in new drums, we know that it is caused by the fabrication process but it is not clear exactly what part of the process causes these unusually consistent zigzag bulges that cover the entire length of drums.

CONCLUSION

The common assumption that coke drum bulging is a single type of defect caused by the same failure mechanism has been proven inaccurate. In this paper, we have identified nine distinct types of bulges that appear to be caused by different combinations of factors. This new understanding of bulging types and causes should help design, fabricate, and operate coke drums in a more informed manner.

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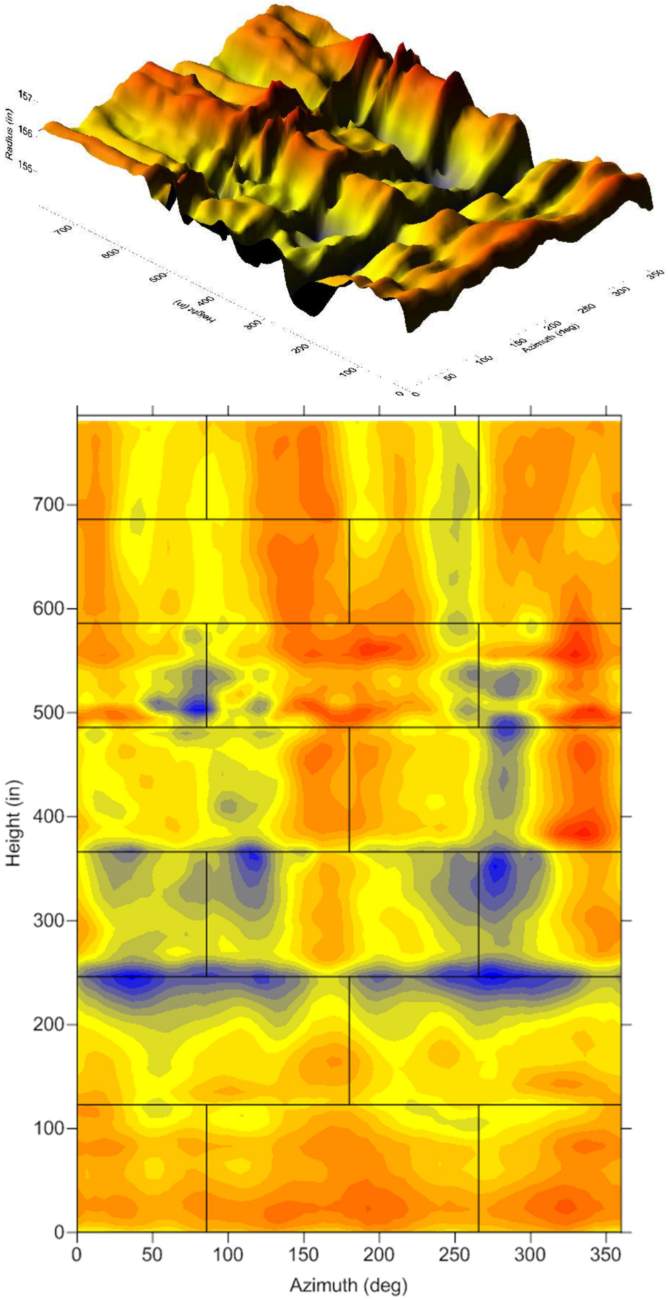

Figure 1: Three and two-dimensional maps of a coke drum with Seam Bulging

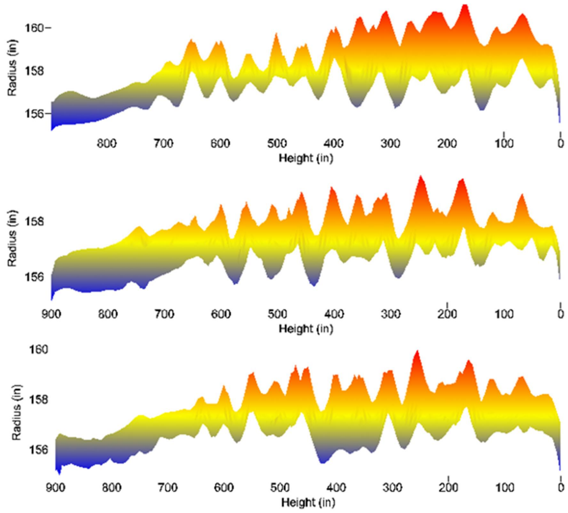

Figure 2: Bottom Growth

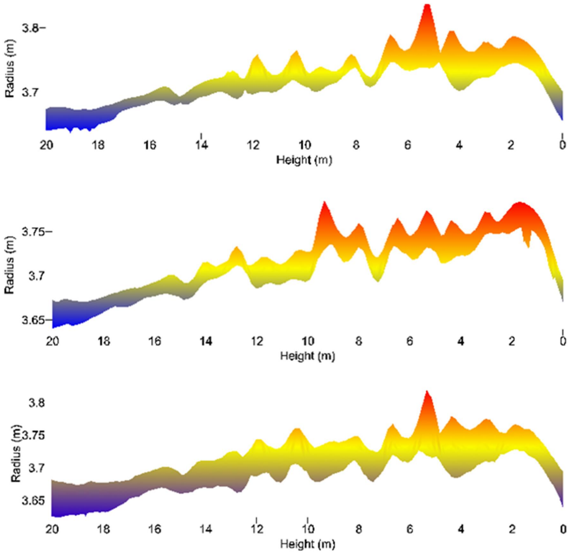

Figure 3: Tapered Growth

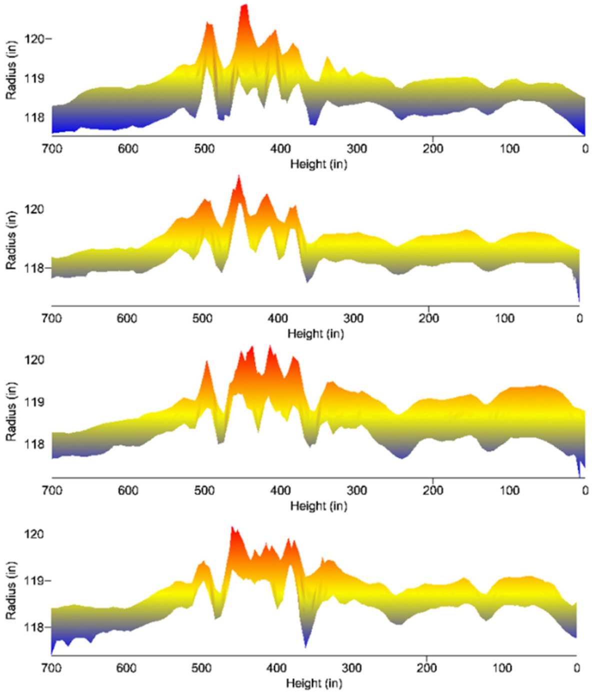

Figure 4: Outage Growth

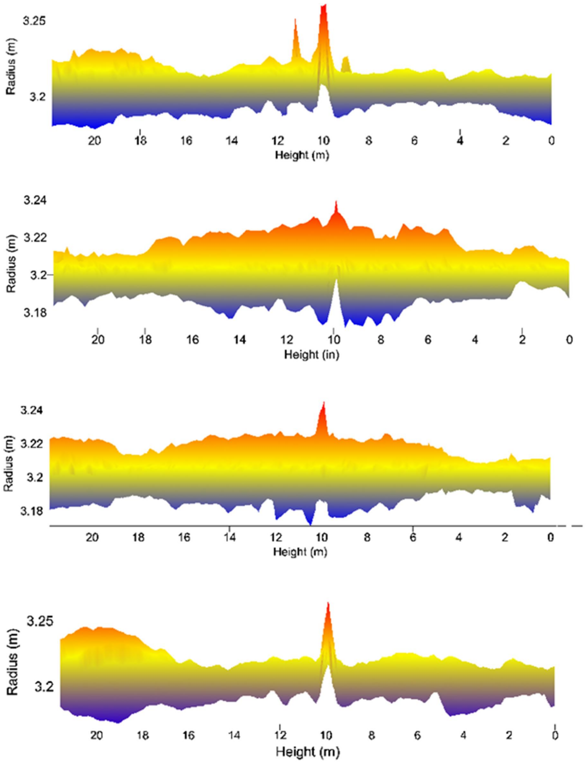

Figure 5: Mid-height Growth

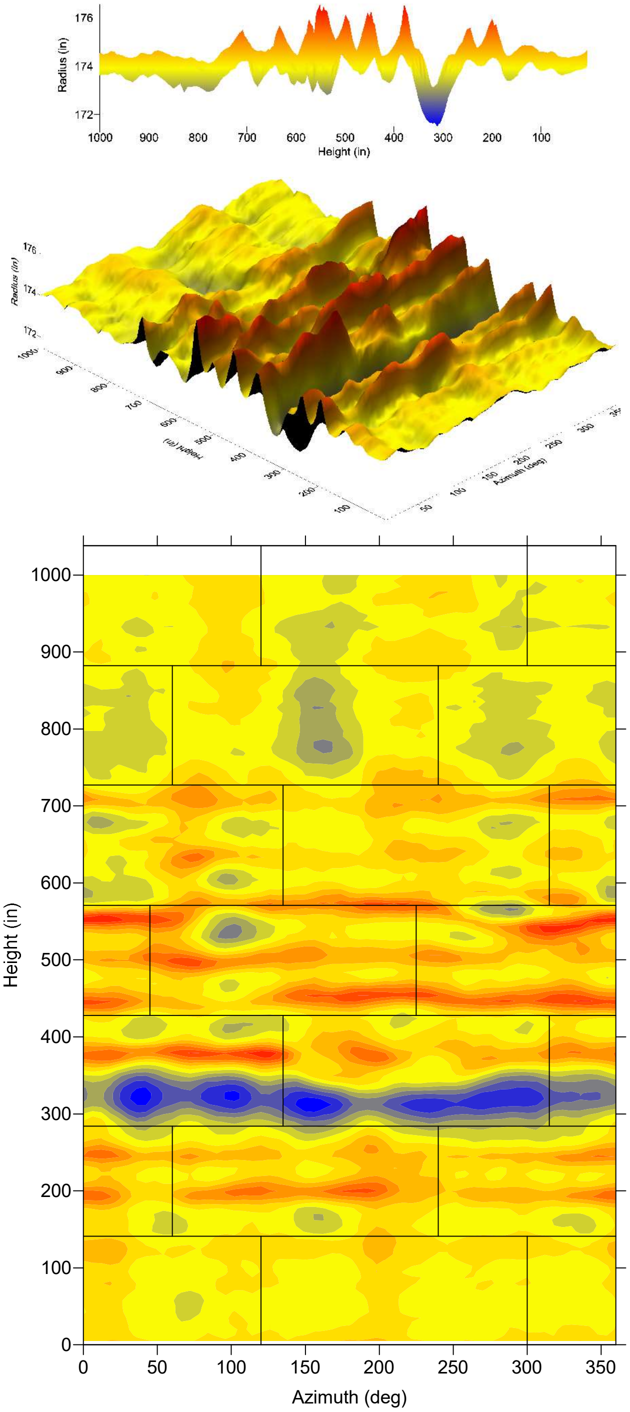

Figure 6: Band Bulging

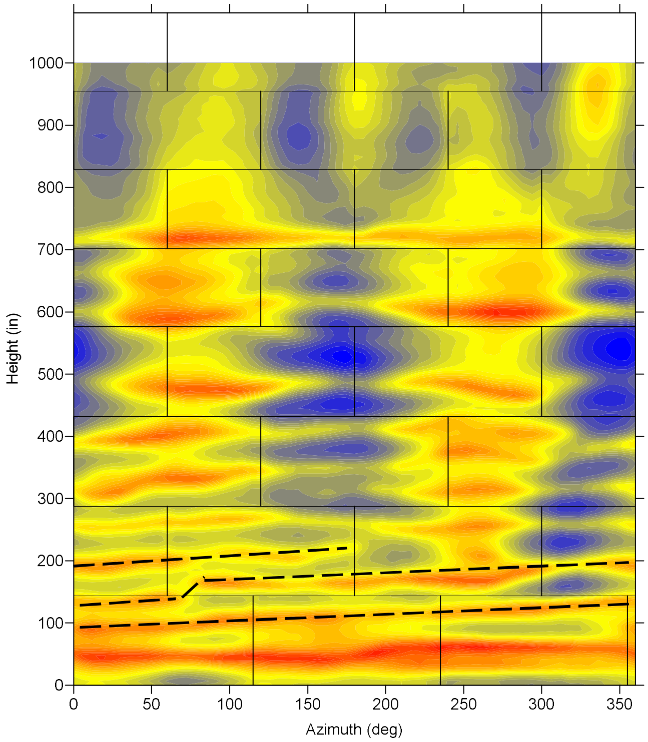

Figure 7: Helical bulging (indicated by dotted lines)

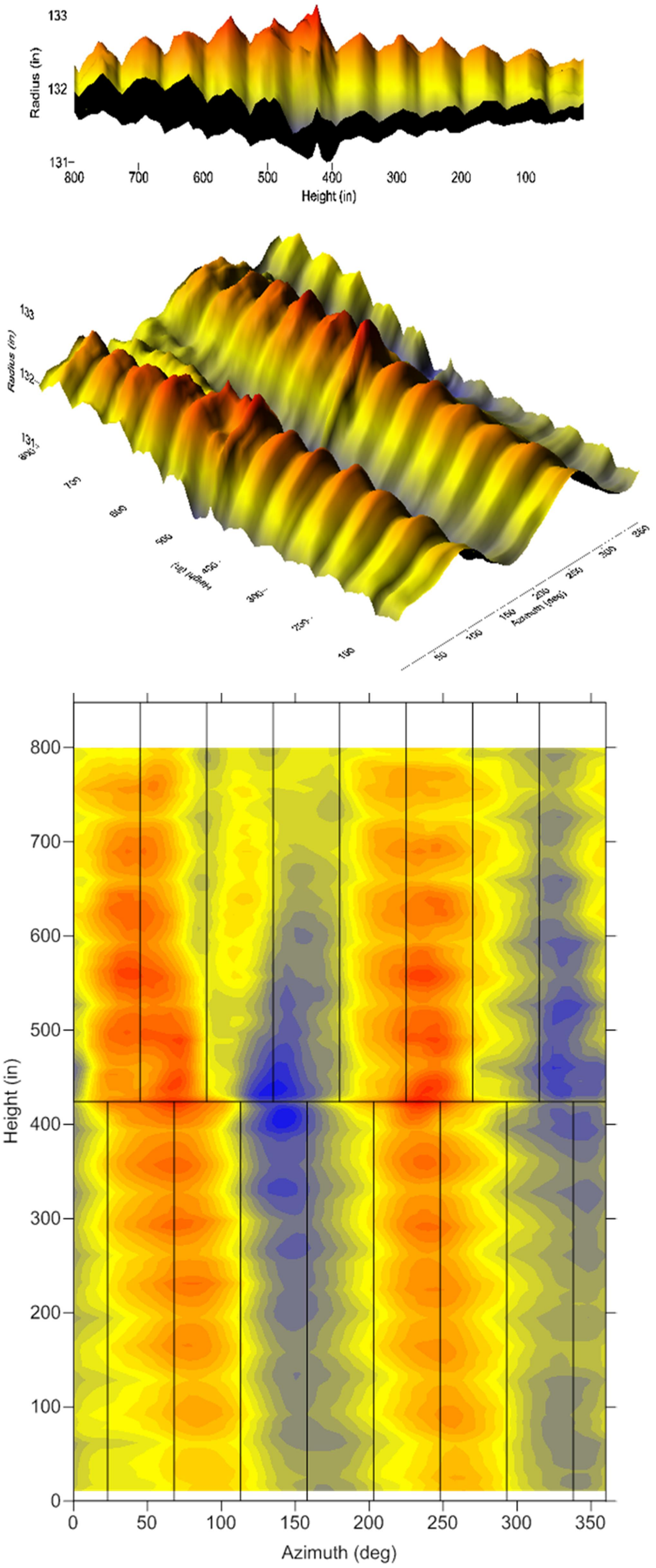

Figure 8: Accordion bulging