# Gravitational Compaction, A Neglected Mechanism in Structural and Stratigraphic Studies: New Evidence from Mid-Continent, USA[1]

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ABSTRACT

**Compaction of sedimentary rocks over basement hills was first recognized as a cause of structural closure in 1919. In the ensuing decade, many leading petroleum geologists espoused and expanded the concept to include compaction over hills on unconformity surfaces higher in the sedimentary section, compaction over sand buildups within the sedimentary section, and compaction over carbonate reefs. However, following the initial flurry of interest, compaction as a cause of structure was relegated to a minor role in petroleum exploration or was dismissed altogether by most workers. In 1983, studies undertaken at Applied Geophysics, Inc., indicated that many oil fields on structural closure in Oklahoma and Kansas coincided with basement fault blocks deduced from high-resolution residual aeromagnetics. A literature search, followed by a geological library search for closely spaced basement penetrations in the Mid-Continent, has located 30 basement hills, all of which show structural closure in the overlying sedimentary rocks. One must conclude that compaction as a cause of structure is a pervasive geological phenomenon. Additional findings of the ongoing study have been that (1) thinning over structural highs can be explained by compaction of lower beds surrounding basement hills while the overlying strata were being deposited, that is, by syndepositional compaction, (2) flank fracturing can result by compaction over dense underlying hills if lithification takes place prior to deposition of overlying beds, (3) crestal porosity on compaction structures can result when deposition proceeds slower than compactional settling, (4) salt domes may be localized over the top of compaction structures, and (5) much "tectonic" disturbance is not tectonic at all but is the result of compactional tilting followed by erosion and deposition of flat beds over the tilted ones on the flanks of compaction structures.**

## INTRODUCTION

In 1919-1920, during the nascent period of petroleum geology and only three years after the founding of the American Association of Petroleum Geologists, three noted American geologists presented papers nearly simultaneously announcing that the compaction of sediments over hills carved on an underlying basement or other dense unconformity surface could cause structural closure on overlying sedimentary formations. The geologists were Mehl (1920), Blackwelder (1920), and Moore (1920). Their conclusions followed logically from earlier recognition and understanding of the compaction and lithification of sedimentary units with geologic time. Somewhat later, Teas (1923) proposed that lateral changes in compactibility within a given sedimentary formation (e.g., a change from shale to sand) could also cause structural deformation on overlying formations. In 1925, compaction over carbonate reefs was recognized, but the account was not published until much later (Terzaghi, 1940). The writer believes that these three compaction mechanisms proposed in the formative years of petroleum geology are responsible for a significant percentage of the oil and gas producing structures in the Mid-Continent, United States. By inference, such structures, drilled and undrilled, must exist elsewhere in the world. However, a study of the journal and textbook literature and extensive personal communication with petroleum geologists over the last six years have shown that in the seven decades following the first announcements of compaction as a cause of structure, the geological profession has largely ignored, and in many instances rejected, this logical and inevitable structure-forming mechanism.

Paradoxically, compaction as a cause of densification of sedimentary rocks is a well known and well accepted phenomenon. First proposed and studied in 1908 by Sorby in England, it was extensively researched and quantified in the 1920s by Monnett (1922), Hedberg (1926), and Athy (1930). Gravitational compaction continues to be a subject of great interest today as exploration geologists, geophysicists, and petroleum engineers alike depend on it to understand seismic velocities and petroleum reservoir porosities and permeabilities. However, if compaction of sedimentary rocks occurs,

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compaction-induced structure is inevitable and therefore is inevitably pervasive in sedimentary basins. This paper summarizes the principles of compaction structures deduced 55-65 years ago and expands our understanding of these structures by analysis of the much larger amount of geological data available today.

## BRIEF SUMMARY OF EARLY WORK

AAPG's highest award for individual achievement in petroleum geology is the Sidney Powers Memorial Medal. The award was established in 1943 to honor a prominent geologist who had an extremely prolific but short (1911-1932) career in petroleum geology during the profession's most formative years (see Powers, 1922). Yet how many geologists realize that "The name of Sidney Powers...probably always will be, primarily associated with the idea of 'buried hills' " (Clark, 1933, p. 339).

Although Powers did not originally connect the concept of compaction with structural closure as did Mehl, Blackwelder, and Moore, he had made an observation that may have been seminal for those authors. Writing of the Healdton field in Carter County, Oklahoma (Powers, 1917), he stated, "Anticlines were developed, during folding, over the summits of buried hills...," in this case, Arbuckle (Cambrian-Ordovician) hills. Of perhaps equal impact on the thinking of geologists of this period was a revelation by C. H. Taylor (first editor of the *AAPG Bulletin*) on drilling results along the Nemaha ridge in Kansas, "It appears that the [high] granite so far encountered has been found invariably under surface folds" (Taylor, 1917).

The groundwork thus was laid, and in 1919, Maurice G. Mehl, in an address at the annual AAAS meeting in St. Louis, stated, "It is thought that...the small isolated dome-like anticlines typical of the Mid-Continent oil field...are chiefly the result of the differential compression of sediments." (At that time, the entire Mid-Continent area was termed the "Mid-Continent oil field.")

The first diagram of the concept appeared in *Economic Geology* in an article by Monnett (1922). The diagram is reproduced here as Figure 1. The drawing is theoretical; no actual well data were used (and it is doubtful if they were available).

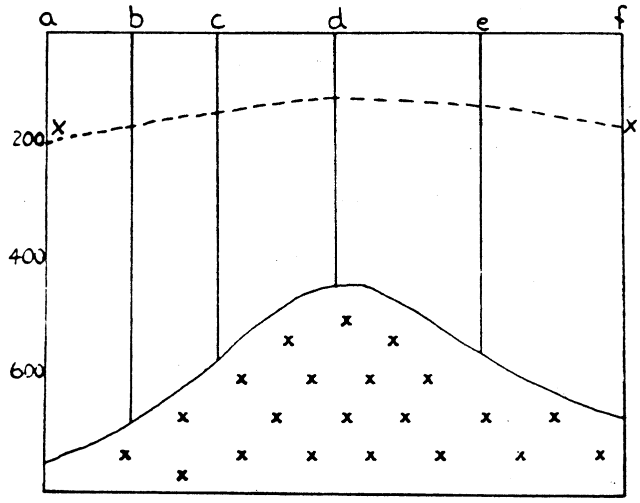



**Figure 1—Reproduction of first published drawing diagramming mechanism of compaction-induced structure (from Monnett, 1922, p. 197). Original caption and text explained that 25% reduction in distance between each vertical line (a through f) corresponded to uniform 25% compaction of underlying sediments, resulting in structure illustrated by line xx ′.**

By the mid-1930s, the following principal tenets of compaction theory had been well established.

(1) Compaction structures form by compaction of compressible sedimentary layers over topographic highs on an underlying, less compressible surface.

(2) The dip of the beds on the flanks of a compaction structure increases with depth, but is always less than the dip of the underlying causative surface.

(3) The amount of structural closure (amplitude) on compaction structures increases with depth.

(4) The area of compaction structures decreases with depth.

(5) The axial plane of compaction structures is vertical over symmetrical causative hills and inclined over asymmetrical hills, being tilted toward the gently dipping flank of the asymmetric hill.

(6) The structural relief on compaction structures may be modified either positively or negatively by faulting on the flanks.

(7) Upward isostatic pressure exists over basement hills loaded with sediments, so crustal arching may contribute slightly to the structural relief observed on compaction structures, particularly for broad structures.

(8) Initial dip of sediments due to purely depositional factors may occur on the flanks of compaction structures at the level of the causative hills, but probably does not contribute greatly to dips observed in strata above the crest of the hills.

(9) Compaction structures may form over sandstone bodies surrounded by shales or over any other lateral variation in compressibility within the sedimentary section.

(10) Compaction structures can form over reefs (bioherms) if the surrounding sediments are more compressible than the bioherm itself.

However, not all geologists of the period accepted the concept of compaction as a cause of structure, and many alternate hypotheses were proposed to explain away what some felt were obvious compaction structures. These concepts included (1) horizontal compressive stress, as per strain theory (e.g., Lilley, 1928), (2) "uplift," via faulting along the boundaries of structures (e.g., Fath, 1921; Clark, 1932; McCoy, 1934), (3) "uplift" via bending, "arching," or "flowage" of the underlying crust (basement) (e.g., Emmons, 1931; Hoffman, 1940), and (4) "initial dip" of deposition (e.g., Dake and Bridge, 1932). Although these explanations are valid when and where properly applied, they do not invalidate compaction as an equally valid mechanism for causing structure.

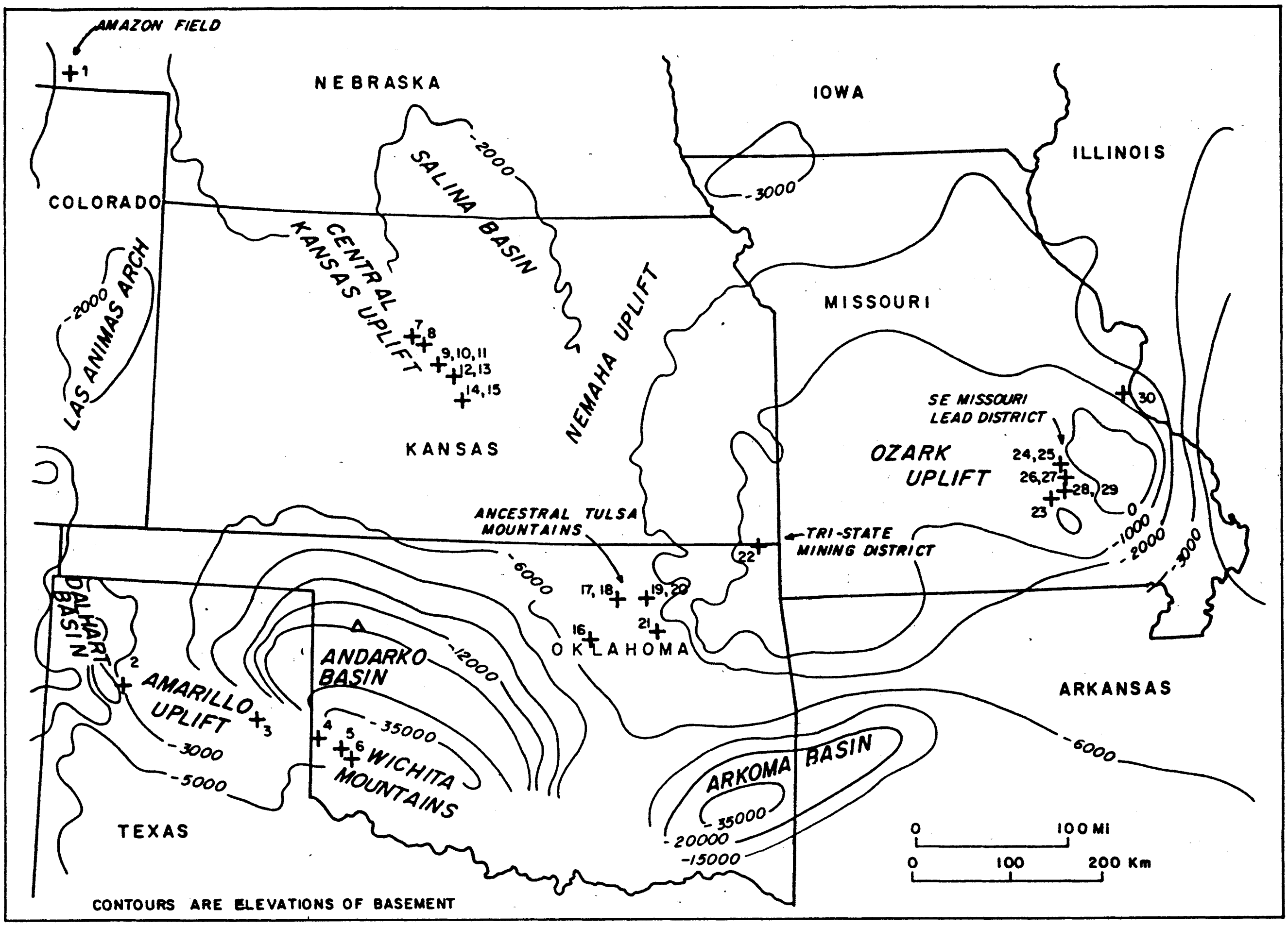



**Figure 2—Index map of Mid-Continent region (after Bayley and Muehlberger, 1968) showing locations of basement hills for which we have constructed or examined cross sections documented by multiple well intercepts (see Table 1). All basement hills, without exception, exhibit closure in overlying sedimentary section.**

## DOCUMENTED EXAMPLES OF BASEMENT HILLS AND COMPACTION STRUCTURES

In a previous extensive study on compaction as a cause of structure, the writer examined or constructed cross sections of 30 buried basement hills underneath the sedimentary section in the Mid-Continent region (S. P. Gay, 1985, unpublished data). All cross sections were from logged wells taken from reliable, and in many instances, publicly available sources. Fifteen of the resulting basement hills were from existing literature and 15 were produced by original work of the writer or by colleagues working on mining projects in Missouri.

The approximate locations of the 30 basement hills are shown in Figure 2. Table 1 lists the locations by section, township, and range, and provides the source of the data.

No hills examined either in the literature search or in my own constructions were rejected except for lack of closure on the basement surface or for lack of documentation of the well locations. All cross sections were required to have a minimum of three wells (i.e., one well near the crest of the hill and one on each side of the hill) to document opposing dips, although in reality most sections have two to three times this many wells.

All of the 30 basement hills so documented, without exception, exhibit closure in the overlying sedimentary section. One therefore may conclude that structural closure over basement hills is not an isolated phenomenon, and must be pervasive in sedimentary rocks everywhere.

I could not include cross sections of all 30 structures listed in Table 1 in this paper. Only a few of the more illustrative examples are shown.

Figure 3 is an exceptionally complete cross section over a basement hill from a lead-zinc exploration project in east-central Missouri on the east flank of the Ozark uplift (Figure 2, number 30). Length of the section is 8,000 ft (2.4 km), and the basement hill rises 400 ft (120 m) or more above its base. About 1,200-1,500 ft (365-460 m) of sedimentary section, divided into nine formations, covers the hill. The lowermost formation, the Lamotte, is a sandstone; this is overlain by the Bonneterre limestone, the Davis shale, and a succession of dolomitic formations. Farther west, in Oklahoma and Kansas, this entire sequence of Cambrian-Ordovician rocks is lumped by petroleum geologists under the term "Arbuckle."

In line with the deductions of the earlier geologists, this structure shows decreasing closure and decreasing dip

**Table 1. Locations of Basement Hills Documented by Well Sections***

| Index no. on Figure 2 | State | Location | Name | Source |
|---|---|---|---|---|
| 1 | Nebraska | Secs. 27, 28, T14N, R52W | Amazon oil field | Cox, 1982 |
| 2 | Texas | Sec. 75, Blk 5, G&M Survey, Oldham Co. | O'Brien hill | Gay, 1985, his Figure 4-21** |
| 3 | Texas | Sec. 119, Blk 23, H&GN Survey, Gray Co. | Turner hill | Gay, 1985, his Figure 4-20 |
| 4 | Oklahoma | Sec. 1, T7N, R26W<br>Secs. 25, 26, T8N, R26W | Smith hill | Gay, 1985, his Figure 4-17 |
| 5 | Oklahoma | Secs. 5, 9, T6N, R23W | Reynolds hill | Gay, 1985, his Figure 4-19 |
| 6 | Oklahoma | Sec. 26, T6N, R22W | Johnson hill | Gay, 1985, his Figure 4-18 |
| 7 | Kansas | Secs. 4, 9, 10, T14S, R15W | Gorham hill | Walters, 1953 |
| 8 | Kansas | Secs. 23, 25, 35, T14S, R14W | Hall-Gurney hill | Walters, 1953 |
| 9 | Kansas | Secs. 16, 17, 21, T16S, R12W | Beaver hill | Walters, 1946 |
| 10 | Kansas | Secs. 17, 18, T16S, R11W | Prusa North hill | Walters, 1946 |
| 11 | Kansas | Secs. 17, 20, T16S, R11W | Prusa hill | Walters, 1946 |
| 12 | Kansas | Secs. 30, 31, T16S, R11W | Krier hill | Walters, 1946 |
| 13 | Kansas | Secs. 7, 18, T17S, R10W | Breford hill | Walters, 1946 |
| 14 | Kansas | Sec. 27, T18S, R10W | Orth West hill | Walters, 1953 |
| 15 | Kansas | Secs. 25, 26, T18S, R10W | Orth East hill | Walters, 1953 |
| 16 | Oklahoma | Sec. 33, T19N, R5E | — | Gay, 1985, his Figure 4-16 |
| 17 | Oklahoma | Sec. 20, T23N, R8E | — | Gay, 1985, his Figure 4-13 |
| 18 | Oklahoma | Secs. 8, 9, T23N, R8E | — | Gay, 1985, his Figure 4-13 |
| 19 | Oklahoma | Sec. 7, T23N, R11E | — | Gay, 1985, his Figure 4-11 |
| 20 | Oklahoma | Secs. 29, 30, 31, T24N, R11E | — | Gay, 1985, his Figures 4-12, 4-14 |
| 21 | Oklahoma | Secs. 8, 9, T20N, R12E | — | Gay, 1985, his Figure 4-15 |
| 22 | Oklahoma | Secs. 18, 19, T29N, R23E<br>Secs. 13, 14, T29N, R22E | — | Gay, 1985, his Figures 4-4, 4-10 |
| 23 | Missouri | Sec. 4, T31N, R3W | Loggers Lake knob | Gay, 1985, his Figure 4-5 |
| 24 | Missouri | Secs. 16, 17, T34N, R2W | Boss-Bixby South knob | Gay, 1985, his Figure 4-7 |
| 25 | Missouri | Secs. 4, 9, T34N, R2W | Boss-Bixby Central knob | Gay, 1985, his Figure 4-8 |
| 26 | Missouri | Secs. 22, 23, T33N, R2W | Brushy Creek West knob | Gay, 1985, his Figure 4-4 |
| 27 | Missouri | Sec. 23, T33N, R2W | Brushy Creek East knob | Gay, 1985, his Figure 4-3 |
| 28 | Missouri | Sec. 13, T32N, R2W | Fletcher Mine Central knob | Gay, 1985, his Figure 4-2 |
| 29 | Missouri | Sec. 24, T32N, R2W | Fletcher Mine South knob | Gay, 1985, his Figure 4-2 |
| 30 | Missouri | Jefferson County | — | Gay, 1985, his Figure 4-6 |

*Well names and more exact locations are available from the writer.
**S. P. Gay (1985) is unpublished manuscript.

upsection. However, as dips higher up remain steep on the north side, a component of regional north dip appears to have developed between Bonneterre and Roubidoux deposition.

A structure with decreasing closure and decreasing dip upsection like that shown in Figure 3 was termed "supratenuous fold" by Nevin (1931) and renamed "growth anticline" by Chapman (1973). However, the terms "compaction structure" or "compaction anticline" as used by the early workers, or "gravicline" as I proposed informally in 1985 (unpublished manuscript) and propose again in this article, are more genetic and hence preferable for this type of structure, in my opinion.

Figure 4 shows a much narrower basement hill resulting from petroleum exploration drilling on the west side of the Ozark uplift in northeastern Oklahoma (Figure 2, well 16). The hill's overlying compaction structure shows decreasing dip and decreasing closure upsection. Some of the earlier workers invoked crustal "bending" or "arching" as arguments against structures forming by compaction over basement hills, but the narrow widths of the basement hills of Figures 3 and 4, and especially the latter (only 0.6 mi or 1 km wide in an area where the crust is approximately 22 mi or 35 km thick), preclude crustal bending. The structure shown in Figure 4 is located in the "ancestral Tulsa Mountains" (Ireland, 1955), an area where many similar structures produce oil. Six of these were documented as compaction structures over basement hills for the present study, and further study of well logs in this area could document many others.

Figure 5 is a cross section across a basement hill 4 mi (6.5 km) wide on the Amarillo uplift in the Texas panhandle (Figure 2, well 2). The same characteristics of decreasing dip and decreasing closure upsection are evident. A corresponding residual magnetic map indicates that the basement hill was carved on a magnetic basement block and that the western block boundary is coincident with well 2. As block boundaries are generally basement shear zones comprised of crushed and broken (mylonitized) rock, they may be expected to erode low, as happened here.

The cross sections in Figures 3-5 are typical of the compaction structures over the 30 basement hills listed in Table 1.

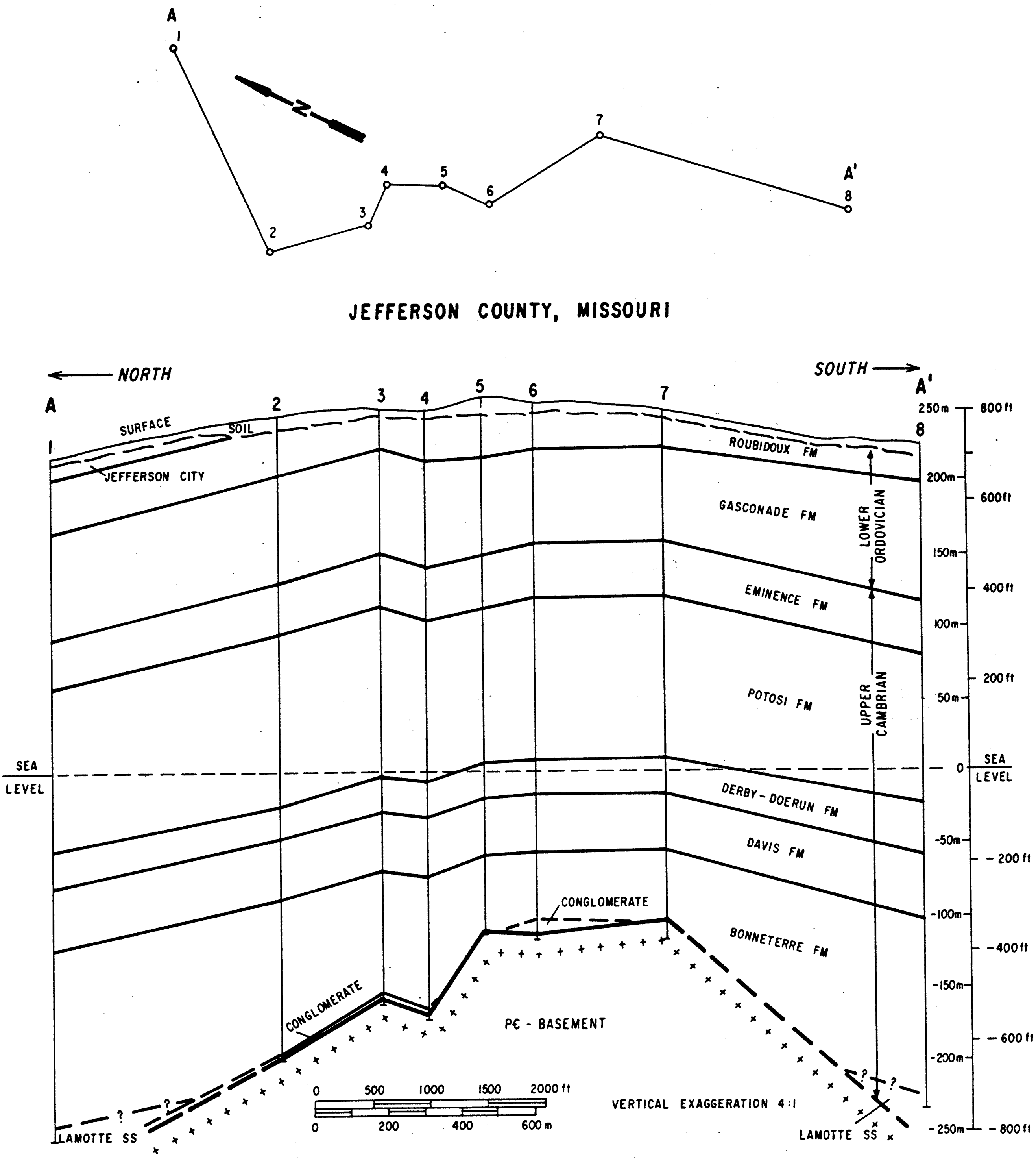
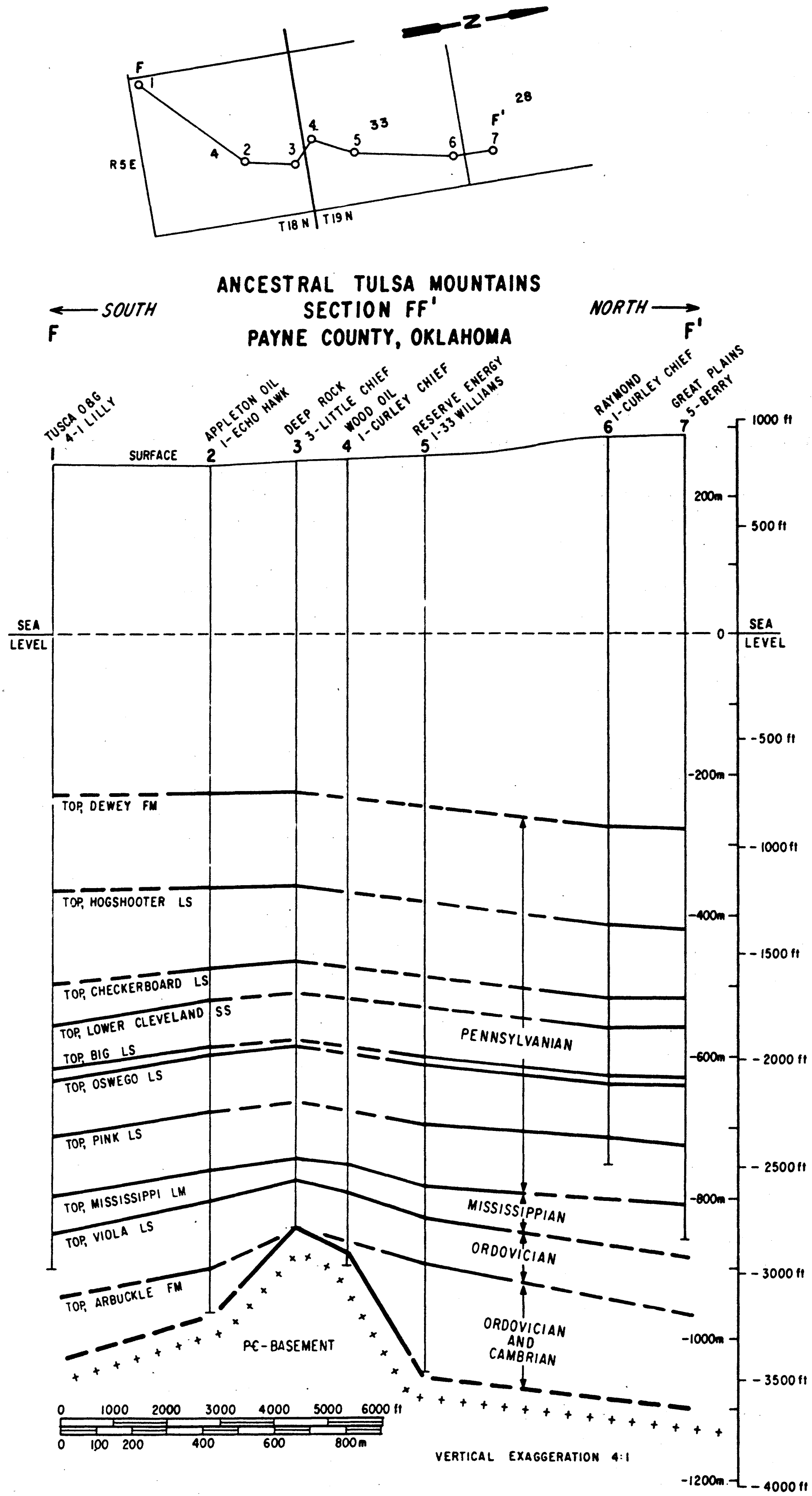



**Figure 3—Cross section showing typical "drape" or compaction structure (Figure 2, number 30) over shallow basement hill in Jefferson County, Missouri. Data courtesy of P. E. Gerdemann, St. Joe Minerals Corporation, Viburnum, Missouri.**

## DOCUMENTATION OF THINNING OVER BASEMENT HILL DUE TO COMPACTION

Thinning of beds over structural highs is a well-known concept in petroleum exploration, and isopaching of beds to look for thinning is a common means of searching for potentially productive structures. The thinning is generally attributed to nondeposition, erosion, slumping, drape, or dissolution of beds on the crest of a "growing" structural high. However, thinning of beds over a compaction structure is also a natural consequence of the compaction process itself, where compaction of beds surrounding the underlying basement hill is taking place while the overlying beds are being deposited. This may be termed "syndepositional compaction," and should be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NORTH
TUSCA O&G 4-1 LILLY
APPLETON OIL 1-ECHO HAWK
DEEP ROCK 3-LITTLE CHIEF
WOOD OIL 1-CURLEY CHIEF
RESERVE ENERGY 1-33 WILLIAMS
RAYMOND 1-CURLEY CHIEF
GREAT PLAINS 5-BERRY
SURFACE
SEA LEVEL
TOP DEWEY FM
TOP HOGSHOOTER LS
TOP CHECKERBOARD LS
TOP LOWER CLEVELAND SS
TOP BIG LS
TOP OSWEGO LS
TOP PINK LS
TOP MISSISSIPPI LM
TOP VIOLA LS
TOP ARBUCKLE FM
PENNSYLVANIAN
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VERTICAL EXAGGERATION 4:1

**Figure 4—Narrow basement hill in northeastern Oklahoma showing well-developed compaction structure (Figure 2, number 16). This structure exhibits typical decreasing dip and closure upsection predicted by compaction theory. Structure is much too narrow (0.6 mi or 1 km) to have resulted from crustal "bending" proposed by some earlier workers as alternate explanation for compaction mechanism.**

considered the general occurrence, since compaction is an ongoing process beginning when sedimentary beds are first deposited and continuing until they are exhumed by erosion.

The compaction phenomenon affects a compacting bed approximately as a ratio, or percentage, of its thickness, as deduced by Monnett in 1922 (Figure 1). That is, a 300-ft (91-m) thick bed that compacts 5% in a given time interval will decrease in thickness by 15 ft (4.5 m). If such a 300-ft (91-m) thick compacting bed surrounds a basement hill where its thickness varies from zero at its pinch-out point near the crest of the hill to 300 ft (91 m) away from the hill, then the amount of compaction will also vary. Compaction will be zero where the thickness of the bed is zero on the crest, of course, and will continuously increase to 15 ft (4.5 m) away from the hill where the bed exhibits a full thickness. An overlying bed being deposited during this time interval therefore will be 15 ft (4.5 m) thicker away from the hill than near the crest. This concept is explained in detail in Figure 6.

Study of Figure 6 will show that viewing compactional thinning over the crest of a structure as compactional "thickening" on its flanks perhaps is more logical. However one looks at it, crestal thinning of beds over compaction structures is integral to the compaction phenomenon itself.

Where the foregoing discussion is theoretical, as has been the case with nearly all work on compaction structures to date (with the exception of certain studies of carbonate reefs), the writer has been able to construct a detailed drill section over an actual basement hill that exhibits compaction contemporaneous with deposition as theoretically described. This cross section (Figure 7) was constructed from drill hole data obtained on a basement mineral exploration project in southeast Missouri in the 1950s and 1960s (Figure 2, number 25). Fourteen wells extend to basement and four others help define the sedimentary section—a total of 18 wells in a horizontal distance of 8,000 ft (2.4 km). Truncation of the Lamotte Sandstone and Bonneterre carbonate units against the hill and drape of the Davis shale, Derby-Doerun dolomite, and higher formations over the hill may be observed. Thinning of the Davis shale over the structure may not be perceptible to the eye but is readily measured on the figure with a pair of dividers. Thinning amounts to approximately 15 ft (4.5 m) in 160 ft (49 m).

By plotting the Bonneterre limestone thickness (the unit surrounding the basement hill) vs. Davis shale thickness (the first unit overlying the hill) for all the wells shown in Figure 7, the relationship of increasing Davis thickness with increasing Bonneterre thickness is clearly apparent (Figure 8). A least-squares straight-line fit to this plot reveals a 5.2-ft (1.6-m) increase in Davis thickness for each 100-ft (30-m) thickness of Bonneterre. This means that where the Bonneterre has zero thickness near the crest of the hill the Davis exhibits a "normal" thickness of 143 ft (44 m); where there is 100 ft (30 m) of Bonneterre on the flanks of the hill, the Davis is approximately 5.2 ft (1.6 m) thicker (as in our theoretical example); where the Bonneterre thickness increases to 200 ft (61 m) farther down the hill, the Davis is $2 \times 5.2 = 10.4$ ft (3.2 m) thicker; and where the Bonneterre reaches its own normal thickness of approximately 300 ft (91 m) still farther down the hill, the Davis is $3 \times 5.2 = 15.6$ ft (4.7 m) thicker. This direct relationship between Davis thickness and Bonneterre thickness demonstrates that an ongoing ("syndepositional") thickness decrease of the Bonneterre of 5.2 ft (1.6 m) per 100 ft (30 m) (i.e., 5.2%) was taking place while the overlying Davis formation was being deposited. The writer attributes this thickness decrease to compaction and offers these results as quantitative proof of the compaction process, as well as an explanation for thinning over structural highs (i.e., those highs due to compaction over dense, underlying hills).

Successive thinning of beds over a structure has previously been considered by some as evidence for the "growth" or uplift of that structure with time. This implies that, somehow, an area of the brittle basement underlying a structure is being forced upward by unknown forces. However, the present data show that the growth is only relative. Rather than the basement moving up into the sedimentary section, the section is moving down around the basement hill.

We can make an additional important observation on thinning by referring to Figure 6. In stage 2, we see that the top and bottom layers of a bed laid down over an actively compacting structure are not parallel because of the intervening time interval required to deposit the bed; this departure results in the thinning. If a bed were lain down instantaneously, geologically speaking, no thinning would occur. This happens with turbidites, for example, and some sandstones. If a bed were deposited slowly, as with some limestones and shales, the thinning is accentuated. Therefore, the degree, or percentage, of thinning of a bed on the crest of a compaction structure depends on the time interval required to deposit that bed, other depositional factors being equal. The widely varying amounts of thinning of different beds that we observe over some structures are simply telling us something of the varying rates of deposition of these beds.

Nevertheless, as every rule has its exception, or apparent exception, compactional thinning may not always be evident on the crest of a compaction structure. In a carbonate depositional environment, for example, reef growth may thicken the sediments on the crest much faster than compaction settling thins them. In a clastic depositional environment, clean winnowed less compactible sands may be deposited on the crest of a compaction structure resulting in the same apparent phenomenon. Although compaction is still occurring in both cases, it is overshadowed by other depositional effects. These complicating phenomena are discussed in a later section.

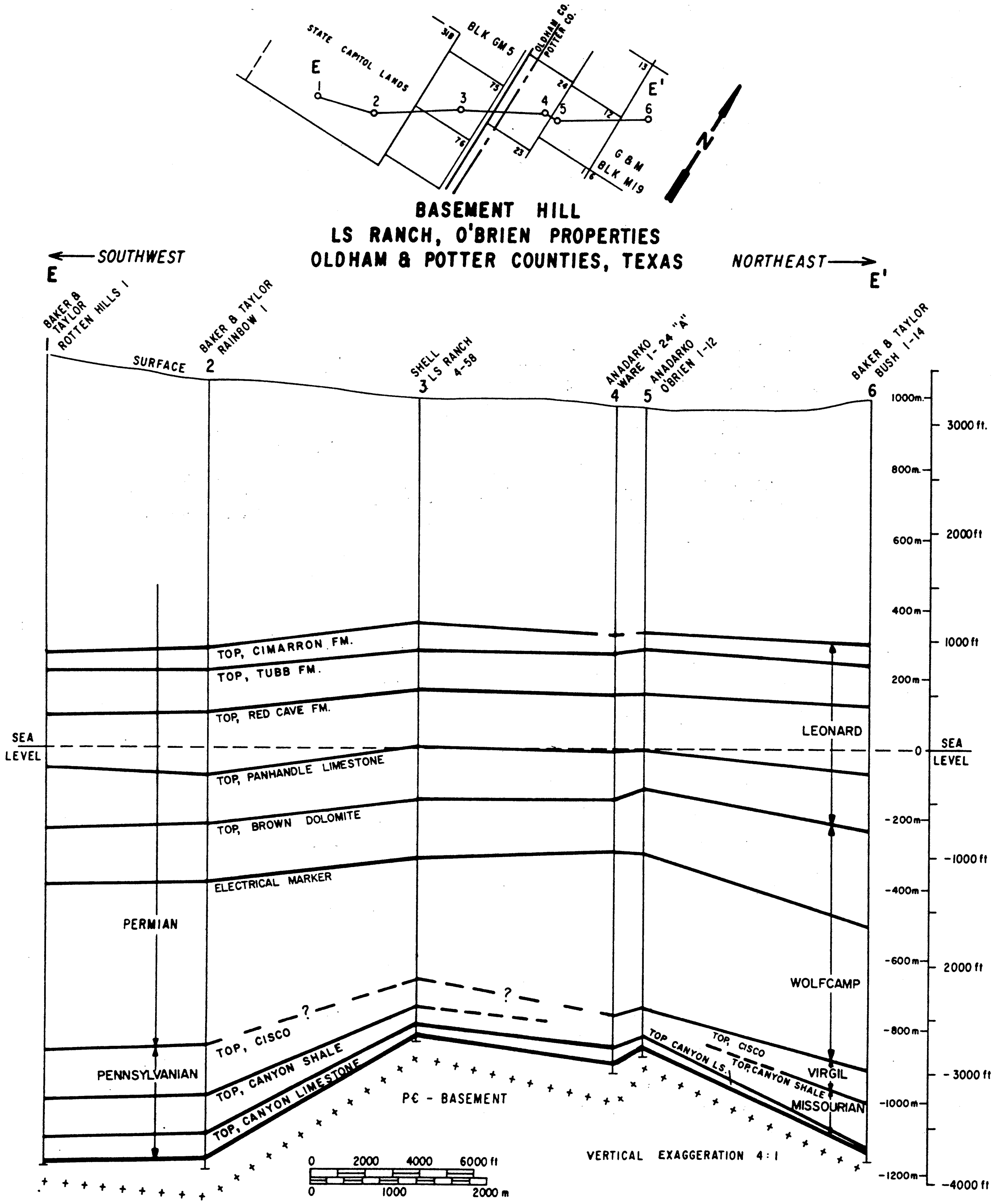



**Figure 5—Formational picks, through 5,000 ft (1,524 m) of sedimentary section in this example from Amarillo uplift, show decreasing closure and formational dips upsection typical of compaction structures. (Location on Figure 2, number 2.)**

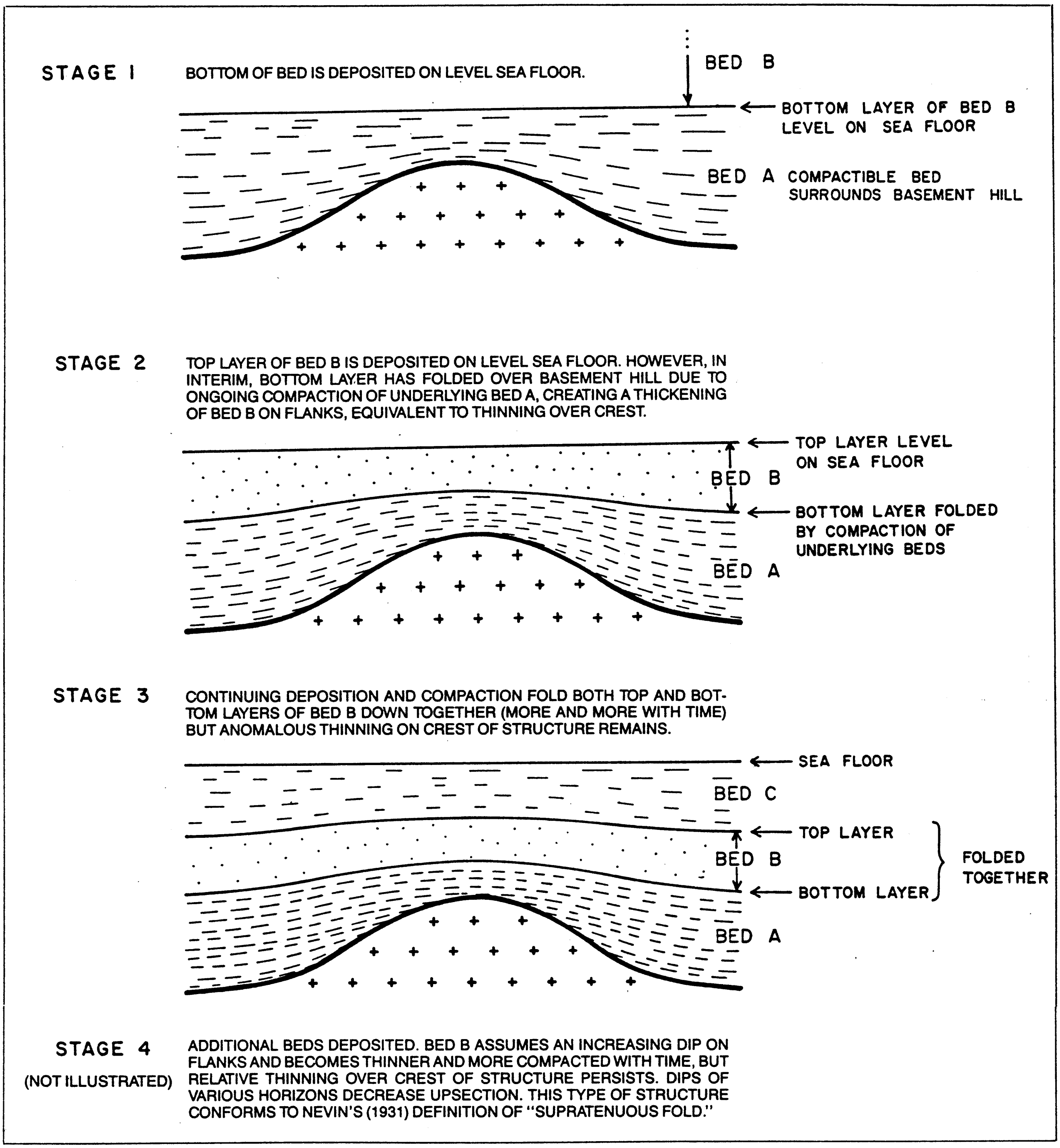



**Figure 6—Thinning of strata over structural highs—heretofore explained by nondeposition, erosion, slumping, drape, or dissolution of thinned beds—is shown to be logical and expected consequence of compaction of underlying beds contemporaneous with deposition of thinned bed.**

## PERVASIVE NATURE OF COMPACTION PHENOMENA

If sedimentary structure due to compaction is as pervasive a phenomenon as suggested here, we should be able to observe it in map fashion over a large area (i.e., some place where we can see that the structures in the sedimentary section, both highs and lows, indeed mimic the basement topography). However, the writer knows of no area where the basement topography is sufficiently well known at a large enough scale to make such a comparison. We can construct detailed regional maps of the structure in the sedimentary section in many areas, but basement intercepts are generally one to two orders of magnitude less numerous, making a valid comparison impossible.

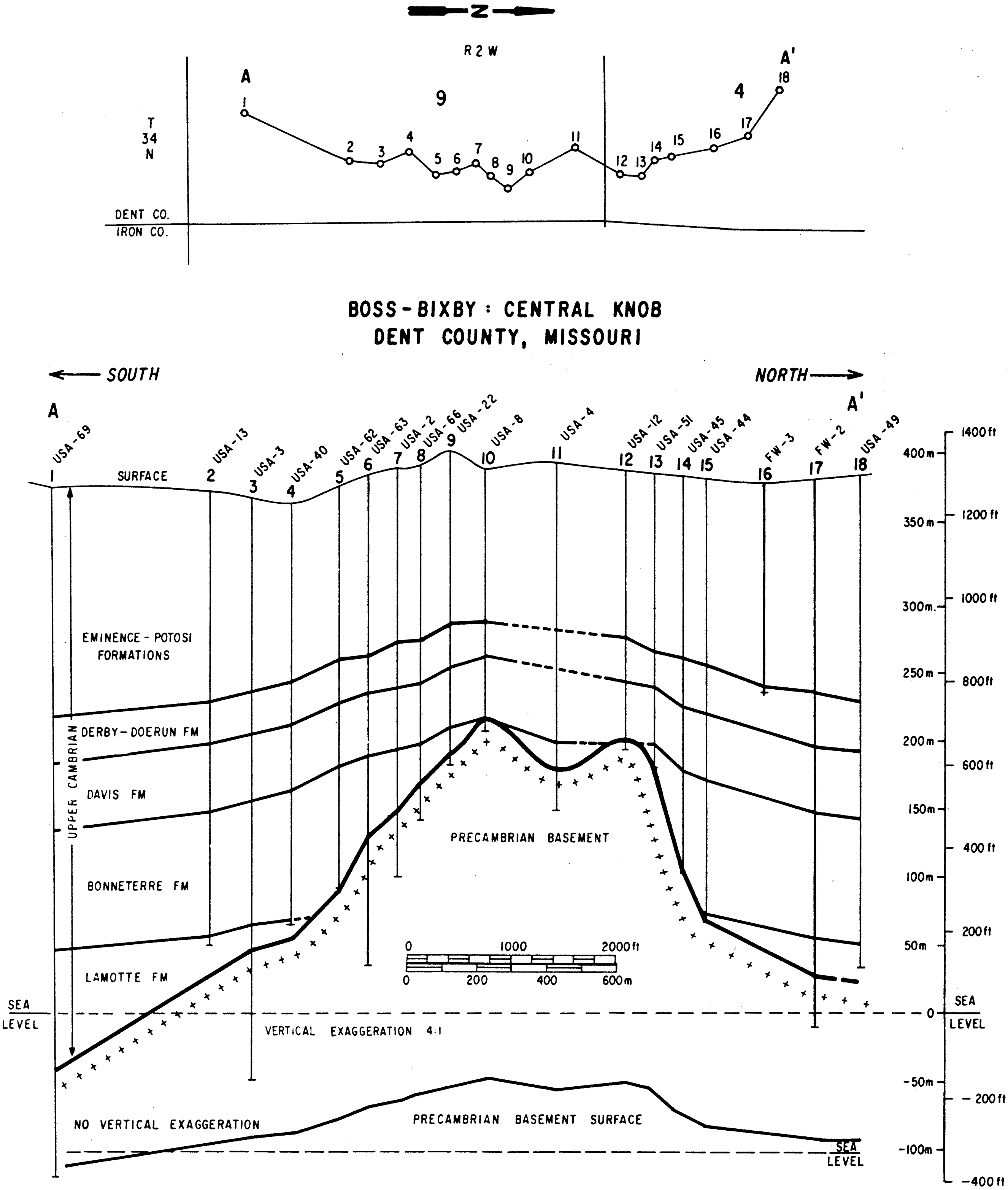



**Figure 7—Detailed cross section (18 wells total, 14 to basement) documenting prominent basement hill in Dent County, Missouri. Thickness plots of overlying Davis (Figure 8) and Derby-Doerun formations (not shown) demonstrate that Bonneterre Dolomite was compacting while overlying beds were being deposited. Unpublished data courtesy of Cominco American, Inc., and Louis Rove, Getty Minerals.**

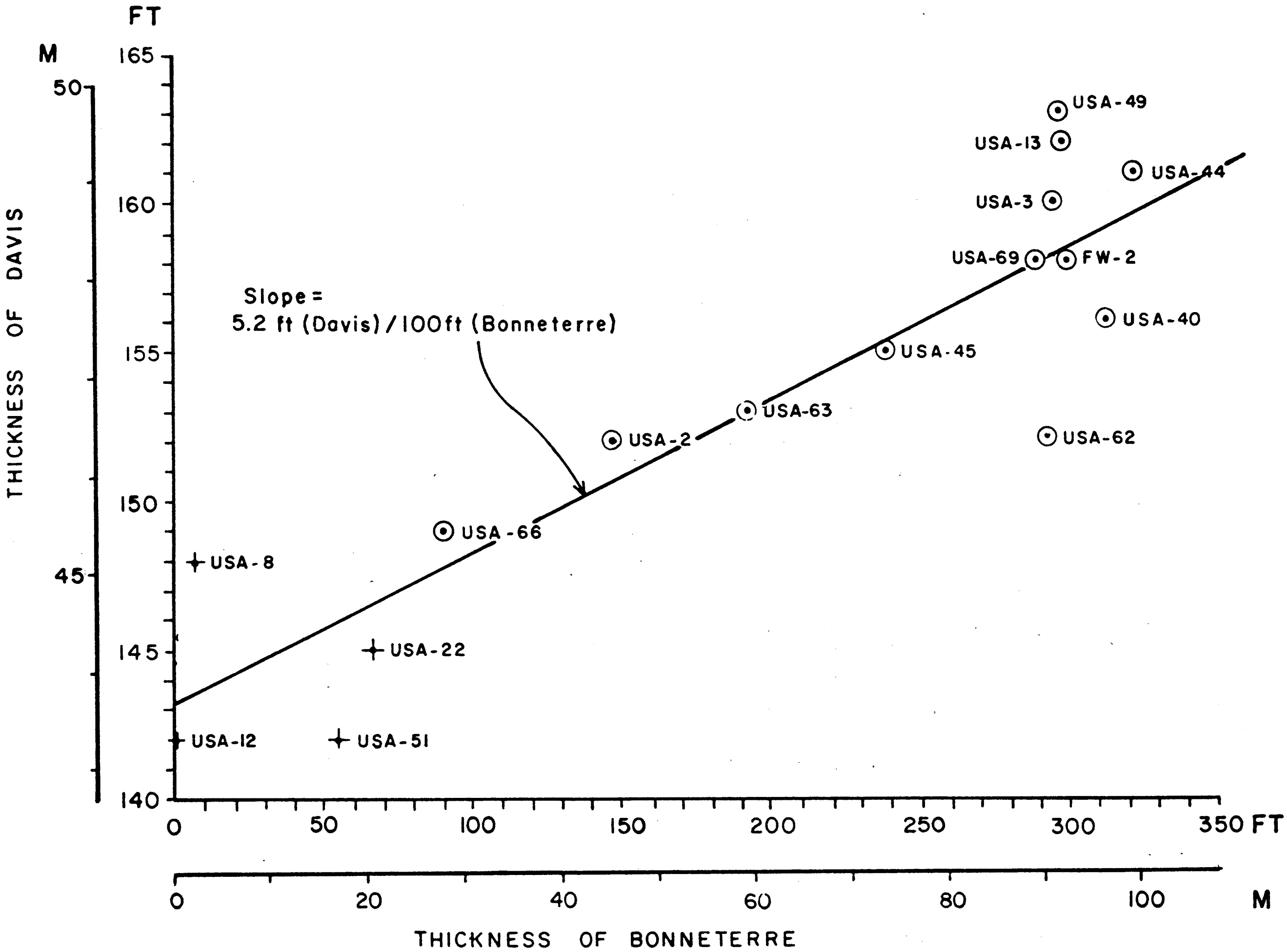



**Figure 8—Proportionality plot of Bonneterre and Davis thicknesses over Boss-Bixby central knob (thickness-thickness plot). Least-squares straight-line fit to this data shows increase of 5.2 ft (1.6 m) of Davis for each 100-ft (30-m) thickness of Bonneterre. That is, where there is zero Bonneterre at crest of basement hill, expected Davis thickness is 143 ft (44 m) (intercept of plot); where Bonneterre is 100 ft (30 m) thick, it compacted 5.2 ft (1.6 m) during Davis deposition allowing extra 5.2 ft (1.6 m) of Davis for a total of 148.2 ft (45 m); where Bonneterre is 200 ft (61 m) thick, there is yet another 5.2 ft (1.6 m) of Davis; and where full Bonneterre thickness of 300 ft (91 m) is present, Davis is 15.6 ft (4.7 m) thicker, for a total of approximately 15.6 ft (4.7 m) of Bonneterre compaction (full section) while Davis formation was being deposited above it—an exact quantitative measurement of a qualitative effect predicted by compaction theory.**

One kind of data, however, has become available in recent years for mapping the basement geology and can perhaps resolve this problem. Newly developed residual aeromagnetic maps of high resolution do a reasonable job of mapping the basement lithologies, and hence, the basement fault block pattern. The maps do not indicate which blocks are topographically high on the basement, however, because high topography can exist over a quartzite block of low magnetic susceptibility as well as over a granite of moderate to high susceptibility. These magnetic maps do show, nevertheless, the basement trend directions, the basement faults, and the basement block boundaries, and thus provide an indirect means of comparing the basement topography with a structural horizon in the overlying sedimentary section over large areas.

In 1983, such a study was done for an area measuring 40 × 50 mi (65 × 80 km) in south-central Kansas. An excellent structural map of the Ordovician Simpson formation lying approximately 1,000 ft (300 m) above basement (Williams, 1968) was compared to a high resolution "NewMag"[3] residual map prepared by Applied Geophysics, Inc. Trend lines of highs and lows were drawn on both maps and overlaid. A correlation factor of 74.4% was obtained (i.e., 74.4% of the residual magnetic trends arising from basement corresponded to Simpson structural trends) despite a high diversity of trend directions throughout the area. For this area, we concluded that control by basement topography on structure in the lower part of the sedimentary section in this area is indeed ubiquitous. We have no reason to believe that this

[3]NEW Basement Tectonics Enhanced MAGnetics. A Registered Trade Mark of Applied Geophysics, Inc.

phenomenon is not pervasive, affecting all sedimentary basins in similar fashion worldwide.

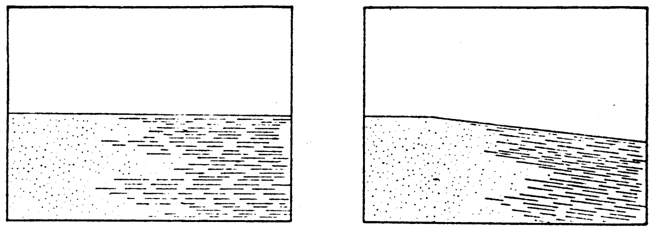
## HILLS ON HIGHER UNCONFORMITY SURFACES AND LATERAL COMPACTIBILITY VARIATIONS WITHIN SEDIMENTARY SECTION

If basement topography is so important in influencing the structure of overlying sedimentary units, what of unconformity surfaces higher in the sedimentary section? These should also be important in controlling the structure and thickness of overlying strata. Many examples could be cited but only one is discussed here. A study of Pennsylvanian Morrow sandstone deposition in Woodward and Ellis Counties, Oklahoma, on the northern shelf of the Anadarko basin was made by Webster (1983). He showed that two sandstone units within the Morrow, the Hamilton prograding beach complex and the Yellow Sand delta-front complex, exhibit paleothicks that coincide nearly precisely with valleys carved by erosion into the Mississippian Chester limestone underlying the Morrow. He stated that "the Chester paleotopographic surface has caused local thick sand deposits with good porosity to strike north-south along the paleovalleys...a logical result of a basal transgressive unit filling in a drowned topographic surface...." However, the sands do not occur within the 50-100 ft (15-30 m) deep paleovalleys, but are located 100-300 ft (30-91 m) above them. The valleys are completely filled with a lower Morrow shale unit, so how is it possible that the drowned hills can manifest themselves on the thicknesses of overlying sandstone units? I suggest that the controlling mechanism is compaction, as described and documented herein.

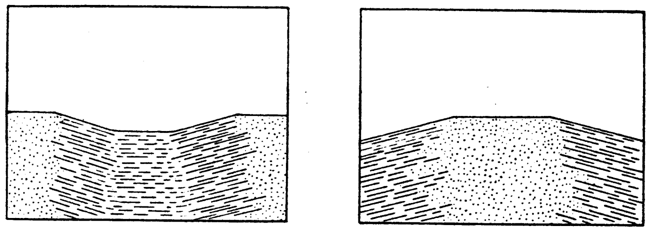
Compaction concepts are not prevalent in stratigraphic geology, and Webster's (1983) study is but one of literally hundreds of analyses where a better understanding could be gained by the application of compaction theory.

The foregoing example also illustrates how basement influence must diminish as one goes higher in the sedimentary section. New unconformity surfaces, such as the Mississippian Chester surface, truncate underlying compaction structures and introduce new ones. In Walters' (1953, his Figure 3) cross section, the top of the Missourian Series shows a combination of compaction structures resulting from both basement topography and Arbuckle (Cambrian-Ordovician) topography. Also, if the older, underlying compaction structures are not thoroughly compacted, they may remanifest themselves above a new unconformity surface, thus intermingling basement-caused and higher compaction structures.

Two other basic types of compaction structures result from sedimentary processes within the sedimentary section. Shaw (1918) stated, "An anticline may conceivably be formed by irregular settling if near the base of the sedimentary pile there is a thick sand...." This concept was expanded on by Teas (1923) who published the first diagrams showing how structure could result from lateral



LEFT —Gradual transition from sand to clay.
RIGHT —Resultant gradual dip after compacting.



LEFT —Section showing differential compacting resulting in apparent synclinal dips.
RIGHT—Section showing differential compacting resulting in apparent anticlinal dips.

**Figure 9—Reproduction of first published diagrams (Teas, 1923, p. 372, 375) showing structure resulting from lateral changes in compactibility within sedimentary section. (Top) Monoclinal dips resulting from facies changes; (bottom) synclinal and anticlinal dips resulting from localized areas of clay or sand deposition, respectively.**

variations in compactibility due to facies changes from sand to clay (Figure 9). However, the same effect could as easily result from a change from sandstone to limestone or limestone to shale. I know of no published stratigraphic study in the intervening 65 years that has attempted to document this type of compaction structure from well data, although these structures undoubtedly exist. The most obvious place to look for them, and perhaps one of the easiest to prove, would be over sand bars or sand-filled channels surrounded by shale. In fact, searching with offset wells for shale "thins" over underlying sand bars has been largely responsible for success in drilling Pennsylvanian Morrow point bar sandstones in southeastern Colorado (M. Kidwell, 1985, personal communication) in a "difficult" play (Keener, 1987).

Another common type of compaction structure is that occurring over carbonate reefs. This type of structure apparently was first recognized in 1925 by Ruth Daggett Terzaghi in a limestone quarry in Illinois, but her data were not published until 1940. Such structures have been extensively described by later workers (Yungel, 1961; Ferris, 1969) and in highly quantitative studies made in Canada by Labute and Gretener (1969) and O'Connor and Gretener (1974a, b). O'Connor and Gretener (1974b) made plots of the structural closure vs. overburden thickness over reefs and were able to determine not only the amount of compaction with time but also the time of collapse of the reef core due to overburden pressure.

## THICKNESS-THICKNESS PLOTS AND TIME RATE OF COMPACTION

The use of thickness-thickness plots over basement hills (as in Figure 8) is a new and valuable way of estimating the amount of compaction of sedimentary rocks. These plots also tell something about the time rate of compaction. For example, thickness-thickness plots were made from the data for 12 wells over a Missouri basement hill lying 1.2 mi (2 km) southwest of the cross section of Figure 7. The hill is completely surrounded by Lamotte Sandstone, and the plots revealed a 2.0% compaction of the Lamotte during Bonneterre deposition, and another 2.7% during Davis deposition, for a total of 4.7% compaction of the Lamotte Sandstone during only a fraction of the Late Cambrian. Because many other Upper Cambrian and Ordovician units originally overlay the Lamotte in this area of Missourian rocks (see Figures 3, 7), total compaction of the Lamotte Sandstone could have surpassed 20%. Also, if we knew the time required for deposition of 305 ft (93 m) of Bonneterre limestone or 155 ft (47 m) of Davis shale, we could calculate the compaction of the Lamotte in millimeters, or millipercent, per year.

The material surrounding a basement hill is important in the formation of the overlying compaction structure. Structures over hills surrounded by highly compactible materials, such as shales or limestones, will not only form structures of greater closure, but will also form faster than those surrounded by sandstones. These faster forming structures will exhibit greater dips on the flanks and more accentuated thinning on the crest. Therefore, they will persist farther up section and, more importantly, they will more likely be the loci of sea floor highs because depositional infilling may proceed slower than compactional "draping," a subject discussed in the next section.

At the low end of the spectrum of compressibility are older precompacted formations partially stripped off basement hills by erosion, leaving the tops of the hills exposed to a new cycle of deposition and compaction. The already compacted materials surrounding the hills undoubtedly compact even less than sandstone, and the overlying compaction structures would be correspondingly less prominent. Several such hills, surrounded by Cambrian-Ordovician Arbuckle dolomites and exposed by an Ordovician erosional surface on the Central Kansas uplift, are documented by Walters (1946, 1953) (see Table 1) and exhibit low amplitude, but nevertheless are measurable compaction structures.

## CRESTAL POROSITY, FLANK FRACTURING, SALT DOMES, AND "REGIONAL" UNCONFORMITIES

### Crestal Porosity

On top of an actively forming compaction structure in a basin still undergoing deposition, what happens if deposition proceeds slower than compaction and does not level the sea floor fast enough to keep pace with compactional folding? In this case, sea floor highs are created over underlying topographic highs or other types of compressibility anomalies. If the sea floor high is of sufficient amplitude, the crest of the structure will be exposed to a shallower, higher energy wave environment and, therefore, subject to deposition of coarser clastics (Figure 10), resulting in crestal porosity enhancement. This mechanism, winnowing of sediments over compaction-induced sea floor highs, was apparently first suggested by Martin (1966, p. 2281). However, even in deep water, sand bodies have been found to develop over sea floor highs due to bottom currents (Swift and Rice, 1984), so crestal porosity over compaction structures may not be an uncommon occurrence.

Where crestal sea floor highs appear persistently upsection due to ongoing depositions slower than compaction and the coarser clastics are less compactible than the finer materials deposited in the troughs, the amplitude of the gravicline will not die out as fast upsection and could actually increase, thus contravening rules 2 through 4 (summarized in the section on earlier work). Where deposition proceeds slower than compaction in carbonate environments, reef development may occur over the protruding sea floor highs (Figure 10), also accentuating the closure over the structure and again contravening the rules that amplitudes and dips on compaction structures always decrease upsection and areas increase. Scholten (1959) termed such structures "synchronous highs" and emphasized their importance as petroleum reservoirs. Because of the persistence of such structures upsection, many of them produce hydrocarbons from multiple zones.

In the Paradox basin of Utah, Mississippian structural highs topped by reef buildups over probable basement hills located by residual magnetics ("NewMag") under the Salt Wash and Nicholas Wash fields appear to be due to the compaction process.

### Flank Fracturing

In compactional folding, formerly horizontal beds become tilted on the flanks of a compaction structure. This tilting causes tensional stress on the flanks since the tilted length is longer than the original horizontal length. The relationship is expressed mathematically by the secant function of the tilt angle. If the beds have become brittle following lithification, fracturing inevitably results (see Figure 11), thereby increasing permeabilities on the flanks but not on the crest where the beds remain horizontal. Keep in mind, however, that some (or much) of the compactional folding may have occurred prior to lithification and would not have resulted in brittle fracturing. Also, porosity enhancement can occur on the crests of compactional structures due to various depositional and/or dissolution effects unique to a topographic prominence. Oil or gas fields developed on a compaction structure with crestal porosity enhancement thus may show better production on the crest, obscuring the beneficial effects of flank fracturing. Nevertheless, in the absence of crestal porosity development, flank fracturing readily explains flank production found on some oil-

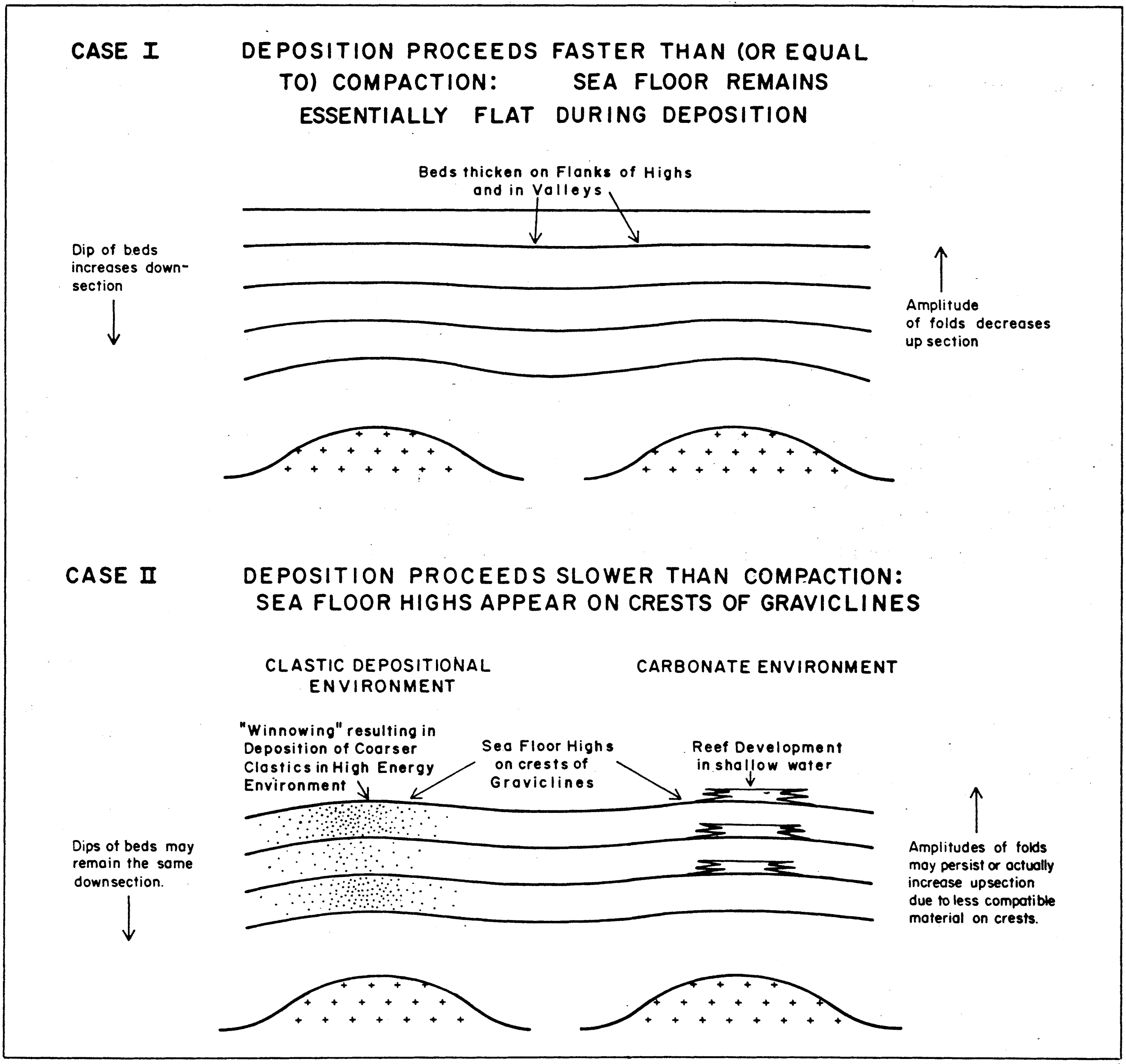



**Figure 10—Previous discussions on graviclinal folding assume that graviclinal compaction highs do not appear on sea floor because depositional infilling levels sea floor faster than compaction folds it (case I). However, where deposition proceeds very slowly (case II), sea floor highs may appear over crests of graviclines due to compaction. Here, many depositional effects due to location in higher energy, shallower water depths will be felt, such as winnowing of sediments in clastic environments resulting in higher porosity, and growth of coral in carbonate environments resulting in reef formation. These effects will contravene usual rules of decreasing dips and amplitudes of graviclines upsection, as both coarser sediments and reefs form hard, less compactible cores that will perpetuate graviclinal folds higher in section. The name "synchronous high" as discussed by Scholten (1959) applies here.**

and gas-bearing structures and perhaps some "halo" effects encountered in geochemical studies of oil fields.

## Salt Domes

A sedimentary section containing a horizontal salt layer overlain by a thick blanket of denser sedimentary units is in a state of unstable equilibrium. The less dense salt tends to rise to the surface and is prevented from doing so only by its low viscosity and the lack of vertical pathways. Many mechanisms for salt dome initiation have been proposed, but the mechanism most generally accepted is that once an area of higher elevation on the top surface of the salt is formed, for whatever reason, then that area becomes a point of release for the upward pressure of the salt, and a salt dome, or diapir, results (Billings, 1972, p. 300). Compactional folds over hills on

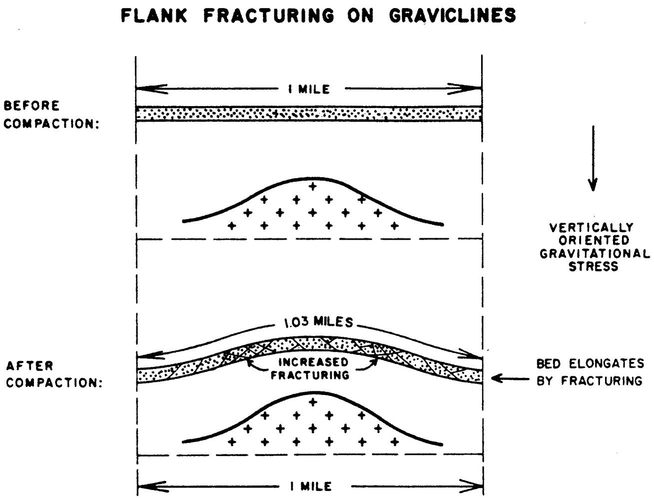



**Figure 11—Flank fracturing on graviclinal structures is inevitable result of increase in distance bed is forced to lengthen due to bending. Brittle beds, such as limestones and sandstones, may elongate only by fracturing, resulting in increased permeabilities mainly on flanks where dips are greatest. Here, an arbitrary elongation of 3% is used, amounting to 159 ft/mi (30 m/km), a considerable amount of additional "space" in terms of porosity.**

unconformity surfaces beneath the salt thus are logical initiators of salt domes, and they are sufficiently pervasive in the sedimentary section to explain the apparently random nature of salt dome locations in the many salt basins of the world. A documented case of a salt dome occurring over a basement hill appears to be Upheaval dome in the Paradox basin of Utah (Mattox, 1965, 1968).

### "Regional" Unconformities

Whenever "angular rotation" or tilting of beds is observed beneath an unconformity surface in a sedimentary sequence, a "tectonic disturbance" at this time level is said to have occurred. If the angularity is observed only locally, then a "local" disturbance has occurred. However, we can observe the same angularity after a period of compactional folding in an area followed by erosion and truncation of compaction structures and deposition of horizontal beds over the tilted ones. Obviously, many angular unconformities observed by geologists are due to compaction. A careful application of compaction concepts by structural geologists could probably decrease the number of "disturbances" attributed to tectonic processes in sedimentary basins manyfold.

## BRIEF REVIEW OF TEXTBOOK LITERATURE PERTAINING TO COMPACTION STRUCTURES

This section briefly documents the finding that compaction as a cause of structure is a neglected concept. I continually meet qualified geologists, especially younger ones, who have never heard of compaction-induced structure. Most of those who do know and use the compaction concept are older geologists who have apparently learned it from experience or from other colleagues since leaving the university. Even these workers, however, seem to be unaware of the pervasive nature of compactional folding, which is understandable, as a review of the textbook literature reveals a general lack of knowledge of compaction-induced structures. My findings, from a review of petroleum and structural geology texts of the last 40 years, were as follows.

(1) Eleven pertinent textbooks make no mention of compaction as a cause of structure (de Sitter, 1956; Whitten, 1966; Ramsay, 1967; Ragan, 1973; Hobbs et al, 1976; Hunt, 1979; Park, 1983; Perrodon, 1983; Uemura and Mizutani, 1984; Suppe, 1985; Lowell, 1985). Some of these texts attempt to explain the dome and basin structures or plains-type folding resulting from compactional folding by horizontal compressive stress. For example, Hobbs et al (1976) stated: "It is not clear, however...[if] the domes and basins represent embryonic [compressional] folds that are just starting to be amplified in a more or less undeformed sheet."

(2) Fourteen textbooks make cursory mention of compaction as a cause of structure (one sentence to one page), some being more favorably disposed to it than others (Pettijohn, 1949; Landes, 1951; Dunbar and Rodgers, 1957; Lahee, 1961; Hills, 1963; Levorsen, 1967; Billings, 1972; Dennis, 1972; Spencer, 1977; Chapman, 1973; Link, 1982; Davis, 1984; Hyne, 1984; Selley, 1985).

(3) Four textbooks give the subject matter adequate treatment. Lalicker (1949) presented the most thorough discussion (20 pages) on compaction theory. Nevin's (1931) textbook, which persisted to a 4th edition in 1949, also gives a good exposition of the subject. Nevin was an original contributor to compaction theory with an important early paper (Nevin and Sherrill, 1929). Russell (1951) also discussed the compaction mechanism in detail, both over basement topography and over less compactible strata and unconformities within the sedimentary section. However, North (1985) is the only recent textbook author who makes more than a cursory mention of compaction as a cause of structure.

## IMPORTANCE OF COMPACTION CONCEPTS IN PETROLEUM EXPLORATION

If compaction-induced structure is indeed as common a phenomenon as the present study indicates, the implications are important. The lower parts of the sedimentary sections of all petroleum basins formed on cratons can be expected to contain hitherto unsuspected basement-caused compaction structures in abundance. Also, much poorly understood folding higher in the sedimentary section due to compaction over unconformity surfaces above basement will undoubtedly become more prospective.

New compaction structures probably will be found not only in the obvious "mature" areas of Oklahoma, Texas, Kansas, and other Mid-Continent states (areas not mature in terms of "bottom" geology), but also in areas of prolific production higher in the section such as the Hugoton basin, where a bottom-leasing program is already under way; in the Denver basin, where the deep Paleozoic play has recently started; in overthrust areas where the lower plate still lies on basement; in the Appalachians where structural closure has never been a major target; etc. Additionally, dozens of areas exist around the globe where targets so far have been mainly in Tertiary or Mesozoic rocks far above basement, and the underlying compactionally folded Paleozoic section has remained largely untested.

Gravity and magnetic methods, similar to those cited briefly herein, will become more important tools in this search, and the resolution of seismic methods will undoubtedly improve to meet the challenge. Paleogeomorphology will come into its own, and petroleum companies may be sending their geologists to seminars in hard-rock areas like Canada or Scandinavia to better understand Precambrian geology and geomorphology. Explorationists then can search for stratigraphic phenomena, such as the ever-present thinning over compaction structures, flank fracturing, and steeper dips over the flanks with depth. These phenomena will become better understood and, consequently, more important in the exploration process.

Because of the enormous importance of compaction phenomena in oil and gas exploration, the writer hereby formally proposes the name "gravicline" for compaction structures. The definition for gravicline would be a positive structure within the sedimentary section resulting from differential compaction of the sedimentary rocks due to a lateral change (i.e., anomaly) in compactibility. Basement hills, hills over higher unconformity surfaces, reefs, and other lateral lithologic changes within the section all represent lateral compactibility (compressibility) anomalies that give rise to graviclines as the section compacts from its own weight, the weight of overlying sediments, and water in a marine setting when an aquiclude is present. A paper is presently in preparation outlining a more complete nomenclature for the various categories of graviclines briefly discussed here.

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