The Anatomy of a Silent Disaster: Ongoing Subsidence and Inundation of the Northern Margin of the Gulf of Mexico Basin

An Interview with Dr. Roy Dokka

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Dr. Roy Dokka spoke at a joint meeting of the Houston Geological Society and Society of Professional Engineers in Houston, November 11, 2004 at the Petroleum Club in Houston. Dokka's message is simple and clear: much of southern Louisiana is likely to be inundated by Gulf of Mexico waters by the beginning of the next century, and Texas may not be far behind. The reason: tectonically-related subsidence and accompanying salt and shale movement in response to sediment loading. I interviewed Dr. Dokka following his presentation and a transcript of that discussion follows a summary of his talk.

If eustatic rise continues or increases and humans fail to build protection levees to appropriate heights, substantial portions of the Gulf Coast (primarily Louisiana) will lie below sea level and be inundated by the end of this century.

Diagnosis of the Problem

Coastal areas of the south-central United States are the site of America's greatest wetland, the gateway to America's energy heartland and home to over 10 million people. This area is being increasingly threatened by progressive inundation owing to the relative rise of Gulf of Mexico sea level. The landscape of the northern coast of the Gulf of Mexico is undergoing fundamental change. This change is most obvious in wetland areas of the modern Mississippi River delta. Storms seem to do more damage than they used to. Meanwhile, people living along the coast have noticed that

- areas that were once land or marsh are now open water.
- tropical storms now produce the damage and flooding of past hurricanes.
- coastal deterioration is ubiquitous.

The main observations and assumptions about coastal subsidence prior to Dokka's investigation included the following

- South Louisiana is deteriorating rapidly as a result of progressive inundation by the waters of the Gulf of Mexico.
- Louisiana lost more that 4000 square kilometers of its coast during the 20th century and continued loss constitutes a major threat to America's natural systems, related economic interests and energy security.
- Land loss is confined to wetlands. Causes include sediment compaction and consolidation, erosion, eustatic sea level rise, and the results of human's activities.

The idea that the load of the Mississippi Delta had an impact on subsidence was put forth back in the 1930s by Richard Russell. A model of flexural loading by the crust by the column of sediment deposited by the Mississippi River delta evolved and has dominated thinking about the nature and cause of subsidence in southern Louisiana (Figure 1).

Inundation has been linked to several causes including subsidence of the land, eustatic sea level rise, erosion and canal dredging (Figures 2 and 3). The lack of precise rates for these processes has prevented the development of a theory that can explain inundation. Subsidence, however, is suspected by most workers to be the dominant factor based on 1) the region's deltaic geologic setting and 2) the observed magnitude of subsidence implied by a few marine tide gauges along the coast (relative sea level rise minus the eustatic component).

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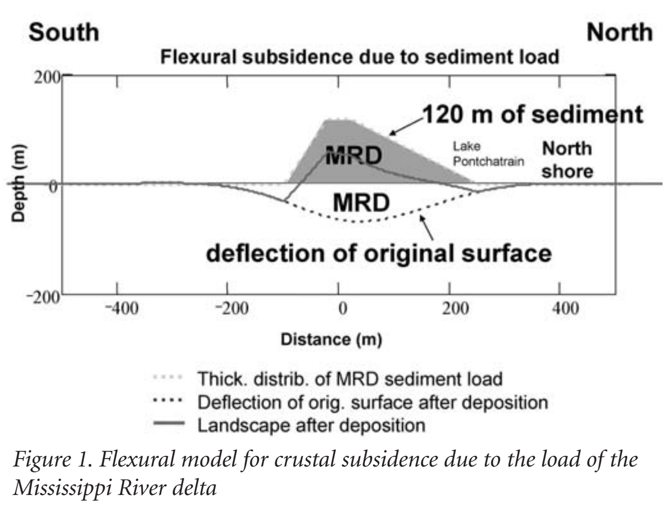

Figure 1. Flexural model for crustal subsidence due to the load of the Mississippi River delta

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The most obvious physical/biologic symptom of whatever is happening along the coast occurs in the wetlands. Healthy freshwater marsh has converted to open marine conditions. Therefore, it has been concluded that the problem also resides there. Virtually all research has been focused on wetlands studies.

Recent analysis by Louisiana State University (LSU) and the National Oceanic and Atmospheric Administration (NOAA)/ National Geodetic Survey (NGS) has determined that most areas bordering the Gulf of Mexico lack accurate vertical control to support infrastructure, public safety and future development. The Louisiana Spatial Reference Center at LSU undertook to determine new elevations, understand the causes and explain it to the public. First-order leveling data produced vertical velocities for over 2700 benchmarks in Louisiana, Mississippi, Alabama, Texas, Arkansas, Florida and Tennessee. Motions were related to the North American Vertical Datum of 1988 (NAVD88) and show that subsidence is not limited to coastal wetland areas but, rather, includes the entire coastal zone as well as areas several hundred kilometers inland (Figures 4, 5 and 6) .

Methodology

The methodology employed by Dokka and the LSU team tied first-order geodetic benchmarks to the Grand Isle tidal gauge (Figure 7). A benchmark reflects vertical changes to the center of the Earth. Because measurements are related to a spatially and temporally precise continent-wide datum, local and regional process effects can be recorded. The study used both deep- and shallow-set benchmarks; no significant difference was found in subsidence means between benchmark types. Benchmarks provide a superior measure of recent and near-future subsidence over all other methods because of the quality of datums available and the precision of measurements.

Benchmarks attached to rods (Figure 8) driven into the earth generally don't record the compaction component of subsidence. Subsidence at any benchmark is the product of regional and local causes. Changes in height of the benchmark reflect deeper processes such as faulting and crustal flexure. The total subsidence of the Earth's surface is the sum of both deep and shallow processes. Each benchmark tells a local and a regional story.

Faulting is intimately related to salt (and shale) migration. These passive processes are driven by gravitational instabilities created by differential sediment loading. Surface high-angle normal faults are generally related to detachment systems in the subsurface. Faults do not move continuously but instead surge for finite intervals of time. Small to moderate earthquakes are possible. Faults produce subsidence in two ways: 1) local subsidence near the fault by hanging wall displacement or hanging wall roll-over and 2) regional sagging caused by temporary reduction in elastic thickness of the lithosphere. When faults surge, high, broad subsidence occurs. When faults are dormant, the lithosphere is strong and without subsidence. Important fault movement has occurred during the last half of the 20th century in South Louisiana during what Dokka terms "the big easy Earth surge" (Figure 9). The big easy earth surge is similar to what some scientists call a "slow earthquake." This slow earthquake has lasted for more than 38 years.

Measurement of vertical motion of the Earth's surface requires two elements: 1) a measuring device precise enough to detect a change of height of the Earth's surface over an interval and 2) a datum. In the study, change was measured using first-order geodetic leveling methods, marine water level gauges, and Geographic Positioning System (GPS) Continuously Operating Reference Stations (CORS). The datum was NAVD88. If the day, month and year of leveling measurements is known, subsidence rates can be determined in terms of millimeters/year.

NOAA spent one-and-a-half years checking the results of the LSU study. NOAA checked predicted elevations

Figure 2. Inundation of coastal regions of southern Louisiana.

with GPS surveys done in 2003–4. Data successfully predicted the behavior of coastal water level gauges and successfully predicted behavior of CORS GPS stations. The rates are now the basis for elevation recalibration in Louisiana. These rates holdup to scrutiny while previous rates do not. Results are to be published in a NOAA technical report this February.

Conclusions

Regionally, vertical velocities of subsidence range from –30 mm/yr along the coast to over +5 mm/yr in eastern Mississippi-Alabama. The mean rate is ~11 mm/yr in coastal Louisiana. In the Mississippi River deltaic plain, subsidence was significantly higher than previous estimates based on long-term geologic

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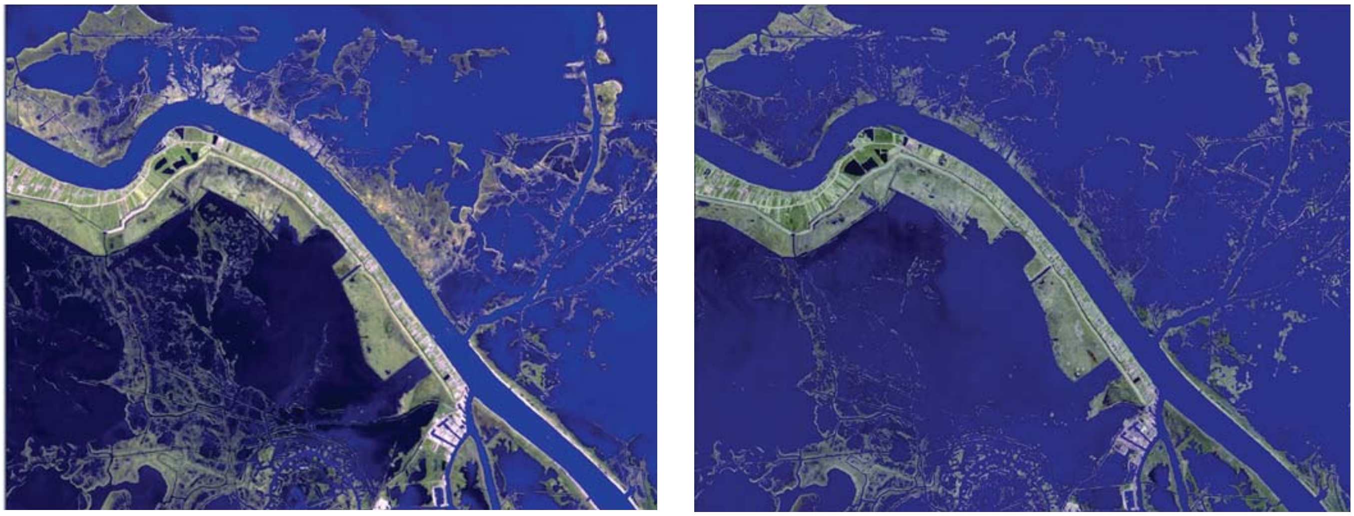

Venice, LA Landsat Image 1992 *Venice, LA Landsat Image 2002*

Figure 3. Inundation of coastal regions of southern Louisiana showing change from 1992 to 2002.

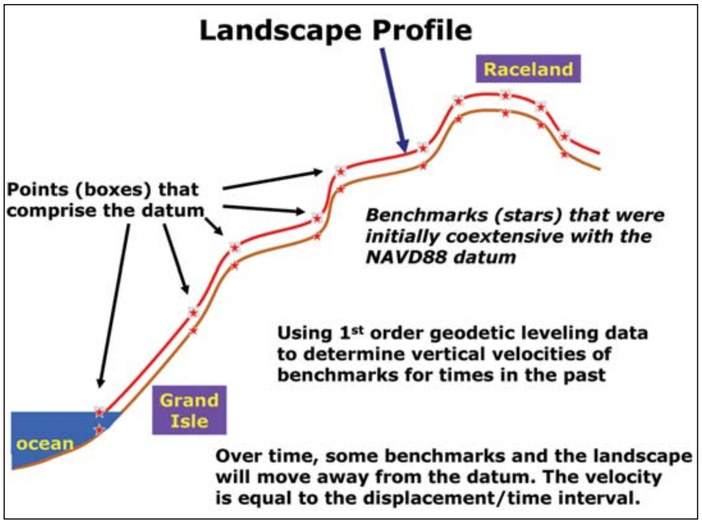

Figure 4. Landscape profile showing benchmark datum and displacement away from the datum over time.

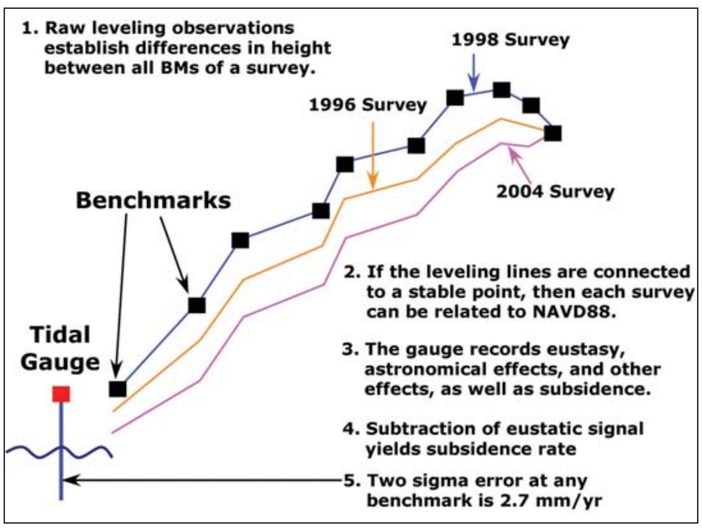

Figure 5. Leveling observations in southern Louisiana, 1996–2004.

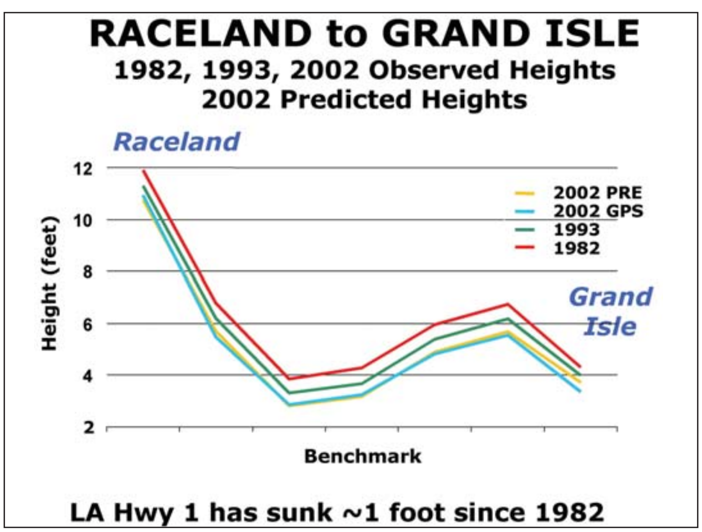

Figure 6. Observed and predicted elevation heights in southern Louisiana, 1982–2002.

measurements. Benchmark motions show that the entire coast, as well as peripheral areas, are affected. Rates are 200–5000% faster than predicted by other methods. Linear extrapolation of the rates imply that coastal areas unprotected by sea walls and that lie between zero and one meter above sea level will be inundated by the Gulf of Mexico by the end of the century. Dokka believes that subsidence rates are not generally linear and may have slowed somewhat over the past 10 years as faulting has slowed. However, it is expected that faulting and associated subsidence will again accelerate in coming years. The data also indicate that adjacent alluvial ridges where the population is concentrated have been similarly affected. In the chenier plain and Cajun prairie of southwestern Louisiana, areas previously thought to be only slowly sinking, are actually subsiding at rates similar to those of the deltaic plain.

These new data cannot be explained by the paradigm (Figure 10) that has guided thinking on mitigation strategies for the coast. That paradigm regards coastal change to be a problem wholly centered in the wetlands areas of the delta and alluvial valley of the Mississippi River and predicts that subsidence should occur only within that geographic region. Subsidence of the land has been viewed as a local effect associated with natural sediment compaction, oil/gas exploitation, canal building and other anthropomorphic causes. Benchmarks show that subsidence extends well beyond the limits of the delta and alluvial valley. Benchmarks are not generally located in the wetlands, but are instead located where people live.

Recognition that all areas of the coast as well as inland areas are sinking implies that subsidence recorded by benchmarks is not just due to local sedimentary processes and/or the activities of humans. Geodetic data, when combined with subsurface geologic information, suggest that subsidence includes a large tectonic component due to lithospheric flexure and normal faulting. Tectonic effects can be attributed to late Quaternary sediment loads such as the modern Mississippi River delta and Pleistocene deposits offshore. Previous models of simple flexure are inadequate, however, to explain the regional component of subsidence. It is proposed that active faulting in coastal areas influences regional subsidence by episodically weakening the lithosphere, which in turn changes the way that the lithosphere bears the load of sediments over time. Evidence also suggests that substantial subsidence in southwestern Louisiana is due to salt intrusion and evacuation induced by sediment loading (active mini-basin formation).

It is likely that the natural processes that have caused subsidence of benchmarks over the past 50 years will continue into

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the near future and at similar rates. Thus, if eustatic rise continues or increases and humans fail to build protection levees to appropriate heights, substantial portions of the Gulf Coast (primarily Louisiana) will lie below sea level and be inundated by end of this century. In Louisiana, this will result in a loss of ~$140 billion of land and property, as well as the jobs, homes and cultural heritage of over 2 million people.

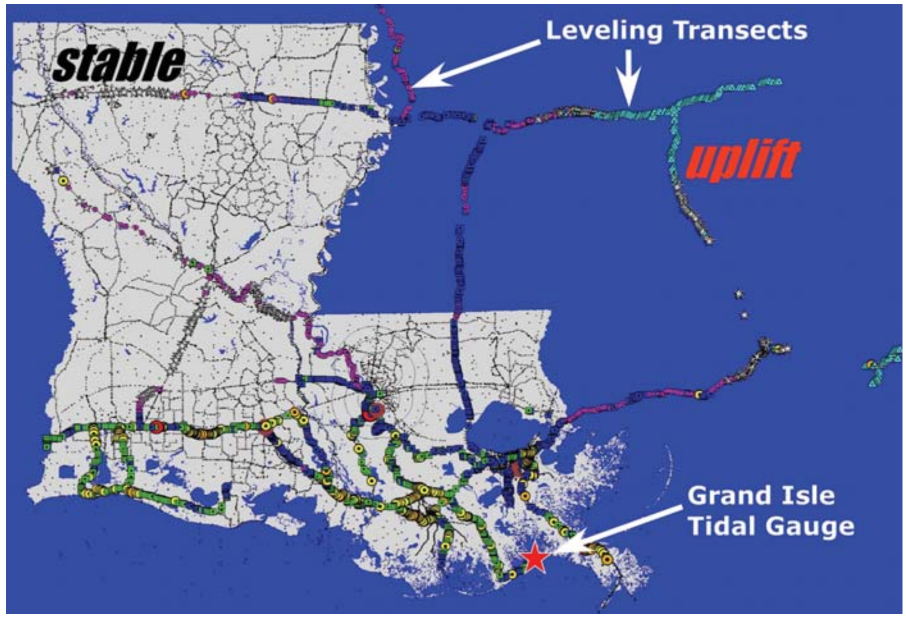

Figure 7. Geodetic leveling transects in Louisiana and adjacent areas.

The Interview

BULLETIN: How is it that we did not realize the rate and impact of the subsidence of South Louisiana? We've been aware of the problem for 60 years. How is it, from a scientific standpoint, that we simply thought that the issue was one of local subsidence around the Mississippi Delta?

ROY DOKKA: The idea that the load of the Mississippi Delta had an impact on subsidence was put forth back in the 1930s by a geographer at LSU, Richard Russell. At the time, he said, "In the end, it's all going to be about measurement."

Dr. Roy Dokka

Can you measure it? Somebody finally got around to dealing with the measurements and we've used data that's several decades old. We put it together, finally, and this is showing, at least in part, what Russell said: that sediment, that loading, is causing a deflection of the crust. He called it the Gulf Geosyncline.

Figure 8. A Benchmark attched to a 40-foot underground rod.

In the age of plate tectonics, we don't believe in geosynclines anymore, except that the Gulf of Mexico Basin is a geosyncline. It's really where the earth has yielded, allowing 60,000 feet of sediment to be deposited since the opening of the Gulf of Mexico back in the Jurassic.

BULLETIN: When the Corps of Engineers came in and did all of its monumental work, were they simply focused on a particular objective? In other words, preserving the city of New Orleans, or was there any comprehension of the fact that this was more of a regional issue?

ROY DOKKA: The Corps of Engineers has two objectives: one is navigation, keeping the Mississippi open for commerce. The other is flood protection. The tell-tale signs have been showing up over the years and the Corps of Engineers are actually some of the people that got the initial work funded because they knew that elevations were changing. And they also needed correct elevations to build their projects. So, it's not really reinventing the wheel, it's not that suddenly great discoveries are being made by us out of the blue but, rather, a number of things that have come together that has made it happen.

It also is leading to new understanding of how the system works. It's a very difficult physical/biological system that we're trying to understand here. You can't understand the Mississippi River Delta by just **The Anatomy of a Silent Disaster** *continued on page 41*

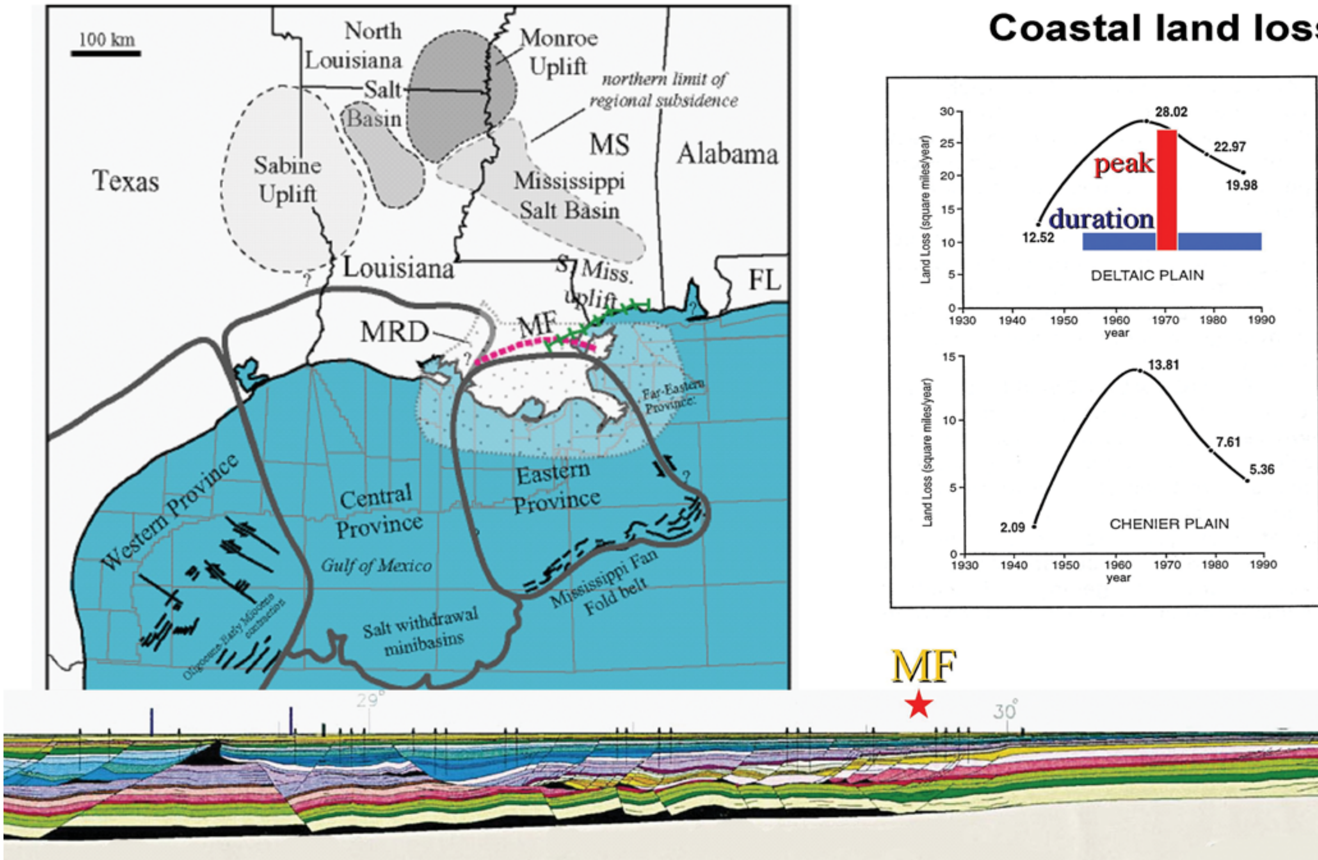

Figure 9. "Big Easy" Event occurred in the second half of the 20th century along a known subsurface fault (Michoud-Vermillion Bay fault).

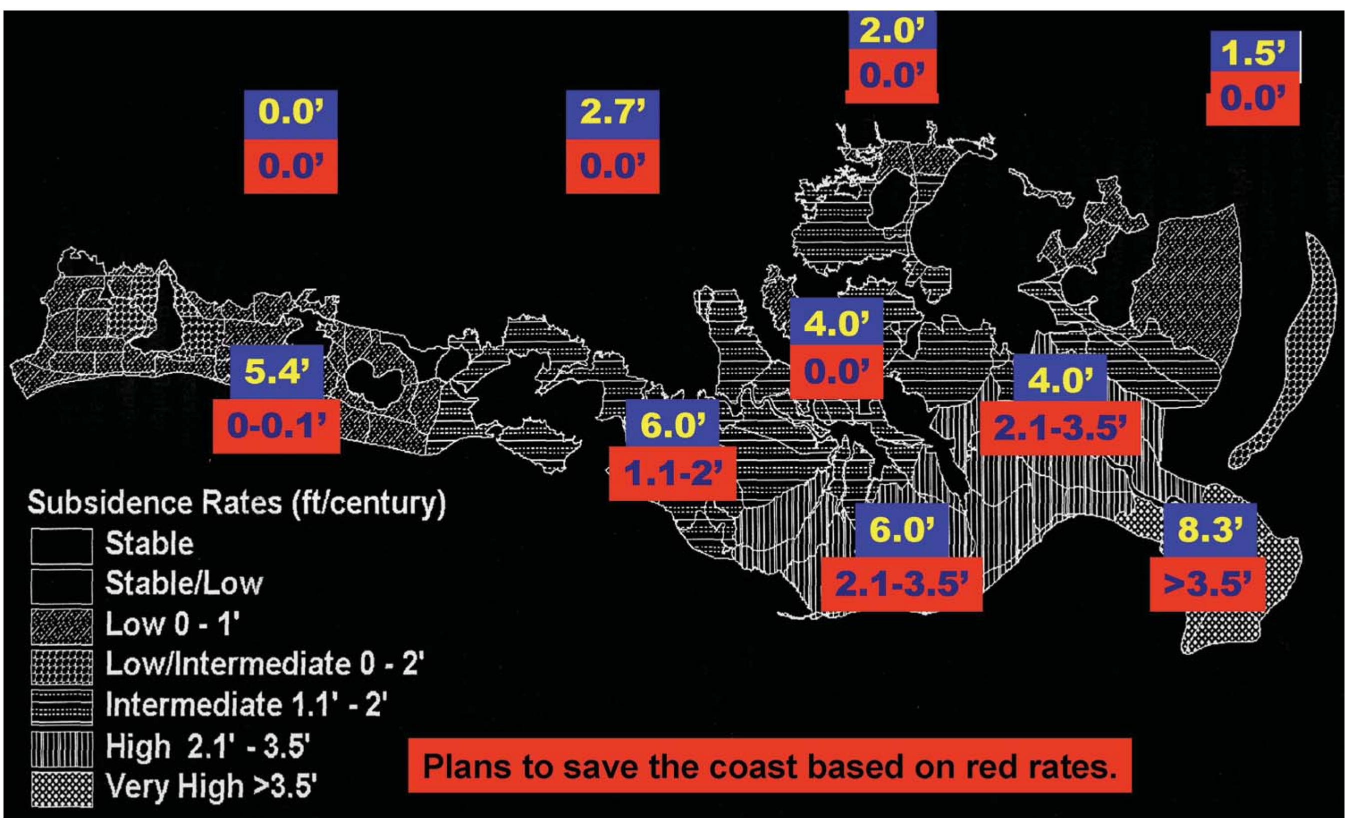

Figure 10. Benchmark data (in blue) do not support paradigm of low subsidence rates (in red).

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studying the biology. On the other hand, you'll never understand it if you just look at the geology. And, so, you really need to do both to be able to understand these complex systems, because they're inter-related.

BULLETIN: Is the issue really one of recognizing that, yes, there's subsidence, but that it extends beyond the area of the immediate problem? Is it the fact that you have all the measurements that's made the difference, or is there something more fundamental that the integration process has brought to bear on the analysis?

ROY DOKKA: The key thing is this concept of the datum. You've got to have something that you can reference your measurements against. What we have in our measurements is a very precise datum, the North American Vertical Datum of 1988. That allows us to understand how everything in South Louisiana is moving with respect to other parts of North America. If you are using many of the geological measurements that have been made have been based on sea level, sea level is a notoriously bad datum to use. Besides, how do you access sea level if you're in southern Mississippi making your measurements? You can't. So, you're restricted, spatially, to the coast and so, you only study the coast. You only get measurements from the coast; therefore, the problem is not defined properly.

Now we have measurements that can be related to Kansas and that are outside of the area of whatever's going on in the Gulf Coast. Now we're able now to see the regional component. That's what you can't see if your reference is local. You can't see the regional component and that's the part that people have been missing.

People have been able to assemble very nice pieces of the puzzle, except there were more pieces to the puzzle. Now, we've got more of them. Hopefully, it's enough to see what's going on in the bigger picture. But we have to continue to ask ourselves, What are we missing? Are we sure that we have everything? And I think you get into trouble if you basically stop and get complacent. We should constantly be asking ourselves, Do we really know what we're saying and how do we know? We need to make sure that we have other methods to test the concepts that we have developed. We need to be always looking for new ways of testing the models and that's what we've been able to do here.

BULLETIN: Explain to me, as a former land surveyor, how do you come off an elevation in Central Kansas? I mean, how do you carry that vertical datum, wherever it's established, into the area that you're actually studying? What's the physical process?

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Roy Dokka: What you need is a team of at least three—it's usually four—surveyors to start in Kansas at a benchmark where they know the elevation. Using very precise surveying equipment, they would then determine the height differences as they went along carrying this level line. They would then determine the height difference between that starting point and, ultimately, the end point in Louisiana.

When they got down to the end, they would turn around and carry the elevations all the way back to Kansas. The problem with that is that it's extremely expensive to do. Just in the state of Louisiana, it would cost something like $25 million to re-survey the state elevations. As we've seen with our numbers, some areas go out of calibration within a year. So, you'd have to do it again, and again and again. It's just prohibitively expensive to do.

They would start in Kansas. They would, perhaps, go to Pensacola and then from Pensacola to Galveston, and then from Galveston back up to Kansas again. The methodology really hasn't changed that much in 100 years. The precision is just incredible. It's just too expensive.

Bulletin: So, it's only done periodically. Is what you're saying?

Roy Dokka: It's not done any more.

Bulletin: Since 1988, that was the last time it was done?

Roy Dokka: The last place in South Louisiana that was done in that way was in 1993 and 1995 although, at LSU, I have a leveling crew with the most up-to-date equipment. It's like a bar-code reader that you see in the supermarket for scanning food items. That's what we use to measure height differences with an automatic geodetic level. But we're not going to Kansas. Instead we use GPS. We have a network of twenty-two GPS stations in Louisiana that provides us with a way of updating and maintaining our connection to the national data.

Bulletin: How far up the Mississippi do you have to go before you reach some point of relative stability? I saw in one of your slides there was a zero subsidence area, but it also had a label that said, "uplift," so I'm not really sure how much of that was compensatory.

Roy Dokka: What we found was that doing these measurements is kind of like eating peanuts. Once you start, you don't want to stop. Most of the data follows the Mississippi River. This was done in support of activities of the Corps of Engineers. We went up the Mississippi River and we continued to see subsidence.

It finally dawned on me what this is about. The Holocene load of the Mississippi River in the alluvial valley is enough to deflect the crust and produce the subsidence rates that we see, especially if there are some faults that occur along, effectively, the Mississippi Embayment. That's yet another part of our research that we're looking into. These things continue all the way to New Madrid (Missouri, epicenter of 1811 and 1812 earthquakes). All of our measurements go up to New Madrid, and they're showing subsidence. When you get to the other side of New Madrid, what you see is uplift. People studying GPS related this to post-glacial rebound associated with the ice sheets melting back at the end of the Holocene: the area is springing back up, the area to the south is subsiding. It sounds like you have everything you need to make an earthquake.

Bulletin: The history of the Mississippi Valley system goes back into the Precambrian as a failed rift arm. There wasn't a continent-draining river system then, not same magnitude of the modern Mississippi river until relatively recently, the Pliocene or Pleistocene—probably the Pleistocene. And then there's the salt. The special thing about the Gulf of Mexico is the layer of salt underneath that allows for particularly efficient gravity gliding. Now that you've looked at all this what's the piece that, to you, stands out and is maybe what people were missing?

Roy Dokka: Again, I go back to 1936 when Richard Russell identified the fact that the Mississippi Delta is a large enough sediment load to cause the earth to yield. It's in the process of adjusting itself, this concept of isostasy.

What strikes me is that people seem to have forgotten this. And, now, as someone coming into this after not spending a lot of time looking at the Gulf Coast, I'm wondering why did they stop, when Russell had it pretty much figured out? What happened? As I see it, there's not a lot of communication between people in the oil industry—and the Gulf of Mexico is the most studied geological terrain on Earth—and people who are trying to understand what is happening today (with subsidence in south Louisiana). There's not a lot of cross-pollination between the industry and coastal geologists over time.

Bulletin: As a person who lives in the Gulf Coast, I know that beaches that used to be here 15 years ago are gone now and the explanation generally given is long-shore erosion. But you would say that that's only part of the problem.

Roy Dokka: It's part of the problem, but in the end you have to ask yourself, What happens when a new data set shows up? What's it going to do to the paradigm? Well, a new data set has shown up. And now, we're examining the old paradigm in terms of whether it can be supported. And it can't. It can't be supported. However, that doesn't mean that this is the end-all. It means that what we need to do The Anatomy of a Silent Disaster continued on page 46

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is to see how we can integrate these new data with other insights and come up with a stronger, better, new paradigm to what's going on.

I think that what we're going to learn is that the things that are studied in the petroleum industry have tremendous implications for what's going on with subsidence in the Gulf of Mexico. Why should we expect things should be all that different, other than the fact that human beings have shown up? I think that human beings tend to think that maybe what we have had more affect than nature has, which is ridiculous. What we should do is understand what is likely to happen based on geologic models and we'll find that this is the history of the Gulf of Mexico. We're just beginning to understand that all of this is related, and that what we're seeing at the surface is undoubtedly also what is seen in seismic sections that people look at every day.

The modern is a hard thing to look at, because our measurements have time scales of just a few years. But with oil industry data, we're looking at the integration of processes that have occurred over at least a couple of million years. So in some ways, the recent and geologic time, they're apples and oranges, but they all fit together in the same plate of fruit, so to speak. In structural geology as, for instance, with earthquakes, we see all kinds of transient strains that occur. We see areas inflate before an earthquake and then, after the earthquake, they sink down.

The earth moves in all kinds of ways. In structural geology, it's all mechanics. If you want to understand something, it's about what we call the strain path. You have to understand how it got to be where it is. There's a million different ways to get from here to there. And that tells you what kinds of mechanics were involved. It's the same thing with sequence stratigraphy. You're looking at the end product. You don't know what was removed or preserved—unless you're very clever and it's very difficult to figure out. When was it taken away? How many amalgamation events have occurred? You're just stuck with the end product, the finite strain.

You don't see the increments of all the things that have happened. When we go to the beach, we see the waves come in and out, we see the sand go back and forth—how much of that is preserved? That's a question that geologists have always asked themselves. It takes very special circumstances for something to get preserved. The day-to-day is not necessarily what gets preserved. What I'm showing here is day-to-day. But will this ever get preserved? No. It'll never get preserved. You don't have datums to go back into time and you have to have precise datums. That is the advantage of working in the modern.

Our common friend Dag Nummedal started off working coastal process, because he wanted to see how the earth actually worked, at least at this particular time in history. Then, he went back and started looking at ancient rocks, because he now knows what is and what could be. It's the same thing in structural geology and drawing cross sections. If you don't know how a thrust belt works, you'll never be able to draw a cross section, because there are so many pieces that are going to be beyond your ability to observe, unless you have seismic data, for instance.

Bulletin: I think what you're saying, if I understand it, is that there's this interaction between data and a model. The model grows as the data modifies it but, without the model, we're all kind of babes in the woods starting over.

Roy Dokka: Yes. That's why we study mechanics, why we study the behavior of materials, so we can understand what could be. Usually we have to deal with the scraps of what nature's decided to leave behind. With a model, an idea of how things could be, and a concept of process, geologists can begin to reconstruct because, as Hutton said, "The present is the key to the past."

Well, that's very, very true, assuming that everything that's going on today that represents the range of all the things that were going on in the past. But, obviously, that's not always true, either. I don't recall seeing a huge asteroid coming down and smashing into the earth, but we see—hopefully we don't have to see that process—that that is something that has happened. That's why we're in geology, because it's a function of duration.

Bulletin: The farther back you go, the more likely you are to encounter things that you would not anticipate. But, to come back to a point that we discussed prior to your visit, how is it that this issue of salt movement, the interrelationship between salt movement and sediment loading, salt mechanics, the relationship between salt and fault movement—how is it that this, somehow, is still a little bit elusive? What's your analysis of that? What's missing here?

Roy Dokka: We have become more specialized in our training. I remember when I was a graduate student, I went to my first meeting of AAPG. It was held in Anaheim, California. And I remember going to this meeting, because I thought it was so neat that I could walk into any room and I could actually understand some of what these people were saying. As a student, that was the first time I'd heard things discussed that I had learned, actually in the real world.

When you go to a geological convention these days, you'd better be careful which doors you go into, because what is said behind some of them, you won't understand. It's gotten so specialized that I think we've suffered as a science, because we don't have that common knowledge that we used to have. On the other hand, we've learned a lot. You have to decide what you're going to spend your time on. If you're going to be a stratigrapher, or an oil finder, do you really spend a lot of time taking igneous petrology courses or trying to stay current on that as you go through your career?

As it turns out, salt is a fluid that moves. It's a passive fluid that moves according to the pressure gradients in the earth. Well, that sounds like plutons and volcanic rocks. They probably behave in a similar way. In fact, if the folks studying plutons would spend more time looking at the Gulf Coast, they would really gain some insights into mechanisms and how these fluids—low density fluids—work their way to higher levels in the crust.

I think the key thing here is that we've gotten too specialized and maybe what we need to do is to become more general in the future.

Bulletin: To carry that a little bit farther, we have a salt province in Louisiana and a shale province in Texas. We have the same Gulf of Mexico basin that's gliding away from the coastline. You haven't studied Texas yet but, what do you expect to find, other than maybe a slightly differential rate of movement?

Roy Dokka: People have already looked at many of these concepts in the Texas Gulf Coast in terms of trying to understand the architecture and the sedimentation. It's all about loading, it's all about the amount of sediment, it's all about sea level, it's all about detachments—you have salt, you have shale—and the rates of sediment loading. I think we begin to see how all of these things are completely related to one another and people have been trying to find these connections. What we're doing now is helping people to better understand the process. So, maybe someone sees something in one of my talks and says, "Hey, there might be something here. What if things work that way in the Miocene? Would I see things differently? Would it generate new ideas?"

My basic concept and driving principal in geology is that you only find what you look for. If you don't look, you're never going to find it. I mean, this is what oil exploration is all about. Unless you drill, the job's not done.

Bulletin: But how do you get somebody to drill? You need to have a new idea. You must have a model that allows familiar observations and results to be interpreted in some new way that gives you a reason to invest money to drill another well, right?

Roy Dokka: That's right and isn't that the history of the oil industry? It's about developing a compelling case to try something different. When people started looking at salt, when gravity meters were invented, suddenly here you had a new method of identifying where you might look for structures associated with salt.

Bulletin: That might have been the single-most successful period of low-risk exploration in the history of the planet.

Roy Dokka: That's right. But maybe there's something else out there. Maybe, if you look at it in just the right way, suddenly a new boom will start. It's just a matter of generating ideas that make sense and hopefully we'll develop some ideas here that people might be able to capitalize on. ■

Members on the Move

Mike Campbell was inducted as a Fellow in the GSA during the November annual meeting of the Geological Society of America in Denver, Colorado.

Mr. Campbell is licensed as a Professional Geoscientist and Geologist in the States of Texas, Wyoming, Mississippi, and Washington, licensed as a Professional Hydrogeologist in the State of Washington, and holds national professional certifications in geology and hydrogeology. He is a principal in M. D. Campbell and Associates in Houston.