

ROUND TABLE

Gravity gradiometry resurfaces

ROBIN E. BELL, ROGER ANDERSON AND LINCOLN PRATSON, Lamont-Doherty Earth Observatory, Palisades, New York

"The *Red October* was heading southwest on...Gorshkov's Railroad. His speed was thirteen knots.... Installed in the...keel was a highly sensitive device called a gradiometer, essentially two large lead weights separated by a space of one hundred yards. A laser-computer system measured the space between the weights down to a fraction of an angstrom. Distortion of that distance or lateral movement of the weights indicated variations in the local gravitational field....With careful use of gravimeters...he could plot the vessel's location to within a hundred meters...."

Twelve years ago, reading this passage from the submarine novel *The Hunt for Red October* by Tom Clancy was as close as any exploration geophysicist got to gravity gradiometry. This early technique in Gulf Coast exploration, which faded from use with the development of modern gravity instrumentation in the 1930s, had been relegated to brief historical sections of introductory texts. In the 1970s, driven by both navigation and missile launching requirements, the U.S. Navy spent hundreds of millions of dollars developing a system to measure gravity gradients; this system was somewhat more complex than the fictional one Clancy installed on the *Red October*. The end of the Cold War triggered the introduction of classified military technology to exploration geophysics and other fields. Three years ago the U.S. Navy began to explore civilian applications for submarine gravity gradient technology. This article describes gravity gradients, the developing uses of gravity gradiometry in exploration, and future possibilities for the technique.

The obvious starting point is to define gravity gradient measurements and explain how they differ

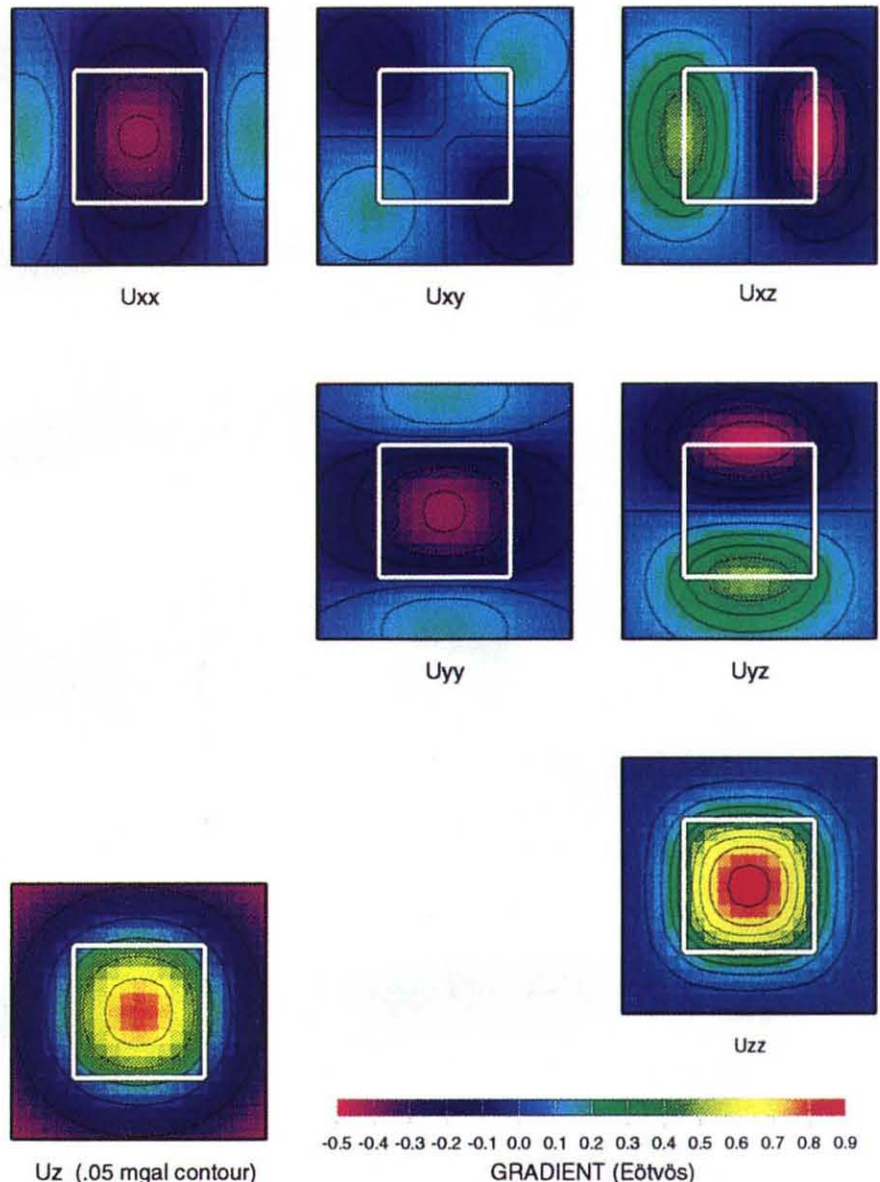


Figure 1. Standard Free Air Gravity Anomaly (lower left, U_z) and Gravity Gradients (U_{ij}) calculated over a simple cube shown by the white box. The free air anomaly is a diffuse circular structure centered over the cube. The gradients more closely define the edges of the box. For example, U_{xx} (upper left) highlights the north-south trending boundaries, while U_{yy} highlights the east-west boundaries. The U_{zz} anomaly (lower right) highlights all the edges. In the right hand column U_{xz} and U_{yz} contain the center of mass of the box. Finally, U_{xy} (center top) shows distinctive circular anomalies associated with corners.

from the marine and airborne gravity measurements used in exploration today.

Modern gravity measurements record the strength of the Earth's gravity field but are insensitive to edges of bodies and contain no directional information. In contrast gravity gradients directly recover sharp signals over the edges of structures (Figure 1). Thus the concept that gravity gradiometry is 3-D gravity. Gravity gradiometry anomalies reflect the edges and shapes of sources rather than just mass distribution.

For a simple positive density cube, a classic gravity measurement

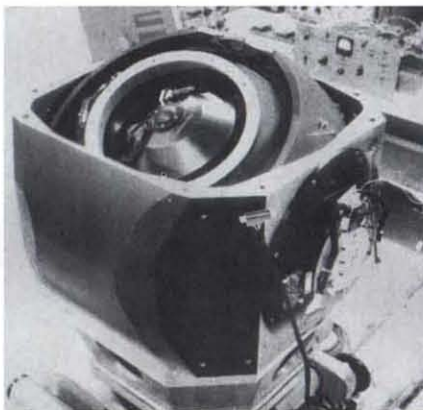


Figure 2. Modern rotating gravity gradiometer system developed for submarine applications and now employed for exploration.

would show a diffuse circular anomaly centered over the body (Figure 1). The six gravity gradients recovered from a gravity gradiometer provide a powerful tool for delineating the shape of the body. The gravity gradients are closely related to the edges, corners and center of mass of the causative body.

The unit for the familiar free air and Bouguer gravity field measurements is the milliGal (mGal), equivalent to 10^{-5} m/s^2 . Since gravity gradients are the spatial derivative of the gravity field, the units of gravity gradients are mGal over distance such as mGal/m. The standard unit of gravity gradiometry is the Eötvös (E) which is equal to $10^{-9}/\text{s}^2$ or a tenth of

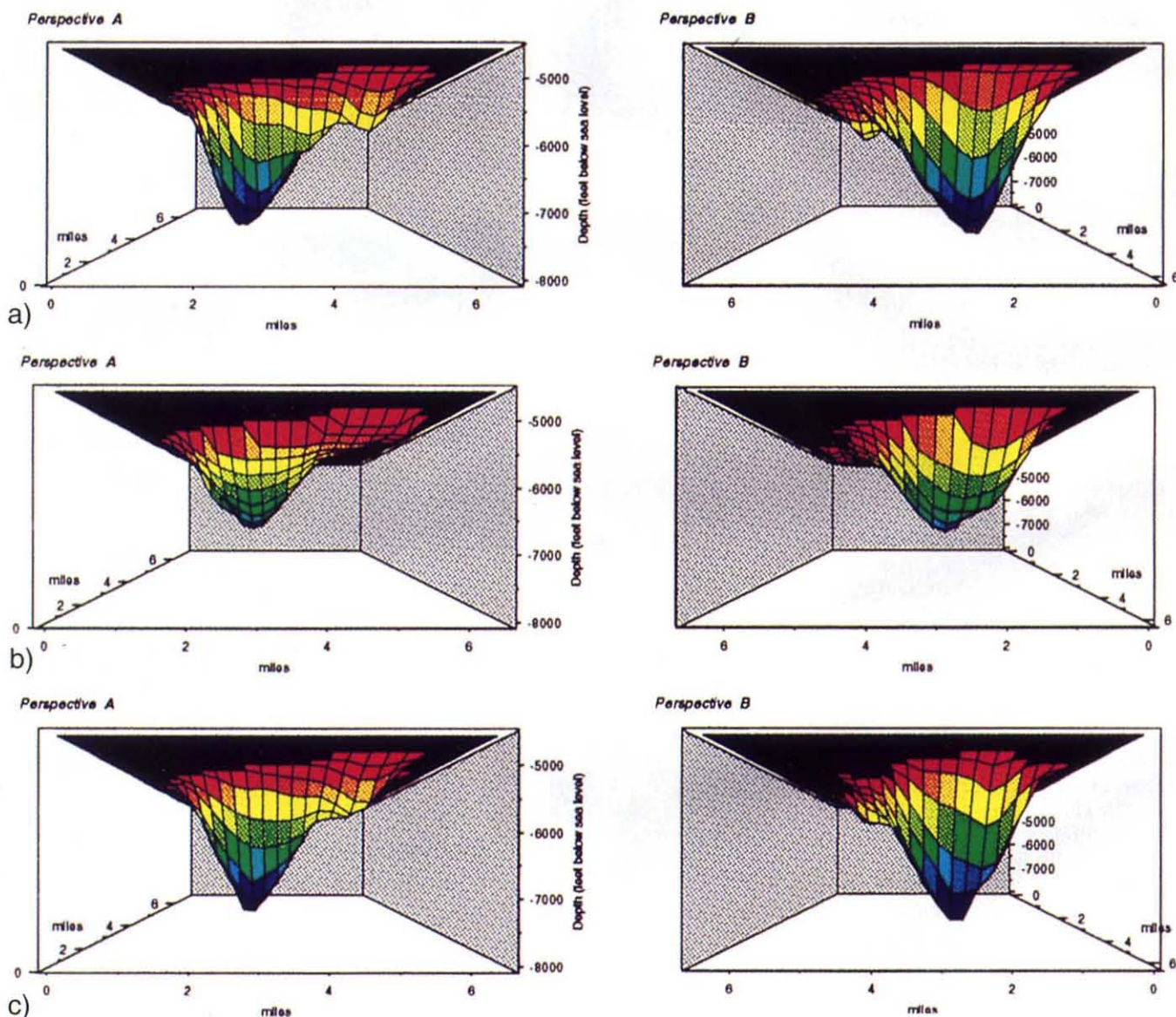


Figure 3. Inversions for a base of salt to illustrate improved recovery with gravity gradients. Two perspectives are shown for each image. (a) Target structure with steep sides and rough base. (b) Results of an inversion for base of salt using standard gravity measurements alone. Note the failure of the inversion to closely match the target structure. (c) Inversion with gravity gradients and standard gravity measurements. Note the improved recovery of the steep sides, the shallow subsalt roughness, and the maximum depth.

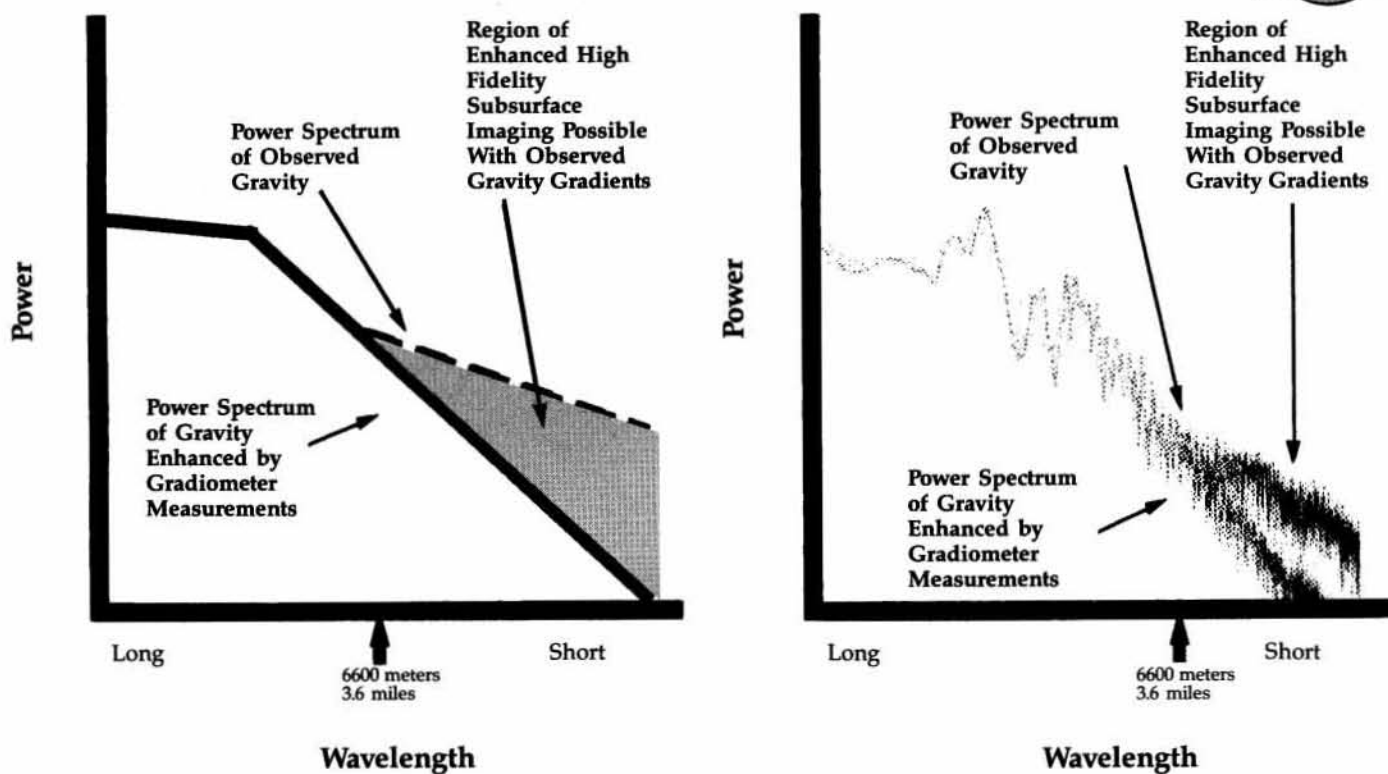


Figure 4. Power spectrum of standard marine gravity data and gravity data that has been enhanced with measured gravity gradients. Cartoon on left illustrates the flattening of the standard marine gravity power spectrum at 3.6 miles indicating a resolution floor. In contrast, the steep curve of the gradiometry enhanced curve reflects the improved resolution possible with gravity gradients. The actual power spectra are shown on the right.

a mGal over a kilometer. Geologically sourced gravity gradient signals are typically in the +/- 200 E range. The gradient signatures of shallow Texas salt domes are typically 50-100 E.

Historical use in the oil industry. Early in this century, gravity gradients were the first potential field measurements widely used in oil exploration. The torsion balance, essentially a gravity gradiometer, was initially developed to measure basic physical constants. This large instrument was mounted on a tripod assembly and recorded the gravity gradients with small weights at opposite ends of a bar suspended by a wire. These weights would rotate in response to the varying shape of the gravity field. In Europe the first geologic gradiometry efforts, in the upper Rhine Valley and northern Germany, led to the mapping of the Czechoslovakian Egbeil Oil Field in 1915. World War I delayed introduction of this technique to the U.S. until 1922. Amerada and Gulf imported gravity gradiometers in that year and

in 1924 Amerada identified the first salt structure with this technique in the U.S. Other salt domes and oil fields, including the Lovell Lake field in Jefferson County, Texas and the South Houston Oil Field, were initially identified with gravity gradiometry. When these salt domes were confirmed by drilling and seismic, the use of gravity gradients exploded. By 1935, 40 crews, recording 2-3 stations per day at a cost of \$100/station, were continuously acquiring gravity gradiometry data. The entire Los Angeles Basin, and parts of Texas, were mapped in detail. Measurements were generally good to +/- 1 E although possible sources of error included belt buckles, low hanging telephone wires, filled in cellar holes, and magnetic storms!

The drawbacks of gravity gradiometry were the difficulty of interpreting gravity gradients over complex structures and the great care and time required for an individual gradient observation. The heyday of land-based gravity gradients was brief. Their use declined in the 1930s as the reliability of much easier-to-

use gravity meters improved. These instruments could collect data 10 times faster than gravity gradients and they also produced a more easily interpretable data set. Few gravity gradient measurements have been acquired since the 1930s.

Stealth technology declassified. Three-dimensional gravity gradiometry is a "stealth" technology developed by Bell Aerospace for the U.S. Navy Trident submarine program. The gravity gradiometer (Figure 2) consists of 12 separate gravimeters measuring the differences in earth's gravity over a distance of 1 m as the meters tumble in a "binnacle." The result is an accurate measurement of gravity, and the full tensor of the gravity field or the 3-D changes in gravity with direction. Therefore, this technology offers the possibility of imaging density contrasts beneath salt to much higher resolution and accuracy than previously possible. Present accuracy estimates of this system based on measurement programs in the Gulf of Mexico suggest gradient accuracies of 0.5 E over 1 km,

ROUND TABLE

roughly equivalent to 0.05 mGal/km.

A company has been licensed to make the Navy's now declassified 3-D gravity gradiometry system available to the deepwater oil industry. Bell Geospace has already conducted three seasons of gravity gradiometry surveying in the deepwater Gulf of Mexico aboard U.S. Navy vessels, and a program to acquire data far onto the salt canopy is being developed. In collaboration with eight major oil companies which hold substantial positions in the area, Bell has acquired gravity gradiometry over most of the deepwater discoveries to date. Fields surveyed include Brutus, Bullwinkle, Diana, Fuji, Gemini, Jolliet, Luna, Marquette, Mars, Mickey, Popeye, Ram-Powell, and Vancouver.

How to find oil and gas with gravity gradients. Since this technology was abandoned over 60 years ago, why do some think it can help today's exploration industry?

The answer is there is a difference between what can be accurately imaged with standard gravity and gravity gradients. This can be illustrated by examining inversion results and by looking at the power spectrum of standard marine gravity and gravity which has been enhanced by gravity gradients.

An obvious goal of gravity gradients is improved imaging of the base of salt. In this example we constructed a synthetic base of salt which contains features difficult to image seismically, both steep slopes and a rough base, in the shallow section (Figure 3). The goal is to illustrate the result of inverting for the base of salt. When only standard gravity is used, the result is a structure which does not recover the steep sides, the shallow roughness or the maximum depth of the salt body. When the gravity gradients are included in the inversion, the steep sides are recovered, the maximum depth is much closer to reality, and the detailed roughness is well approximated.

Figure 4 compares the power spectrum of standard gravity and one which has been enhanced with gravity gradients. The power spectrum for the standard gravity begins to flatten at about three km, indicating a resolution floor in the data.

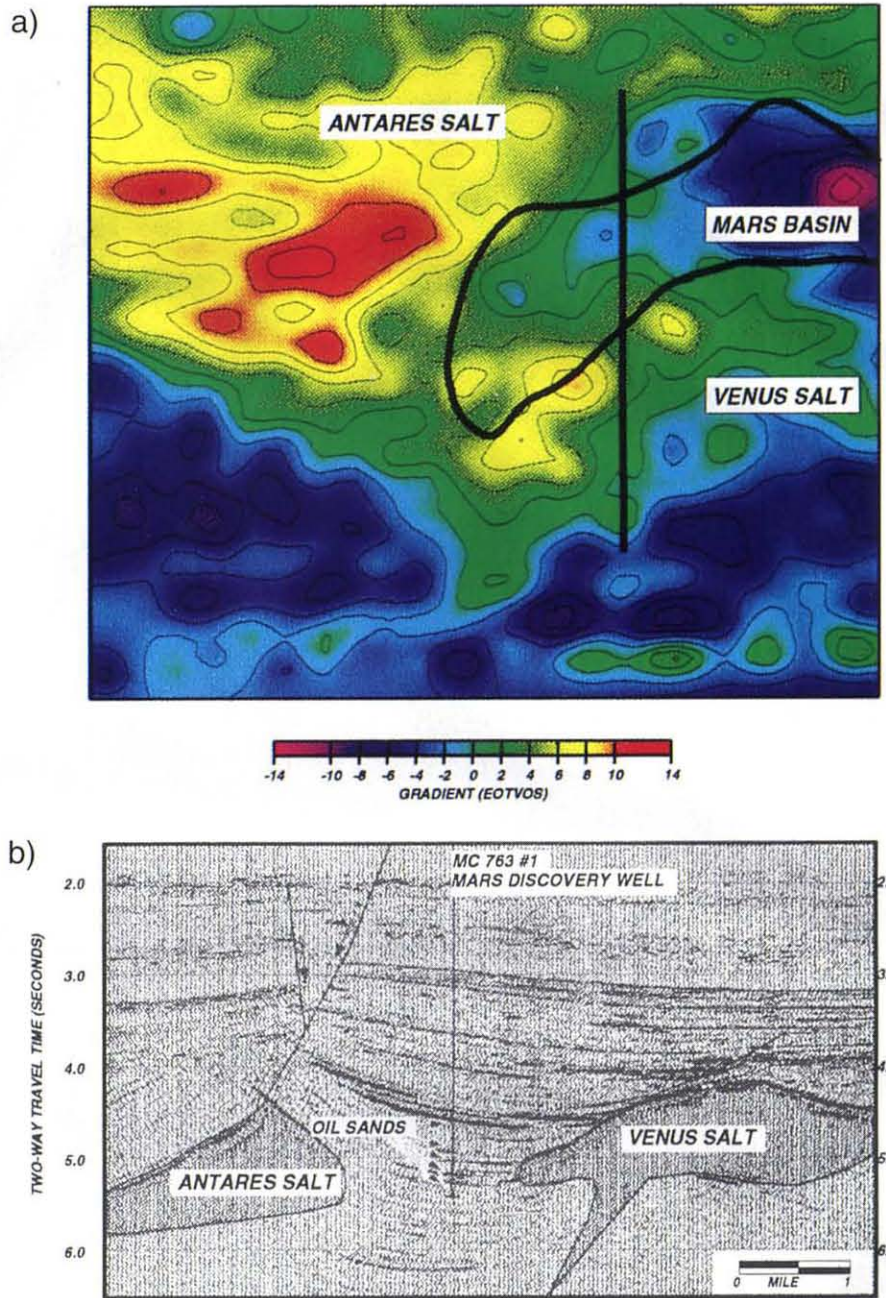


Figure 5. (a) Easting gravity gradient (U_{xz}) over the Mars Basin, Mississippi Canyon region. Gradients outline the basin and the boundaries with surrounding salt. The gradients may also reflect the oil-water contact. **(b)** Seismic profile across the Mars Basin, shown in 5a.

The integration of gravity gradiometry measurements into standard gravity measurements significantly changes the power spectrum slope, indicating improved resolution of small features. The steepness of the power spectrum below three km suggests that the gravity gradients significantly improve the capability of gravity to constrain the location of structures.

Finally gradients may have a "time lapse" monitoring capability.

Consider the gravity gradiometry results around the Mars fields, for example. The "easting" tensor, or the difference in gravity measured by two gravimeters when lined up exactly in the east-west orientation, shows the boundary of the Mars basin with its sediments lapping onto the Antares (to the north) and Venus (to the south) salt canopies (Figure 5). In addition, there is an interesting density boundary, or observed downdip, in the center of



the basin itself, that, coincidentally or otherwise, corresponds in general location to the seismic oil/water contact. It will remain for new surveys to establish whether the density contrast from the drainage of oil from this basin will be large enough to allow repeated gravity gradiometry surveys to track the movement of hydrocarbons as production proceeds

Airborne gradiometry. Interest in airborne gravity gradiometry is intense because such a system would be inherently less sensitive to the positioning errors which plague current airborne gravity measurements. Such a system would enhance the use of gravity for reconnaissance purposes, specifically over inaccessible areas such as jungles and mountainous regions. The mining industry is keenly interested in such a system; several groups have supported development efforts over the last decade. An Australian group, lead by Frank Van Kann of the University of Western Australia, is using "scissoring beams in a superconducting environment" and is targeting airborne trials within two years. In addition, Russian scientist Alexey Veryaskin from Moscow University is developing a vibrating string instrument placed in a superconducting environment, with a basic sensor similar to the MIT Vibrating String gravimeter developed in the 1960s. This effort, now being coordinated from New Zealand, is targeting an airborne system in the next two years.

Bell Geospace plans to implement an airborne system in two years based on the technology now used for shipboard measurements. This system has been flown, but only in an experiment: a gravity gradiometer was installed inside a Winnebago which was driven aboard a Lockheed C-130. Other airborne gravity gradiometry systems are also under development.

Clearly this technology is rapidly developing. The race for the skies is on. The next two years should prove very interesting. Hopefully industry will develop this technology before Clancy spins it into yet another novel. ■