special report

on gravity surveys

In Gravity's Pull

Petroleum Industry Benefits From Renaissance Of Gravity Methods

In the foothills of North and South America, the thrusted geological strata sometimes dip so steeply that seismic data cannot adequately image the exact location of subsurface structures containing oil and gas. And, in the offshore regions of the Gulf of Mexico, significant undiscovered natural gas reserves lie, undetected, below seismically impenetrable beds of salt. In both cases, the seismic exploration method is pushed to the limits of its resolution as it attempts to image complex geological environments and structural geometries.

In what is being hailed as a renaissance of geophysical exploration methods, oil and gas geophysicists are returning to their roots, employing potential field methods that include gravity and magnetic surveys into their workflows. Airborne, marine and land gravity methods are being used to explore for hydrocarbons at the regional, prospect and reservoir levels.

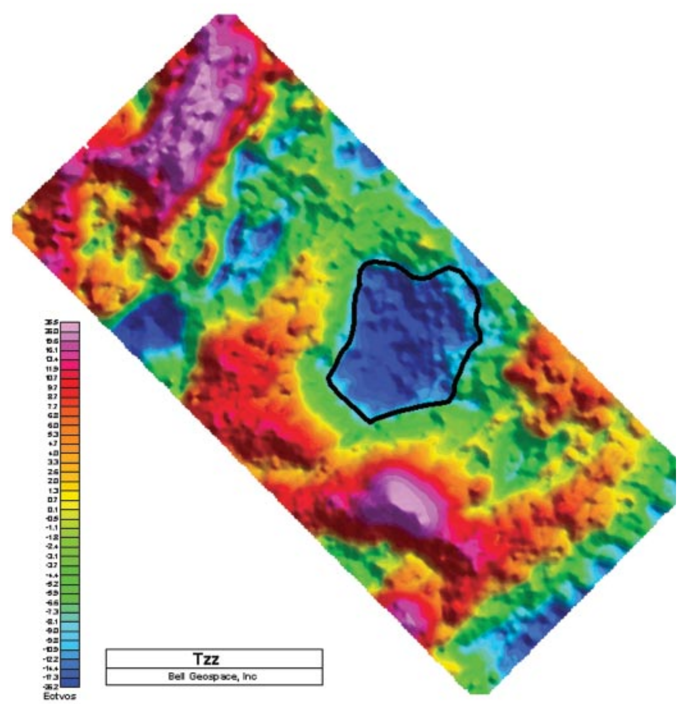
During the past five years, exploration geophysicists have recognized the benefits of using co-located data — seismic, gravity and magnetic acquired along the same transects — to build "Earth models" that incorporate lateral changes in rock density and magnetic mineral content in subsurface beds. Using co-located data to test play concepts, geophysicists can discriminate between different interpretations of the same seismic data set.

Is that dipping bed composed of salt, volcanic rock or limestone?

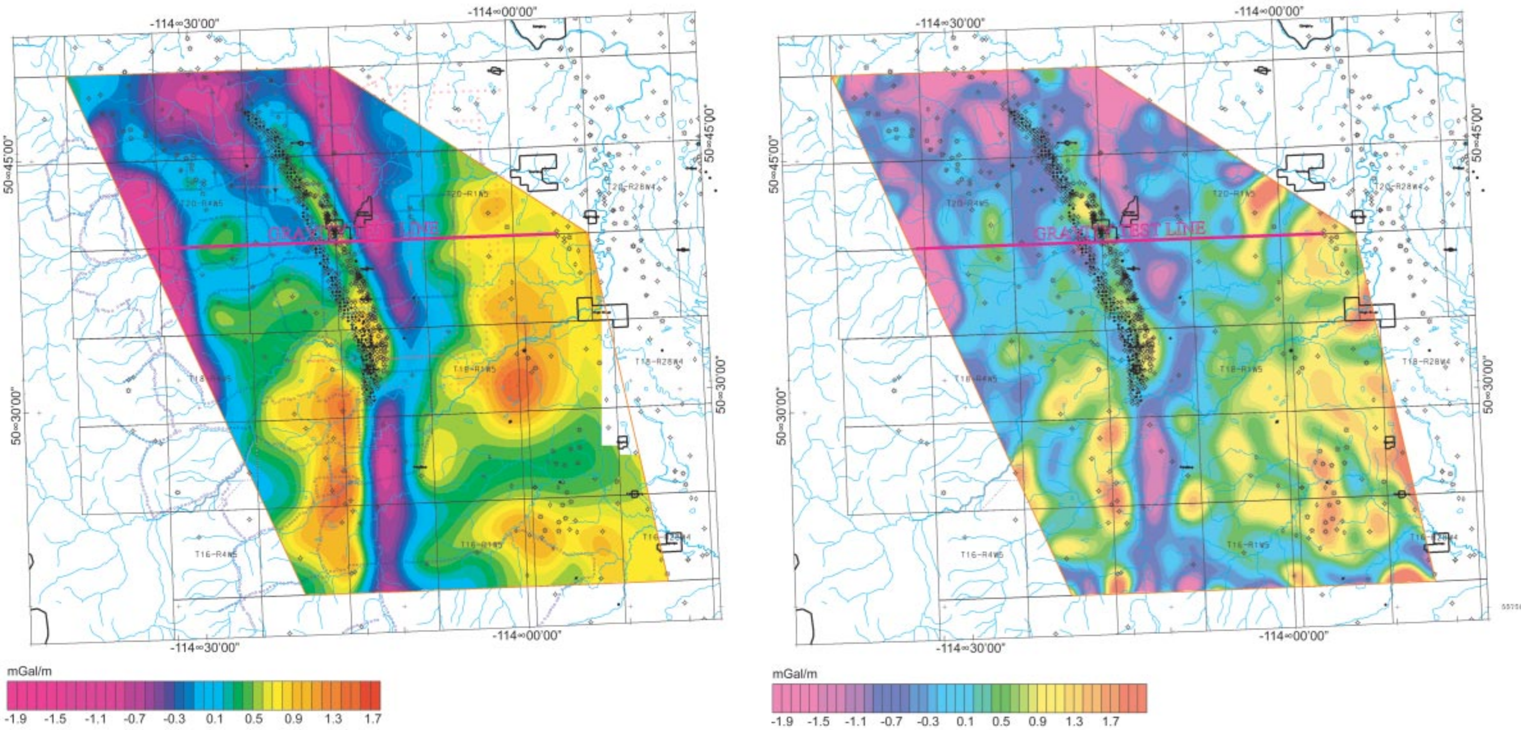
"Eliminate what you know," advises Scott Hammond, president and chief operating officer of Houston-based Bell Geospace, Inc., a key player in the new generation of airborne and marine gravity survey technologies. "You'll never get your velocities right if you don't get your shallow layers right; the seismic ray paths just go crazy when you hit vertical or steeply dipping beds."

Bob Charters is a geophysicist with Calgary-based GEDCO (Geophysical Exploration & Development Corporation). Charters describes a recent interpretation project in the foothills of Colombia, South America, where high dips and high velocity contrasts caused a "wipe out zone" in the seismic data. "Gravity worked really well in filling in the interpretation through the wipe out zone," he explains.

Historically, the oil and gas industry viewed gravity suspiciously, classifying it in the category of an ambiguous — even mysterious — black box. Used extensively in the mining industry since the 1970s, airborne gravity technologies have advanced rapidly during the past decade due to the advent of onboard differential digital GPS (global positioning satellite) navigation. Equally important has been the development of onboard laser survey instruments, enabling the



GRAVITY'S UPS AND DOWNS
A marine gravity gradiometer survey located west of Britain in the Faroes Shetland Basin, acquired in 1999 and measuring approximately 120 x 50 square kilometres. Tzz gradient data measures up-down changes in up-down gravity. Tzz represents the difference between the near and far response. It highlights all edges and is the easiest gradient to interpret directly. The geologic structure circled represents a gravity low and is interpreted to be a sediment-filled basin. Image source: Bell Geospace, Inc.



FILLING IN THE GAPS

First Vertical Derivative (1VD) of complete Bouger Gravity at Turner Valley, Alberta. The left image is the 1VD of the ground gravity data. The right image is the 1VD of the airborne gravity survey. Most of the differences in these maps reflect the additional detail derived from the uniform sampling of the airborne gravity survey. Source: GEDCO (Geophysical Exploration & Development Corporation).

acquisition of digital terrain models along flight paths that image the Earth's surface topography on the scale of centimetres. Because topographic variations exert significant gravitational effects, they must be removed during data processing.

Differential digital GPS navigation enables the calculation and removal of aircraft inertial acceleration that affects gravity measurements. "When you collect airborne gravity, you're effectively collecting acceleration gravity of the plane," explains Terry McConnell, vice-president and general manager of Montreal-based Fugro Airborne Surveys Quebec Limited. Air turbulence, fuel draw down, and the ground speed and altitude of the aircraft must all be factored into gravity data processing. Some programs are flown at night to avoid air turbulence.

Air turbulence from gusty chinook winds — as they race across the foothills of southern Alberta — creates a significant challenge for airborne gravity surveys. During the summer of 2001, however, Sander Geophysical Limited (SGL) of Ottawa flew its in-house AIRGrav system in a "severe foothills environment" to map subsurface thrust belt geometries of the Turner Valley field and the adjacent Highwood structure. SGL has also flown a program at Butler Ridge, northeastern British Columbia, where AIRGrav is being used to resolve structures associated with a Debolt carbonate play.

The AIRGrav system (Airborne Inertially Referenced Gravimeter) comprises three orthogonal accelerometers mounted on a three-axis, gyro-stabilized platform. According to Stephan Sander, co-president of SGL, the system is more stable in attitude and therefore less subject to noise from horizontal aircraft accelerations. Sander says airborne acquisition costs range from between $40 to $60 (U.S.) per linear kilometre.

At Turner Valley, 12 500 linear kilometres of combined gravity and magnetometer data were acquired in less than five weeks. Flown at an acquisition speed of 100 knots, the Cessna 208B Grand Caravan aircraft flew a drape program, averaging 500 metres of ground clearance over the Turner Valley structure. Aircraft flying gravity surveys are generally equipped with magnetometers mounted in tail stingers extending from the rear of the aircraft. The survey was flown east-west at a tight line spacing of 250 metres, with a north-south control line every 1,000 metres. In contrast, the pre-existing ground-based gravity coverage consisted of an irregular grid with gaps on the order of 10 kilometres.

Gravity methods measure lateral changes in rock density, while magnetic methods measure lateral changes in the magnetic susceptibility (magnetic mineral content) of rocks and sediments. The typical density of a carbonate (limestone or dolomite) is 2.7 grams per cubic centimetre (g/cc), while clastic (sandstone/siltstone) rocks are 2.5 g/cc, and salt is 2.16 to 2.2 g/cc. Because the seismic method measures changes in acoustic impedance — the product of velocity and density — geophysicists need to be able to quantify variations in rock densities.

The Turner Valley field represents a good candidate for an airborne gravity meter survey: the carbonate reservoir produces at about 1 500

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ON THE FLY

One of SGL's (Sander Geophysics Ltd.) Cessna 208B Grand Caravan planes configured for a combined gravity and magnetic survey. The gravimeter is mounted inside the aircraft's cabin, while the magnetometer is mounted in the stinger extending from the rear of the aircraft (photo courtesy of Mike Reyno).

metres in the subsurface. The density contrast of 0.2 g/cc between the clastic rocks above and the carbonate sheet is sufficient to generate a gravity signal to map the subsurface thrust structures. Previous mapping — using ground-based gravity data — illustrated the thrust structures in a gross sense. Finally, the existence of abundant seismic lines and wells within the survey area enabled calibration or "ground truthing" of the gravity and magnetic data.

"Fundamentally, you need a density contrast associated with your economic rocks," says Charters, who interpreted the Turner Valley survey. "If you can't see that density contrast on the ground, you won't see it in the air."

Because the spatial resolution of a gravity meter survey largely depends upon the flight line spacing, the Turner Valley program was flown in a tight grid, increasing the signal to noise ratio with repeated sampling of the gravity field at the frequencies of interest. "Noise is line dependent," explained Carter. "You're going to suppress the noise because you've got more data."

Calgary-based Talisman Energy Inc. participated in the Turner Valley program to test the AIRGrav technology. Wayne Abraham, Talisman's exploration geophysicist, admits that this was his first real exposure to airborne gravity as an exploration tool. "I'm pleased with the results," he says. "There's good correlation with the air gravity and the existing ground gravity." However, mapping with the AIRGrav data revealed far more complex details of thrust geometries, including delineating the lateral transition from the Turner Valley to Highwood thrust structures.

With respect to Foothills exploration, Abraham views gravity data as a more regional tool, saying, "I feel that we're within a 1 000 metres of being able to detect the carbonate thrust edge." He adds, "I do think that there's value in using gravity to determine where you'll locate your seismic lines."

In environmentally sensitive areas — where ground access for seismic is limited — airborne gravity and magnetic surveys reduce the environmental footprint of front-end exploration activities. Airborne potential field methods are ideally suited to hard-to-access areas such as dense jungles, rugged foothills, mountains and coastal transition zones between land and ocean. ntm **— Susan Eaton**

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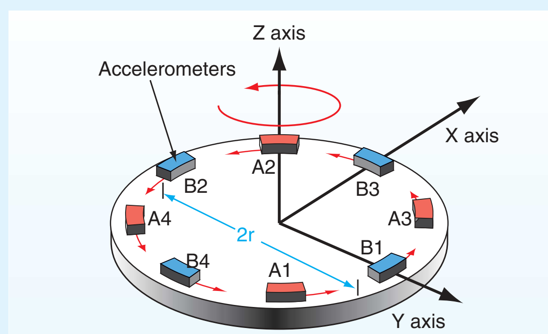
Gradiometers versus Gravity Meters

In 1994, the U.S. government declassified its moving platform gradiometer, an instrument that was designed to measure spatial rates of change (or gradients) in the Earth's gravity field. Developed by the U.S. government and Lockheed Martin Federal Systems as a stealth navigation system for Trident class nuclear-powered submarines, the gradiometer has made a smooth transition from defence applications to land, marine and airborne exploration for subsurface accumulations of petroleum and minerals.

Weighing in at 1,000 pounds and costing several millions of dollars apiece, the Lockheed Martin gradiometer is mounted on the most stable part of the aircraft's interior. The instrument can detect rates of change in the order of one trillionth of the force of gravity.

"I think that it's mind boggling," says Manik Talwani, a geophysics professor who specializes in oil and gas exploration. "It's kind of hard to visualize this thing, but it works." Talwani holds the Schlumberger Chair of Advanced Studies and Research at Rice University in Houston.

Because Lockheed gradiometers measure spatial rates of change in the Earth's gravity field, they are sensitive to shorter wavelengths than gravity meters. Gradiometers therefore excel at measuring gravity responses from shallower, higher frequency geological structures — on the scale of hundreds of metres. In contrast, gravity meters (also called gravimeters) measure the Earth's total gravity field.



Note the four accelerometers, A1, A2, A3 and A4. Opposing pairs of gradiometers (for example, A1 and A2) are mounted on a horizontal disc that rotates. Another set of accelerometers called the "B" set simply doubles the measured gradients.

Gravimeters have been traditionally used to map structural and stratigraphic features in sedimentary basins on the scale of a couple of kilometres.

Accordingly, gradiometers and gravimeters occupy different niches with respect to oil and gas exploration. Both technologies are dependent upon the size of the body and the depth that it's buried, and how far away the aircraft is from the body. The farther you get away from the target, the weaker the signal-to-noise ratio. "What is the wavelength of the actual data of the geological structures that you want to image?" asks McConnell. "What is it that you are actually recording?" Two very good questions indeed.

"Gradiometer data is not as straight forward as gravimeter data," explains Talwani. "With gravimeter data, if you have a dense body in the subsurface, you have a gravity high over it. But with the various gradients measuring in various directions (tensors)," he explains, "you have to do some fancy math; you have to invert five independent components in repeated forward modelling."

The resolution of gravimeter anomalies hinges on the capability of distinguishing or separating two features that are closely spaced. Gravity is measured in milliGals (mGal) at the shortest resolvable signal wavelength, which is measured in kilometres. A gravity signal wavelength is defined as half of the sine wave distance ($^1/_2$ wavelength). At the Turner Valley survey, for example, the dominant signal wavelength of 5 300 metres enabled the resolution of individual structures on the order of 2 650 metres.

Talwani is interested in gradiometers because they are "drift free," making them ideal for conducting time-lapse or four-dimensional studies, the fourth dimension being time. In late April, Talwani's first gradiometer project was flown to map density contrasts across the San Andreas Fault in California. The 10-square-kilometre survey — designed to investigate the low density fault zone that extends down a few kilometres from the surface — will be integrated with the results from a 3 000 metre deviated well recently drilled through the San Andreas Fault. Sponsored by U.S. National Science Foundation and several oil and gas companies, the joint gradiometer and drilling project is being run under the banner of the International Intercontinental Drilling Project. The airborne gravity survey will establish a baseline data set for the area, setting up the possibility for repeat passes that may yield new insights on how the fault is propagating with time.

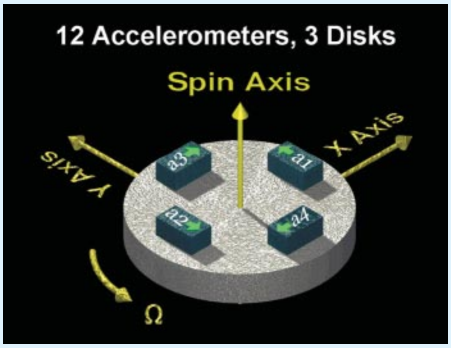
Heralded as the next generation of gravity instrumentation, the Lockheed Martin gradiometer records one vertical and two horizontal vectors. Each vector is comprised of three tensors. When the gradiometer — consisting of four pairs of opposing accelerometers mounted on a rotating disc — is attached to a moving platform (the aircraft), linear inertial accelerations of the platform are cancelled out. The gravity gradient measured in the plane of the disc represents the difference between values measured by two opposing accelerometers.

"Gravity gradients are what will allow us to make a quantum leap forward," says Fugro's McConnell. Fugro is contracted by BHP Billiton Ltd. to fly its proprietary FALCON gravity gradiometer. BHP Billiton's proprietary gradiometer was modified in the 1990s from the Lockheed Martin instrument, and measures the Earth's vertical gravity vector (the z direction with three tensors). Fugro also flies airborne gravity surveys using the tried and true Lacoste & Romberg gravimeters.

FALCON, the world's first airborne gradiometer, commenced commercial production in 1999 after a 10-year R&D project and a $30 million (U.S.) investment by BHP Billiton and Lockheed Martin.

"The carrot on the stick for BHP Billiton," says McConnell, "was using gradiometers to see mineral deposits on the scale of hundreds of metres."

Alan Carter is the manager of business development for BHP Billiton World Exploration Inc. According to Carter, the FALCON system has been successfully used in Canada's Northwest Territories to detect shallow kimberlite pipes — unique rocks that often contain diamonds — measuring only 60 metres in diameter.



Bell Geospace's 3-D FTG system consists of three gravity gradiometer instruments (GGIs). Internal to each GGI is a rotating disk with four accelerometers. The opposing pairs of matched accelerometers are mounted 10 cm apart. The disk rotates at a commanded rate, usually 0.5 Hz. Data is sampled at 128 Hz.

"Airborne gradiometry does have significant applications for oil and gas," says Carter. "In theory, we should be able to see reef complexes with good density contrasts." In the Bass Strait, offshore Australia, a FALCON survey has demonstrated that known oil and gas fields occur on the flanks of gravity highs coincident with interpreted faults. Flying surveys at 120 metres above ground, the FALCON system has been used to map Australia's coal resources. Given coal's characteristically low gravity signature, the FALCON system can resolve steeply dipping seams (greater than 15˚) that are at least 10 metres thick.

The FALCON system, however, has new competition in the skies.

In February, Bell Geospace announced the commercialization of Air-FTG, its proprietary, airborne gradiometry technology. The Air-FTG system is based on Bell Geospace's in-house, three-dimensional Full Tensor Gradient (3-D FTG) acquisition system, which was also adapted from the Lockheed Martin gradiometer.

The 3-D FTG system measures three vectors (x, y and z directions) and three tensors for each vector. Five of the tensors are independent; four are redundant. Explains Hammond: "The more independent measurements you've got, the better the data are." The x direction measures east-west gradients, the y direction north-south, and the z direction up-down gradients. The z or vertical direction most closely represents geological structures. That's why the competing FALCON system also measures the z direction.

Following an extensive and costly R&D program during the 1990s, Bell Geospace began acquiring ship-borne 3-D FTG surveys in 1998. Seismic vessels — equipped with the 3-D FTG system and a magnetometer — acquire co-located 3-D seismic, gravity and magnetic data sets concurrently. In the marine exploration environment, geophysicists integrate co-located data to improve their interpretations of sub-salt and sub-basalt (volcanic rock) plays. According to Hammond, oil and gas companies are using ship-borne gradiometry data at the regional and prospect levels.

Proved to be versatile on multiple platforms — from Trident submarines to ships to aircraft — the Lockheed Martin gradiometer has been recently adapted to work on the ground.

Next year, Talwani plans to test the ground-based Lockheed Martin gradiometer at a heavy oil field in northern Alberta that is currently under VAPEX production. Because he's going to conduct time lapse or 4-D reservoir studies, Talwani won't have to bother with complex mathematical corrections for surface topography. In a joint venture with Lockheed Martin, Talwani intends to take measurements every six to 12 months. The time-lapse survey is designed to track density changes in the subsurface that correlate with heavy oil movements.

The VAPEX process involves injecting propane into the reservoir — along with a displacement gas — to mobilize and sweep the viscous oil toward parallel, horizontal production wells. Gravity gradiometry is especially suited to such an application, as VAPEX represents a non-thermal process that is difficult to measure in the subsurface.

Talwani fears, however, that monitoring reservoir changes at the VAPEX field — once or twice a year — may evolve into a lifelong investigation. "The downside (of the project) is that production changes in the reservoir are at a glacial pace," he says. ntm **— Susan Eaton**