REDUCING 3-D SEISMIC PITFALLS USING (HEAVEN-FORBID) GRAVITY & MAGNETICS

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Introduction

Although the 3-D seismic method continues to astound explorationists with the amount of detail that can be inferred, the method is extremely expensive and the data can oftentimes be non-unique. In the past, gravity and magnetics data have been used only peripherally in mature areas, such as the Gulf of Mexico Salt Basin, giving way instead to the greater imaging power of the seismic method. However, many complex geologic environments have not yielded all of their secrets to the 3-D seismic method. A revival is underway in the use of gravity and magnetics data to yield better geologic interpretations from seismic data.

Gravity and magnetics data, when integrated with the full detail obtained from the seismic results, can be used to discriminate between alternative and equally viable seismic interpretations. This multi-disciplinary integration also can provide valuable information where seismic data alone may be difficult to interpret. For example, integrated gravity, magnetic and seismic modelling has been used in the Gulf of Mexico to provide information about salt geometries and dip angle to the seismic processors so that the seismic data processing methods can be focused using the most likely structural attitudes.

Bootstrapping is defined by Sheriff as: "To attempt the impossible, as "to lift oneself by one's bootstraps". Stated geophysically, "Derive an earth model, test it, refine it, test it...." Gravity and magnetic modelling and interpretation has relied heavily on this philosophy from the beginning. This philosophy, while poked at for some time by the seismic method, is fast-becoming more routine. Methods such as AVO modelling, pre-stack depth migration, turning wave, etc, all have an inherent structural and/or velocity model as the starting premise. Tuning of this model is then performed and used as a refinement on the seismic processing parameter selection. Other independently measured geophysical techniques, which respond to the same (or are linked to the same) lithological parameters as the seismic method, can be used to provide important input and constraint to the selection of these starting point models.

This is summarized with the following Q & A:

> **Question**: Can a single earth model be derived which satisfies all of the geophysical and geological data?
>
> **Answer**: Typically, no. However, if we can support a geological interpretation using several independently-measured geophysical techniques, we harbor less doubt about our answer.

The following examples are given in this discussion:

Interpretation:
Depth model verification
Fault analysis, position, type, throw
Salt / shale volume, structure
Sub-salt / shale, or deep seismic structure
Volcanic / igneous body

Processing:
Test seismic processing velocities
High resolution gravity & magnetics data for seismic statics corrections
Test dip parameters using magnetics
Reduce number of iterations for pre-stack depth, turning-wave
Improve compass records on streamer positions

Depth Model Verification

Although the conversion of time to depth in seismic interpretation is considered routine for certain geologic conditions, seldom is the process error free, especially in areas of complex geology having velocity gradients, diffractions, and geometric ambiguities. One efficiently imposed constraint is the use of gravity and magnetics data to substantiate or refine the assumed time to depth function and resultant velocity distribution.

Figure 1 contains an example of this methodology, taken from the North Sea Central Graben. The main structural feature is a collapsed salt ridge overlying tilted block faults of the Rotliegendes and older section. Input time picks and stacking velocities are input to a DSite™ model with interval velocities calculated using the Dix formula. Forward modelling is then performed using offset raytracing to yield reflection travel times and associated stacking velocities for comparison with the input data. Figure 1a contains a comparison of the input and calculated travel times and stacking velocities. The starting interval velocity field is then improved through automatic inverse ray tracing, ending when a reasonable convergence to within the data uncertainties is reached. The final seismic-derived depth conversion and velocity field are shown in Figure 1b.

The resultant seismic-derived depth model is then input directly into LCT's gravity and magnetic modelling system, 2Mod™. Synthetic density values are obtained from the velocity field obtained in DSite™ and are compared with logged density from well data. The theoretical gravity and magnetics fields are then computed for the model and compared with the observed fields, as shown in Figure 1c. The seismic display and the depth model are dynamically linked using the LCT system, and various sensitivity tests are performed.

Of course, if the time interpretation, depth conversion and lithological parameters were perfect, the computed and observed fields would match. Differences between the fields can be reconciled in real time by altering the depth model, which inherently requires an update to the velocity field if the time interpretation is deemed correct. Once an altered model is derived which best satisfies all of the geological and geophysical data, the depth model can be converted back to time and overlayed on the input seismic section. This process is continued until a combined earth model is derived, which satisfies all of the available input data constraints and concepts.

This example demonstrates that a higher degree of confidence is gained when a time interpretation is converted to depth, the velocity field tested and updated using inverse raytracing, and the result further verified or altered using the gravity and magnetic constraint.

Fault Interpretation / Thickness of Volcanics

Another useful application for gravity and magnetics is the ability to provide information below areas which are difficult to penetrate with seismic energy. One such example is included in Figure 2, taken from the Central Graben region of the U.K. North Sea. This area has recently been surveyed using a multi-sensor marine vessel to collect 3-D seismic data and high resolution gravity data. In addition, a high resolution aeromagnetic survey was flown over the area, extended to include a large halo around the marine survey. The primary utility of the combined study was to utilize the seismic data to derive a highly accurate model of the top of the volcanics, with gravity and magnetics then used to extend the interpretation of the base of volcanics and below.

Figure 2a illustrates the initial seismic interpretation, with the interpreted time horizons indicated. This model was then depth converted and analyzed using the gravity and magnetics data. The magnetics data were used to identify variations in basement type, with a high susceptibility "basaltic" complex in the center, rimmed by lower susceptibility "acidic" components, as shown in Figure 2b. Of particular note was the low angle basement contact on the right side of the model, as interpreted from the magnetics data. Much of the primary faulting in the area appears to be coincident with or related to these large apparent basement contact zones, indicating that the younger structuring may be a reactivation of older basement faulting. The magnetics data were also combined with the seismic and gravity data to yield an alternative and (deemed-to-be) more viable thickness for the volcanic sequence.

An interesting correlation can be noted between the high frequency magnetic anomaly and the small basement horst feature indicated on Figure 2b. However, it is easily demonstrated that the maximum depth the magnetic anomaly can be sourced-from is substantially shallower than the horst feature. Detailed analysis of the magnetics data using LCT's MagProbe™ suggests source depths for the magnetic features in the range of 100 to 300 meters. Close inspection of the shallow seismic data suggests glacial channels may be present which would tend to be slightly higher in magnetic susceptibility than the surrounding sediments. Figure 2c contains the expanded area of the apparent glacial channel, which is modelled using the seismic, gravity and magnetics data. The seismic data in this area indicate a possible velocity push-down resulting from the occurrence of somewhat lower velocities in the channel than assumed for the shallow section.

This example demonstrates that improved geologic understanding is gained using a multi-disciplinary seismic, gravity and magnetics approach. Shallow seismic processing can be improved by identifying low density, slightly higher susceptibility channels, which may be corrupting the shallow seismic processing.

Shallow Sand Channel and Salt Mapping via Seismic / Magnetic Modelling

The magnetization of shallow Gulf of Mexico sediments typically varies between 0 - 300 μ CGS units, with 70 μ CGS being a useful average. Salt, by comparison, is slightly diamagnetic (minor negative susceptibility), but virtually zero or non-magnetic. Accordingly, much of the salt-prone areas are characterized by small amplitude, high frequency magnetic lows, owing to the replacement of low magnetization sediments with non-magnetic salt. Figure 3 (after Saad, 1993) illustrates the aeromagnetic signature over two salt plugs. The associated magnetic lows have amplitudes in the range of 4 - 10 nT (gammas), with excellent correlation between the high anomaly gradients and the seismic-derived salt interfaces. Interesting to note is the sand channel in the center of the seismic display, which correlates with a subtle (2 - 4 nT) positive magnetic anomaly. While small in amplitude, the signature is easily correlated with seismic and then used as an additional guide for linking up the seismic events. This signature is well within the limits of current high resolution airborne magnetics (where tenths of nT are commonly repeated). Note also, the apparent velocity push down below this sand channel, in response to the less consolidated channel fill.

This example shows that high resolution magnetics can be helpful in the corroboration and delineation of sand trends and can be used to differentiate between salt masses and thick sands.

Improvement of Compass Records on Streamer Data

Compasses used in most marine seismic streamer cables can be corrupted by extraneous magnetic effects. The primary causes of this are: 1) diurnal magnetic storm activity, 2) local geologic anomalies, and 3) local cultural effects. The result of each of these effects is the same, namely, the compasses are measuring the vectorial sum of earth's main field component and the additional magnetic disturbance. The effects can be moderate to non-existent, but can also produce large errors in compass data.

Long period daily variations can routinely be tens of nT, and up to hundreds of nT not uncommon. However, micropulsations caused by high frequency bursts in solar wind can produce large error spikes in the apparent magnetic declination. Figure 4a illustrates the variation of declination measured using a shore-based base station magnetometer. This record shows one week of fairly typical magnetic fluctuation, with only moderate high frequency activity, and a dynamic range in declination variation of 0.25 degrees. Figure 4b shows a higher degree of magnetic storm activity, but the variation is still quite subtle in overall dynamic terms (and therefore, easily missed in standard quality checks). In this example, variations up to 0.3 degrees are observed over periods less than an hour, with both short period and intermediate periods observed. During moderate to high magnetic storm activity, errors in magnetic declination can exceed 0.5 degree over short periods from magnetic storm activity. These effects can be subdued / removed using a time-varying decorrelation technique.

Local geological anomalies and cultural features (e.g., pipelines, rigs) can also cause large errors in the apparent magnetic declination. A geological anomaly, with magnetization dramatically different from the surrounding material, can cause high gradient magnetic anomalies with amplitudes in excess of 1000 nT. These features will locally alter the apparent earth's magnetic field declination, causing an incorrect usage of the compass data. An example is included in Figure 4c, which is the computed magnetic declination over a short wavelength actual magnetic anomaly from the North Sea. The local declination "error" is shown to be greater than 1 degree over 2-3 km, in the example shown.

These examples show that the positioning of 3-D seismic streamers using compass records can be corrupted by magnetic storms and local geological/cultural magnetic anomalies. When combined with magnetic observatory data and observed magnetic field data, streamer compass records can be improved using decorrelation methods.

High Resolution Gravity & Magnetics Data

For studies of this type to be successful, the gravity and magnetics data must be of high fidelity. While water-bottom gravity data continue to produce high quality results, the high cost factor has nearly removed this method from routine practice. However, recent studies (LaFehr, et al, 1992) suggest that accuracies of dynamic shipborne gravity data are approaching and, in some cases, exceeding that of static water-bottom surveys. High precision gravity surveys are capable of producing +/- 0.1 to 0.5 mGal in calm to moderate sea states. Also, water-bottom stations are typically acquired on a grid, with oftentimes large gaps between discrete stations.

Shipborne gravity data on 3-D seismic surveys benefit from the extremely high sample rates along-line (3 meter sampling on the LCT - ZLS systems) and the tight line spacing on 3-D seismic programs. This high density of gravity samples results in a large redundancy of data. This redundancy, when coupled with high accuracy Eötvös and horizontal acceleration corrections from high precision GPS, has allowed the evaluation of short wavelength, low amplitude anomalies which would previously have been filtered out with conventional processing. This new level of anomaly resolution is encouraging a closer link between the seismic and potential field methods.

One extremely important factor in high resolution marine gravity and airborne magnetics is that the data can typically be processed in a much shorter time frame than the 3-D seismic data. Accordingly, the potential field data can (and should) be used at the earliest stages of seismic processing parameter selection.

Some recently acquired high resolution marine gravity data and airborne magnetics data from the Gulf of Mexico are displayed. These data sets have been acquired in conjunction with an ongoing 3-D seismic program.

Additional Examples

Several other examples are included in the discussion to illustrate the higher resolving power of 3-D seismic data when combined with gravity and magnetics. These include: 1) Discrimination between reef and volcanics,
2) dip angle for a salt wall, and 3) sub-salt velocity model tested using constrained seismic, gravity and magnetics modelling and interpretation.

Conclusions

The results discussed herein demonstrate that pitfalls in 3-D seismic data can be reduced using gravity and magnetics to:

- Provide rapid access to newly acquired gravity/magnetics data
- Investigate viable structural attitudes for seismic processing input
- Provide validation of the seismic model
- Evaluate alternative velocity models
- Resolve multiple and equally viable seismic interpretations
- Decrease streamer positioning errors from compass records
- Scrutinize density and velocity
- Discriminate between volcanics and reefal carbonates
- Assess fault throw and lineament position

References

LaFehr, T.R. Valliant, H.D., and MacQueen, J.D., 1992, High-resolution marine gravity by digital control: 62nd Annual International Meeting, Society of Exploration Geophysics, Expanded Abstracts, 559-560.

Saad, A.H., 1993, Interactive integrated interpretation of gravity, magnetic and seismic data - tools and examples, Offshore Technology Conference, Paper number: OTC # 7079.

Sheriff, R.E., 1991, Encyclopedic Dictionary of Exploration Geophysics, Third Edition

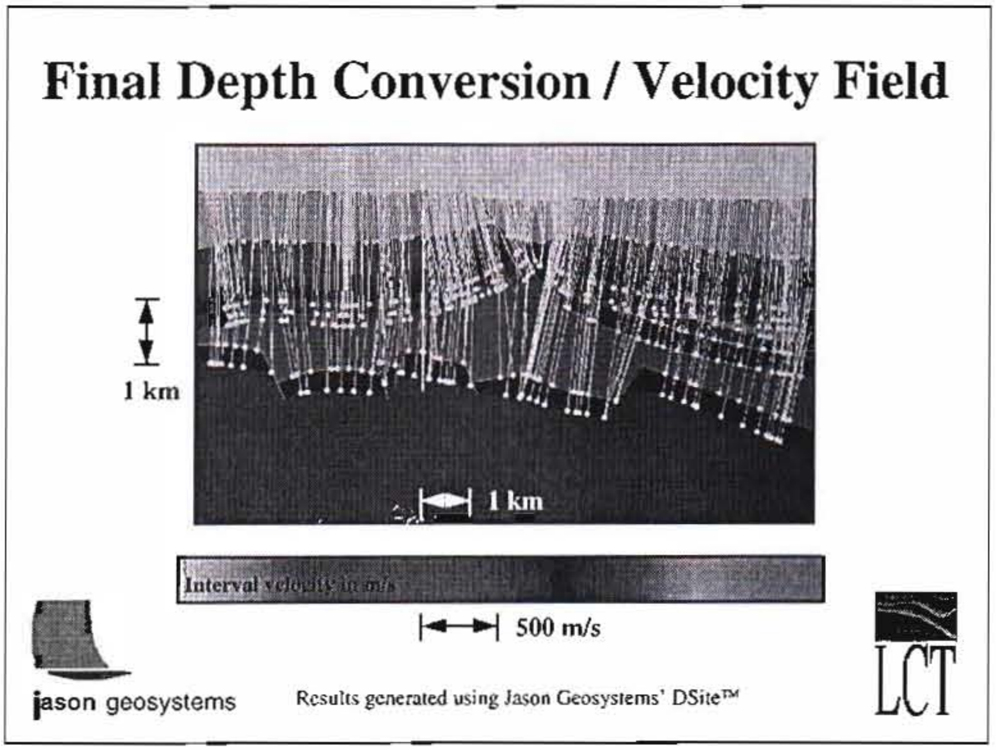

Figure 1a

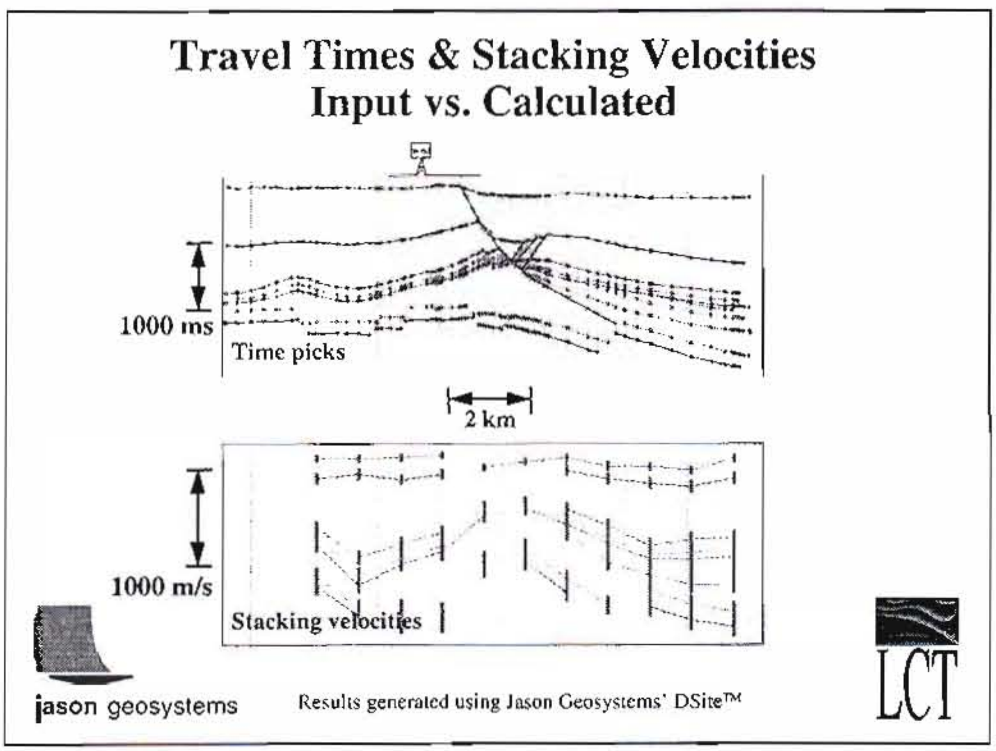

Figure 1b

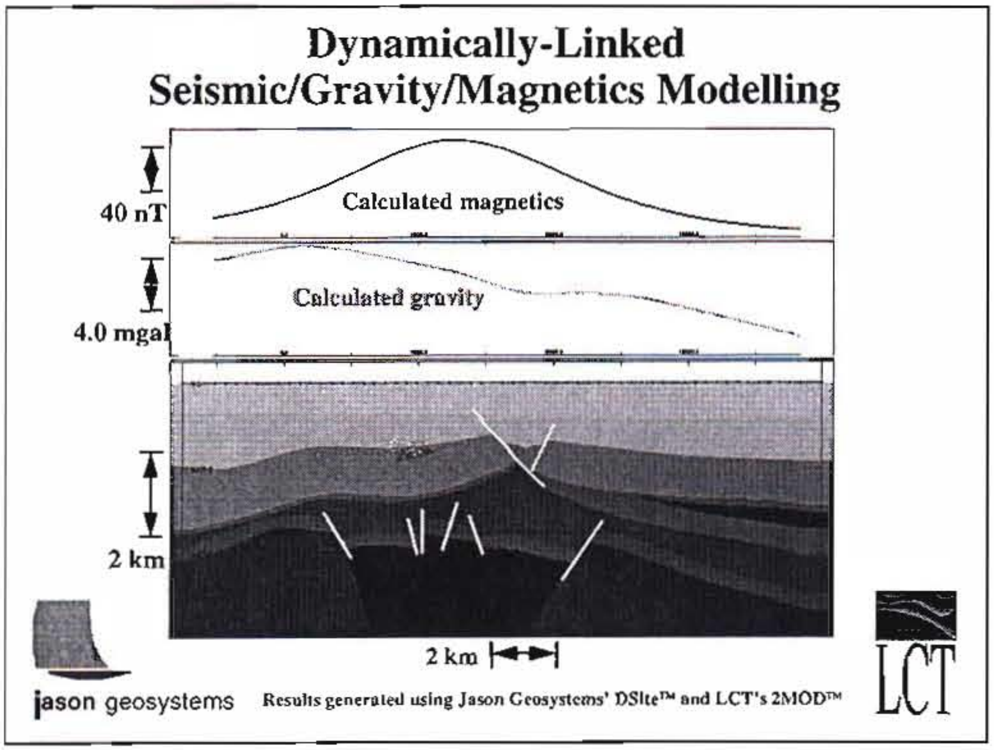
Dynamically-Linked
Seismic/Gravity/Magnetics Modelling
40 nT
Calculated magnetics
4.0 mgal
Calculated gravity
2 km
2 km
jason geosystems
Results generated using Jason Geosystems' DSite™ and LCT's 2MOD™
LCT

Figure 1c

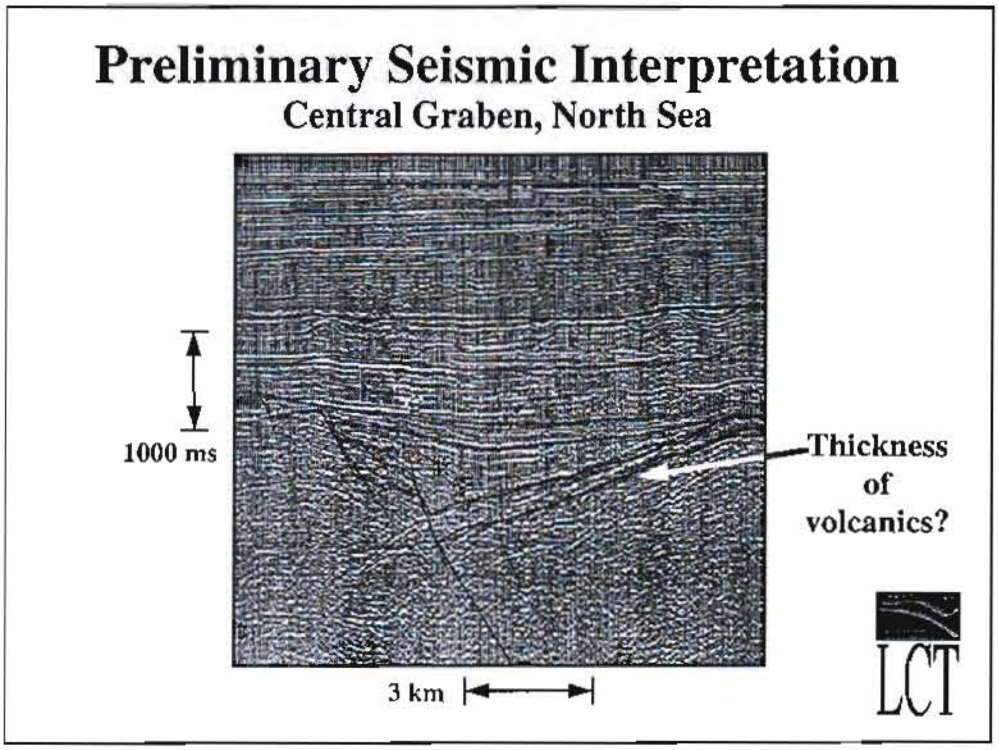

Figure 2a

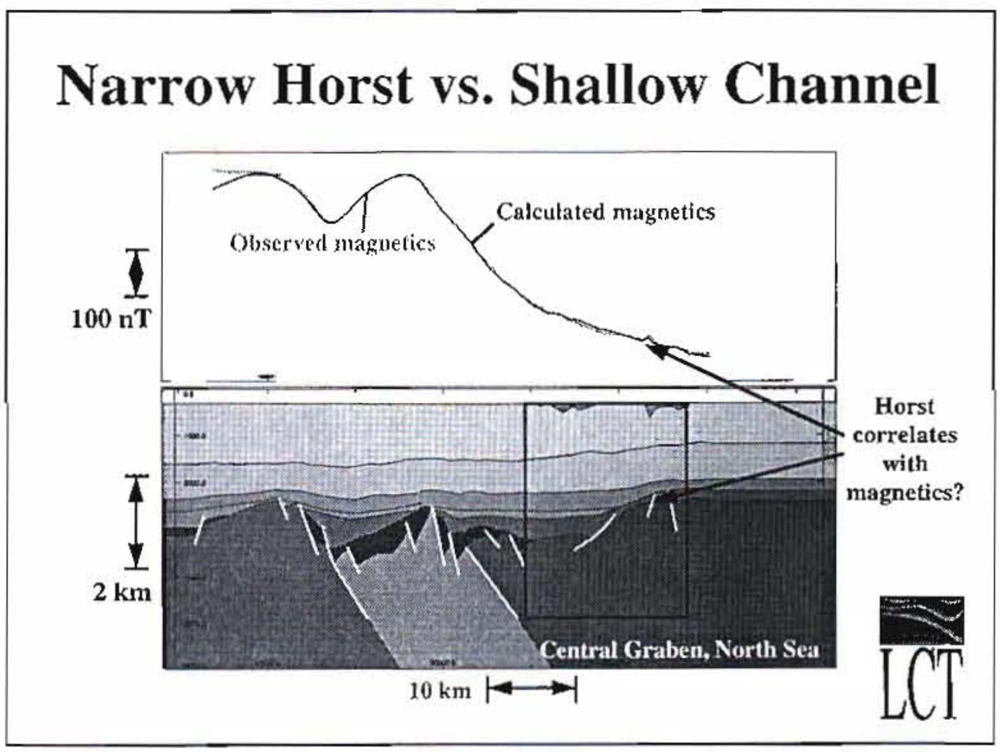

Figure 2b

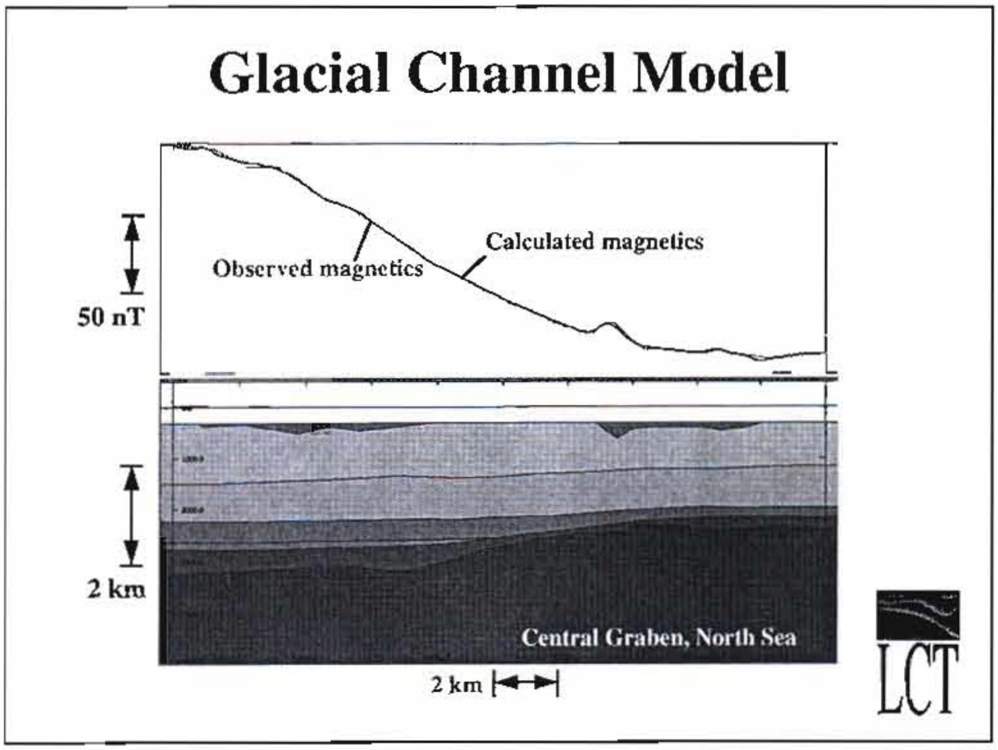
Glacial Channel Model
Calculated magnetics
Observed magnetics
50 nT
2 km
Central Graben, North Sea
2 km
LCT

Figure 2c

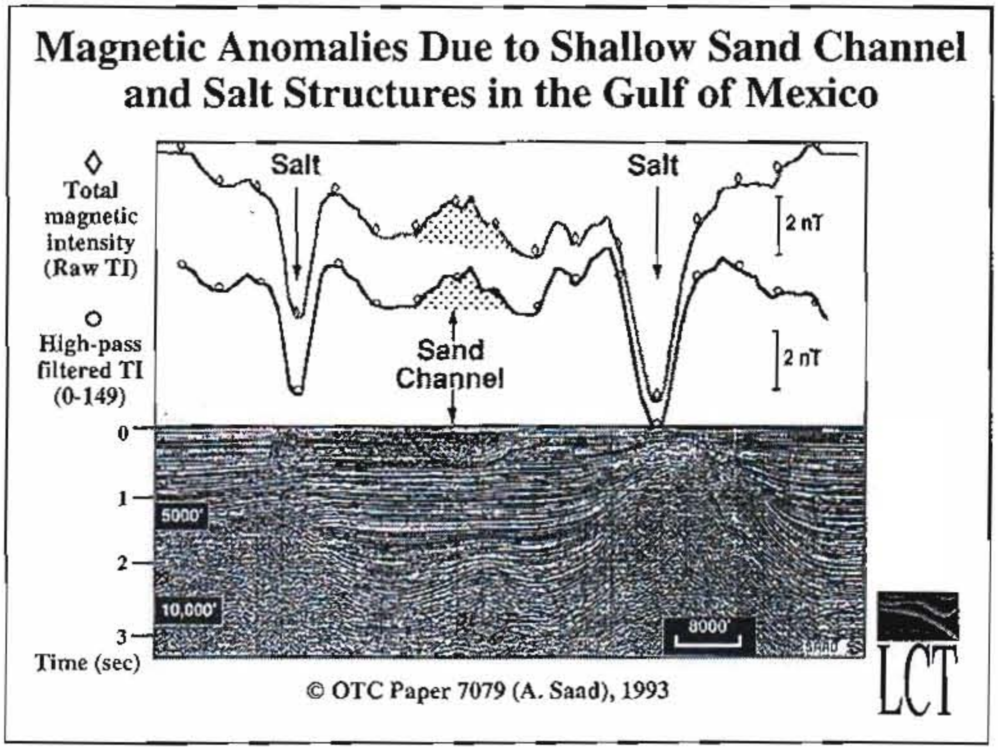
Magnetic Anomalies Due to Shallow Sand Channel and Salt Structures in the Gulf of Mexico
Total magnetic intensity (Raw TI)
High-pass filtered TI (0-149)
Salt
Salt
Sand Channel
2 nT
2 nT
0
1
2
3
Time (sec)
5000'
10,000'
8000'
© OTC Paper 7079 (A. Saad), 1993
LCT

Figure 3

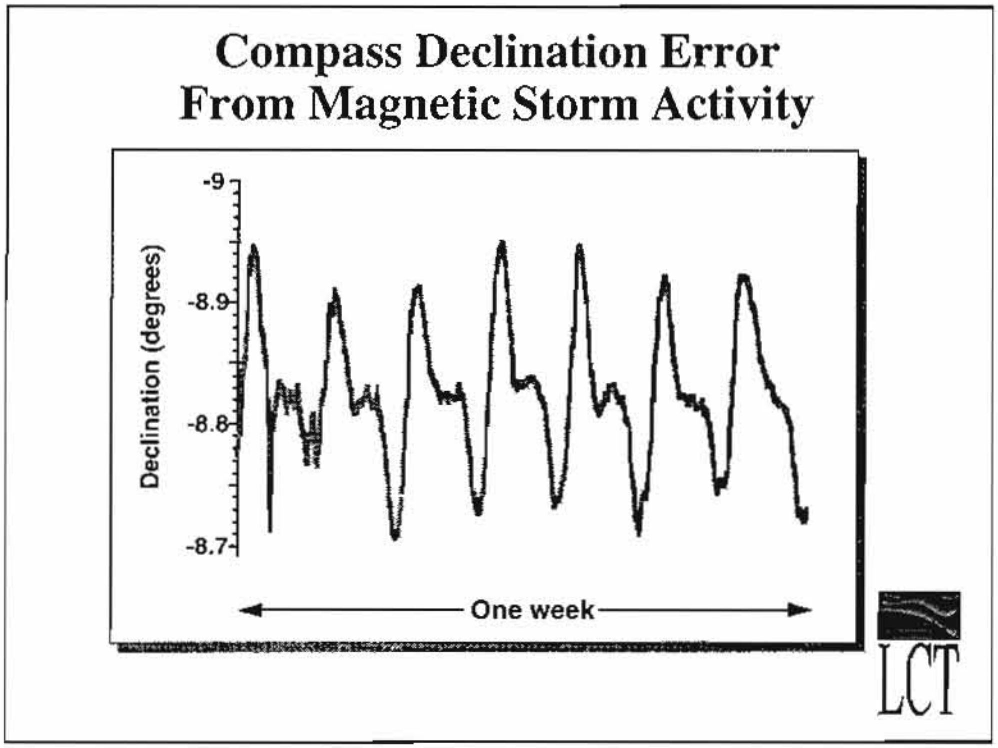

Figure 4a

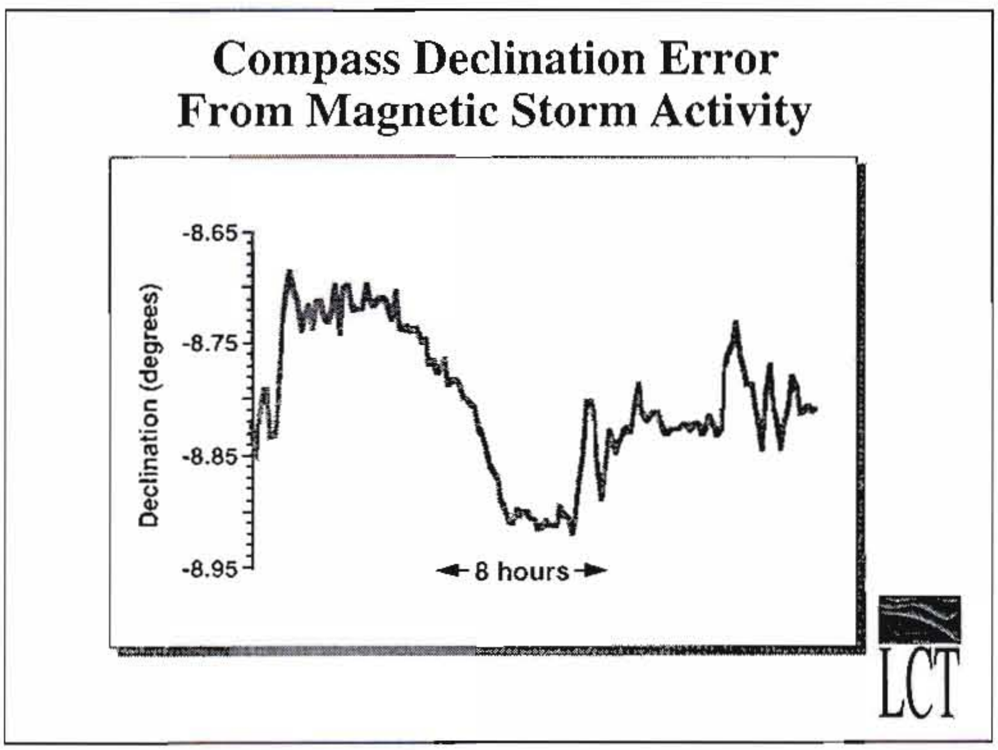

Figure 4b

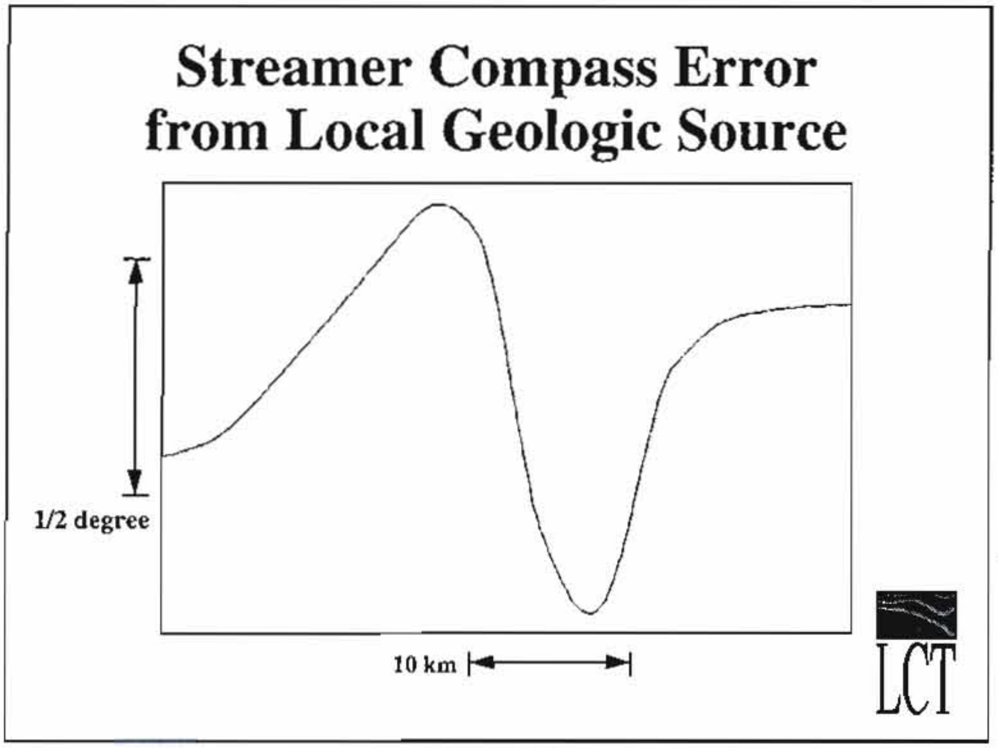
Streamer Compass Error
from Local Geologic Source
1/2 degree
10 km
LCT

Figure 4c