GRAVITY / MAGNETIC SIGNATURES OF VARIOUS GEOLOGIC MODELS - AN EXERCISE IN PATTERN RECOGNITION

By:

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Introduction

In every geologic province the physical parameters are unique. The prospective anomaly signature associated with each individual area will vary accordingly. The pattern recognition of an anomaly signature is of vital importance to all interpretation sciences. The following discussion is intended for geophysicists and geologists interested in obtaining a working knowledge of what type of signal pattern should be observed for the purpose of integrating gravity and magnetic data with seismic and geological data for development of exploration targets. The incorporation of the integration process in exploration has been known to reduce risk and therefore reduce the total cost of exploration.

The gravity and magnetic anomaly signature characteristics are results of one or more physical parameters such as the configuration of the anomalous zone, density, velocity, and porosity contrasts, magnetic susceptibility contrasts, and the depth to the anomalous body. An excellent tool to aid in pattern recognition is structural modeling. A simple collection of geologic structures have been modeled and their calculated gravity and magnetic responses are discussed to identify anomaly characteristics. The collection is not intended to be a library of curves, but rather an exercise in pattern recognition. The two-dimensional modeling scheme utilized an interactive graphic system. The well known Talwani algorithm (see References) was used as the basis for the computations.

The density and magnetic susceptibility contrasts are based on data from various geographical areas from The Superior Oil Company exploration cases and from published literature. The structures of the models have been kept simple to emphasize how depth, density, and susceptibility contrasts vary the anomaly characteristics.

The following discussion refers to the residual anomaly as the observed gravity and magnetic field. This distinction is made early so as to avoid confusion. The gravity and magnetic interpreter is aware of the importance of a good geologically based first-order residual field. Another clarification is that the magnetic calculations use the magnetic inclination of 60° N, which is the average magnetic inclination for the United States. It is important to note that the magnetic signal of a structure is highly dependent on its geographical location on the earth. The interpreter should initially identify the magnetic signal due to the structure in question; i.e., the geographical location of the structure and effect of the magnetic inclination on the magnetic anomaly due to the structure.
I. FAULTS

The standard recognized fault signature is a steep gradient, whether it is on a gravity, magnetic, structure, or a seismic time map. In the gravity case, the gradient steepens as the fault becomes shallower as illustrated on Figure F1. But note that the inflection point of the gradient is at the center of the fault at all depths. This signature is valid for a sedimentary fault in which homogeneous beds are not substantially offset. A magnetic anomaly would not exist in this case since the basement was not involved in the faulting and the sedimentary section was also assumed to be non-magnetic. When the basement or a magnetic sedimentary layer is faulted, a magnetic anomaly does occur as shown on Figure F2. The anomaly amplitude depends on both depth and magnetic susceptibility. In certain exploration environments, the question of basement involvement is often answered through the perusal of a gravity and magnetic map. If the gravity and magnetic anomalies are positive over a questionable seismic structure, the basement is probably involved.

A second case for a normal fault is shown on Figure F3. A high-density layer has been introduced into the geometry. It produces a gravity gradient as in the first case, but the gradient has increased due to the increase in the density contrast of the layer which is faulted. The high-density layer could represent a carbonate formation. The lower density layers could represent a clastic sequence. In this case, the basement is involved in the faulting; therefore, a magnetic signature is generated. The model calculation shown is for a 60° magnetic inclination. Note that the magnetic anomaly calculated appears as a negative anomaly. This is due to various geophysical parameters: 1) the geometry of the structure, the fault, 2) magnetic inclination, and 3) direction of the model traverse, here 0 degrees azimuth.

The same fault model as shown on Figure F3 with a low-density layer substituted for the high-density layer is shown on Figure F4. A positive gravity anomaly occurs when the low-density layer is completely offset by the fault and is displaced by the higher density layers. The magnetic signature would remain as shown on the previous example (Figure F3) since the basement structure has not changed.

The three geologic cases described have distinct anomaly characteristics that can be correlated to rock composition or structure or both. The amplitude of the anomaly will vary as contrasts and depth vary, but the signature characteristics for each case should remain the same.
II. DIPPING BEDS

A dipping bed produces a gravity anomaly similar to that of a fault. The main difference is that as the bed nears the surface, the gradient of the anomaly becomes steeper and the magnitude of the anomaly tends to be greater. The structural model calculation of the gravity effect as shown on Figure D1 uses density contrasts which could represent the thrusting of older beds over younger beds, or a dike intruding into a sedimentary sequence. The edges of the denser bed can be associated with the inflections on the gravity curve. The highest amplitude on the curve occurs in the direction of denser beds. The closer the dip of the beds to vertical, the greater the symmetry in the gravity anomaly that will be observed. The amplitude of the anomaly is dependent on the density contrast and depth. If gravity data over an overthrust bed and a constraint from seismic data for the top of the overthrust bed were available, structural modeling the gravity data would assist in resolving the thickness of the overthrust section.
III. SYNCLINES

A syncline produces a minimum closure on most geophysical maps. The amplitude and characteristics of the gravity and magnetic anomaly associated with a syncline are dependent on 1) depth, 2) the type of sedimentary fill, 3) the amount of sedimentary warping, and/or 4) the involvement of the basement rocks. The magnetic inclination also plays an important part in the character of the magnetic anomaly. In these discussions, the inclination has been kept constant at 60°N.

A folded sedimentary syncline with uniformly increasing density with depth as shown on Figure S1 will produce a minimum gravity anomaly (due to sedimentary warping) centered over the syncline; this model does not produce a magnetic anomaly since the sedimentary section is shown as non-magnetic. The basin model shown on Figure S2 illustrates the gravity and magnetic anomaly characteristics that will identify a basin's extent and depth. The basement involvement increases the amplitude and sharpness of the gravity signature, and it also generates a magnetic anomaly. The areal or lateral extent of the basin or graben can be delineated by identification of the gravity and/or magnetic basin-boundary fault signatures. Again, remember that the magnetic signal is dependent on its location on the globe. The broad minimum magnetic anomaly shared by the two maxima situated at the edges of the basin would be characteristic of the 60° N inclination. The basin would be expressed as a minimum magnetic closure surrounded by higher frequency maximum closures.
The faulted-folded syncline shown on Figure S3 is an example of a more complicated geology. The gravity and magnetic signatures are distorted, yet the signature characteristics remain. The gravity minimum is still present although it is offset over the upthrown side of the fault. The magnetic signature is more complicated, but the basement faults are identifiable. The basin edges can be noted and the magnetic anomaly in the center of the syncline indicates the central fault structure.

A syncline can often be masked on the seismic section by diffractions or velocity problems. Assuming increased density with depth, the syncline gravity signature will be a minimum anomaly; the magnetic signature will occur only if basement rocks (assuming non-magnetic sedimentary section) are involved in the structure. It is rare that gravity and magnetic data cannot verify a synclinal structure.
IV. ANTICLINES

A simple folded symmetrical anticline produces a symmetrical positive gravity anomaly. The amplitude and characteristics of the gravity and magnetic anomaly associated with an anticline are dependent on 1) depth, 2) the amount of sedimentary warping, and/or 3) the involvement of the basement rocks. The magnetic inclination also plays an important part in the character of the magnetic anomaly. In these discussions, the inclination has been kept constant at 60°N.

As the geology becomes more complicated, so do the gravity and magnetic responses. So we depart from the simplest of structures and start the discussion with a faulted anticline.

A normal-faulted anticline as shown on Figure A1, consists of a sedimentary sequence of density values that increase with depth and a faulted basement uplift. This structure produces a broad maximum gravity anomaly indicating the areal extent of the entire uplifted section. Two higher frequency positive anomalies are superimposed on the broad anomaly; one anomaly is associated with the surface outcrop of the fault and the second anomaly is situated over the apex of the rollover. The minimum between the two high frequency closures is due to the wedge of relatively low density material between the fault and the rollover. The magnitude of this minimum anomaly is governed by the density contrasts and the thickness of the wedge, but is an anomaly characteristic generally observed on faulted anticlines.

The magnetic anomaly occurs only when the basement is involved in the structure. The magnetic anomaly calculation shown on Figure A1 is for an anticline with a basement structure. For comparison the magnetic anomaly calculation shown on Figure A2 is for an anticline without basement structure. Note the individual fault signatures on the model in Figure A2; the first one occurs at the inception of the upwarping of the anticline on the left side of the model, the second fault is at the apex of the anticline, and a third fault is at the downwarp of the anticline on the right side of the model. The faults all vary in amplitude and wavelength indicating diverse structural characteristics. If the question is "what is the extent of basement involvement in an exploration prospect structure", magnetic data can generally confirm basement and determine any secondary faulting.
The normal-faulted anticline previously discussed has been complicated with the introduction of a high-density layer as shown on Figure A3. The anomaly produced is similar to the previous model (Figure A1). The increase in density contrast sharpens the frequency of the anomalies previously identified. The higher density layer could represent a tight limestone, limestone/anhydrite, or a volcanic sequence. The magnetic anomaly would remain the same as shown on Figure A1 unless the high-density layer was magnetic volcanic rocks.

The case model shown on Figure A4 illustrates the complexity in the observed signatures caused by the introduction of a shallow (or surface) high-density layer. This model could represent surface volcanics or a tight limestone. If the local geology is not well known, magnetic data would clearly distinguish between the volcanics and the carbonates. The case shown on Figure A4 has magnetic susceptibility assigned to the high-density layer, which would suggest it to be volcanics. The magnetic anomaly caused by the basement alone (Figure A1) has been complicated with the introduction of the shallow magnetic sequence. If the shallow layer was dense carbonate, the magnetic signature would be as shown on Figure A1. This model is shown to illustrate that not all gravity and magnetic observed anomalies are easily interpreted without structural modeling to assist the interpreter in separating the signatures of the causative structures.
The final example of an anticline signature illustrates perhaps one of the most forgotten and most important aspects of gravity interpretation. The gravity anomaly is a composite signal of all the density contrasts due to 1) the basement structure and 2) the sedimentary warping of the all beds above the basement structure. In order to determine the total thickness of the sedimentary section in a basin or to verify a structure for a prospect, the total gravity contribution due to all the density contrasts through out the section to the observed gravity anomaly must be kept in mind. When computing the gravity effect of a basement horst, it is important to include the more subtle effects due to the resultant sedimentary warping above the horst. As shown on Figure A5, when the warping extends upward through several formations, the combined gravity effect of each sedimentary layer to the total anomaly can easily exceed the basement contribution.

The salt pillow (Figure A6) is a common anticlinal model. It has a negative density contrast due to the sediment/salt interface and therefore a resultant
minimum anomaly signature. The amplitude is dependent upon depth to the top of the pillow and thickness of the pillow. A point to note is that the positive gravity contribution due to sedimentary warping over a salt pillow could cancel the negative signature. But that fact in itself would assist in the interpretation of the salt structure. Many seismic prospects are dependent on the existence of a salt structure or a salt withdrawal. An integration of the seismic and gravity data could provide an answer through the gravity calculation of the structural configuration of the seismic geometry. For example, if the observed gravity data have no anomaly where the seismic section indicates sedimentary warping (or a potential structure), the introduction of a salt pillow would be necessary to eliminate the positive anomaly resulting from the draped beds; therefore, the gravity substantiates the seismic structure.
A case for a carbonate buildup is shown on Figure A7. This example represents a limestone reef embedded in a clastic sequence. The reef would produce a positive gravity anomaly. The lateral extent of the reef can easily be identified with the extent of the positive gravity anomaly. If the top of the reef could be constrained, the thickness of the reef could be modeled using gravity data.

The following discussion of characteristics that can be observed in gravity anomalies is very dependent on the quality and coverage of the gravity data available over the reef. The amplitude and shape of a gravity anomaly varies noticeably because of porosity variations. The reef modeled in Figure A7 is a symmetrical reef. It is shown with no porosity (blue curve) which produces a symmetrical gravity anomaly. The gravity anomaly due to a reef with 10% porosity filled with either oil or gas has been reduced in amplitude but a more important characteristic is that the anomaly has been flattened compared to the anomaly due to no porosity. Many reefs produce from the fore-reef zones rather than uniformly from across the top. The character of the gravity anomaly will vary depending on the position of the porous zone as illustrated on Figure A8. The capability of distinguishing oil-from gas-filled porosity is difficult, mainly due to acquisition problems. Strict field specifications must be adhered to and in many cases the access to an area restricts the capability to acquire data for the repeatable 0.10 milligal data quality required.
V. INTRUSIVES

Intrusives can be of many sizes and compositions and can occur in many geologic provinces. Due to well-known diffraction problems, seismic sections reveal intrusives by the no-reflector zone they generate. Often, no useful velocity information can be extracted to aid in the determination of the rock composition of the intrusive. A solution to this problem can be determined by interpreting the gravity and magnetic signature of the intrusive.

Three typical intrusive compositions are salt (Figure I1), shale (Figure I2), and basalt or mafic igneous (Figure I3). In our examples, all assumed variables are constant except the density value due to the intrusive. It is shown intruded into a typical sedimentary sequence where density increases with depth, and where the sedimentary section has no significant magnetic susceptibility value. The respective gravity signatures, due to the intrusives, are significantly different. Salt produces a substantial negative gravity anomaly and minimal magnetic anomaly (not shown). Shale produces a minimum gravity anomaly, an order of magnitude less than that produced by the salt, and no magnetic anomaly would be generated. The basalt or mafic intrusive would produce a significant positive gravity and magnetic anomaly. The sharpness (frequency) of the anomalies due to the salt and the basalt will increase as the depth to the top of the intrusive decreases or as the circumference of the intrusive decreases.
The model in Figure 14 illustrates the gravity anomaly produced by a salt dome at various depths to the top of salt. The deepest salt column produces the broadest negative anomaly, shown here at a depth of 12,000 feet (3.66 km.). As the salt dome shallows, the anomaly increases in amplitude and sharpness (frequency). The gravity effect due to the salt in the crossover zone contributes nothing to the anomaly. Crossover or Nil zone is the area where the salt and sediment densities are equal ($\rho = 2.2$ g/cc), therefore generating a zero density contrast. The crossover zone illustrated on Figure 14 is shown as 2,500 feet (762 m.) thick for emphasis. In general this zone is a few hundred feet thick. As the salt moves above the crossover zone, a positive gravity anomaly is generated and superimposed on the broader negative anomaly due to the deeper density contrasts. The addition of caprock adds to the positive anomaly situated on the broad negative anomaly. This is a characteristic anomaly signature for many shallow Gulf Coast salt domes. The sediment densities shown are typical of the US Gulf Coast region.
Igneous intrusives produce a variety of signatures with characteristics dependent on magnetic inclination, magnetic susceptibility, and configuration. The first two figures show models for a very thin dike and sill computed at two locations; Figure I5 is at 90°N inclination or at magnetic north, Figure I6 is for 60°N or at an average inclination for the US. The skewness or distortion of a magnetic anomaly due to the magnetic inclination is identifiable and easily calculated. Note that the anomalies generated at 90° N are symmetrical in character. The interpreter must identify the signal pattern for his geographical area before attempting to integrate the magnetic information. An anomaly will exhibit total reversals in signature when observed in the southern hemisphere.

The dip of a dike can be interpreted from the anomaly curve. The dike model shown on Figure I5 is rotated through 90° to become a horizontal sill. The resulting anomaly shown on Figure I5 changes from a steep symmetrical anomaly (90° dip at 90° inclination) to an asymmetrical anomaly (45° dip at 90° inclination) and back to a symmetrical anomaly with a maximum amplitude for the sill at 90° inclination.

The dike/ sill model is repeated on Figure I6 except this time the magnetic inclination has changed to 60° N. The anomalies generated are now identified as asymmetric, and vary as demonstrated.

The magnitude of all the anomalies is dependent on the magnetic susceptibility and will vary according to the magnitude of the magnetic susceptibility of the type of the rocks involved. The effect is linear; the higher the magnitude of susceptibility, the higher the amplitude of the magnetic anomaly. For example, a mafic intrusive at the same depth, the same geometry and intruding the same sedimentary section will have two times or more the amplitude of a granitic plug.

As a sill extends laterally, there is a distance where the anomaly will gradually separate into two distinct responses. In the northern hemisphere at 60° N inclination, the southern (left) end exhibits the positive half of the anomaly, and the northern (right) end exhibits the negative half. The addition of a feeder root to the sill generates another complete anomaly (positive/negative pair) to the magnetic signature as shown on Figure I7. The edges of a sill, and the width, dip and depth of the feeder root can be interpreted from the magnetic signature. If the source of the anomalies were due to a shallow salt sill and intrusive, the anomalies would be reversed and be an order of magnitude less in amplitude than from those anomalies shown on Figure I7.
Salt has a unique magnetic characteristic that currently has the exploration community interested. The magnetic anomalies are low amplitude but are nonetheless identifiable with state-of-the-art data-acquisition techniques. Due to the diamagnetic character of salt its magnetic signature is reversed or negative. Therefore, the dike/sill anomalies shown on Figures I5 and I6, if they had been generated by salt, would be the reverse of what is shown, and the magnitude of the anomalies would be minimal. In general, the maximum depth for identifiable, repeatable magnetic anomalies due to salt is 8,000 feet (2.44 km.) below recording source.
VI. BASEMENT MODELS

Magnetic anomalies from crystalline or magnetic basement need not be associated with structure on the basement. The broad magnetic closures seen on total magnetic intensity anomaly maps are often due to changes in the rock composition within the basement. When tectonic stresses were applied, these zones of weakness were more likely to fracture and fault. Therefore, the variation of basement composition is often correlated to basement structure. In the following examples, the horizontal scale was expanded to include more than one lithologic contact in a model. Areas of higher susceptibility were assigned a positive density contrast.

A simplified basement transition zone has been modeled on Figure M1 as one vertical boundary. Depth to basement is at 20,000 feet (6.1 km.). Both the magnetic and gravity anomaly responses for the intrabasement contrast have been generated. The magnetic response for two magnetic inclinations (60° N and 90° N) are also shown for comparison. The contrasts shown are considered to be conservative. The important characteristic here is the anomaly wavelength (approximately 50,000 ft or 15.2 km) produced by the transition zone at this depth. Intrabasement anomalies generally have broad wavelength anomalies.

Additional examples of the magnetic anomaly responses for two magnetic inclinations for intrabasement variations are shown on Figure M2. This example illustrates multiple boundaries, each having an assigned magnetic susceptibility. The two magnetic anomalies generated are due to the two blocks with contrasting geophysical parameters. Note that the narrower block produced a lower amplitude anomaly. A corresponding broad gravity anomaly is generated and shown on Figure M3. These models have anomalies generated by only the lithology variations within the basement.
Suprabasement effects (basement topography) have been generated using a uniform basement lithology. Structure (5,000 ft or 1.52 km) has been added to two blocks and assigned a density contrast with the sediments equal to 0.25 g/cc. Both anomaly amplitudes exhibit an increase in frequency content; Figure M4 shows the magnetic response and Figure M5 shows the gravity response. When comparing the magnetic anomalies generated by basement structure vs. basement lithology variation (Figures M4 and M2 respectively), the anomaly wavelength and amplitudes must be examined. The anomalies due to structure will always exhibit higher frequencies. The gravity responses calculated for the same structures are shown on Figures M3 and M5. The amplitude and the frequency content of the gravity anomaly due to variation in basement lithology has been increased by the addition of anomalies due to the basement structures, compare (Figures M3 and M5).

The principal difference between intrabasement (lithology variation) and suprabasement (basement topography) anomalies is that the former have lower frequencies and higher amplitudes than the latter. In many cases, when trying to match an intrabasement anomaly with a suprabasement model, the structure computed is generally geologically unsound and usually the solution violates other available geophysical data. The differences in the characteristics of magnetic anomalies due to intrabasement (lithology) and suprabasement (topography) causes can always be distinguished.
CONCLUSION

In conclusion, the geological models shown have been limited to basic structures for the express intention of illustrating the variation of anomaly signatures due to variations in rock properties. By no means is this the extent of gravity and magnetic interpretation or modeling capabilities. Complex structures can be interpreted and modeled with confidence. The quality of the solution is governed by the variety of constraints. For example, if seismic data can input a minimum and maximum depth to an anomalous zone, gravity and magnetics can assist in determining the lithology and the configuration of the anomalous zone. In certain geologic provinces gravity and magnetic data can also be used as a good quality-control monitor on seismic data. For example, the question "Is it velocity or structure?" can generally be resolved with the integration of potential-fields data.

Pattern recognition is the basis of effective interpretation. One of the keys to accurate pattern recognition is the modeling of the prospective structure, either to identify the characteristic signal or to support the interpreter's concepts.
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