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Deriving geological contact geometry from potential field data

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Abstract. The building process of any geological map involves linking sparse lithological outcrop information with equally sparse geometrical measurements, all in a single entity which is the preferred interpretation of the field geologist. The actual veracity of this interpretative map is partially dependent upon the frequency and distribution of geological outcrops compounded by the complexity of the local geology. Geophysics is commonly used as a tool to augment the distribution of data points, however it normally does not have sufficient geometrical constraints due to: a) all geophysical inversion models being inherently non-unique; and b) the lack of knowledge of the physical property contrasts associated with specific lithologies. This contribution proposes the combined use of geophysical edge detection routines and 'three point' solutions from topographic data as a possible approach to obtaining geological contact geometry information (strike and dip), which can be used in the construction of a preliminary geological model. This derived geological information should first be assessed for its compatibility with the scale of the problem, and any directly observed geological data. Once verified it can be used to help constrain the preferred geological map interpretation being developed by the field geologist. The method models the contacts as planar surfaces. Therefore, it must be ensured that this assumption fits the scale and geometry of the problem. Two examples are shown from folded sequences at the Bathurst Mining Camp, New Brunswick, Canada.

Key words: Bathurst Mining Camp, potential fields, 3D modelling, topography.

Introduction

All geological maps report two types of data: a) the spatial distribution of outcrops of differing rock types as identified by the field geologist; and b) the geometrical (structural) relationships within and between rock units. The final map links the sparse lithological outcrop information with equally sparse geometrical measurements in a single entity which is the preferred interpretation of the field geologist. The actual veracity of this interpretative map is partially dependent upon the frequency and distribution of geological outcrops compounded by the complexity of the local geology. In areas with relatively flat-lying sediments it is possible to derive a reasonable estimate of the distribution of lithological units by carefully logging a few stream profiles. In contrast, for areas that are typified by multiple phases of igneous intrusion and deformation, a high proportion of outcrop exposure is required to produce a geological map product that can be believed with any degree of confidence.

To overcome limitations imposed by inadequate geological outcrop, it is common practice to establish possible linkages between discrete outcrops using the continuous coverage provided by potential field geophysics. 'Commonly, sharp contrasts evident in potential field data (edges or gradients) are assumed to result from sharp discontinuities or interfaces between contrasting rock materials such as faults, unconformities, or intrusive contacts' (Holden et al., 2008). This is especially relevant for Pre-Cambrian shield-like regions where locating lateral changes in the magnetic characteristics of crystalline rocks can provide a spatial constraint on possible contacts in areas which are either completely covered, or have very limited outcrop. It must be remembered though, that not all magnetic contacts will correspond to silicate defined lithological contacts and vice versa. Pilkington and Keating (2004) have examined five different methods that might be used to delineate the edges of anomalously magnetic or anomalously dense source bodies. Not one of the five methods is uniformly better, because much depends on the individual setting. Variables which might impact on the result produced by an individual method include: presence of remanent magnetization, dip of contact, presence of noise in original data, physical rock properties among the geological units being mapped and cross-sectional shape of source body. Clearly observation of co-located solutions from each of the five different methods provides increased confidence in the reliability of a given contact location.

One possible approach to testing the veracity of an interpretative geological map is to attempt the construction of a 3D geological block model from a series of 2D geological profiles. However, as noted by Musgrave et al. (2006) 'lack of outcrop and initial uncertainty between competing tectonic and structural interpretations may preclude construction of a meaningful model.' Indeed, having limited surface outcrop means there will be limited structural information (bedding planes or foliations). Critical to this type of 3D model construction is having access to information which provides some constraint on the geometry of geological contacts and their extension in the subsurface. In mineral exploration it is common to incorporate geological information derived from borehole logs to provide additional depth-based data to complement the existent surface geological and geophysical data. This additional geological data can then be used to assess the validity of prior predictions made by modelling. Yet, before the discovery of some resource commodity, it is likely that only a small number of boreholes will be available and in many cases these may have very limited depth extent, so in most cases the interpreter must rely on other types of depth constraints.

Edges detected by potential field data do not necessarily correspond to a near surface geological contact. All potential field measurements represent an integration of the signals from all anomalous physical property contrasts that fall within some range

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of the sensor. This property of potential field data has been exploited through the application of multi-scale edges, or 'worm' plots. As demonstrated by Holden et al. (2008) and Hornby et al. (1999), computing 'worm' traces or edges after multiple steps of upward continuation produces an envelope of solutions whose form has a broad scale relationship to the dip of the geological unit that is being imaged. The multi-scale edge approach does not, however, provide any direct estimate of the dip of the geological unit.

Estimates of the subsurface distribution of petrophysical contacts have been derived from mathematical inversion of observed potential field data. Unfortunately, potential field inversions are inherently non-unique. It is, however, possible to reduce the number of possible solutions if some prior geological information is included in the inversion process (Barbosa and Silva, 2006; Holden et al., 2008). In an earlier study Paterson and Reeves (1985) demonstrated that the same total magnetic intensity (TMI) anomaly can be produced by a vertical dyke that is magnetized by near vertical present day inducing field, and an inclined dyke where the magnetic remanence direction is in the plane of the dyke. To directly address these issues recent modifications to the University of British Columbia Geophysical Inversion Facility (UBC-GIF) magnetic and gravity inversion codes (Li and Oldenburg, 1996) have included the incremental addition of various geologically derived constraints which impose some limit on the resulting model solution (Williams, 2008). At the opposite end of the inversion spectrum is the GeoModeller style approach where one begins with a well defined geological model and then tests the ability of this model to satisfy the observed potential field data by iteratively modifying the physical rock property contrasts (Calcagno et al., 2006).

This analysis shows that to improve the validity of interpretative geological maps requires that we have much better control on the geometry of lithological contacts in the subsurface. Ideally this information should be derived from direct observations of features that provide 3D information, but in locations where outcrops and boreholes are sparse, there are large regions of speculation. The depth extent of anomalous source bodies are particularly poorly controlled by inversion schemes applied to supra-surface potential field surveys. To reduce the range of possible solutions which might satisfy a dataset requires the same additional geological information which is needed to construct a basic geological model. Potential field data are extremely good at defining the lateral extent of anomalous source bodies; therefore edge detection procedures offer ideal information for helping constrain the subsurface morphologies. As currently implemented, however, a severe limitation of edge detection routines is no control on the depth of the edges. The use of topographic data can aid on improving the geometry of the anomalous sources on surface, and therefore restrict the range of possible solutions and their depth.

All modern airborne potential field surveys include a sensor which records the distance between the aircraft and the underlying topographic surface. This data, combined with the standard Differential Global Positioning System (DGPS) altimeter that provides absolute elevation of the aircraft can yield high-resolution digital elevation models (DTM). In this short note we demonstrate how combining the topographic and potential field data can provide absolute dip and dip direction information regarding blind geological contacts.

The geological approach

The locus of any lithological boundary on a geological map is defined by the interaction between two 3D surfaces, one representing the envelope bounding the lithological unit and the other being the topographic surface. A third 3D surface, a fault plane, may impact on the morphology of both the topographic surface and the geological contact surfaces. On the topographic surface a fault may be represented by a lineament related to a zone of increased erosion. In most instances adjacent geological contacts should exhibit similar displacement magnitudes.

Figure 1*a* demonstrates common aspects of the interplay between the three 3D surfaces. This model incorporates an older stratigraphic sequence (strat1) which has been folded into a series of north plunging folds (fold). This older sequence was cut by a flat lying unconformity (unc) which preceded deposition of a second stratigraphic sequence (strat2). Upon completion of this phase of deposition the complete stratigraphic column was tilted to the north (tilt) and then cross-cut by two normal faults (fault1 and fault2). Finally the area is eroded and what we now see is the interplay between the geology and the current topographic surface. In an ideal scenario of 100% outcrop, if the geologist were able to see and correctly interpret the observations, the result would be the image produced in Figure 1*b*.

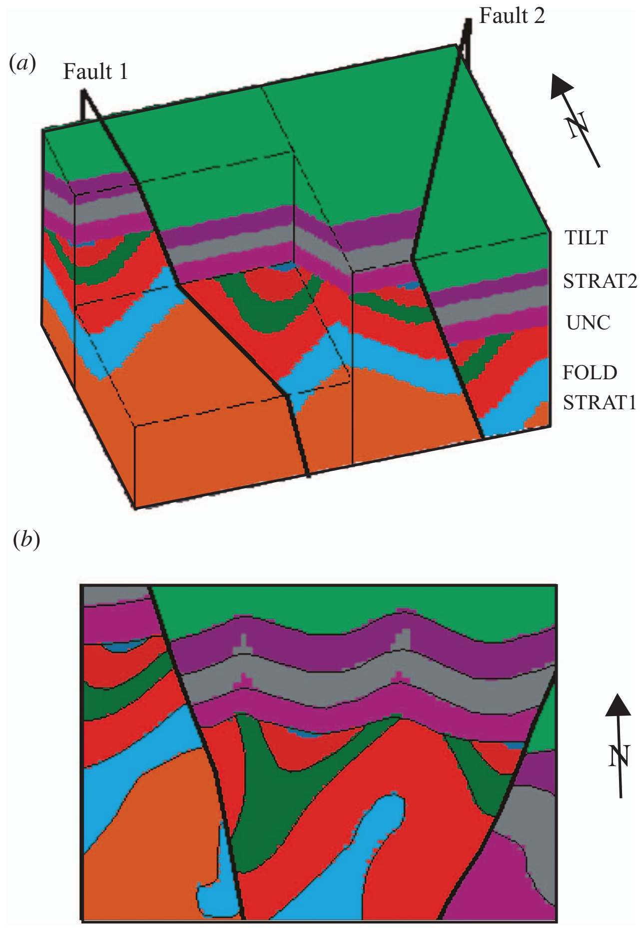

Fig. 1. (*a*) 3D perspective view of a synthetic geological model utilised to demonstrate the relationship between geological elements and current topographic surface. Strat1: older stratigraphy; fold: first folding event of strat1; unc: flat lying unconformity after the folding event; strat2: younger stratigraphic sequence deposited above the unconformity; tilt: north-rotation after the previous sedimentation event; fault1, fault2: two normal faults that cut the entire block. In order to make the geological processes/units more visible, this model does not show the topographic surface added on top (Figure 3*b*) before the computation of the geophysical images of Figure 2. (*b*) Plan view of the above.

Of course depending on one's location the amount of outcrop may actually be less than 1%. In this situation the geologist employs geometrical aspects of the relationship between topography and geology to derive an improved model from the sparse observations. An essential element common to all of the surfaces is the concept of a strike line (Figure 2*a*). This is a line that joins all points having a common elevation where the contact crops out at the surface. Each individual line is part of a family of similar lines which together define the geometry of a planar surface. In more general terms that planar surface could be a geological contact, or a fault plane. When the elevation control is provided by equi-spaced contours the resulting spacing between strike lines is directly related to the dip of the planar surface. For steeply dipping beds the strike lines are closely spaced, and vice versa for shallowly dipping beds. As implied by the name 'strike line' the direction of dip is perpendicular to the trend of the line.

Certainly the strike line approach is somewhat idealistic and is only practical in less deformed geological settings. An alternative approach is the 'three point' solution (Figure 2*b*). That is, knowing the elevation of three points which are assumed to reside on a common planar surface, it is possible to compute the dip and dip direction of that planar surface. Using this approach provides a population of apparent dip and strike data points. The overall geometry of each surface can then be defined by the family of observations that are relevant to that surface. Derivation of the surface geometry can be inferred from the mapped spatial distribution of the geometrical elements, or determined through use of a stereonet projection.

The geophysical approach

Irrespective of which geophysical sensor is deployed, all modern potential field surveys provide an image of the topographic surface in addition to the specific physical property being measured (i.e. TMI for magnetic surveys, apparent conductivity for electromagnetic [EM] surveys, etc.). After applying the relevant suite of corrections to the physical property dataset (levelling, microlevelling, reduction to the pole (in case of magnetic data), and regional/residual separation) the resulting image file contains data pertaining to physical property variations from the immediate subsurface and some contributions from deeper sources. Central to many edge detection algorithms, is the use of field gradient calculations, which further accentuate the high frequency signal content. This will highlight the presence of any near surface lithological contacts defined by the geophysical data. Although this reasoning applies to any type of geophysical data (magnetic, gravity, electromagnetic), we will focus on TMI data, due to the higher dynamic range of the data as compared to gravity, and ease of modelling compared to EM data.

In our hypothetical geological model of Figure 1 we assigned strong magnetic susceptibility values to two stratigraphic units in each of the two sequences. Computing the total magnetic field as recorded by a drape survey flown at a height of 30 m ground

(*a*)

(*b*)

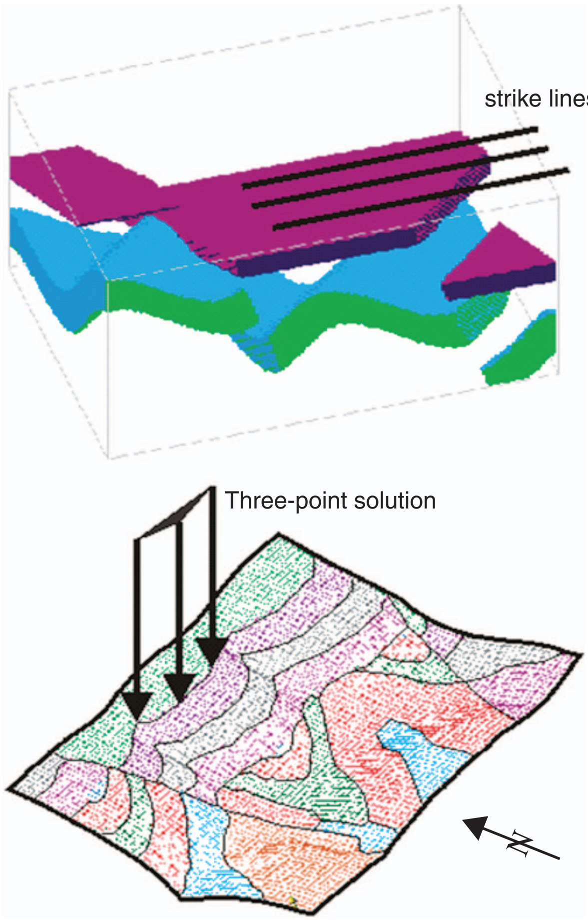

Fig. 2. The 'three point' solution approach applied to the model of Figure 1, with topography added. (*a*) 3D perspective view of the model draped on topography. Only three units are shown for simplicity. Strike lines are given on the purple unit; (*b*) The model of Figure 1*b*, draped on topography. The 'three point' solution approach consists in taking three points on a contact and solving for strike and dip of the plane defined by the points.

(*a*)

(*b*)

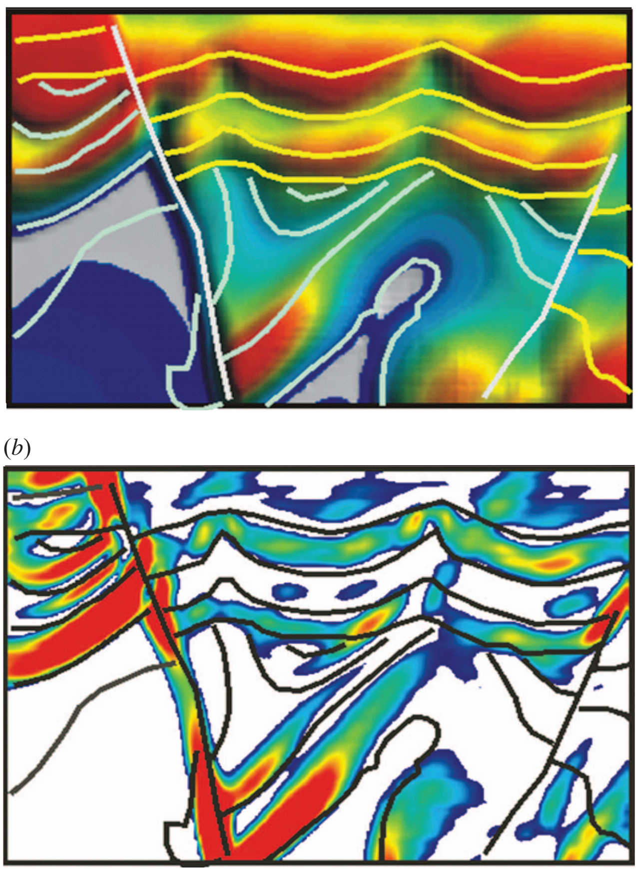

Fig. 3. Geophysical response of the model defined in Figure 1. (*a*) Total magnetic intensity (TMI) observed on surface. The geological contours from Figure 1b are shown for reference. (*b*) Total horizontal gradient from the previous TMI image, with the geological contours from Figure 1*b* for reference.

clearance in area with a local Earth's field of D = 0°, I = 75°, and intensity = 55 000 nT results in the image presented in Figure 3*a*. As expected the magnetic data clearly shows the unconformity with the younger layered sequence cross-cutting the older terrane. Details of the complex fold structure are less clearly outlined. The westerly fault is more clearly defined than the easterly fault. Computing the total horizontal gradient after RTP filtering produces the image in Figure 3*b*. It readily becomes apparent that the magnetic data do replicate many of the contacts defined in the original geological model. So clearly it would be possible to use this information to augment any sparse geological data recorded on surface. Nevertheless, it must be cautioned that the exact location of the horizontal gradient maximum does not exactly correspond to the position of the associated geological contact.

Draping the gradient-processed TMI data on the topographic surface gives direct access to a suite of X, Y, Z data points which describe the geometry of the geophysically defined contact. Assuming that these points define the surficial expression of a contact, they can then be used in a simple three point solution routine to define the local dip and dip direction of the associated contact surface. Some care is needed when choosing the location of points to be used in the three point computation. First, it must be remembered that both the physical property (magnetic/EM) and the topographic data are actually surfaces that have been inferred from a dataset which have a sparser distribution than the cell size of the gridded data. It follows from this argument that there should be significant elevation differences and spatial separation between the three points used in the calculation. If the elevation data are similar then the dip direction is weakly constrained and not representative of the main trend. This is because we are using three points to solve the equation of the plane defined by the three-points set; if the points are not sufficiently spaced in 3D space, it follows that the solution would only be representative of the small region enclosing the three points, but not necessarily would represent the more regional planar surface/structure that we want to define. Second, and in contrast, care should be exercised in regions of sharp topographic change. The minimum curvature gridding algorithm commonly used to interpolate the DTM profile data into a surface will always smooth out what are in reality sharp topographic discontinuities. It is probably more beneficial to use a triangulation (tinning) approach to defining the topography before attempting any contact/structural mapping.

Finally, it must be remembered that we are attempting to use this information to augment geological data in areas of limited outcrop. This means that the topographic surface is not the actual bedrock surface (Figure 4). If the overburden is uniform over the area then this will have little impact on the geometry of the computed geological contact surface. However, if there are large changes in overburden thickness then this could result in false geological contact information. Two possible approaches to detect false solutions based on inter- and intra-point analyses are suggested. Using the simple three point approach then, there

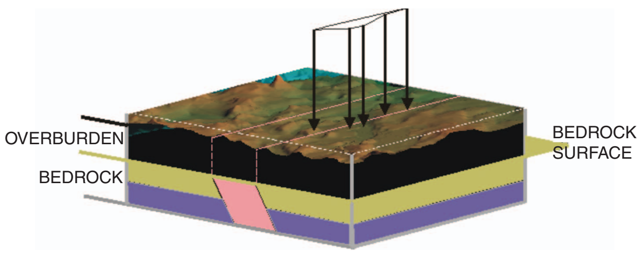

Fig. 4. Relationship between surface topography, overburden, bedrock surface and the solutions obtained by the three-point-solution method.

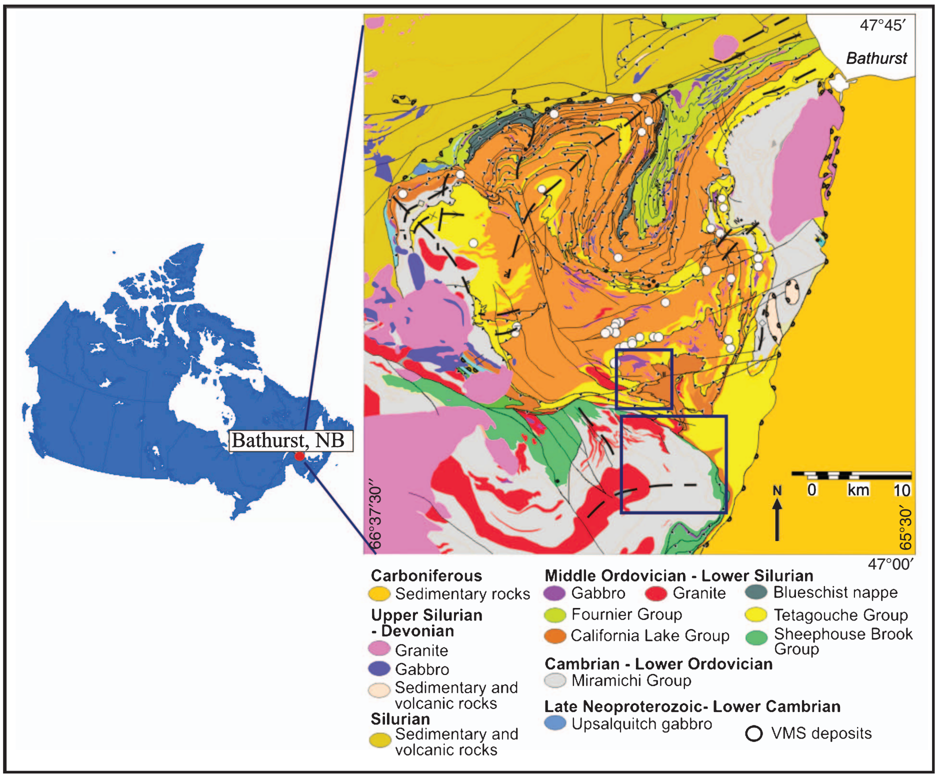

Fig. 5. Location map of the Bathurst Mining Camp and its regional geology. The small rectangle marks the location of the detail area in Figure 7; the bigger rectangle marks the location of the detail area in Figure 9. Regional geological map modified from (Galley et al., 2007).

should be some level of agreement between the geological contact information derived from adjacent solution sets; that is, all adjacent solutions along one structure/contact should cluster around the main regional trend. Thus, a kernel density approach should be able to reject the outliers from concordant solutions (Silverman, 1986). Alternatively, if one took a group of five observation points instead of just three, from this it is possible to generate 10 three-point combinations and associated strike and dip solutions. Then we cannot only compute a median and standard deviation of the strike and dip for the distribution, but generate also an error envelope that provides a measure of the internal consistency of the solution. Selecting an error threshold could be used to identify possible erroneous solutions. Both techniques are suggested as possible approaches for filtering spurious solutions, but because the goal of this article is presenting the advantage of using topography derived geometrical information rather than the filtering of it, they are not applied here.

Combining the observed magnetic and gravity data together with the commonly observed topographic data can result in the generation of a significant population of geological dip and dip direction data. This information can then be used directly to augment geological map compilation and hopefully help constrain the future geophysical model inversions.

Application of the method

The Bathurst Mining Camp (BMC) in New Brunswick, Canada (Figure 5) is one of the most important base metal mining districts in Canada. The camp hosts numerous sediment- and volcanic-hosted massive sulphides deposits and occurrences. Primary genesis of the sulphides ore bodies is directly linked to the late Cambrian and early Ordovician ocean floor volcanism related to the Paleozoic opening and closing of the Iapetus ocean. As a consequence of a long and complex history of multi-generational folding, thrusting and faulting events many of the mineral

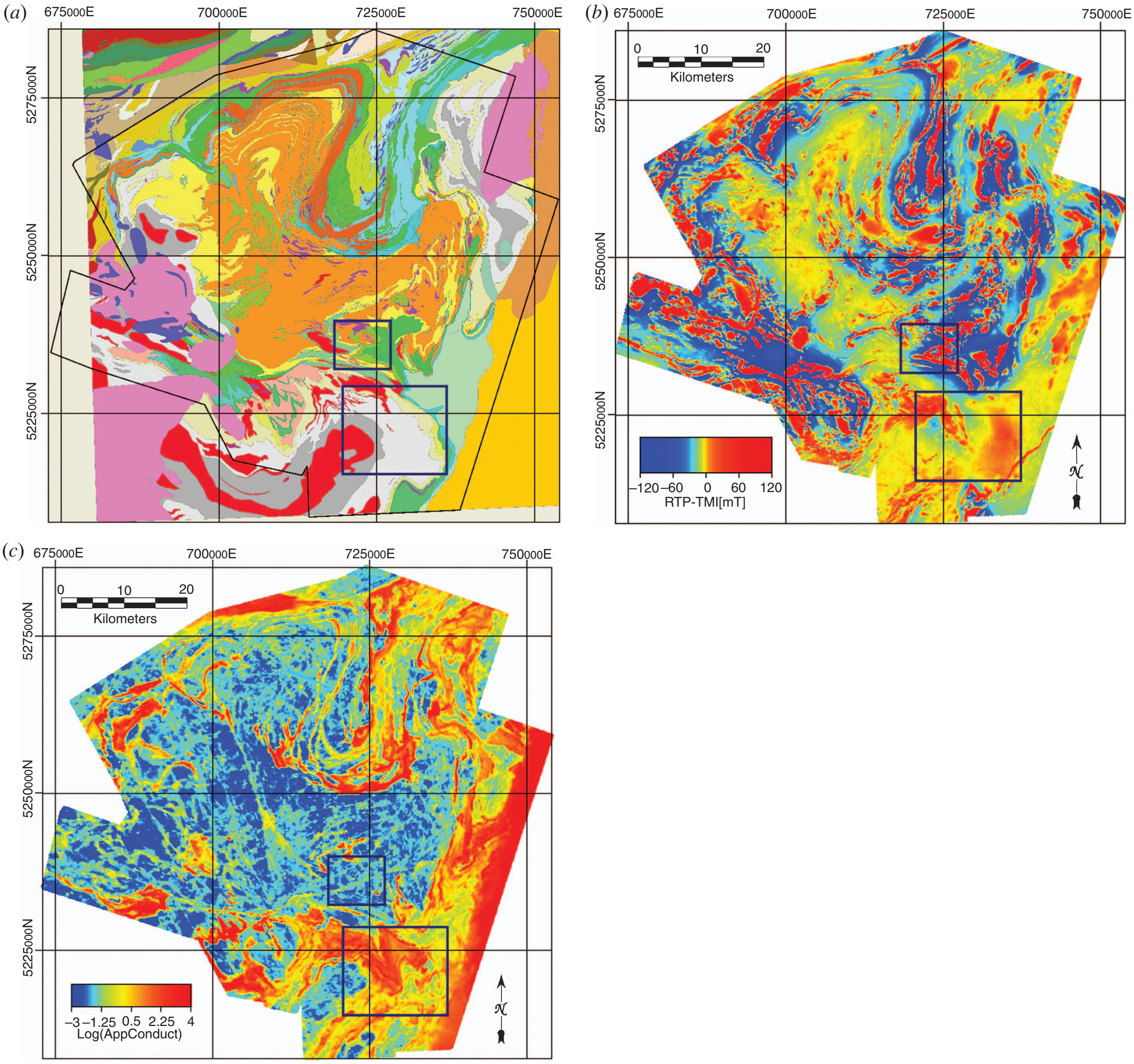

Fig. 6. Regional geology and airborne geophysics at the Bathurst Mining Camp. Geophysical data from Geological Survey of Canada (1996). (*a*) Regional geology (modified from van Staal et al., 2003). Geological legend as on Figure 5; (*b*) Pole-reduced total magnetic intensity (RTP-TMI); (*c*) Apparent conductivity (4433 Hz), displayed with a logarithmic colour scale for improved contrast. The blue rectangles in all diagrams identify the detail areas of Figures 7 and 9.

deposits have been remobilised (van Staal et al., 2003). Therefore developing a good understanding of the geometry of these fold and fault structures is critical in finding any new deposits. Outcrop in the BMC is scarce; therefore any structural information that can be derived from airborne geophysical data is invaluable.

While the sparse outcrops provided specific lithologic and structural information, the general morphology of the regional

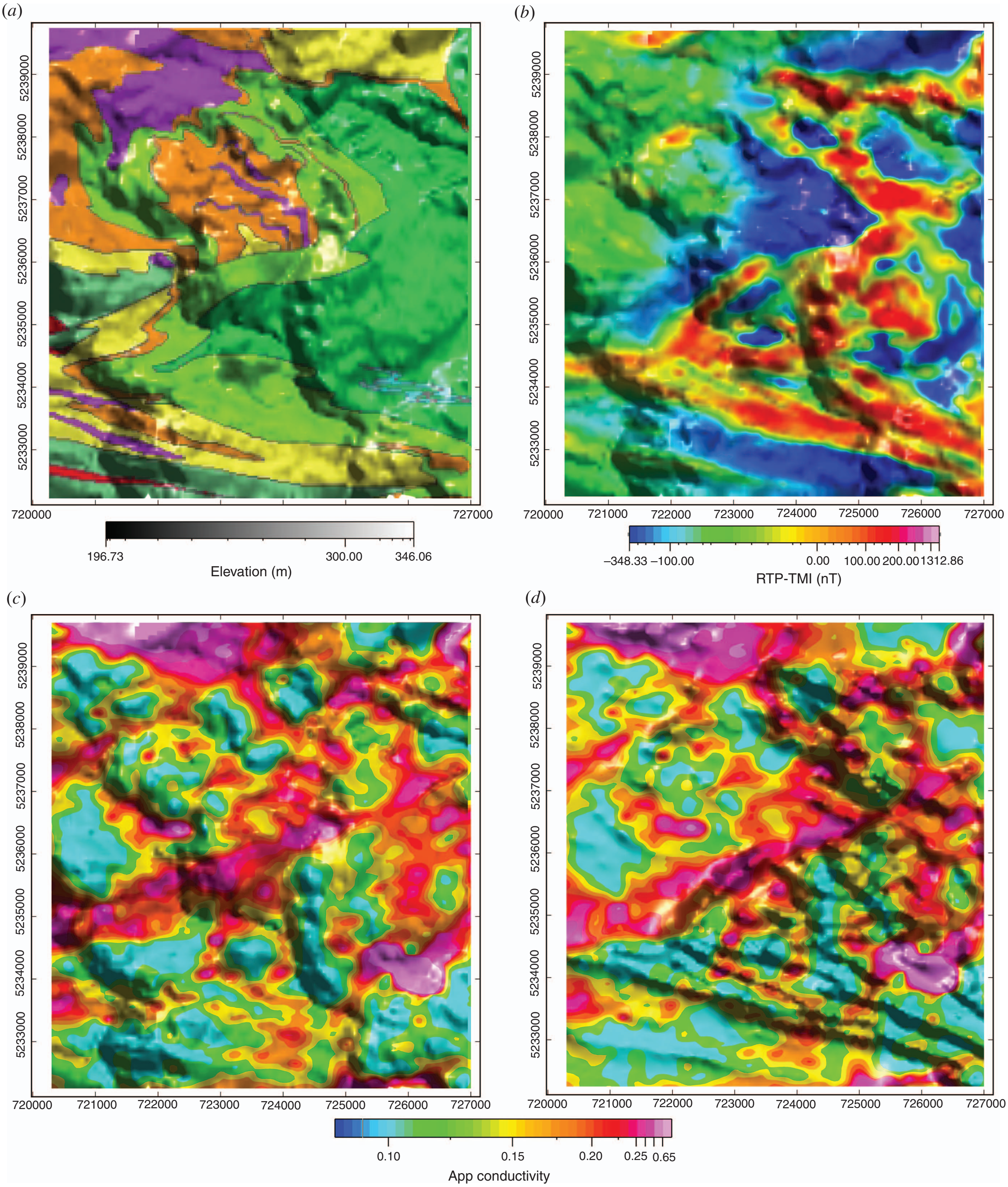

Fig. 7. Geology and airborne geophysical data at the northern inset shown on Figure 6. Geophysical data from Geological Survey of Canada (1996). Different combinations of colour and intensity layers were utilised to emphasise the existing (or lack of) correlation between the different datasets. (*a*) Regional geology (modified from van Staal et al., 2003) draped over topography; (*b*) Pole-reduced total magnetic intensity (RTP-TMI) draped over topography; (*c*) 4433 Hz apparent conductivity displayed with a logarithmic colour scale and draped over topography; (*d*) 4433 Hz apparent conductivity displayed with a logarithmic colour scale and draped over the RTP-TMI dataset of (*b*).

geology was primarily derived from airborne geophysical data. The data utilised in this study comes from the second round of the Exploration Science and Technology Initiative (EXTECH 2), carried out by the Geological Survey of Canada (GSC) in 1994 (Geological Survey of Canada, 1996). The EXTECH2 included an airborne geophysical program that comprised total field magnetic, gamma-spectrometry, and electromagnetics. The entire BMC was divided on four blocks with different flight-line directions, perpendicular to the main geological trends. All of them were flown at 60 m above the terrain and with 200 m line spacing. The magnetic and gamma-spectrometry data were microlevelled to reduce corrugations associated to line-to-line levelling artefacts. A terrain correction was applied to the magnetic data via the application of a 2nd order Taylor series to transform the data to a surface parallel to the ground, and therefore normalise the amplitude of the observed anomalies. In general the magnetic data shows the contrast between weakly magnetic felsic volcanic units and basalts, gabbros and other mafic volcanic and intrusive units (Keating et al., 2003; Figure 6). The high frequency EM response highlights the presence of conductive lithologies in the immediate near-surface area (Figure 6*c*). Locally this signal is driven by the presence of sulphides, and more graphitic shaley horizons. In many areas there is a close similarity, or complementary relationship between the magnetic and electromagnetic data suggesting that where present, the overburden coverage is of very limited depth extent and mostly non-conductive.

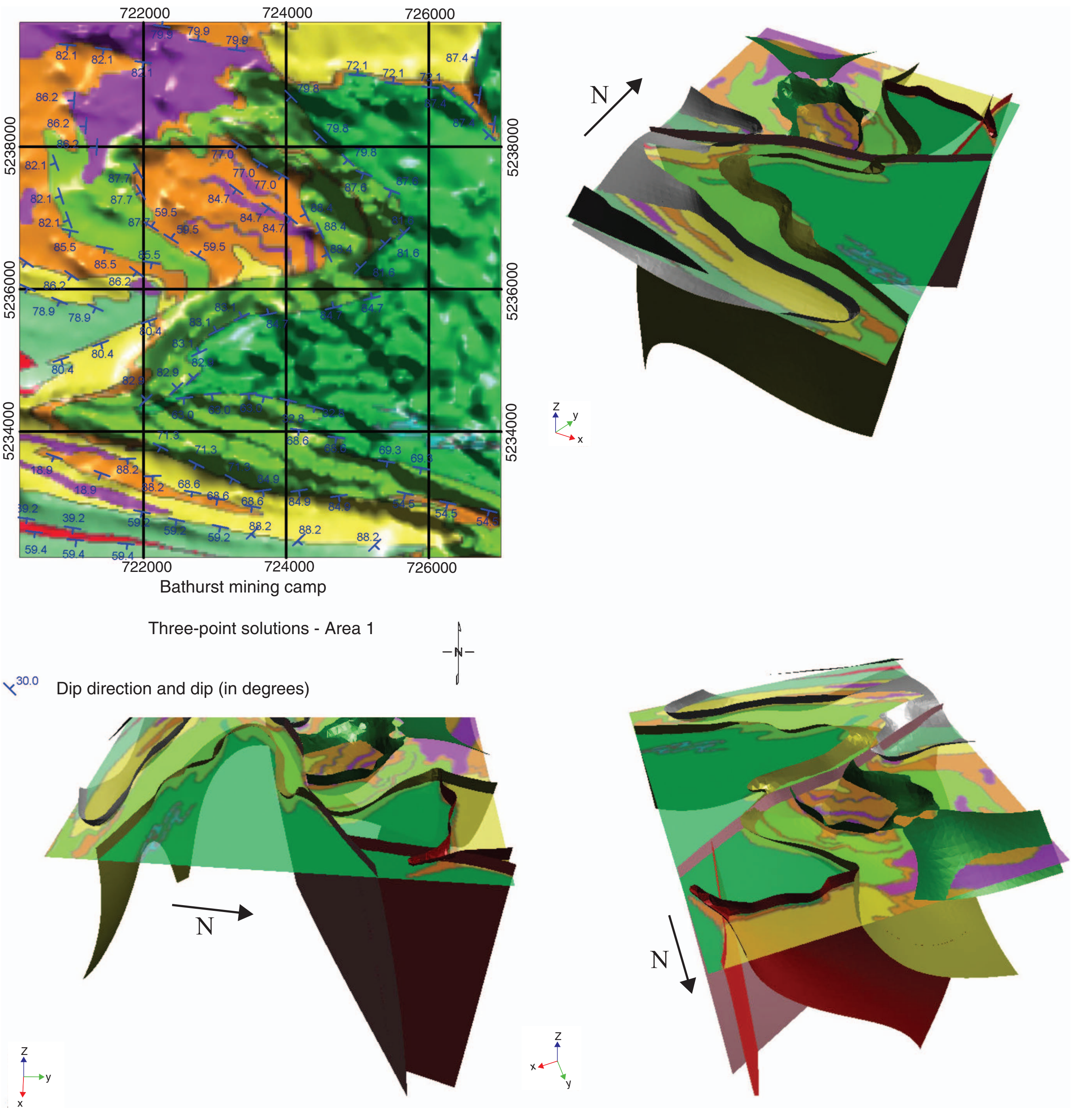

Fig. 8. Results over the first area of study (Figure 7). Strike and dip information obtained from the algorithm (top left), and perspective views of the 3D-modelling of thrust surfaces from three-point solution information. See text for details.

Locally within the camp, geological field mapping has suggested the presence of steeply plunging fold structures that are directly related to the much larger regional scale features which describe the BMC. Electrical conductivity and magnetic susceptibility varies within the different rock types within the camp. Therefore, there is no single recipe for mapping the geological contacts from their geophysical signature. We present two cases, one where the mapped geology matched the magnetic data pretty well (Figure 7), and another where the contacts were redefined after the apparent conductivity map and some discussion with geologists involved in the area (van Staal, 2009, pers. comm.; Figure 9).

Critical to the proposed method of deriving geometrical (structural) information from the relationship between the topographic surface and the geophysically defined source edges is developing some confidence in the defined location of the geological contact. That can be accomplished by computing the edges using three different approaches, as suggested by Pilkington and Keating (2004): mapping them from different datasets and establishing correlations between them; or by using the contacts from the geological map, if there is confidence on their location despite their relationship to the associated geophysical maps. In this case we used both approaches. The first case shows a situation where the mapped folds and fault

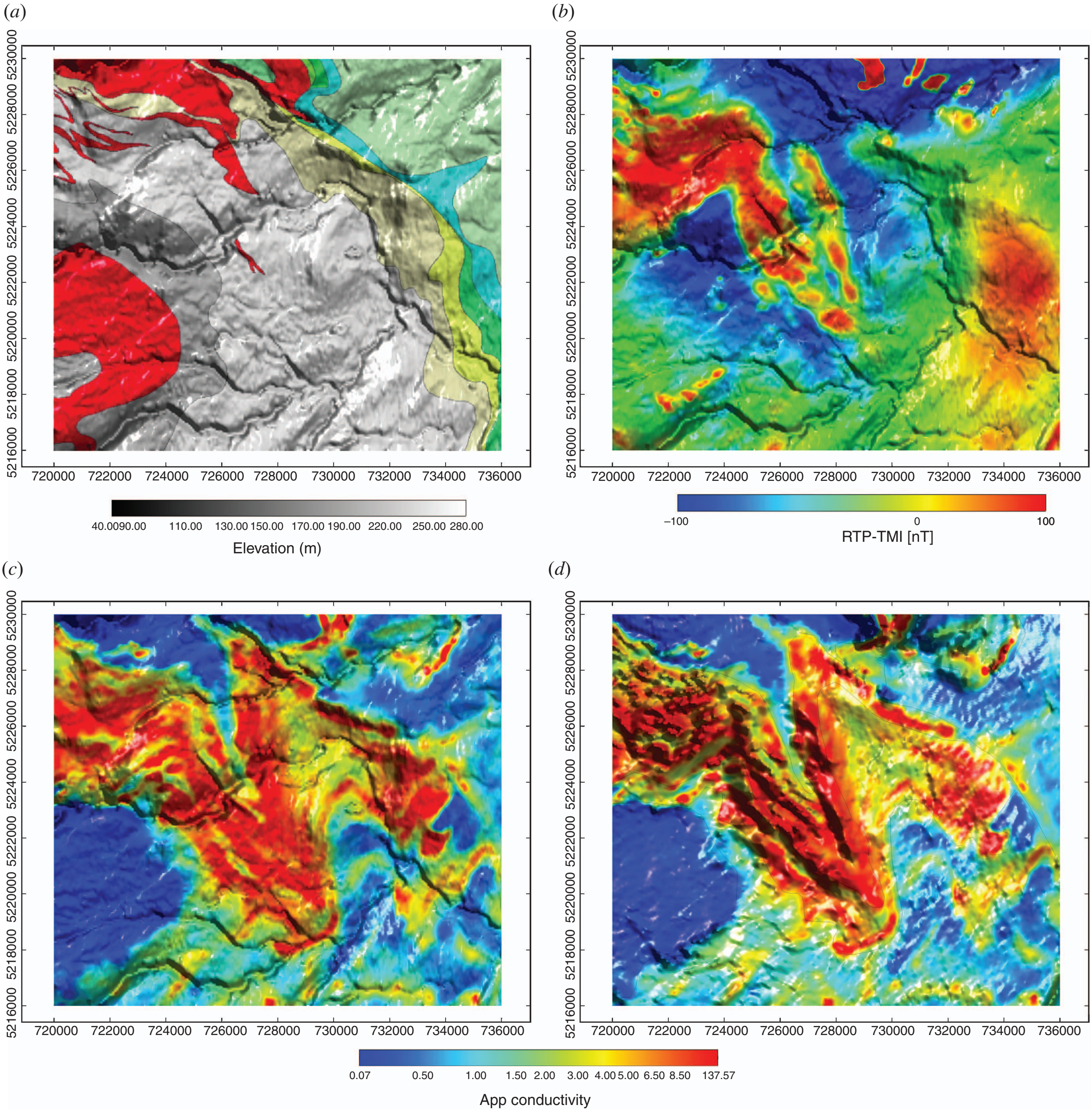

Fig. 9. Geology and airborne geophysical data at the southern inset shown on Figure 6. Geophysical data from Geological Survey of Canada (1996). Different combinations of colour and intensity layers were utilised to emphasise the existing (or lack of) correlation between the different datasets. (*a*) Regional geology (modified from van Staal et al., 2003) draped over topography; (*b*) Pole-reduced total magnetic intensity (RTP-TMI) draped over topography; (*c*) 4433 Hz apparent conductivity displayed with a logarithmic colour scale and draped over topography; (*d*) 4433 Hz apparent conductivity displayed with a logarithmic colour scale and draped over the RTP-TMI dataset of (*b*).

structures exhibit strong correlation with the pole reduced magnetic (Figure 7*a*, *b*), whereas the apparent conductivity map showed poor contact definition due to low signal. In this case, the original contacts on the geological map were utilised for the subsequent derivation of three-points sets.

By picking a series of three elevation points on the contact and computing the dip of the assumed planar surface using a standard plane equation routine given three points in (X, Y, Z) space, the dip and strike of the lithologies on the different limbs of this small fold were derived. Since the contacts are not strongly influenced by the topography present in the study area it should be readily apparent that these rocks are steeply dipping. If we take the more easterly fold, just south of coordinate 5 236 000 N, our analysis shows that the north and south fold limbs are dipping, respectively, at 83.7° towards north and 63.7° towards south (Figure 8*a*). Assuming that the rocks have not been overturned then this pattern is compatible with a synclinal structure.

Knowing the dips of the same strata on each limb of the fold an estimate of the plunge of the fold can be derived using a stereonet analysis. Combining all of these structural elements provides sufficient data to construct a 3D representation of the fold structure and associated thrust surfaces (Figure 8). The fold geometry derived from this analysis is compatible with the limited geological data that is available for this area. The algorithm presented here generates planar surfaces. However, these surfaces can be curved by adding more three-point solutions on the inflection points. As with any interpolation algorithm, the quality of the resultant surface depends on the number of input points.

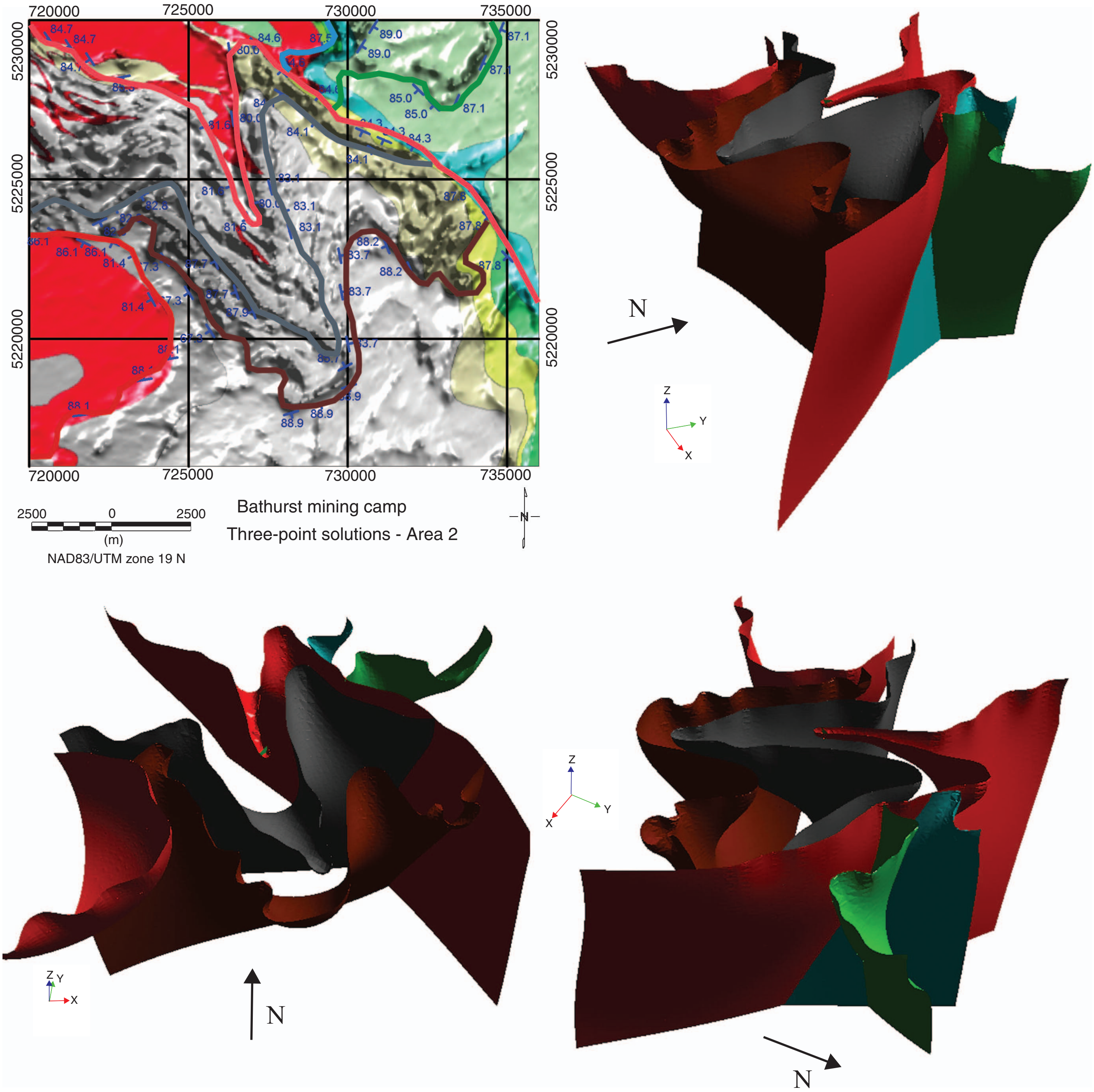

Fig. 10. Results over the second area of study (Figure 9). Strike and dip information obtained from the algorithm (top left), and perspective views of the 3D-modelling of thrust surfaces from three-point solution information. See text for details.

Second, we tried the same technique on another area south of the previous one (Figure 9; see Figure 6 for location), where the local geology was less constrained (van Staal, 2009, pers. comm.). In this case both the RTP-TMI and Apparent Conductivity maps show a series of tight folds in the centre of the area (724 000 to 732 000 E and 5 218 000 to 5 228 000 N), whereas the current geological map shows it all as a uniform unit of metasediments of the Miramichi group (van Staal et al., 2003). By using the Apparent conductivity map to redefine contacts (Figure 10*a*), the same approach of digitizing sets of three-points in (X, Y, Z) space was followed. Strikes and dips were then computed as on the previous case, and a 3D model of the entire area was computed (Figure 10). In this case, the fold structure shows steeper dipping limbs (>80°) than on the previous example. The Middle Ordovician granites of the western side of the area (in red) are limited by a fold structure steeply dipping at 88°.

Conclusions

All geophysical inversion models are inherently non-unique. Often a primary limitation is imposed by a lack of knowledge of the physical property contrasts associated with specific lithologies. Many of the newer geophysical inversion packages attempt to minimise the range of possible inversion solutions by introducing some form of a priori geological constraint at the beginning of the inversion process. One of the more difficult issues to address with this type of approach is determining any geometrical constraint on a contact boundary. In the absence of any evidence to the contrary, a completely unconstrained inversion usually produces vertically aligned structures. This interpretation may be in total conflict with the actual geology. A further complication arises when magnetic remanence is present. It is easily possible to confound the divergent geometry of the magnetic field for dipping geological strata. Depending on the relationship between the direction of the remanent magnetic field and the dip of the geological strata it is possible to observe the same total magnetic field anomaly over a rock having only an induced magnetization and one in which remanence dominates. Even when the magnetic field is wholly induced, 2D magnetic modelling is only really capable of detecting any difference in the direction of dip of a rock unit when that rock unit is shallowly dipping. When rocks are steeply dipping rarely is it possible to determine the dip direction since the difference between the two options is often within the noise limits of the magnetic data.

The combined edge detection/topographic technique outlined in this study provides a possible approach to obtaining geological contact geometry data which can be used in the construction of a preliminary geological model. This derived geological information should first be assessed for its compatibility with any directly observed geological data. Once verified it can be used to help constrain the preferred geological map interpretation being developed by the field geologist. However, for the method to work, the scale of the problem and the resolution of the data being utilised must be consistent. That is, one should not attempt to resolve local-scale features with regional-scale topography and/or geophysics. Most of the public domain topography (Shuttle Radar Topography Mission [SRTM], Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model [ASTER-DEM]) is limited to 30 m pixel size. That would be sufficient for kilometre-scale features, but not for features in the same order of magnitude of the pixel size. If higher resolution is required, one option is airborne-survey derived DEMs (although to overcome the 30 m resolution, <100 m line spacing would be required, considering the standard grid cell size of 1/4 or 1/5 of the line spacing). Otherwise, topographically surveyed DEMs are required. A further limitation/restriction is the assumption of planar surfaces for the contacts/surfaces being modelled. Depending on the scale of the problem, this simplification might or might not be suitable.

Future possible extensions of this approach might include linking the computed dipping surfaces with subsurface multi-edge (worm) contacts.

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References

Barbosa, V. C. F., and Silva, J. B. C., 2006, Interactive 2D magnetic inversion: A tool for aiding forward modeling and testing geological hypotheses: *Geophysics*, **71**, L43–L50. doi:10.1190/1.2258093

Calcagno, P., Courrioux, G., Guillen, A., Fitzgerald, D. J., and McInerney, P., 2006, How 3D implicit geometric modelling helps to understand geology: The 3D-geomodeller methodology: *XIth International Congress, Society for Mathematical Geology*.

Geological Survey of Canada, 1996, Release of Airborne Geophysical Survey Data: Bathurst, New Brunswick. Open File 1394, 1394.

Galley, A. G., Hannington, M. D., and Jonasson, I. R., 2007, Volcanogenic massive sulphide deposits. *In* W. D. Goodfellow (ed.). *Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces and Exploration Methods*: Geological Association of Canada, Mineral Deposits Division, 141–161.

Holden, E.-J., Dentith, M., and Kovesi, P., 2008, Towards the automated analysis of regional aeromagnetic data to identify regions prospective for gold deposits: *Computers & Geosciences*, **34**, 1505–1513. doi:10.1016/j.cageo.2007.08.007

Hornby, P., Boschetti, F., and Horowitz, F. G., 1999, Analysis of potential field data in the wavelet domain: *Geophysical Journal International*, **137**, 175–196. doi:10.1046/j.1365-246x.1999.00788.x

Keating, P., Thomas, M., and Kiss, F., 2003, Significance of a high-resolution magnetic and electromagnetic survey for exploration and geologic investigations. Bathurst mining camp: *Economic Geology Monographs*, **11**, 783–798.

Li, Y., and Oldenburg, D. W., 1996, 3-D Inversion of magnetic data: *Geophysics*, **61**, 394–408. doi:10.1190/1.1443968

Musgrave, R. J., Grewar, J., and Vega, M., 2006, Significance of remanence in stawell goldfield aeromagnetic anomalies: *Australian Journal of Earth Sciences*, **53**, 783–797. doi:10.1080/08120090600827454

Paterson, N. R., and Reeves, C. V., 1985, Applications of gravity and magnetic surveys: The state-of-the-art in 1985: *Geophysics*, **50**, 2558–2594. doi:10.1190/1.1441884

Pilkington, M., and Keating, P., 2004, Contact mapping from gridded magnetic data-A comparison: *ASEG, 17th Geophysical Conference and Exhibition*.

Silverman, B., 1986, *Density Estimation for Statistics and Data Analysis*: Chapman & Hall.

van Staal, C. R., Wilson, R. A., Rogers, N. A., Fyffe, L., Langton, J. P., McCutcheon, S. R., McNicoll, V., and Ravenurst, C. E., 2003, Geology and tectonic history of the bathurst supergroup, Bathurst mining camp, and its relationships to coeval rocks in southwestern New Brunswick and adjacent maine – a synthesis: *Economic Geology Monographs*, **11**, 37–60.

Williams, N., 2008, Geologically-Constrained UBC-GIF Gravity and Magnetic Inversions with Examples from the Agnew-Wiluna Greenstone Belt, Western Australia: University of British Columbia.

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ポテンシャル場データからの地質境界抽出法

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要 旨： 地質図作成過程において、点在する露頭の情報は空間的に疎な幾何学的計測と結合され、フィールド地質学者の解釈のもとで一つのものとして実体化される。この解釈図の実際の真実性は、その地域の地質の複合体からなる露頭の頻度や分布に部分的に依存する。物理探査は一般に、データ点の分布を拡張する道具として使用される。しかしながら、(a) 物理探査の逆解析は本来的に解の唯一性の問題があることや(b) 特定の岩層に関する物理学的特性に関する知識が不足していることなどにより、物理探査は幾何学的な制約条件を十分に与える事ができないことが一般的である。
本論文では、地球物理学的なエッジ検出ルーチンと地形データからの「三点」解法の併用を走向・傾斜のような地質境界の抽出手法の一つとして提案する。この手法は、地質学的初期モデルの構築に役立つ。得られた地質情報に関して、最初に問題のスケールと整合することを確認し、その後に直接計測された何らかの地質学的データとの整合性を評価する必要がある。いったん実証されると、フィールド地質学者によって作成中の地質図に対する適切な解釈に制約条件を与える目的で、その情報を使用することが可能となる。この手法は地質境界を平面としてモデル化する。そのため、この仮定が問題のスケールや幾何を満たすことを確認する必要がある。カナダのバサースト・マイニングキャンプおよびニューブランズウィックの二つの褶曲層序における適用例を示す。

キーワード：バサースト，ポテンシャル場，3 次元モデリング，地形

포텐셜 필드 자료를 이용한 지질학적 경계 구조 해석

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요 약： 연결성이 좋지 않은 노두, 주향 경사 등의 지질 구조선을 연결하여 지질도를 작성하는 과정은 지질학자의 주관적인 견해를 배제하기 어렵다. 따라서 이러한 지질도는 좁은 지역들에서 나타나는 노두의 복잡한 공간적 분포를 이용하여 해석하게 된다. 또한, 물리탐사 자료를 이용하여 부족한 지질구조 정보를 보완하는 연구들이 수행되고 있으나, 물리탐사 자체가 가지는 역산해의 비유일성 및 각 지질 구조간의 물성 차이에 대한 불확실성으로 인하여 많은 제한점을 갖고 있다. 이번 연구에서 제안하는 방법은 예비 지질 모델 구현에 이용될 수 있는 물리탐사 자료 해석을 통해 획득된 구조 경계 정보와 지형학 자료의 삼점 해석 결과를 이용하여 주향 경사와 같은 지질 구조 정보를 제공할 수 있다. 이를 통하여 추정된 지질 정보들이 지질 조사를 통해 획득된 정보와 결합되기 위해서는 공간 규모 측면에서의 호환 가능성이 검증되어야 하며, 검증된 자료들은 평면상의 자료로 구성되어 지질학자들이 지질도를 작성하는 과정의 초기 자료로 이용되어진다. 따라서 해석된 지질도는 추정된 지질 정보와 공간적 구조적으로 부합되어져야 한다. 이 연구에서 개발된 알고리즘은 캐나다 뉴브런즈윅주 배서스트 광산 부근 두 지역의 습곡구조에 적용하여 해석하였다.

주요어：배서스트, 포텐셜 필드, 3 차원 모델링, 지형