Eugen Tudor, 2013

# 3-Dimensional analyses* of deep-water deposits in Los Molles Formation, La Jardinera area, Neuquen Basin

*Calculating thickness trends for stratigraphic units using remote sensing data

## 1. Introduction

The Los Molles formation, part of the Cuyo Group, is a sedimentary succession deposited during the Early Jurassic during a period of increased subsidence, outcropping in the Southern Neuquen basin, in the La Jardinera area (fig.1). It presents great outcrop exposure for deep water lithologies, offering a clear perspective of an oblique down-dip profile and along strike profile according to the progradation of the deep water depositional system towards the NE.Being affected by a typical arid climate as part of Northern Patagonia and located close to the foothills of the Andes, the area is not covered by proeminent vegetation, with the sandstone cropping out on steeper slope profiles with the finer deposits (mudstones) dominating the low gradient slopes, overlain by a thin interval of soil. The goal is to use slope gradients, xyz data and field data (strike-dip measurements, GPS measurements) in order to isolate the most continuous sandstone intervals over the entire area, creating structural and thickness maps for different stratigraphic intervals.

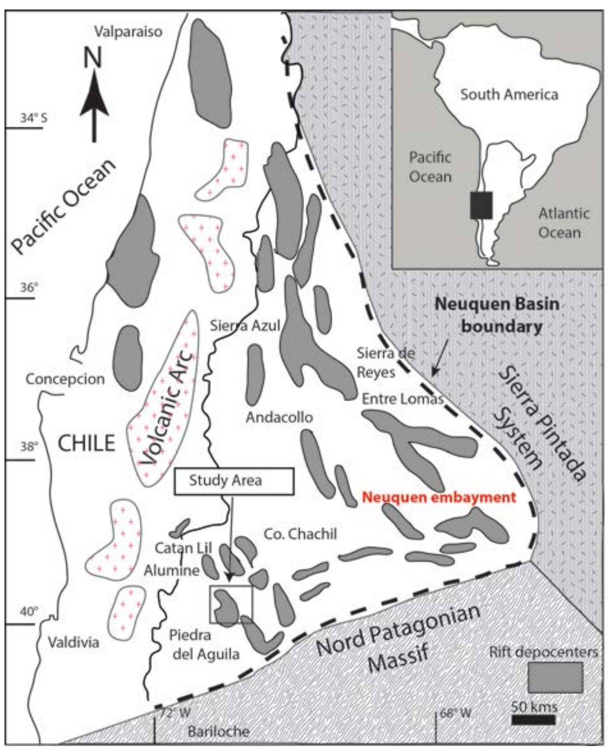



Fig. 1 Location Map of Study Area (Franzese 2006)

## 1. Dataset

A digital elevation model (DEM, Res: 30 m) is an essential part of spatially analyzing the elevation data, associated with a satellite high resolution image offers a good perspective for lithology distribution in the area. Field data (GPS data acquired using a hand held Garmin GPS device, strike-dips measurements using a Brunton geologic compass) will be associated with the DEM and the satellite image(fig. 2) in order to better illustrate spatial correlation.

The DEM data (fig. 3) is available through the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The ASTER data (0.00027777778, 0.00027777778) was downloaded online (http://asterweb.jpl.nasa.gov/gdem.asp) and georeferenced over the study area (La Jardinera area, using WGS 1984, UTM zone 19 S as a projection datum). Additional data was added from the field (GPS data points) acquired by "walking out the units" in order to determine regional correlation for stratigraphic units.

All the data must be converted to the UTM coordinate with the following properties:

Spatial Reference: WGS_84_UTM_zone_19S

Linear Unit: Meter (1.0000000)

Angular Unit: Degree (0.0174532925199433299)

False easting: 500000

False northing: 10000000

Central meridian: -69

Scale factor: 0.9996

Latitude of origin: 0

Datum: D_WGS_1984

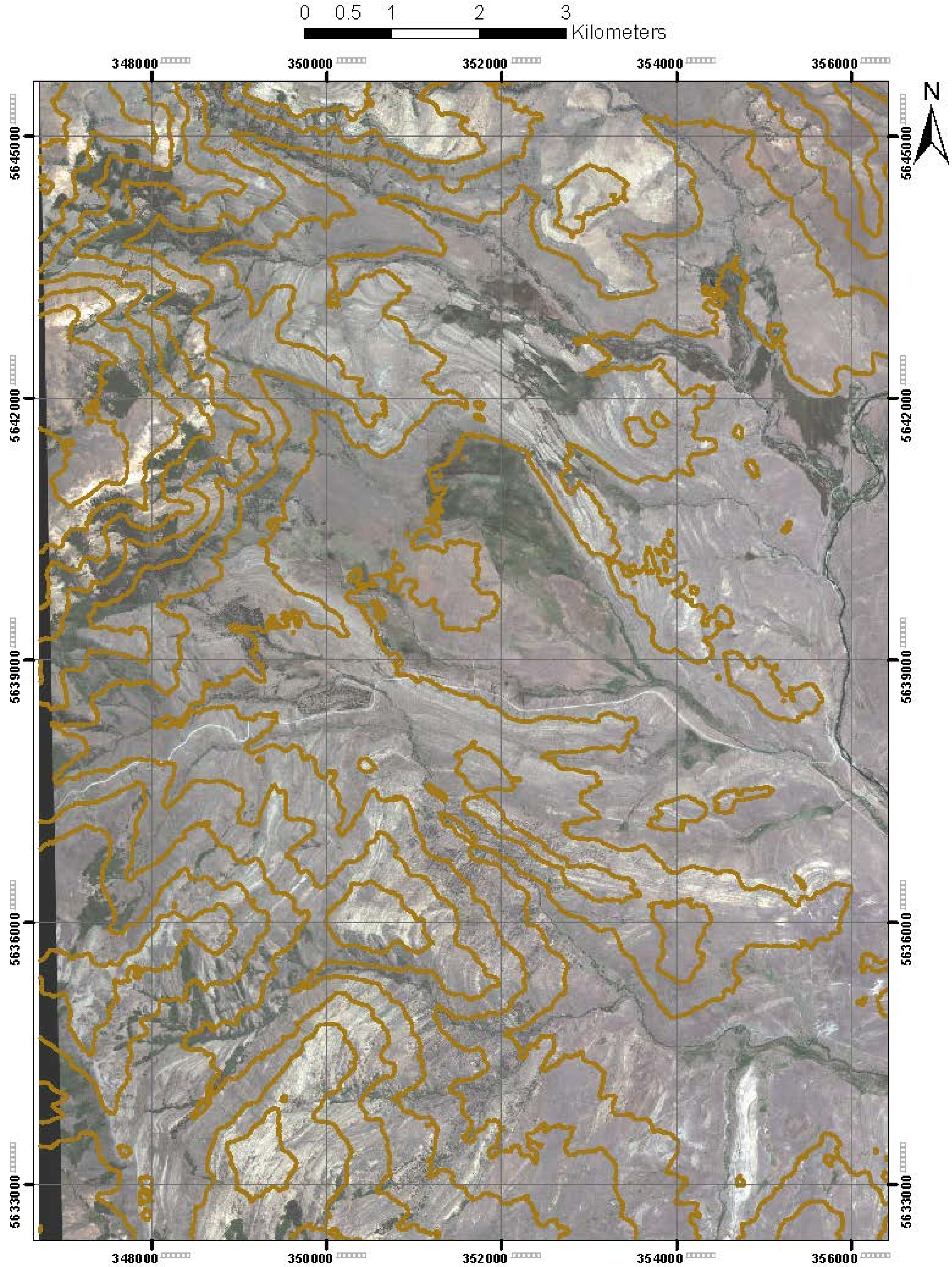



Fig. 2 High resolution satellite image showing outcrop exposure in the La Jardinera area with contours (100 m spacing)

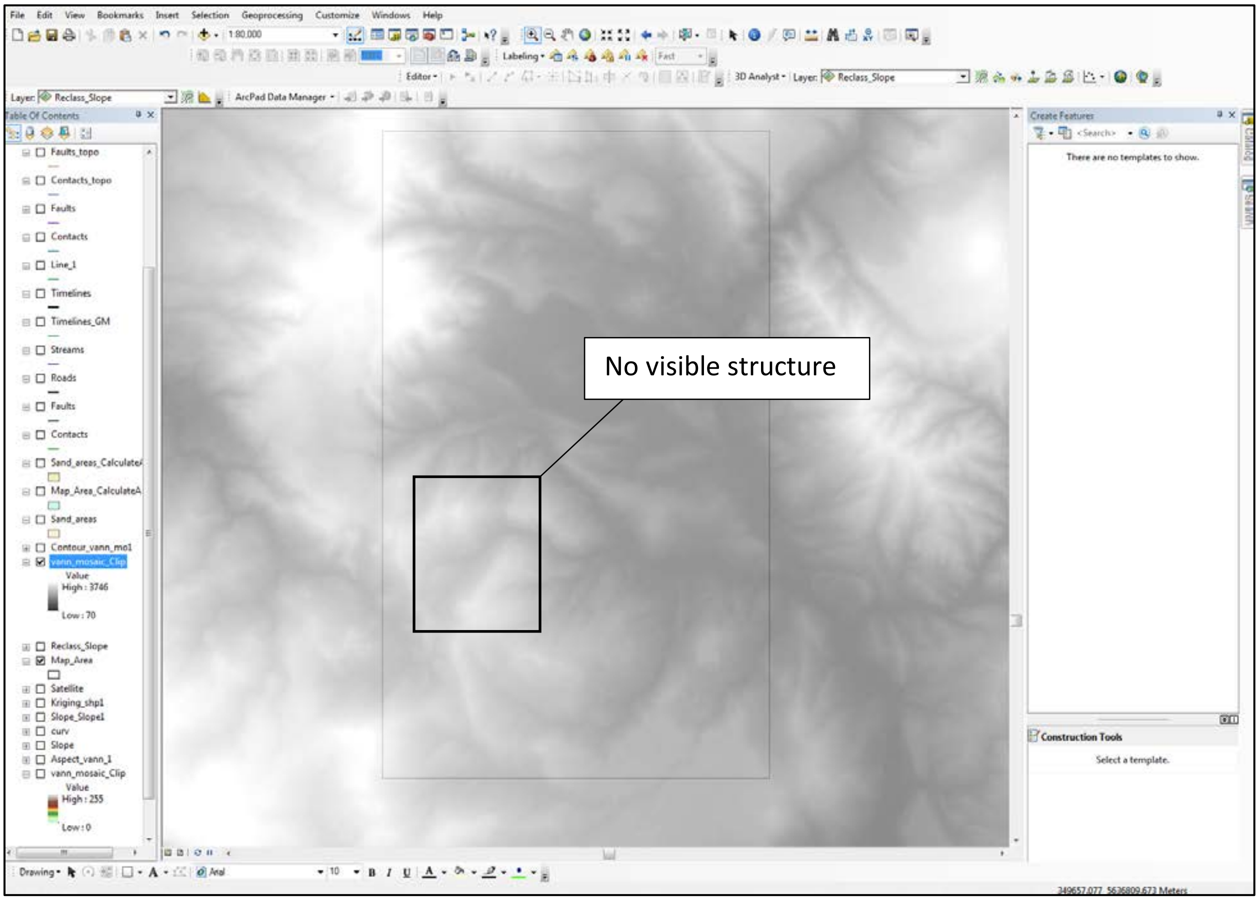



Fig. 3 Snapshot of DEM in the study area showing no discernable structure in the area

## 2. Workflow

In order to identify stratigraphic intervals we will use a combination of field data and satellite imagery. We are interested in obtaining a good regional stratigraphic correlation and to observe, if possible, thickness variations along the stratigraphic intervals. The area presents structural complexity with an anticline and a syncline deforming the strata (fig. 4). Using strike and dip measurements from the field we know that the variability of the dipping strata is extensive, with bigger dip values close to the axis of the structural features and smaller dip values as we move away from the axes. Besides the structural complexity that resulted from the thrusting, the volcanic intrusions also complicate things. We observe topographic highs where magmatic intrusions have intruded the surface. The stratigraphy doesn't seem to be displaced, but the topographic variability complicates things, thus we need to take into account the slope gradient for thickness calculations.

In order to calculate the true thickness for a given stratigraphic interval we will need digitized polylines, from which we will extract z values from the DEM and together with the slope and dip values of a given unit we can apply the mathematical formula (Thickness=Width*sin(Dip-Slope)).

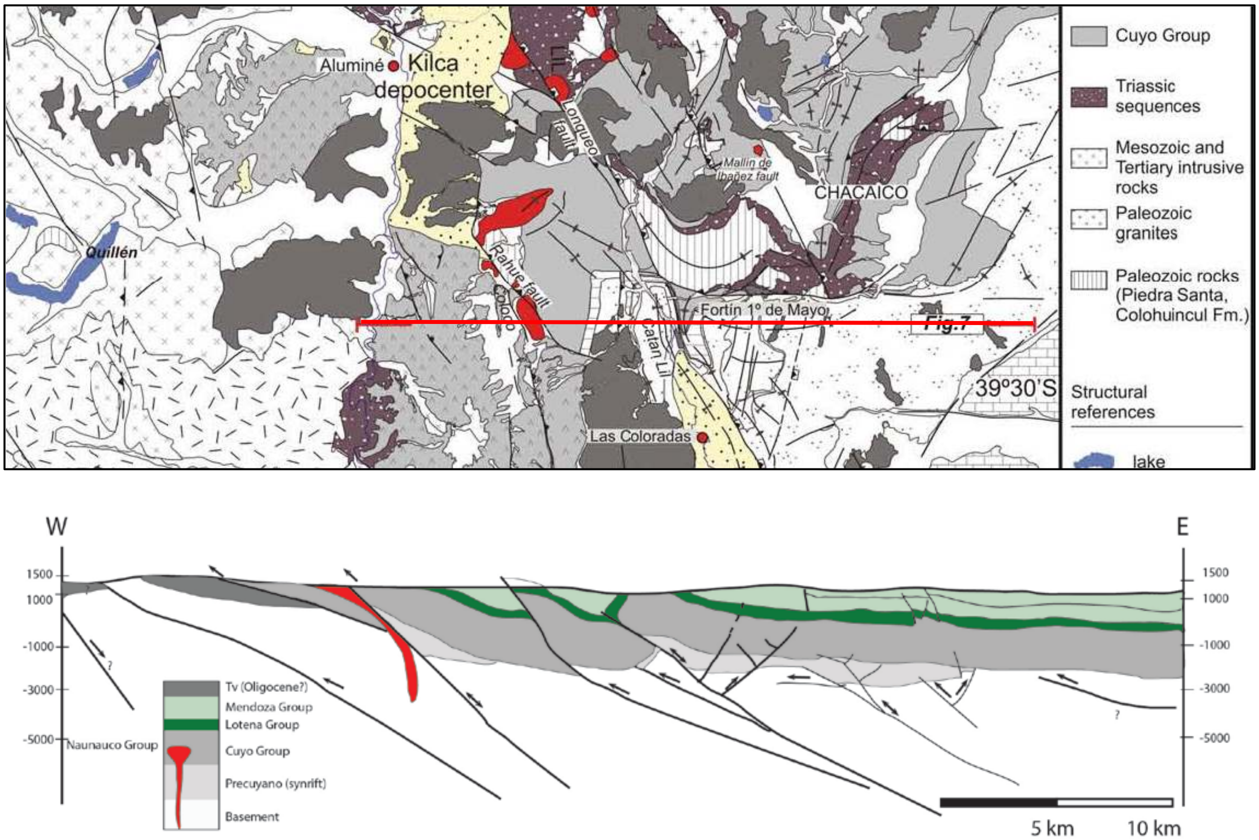



Fig.4 Geologic map of the study area and cross-section showing the structural complexity (García Morabito and Ramos 2012)

## 3. Data Processing

3.1 The Color map for the satellite image (fig. 5) has been changed in order to better illustrate the outcrop belt.

3.2 Create contours using 3D Analyst Toolbox - > Raster Surface -> Contour. Define contour spacing as you wish.

3.3 Trace top and base of the stratigraphic unit using satellite image (fig. 4) and GPS data from the field, with the 3D Analyst tool -> Interpolate Line -> Profile Graph. Export data to .xls format and import the data in ArcMap as x, y data (File-> Add Data -> Add XY Data).

3.4 Open Attribute Table. You should have X, Y, Z data from the topographic profile for each profile (top and base of strata)

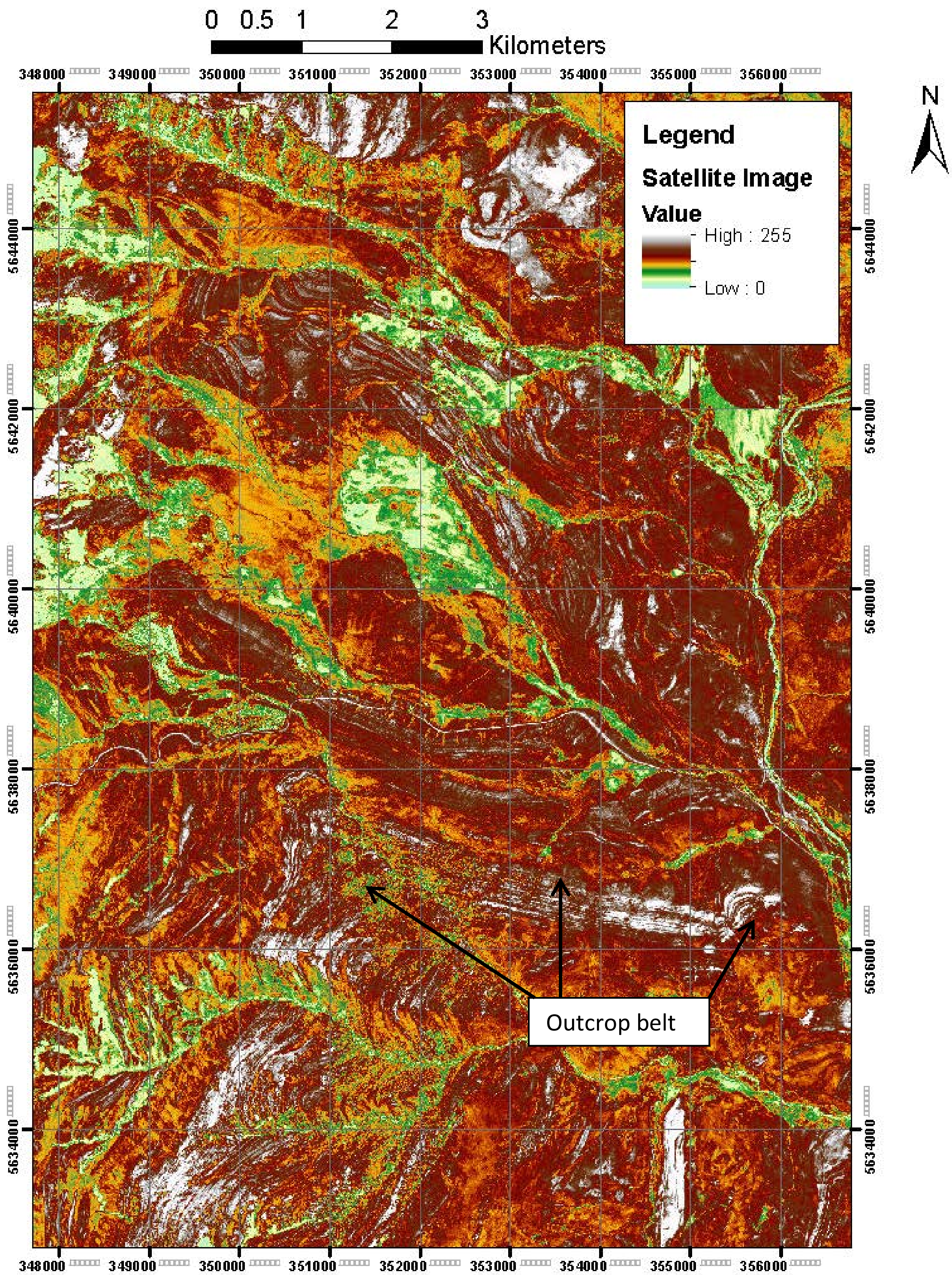



Fig. 5 Satellite image showing outcrop traces in the area

3.5 Create a table that contains these fields (at the very least:

a) Unique ID: This might be a concatenated field based on the IDs of your two points. If your table contains the IDs of both points as well as a concatenated ID field, you can join the data together at the end.
b) X coordinate of the first point
c) Y coordinate of the first point
d) X coordinate of the second point
e) Y coordinate of the second point
f) Note: X and Y coordinate fields can be created by calculating geometry in a point layer's attribute table

3.6 Open the XY to Line tool (Data Management Tools > Features > XY to Line).

a) Make sure the ID field is specified.
b) GEODESIC should be the line type so that a straight line is created

1. Open the attribute table of the resulting layer.
2. Add a field (type: Double) named Distance
3. Right click on the heading of Distance, click Calculate Geometry, and calculate the length in whatever units you wish.
   (Workflow can be found here: http://kb.mit.edu/confluence/pages/viewpage.action?pageId=11338190)

Next steps:

At this point you should have two layers with points evenly spaced and a layer (polylines) with the distance between the two layers (a swath of lines connecting opposite matching points).

1. In order to calculate the thickness (fig. 6) we will need to assess in which direction are the beds dipping:

   In our case the beds are dipping in the same direction of the slope at an angle greater than the slope with an apparent thickness measured parallel to dip direction. This case can change often throughout the study area. The formula must be modified accordingly.

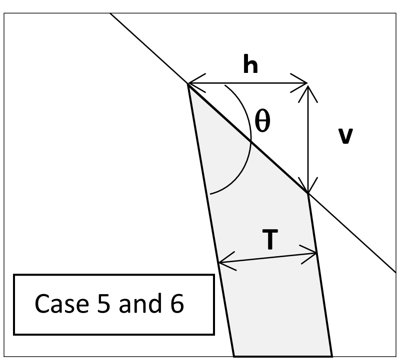



Fig. 6 Case for Dipping beds and Slope

T =h(sin θ) - v(cos θ)

-where h represents the horizontal (map) apparent thickness in dip direction
-where v represents the elevation difference between top and bottom of bed
-where θ represents the true dip of bed
-where T represents true thickness

The angles θ should be converted from Degrees into Radians for the Field Calculator using: Radians= (Degrees*π)/180

From the two layers we found the Distances between points (that will be the width of the outcrop (W). Now we need to find the height (H) between the two layers.

a) Open Attribute Table of the layer you just created. You will need the elevation values from the input data. Join the data from the tables using the "Join" function. Turn all fields off that don't contain X, Y data from the two layers, Distances and the two fields with elevation. "Add field" (type: Long Integer) and name it Differences. Open Field Calculator for the layer and calculate (Elevation 1 – Elevation 2).
b) "Add field" – we will need to calculate the DIP for the strata using the "three point problem" method. Add Dip values to the field after calculating using point values chosen by the user according with the geology (outcrop belt can change strike orientation). In this case from field measurements it looks that the strike remains constant and the dip has a similar value along the outcrop belt.
c) "Add field" – we will need to convert the Dip into Radians (Radians= (Degrees*π)/180)

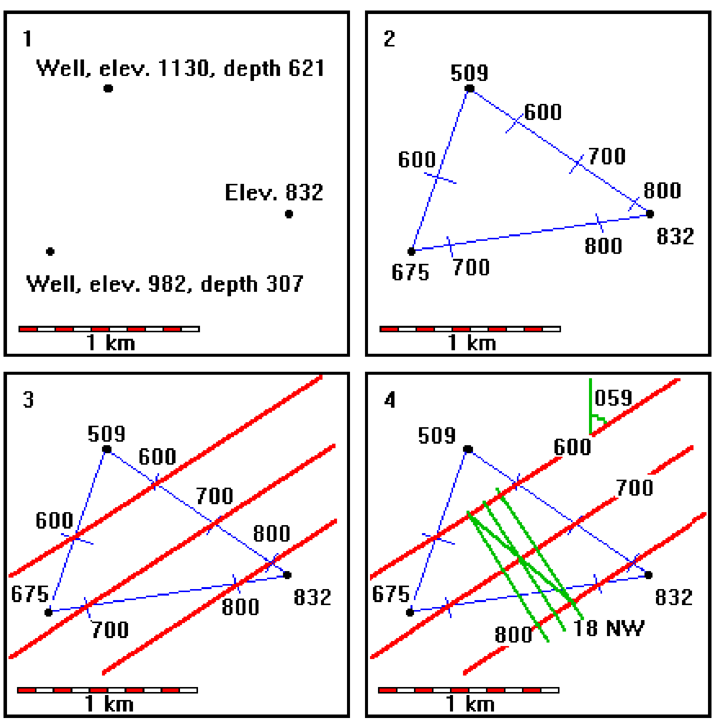



Fig. 7 "Three Point Problem" graphical method illustration

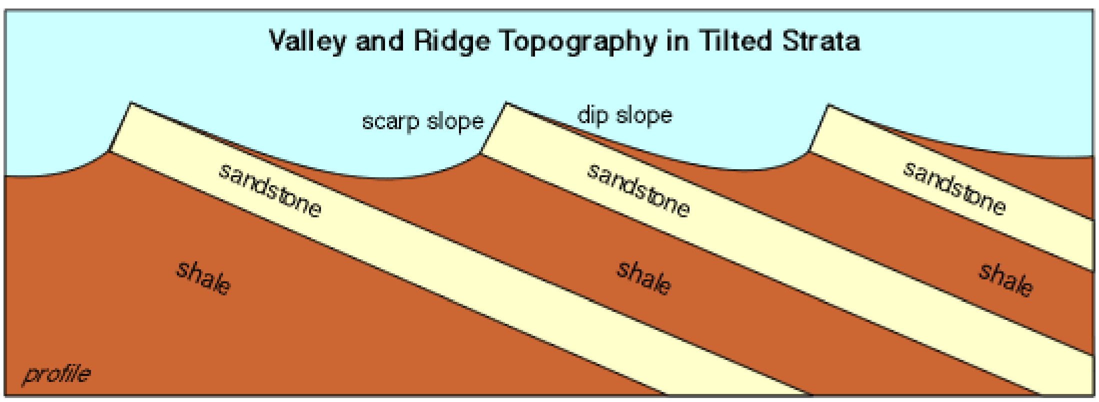
**Results**

The aim of this project is to produce thickness maps using remote sensing data with field data, if possible.

In order to create maps we have the possibility of using several spatial interpolation techniques in ArcMap. For this project we used Natural Neighbor (ArcToolbox/Spatial Analyst Tools/Interpolation/Natural Neighbor), this method is ideal as it won't produce peaks or pits outside of the data. Other methods such as Trend, inverse distance weighting or krigging were tried but the results weren't useful.

The map was created using calculated thicknesses and XY data (top of unit) from the Attribute table of the outcrop belt.

A structural map was created using the same technique in order to illustrate the elevation variation along the outcrop belt. The data shows dip towards the West (valley) and N-NE (general trend) with a small slope towards the East (valley). The following figure illustrates the general trend along a cross-section parallel with the dip.




**Observations**

This method can be applied using only Digital Elevation Models and satellite imagery. The dip and strike if not measured from the field can be calculated directly in ArcGis, this is highly recommended especially if the outcrop belt is changing orientation along a profile. The slope orientation in relationship with dip direction for strata is an important aspect as it can give calculation errors (negative values) for the true thickness.

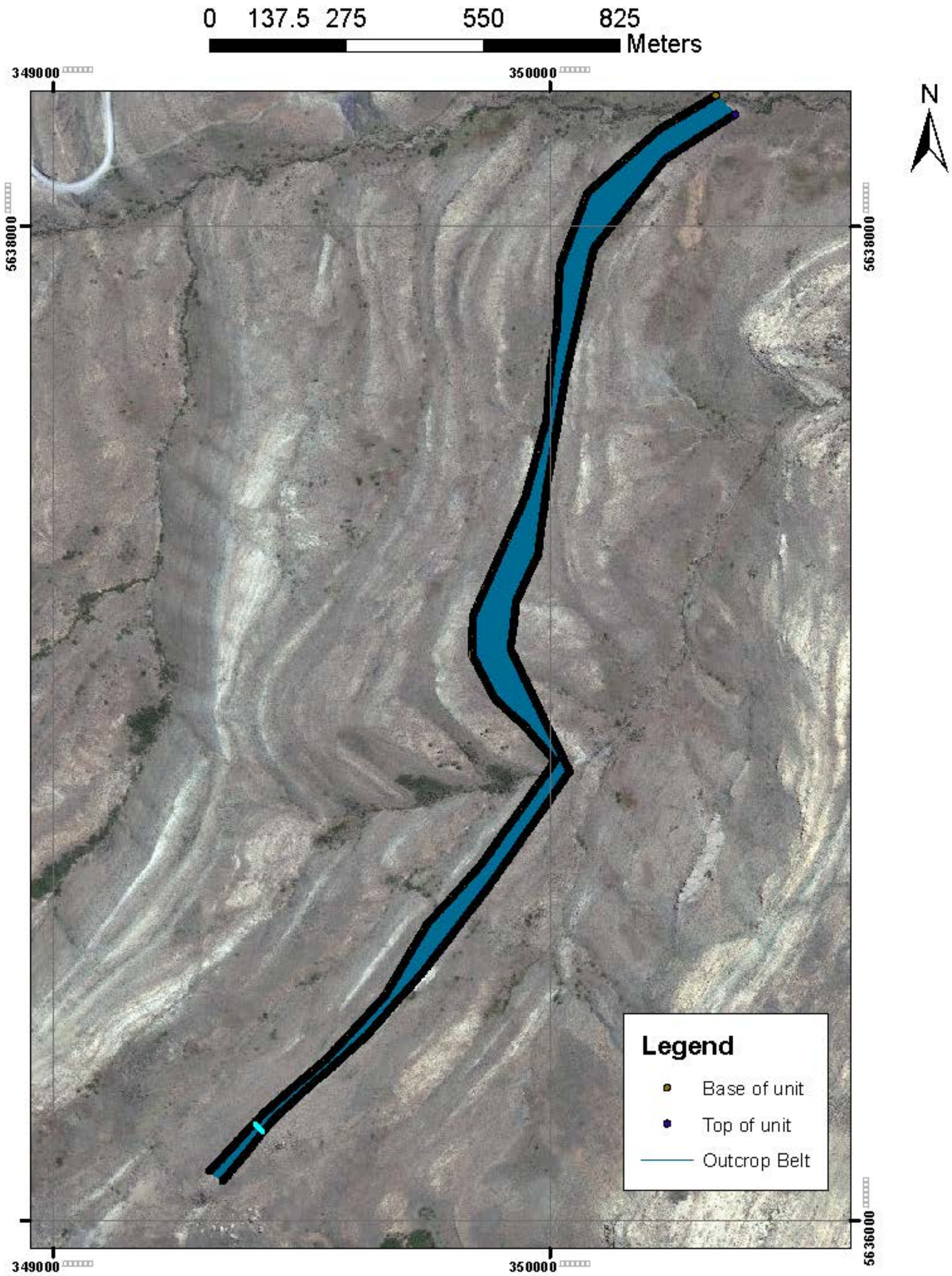



Fig. 8 Outcrop belt with Top and Base of unit (point features)

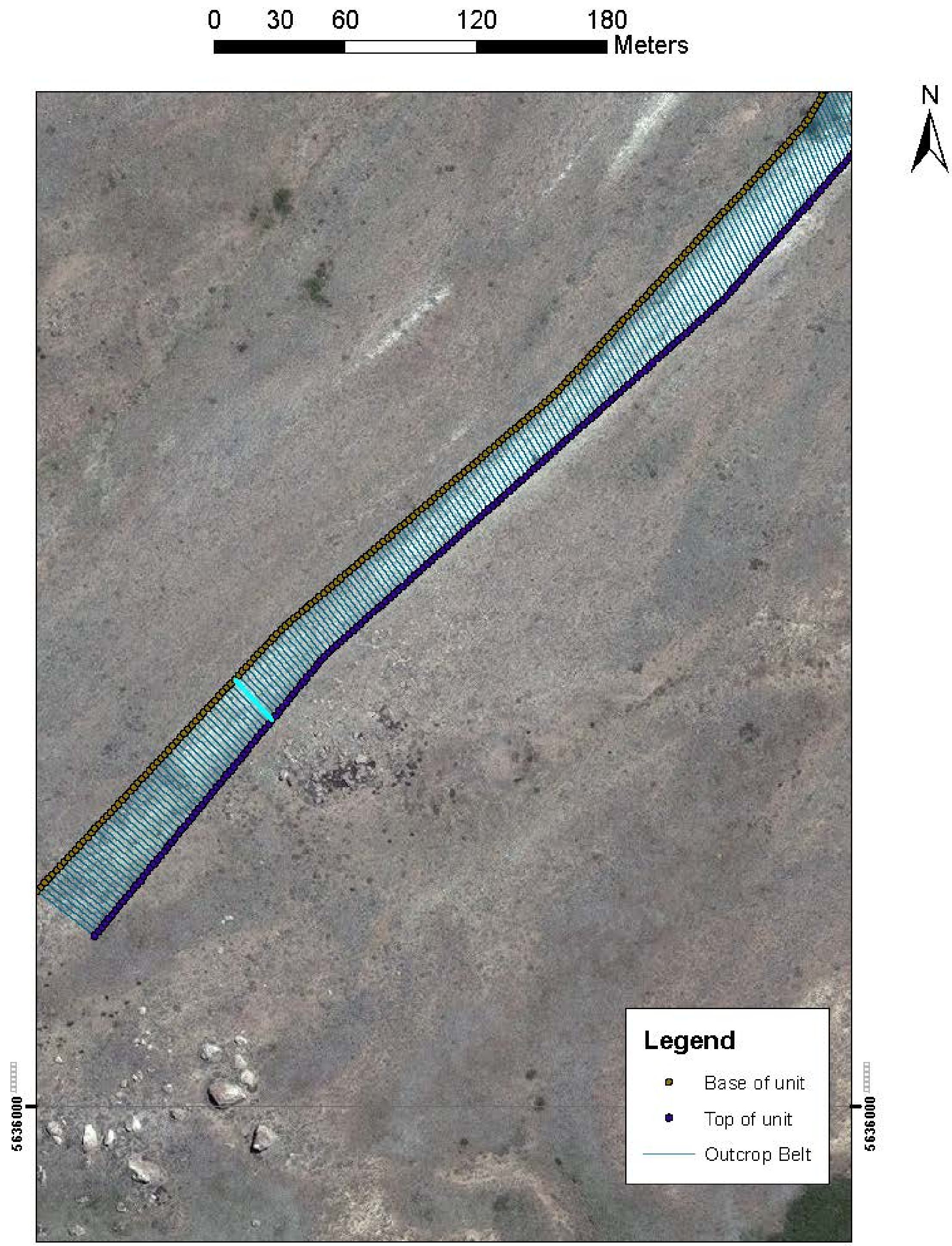



Fig. 9 Zoom in map of the outcrop belt location with distance lines between points

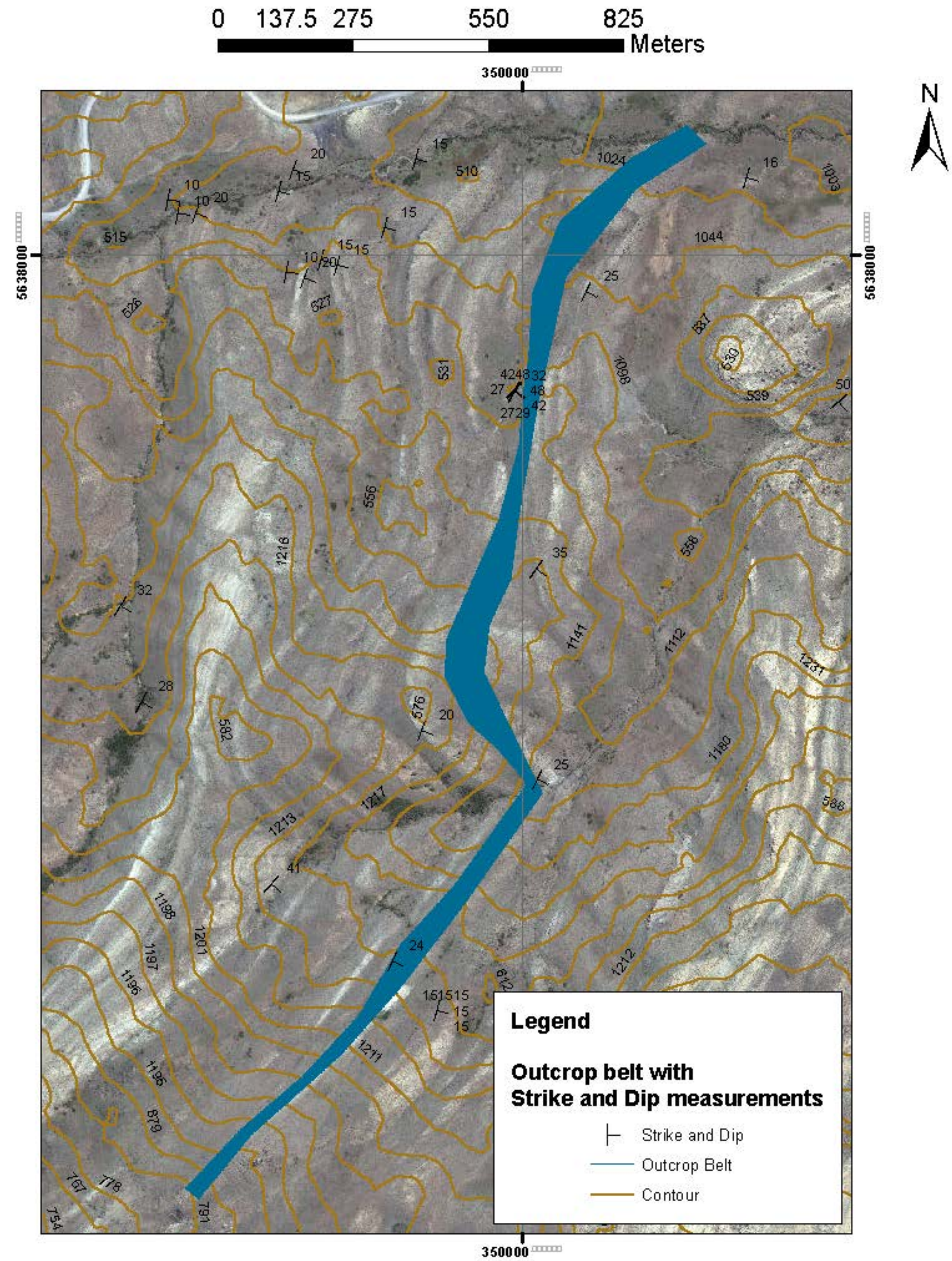



Fig. 10 Outcrop belt with Strike and Dip measurements (observe that the strike remains relative constant along the profile)

Table

Outcrop Belt

| FID | Shape | ID | X | Y | X1 | Y1 | Distance | Difference | Dip | Radians_Di | Angle | Angle_rad | Elevation1 | Elevation | xyline22.Thickness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | Polyline | 1 | 5636078.024745 | 349341.685676 | 5636098.542145 | 349315.184307 | 33.515463 | 3.94 | 25 | 0.279111 | 0 | 0 | 1521.86 | 1517.43 | 8.15 |
| 1 | Polyline | 2 | 5636079.967636 | 349343.279469 | 5636100.446083 | 349316.960129 | 33.34778 | 3.77 | 25 | 0.279111 | 0 | 0 | 1521.37 | 1516.75 | 8.15 |
| 2 | Polyline | 3 | 5636081.910526 | 349344.873263 | 5636102.350031 | 349318.73596 | 33.180295 | 3.44 | 25 | 0.279111 | 0 | 0 | 1520.52 | 1516.37 | 8.19 |
| 3 | Polyline | 4 | 5636083.853416 | 349346.467058 | 5636104.253968 | 349320.511783 | 33.01301 | 3.21 | 25 | 0.279111 | 0 | 0 | 1519.81 | 1515.68 | 8.21 |
| 4 | Polyline | 5 | 5636085.796306 | 349348.060854 | 5636106.157904 | 349322.287607 | 32.845927 | 2.97 | 25 | 0.279111 | 0 | 0 | 1518.89 | 1515.24 | 8.23 |
| 5 | Polyline | 6 | 5636087.739195 | 349349.654651 | 5636108.06184 | 349324.063433 | 32.67905 | 2.74 | 25 | 0.279111 | 0 | 0 | 1518.21 | 1514.58 | 8.25 |
| 6 | Polyline | 7 | 5636089.682084 | 349351.248448 | 5636109.965786 | 349325.83925 | 32.512397 | 2.34 | 25 | 0.279111 | 0 | 0 | 1517.32 | 1514.14 | 8.31 |
| 7 | Polyline | 8 | 5636091.624983 | 349352.842246 | 5636111.869721 | 349327.615077 | 32.345934 | 2.19 | 25 | 0.279111 | 0 | 0 | 1516.48 | 1513.49 | 8.31 |
| 8 | Polyline | 9 | 5636093.567871 | 349354.436036 | 5636113.773655 | 349329.390905 | 32.179688 | 2.42 | 25 | 0.279111 | 0 | 0 | 1515.68 | 1512.87 | 8.2 |
| 9 | Polyline | 10 | 5636095.510759 | 349356.029836 | 5636115.6776 | 349331.166724 | 32.013682 | 2.14 | 25 | 0.279111 | 0 | 0 | 1515.29 | 1512.39 | 8.23 |
| 10 | Polyline | 11 | 5636097.453647 | 349357.623628 | 5636117.581534 | 349332.942545 | 31.847884 | 2.15 | 25 | 0.279111 | 0 | 0 | 1514.53 | 1511.67 | 8.18 |
| 11 | Polyline | 12 | 5636099.396545 | 349359.21743 | 5636119.485478 | 349334.718376 | 31.682312 | 1.84 | 25 | 0.279111 | 0 | 0 | 1513.82 | 1511.28 | 8.22 |
| 12 | Polyline | 13 | 5636101.339431 | 349360.811223 | 5636121.389411 | 349336.494198 | 31.51697 | 1.71 | 25 | 0.279111 | 0 | 0 | 1513.12 | 1510.63 | 8.21 |
| 13 | Polyline | 14 | 5636103.282329 | 349362.405018 | 5636123.293354 | 349338.270022 | 31.35186 | 1.71 | 25 | 0.279111 | 0 | 0 | 1512.34 | 1509.98 | 8.17 |
| 14 | Polyline | 15 | 5636105.225215 | 349363.998813 | 5636125.197286 | 349340.045846 | 31.186988 | 1.01 | 25 | 0.279111 | 0 | 0 | 1511.69 | 1509.65 | 8.31 |
| 15 | Polyline | 16 | 5636107.1681 | 349365.592609 | 5636127.101228 | 349341.821671 | 31.022364 | 0.84 | 25 | 0.279111 | 0 | 0 | 1510.66 | 1509 | 8.32 |
| 16 | Polyline | 17 | 5636109.110997 | 349367.186406 | 5636129.00517 | 349343.597489 | 30.857983 | 0.19 | 25 | 0.279111 | 0 | 0 | 1509.84 | 1508.62 | 8.45 |
| 17 | Polyline | 18 | 5636111.053881 | 349368.780204 | 5636130.909111 | 349345.373316 | 30.693852 | 0.03 | 25 | 0.279111 | 0 | 0 | 1508.81 | 1508.06 | 8.45 |
| 18 | Polyline | 19 | 5636112.996777 | 349370.373994 | 5636132.813041 | 349347.149144 | 30.529952 | -0.51 | 25 | 0.279111 | 0 | 0 | 1508.09 | 1507.7 | 8.55 |
| 19 | Polyline | 20 | 5636114.939661 | 349371.967793 | 5636134.716982 | 349348.924964 | 30.366336 | -0.84 | 25 | 0.279111 | 0 | 0 | 1507.19 | 1507.06 | 8.6 |
| 20 | Polyline | 21 | 5636116.882556 | 349373.561584 | 5636136.620922 | 349350.700793 | 30.202961 | -1.25 | 25 | 0.279111 | 0 | 0 | 1506.22 | 1506.47 | 8.67 |
| 21 | Polyline | 22 | 5636118.82545 | 349375.155385 | 5636138.524861 | 349352.476615 | 30.039864 | -1.37 | 25 | 0.279111 | 0 | 0 | 1505.22 | 1506.1 | 8.65 |
| 22 | Polyline | 23 | 5636120.768333 | 349376.749178 | 5636140.428801 | 349354.252438 | 29.877036 | -1.77 | 25 | 0.279111 | 0 | 0 | 1504.73 | 1505.53 | 8.72 |
| 23 | Polyline | 24 | 5636122.711227 | 349378.342972 | 5636142.332739 | 349356.028262 | 29.714476 | -2.24 | 25 | 0.279111 | 0 | 0 | 1503.76 | 1505.07 | 8.8 |
| 24 | Polyline | 25 | 5636124.65412 | 349379.936767 | 5636144.236678 | 349357.804086 | 29.552193 | -2.67 | 25 | 0.279111 | 0 | 0 | 1502.83 | 1504.57 | 8.88 |
| 25 | Polyline | 26 | 5636126.597013 | 349381.530562 | 5636146.140615 | 349359.579911 | 29.390193 | -2.92 | 25 | 0.279111 | 0 | 0 | 1501.9 | 1504.1 | 8.9 |
| 26 | Polyline | 27 | 5636128.539894 | 349383.124359 | 5636148.044553 | 349361.355738 | 29.228489 | -3.18 | 25 | 0.279111 | 0 | 0 | 1501.18 | 1503.46 | 8.93 |
| 27 | Polyline | 28 | 5636130.482787 | 349384.718156 | 5636149.94849 | 349363.131556 | 29.067075 | -3.35 | 25 | 0.279111 | 0 | 0 | 1500.28 | 1502.81 | 8.93 |
| 28 | Polyline | 29 | 5636132.425679 | 349386.311954 | 5636151.852426 | 349364.907384 | 28.905953 | -3.36 | 25 | 0.279111 | 0 | 0 | 1499.46 | 1502.27 | 8.89 |
| 29 | Polyline | 30 | 5636134.36857 | 349387.905752 | 5636153.756362 | 349366.683204 | 28.745139 | -3.31 | 25 | 0.279111 | 0 | 0 | 1498.91 | 1501.63 | 8.83 |
| 30 | Polyline | 31 | 5636136.311461 | 349389.499543 | 5636155.660309 | 349368.459034 | 28.584628 | -3.59 | 25 | 0.279111 | 0 | 0 | 1498.32 | 1501.15 | 8.86 |
| 31 | Polyline | 32 | 5636138.254352 | 349391.093344 | 5636157.564244 | 349370.234856 | 28.424434 | -3.72 | 25 | 0.279111 | 0 | 0 | 1497.56 | 1500.5 | 8.86 |
| 32 | Polyline | 33 | 5636140.197242 | 349392.687136 | 5636159.468179 | 349372.010679 | 28.264552 | -3.79 | 25 | 0.279111 | 0 | 0 | 1496.78 | 1499.78 | 8.83 |
| 33 | Polyline | 34 | 5636142.140132 | 349394.28093 | 5636161.372124 | 349373.786503 | 28.105 | -4.04 | 25 | 0.279111 | 0 | 0 | 1495.99 | 1499.38 | 8.86 |
| 34 | Polyline | 35 | 5636144.083022 | 349395.874724 | 5636163.276058 | 349375.562327 | 27.94577 | -4.04 | 25 | 0.279111 | 0 | 0 | 1495.34 | 1498.52 | 8.81 |
| 35 | Polyline | 36 | 5636146.025911 | 349397.468527 | 5636165.179991 | 349377.338153 | 27.786881 | -3.96 | 25 | 0.279111 | 0 | 0 | 1494.48 | 1497.75 | 8.75 |
| 36 | Polyline | 37 | 5636147.9688 | 349399.062323 | 5636167.083935 | 349379.113971 | 27.62834 | -3.93 | 25 | 0.279111 | 0 | 0 | 1493.79 | 1496.78 | 8.69 |
| 37 | Polyline | 38 | 5636149.911688 | 349400.656111 | 5636168.987867 | 349380.889798 | 27.470125 | -4.08 | 25 | 0.279111 | 0 | 0 | 1492.85 | 1496.22 | 8.69 |
| 38 | Polyline | 39 | 5636151.854576 | 349402.249909 | 5636170.89181 | 349382.665626 | 27.312276 | -4.42 | 25 | 0.279111 | 0 | 0 | 1492.14 | 1495.59 | 8.74 |
| 39 | Polyline | 40 | 5636153.797475 | 349403.843707 | 5636172.795753 | 349384.441446 | 27.154783 | -4.77 | 25 | 0.279111 | 0 | 0 | 1491.17 | 1494.88 | 8.8 |
| 40 | Polyline | 41 | 5636155.740363 | 349405.437506 | 5636174.699684 | 349386.217267 | 26.997656 | -5.21 | 25 | 0.279111 | 0 | 0 | 1490.11 | 1494.34 | 8.87 |
| 41 | Polyline | 42 | 5636157.683249 | 349407.031297 | 5636176.603625 | 349387.993098 | 26.840895 | -4.96 | 25 | 0.279111 | 0 | 0 | 1489.13 | 1493.65 | 8.76 |
| 42 | Polyline | 43 | 5636159.626136 | 349408.625098 | 5636178.507556 | 349389.768921 | 26.684516 | -5.52 | 25 | 0.279111 | 0 | 0 | 1488.69 | 1493.28 | 8.87 |
| 43 | Polyline | 44 | 5636161.569033 | 349410.21889 | 5636180.411496 | 349391.544745 | 26.528515 | -5.83 | 25 | 0.279111 | 0 | 0 | 1487.76 | 1492.51 | 8.91 |
| 44 | Polyline | 45 | 5636163.511919 | 349411.812684 | 5636182.315437 | 349393.32057 | 26.372913 | -6.17 | 25 | 0.279111 | 0 | 0 | 1486.68 | 1491.8 | 8.97 |
| 45 | Polyline | 46 | 5636165.454805 | 349413.406479 | 5636184.219376 | 349395.096395 | 26.21771 | -6.39 | 25 | 0.279111 | 0 | 0 | 1485.63 | 1491.17 | 8.98 |
| 46 | Polyline | 47 | 5636167.397701 | 349415.000274 | 5636186.123316 | 349396.872213 | 26.062909 | -6.54 | 25 | 0.279111 | 0 | 0 | 1484.78 | 1490.4 | 8.98 |
| 47 | Polyline | 48 | 5636169.340586 | 349416.59407 | 5636188.027255 | 349398.64804 | 25.908523 | -6.87 | 25 | 0.279111 | 0 | 0 | 1483.86 | 1489.76 | 9.03 |
| 48 | Polyline | 49 | 5636171.283481 | 349418.187867 | 5636189.931193 | 349400.42386 | 25.754555 | -6.71 | 25 | 0.279111 | 0 | 0 | 1482.89 | 1488.97 | 8.94 |
| 49 | Polyline | 50 | 5636173.226365 | 349419.781664 | 5636191.83512 | 349402.199689 | 25.601008 | -7 | 25 | 0.279111 | 0 | 0 | 1482.26 | 1488.39 | 8.98 |
| 50 | Polyline | 51 | 5636175.16926 | 349421.375463 | 5636193.739058 | 349403.975511 | 25.447902 | -7.24 | 25 | 0.279111 | 0 | 0 | 1481.39 | 1487.84 | 9.01 |
| 51 | Polyline | 52 | 5636177.112143 | 349422.969253 | 5636195.643006 | 349405.751333 | 25.29525 | -7.86 | 25 | 0.279111 | 0 | 0 | 1480.6 | 1487.48 | 9.13 |
| 52 | Polyline | 53 | 5636179.055037 | 349424.563053 | 5636197.546943 | 349407.527156 | 25.143038 | -8.26 | 25 | 0.279111 | 0 | 0 | 1479.62 | 1486.79 | 9.2 |
| 53 | Polyline | 54 | 5636180.997931 | 349426.156846 | 5636199.450879 | 349409.302989 | 24.991274 | -8.55 | 25 | 0.279111 | 0 | 0 | 1478.53 | 1486.12 | 9.24 |
| 54 | Polyline | 55 | 5636182.940813 | 349427.750647 | 5636201.354815 | 349411.078805 | 24.840004 | -8.39 | 25 | 0.279111 | 0 | 0 | 1477.57 | 1485.52 | 9.15 |
| 55 | Polyline | 56 | 5636184.883706 | 349429.344441 | 5636203.25875 | 349412.854631 | 24.68919 | -8.52 | 25 | 0.279111 | 0 | 0 | 1477.13 | 1484.78 | 9.15 |
| 56 | Polyline | 57 | 5636186.826599 | 349430.938236 | 5636205.162685 | 349414.630457 | 24.538861 | -8.49 | 25 | 0.279111 | 0 | 0 | 1476.26 | 1483.9 | 9.1 |
| 57 | Polyline | 58 | 5636188.769491 | 349432.532031 | 5636207.06663 | 349416.406285 | 24.389035 | -8.39 | 25 | 0.279111 | 0 | 0 | 1475.41 | 1482.95 | 9.03 |
| 58 | Polyline | 59 | 5636190.712372 | 349434.125828 | 5636208.970564 | 349418.182104 | 24.239718 | -8.02 | 25 | 0.279111 | 0 | 0 | 1474.56 | 1481.81 | 8.89 |
| 59 | Polyline | 60 | 5636192.655263 | 349435.719625 | 5636210.874498 | 349419.957925 | 24.090905 | -7.82 | 25 | 0.279111 | 0 | 0 | 1473.79 | 1480.79 | 8.79 |
| 60 | Polyline | 61 | 5636194.598154 | 349437.313423 | 5636212.778442 | 349421.733755 | 23.942617 | -7.99 | 25 | 0.279111 | 0 | 0 | 1472.97 | 1480.15 | 8.8 |
| 61 | Polyline | 62 | 5636196.541045 | 349438.907213 | 5636214.682374 | 349423.509577 | 23.794853 | -7.81 | 25 | 0.279111 | 0 | 0 | 1472.16 | 1479.5 | 8.71 |
| 62 | Polyline | 63 | 5636198.483935 | 349440.501012 | 5636216.586318 | 349425.285401 | 23.647645 | -7.99 | 25 | 0.279111 | 0 | 0 | 1471.69 | 1478.87 | 8.72 |

0 (0 out of 1025 Selected)

Fig. 11 Attribute Table for Outcrop Belt thickness calculation

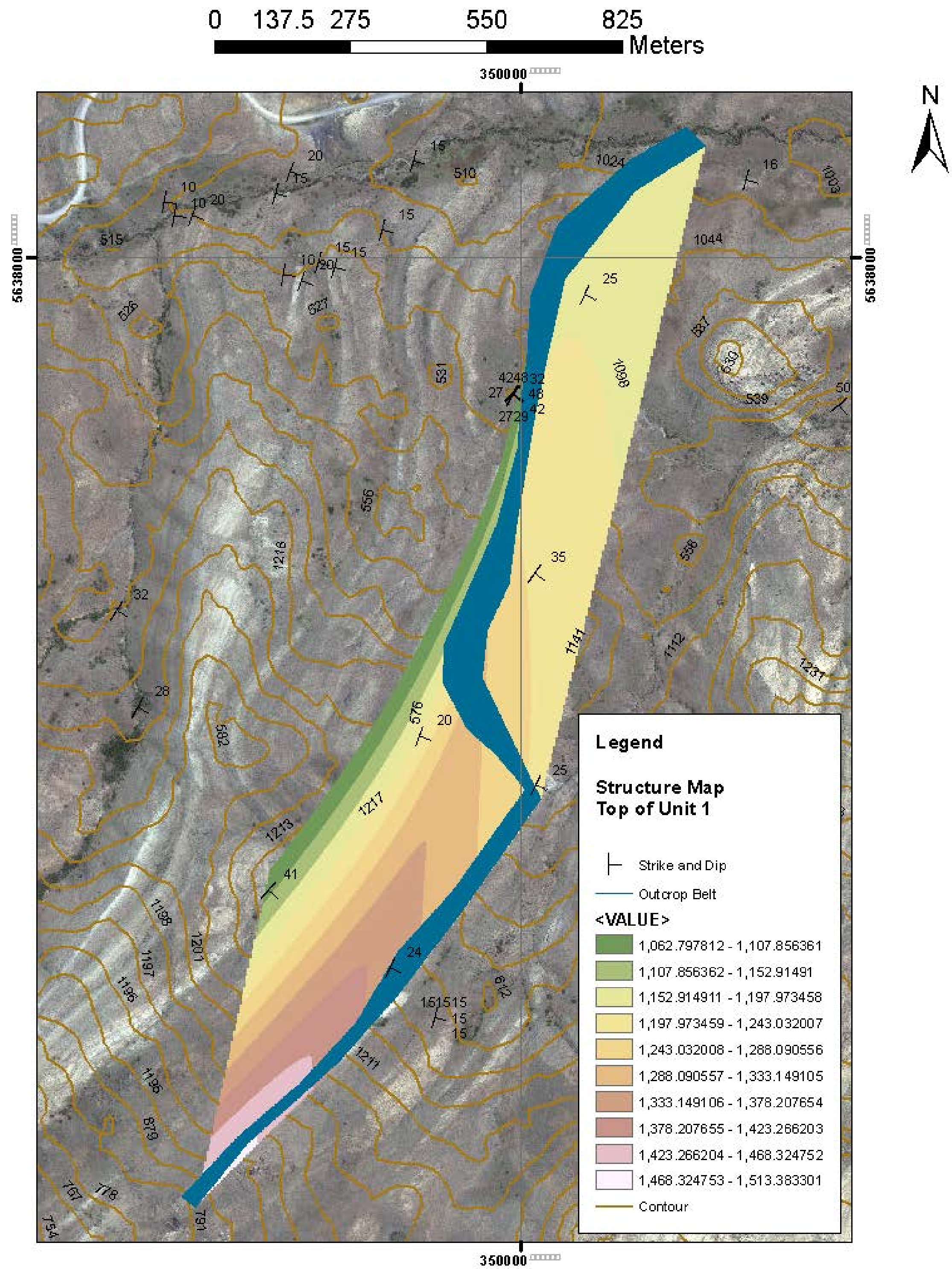



Fig. 12 Top of unit 1 structure map

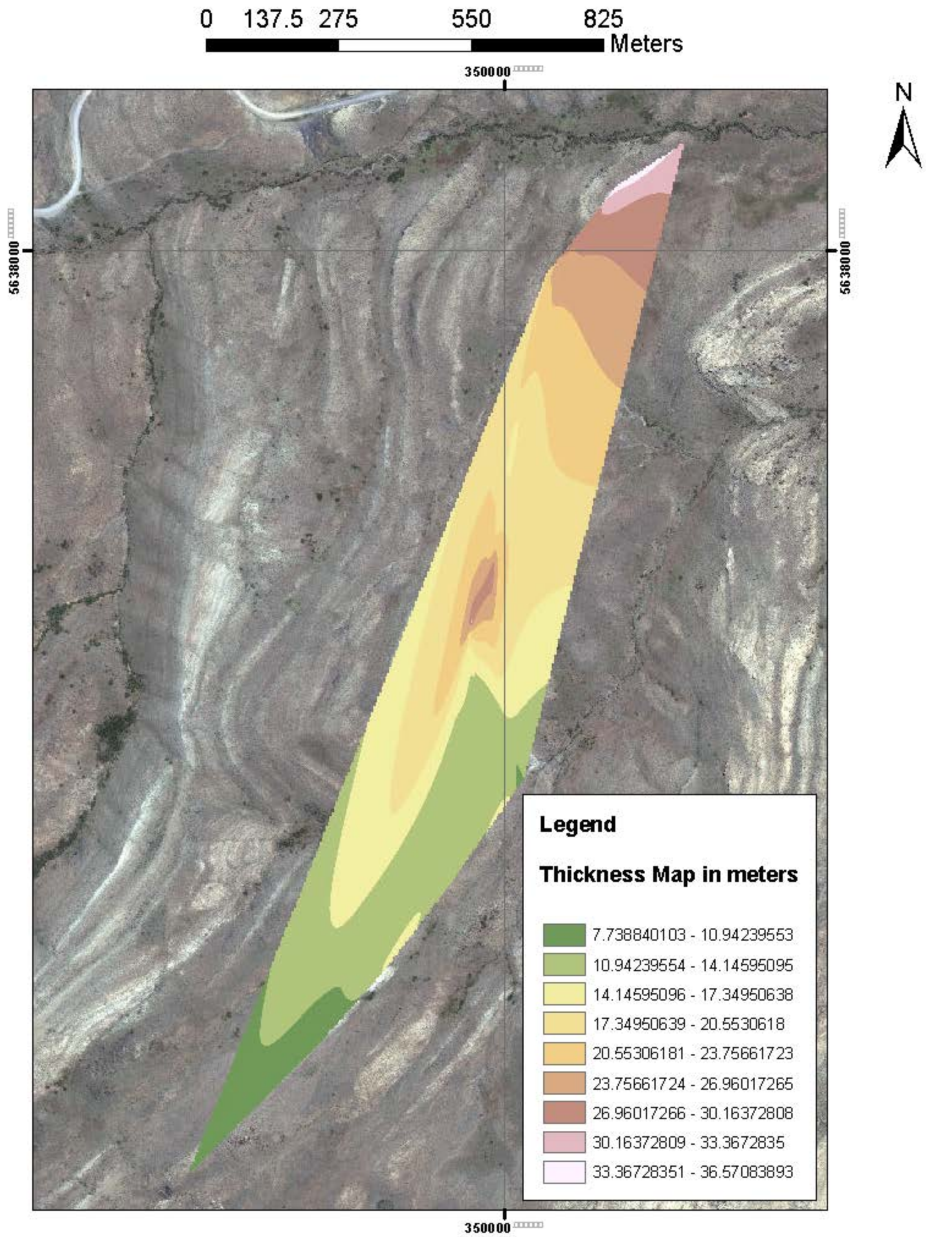



Fig. 13 Thickness Map showing increase thickness along the outcrop belt towards the North

Reference

"<Franzese 2006.pdf>."

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