GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8005

3D Linear Referencing -
A Methodology

R.M. Montsion and E.A. de Kemp

2016

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8005

3D Linear Referencing -
A Methodology

R.M. Montsion[1] and E.A. de Kemp[2]

[1] University of Ottawa, Ottawa, Ontario
[2] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario

2016

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Publications in this series have not been edited; they are released as submitted by the author.

TABLE OF CONTENTS

Abstract

Assigning data to a 3D framework is important for 3D modelling as it provides the backbone for all analysis. Linear Referencing is presented here as a method to capture and register drill hole data in a digital 3D work environment.   Several specialized 3D modelling applications currently exist that provide similar workflows however, these applications may not be accessable due to high costs and limited user bases. Additionally, a large portion of the geoscience community regularly uses full featured 2D GIS platforms such as ESRI© Arcmap^{TM} and in 3D with 3D Analyst^{TM} and ArcScene^{TM}to store and analyse their data.

Currently, performing linear referencing in ArcMap^{TM} and ArcScene^{TM} is a complicated process with limited documentation . This open file was created to guide users through the workflow from data compilation to a 3D georeferenced dataset. The workflow is demonstrated using real world data from the Sullivan Mine, Kimberly, British Columbia and a test dataset

Introduction

The Geological Survey of Canada has been working to update geoscience knowledge through its Targeted Geoscience Initiative (TGI) programs. Part of this initiative is to explore new methods to better understand, detect and delineate deep, buried mineral deposits within Canada. To accomplish this task, borehole data management, visualization, analysis methodologies and tools within three-dimensional (3D) geographic information systems (GIS) must be established. This document outlines the methodology for linear referencing one dimensional data to 3D drill holes using GOCAD-SKUA®, ArcMap^{TM} and Microsoft Access®. This methodology can be used for geostatistical analysis, modelling and mineral explorations.

To support 3D models, drill hole data must be digitized for analysis and reconstruction. Drill hole geometry and survey information must be recorded along with geological attribute data. The methodology to recreate geologic features in the sub-surface presented here involves 2 main steps: 1) geometric reconstruction of this data 2) populate the reconstructed drill holes with geoscience attributes (e.g., stratigraphic and geochemical).

Several 3D modelling applications that provide workflows to import and digitize borehole data currently exist (e.g., GOCAD-SKUA® Leapfrog GEO, Gemcom^{TM} and MicroMine^{TM}); however, there are advantages to working with drill data directly in a full-featured 2D GIS such as ESRI© Arcmap^{TM} and in 3D with 3D Analyst^{TM} and ArcScene^{TM}. These GIS platforms take advantage of a rich set of spatial and attribute query and analysis tools as well as providing cartographic and projection features. The linear referencing methodology demonstrates how 3D referenced data can be constructed using GOCAD-SKUA® in combination with ArcGIS. Due to the widespread use of these GIS applications and well-established user support network, this methodology is potentially more accessible than using specialized 3D modelling software. Currently, performing linear referencing in ArcMap^{TM} and ArcScene^{TM} is a complicated and poorly documented process which may be difficult to navigate successfully. This open file was created to guide users through the workflow from data compilation to produce a 3D georeferenced dataset.

Linear Referencing

Linear referencing is a method of storing one-dimensional data, either as line segments or points, along a linear feature (eg. drill hole). The advantage of linear referencing is the ability to use one-dimensional

information (*measure*) and a linear feature to assign data to positions in a 3D framework. Linear features in this open file are reconstructed drill holes from the Cominco mine in the Sullivan orebody and a test hole set which represents many possible drill hole orientations. Each linear feature is referred to as a "route" along which "events" are located. Events are line segments (linear events) or points (point events) along a route where data exists.

Linear referencing with line segments

Linear referencing using an interval along a route is called "line segment linear referencing". "From" and "to" depth measurements record the beginning and end of a linear event along your route. An example of this is stratigraphic data where layers are measured in continuous, discrete intervals along a drill hole. Line segment linear referencing can also utilize discontinuous data intervals (e.g., alteration zones, lost core). Figure 1a illustrates four continuous linear events along a route (drill hole).
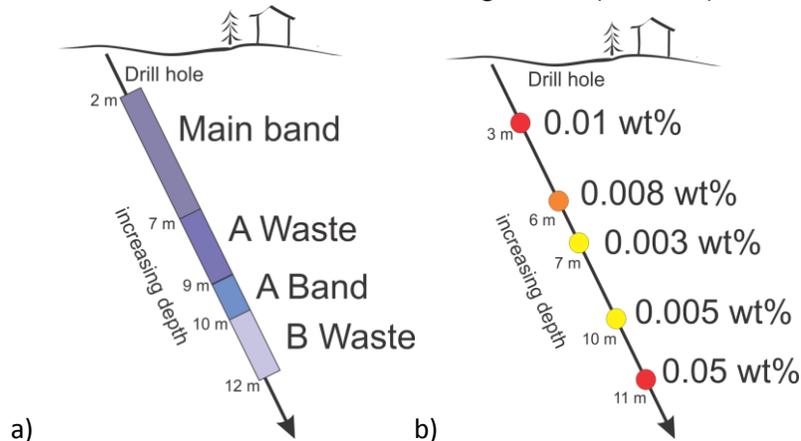

Figure 1 a) Linear referenced line segments; b) Linear referenced points

Linear referencing with point data

Linear referencing with point data is called "point linear referencing". It refers to discrete point measurements (e.g., assay values) referenced to a single point along a route (Figure 1b). This is useful where only point data exists or as a compliment to interval data.

3D ESRI© Sullivan Mine Geodatabase

The Sullivan Mine geodatabase was created for the visualization and analysis of drill hole geochemistry, lithostratigraphic and structural surface data in ArcScene™(3D) and ArcMap™ (2D)(Joseph et al., 2008; Joseph et al., 2011, Montsion, 2014). A subset of this geodatabase will be used to demonstrate the processes discussed in this paper; the full geodatabase will be made available at a later date. For detailed descriptions of feature classes and attribute fields in this geodatabase, refer to Appendix A.

Collar and deviation data were compiled using Cominco mine records and Microsoft Access® data from Geological Survey of Canada's Open File 5913 (Joseph et al., 2008). Lithostratigraphic data was extracted from Cominco mine drill logs and OF 5913

3D ESRI© Test Data Geodatabase

This database contains an artificial series of possible drill paths extending for 1100 m for every 5° change in azimuth with variable dips. There is only one collar location for all drill holes. The purpose of this dataset is to represent many possible drill hole geometries and orientations that may appear in a mine site.

Workflow

This section will guide users through the workflow of preparing and processing data to generate geological data in a 3D framework using drill holes for reference. This is demonstrated using real world data from the Sullivan Mine, Kimberly, British Columbia and a test dataset which represents most drill hole orientations. These datasets are stored in the accompanying folder as "Mine_Data" and "Test_Data" and their file and naming structure is described in Appendix B. The workflow is performed using GOCAD® 2009, GOCAD® 2014, ArcScence[TM] and Microsoft[TM] Access 2003. Figure 2 outlines all the steps in the workflow. For screen shots of workflow steps, see Appendix C. Appendix D outlines common issues that users may encounter during the workflow and their solutions.

Figure 2 Workflow for linear referencing geologic data to 3D drill cores

Step 1 – Data Preparation

Data preparation for linear referencing is the most important step in this protocol. Most errors result from data formatting oversights and inconsistencies within the data. Data should be standardized and projected to an appropriate coordinate system. For this methodology, Sullivan Mine coordinates were transformed to NAD 83 UTM Zone 11N. See Appendix A for details of this transformation. The test dataset was created using the same coordinate system.

Data should be tabulated in a geodatabase or database according to Table 1 for collar data and Table 2 for survey data. This methodology uses MS Access® 2003. Refer to Appendix A for descriptions of feature classes and attribute fields.

Common mistakes to correct when preparing borehole data include:

- Inconsistent measurement units: Measurement units should not differ
- HOLEID duplicates: Ensure that all HOLEID entries in the collar table are unique. Duplicates will cause errors in the next stage.
- Duplicate column headings: If you have merged data recently merged data in ArcMap, you may have duplicate column headings. Before beginning the workflow, remove duplicate columns.
- Too many columns in table: It is important to have as few data columns as possible. GOCAD-SKUA® will not reconstruct drill holes if the input CSV tables are not labelled and organized as seen below (Table 1, Table 2). Your table must be an exact match; otherwise, GOCAD® will become confused. It should be noted that GOCAD® 2014 can select which columns are used in the construction, thereby removing the requirement that the input table be an exact match.
- Drill hole polarity is inconsistent: Make sure that all drill holes have accurate positive (up) or negative (down) dips in the survey table.
- Negative depths: Make sure that all depth values are positive. Negative depths imply that the data is above the collar.

Table 1 Collar table

HOLEID	X	Y	Z	LENGTH
DD9999	572332.2	5508220	848.56	24.2316
DD9998	572372.9	5508239	851.46	109.355
DD9997	572632.8	5508199	878.12	156.214
DD9996	572549.1	5508350	814.9	20.654
…				

Coordinates in NAD 83 UTM Zone 11N, Length in meters

Table 2 Deviation Table

HOLE ID	DISTANCE	AZIMUTH	DIP
DD9999	6	69.8	-90
DD9999	10	184.6	-84
DD9999	16	254.7	-61
DD9999	21	1.5	-52
DD9998	20	271.5	-90
DD9998	49	183.8	-83
DD9998	68	35.4	-74
DD9998	105	79.4	-63

Step 2 – 3D Reconstruction

In this section, drill hole data is used to construct digitized, 3D drill holes in GOCAD-SKUA®. This requires the collar table and deviation table created in Step 1.

a) Export the data from the COLLAR TABLE to a comma-separated values (.csv) file.
b) Export the data from the DEVIATION TABLE to a comma-separated values (.csv) file. Make sure that all records are sorted by distance along the drill hole so that nearest records are listed first.

Note: GOCAD-SKUA® requires the CSV to be set up according to the templates above (Table 1 and Table 2). Also note that there should be no 'text qualifiers' which interrupt the CSV string. See Appendix C for screenshots of the export wizard in MS Access®.

c) Open GOCAD® 2009 and navigate to FILE → IMPORT OBJECTS → MINING IMPORTERS → ASCII FILES → DRILLHOLES

Note: Alternatively for GOCAD® 2014, navigate to FILE → IMPORT → MINING IMPORTERS → DRILLHOLES → ASCII DRILLHOLE PATHS

d) A pop-up window will open. Select the COLLAR.csv and DEVIATION.csv files for each file and follow directions in Appendix C Figure 1 for GOCAD® 2009 and Figure 2 for GOCAD® 2014.

Note: If drill holes are being reconstructed incorrectly (they are upside down), separate out all drill holes that go up (have a positive dip) and from those that go down (negative dip). Repeat steps 2a to 2d and complete the following steps for both sets of drill holes separately.

For an example of upside down drill holes, see Error_Mine_drillholes in GOCAD_project.sprj and compare to the Positive_Mine_drillholes and Negative_Mine_drillholes. The only difference between these files is the deviation tables used to make the drill holes.

e) When processing is finished…
- GOCAD® 2009: Select the "Objects" tab and open the "Group" dropdown menu. There should be a new entry with your group name. When you check the "Drillholes" box, the newly constructed drill holes should appear.
- GOCAD® 2014: The well group is saved under the "Wells" menu in the assigned objects box

Once the drill holes have been reconstructed, they must be reformatted into "curves" for exportation into ArcScene™.

A curve is a polygonal line (called *pline* in GOCAD®) comprised of a succession of segments. The ASCII file associated with a curve will contain a set of vertices which define the geometry of the pline and a set of segments built on the vertices. These segments define the topological information of the pline (Mallet, 2002).

f) Open the "Commands" dropdown menu and select "Curve".
g) When the "Curve" command bar is visible, select NEW→ WELL PATH → CURVE GROUP FROM WELL GROUP.
h) A pop-up window will prompt you to select the input "well group" or "well list", name the new curve group and indicate the resampling interval. The resampling interval represents the distance between each vertex and the length of each segment. In most cases, 1 m is used. Click OK. For GOCAD® 2014, also select the "Linear" classification when asked and make sure to give a feature name.

This recalculation may take some time depending on your data set. The new file will pop up under "Group", right above the drill hole file.

i) To export the new data, go to FILE → EXPORT OBJECTS → CURVE → DXF.
j) A pop-up window will prompt you to select the file's source and destination. In GOCAD® 2009 the entire group can be selected using the heading label. In GOCD 2014 all the individual drill holes must be selected. Click EXPORT.

> Note: If the export fails, try manually typing in the .dxf file extension after the file name.

Step 3 – Data Preparation in ArcMap^{TM}

Once 3D drill holes have been created and exported from GOCAD-SKUA®, they need to be prepared for linear referencing in ArcMap^{TM}. Preparation will include defining projections, formatting the attribute table and changing file formats. This methodology uses ArcMap^{TM} 10.2 but the processes described here can be applied to ArcMap^{TM} 9 and ArcMap^{TM} 10
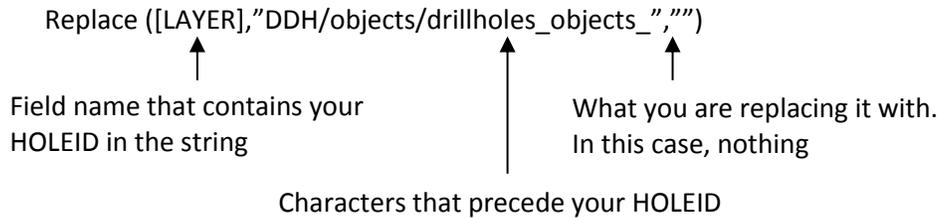
a) Open a new project in ArcScene^{TM}.
b) Bring the .dxf in: Open ArcCatalog^{TM} and navigate to the .dxf file exported from GOCAD®. Open the dropdown for the .dxf and drag the "polyline" file into the map data frame.
c) Make Polyline into Shapefile: Right click on the polyline layer and navigate to "Export" in the dropdown menu. Save the new shapefile. The file may be saved to any destination; however, it may be more successful if saved as a feature class in a geodatabase.

> Note: It is important when saving and naming files in ArcScene^{TM} that the name should not contain ANY spaces or invalid characters (ie. !, @, #, etc.). Instead of a space, use the underscore symbol.
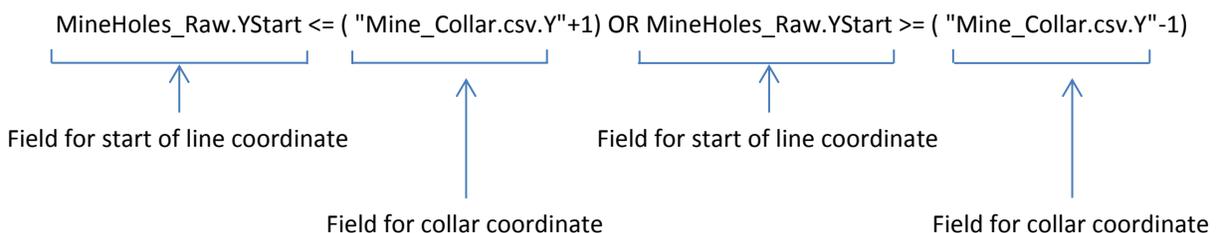
d) When the export is complete, ArcScene^{TM} will ask if the new shapefile should be added to the map. Click YES

Now that the drill holes are in ArcScene^{TM}, some modifications need to be made to the data in the attribute table.

e) Isolate HOLEID: GOCAD-SKUA® does not keep the HOLEID of each drill hole separate from the file name. Use Arc's in-house Field Calculator to isolate desired information.
  i. Open the drill holes' shapefile attribute table.
  ii. Add Field: Navigate to TABLE OPTIONS → ADD FIELD (Note: this option will be greyed out if an edit session is open)
  iii. Name and format the new field. Field "Type" should be "Text" and length can be any value as long as it can contain your longest text string. For more information about field properties see Appendix A and for naming conventions see Appendix E.
  iv. Right-click on the new field heading and select "Field Calculator" from the dropdown menu.
  v. Under "Type" select "string" and under "Functions" select "Replace ( )". The rest of the calculation should look like this:

Replace ([LAYER],"DDH/objects/drillholes_objects_","")

Field name that contains your
HOLEID in the string

What you are replacing it with.
In this case, nothing

Characters that precede your HOLEID

    vi.   Click OK

    vii.   Repeat steps i through vi to replace the characters that follow the HOLEIDs with nothing using the same calculation but with new characters.

f) Define projection of the shapefile in ARCTOOLBOX → DATA MANAGEMENT TOOLS → PROJECTIONS AND TRANSFORMATIONS → DEFINE PROJECTION (be sure to select the XY and Z coordinate system appropriate for your data)

g) Calculate length geometry of the hole:

    i.   Before you begin, double check that 3D Analyst has been turned on. Go to CUSTOMIZE→EXTENSIONS→Check box for 3D Analyst

    ii.   Open the attribute table for the new shapefile and add a new field called "HoleLength". This field should have a "double" data type with a precision of 7 and a scale of 3.

    iii.   Right click on your new "HoleLength" column in the attribute table and select "Calculate geometry" from the dropdown menu.

    iv.   In the "Property" field, select "3D length" from the dropdown menu.

    v.   Double check the coordinate system and units are appropriate.

h) Make sure that your holes are pointing the right way: During the DXF export process coordinate priority sometimes changes the direction of some drill holes. That is to say, the geometry is correct but the internal measurements of where a hole begins and ends are backwards. To make sure you have drill holes going the correct way, you needs to perfom the following steps:

    i.   Open the attribute table and add three new fields called "XStart", "YStart" and "ZStart". These fields should have a "double" data type with a precision of 15 and a scale of 7.

    ii.   Right click on each field and select "Calculate geometry" from the dropdown menu.

    iii.   In the "Property" field, select "X Coordinate of Line Start", "y Coordinate of Line Start" and "Z Coordinate of Line Start" respectively.

    iv.   Compare these columns with the coordinates of your collar points. If the coordinates given in your new field do not match your collar coordinates, then that hole is going in the wrong direction. To test this, use join by attributes and using a selection query on the joined table. Below is an example of a selection query that is known to work:

MineHoles_Raw.YStart <= ("Mine_Collar.csv.Y"+1) OR MineHoles_Raw.YStart >= ("Mine_Collar.csv.Y"-1)

Field for start of line coordinate

Field for start of line coordinate

Field for collar coordinate

Field for collar coordinate

i) If some of the holes are backwards, simply select them in the attribute table, export them to a new shapefile or feature class and flip them using ATCTOOLBOX → EDITING TOOLS → FLIP LINE. The remaining good holes should be exported into a second shapefile or feature class.

j) Once the problem holes have been flipped, merge the good holes and flipped holes using the Merge tool. ARCTOOLBOX → DATA MANAGEMENT TOOLS → GENERAL → MERGE.

k) If possible, save your data as a feature class in a geodatabase. This file type is more likely to succeed than shapefiles

Step 4 – Create Routes

The Create Routes tool converts existing line segments into one continuous path and assigns measurements of distance along a drill hole.

a) Open ArcToolbox and navigate to the "Linear Referencing" toolkit.

b) In the toolkit, select the "Create Route" option. A pop-up window will appear. Use the following information to populate the table:

- **Input Line Feature:** Your drill hole shapefile or feature class
- **Route Identifier Field:** HOLEID
- **Output Feature Class:** Name and save new route layer
- **Measure Source:** How the measure values are to be obtained. When using 2D paths, any one of the following three options can be used depending, on what information you have available. When using 3D paths, the "TWO FIELDS" option is the only one that will work.
  - **Length:** The 2D geometric length that ArcMap^{TM} automatically calculates
  - **One_Field:** Uses a field in the attribute table and you manually select coordinate priority. This is not good for 3D routes
  - **Two_Fields:** Uses from/to information in the attribute table as well as internal direction information from the polylines.
- Leave all other fields as default.

c) Click OK

d) ArcScene^{TM} will ask if the new layer should be added to the map. Click YES

Note: This feature class can be used multiple times for various datasets. The shapefile is never altered because linear referencing creates a new event layer for every computation.

Take a moment to quality check your work. Create points at the start of each route and compare with collar points as you did in Step 3h.

Step 5 – Event Table Preparations

In this step, the event table which contains data to be referenced to the drill holes should be formatted and quality checked before proceeding. The most important thing to note in this step is that the table must be brought into a database software if it is not there already. The software will format all columns correctly. Excel is not capable of retaining correct/compatible formatting when tables are brought into ArcScene^{TM}. Also, is data formatting is inconsistent in anyway, linear referencing will fail here.

To create line events, the input table should look like Table 3.

Table 3 Line event table

HOLEID	LENGTH	FROM	TO	POSITION
DD9999	24.2316	23.5497	12.6492	MB
DD9999	24.2316	12.6492	10.2679	A
DD9999	24.2316	10.2679	5.2697	B
DD9998	109.355	76.5498	54.2197	MB
DD9998	109.355	54.2197	34.5469	A
…				

In Table 3, the HOLEID, full length of the hole (LENGTH), FROM, TO, and stratigraphic position (POSITION) have been recorded. Notice that there are as few columns as possible. This will make processing quicker and error detection easier.

When using point data, use the template shown in Table 4.

Table 4 Point event table

HOLEID	DISTANCE	Pb	Zn	Ag	Fe
DD9999	9.144	17.2	20.2	7.9	28.3
DD9999	24.162	16.5	14.5	6.9	30.2
DD9998	45.643	18.5	16.5	8.5	32.5
DD9998	67.549	15.2	19.3	5.8	27.4
…					

In Table 4, the HOLEID, distance from collar (DISTANCE), and various geochemical concentrations are recorded. Here you can have more than the minimum number of columns; however, for efficiency and accuracy's sake, you can reference one item at a time.

Once the data tables are complete, export them as .DBASE5 or .CSV files and store them in an easy access folder.

Ensure that all names along the folder path and the file name itself contain no spaces and invalid characters as listed above in Step 1. Also, long file names or folder paths can cause failure. Keep all names as short as possible.

Bring data into ArcScene™.
a) Open ArcCatalog™ and navigate to the new file.
b) Drag the file into the map data frame.

> Note: The file will not appear in the Table of Contents unless layers are listed as "List by source". This can be selected right under the Table of Contents heading

Step 6 – Make Route Event Layer

In this step, data from the event table will be referenced to the drill holes (routes) and stored in a temporary file. This is done using the "Make Route Event Layer" tool in ArcToolbox.

a) In ArcToolbox, under the Linear Referencing toolkit, select "Make Route Event Layer".

 - **Input Route Features:** New route layer
 - **Route Identifier field:** HOLEID field
 - **Input Event Table:** Table just added to map
 - **Event Table Route Identifier Fields**: HOLEID
 - **Event Type:**
    - "Line" if data includes FROM and TO fields
    - "Point" if data includes DISTANCE field.
 - **From-Measure Field:** FROM field
 - **To-Measure Field:** TO field.
 - Check the box for " Generate a field for locating errors"
 - Leave all other fields with their default settings.

b) Click OK
c) Export Event: Right click on the newly created event layer and export it as a shapefile as described in Step 3C.

> Note: For vertical (90°) holes, using points instead of line events should be considered. ArcMap has a bug where it gives all events along a vertical hole zero length geometry. Additionally, the dip of drill holes can be changed in the deviation table so that they are not purely vertical. ArcMap does not support purely vertical polylines so the base of a drill hole must be offset by at least 1 cm from the collar position.

> For an example of this, observe the errors recorded in the "Mine_Stratgaphy_line" feature class in the Mine_Scene project. All records with a "ZERO LENGTH EXTENT" error correspond to vertical drill holes. Next, observe the "Mine_Stratigraphy_points" file and note that there are no longer any "ZERO LENGTH EXTENT" errors.

Conclusion

For 3D modeling, assigning data to a 3D framework is important as it provides the backbone for all analysis. Many programs such as GOCAD-SKUA® Leapfrog GEO, Gemcom[TM] and MicroMine[TM] exist to accomplish this task; however, not all users may have access to these specialized programs. Instead, most of the geoscience community uses ESRI© products such as ArcMap[TM] and ArcScene[TM] as a GIS platform to store and analyse geoscientific data. The Linear Referencing methodology presented here can guide users through the complicated workflow of linear referencing data to drill holes within an ArcGIS[TM] environment.

Acknowledgments

Bibliography

ESRI©, 2014, ArcGIS Resources: ArcGIS field data types,
http://resources.arcgis.com/en/help/main/10.1/index.html#//005s0000000p000000

Joseph, J M R; Ransom, P W., 2008, Geoscience data archive from the Sullivan Mine, southeastern British Columbia' Geological Survey of Canada, Open File 5913; 1 DVD, doi:10.4095/226168

Joseph, J.M.R., Brown, D., and Walker, R., 2011, Diamond drillhole database of the Purcell Basin: Geological Survey of Canada, Open File 6549, 1CD-ROM, doi: 10.4095/288015.

Klohn-Krippen Engineering, 2000, Design Criteria Manual for Cominco's Sullivan Mine, Vancouver, BC

Mallet, Jean-Laurent. *Geomodeling*. Oxford University Press, Feb 7, 2002

Montsion, R., 2014, Zonation of Pb, Zn, Ag and Fe along the Sullivan Horizon, Kimberley, British Columbia: Unpublished B.Sc. Thesis, Carleton University, Ottawa,

Schetselaar, E.M., de Kemp, E.A., Ransom, P.W., Buenviaje, R., Nguyen, K., Montsion, R., and Joseph, J., 2015. Drill hole database compilation from legacy archives in support of 3D geological modelling and mineral exploration in the Purcell Anticlinorium, British Columbia, in Paradis, S., ed., Targeted Geoscience Initiative 4: sediment-hosted Zn-Pb deposits: processes and implications for exploration; Geological Survey of Canada, Open File 7838, p. 226-235. doi:10.4095/296328

Appendix A - Feature class and attribute field descriptions and properties

Feature class and attribute field descriptions for Collar and Deviation tables

Name	Description
Collar table	Table that records information at the top of a drill hole. This data should include a HOLEID, easting (X), northing (Y), elevation (Z) and LENGTH.
HOLEID	Unique identifier for each drill hole. Duplicate names in a collar table will cause linear referencing to fail.
X	Easting or x-coordinate of a collar position
Y	Northing or y-coordinate of a collar location
Z	Elevation of collar referenced to mean annual sea level
Deviation Table	Table that records a drill hole's HOLEID, DISTANCE, AZIMUTH and DIP
DISTANCE	Depth at which the deviation measurement was taken. This is the distance from the collar NOT elevation.
AZIMUTH	Direction the drill hole is dipping. Starts from North (0°) and goes to 360°.
DIP	The angle from the horizontal plane to the drill hole. If the collar position is at y = 0, the dip value is positive if drill hole is dipping in the positive y-direction. Value is negative for drill holes dipping in the negative y-direction.

Field properties for ArcMap™/ArcScene™ attribute table fields (ESRI©, 2014)

Name	Description	Precision (Field Length)	Scale (Decimal Places)
Short Integer	Whole numbers within the range of -32,768 to 32,767	1 – 5	0
Long Integer	Whole numbers within the range of -2,147,483,648 to 2,147,483,647	6 – 10	0
Float	Fractional numbers within the range of -$3.4x10^{-38}$ to $1.2x10^{38}$	1 – 6	1 – 6
Double	Fractional numbers within the range of -$2.2x10^{-308}$ to $1.8x10^{308}$	7+	0+

Appendix B - Data and File Structure

Mine_Data
- **Mine_Data.gdb**
  - **No_Flip:** Drill holes that have the correct geometry and orientation. They do not need to be flipped
  - **Mine_Stratigraphy_line:** Line events of important mine horizons that were linear referenced to the mine drill holes
  - **Mine_Stratigraphy_points:** Point events of important mine horizons that were linear referenced to the mine drill holes. Take from the "FROM_M" field in the Mine_Stratgraphy.csv table
  - **Mine_Routes:** Routes made from the mine drill hole dataset
  - **MineHoles_Corrected:** All drill holes are merged into this feature class after incorrect hole have been flipped. All holes in this feature class have the correct orientation.
  - **MineHoles_Raw:** Drill holes that have just been exported from DXF to a feature class
  - **To_Flip:** Drill holes with incorrect orientation and need to be flipped
- **Deviation_AllHoles.csv:** Deviation table for all drill holes in the Sullivan Mine
- **Deviation_NegativeHoles.csv:** Deviation table for holes which go down (have negative dip)
- **Deviation_PositiveHoles.csv:** Deviation table for holes which go up (have positive dip)
- **Mine_Collar.csv:** Collar coordinates for mine drill holes
- **Mine_Stratigraphy.csv:** Table of important stratigraphic mine horizons
- **Mine_Data.mdb:** Microsoft Access database which stores relevant tabular data for the mine drill hole dataset
- **Mine_Scene.sxd:** ArcScene project containing all relevant data related to the Mine drill hole dataset.

Test_Data
- **Test_Geodatabase.gdb:** Geodatabase that stores all feature class files related to linear referencing data to the test drill hole dataset.
  - **No_Flip:** Drill holes that have the correct geometry and orientation. They do not need to be flipped
  - **Test_Data_Lithology:** Line events of lithology that were linear referenced to the test drill holes
  - **Test_Data_markers:** Point events of lithology that were linear referenced to the test drill holes
  - **Test_Routes:** Routes made from the test drill hole dataset
  - **TestHoles_Corrected:** All drill holes are merged into this feature class after incorrect hole have been flipped. All holes in this feature class have the correct orientation.
  - **TestHoles_Raw:** Drill holes that have just been exported from DXF to a feature class
  - **To_Flip:** Drill holes with incorrect orientation and need to be flipped
- **Test_Data_collars.csv:** Collar coordinates for test drill hole dataset
- **Test_Data_Deviation.csv:** Deviation data used to reconstruct test drill hole dataset
- **Test_Data_Lithology.csv:** Lithological data for test drill hole dataset
- **Test_Data_Markers.csv:** Marker data for test drill hole dataset
- **Test_Holes.dxf:** export of DXF drill hole file from GOCAD

- **TestData.mdb:** Microsoft Access database which stores relevant tabular data for the test drill hole dataset
  - Test_Data_Collars
  - Tast_Data_Deviation
  - Test_Data_lithology
  - Test_Data_Markers

Test_Scene.sxd: ArcScene project containing all relevant data for this open file related to the test drill hole dataset
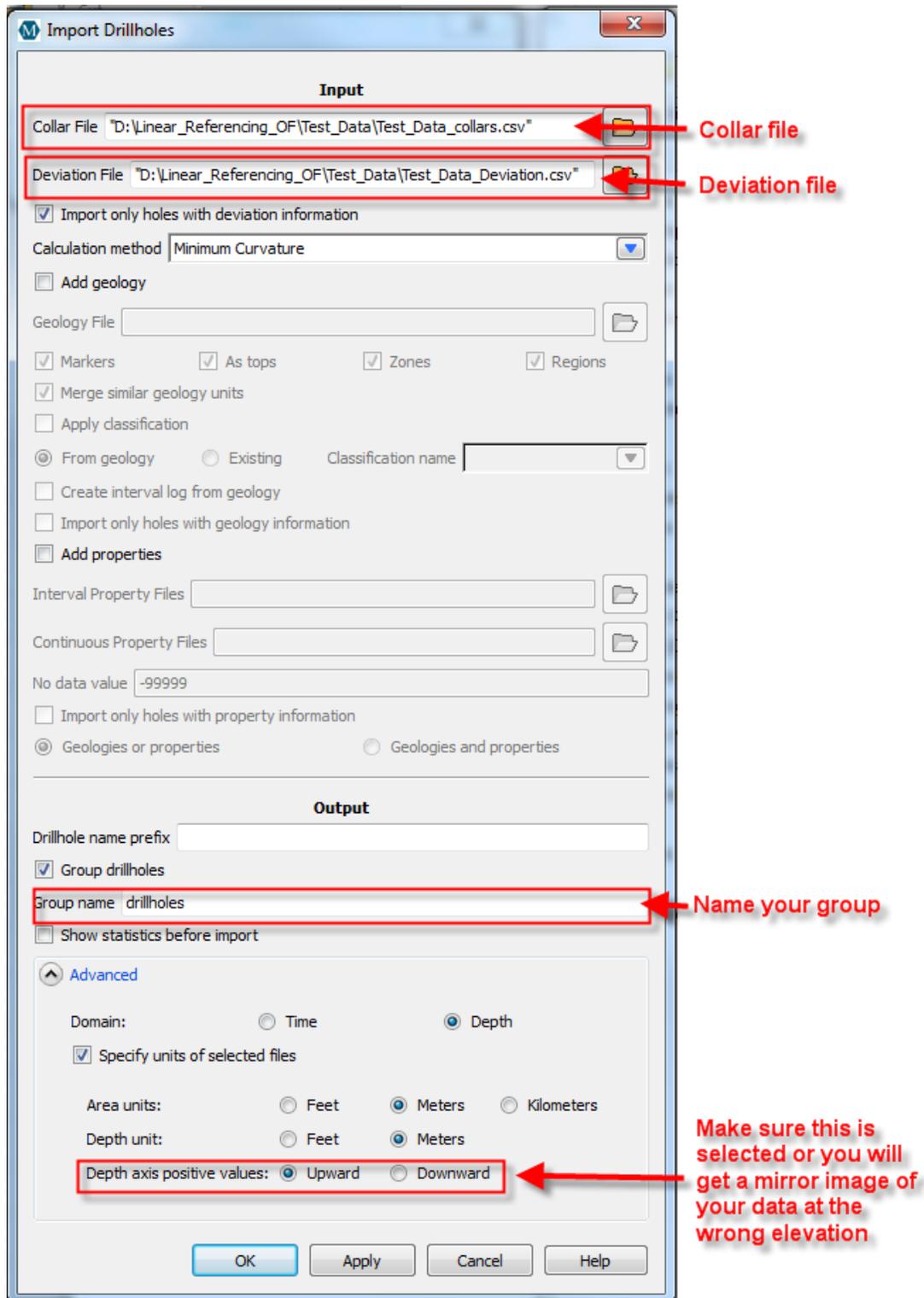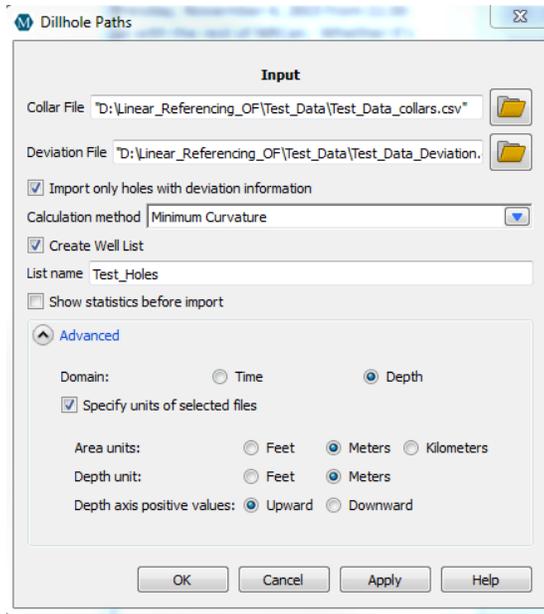
Appendix C - Screenshots

Figure C1 – Step 2d) Screen shot of import drill holes window in GOCAD® 2009. Note* you only need to change the depth axis values if your project settings have Depth Axis Positive Values: downward.

Figure C2-Step 2d) Screen shot of import drill holes window in GOCAD® 2014. Note* you only need to change the depth axis values if your project settings have Depth Axis Positive Values: downward.
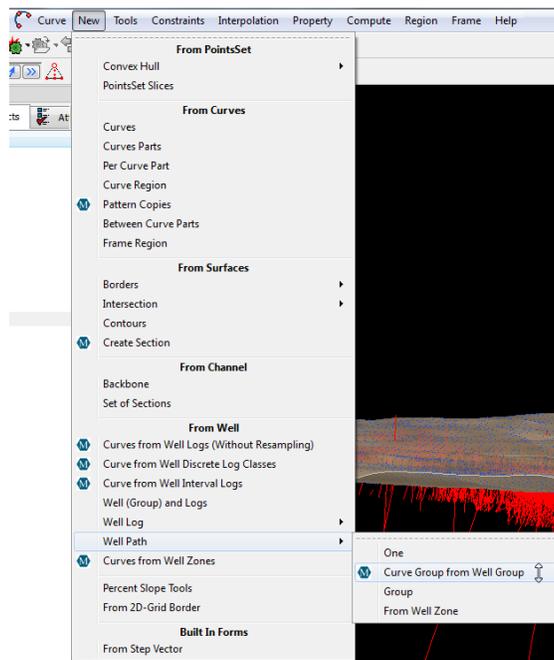
Figure C3 – Step 2g) When the "Curve" command bar is visible, select NEW → WELL PATH → CURVE GROUP FROM WELL GROUP
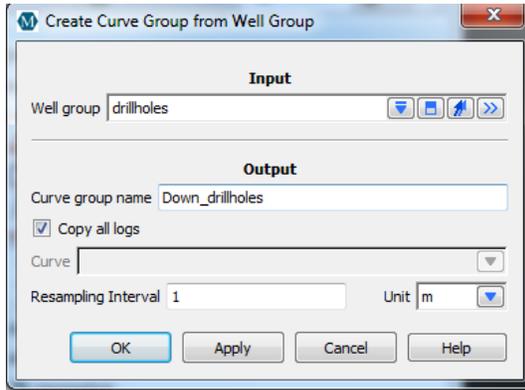
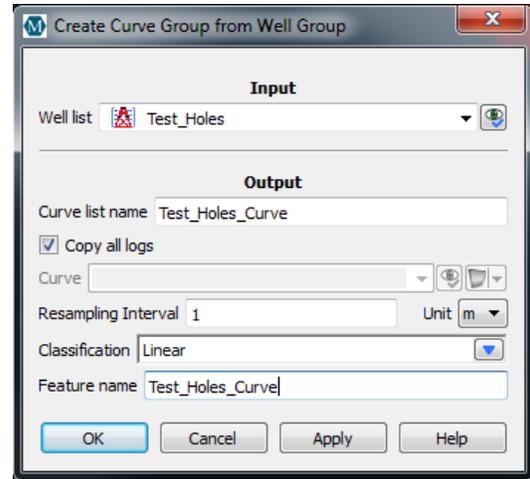**Figure C4 – Step 2h)Making curve group from well group in GOCAD® 2009**

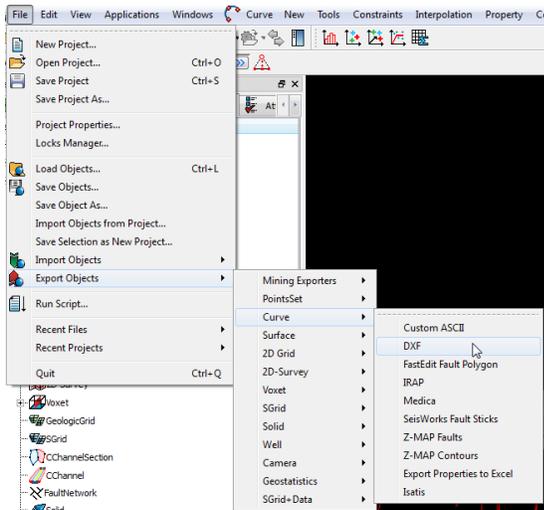**Figure C5-Step 2h) Making curve group from well group in GOCAD® 2014**
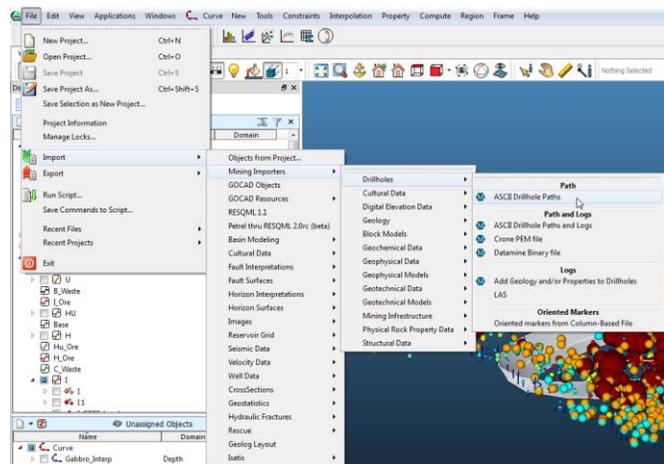

Figure C6 - Step 2i) Export DXF in GOCAD® 2009
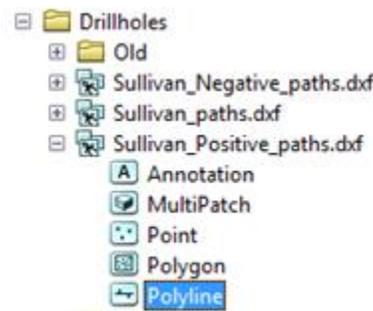

Figure C7 – Step 2i) Export DXF in GOCAD® 2014

Figure C8 – Step 3b) Bring in DXF polyline in to ArcScene^(TM)
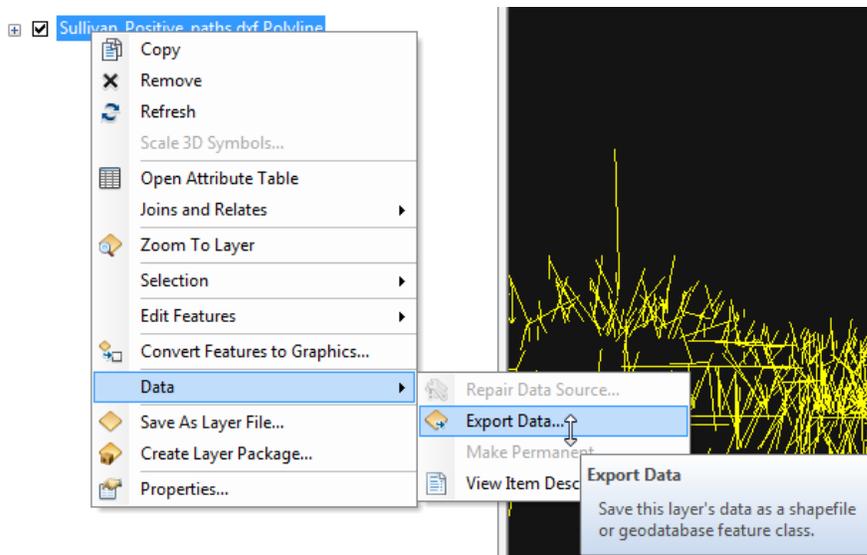
Figure C9 – Step 3c) Export temporary file to shapefile

Figure C10 - Step 5b) List by Source in Table of Contents

Appendix D - Errors and Troubleshooting

Below are listed some errors/problems that you may encounter:

"Create route" tool fails

When using the "Create Routes" tool in ArcToolbox, it is important to understand how your paths are constructed geometrically. In most cases, this error is caused by bad data or misunderstanding of path's geometry. The "Create Routes" tool allows you to choose the "Measure Source". If you select the wrong option, the tool will fail and ArcScene^{TM} is likely to crash. This is especially true for 3D drill holes.

- **Solution:** (This solution applies for both 2D and 3D paths) Although paths may appear to be continuous, they are not. Drill holes were segmented during the "making curves" process in Step 2F. To join all the segments, you must prepare your shapefile attribute table as described in Step 3F and 3G and create routes as described in step 4. Creating these fields is absolutely necessary for this tool to work.

No drill holes displayed after using "make route event layer" tool

There are several possibilities for this error. The most likely cause is bad data. If there are duplicate HOLEID entries or data is not formatted correctly, ArcScene^{TM} will not render a path because it cannot decide which data to use or cannot match the data.

- **Solution 1:** To fix this problem, go back to the original data in your database and double check that there are no duplicate HOLEID entries.
- **Solution 2:** If there are no duplicates, there may be an issue with the HOLEID formatting. HOLEIDs in the event data table and in the shapefile must match **exactly**. This means of your HOLEIDs are in text/string format, you must have an event data table with a text/string HOLEIDs. If you are using excel, you must save the table as a .CSV file. Other default formats, likle.XLS, are not able to format text correctly. If possible use a database that supports DBASE or INFO files since ArcScene^{TM} is most compatible with those file formats. If the HOLEIDs do not match exactly, no data will be referenced to the path and, therefore, will not be displayed.
- **Solution 3:** If the above two solutions still do not resolve the issue, check event table records for overlapping FROM/TO entries. The tool may run with overlaps, but there will be increased error for each of the overlapped entries. The best way to get reliable data is to remove all overlapping entries.

Only parts of drill holes are displayed after using "make route event layer" tool

This error is caused by partial matches of data along a path or skipped data. The most likely cause is not using common units for data, using negative values in the events table or coordinate priority is incorrect.

- **Solution 1:** Data recorded in tables may not be in a common unit. All data must be recorded in the same unit for this tool to work and be accurate. For example, if your drill holes were reconstructed using meters as the common unit, but your event table, say stratigraphic intervals, is in feet, ArcScene^{TM} will interpret the very large feet values as meter values and will only create a partial match for the drill holes. To catch errors as they arise, check the "Generate a field for locating errors" box when making the route event layer. This will record paths with partial matches.
- **Solution 2:** Negative values or values greater than then length of the path are skipped when using the "Make Route Event". To resolve this issue, confirm that no records in the event table exceed the length of the path that it will be referenced to. Also, double-check that there are no negative values.

- **Solution 3:** The coordinate priorities for your routes are important because they tell ArcScene^{TM} where to begin measuring M-values (distances along path). For 2D paths, this is easy. Select "LENGTH" in the "Measure Source" dropdown menu and which quadrant you want to start measuring from in the "Coordinate Priority" menu. For reconstructed paths from GOCAD®, this error is irrelevant since you have indicated your FROM/TO information and coordinate priority is not needed. If you feel that selecting coordinate priority is necessary, use the following method. Before selecting "TWO_FIELDS" from the "Measure Source" menu, you should select your "Coordinate Priority". Once "TWO_FIELDS" has been selected, the coordinate priority menu will be greyed out.

Need to adjust position and/or length of route and events after using "make route event layer" tool

If you have already run your data through the "Make Route Event Layer" tool and need to make adjustments, use the "Transform Route Events" tool. This tool transforms the M-values (measurements) from one route reference point to another and creates a new event table in the process.

No data in attribute table after using "make route event layer" tool

Usually this means that the HOLEIDs in the event table do not match the shapefile table. There are several steps you must go through to resolve this issue.

- **Solution 1:** Create/Confirm identical HOLEID fields in the event table and shapefile. The entries in each field and the formatting of the field itself must be identical for this to be successful.
- **Solution 2:** Make sure all field names in the event table and route shapefile attribute table follow ArcScene's^{TM} rules for naming. See Appendix E for more information and rules about naming fields.
- **Solution 3:** Name your event table correctly according to naming rules listed in Appendix E.
- **Solution 4:** Save your event table as a .CSV, .DBASE5 or .INFO files. These file formats are compatible with ArcScene^{TM}. Excel files such as .XLS are not compatible and will cause linear referencing to fail.
- **Solution 5:** Save your file in an appropriate folder. Files saved in folders with long source paths or folders with illegal names will cause errors in calculation.
- **Solution 6:** Never save files to the desktop of your computer.
- **Solution 7:** Always work locally. Never run calculations and transformations off of files saved to a USB portable drive. If you need to use a USB drive, save the file to a folder on the computer and copy to USB when everything is saved and ArcScene^{TM} is shut down.

"The table you specified does not have the object ID field so that you will not be able to select, query or edit features"

All data in ArcScene^{TM} must have a unique identifier, known as an OID or primary key. If such an identifier is not present, ArcScene^{TM} will not be able to work with the data. This error often arises when using MS Excel® to store data since Excel does not generate primary keys automatically.

- Solution 1: Export the events to a shapefile. After processing your linear referencing request, ArcScene^{TM} produces an event layer (temporary layer). Until you export this layer to a shapefile or feature class, it will remain temporary and will not allow you perform any analysis with the attribute table.
- **Solution 1:** Add a unique identifier for each event field (row) manually into the excel sheet.
- **Solution 2:** Import the excel sheet into a database. The most user friendly database is MS Access®. The database will prompt you to select or make a primary key.

Symbology error

Again, this error is caused by bad data. When headers are chosen for either the shapefile or event table, you should keep the following things in mind. If invalid headers are used and are incorporated into the route event layer attribute table, some of the symbology functions will fail.

- Never use illegal (special) characters such as !, @, #, $ etc.
- Never use spaces. Try to keep all headers to one word or use an underscore.
- Keep it short. Long header names can cause issues.
- Do not use reserved words. ArcScene^{TM} will not allow you to add fields named with reserved words; however, excel or your database program will not prevent it. When the table is brought into ArcScene^{TM}, the fields with reserved words will automatically have an underscore ("_") at the end. See Appendix E for a list of all current reserved words.

Offset values for routes will not update

If you have already created a new route event layer and need to adjust offsets, it is best to create a new route event layer with the updated offset information. Other methods are more complicated then they need to be.

DXF won't export

Try using FILE → EXPORT OBJECTS → MINING EXPORTERS → AUTOCAD → DXF and selecting all individual curves in the folder tree rather than just the group. This issue may cause 3D drill holes to display as 2D holes in ArcMap® when the file is exported to a shapefile.

Drill holes are 2D when they are exported to a shapefile

This is related to how the DXF was saved in GOCAD®. Try using the solution above (DXF WON'T EXPORT PROPERLY) to solve this issue

Drill hole routes are backwards

This happens either in GOCAD® when you export the DX or when you set your origin during the create routes step. You can either manually flip the routes or use the "Flip line" tool in the Editing toolbox. To flip the routes manually:

1. Start an editing session
2. Select a route
3. Double click so you get the green "edit vertices" boxes
4. Right click a green box and choose "flip"
5. Repeat for all the lines that are wrong

Appendix E - Naming fields and files in ArcMap^{TM}

- Never use illegal (special) characters such as !, @, #, $ etc.
- Never use spaces. Try to keep all headers to one word.
- Keep it short. Long header names can cause issues.
- Do not use reserved words. ArcScene^{TM} will not allow you to add fields named with reserved words, however, excel or your database program will not prevent it. When the table is brought into ArcScene^{TM}, the fields with reserved words ill automatically put an underscore at the end ("_"). See below for a list of all current reserved words.

Reserved words:

ADD	DESC	NULL
ALTER	DROP	OR
AND	EXISTS	ORDER
AS	FOR	SELECT
ASC	FROM	SET
BETWEEN	IN	TABLE
BY	INSERT	UPDATE
COLUMN	INTO	VALUES
CREATE	IS	WHERE
DATE	LIKE	
DELETE	NOT	

Appendix F - Coordinate Systems and Transformation

Spatial parameters, coordinate information and transformations

Regional UTM coordinate parameters:

NAD_1983_UTM_Zone_11N
WKID: 26917 Authority: EPSG

Projection: Transverse_Mercator
False_Easting: 500000.0
False_Northing: 0.0
Central_Meridian: -81.0
Scale_Factor: 0.9996
Latitude_Of_Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System: GCS_North_American_1983
Angular Unit: Degree (0.0174532925199433)
Prime Meridian: Greenwich (0.0)
Datum: D_North_American_1983
 Spheroid: GRS_1980
  Semimajor Axis: 6378137.0
  Semiminor Axis: 6356752.314140356
  Inverse Flattening: 298.257222101

Coordinate transformations:

Drill hole collar locations were unified into NAD 83 UTM Zone 11N using conversion factors or affine transformations that were estimated from control points digitized from legacy map archives. These points include mine grids and topographic landmarks such as intersections and bends in rivers and roads (Schetselaar et al., 2015). The mine coordinate system can be transformed into UTM coordinates using the following formulae:

Sullivan Mine Grid (M) – UTM NAD83 Zone 11N conversion equations:

$$\text{Northing}_{83} = 5504368.9257 + E_M(0.001592195) + N_M(0.304645839)$$
$$\text{Easting}_{83} = 570528.8681 + E_M(0.304645839) - N_M(0.001592195)$$

Where: N_M is the mine imperial northing in feet and E_M is the mine imperial easting in feet.

$$Z_0 = 0.3048\ (Z_M + 49.11)$$

Where Z_0 is the geodetic elevation in meters and Z_M is the mine elevation in feet