THE USE OF AUTOMATED CORE LOGGING TECHNOLOGY TO IMPROVE ESTIMATION OF FRACTURE MINERALOGY AND WEATHERING FOR GEOTECHNICAL INDEX CALCULATIONS

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ABSTRACT

In underground mining, it is vitally important to characterise the rock mass conditions as they relate to ground support requirements. Rock mass characterisation is often achieved through the calculation of geotechnical indices. These indices reflect the properties affecting rock mass stability. Fracture parameters such as spacing, density, roughness and orientation are used to design appropriate ground support. The mineralogical properties within and immediately adjacent to fractures also affect the rock mass strength. Therefore, the relative hardness, thickness, and weathering of minerals along fractures are key input parameters in determining overall rock mass characteristics.

Commonly, geotechnical index parameters are collected manually by geotechnical engineers and geologists on drill core. Recent advances in automated core logging technology provide an opportunity to rapidly and consistently collect surface topography (3D laser height data) and mineralogical information (hyperspectral data) from drill core. From a combination of the 3D laser image data and a series of experience-based logical image processing steps, fracture surfaces can be automatically identified and extracted as a group of neighbouring pixels. The mineralogical data is co-registered with the 3D laser data, so the mineralogy of a pixel group representing a fracture can be queried. Mineral hardness and weathering effects can be estimated by analysing the mineralogy within and surrounding a fracture. Fracture fill thickness can be calculated using the number of pixels of each mineral across a fracture. The automated quantification of fracture fill characteristics ensures that these parameters are collected consistently, greatly improving the calculation of geotechnical indices.

INTRODUCTION

Understanding the conditions of a rock mass provides critical information in an underground mining scenario, particularly as it relates to ground support requirements (Hoek et al., 2000). While many of the geotechnical parameters relate to the morphological properties of the rock (e.g. fracture spacing, roughness, etc.), the mineralogical properties are vitally important in understanding geotechnical characteristics. Current practice is to collect mineralogical geotechnical data from drill core by visual inspection and manual logging by a geologist or geotechnical engineer. This method is effective, but can be both time consuming and inconsistent.

Automated hyperspectral drill core logging technologies are becoming increasingly important in ore deposit characterisation, particularly in the area of geologic modelling. The advantages of these automated scanners include fast throughput, low running costs and high resolution (Keeling et al., 2004). Automated geotechnical assessment is not a new concept. The mining industry commonly uses acoustic televiewer down hole logging systems to measure fracture orientations in situ down hole (Shigematsu et al., 2014; Trofimczyk and Du Pisani, 2009). While the televiewer system provides accurate fracture orientations, it does not provide mineralogical information. The Corescan automated core logging system utilises the Hyperspectral Core Imager Mark-III (HCI-3) logging technology for the rapid, non-destructive analysis of drill core. Three high resolution data sets are collected: (1) red-green-blue (RGB) visible imagery (50 µm pixel size), (2) 3D laser height profiles (200 µm pixel size), 15 µm vertical resolution), and (3) visible near-infrared and short wave infrared (VNIR-SWIR) spectra (3.84 nm spectral resolution, 0.5 mm pixel size). These three datasets are co-registered, so the core images and mineralogical data can be draped over the surface model of the drill core (Figure 1).

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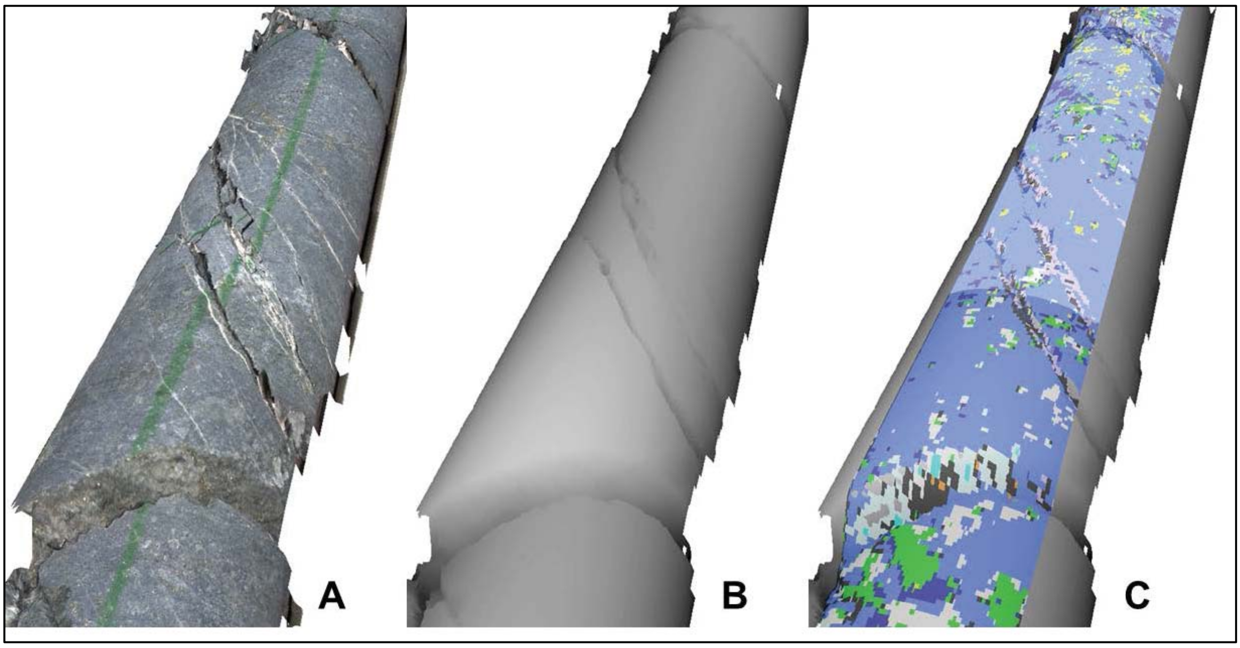
Figure 1. Image showing Corescan outputs for 0.5 m of whole, uncut HQ core. The Corescan system simultaneously collects RGB imagery (A), a 3D laser image of surface topography (B), and mineralogical information (C). The mineralogical data (C) can be draped over the 3D surface to observe the relationship between the fractures and mineralogy.



The aim of this paper is to discuss the use of automated core logging systems to extract fracture aperture, infill mineralogy, and weathering effect information to calculate fracture condition and alteration parameters as they relate to specific geotechnical index calculations.

GEOTECHNICAL INDEX CALCULATIONS

In order to assess the ground support requirements for the installation of underground development and extraction infrastructure, consistent rock classification is required (Brady and Brown, 2013; Hoek et al., 2000). Various authors have proposed geotechnical rock mass characterisation indices, many of which are designed to be calculated using properties measured from drill core. Two commonly used indices are the rock mass rating (RMR) index proposed by Bieniawski (1989) and the Norwegian Geotechnical Institute's tunnelling index (Q-index) developed by Barton et al. (1974). Both indices give guidelines for the excavation type and ground support requirements based on the calculated index value. It should be noted that both the RMR and Q-index calculations refer specifically to 'joints'. Joints are only one type of discontinuity observed in drill core; however, the general term 'fracture' will be used here to reference all types of naturally occurring breaks in the drill core, regardless of geologic origin.

Originally developed for civil engineering applications, the RMR classification is now commonly used to assess underground rock mass conditions (Bieniawski, 1989). The RMR is calculated by the sum of six rock property parameters, one of which is fracture condition which accounts for fracture aperture, hardness of infill, and weathering rating (Table 1) (Bieniawski, 1989). The Q-index was developed by Barton et al. (1974) after comparing numerous case studies of rock behaviour in underground mines. The index is calculated by assigning a numerical value on a scale from 0.001 to 1000 to six geotechnical parameters. The fracture alteration number (Ja) is one of the six parameters required to calculate the Q-index and accounts for fracture infill, aperture and mineralogy (Table 2) (Barton et al., 1974).

Table 1. Criteria for determining the fracture condition in the RMR system. Modified from Bieniawski (1989).

RMR Fracture Condition Guidelines					
Separation (aperture)		Infilling (gouge)		Weathering	
Description	Rating	Description	Rating	Description	Rating
None	6	None	6	Unweathered	6
< 0.1 mm	5	Hard filling < 5 mm	4	Slightly weathered	5
0.1 - 1.0 mm	4	Hard filling > 5 mm	2	Moderately weathered	3
1 - 5 mm	1	Soft filling < 5 mm	2	Highly weathered	1
> 5 mm	0	Soft filling > 5 mm	0	Decomposed	0

Table 2. Criteria for determining the fracture alteration values in the Q-index system. Modified from Barton et al. (1974).

Q-index Ja Guidelines	
Rock wall contact	
Description	Ja value
Tightly healed, hard, non-softening, filling	0.75
Unaltered fracture walls, surface staining only	1.0
Slightly altered fracture walls, non-softening mineral coatings, clay-free disintegrated rock, etc.	2.0
Small clay-fraction (non-softening)	3.0
Softening or low-friction clay mineral coatings	4.0

GEOTECHNICAL PROPERTIES OF MINERALS

The geotechnical behaviour of a rock mass is, in part, determined by the mineralogical properties present within and surrounding fractures. The hardness, swelling potential, and friction potential of the minerals present and the relative abundance of these minerals influence the geotechnical properties of a rock mass. The Corescan system is capable of detecting a number of minerals that are geotechnically significant with respect to their hardness, swelling potential, and friction potential properties (Table 3). Minerals of interest can be divided into four main groups: (1) hard minerals (H), (2) soft, high-friction, non-swelling minerals (SHFNS), (3) soft, low-friction, non-swelling minerals (SLFNS), and (4) very soft, low-friction, swelling clays (VSLFS).

Minerals in group H have consistent geotechnical properties. These minerals are considered to be primary minerals and do not represent weathering as it relates to geotechnical index calculations. Minerals belonging to the remaining three groups (SHFNS, SLFNS, and VSLFS) display very different geotechnical properties than those of group H. These minerals have variable geotechnical properties, but all three are likely the result of weathering affects and must be accounted for in geotechnical index calculations.

Table 3. Geotechnical properties of minerals detected by the Corescan VNIR-SWIR system.

Geotechnical Properties of Minerals Detected by the Corescan System				
Mineral Name	Relative Hardness	Low-friction Potential	Swelling Potential	Geotechnical Mineral Group
amphibole	hard			H
apophyllite	hard			H
epidote	hard			H
prehnite	hard			H
silica	hard			H
tourmaline	very hard			H
carbonate	soft	X		SHFNS
iron carbonate	soft	X		SHFNS
iron oxide	soft	X		SHFNS
chlinochlore	soft	X		SLFNS
chlorite	soft	X		SLFNS
kaolinite	soft	X		SLFNS
phlogopite	soft	X		SLFNS
sericite	soft	X		SLFNS
dickite	very soft	X		SLFNS
gypsum	very soft	X	X	VSLFS
laumontite	very soft	X	X	VSLFS
montmorillonite	very soft	X	X	VSLFS
nontronite	very soft	X	X	VSLFS
vermiculite	very soft	X	X	VSLFS
H = hard, high friction potential, non-swelling minerals SHFNS = soft, high friction potential, non-swelling minerals SLFNS = soft, low friction potential, non-swelling minerals VSLFS = very soft, low friction potential, swelling minerals				

AUTOMATED FRACTURE CONDITION METHODOLOGY

The extraction of geotechnical index parameters requires fracture locations extracted from the laser height data and hyperspectral mineralogical data to determine the minerals present in and around the fracture. The RMR and Q-index input parameters list specific minerals in the classification schemes; however, the infill aperture and extent of weathering away from the fracture are also required. Using the VNIR-SWIR hyperspectral mineralogy and abundance in combination with a series of experience-based, logical, ordered processing steps, the fracture condition and Ja values required in the RMR and Q-index calculations can be automatically determined by the following steps:

- extract fracture infill aperture and mineralogy.
- determine weathering effects away from the fracture.
- calculate fracture condition and Ja.

EXTRACT FRACTURE INFILL APERTURE AND MINERALOGY

To extract the mineralogy and mineral aperture of each fracture, fractures must first be identified. Since drill core is a relatively consistent cylindrical shape, deviations from this shape represent potential fractures. Using a slope analysis of the 3D surface of the drill core, slopes greater than those associated with the curvature of the drill core surface can be filtered, identifying the location of fractures (Harraden et al., 2016). Once neighbouring pixels associated with each fracture are identified, the apparent aperture of the fracture is calculated by multiplying the number of fracture pixels across by the pixel size of 200 μm. In most cases, a fracture is intersected by the drill core at an oblique angle, so this approach calculates apparent aperture. To measure the true aperture, the orientation of the fracture is required. Using the 3D orientation methods outlined in Harraden et al. (2016), simple trigonometry can be used to calculate the true aperture:

$$t = L \cos \rho$$

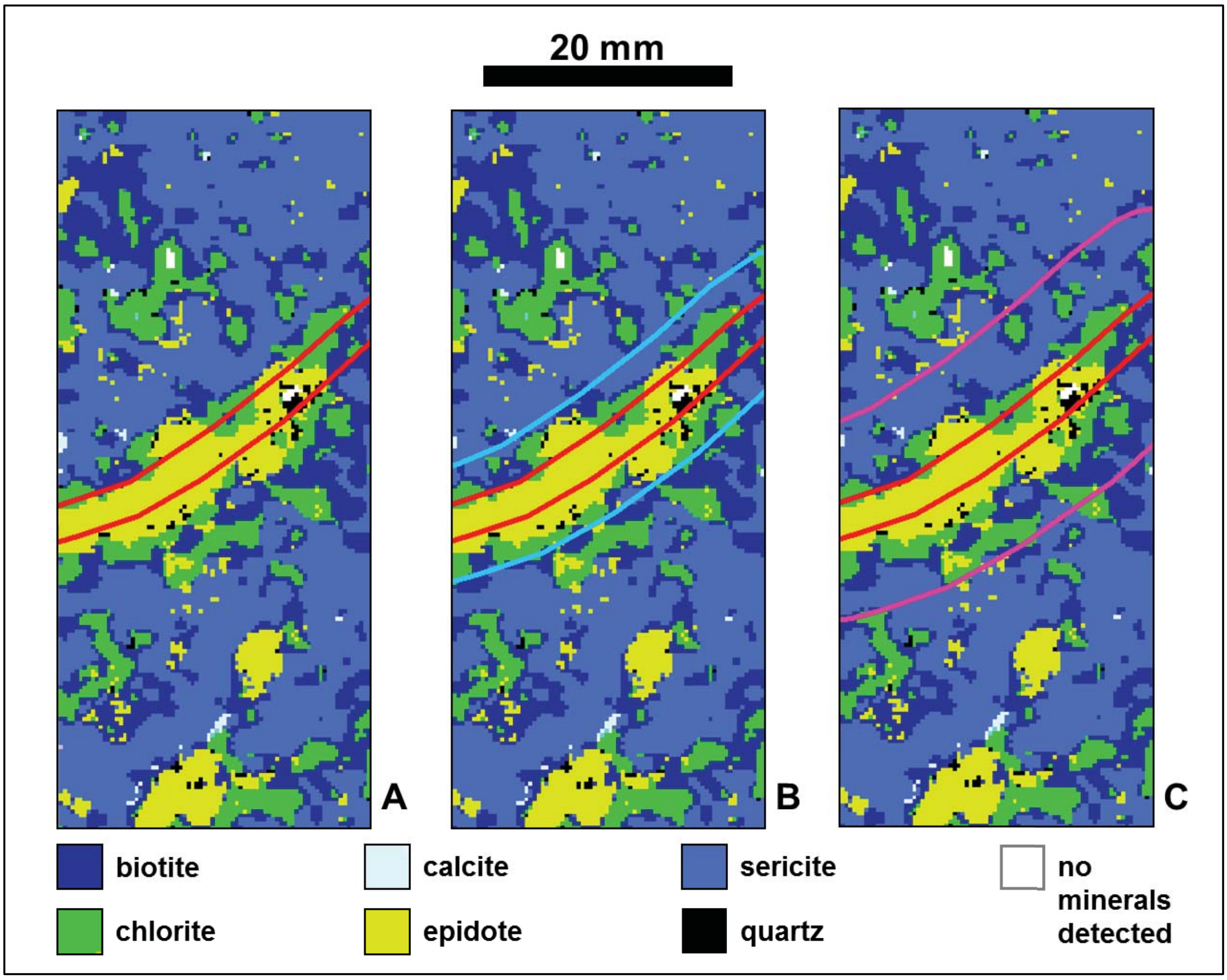
where,
t = true aperture.
L = apparent aperture.
ρ = angle between the pole to fracture plane and the drill hole.
(Charlesworth and Kilby, 1981)

Extracting the mineral abundance of the fracture is achieved through a simple query of the mineralogical data coinciding with the selected fracture pixels. A relative mineral abundance for each fracture is calculated by querying the mineralogy of each pixel within the fracture, then calculating the proportion of the minerals present in the fracture.

DETERMINE WEATHERING EFFECTS AWAY FROM THE FRACTURE

Weathering can affect both fracture surfaces and the wall rock surrounding the fracture. The weathering characteristics of a fracture can be calculated by tracking changes in the abundance of weathering minerals away from the fracture. By buffering the fracture pixels at distances of 5 mm and 10 mm, mineralogy away from the fracture can be used to determine if weathering effects extend beyond the boundaries of the fracture surface. This change is monitored by comparing the relative abundance of weathering minerals within the fracture to the relative abundance of weathering minerals within the 5 mm and 10 mm buffers (Figure 2). If the mineralogy within and immediately adjacent to the fracture is dominated by group H minerals, no weathering effects are observed. Where the fracture is dominated by group H minerals with weathering minerals (SHFNS, SLFNS, and VSLFS groups) detected in the buffers, minor weathering effects are present. Where the mineralogy within the fracture and buffers is dominated by minerals in the SHFNS, SLFNS, and VSLFS groups, significant weathering effects are present within the fracture and extend into the wall rock outside of the fracture boundaries.

Figure 2. By tracking the changes in mineralogy away from the fracture boundary, weathering effects can be assessed. A. The boundary of the fracture (red line) as determined from the surface topography analysis. B. The 5 mm buffer (blue line) relative to the fracture boundary. C. The 10 mm buffer (pink line) relative to the fracture boundary. In this example, the mineralogy within the fracture is similar to the mineralogy of the 5 mm buffer, but changes within the 10 mm buffer. This shows that the weathering effects extend a short distance away from the fracture surface.



CALCULATE FRACTURE CONDITION AND JA

From the mineralogical and weathering information extracted from the Corescan data, a series of logical rule sets are used to assign geotechnical index parameter values to each fracture. In the RMR system, three specific ranking guidelines are used to calculate the total rating for the fracture condition parameter: separation (aperture), infilling (gouge), and weathering. The aperture value is assigned by comparing the measured fracture aperture (calculated in previous steps) to the RMR aperture criteria (Table 1). For the RMR system's fracture infill, a series of logical rule sets that account for the infill aperture and mineral hardness within the fracture are used to rank the infill value (Table 4). Minerals in group H represent hard filling, while minerals in groups SHFNS, SLFNS, and VSLFS represent soft filling. The RMR infill value is assigned based on the criteria outlined in Table 4. Determining the RMR weathering value requires a comparison of the amount of each mineral group present in the fracture, within the 5 mm buffer, and within the 10 mm buffer. The criteria used in the RMR infill processing step is summarised in Table 5. The Q-index requires a single value to calculate the Ja parameter. To assign the Ja value, abundances of the geotechnical mineral groups within the fracture used. Table 6 outlines the specific criteria used in the Ja value rule sets.

Table 4. Decision criteria for the infill RMR parameter using Corescan mineralogical data.

Decision Criteria for RMR Infill Value		
RMR Infill Value	Measured Aperture	Geotechnical Mineral Properties
6	0 mm	H > 50%
4	< 5 mm	H > 50%
2	> 5 mm	H > 50%
2	< 5 mm	SHFNS + SLFNS + VSLFS > 50%
0	> 5 mm	SHFNS + SLFNS + VSLFS > 50%
H = hard, high friction potential, non-swelling minerals SHFNS = soft, high friction potential, non-swelling minerals SLFNS = soft, low friction potential, non-swelling minerals VSLFS = very soft, low friction potential, swelling minerals		

Table 5. Decision criteria for the weathering RMR parameter using Corescan mineralogical data.

Decision Criteria for RMR Weathering Parameter			
RMR Weathering Value	Fracture Mineralogy	5 mm Buffer Mineralogy	10 mm Buffer Mineralogy
6	H > 50%	-	-
5	SHFNS + SLFNS + VSLFS 40 – 60%	H > 50%	-
3	SHFNS + SLFNS + VSLFS 40 – 60%	SHFNS + SLFNS + VSLFS 40 – 60%	H > 50%
1	SHFNS + SLFNS + VSLFS 40 – 60%	SHFNS + SLFNS + VSLFS 40 – 60%	SHFNS + SLFNS + VSLFS 40 – 60%
0	SHFNS + SLFNS + VSLFS > 60%	SHFNS + SLFNS + VSLFS > 60%	SHFNS + SLFNS + VSLFS > 60%
H = hard, high friction potential, non-swelling minerals SHFNS = soft, high friction potential, non-swelling minerals SLFNS = soft, low friction potential, non-swelling minerals VSLFS = very soft, low friction potential, swelling minerals			

Table 6. Decision criteria for the weathering Q-index Ja using Corescan mineralogical data.

Decision Criteria for Q-index Ja Parameter	
Q-index Ja Value	Fracture Mineralogy
0.75	H > 55%
1.0	H 50 – 55%
2.0	SLFNS + VSLFS <10%
3.0	SLFNS + VSLFS 10 – 25%
4.0	VSLFS > 25%
H = hard, high friction potential, non-swelling minerals SHFNS = soft, high friction potential, non-swelling minerals SLFNS = soft, low friction potential, non-swelling minerals VSLFS = very soft, low friction potential, swelling minerals	

CONCLUSION

Since the mineralogical properties of a rock mass dictate rock behaviour, understanding these properties is vital for the production of robust geotechnical models. Recent advances in automated core logging technology provide an opportunity to rapidly and consistently collect coincident surface topography (laser height data) and mineralogical information (hyperspectral data) from exploration and production drill core. By combining core surface topography and mineralogical data obtained from the Corescan automated logging system, fracture infill aperture, infill mineralogy, and degree of weathering of the wall rock surrounding the fracture can be estimated. Key mineralogical and weathering properties affect the geotechnical response of a rock mass, so applying logical, ordered image processing steps allows mineralogical geotechnical index parameters to be rapidly and consistently calculated. Integration of 3D laser data with hyperspectral derived mineralogical data generates large volumes of consistent data for geotechnical assessments, increasing the accuracy and efficiency of geotechnical rock mass characterisation.

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REFERENCES

Barton, N., Lien, R. and Lunde, J., 1974. Engineering classification of rock masses for the design of tunnel support, *Rock mechanics*, v. 6, pp. 189-236.

Bieniawski, Z.T., 1989. Engineering rock mass classifications*: a complete manual for engineers and geologists in mining, civil, and petroleum engineering*, John Wiley & Sons.

Brady, B.H., and Brown, E.T., 2013. *Rock mechanics: for underground mining*, Springer Science & Business Media.

Charlesworth, H. and Kilby, W., 1981. Calculating thickness from outcrop and drill-hole data, *Bulletin of Canadian Petroleum Geology*, v. 29, pp. 277-292.

Harraden, C.L., Berry, R. and Lett, J., 2016. Proposed Methodology for Utilising Automated Core Logging Technology to Extract Geotechnical Index Parameters, *Third AusIMM International Geometallurgy Conference*, Perth, WA, Australia, AusIMM.

Hoek, E., Kaiser, P.K. and Bawden, W.F., 2000. Support of underground excavations in hard rock, CRC Press.

Keeling, J., Mauger, A. and Huntington, J., 2004, Spectral core logger update—preliminary results from the Barns gold prospect, *MESA Journal*, v. 33, pp. 32-36.

Shigematsu, N., Otsubo, M., Fujimoto, K. and Tanaka, N., 2014. Orienting drill core using borehole-wall image correlation analysis, *Journal of Structural Geology*, v. 67, pp. 293-299.

Trofimczyk, K. and Du Pisani, P., 2009. Integration of Borehole Radar and Acoustic Televiewer Data in Geotechnical Boreholes–A Case Study of the Use of Downhole Geophysical Data in Mitigating Risk to a new Mining Shaft Development, *11th SAGA Biennial Technical Meeting and Exhibition, 2009.*