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Analysis of Factors Influencing the Interpretation of a Digitally Examined Fluvial Meanderbelt System: Joggins Formation, Nova Scotia

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Abstract

Clastic reservoir exploration, development, and exploitation are inherently complex with recovery depending largely on the understanding of sand body architecture and interlayered clayey/silty baffles and barriers. Numerous data collection techniques and methods are now widely available for helping to enrich reservoir outcrop analogue data extraction from the well-scale to the larger seismic-scale. This integrated study uses the inherited, combined data from a localized light detection and ranging survey, measurements taken from a portable handheld spectrometer and air permeameter, in addition to total (or absolute) porosity measurements from thin sections to assist with the analysis of components influencing the interpretation of a digitally analyzed fluvial meanderbelt system outcrop. The purpose is not to perform a detailed reservoir characterization or to model a potential reservoir, but rather to study a section of a reservoir analogue and apply reservoir geology with integrated data collection techniques to highlight potential benefits and shortcomings of this type of approach. A point cloud survey generated from light detection and ranging, coupled with other tools including a portable handheld spectrometer and permeameter, supplements data from the light detection and ranging scan and increases the confidence of interpretations. Spectrometer measurements recorded at the outcrop are used to generate a pseudo-gamma log. Handheld air permeameter measurements give a sense of the permeability of corresponding lithologies as well as the variability in permeability of the reservoir both laterally and vertically. Light detection and ranging also provides important information regarding rock properties. The high detail of the outcrop images is used for the assessment of reservoir characteristics. The reservoir data leads to an increased understanding of subsurface reservoirs, particularly of the fluvial meanderbelt type. This study shows the importance and drawbacks of a combined digital data collection approach for the analysis of a sedimentary outcrop.
Keywords: Lidar, Joggins Formation, handheld gamma-ray spectrometer, handheld air permeameter, reservoir heterogeneity, meanderbelt system

Introduction

Fluvial meanderbelt systems form important petroleum-producing reservoirs and are complex to produce. In the petroleum industry, it is normal to perform detailed outcrop studies and then apply the analogous outcrop data and results to a subsurface reservoir that is much more difficult and expensive to directly extract measurements. The distribution and flow of petroleum fluids are controlled by the architecture of the depositional system as well as the internal fabric and geometry of sedimentary features (North and Prosser 1993). To characterize the reservoir and understand and predict the flow and distribution of petroleum fluids, the architectural variability and geological discontinuities need to be defined (Fig. 1). Seismic imaging only resolves the larger-scale architectural features (North and Prosser 1993). Well data offer higher resolution but is widely-spaced within a reservoir (North and Prosser 1993). Therefore, available subsurface data pertaining to a petroleum reservoir are incomplete concerning the spatial and architectural relationships of sandstone bodies (van Lanen et al. 2009). This results in the creation of highly interpretive geological models of subsurface reservoirs that may not be representative of the actual reservoir (van Lanen et al. 2009).

To help fill these gaps of subsurface reservoir architecture, it is often necessary to study modern fluvial meanderbelt systems and ancient fluvial meanderbelt systems from geological outcrops (e.g. Davies et al. 1992; Grammer et al. 2004). Depositional environments with similar characteristics to subsurface petroleum reservoirs over a broad range of scales (seismic to log) provide three-dimensionality and data continuity. Advances in outcrop study over the past two decades have increased the cost efficiency and volume of data that can be collected by means of portable digital field equipment, e.g. the combination of a differential global positioning system with a statically positioned terrestrial...
laser scanner, known as light detection and ranging (lidar), for the rapid acquisition of spatial data (e.g. Bellian et al. 2005; Pringle et al. 2006; Buckley et al. 2010; Hodgetts 2013; Rarity et al. 2014).

Digital field techniques for the study of outcrops has increased as geoscientists recognize the benefits of these applications either as standalone techniques or integrated with other digital field techniques (e.g. portable handheld spectrometer and air permeameter) and traditional field techniques (e.g. outcrop measurement logging and thin section analysis). Studies that have examined the most efficient way to capture, visualize and quantify the data from digital field techniques include Bellian et al. (2005); Enge et al. (2007); Buckley et al. (2008); Hodgetts (2013); Hartzell et al. (2014); Howell et al. (2014). Other applications of digital field techniques include those relating to structural and sedimentological studies (e.g. Bellian et al. 2007; Labourdette and Jones 2007; Fabuel-Perez et al. 2009; Rotevatn et al. 2009; van Lanen et al. 2009; Fabuel-Perez et al. 2010; Keogh et al. 2014; Minisini et al. 2014; Casini et al. 2016; Alhumimidi et al. 2017).

This paper uses the Late Carboniferous (Pennsylvanian) meandering fluvial system outcrop at Joggins, Nova Scotia, to 1) demonstrate methodology for the integration and modelling of data; 2) demonstrate the architectural complexity of a fluvial meanderbelt system; 3) de-risk production from fluvial reservoirs by providing real data and information on reservoir parameters; 4) offer a range of architectural data on fluvial reservoirs and 5) illustrate how traditional field data has been collected and is integrated with modern field data. Other studies of Carboniferous-aged, fluvial meanderbelt examples include the Rocky Ridge Field in North Dakota (Hastings 1990) and the Sorrento Field in Colorado (Sonnenberg et al. 1991; Blott et al. 1999). Additionally, the applications and benefits of these integrated techniques are discussed to show how the analyzing techniques aid in better using the full digital data sets to obtain geostatistical information and improve our understanding of these fluvial systems. Lidar, spectrometer, permeameter, and thin sections provide the opportunity for increased
interpretation reliability.

**Study area**

The study area is located 230 km north of Halifax, Nova Scotia, by the village of Joggins on the shores of Chignecto Bay, an inlet of the Bay of Fundy where the tides rise and fall 13 meters twice daily (Fig. 2). It was selected based on its ease of access and the continuity and quality of the 3D exposure of the outcrop belonging to the Joggins Formation. The section of the outcrop scanned is located just to the north of Coal Mine Point (Fig. 3), which is a sandstone promontory of more resistant rock. The Joggins Formation along with six other conformable formations (Ragged Reef, Springhill Mines, Little River, Boss Point, Claremont and Shepody) were designated in 2008 as a United Nations Educational, Scientific and Cultural Organization (UNESCO) heritage site because of the superbly exposed and preserved rock layers representing the most complete and comprehensive fossil record of life during the “Coal Age”, a time when lush forests and swamps covered much of the Earth's paleotropical latitudes (UNESCO 2008).

**Geological setting**

The Cumberland Sub-basin is one of ten sub-basins that underlie both onshore and offshore portions of the Maritimes Basin (Fig. 4). The Cumberland Sub-basin is approximately 4,500 km² and bounded by faults (Ryan et al. 1987; RPS Energy 2010). Covering large tracts of northwestern Nova Scotia, and to a much lesser extent, areas of southern New Brunswick, the Cumberland Sub-basin (Fig. 5) is situated between the Caledonia Highlands and Westmorland Uplift to the west, the Cobequid Highlands to the south and the Antigonish Highlands to the east (Ryan and Boehner 1994; RPS Energy 2010). The Cumberland Sub-basin is known for its plentiful coal deposits of which numerous seams and old mine workings can be seen in the Joggins Formation. The Cumberland and Mabou groups form a continuous and conformable 14.7 km long outcrop (Fig. 6) along the coast of Chignecto Bay (Grey
and Finkel 2011). Browne and Plint (1994) mention that the margins of the sub-basin include the North Fault to the south, the Caledonia-Dorchester fault system to the north and the Harvey-Hopewell Fault to the west. Martel (1987) suggests the northwestern basin limits may be delineated by a basement horst that formed along the Hastings Fault.

The basin contains a series of synclines with the larger examples being the Athol, Tatamagouche, Scotsburn, Amherst, and Wallace, along with two diapiric anticlines known as the Claremont-Malagash and Minudie anticlines, both of which are enclosed by the synclinal series (Ryan and Boehner 1994). Ryan and Boehner (1994) claim that the structural features contained within the Cumberland Sub-basin are related to basin development features, including growth faults, strike-slip faults, and major synclines. These features are either unrelated or indirectly associated with evaporate tectonics and salt structures such as diapirs, domes, diapiric anticlines, and salt movement-related folds and faults. The Cumberland Sub-basin is classified as a salt-withdrawal basin with syndepositional slump features indicative of syndepositional movement of salt.

**Sedimentology and stratigraphy**

The Joggins Formation is 915.5 m thick and is divided into 14 cycles, each characterized by limestone, coal, or fossiliferous mudstone at their base (Davies and Gibling 2003; Davies et al. 2005). These cycles are grouped into three distinct stratigraphic facies; well-drained and poorly-drained floodplain facies and open-water facies (Davies and Gibling 2003).

The well-drained facies contain reddish-coloured siltstone, mudstone, and sandstone with the occurrence of small-scale channel sandstones and carbonate nodules. Within the well-drained alluvial plain deposits occur thin grey-green layers with millimeter-scale coal laminae, probably the result of alternating high and low water table conditions (Davies and Gibling 2003). Channel bodies are comprised of red and grey sandstone and mudstone with conglomerate and are narrow (~ 1 m) with a
maximum thickness of 6 m (Davies et al. 2005; Rygel 2005). The most likely environments of deposition were well-drained alluvial plains containing anastomosing channels (Davies and Gibling 2003).

The poorly-drained facies contain mainly sandstone and green/grey mudstone hosting rare sub-meter thick coal seams (the target of historical coal mining), carbonaceous mudstone and minor limestone containing siderite nodules (Davies et al. 2005). The famous fossilized trees occur within the thicker sandstone and mudstone beds and may be up to 6 m in height according to recent measurements (Calder et al. 2006). Channel bodies are typically between 1 to 3 m thick and are a regular occurrence, although there are larger channel bodies up to 9 m thick (Davies et al. 2005). The poorly-drained facies are interpreted to have been deposited in a coastal wetland or deltaic plain environment with high rainfall and humidity, similar to the Mississippi Delta (Davies and Gibling 2003; Davies et al. 2005).

The open-water (marine) facies contain organic-rich, well-cemented limestone or “clam coals” as they are locally known due to their dark grey appearance and presence of bivalve fossils (Davies et al. 2005). The limestone is overlain by laminated siltstone, which contains disk-shaped siderite nodules. The siltstones are capped with a few meters of sharp-based sheet sandstones that show evidence of channel downcutting and contain such features as ripple cross-laminations and mud drapes (Davies et al. 2005). The open-water facies are interpreted as having been deposited in a basin-wide, brackish (restricted marine) environment that was equivalent to the modern Baltic Sea with its variable salinity and somewhat enclosed attributes (Grasshoff 1975; Davies et al. 2005).

The Joggins Formation coal beds have been the subject of studies pertaining to their deposition, composition, and hydrocarbon potential, with the findings summarized by Grey and Finkel (2011). Dawson (1854) estimated that the formation contained a minimum of 45 coal beds with varying thicknesses from less than a centimeter to meter-scale. The organic maturation of the Joggins
Formation, based on vitrinite reflectance from surface exposures ranges from 0.67 % to 0.7 %, or qualitatively low (Mukhopadhyay et al. 1991). The coals contain liptinite macerals with Type II-III kerogen, indicating condensate-gas prone source rocks with hydrogen index values ranging from 250-300 mg HC/g total organic content (Mukhopadhyay et al. 1991). Gibling and Kalkreuth (1991) also reported good to very good source rock potential but concluded the coal beds were too thin for economically viable hydrocarbon volumes.

Methods

A variety of common field measurement equipment was used for data collection. This included a terrestrial laser scanner paired with a global positioning system, a portable handheld gamma-ray spectrometer, a portable handheld air permeameter, and hand samples to allow for digital image porosity analysis. The terrestrial laser scanning was performed by the authors. Measurements taken using the spectrometer and air permeameter were performed by colleagues.

Terrestrial Laser Scanning

Static terrestrial laser scanning was completed using the Dalhousie University Basin and Reservoir Laboratory Optech Incorporated Intelligent Laser Ranging and Imaging System (ILRIS) 3D lidar scanner (Fig. 8) with a scan speed of 2.5 kHz and 2,500 points per second. (Optech Incorporated 2006a). Lidar is a highly versatile ground-, air- and water-based tool for the remote collection of data and it has been applied extensively to a variety of disciplines including earth sciences (e.g. Bellian et al. 2005; Bellian et al. 2007; Rotevatn et al. 2009; Moore et al. 2012; Rarity et al. 2014; Grechishnikova 2016; Siddiqui et al. 2018; Zeng et al. 2018). Lidar scanning bombards a surface with laser pulses and measures the gap in time between the initial pulse emission and the returning signal detection. The emitted laser pulse has a wavelength of 1,535 nm (infrared spectrum). For a reflection to be obtained, the rock being bombarded by laser pulses must be of the type to produce a dielectric discontinuity,
thereby allowing the original wave to be reflected to the source.

The section of the cliff was chosen for scanning because of the abundance of channel bodies, quality, and access. The scan was performed on a sunny, clear day to avoid various problems such as the increased reflectivity associated with scanning a wet outcrop and rain droplets. The scan was collected at an average range of 100 m from the cliff face at a 12 mm point spacing in a step-stare scan pattern. The point cloud is an assemblage of approximately 1.4 million points following the decimation of irrelevant points; all which contain an 8-bit intensity value between 0 and 255, in addition to a unique X (latitude), Y (longitude), and Z (elevation) value (i.e., each point has an exclusive coordinate).

The point cloud is georeferenced to provide all points in the point cloud with real-world coordinates. To perform this task, at least three georeferencing targets must be placed at varying X, Y, and Z locations to allow for triangulation. Preferably, placement of the three targets would include one at the top of the section and two at a distance on either side of the lidar unit. The targets consist of a piece of plywood cut into a 0.5 m by 0.5 m square with an outer area covered in black, retro-reflective paint and an inner circle (approximately 12 cm in diameter) that is white and non-reflective. The targets are placed in such a way that the black outer area and white inner circle face the lidar unit. When scanned by the lidar unit, the targets return a distinct signature that when combined with the global positioning system readings of the centers of the non-reflective white inner circles allows for the scans to be georeferenced.

**Global Positioning System**

Static terrestrial laser scanning was paired with a Real-Time Kinematic (RTK) differential Global Positioning System (DGPS) (Fig. 9) for obtaining a fully georeferenced data set. A Real-Time Kinematic differential Global Positioning System applies differential correction techniques to improve the accuracy of location data that is gathered using GPS receivers (Van Sickle 2015). The base station
was erected over a well cap on the backside (cliffside) of the Joggins Fossil Cliffs Centre that has known
surveyed coordinates (UTM Zone 20T Easting = 387,098.72; Northing = 5,061,126.31; Elevation =
26.453 m). The transmission antenna was set up next to the base station to transmit the corrections made
by the base station to the rover in real-time as they become available. The rover was mounted on an
aluminum pole and positioned ~ 0.5 km away from the base station/transmission antenna setup.
Following the placement of georeferencing targets within the lidar scan survey area, the X, Y, and Z
coordinates of each target were recorded. This allows for georeferencing of the lidar point cloud to be
completed post-scan in the Basin and Reservoir Laboratory at Dalhousie University.

Portable Handheld Gamma-Ray Spectrometer

Measurements were taken using a Science Applications International Corporation Exploranium
– Radiation Detection Systems GR-130 miniSPEC spectrometer with a 74 cm³ thallium-activated
sodium-iodide [NaI (Ti)] detector (Exploranium - Radiation Detection Systems 2001). The
spectrometer has numerous functions, and for this study, the gamma-ray scintillometer survey function
was used by selecting the survey mode from the main menu list. A gamma-ray scintillometer is used to
measure the radioactive content of a rock sample by measuring the amount of uranium (U), thorium
(Th) and potassium (K). Readings are taken at regular intervals by merely placing the device against
the rock surface and recording the value displayed. Gamma rays are detected when they encounter the
sodium iodide crystal within the instrument, resulting in the emission of free electrons and light energy,
which are converted into electrical pulses. The stronger the gamma rays encountered, the larger the
produced electrical pulse response will be within the instrument. The number of pulses or counts is
proportional to the amount of radioactive material. The device displays the current count rate in the
form of counts per second (cps).

Typically, finer-grained lithologies, such as siltstones and mudstones, will contain abundant
concentrations of radioactive elements when compared to sandstones. The finer-grained lithologies contain clay minerals (abundant with K), which have large interlayer spacings in their crystal structures, allowing U and Th also to fit in. Sandstones generally have low radioactive content because they have characteristically high amounts of quartz that has very low radioactive element uptake in its crystal lattice. Sandstones are subject to increased working and re-working during transport, meaning that typically the higher the mineralogical maturity, the lower the radioactive content. On a gamma-ray log trace, sandstone will usually display lower values; mudstone will typically display higher values. This allows for the recognition of subtle variations in clay content within the sandstone bodies. Gamma-ray counts can be used to determine baffles and barriers to fluid flow in a reservoir. This portable spectrometer was used at 30 different stratigraphic levels along the base of the studied section. At each of the locations, the sampling time was typically 5 seconds (a few were 6 seconds; one was 7 seconds), with a reading recorded every second. The sampling time was arbitrary. Measurement locations were based on changes in lithology and the nature of the contacts rather than a set interval. Values were also recorded from eight collected hand samples as well as 51 fallen sandstone blocks along the section and the base of Coal Mine Point. The fallen blocks represented material that was at too high an elevation in the cliff to reach.

**Portable Handheld Air Permeameter**

A factory-calibrated portable handheld air permeameter was used to indirectly measure the in-situ permeability of sandstone at different outcrop locations. A total of 24 in-situ measurements were made on rocks representing the well-drained and poorly drained facies associations. The dipping strata allowed values to be recorded along the entire stratigraphic interval. Data was collected using a New England Research Incorporated TinyPerm II Portable Air Permeameter (mini-permeameter), which resembles an elaborate bicycle pump and allows for the indirect, non-invasive, and non-destructive
measurement of rock matrix permeability (New England Research 2013). This type of air permeameter has been successfully applied to numerous geologically-related studies around the world representing numerous depositional environments (e.g. Huysmans et al. 2008; Rotevatn et al. 2008; Fossen 2010; Fossen et al. 2011; Rogiers et al. 2011; Pessemiers et al. 2012; Torabi 2012; Haffen et al. 2013; Rogiers et al. 2013; Antonellini et al. 2014; Magnabosco et al. 2014; Rogiers et al. 2014; Morgan and Murray 2015; O’Connor 2016; Raduha et al. 2016).

The instrument has a detection range from 10 millidarcys to 10 darcys (New England Research 2013). To record the permeability of a (rock) specimen, the pump is first fully extended. The user applies pressure to a 22 mm diameter rubber nozzle with an inlet/outlet diameter of 9 mm (an area of 63.62 mm$^2$), which is held tightly against a relatively flat rock surface and the plunger handle is fully depressed to its lock position (Huysmans et al. 2008). Air from the chamber is forced into the rock surface with a microcontroller unit monitoring the plunger volume and transient vacuum pulse at the surface of the contacted sample. The microcontroller uses signal processing to compute the response function of the instrument/sample system (Rotevatn et al. 2008). The resulting values displayed on the microcontroller can be correlated to a permeability value in millidarcys using a calibration chart (Fig. 7). The correlation between permeameter values displayed on the microcontroller screen and the resulting permeability is linear (Fig. 7), with higher values corresponding to lower permeabilities and vice versa. Permeability was given a rank (Table 1) originally by Levorsen (1954) and modified by Nabawy et al. (2009).

**Digital Image Porosity Analysis**

There are several quantitative aspects of porosity that can be measured and calculated; all relating to different pore spaces. For this study, total (or absolute) porosity was measured. The total porosity is the summation of effective and ineffective porosity (all void spaces), which are related to measurements
of interconnected and isolated pores, respectively (Magnabosco et al. 2014). Digital image porosity analysis was carried out by use of an Olympus BX51 polarizing microscope on thin sections made from gathered hand samples. The thin sections were stained with a blue dye, such that any pores would exhibit a blue colour. The microscope was fitted with a camera to allow for digital images to be captured on the connected desktop computer using the Olympus Digital Projection Controller software. The digital images were imported, one by one, into Image-Pro Plus. The software allowed for the manual selection of porosity. For contrast, the blue-dyed areas representing porosity were coloured in yellow, grains were coloured in blue, and cement was coloured in brown. Apart from porosity, the grain area percentage and cement area percentage were also measured. Three area percentages were calculated; void area, grain area, and cement area, each of which were given a unique colour. The software scanned each image and estimated a total percentage value based on the area defined by each colour. The resulting porosity values were then given a rank, following that originally published by Levorsen (1954) and modified by Nabawy et al. (2009) (Table 2).

**Errors and Uncertainty**

**Terrestrial Laser Scanning**

According to the manufacturer, Optech Incorporated (2006b), the lidar scanner used for this study has a raw range accuracy of 7 mm at 100 m from target and a raw positional accuracy of 8 mm at 100 m from the target. A major limitation of lidar imaging is the inerrant data gaps that occur from overhangs, notches, and promontories (e.g. Xharde et al. 2006; Sturzenegger et al. 2007). At the study area, these features result from shore-based processes that include wave action and freeze-thaw cycles along exposed rock faces. To decrease data gaps, it is often necessary to scan the same outcrop region multiple times from different locations and angles (Sturzenegger et al. 2007). For this study, only one scan from one location was completed. As a result, data gaps are present when the outcrop point cloud
is viewed at an angle other than perpendicular from the scanner setup location. This has the effect of creating areas with no point cloud detail around overhangs, notches, and promontories, but is not detrimental to this study.

Lichti and Harvey (2002) and Sturzenegger et al. (2007) also suggest that rock mass reflectivity is affected by surface water, leading to a decrease in the laser scanning range. Lichti and Harvey (2002) showed that a scanning distance of 3 m, the intensity increased if the reflecting surface was wet, while at 53 m, the intensity decreased for a wet reflecting surface. Sturzenegger et al. (2007) noticed this phenomenon when scanning an outcrop with groundwater seeping from fractures and noted the difference in reflectivity between the dry and wet areas. This is of importance for this study since approximately 14 m of the outcrop is underwater twice a day. For that reason, any outcrop studies done at this location must be efficient. The lidar scan was done while the tide was in full retreat; meaning the equipment was transported, setup, and initialized as soon as the intertidal area was exposed. So, this scan was performed on an outcrop that was wet or at least partially so. It is not known to what extent or magnitude the wet outcrop had on the acquired data.

**Global Positioning System**

The RTK DGPS had a positional accuracy of approximately +/- 2 cm (Van Sickle 2015). As discussed earlier, the base station was set up over a well cap with previously (circa 2008) surveyed coordinates. Not much is known about the survey of the base station (well cap) coordinates, other than it was done using the same high accuracy survey instruments. It is therefore assumed that the coordinates of the well cap are accurate to within +/- 2 cm.

**Portable Handheld Gamma-Ray Spectrometer**

According to Exploranium - Radiation Detection Systems (2001), the spectrometer contains a glass vial as part of its inner workings and is sensitive to humidity and temperature, which affects the
accuracy of measurements. To ensure accuracy is maintained when collecting data, the instrument contains a cesium-137 chip for calibration (Exploranium - Radiation Detection Systems 2001). The manufacturer of the spectrometer lists the normalized standard error as 2.25 (Exploranium - Radiation Detection Systems 2001).

**Portable Handheld Air Permeameter**

Several operational errors are possible when measuring permeability, especially in-situ. The most significant error is the tightness of the seal between the rubber nozzle of the permeameter and the rock surface (Magnabosco et al. 2014). This seal between instrument and rock is influenced mainly by the pressure of the seal against the surface, the angle at which the tip of the probe contacts the rock surface, and the roughness of the rock surface (Brown and Smith 2013; Filomena et al. 2014). Measurements are also sensitive to full or partial sample water saturation, which is of importance for this study because of the rise and fall of the tides at the study area (Brown and Smith 2013). These tides cover the outcrop well above the height at which measurements were taken. Air permeameter measurements have a small area of investigation, so results may not be representative for the entire layer because permeability can have a wide range of values, several orders of magnitude in some instances, in less than a meter (Brown and Smith 2013). Magnabosco et al. (2014) observed that the seal between the sample and the instrument at low temperatures (cold) was less than at higher temperatures, which they attributed to the lack of flexibility in the rubber nozzle of the device at lower temperatures. Filomena et al. (2014) assessed the accuracy of gas-driven permeability measurements using a variety of probe-type permeameter, such as the TinyPerm II and determined that measured permeabilities were 34 to 41% (average of ~ 37%) lower for unconfined samples than core plugs. De Boever et al. (2016) was able to show that permeability measurements made with a TinyPerm II corresponded very well with the Lattice-Boltzmann method for determining permeability with measurements typically in the same order.
of magnitude. For this study, no samples were taken for core plug permeability analysis. There are also no other outcrop studies of the Joggins Formation that have determined permeabilities from an air permeameter or from laboratory measured core plugs; hence, there is no way of comparing current permeability values from this study to other known permeabilities. Quantification of the uncertainty associated with this instrument at the study area is not possible given current data.

**Digital Image Porosity Analysis**

Porosity results can vary significantly across a single thin section and within an outcrop, can vary by an order of magnitude in under a meter (Brown and Smith 2013). During the preparation of a thin section for digital image porosity analysis, holes may inadvertently be created in the thin section. As a result, these holes in the thin section may unknowingly be counted as porosity, thereby increasing the total porosity value.

**Results and Discussion**

**Gamma-Ray Logs**

The total gamma radiation for the studied section (*Table 3* and *Fig. 10*) varied from 82 cps for trough-cross stratified, thinly bedded medium-grained sandstone, to 256 cps for mudstone with average values from 93 cps to 255 cps. Gamma-ray values were recorded at 25 stops along the base of the outcrop (*Fig. 10*) at and near Coal Mine Point, with five measurements per stop along the outcrop. A pseudo-gamma-ray log based on these measurements from each stop was constructed (*Fig. 11*) using the technique described by Slatt et al. (1992). The higher gamma-ray values are associated with mudstone, and lower values are associated with the sandstone bodies. The relationship of the sandstone bodies (lower cps) and mudstone layers (higher cps) with the pseudo-gamma-ray log is apparent when the pseudo-gamma-ray log and stratigraphic section by Rygel (2005) are correlated. The higher gamma-ray values documented from the red mudstone beds probably reflect the presence of potassium-feldspar.
or U, Th, and K-bearing heavy minerals. These mudstones are not visibly rich in organic matter, so any
corribution to the high gamma count can be ruled out. Examples of sandstones with high gamma-ray
readings also occur, likely for the same reasons as the red mudstone beds and/or because of the presence
of extra-basinal clasts, where a sandstone contains intraformational mudstone rip-up clasts, thus
skewing the gamma-ray spectrometer readings to higher values. This is an important consideration and
cannot be discerned from subsurface data unless interpreted on image logs (Nickerson 2010).

Gamma-ray spectrometer readings were recorded on fifty-one visually homogenous sandstone
blocks eroded from the cliff face. A total of 5 measurements at the same location were collected for
each sandstone block (255 total measurements). The sandstone blocks were chosen randomly and
surveyed to determine the variability in gamma counts within the sandstone. The range of gamma-ray
values amongst the fallen blocks was not significant, suggesting they have similar compositional
characteristics. Readings ranged from 97 cps to 195 cps with average values ranging from 109 cps to
163 cps. The average value for all 255 measurements was 136 cps. The increased values suggest the

Eight hand samples were analyzed with the spectrometer for a total of 60 seconds, providing 60
readings for each sample. The average gamma value for the sandstone, limestone, and coal lithologies
is approximately 130 cps for each (Table 4).

Net-To-Gross (NTG) – Scaling Gamma Ray Log

The gamma-ray data set for the measured section (Fig. 10) indicates that values lower than 93 cps
are 100 % sandstone, whereas gamma-ray values greater than 255 cps are indicative of 100 % mudstone.
\[ NTG_{GR} = 1 - \frac{(GR_{\text{value}} - GR_{\text{sand cutoff}})}{(GR_{\text{shale cutoff}} - GR_{\text{sand cutoff}})} = 1 - \frac{(GR_{\text{value}} - 93)}{162} \]  

The average net-to-gross ratio for the measured section (study area) by Rygel (2005) (Fig. 11) was calculated to be 0.478. Although the NTG is nearly 50%, it gives an erroneous calculation of reservoir quality and continuity because the sandstone is not a thick, homogenous unit. The sandstone is divided up into beds of variable thickness separated by thin (cm-scale) to thick (dm scale) beds of mudstone and coal that act as baffles and barriers to fluid migration.

**Permeability**

Permeameter values were collected on eight fresh sandstone blocks eroded from the cliff face (Table 5). Permeameter values from 66 to 1917 md, a range from good to excellent. Permeameter measurements were also recorded along the cliff face. A total of 10 samples were tested. Values ranged from 7 md to 410 md, which is considered fair to very good following Levorsen (1954) and Nabawy et al. (2009). Permeameter values are summarized in Table 5 and plotted on Fig. 12. These values exhibit a wide range, especially the first eight samples measured near the base of Coal Mine Point. Sample 5 and sample 7 occupy the excellent range (1,000 md and over) and represent a sizeable meandering channel body (point bar) at Coal Mine Point. The permeability data displays the wide range of measured values representing different lithologies, but also a large variation within the sandstones, with variations in permeability in both the horizontal and vertical sense (with respect to bedding) (Fig. 13). This demonstrates lateral and vertical heterogeneity. The permeability measurements are another indicator of the complexity of the Joggins Formation and other fluvial reservoirs in terms of reservoir heterogeneity.

**Porosity – Digital Analysis**

The total porosity results obtained from the thin sections and image analysis software indicate representative lithologies had average porosity values ranging from 0.9% (negligible) to 7.4% (poor).
Porosity was measured at numerous areas of each thin section as total porosity. The porosity exhibited by the samples is intergranular as it exists between grains. The total porosity analysis shows the percentage of cement is greater than initially predicted visually and the cement is primarily ankerite. A summary of the cement area, grain area, and porosity of each of the six sandstone lithologies is presented (Table 6). Fig. 13 and Fig. 14 are examples of photomicrographs. Both samples are sandstones, with calculated porosity values of approximately 3%. The range of porosity values measured for each thin section is plotted (Fig. 15).

**Architectural Element Variability and Reservoir Connectivity**

The lidar images show the lateral variations in sandstone body thickness observed at the outcrop. The characteristics of a good reservoir rock can change drastically across short distances (few meters or less) because of factors such as the pinch and swell nature of sandstone bodies. The variability in thickness of these sandstone bodies is just one of the numerous complexities that must be considered when attempting to understand reservoir rocks. The variable bed lithology can be discerned in the lidar images through correlation with the outcrop photographs. Sandstone beds are present between low permeability layers, including coal, mudstone, and sandy mudstone. These deposits vary widely in their thickness from 2 to 10 m for some of the thicker sandstone bodies to 2 to 5 cm for some of the coal strata. These analogous outcrop observations illustrate the various parameters that can affect production from meandering fluvial reservoirs.

Lithologies can be recognized by displaying the point cloud using a colour scheme where the dark brown colours (Fig. 16, 17, and 18) represent sandstone and the light brown colours represent finer-grained lithologies, such as the mudstone and siltstone. Additionally, the light brown colours can represent areas that are extremely water wet or clay-rich, indicating permeability as well as the loose, unconsolidated Quaternary glacial till which lie unconformably over the tilted strata of the Joggins
Formation. In other words, the hotter intensities (dark brown) correlate strongly with the higher reflectivity units.

Calibration of the point cloud for sandstone helps to clarify a variety of reservoir attributes. Fig. 16 is a view of the entire point cloud showing the degree of reservoir compartmentalization, apart from the massive sandstone of Coal Mine Point and the sharp contact between the Joggins Formation and the overlaying Quaternary sediments. In Fig. 16 and all other succeeding images, the alternating lithologies are well defined. Low permeability pathways and impermeable layers (baffles and barriers) to fluid flow, as well as permeable channel sandstones demonstrate a wide variation in permeability from 7 to 1,917 md within the Joggins Formation. Migration of fluids within a sandstone unit of the Joggins Formation is reduced by a low permeability zone within that bed. The finer-grained lithologies such as the mudstone, coal, and siltstone, serve as barriers to fluid migration, presumably with crossflow only occurring along fractures or small faults.

Within the interbedded zones, we can identify false connectivity (Fig. 17 and 18) from the lidar images caused when sandstone is eroded and accumulates on areas of the rough cliff face, which masks the true lithology and leads to an increased net-to-gross ratio. The gamma-ray signature can be used with primary observations of facies to help differentiate low gamma-ray reservoirs (sandstone) from high response barriers and baffles (mudstone/coal). Gamma-ray values (cps) combined with digital photography, corrects the interpretation of recorded intensity data from lidar. Assessment of reservoir connectivity at the outcrop scale using the DOM indicates poor reservoir connectivity. Connected sandstone bodies are important for hydrocarbon reservoirs or aquifers as it effects reservoir production.

**Quantitative Data Summary and Discussion**

The quantitative data are presented in Table 7. These data could be useful for creating a low-resolution 3D block model where the lidar point cloud serves as the starting point for building the
geomodel because changes in lithology can be traced and baffles/barriers can be easily distinguished. The pseudo-gamma ray curve helps to distinguish between sandstone and mudstone. The porosity and permeability data can be used to populate the simple model to allow for basic fluid flow simulations to be run using oil, gas, water, or a combination.

Additionally, carbon dioxide can be used as a simulation fluid since carbon capture and storage are becoming more prevalent. These simulations would help show the flow dynamics within a fluvial meanderbelt system but could potentially be useful for other analogues. Furthermore, the data provide insight into sandstone/mudstone contact architecture and permeability/porosity distributions.

Numerous benefits and problems are recognized in this study. One obvious benefit is how well the lidar intensity correlates with lithology. Also, the study provides a sense of the requirements for data collection versus the size of the outcrop study area. Using the current data to create a geomodel would produce a low-resolution example. A higher density of data is needed for high-resolution models.

One of the problems is the study area was too large for the amount of data collected. Another issue relates to the measurement of permeability and porosity. There is no laboratory-measured permeability to compare with air permeameter measurements of permeability, and there is no laboratory-measured porosity to compare with thin section measurements of porosity.

To improve upon similar studies in the future, it is recommended that the study area be decreased in size and the quantity of data be increased. This would involve selecting one or more areas on the outcrop with a clean, flat surface and perhaps setting up a meter by meter-sized study area, whereby a grid could be superimposed and air permeameter and gamma-ray spectrometer measurements could be recorded at regular intervals both horizontally and vertically. A detailed description of the variation in grain size, sorting, roundness, sedimentary structures, etc. would also yield valuable reservoir rock information. A highly detailed lidar scan (e.g., 1 mm spacing) of the surface would further help to show
variations in quartz abundance and sedimentary structure relations. Numerous core plugs could be collected for porosity and permeability analysis in a laboratory to corroborate values measured at the outcrop and in thin sections. This would result in a higher resolution study, albeit at a smaller scale, that offers more details relating to reservoir characterization, such as the internal architecture and heterogeneity. This information could be used to create a high-resolution 3D geomodel of a small outcrop section populated with closely spaced porosity and permeability data that could be simulated.

**Conclusions**

1. Gamma-ray spectrometry reveals a wide range of values, which are expected from the complex stacking of variable bed lithology of the interbedded strata. It re-iterates the usefulness of gamma-ray spectrometry for aiding with lithology contrasts in complex geology, but cannot selectively measure and identify reservoir heterogeneity such as clast variability.

2. Outcrop permeability data varies widely from 7 md to nearly 2,000 md. The variability in outcrop permeability is not simply the result of a change in lithology between beds; rather, permeability appears to vary within individual beds, as a result of subtle changes in lithology and composition. This relates back to the interbedded nature of the strata in the outcrop.

3. Lidar can be a highly useful tool to characterize the heterogeneity of an outcrop because of its high resolution and high detail of the resulting generated point cloud. The intensity of the reflected light from the rock outcrop that is measured by the lidar system has the added benefit of being a proxy for lithology, at least for an outcrop that displays such widely varying and alternating rock strata, such as at Joggins. For a more lithologically homogenous outcrop, it may be more challenging to extract information from a high-resolution point cloud.

4. Reservoir characterization and heterogeneity studies are further improved when lidar is paired with more traditional approaches of measurement, such as the use of gamma-ray spectrometry and an air
permeameter. Considering the overall studied section, reservoir heterogeneity of the Joggins Formation is stratigraphically controlled with variations in alternating lithology being the apparent reason. Single beds within that overall studied section further exhibit vertical and horizontal heterogeneity as a result of lithological changes within them or changes in grain size, which do occur. It is also likely that sedimentary structures play a role in reservoir heterogeneity within single beds.

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### Nomenclature

\[ \text{cps} = \text{counts per second} \]

\[ GR_{value} = \text{gamma ray value, counts per second (cps)} \]

\[ GR_{sand\ cutoff} = \text{the cutoff gamma ray value for sand, counts per second (cps)} \]

\[ GR_{shale\ cutoff} = \text{the cutoff gamma ray value for shale, counts per second (cps)} \]

\[ k = \text{permeability, md} \]

\[ k(v) = \text{permeability (vertical), md} \]

\[ k(hpar) = \text{permeability (horizontal – parallel to strike of cross-bedding/laminations), md} \]

\[ k(hper) = \text{permeability (horizontal – perpendicular to strike of cross-bedding/laminations), md} \]

\[ NTG_{GR} = \text{net-to-gross ratio} \]

\[ \Phi = \text{porosity} \]
Table Captions

Table 1. Permeability ranking (Levorsen 1954; Nabaway et al. 2009).

Table 2. Porosity ranking (Levorsen 1954; Nabaway et al. 2009).

Table 3. Average gamma-ray measurements within the area scanned by lidar acquired 100 m to the north of Coal Mine Point up to and including the large meandering channel body at Coal Mine Point.

Table 4. Gamma-ray measurements recorded from eight hand samples from the Joggins Formation study area.

Table 5. Air permeameter values with their corresponding permeability value; samples 1 to 8 were collected from random, fallen blocks near the base of Coal Mine Point; samples 9 to 24 are described in more detail, consisting of fallen blocks and direct measurements made on the cliff face near Coal Mine Point. Results are plotted in Fig. 11.

Table 6. Calculated average porosity, cement and grain area values based on image analysis of representative photomicrographs for each of the sandstone hand samples.

Table 7. Summary of the measurements and descriptions completed for samples/locations along the study area.
Figure Captions

Fig. 1. Schematic illustration showing the lithofacies architecture cross section of an upward-fining channel-fill sandbody capped with a limestone and coal layer (Choi et al. 2011). The sandbody is also a geobody, with the internal structures being the architectural elements (Choi et al. 2011).

Fig. 2. The Joggins Formation outcrop as viewed by a merged set of aerial photographs from 2005, prior to the construction of the Joggins Fossil Centre (Nova Scotia Department of Natural Resources 2005; Calder and Boon 2007).

Fig. 3. Digital photograph of the section of Joggins Formation scanned by lidar. Coal Mine Point is the headland on the right-hand side of the photograph.

Fig. 4. The extent of the Maritimes Basin of Eastern Canada showing the onshore distribution of Carboniferous to Permian outcrops. The fault zones are as follows: CCFZ, Cobequid-Chedabucto Fault Zone; CFZ, Cabot Fault Zone; HFZ, Hollow Fault Zone (Allen et al. 2013).

Fig. 5. Simplified plan view showing the Joggins Fossil Cliffs geology (Grey and Finkel 2011).

Fig. 6. The permeability calibration chart used to correlate a TinyPerm II value (Y-axis) with corresponding permeability. The points indicate the measured data points. The black line is the trendline with corresponding equation of the line.

Fig. 7. An image of the Optech ILRIS-3D lidar scanner setup. In this image, the laser scanner (1) is mounted atop the pan/tilt base (2), both of which are connected to a tripod (3). A ruggedized laptop (4) is used to adjust scanner settings and initiate a scan. The lidar unit (1 and 2) are powered by a battery pack (5). The tilted strata of the Joggins Formation can be seen in the background. The distance from the lidar setup to the face of the outcrop is approximately 100 m and indicated by the dashed yellow line.

Fig. 8. Simplified sketch of the global positioning equipment used to provide a georeferenced lidar data
set (modified from Van Sickle 2015). The base station was set up over a well cap with a known set of coordinates. The transmission antenna was erected next to the base station. The rover was taken to the lidar survey area for use with measuring the coordinates of the three lidar survey markers.

Fig. 9. (a) Location of 27 spectrometer measurements along the exposed outcrop scanned by lidar. Measurements were recorded north of Coal Mine Point. (b) Location of 3 spectrometer measurements taken on fallen blocks from the large meandering channel sandstone body, on the south of Coal Mine Point.

Fig. 10. Measured section with measured gamma-ray curve (red) and NTG curve (blue) (modified from Rygel 2005).

Fig. 11. Values as from Table 5 plotted with the rank, after Levorsen (1954) and Nabaway et al. (2009). All data points are labelled with their respective sample number. Samples 1 to 8 are shown in red. Samples 9 to 24 are uniquely labelled by shape and colour. Squares represent the sample being measured in a horizontal sense (the way it would have been deposited originally). Triangular points represent the sample being measured in a vertical sense (in relation to the way it would have originally been deposited).

Fig. 12. Schematic illustration representing a cross-laminated or cross-bedded sandstone showing different core plug orientations and associated permeability (k) measurement nomenclature (modified from Meyer and Krause 2006). The k(v) is vertical permeability, k(hpar) is horizontal permeability parallel to the strike of the cross-bedding/cross-laminations and k(hper) is horizontal permeability perpendicular to the strike of the cross-bedding/cross-laminations.

Fig. 13. Left; Photomicrograph of thin section GW102-2013TK-1 (at 10X) in normal light with porosity shown in blue (dye). Right; Photomicrograph of thin section GW102-2013TK-1, but with porosity
shown in yellow, grains as blue and cement as brown. The porosity is 3.0 %.

Fig. 14. Left; Photomicrograph of thin section GW106-2013TK-6 (at 10X) in normal light with porosity shown in blue (dye). Right; Photomicrograph of thin section GW106-2013TK-6, but colourized to show porosity in yellow, grains as blue and cement as brown. The porosity is 3.4 %.

Fig. 15. Plot showing the variation in calculated porosity for each thin section of each sandstone sample. Thin section 10 for sample GW102-2013TK was not included because it was determined to be an outlier. The coal (GW104-2013TK) and limestone (GW105-2013TK) samples were not plotted.

Fig. 16. The generated point cloud cliff section viewed from the West. A colour scale has been applied based on the intensity of the reflected light, which ranges between 0 and 255. The lower intensity values correlate with the finer-grained, quartz-poor lithologies and unconsolidated sediments. The higher intensity values correlate with the good quality quartz sandstone, as well as vegetation and sandstone-rich mine tailings.

Fig. 17. Close-up view of the generated digital outcrop model (point cloud) looking from the West. This view shows the highly-compartmentalized nature of the Joggins Formation outcrop with the lower intensity values (see intensity scale) correlating with the finer-grained, quartz-poor sandstones, mudstones, and unconsolidated sediments and the higher intensity values correlating with the good quality quartz sandstone.

Fig. 18. Close-up view of the generated digital outcrop model (point cloud) looking from the West showing numerous interpreted features. In general, the higher quality quartz sandstone appears as the darker intensity colours, while the finer-grained material, such as mudstone appear as the lighter intensity colours. Where the sandstone has eroded and accumulated on small promontories (areas outlined by the white) along the cliff face to mask the true lithology and appear as though the area is entirely good quality sandstone. The unconformity between the dipping Joggins Formation strata
and the overlying Quaternary sediments (poorly sorted glacial till/clay to boulder size) is visible.

Examples of the good quality sandstone (yellow) are shown as are examples of the finer-grained lithologies (grey).
Table 1. Permeability ranking (Levorsen 1954; Nabaway et al. 2009).

| Rank       | Fair           | Good           | Very Good       | Excellent      |
|------------|----------------|----------------|-----------------|----------------|
| Range      | $1 < k \leq 10$ md | $10 < k \leq 100$ md | $100 < k \leq 1000$ md | $1000 < k$     |

Table 2. Porosity ranking (Levorsen 1954; Nabaway et al. 2009).

| Rank | Negligible | Poor | Fair | Good | Very Good | Excellent |
|------|------------|------|------|------|-----------|-----------|
| Negligible | $0 < \phi \leq 5$ % | $5 < \phi \leq 10$ % | $10 < \phi \leq 15$ % | $15 < \phi \leq 20$ % | $20 < \phi \leq 25$ % | $25 < \phi$ |

Table 3. Average gamma-ray measurements within the area scanned by lidar acquired 100 m to the north of Coal Mine Point up to and including the large meandering channel body at Coal Mine Point.

| Site | GR (cps) | Description |
|------|----------|-------------|
| 1A   | 166      | host sst with shale rip-up clasts; f.g. to m.g. sst; angular to subangular clasts (up to 4 cm) |
| 1B   | 196      | base of sst channel body from 1A above |
| 1C   | 172      | ancient tree trunk, replaced by sst and found within 1A above |
| 2    | 182      | f.g. to m.g. sst |
| 3    | 249      | grey, silty- sst; small, blocky and fissile; scintillometer detector sounded, indicating uranium |
| 4    | 222      | massive siltstone bed (~ 30 cm in thickness) |
| 5    | 203      | v.f.g. sandy siltstone |
| 6    | 62       | current rippled sst; trace fossils on surface |
| 7    | 224      | slightly sandy siltstone with iron-pyrite nodules (up to 5 cm) |
| 8    | 198      | f.g. to m.g. sst |
| 9    | 231      | red to grey interbedded siltstone |
| 10   | 189      | parallel laminated f.g. sst; some ripples; slightly silty |
| 11   | 210      | red to grey v.f.g. sst; current ripples |
| 12   | 246      | dark grey; small blocky; silty clay |
| 13   | 202      | silty v.f.g. sst |
| 14   | 227      | small, blocky, sandy siltstone |
| 15   | 216      | red claystone; forms part of a channel body along with location 16 and 17 |
| 16   | 203      | inter shale (10 cm thick); forms part of a channel body along with location 15 and 17 |
| 17   | 181      | sst; forms part of a channel body along with location 15 and 16 |
| 18   | 261      | m.g.; small blocky; silty clay sst |
| 19   | 181      | v.f.g. to f.g. sst with 30-50 cm beds; capped with small 1 x 5m (w x h) channels |
| 20   | 220      | v.f.g. to f.g. silty sst |
| 21   | 203      | v.f.g. silty sst |
| 22   | 181      | v.f.g. silty sst |
| 23   | 235      | m.g.; grey; silty clay; blocky |
| 24   | 211      | coal; 15 cm |
| 25   | 198      | f.g. sst with fine-laminations of grey-silty claystone (cm scale) |
| 26   | 97       | massive m.g. sst; located near large meandering channel body at Coal Mine Point |
| 27   | 93       | trough-cross; thin beds; m.g. sst; located near large meandering channel body at Coal Mine Point |
| 28   | 98       | massive m.g. sst; located near large meandering channel body at Coal Mine Point |
Table 4. Gamma-ray measurements recorded from eight hand samples from the Joggins Formation study area.

| Hand Sample Number | Lithology | Gamma-Ray Counts (minimum value) | Gamma-Ray Counts (maximum value) |
|--------------------|-----------|----------------------------------|----------------------------------|
| GW101-2013TK        | sandstone | 115                              | 155                              |
| GW102-2013TK        | sandstone | 116                              | 151                              |
| GW103-2013TK        | sandstone | 118                              | 149                              |
| GW104-2013TK        | coal      | 111                              | 154                              |
| GW105-2013TK        | limestone | 113                              | 143                              |
| GW106-2013TK        | sandstone | 120                              | 143                              |
| GW107-2013TK        | sandstone | 112                              | 145                              |
| GW108-2013TK        | sandstone | 112                              | 142                              |

Table 5. Air permeameter values with their corresponding permeability value; samples 1 to 8 were collected from random, fallen blocks near the base of Coal Mine Point; samples 9 to 24 are described in more detail, consisting of fallen blocks and direct measurements made on the cliff face near Coal Mine Point. Results are plotted in Fig. 11.

| Sample # | Lithology                                      | TinyPerm II Value | Permeability (md) |
|----------|-----------------------------------------------|-------------------|-------------------|
| 1x       | Sandstone (near base of Coal Mine Point)      | 10.64             | 527               |
| 2x       | Sandstone (near base of Coal Mine Point)      | 11.38             | 66                |
| 3x       | Sandstone (near base of Coal Mine Point)      | 10.86             | 284               |
| 4x       | Sandstone (near base of Coal Mine Point)      | 10.75             | 387               |
| 5x       | Sandstone (near base of Coal Mine Point)      | 10.33             | 1,258             |
| 6x       | Sandstone (near base of Coal Mine Point)      | 10.44             | 924               |
| 7x       | Sandstone (near base of Coal Mine Point)      | 10.18             | 1,917             |
| 8x       | Sandstone (near base of Coal Mine Point)      | 10.88             | 269               |
| 9x       | Fallen, blocky, silty-sandstone; horizontal   | 11.28             | 88                |
| 10x      | Same as above; vertical                       | 12.04             | 10                |
| 11x      | Fallen, grey, sandy-siltstone; vertical       | 11.99             | 12                |
| 12x      | Same as above; horizontal                     | 11.57             | 39                |
| 13x      | Large fossilized tree trunk, red-brown        | 12.17             | 7                 |
| 14x      | Fine-grained massive sandstone; horizontal    | 11.61             | 35                |
| 15x      | Same as above; vertical                       | 11.68             | 28                |
| 16x      | Fine lower sandstone; vertical                | 11.23             | 101               |
| 17x      | Same as above; horizontal                     | 11.22             | 104               |
| 18x      | Very fine upper shale; vertical               | 11.86             | 17                |
| 19x      | Very fine upper shale                         | 11.17             | 119               |
| 20x      | Coal bed on safe outcrop; horizontal          | 11.25             | 95                |
| 21x      | Same as above; vertical                       | 11.93             | 14                |
| 22x      | Large sandstone bedset; horizontal            | 10.88             | 269               |
| 23x      | Same as above but with climbing ripples       | 10.73             | 410               |
| 24x      | Conglomerate; horizontal                      | 10.97             | 209               |

Table 6. Calculated average porosity, cement and grain area values based on image analysis of representative photomicrographs for each of the sandstone hand samples.

| Sample #       | Cement Area (%) | Grain Area (%) | Avg. Porosity (%) and Rank |
|----------------|-----------------|----------------|---------------------------|
| GW101-2013TK   | 29.2            | 69.1           | 1.7 (Negligible)          |
| GW102-2013TK   | 23.1            | 69.5           | 7.4 (Poor)                |
| GW103-2013TK   | 37.8            | 59.5           | 2.8 (Negligible)          |
| GW106-2013TK   | 25.5            | 70.4           | 4.1 (Negligible)          |
| GW107-2013TK   | 39.6            | 59.6           | 0.9 (Negligible)          |
| GW108-2013TK   | 41.6            | 56.4           | 2.0 (Negligible)          |
Table 7. Summary of the measurements and descriptions completed for samples/locations along the study area.

| Geobody/A.E. | Site/Sample | Facies | $\phi$ | $k$ (md) | GR (cps) | Intensity |
|--------------|-------------|--------|--------|----------|---------|-----------|
|              | 1A          | sst with shale clasts | -      | -        | 166     | 175       |
| channel base | 1B          | sst    | -      | -        | 196     | 255       |
| tree trunk   | 1C          | sst    | -      | -        | 172     | 155       |
|              | 2           | sst    | -      | -        | 182     | 120       |
|              | 3           | silty- sst | -      | -        | 249     | 77        |
|              | 4           | massive siltstone | -      | -        | 222     | 169       |
|              | 5           | sandy siltstone | -      | -        | 203     | 124       |
| ripples      | 6           | current rippled sst | -      | -        | 62      | 226       |
|              | 7           | sandy siltstone | -      | -        | 224     | 105       |
|              | 8           | sst    | -      | -        | 198     | 103       |
|              | 9           | interbedded siltstone | -      | -        | 231     | 187       |
| ripples      | 10          | slightly silty sst | -      | -        | 189     | 114       |
| ripples      | 11          | current rippled sst | -      | -        | 210     | 227       |
|              | 12          | silty clay | -      | -        | 246     | 173       |
|              | 13          | silty sst | -      | -        | 202     | 206       |
|              | 14          | sandy siltstone | -      | -        | 227     | 96        |
| channel body | 15          | claystone | -      | -        | 216     | 208       |
| channel body | 16          | shale    | -      | -        | 203     | 200       |
| channel body | 17          | sst      | -      | -        | 181     | 174       |
|              | 18          | silty clay sst | -      | -        | 261     | 104       |
| channel body | 19          | sst      | -      | -        | 181     | 119       |
|              | 20          | silty sst | -      | -        | 220     | 95        |
|              | 21          | silty sst | -      | -        | 203     | 89        |
|              | 22          | silty sst | -      | -        | 181     | 255       |
|              | 23          | silty clay | -      | -        | 235     | 182       |
|              | 24          | coal     | -      | -        | 211     | 255       |
|              | 25          | sst with silty claystone | -      | -        | 198     | 115       |
| channel body | 26          | sst      | -      | -        | 97      | 158       |
| channel body | 27          | sst      | -      | -        | 93      | 255       |
| channel body | 28          | sst      | -      | -        | 98      | 204       |
|              | GW101-2013TK | sst (hand sample) | 1.7    | -        | $\sim$130 | -         |
|              | GW102-2013TK | sst (hand sample) | 7.4    | -        | $\sim$130 | -         |
|              | GW103-2013TK | sst (hand sample) | 2.8    | -        | $\sim$130 | -         |
|              | GW104-2013TK | coal (hand sample) | -      | -        | $\sim$130 | -         |
|              | GW105-2013TK | lst (hand sample) | -      | -        | $\sim$130 | -         |
|              | GW106-2013TK | sst (hand sample) | 4.1    | -        | $\sim$130 | -         |
|              | GW107-2013TK | sst (hand sample) | 0.9    | -        | $\sim$130 | -         |
|              | GW108-2013TK | sst (hand sample) | 2.0    | -        | $\sim$130 | -         |
| channel base | 1x | sst (base of Coal Mine Point) | - | 527 | - | - |
| channel base | 2x | sst (base of Coal Mine Point) | - | 66 | - | - |
| channel base | 3x | sst (base of Coal Mine Point) | - | 284 | - | - |
| channel base | 4x | sst (base of Coal Mine Point) | - | 387 | - | - |
| channel base | 5x | sst (base of Coal Mine Point) | - | 1,258 | - | - |
| channel base | 6x | sst (base of Coal Mine Point) | - | 924 | - | - |
| channel base | 7x | sst (base of Coal Mine Point) | - | 1,917 | - | - |
| channel base | 8x | sst (base of Coal Mine Point) | - | 269 | - | - |
| - | 9x | fallen, blocky, silty-sst; horizontal | - | 88 | - | - |
| - | 10x | same as above; vertical | - | 10 | - | - |
| - | 11x | fallen, grey, sandy-siltstone; vertical | - | 12 | - | - |
| - | 12x | same as above; horizontal | - | 39 | - | - |
| tree trunk | 13x | fossilized tree trunk, red-brown | - | 7 | - | - |
| - | 14x | fine-grained massive sst; horizontal | - | 35 | - | - |
| - | 15x | same as above; vertical | - | 28 | - | - |
| - | 16x | fine lower sst; vertical | - | 101 | - | - |
| - | 17x | same as above; horizontal | - | 104 | - | - |
| - | 18x | very fine upper shale; vertical | - | 17 | - | - |
| - | 19x | very fine upper shale | - | 119 | - | - |
| - | 20x | coal bed on safe outcrop; horizontal | - | 95 | - | - |
| - | 21x | same as above; vertical | - | 14 | - | - |
| - | 22x | large sst bedset; horizontal | - | 269 | - | - |
| ripples | 23x | same as above with climbing ripples | - | 410 | - | - |
| - | 24x | conglomerate; horizontal | - | 209 | - | - |
Fig. 1. Schematic illustration showing the lithofacies architecture cross section of an upward-fining channel-fill sandbody capped with a limestone and coal layer (Choi et al. 2011). The sandbody is also a geobody, with the internal structures being the architectural elements (Choi et al. 2011). 173 X 58 mm (300 dpi)

Fig. 2. An image showing the extent of the Joggins Formation outcrop. The location of the lidar scan area and Coal Mine Point are also labeled. Base map from ArcGIS. Map created using Microsoft PowerPoint.

Fig. 3. Digital photograph of the section of Joggins Formation scanned by lidar. Coal Mine Point is the headland on the right-hand side of the photograph. 173 X 35 mm (300 dpi) *ORIGINAL
Fig. 4. The extent of the Maritimes Basin of Eastern Canada showing the onshore distribution of Carboniferous to Permian outcrops. The fault zones are as follows: CCFZ, Cobequid-Chedabucto Fault Zone; CFZ, Cabot Fault Zone; HFZ, Hollow Fault Zone (Allen et al. 2013). 85 X 74 mm (300 dpi)

Fig. 5. Simplified plan view showing the Joggins Fossil Cliffs geology (modified from Grey and Finkel 2011). 174 X 124 mm (300 dpi)
Fig. 6. The permeability calibration chart used to correlate a TinyPerm II value (Y-axis) with corresponding permeability. The points indicate the measured data points. The black line is the trendline with corresponding equation of the line. 86 X 63 mm (300 dpi) *ORIGINAL.

Fig. 7. An image of the Optech ILRIS-3D lidar scanner setup. In this image, the laser scanner (1) is mounted atop the pan/tilt base (2), both of which are connected to a tripod (3). A ruggedized laptop (4) is used to adjust scanner settings and initiate a scan. The lidar unit (1 and 2) are powered by a battery pack (5). The tilted strata of the Joggins Formation can be seen in the background. The distance from the lidar setup to the face of the outcrop is approximately 100 m and indicated by the dashed yellow line. 85 X 48 mm (300 dpi) *ORIGINAL.

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Fig. 12. Schematic illustration representing a cross-laminated or cross-bedded sandstone showing different core plug orientations and associated permeability (k) measurement nomenclature (modified from Meyer and Krause 2006). The $k_v$ is vertical permeability, $k_{hpar}$ is horizontal permeability parallel to the strike of the cross-bedding/cross-laminations and $k_{hper}$ is horizontal permeability perpendicular to the strike of the cross-bedding/cross-laminations. 86 X 59 mm (300 dpi)

Fig. 13. Left; Photomicrograph of thin section GW102-2013TK-1 (at 10X) in normal light with porosity shown in blue (dye). Right; Photomicrograph of thin section GW102-2013TK-1, but with porosity shown in yellow, grains as blue and
cement as brown. The porosity is 3.0%. 174 X 58 mm (300 dpi) *ORIGINAL

Fig. 14. Left; Photomicrograph of thin section GW106-2013TK-6 (at 10X) in normal light with porosity shown in blue (dye). Right; Photomicrograph of thin section GW106-2013TK-6, but colourized to show porosity in yellow, grains as blue and cement as brown. The porosity is 3.4%. 174 X 58 mm (300 dpi) *ORIGINAL

Fig. 15. Plot showing the variation in calculated porosity for each thin section of each sandstone sample. Thin section 10 for sample GW102-2013TK was not included because it was determined to be an outlier. The coal (GW104-2013TK) and limestone (GW105-2013TK) samples were not plotted. 174 X 101 mm (300 dpi) *ORIGINAL
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Fig. 18. Close-up view of the generated digital outcrop model (point cloud) looking from the West showing numerous interpreted features. In general, the higher quality quartz sandstone appears as the darker intensity colours, while the finer-grained material, such as mudstone appear as the lighter intensity colours. Where the sandstone has eroded and accumulated on small promontories (areas outlined by the white) along the cliff face to mask the true lithology and appear as though the area is entirely good quality sandstone. The unconformity between the dipping Joggins Formation strata and the overlying Quaternary sediments (poorly sorted glacial till/clay to boulder size) is visible. Examples of the good quality sandstone (yellow) are shown as are examples of the finer-grained lithologies (grey). 174 X 68 mm (300 dpi) *ORIGINAL