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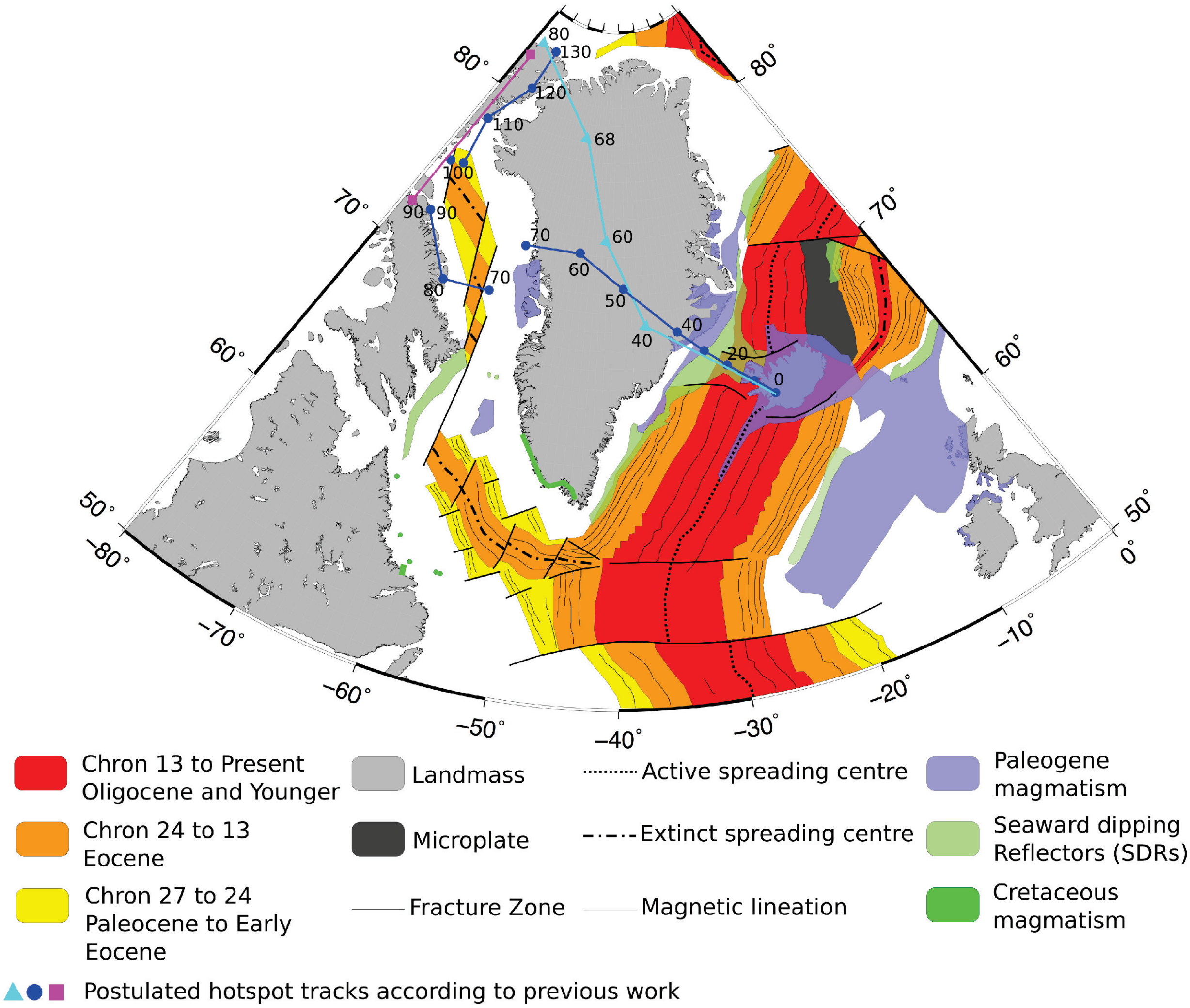


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Geological Association of Canada
c/o Department of Earth Sciences
Memorial University of Newfoundland
St. John’s NL Canada A1B 3X5
Tel: (709) 864-7660
Fax: (709) 864-2532
gacpub@mun.ca
gac@mun.ca
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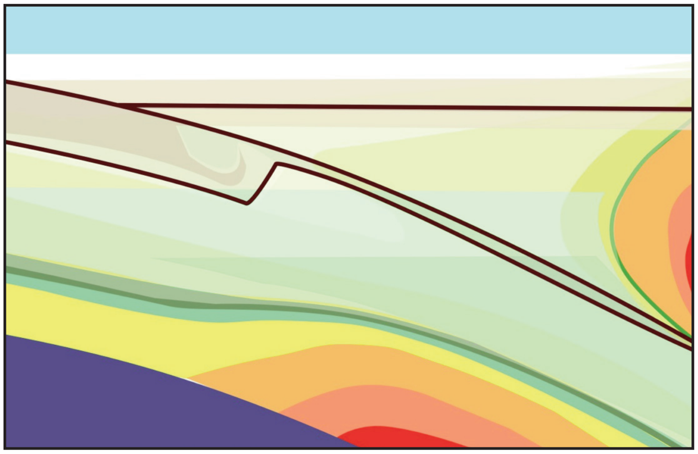
**Cover Image:** The North Atlantic spreading system, showing the ages of oceanic crust, spreading axes, cotemporaneous igneous rocks and postulated hotspot tracks. For data sources and an alternative tectonic hypothesis, see Peace et al. in this issue.
*Image credit: Alexander L. Peace*

# ANDREW HYNES SERIES: TECTONIC PROCESSES



## Evolution of Labrador Sea–Baffin Bay: Plate or Plume Processes?

**Alexander L. Peace[1,2], Gillian R. Foulger[2], Christian Schiffer[2] and Ken J.W. McCaffrey[2]**

[1]*Department of Earth Sciences*
*Memorial University of Newfoundland*
*St. John's, Newfoundland, Canada, A1B 3X5*
*E-mail: alpeace@mun.ca*

[2]*Department of Earth Sciences*
*Durham University*
*Durham, United Kingdom, DH1 3LE*

### SUMMARY
Breakup between Greenland and Canada resulted in oceanic spreading in the Labrador Sea and Baffin Bay. These ocean basins are connected through the Davis Strait, a bathymetric high comprising primarily continental lithosphere, and the focus of the West Greenland Tertiary volcanic province. It has been suggested that a mantle plume facilitated this breakup and generated the associated magmatism. Plume-driven breakup predicts that the earliest, most extensive rifting, magmatism and initial seafloor spreading starts in the same locality, where the postulated plume impinged. Observations from the Labrador Sea–Baffin Bay area do not accord with these predictions. Thus, the plume hypothesis is not confirmed at this locality unless major *ad hoc* variants are accepted. A model that fits the observations better involves a thick continental lithospheric keel of orogenic origin beneath the Davis Strait that blocked the northward-propagating Labrador Sea rift resulting in locally enhanced magmatism. The Davis Strait lithosphere was thicker and more resilient to rifting because the adjacent Paleoproterozoic Nagssugtoqidian and Torngat orogenic belts contain structures unfavourably orientated with respect to the extensional stress field at the time.

### RÉSUMÉ
La cassure entre le Groenland et le Canada a entraîné une expansion océanique de la mer du Labrador et de la baie de Baffin. Ces bassins océaniques sont reliés par le détroit de Davis, un haut bathymétrique constitué principalement de lithosphère continentale et de la province volcanique tertiaire de l'ouest du Groenland. Il a été suggéré qu'un panache du manteau a facilité cette cassure et généré le magmatisme associé. L'hypothèse d'une cassure produite par panache du manteau prédit que la première distension océanique, la plus importante, le magmatisme et l'expansion océanique initial se produisent là où le panache mantélique touche la croûte continentale. Or les observations dans la région de la mer du Labrador–baie de Baffin ne correspondent pas à ces prédictions. Et donc l'hypothèse du panache ne fonctionne pas dans cette région à moins que des facteurs ad hoc déterminants ne soient présents. Un modèle qui correspond mieux aux observations présuppose la présence d'une épaisse quille lithosphérique continentale d'origine orogénique sous le détroit de Davis qui aurait bloqué l'expansion océanique de la mer du Labrador vers le nord, ce qui aurait provoqué une augmentation du magmatisme localement. La lithosphère du détroit de Davis était plus épaisse et plus résistante à l'expansion océanique parce que les bandes orogéniques paléoprotérozoïques du Nagssugtoqidian et de Torngat renferment des structures défavorablement orientées par rapport au champ de contraintes d'extensions de l'époque.

*Traduit par le Traducteur*

### INTRODUCTION
Although many continental rifts and passive margins are magma-rich (Skogseid 2001; Geoffroy 2005; Thybo and Artemieva 2013; Geoffroy et al. 2015), such as the Norwegian margin (e.g. Gernigon et al. 2015), others are relatively magma-poor (Boillot and Froitzheim 2001; Wilson et al. 2001), such as the Newfoundland margin (e.g. Eddy et al. 2017). This has led to polarization of proposed causal mechanisms into views of magma-rich or 'active' rifts (postulated to be driven by deep

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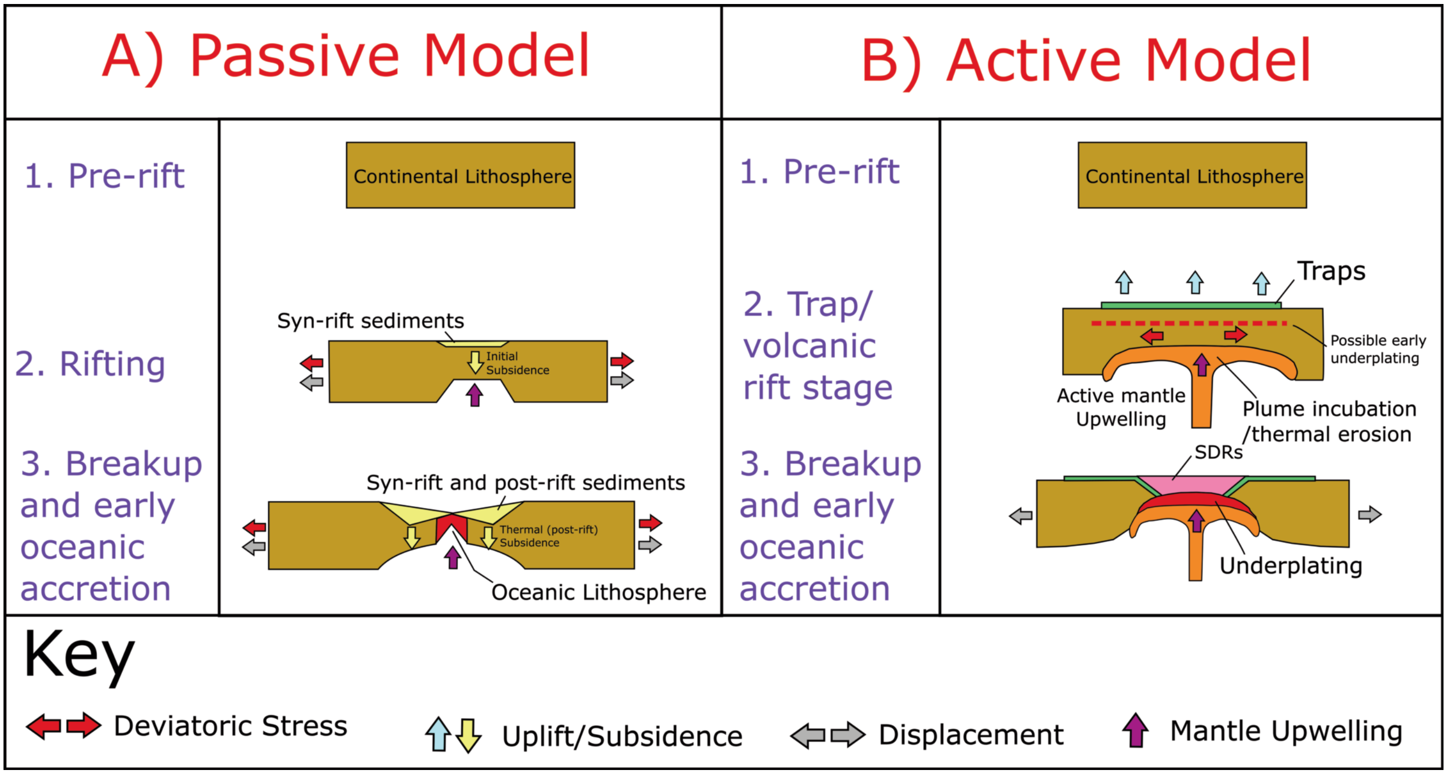


**Figure 1.** Comparison of A) the passive and B) active models of rifting and breakup. Modified from Geoffroy (2005) based on the concepts of Sengör and Burke (1978) and McKenzie (1978). SDRs = seaward-dipping reflectors (e.g. Mutter 1985; Paton et al. 2017; Buck 2017).

mantle plumes, e.g. Morgan 1971; Sengör and Burke 1978), and magma-poor or 'passive' rifts (postulated to be driven by stretching of the lithosphere by far-field plate forces, e.g. McKenzie 1978; Fig. 1). However, magmatism occurs even on margins categorized as 'non-volcanic' or 'magma poor' (e.g. the U-reflector offshore Newfoundland; Deemer et al. 2010; Peace et al. 2017a) because magmatism to some extent invariably accompanies continental breakup (White 1992). This suggests that 'magma-rich' and 'magma-poor' margins are extremes that represent end-members only in a continuous spectrum (Geoffroy 2005; Franke 2013). For this reason the role of the mantle and its relationship with magmatism during continental breakup remains a subject of debate (e.g. Anderson 2000; van Wijk et al. 2001; Foulger 2002; Campbell 2007; Calvès et al. 2008; Foulger et al. 2015; Shellnutt et al. 2017). Furthermore, an unequivocal detection of a Morgan-type mantle plume (i.e. a thermal rising from the deep lower mantle) has yet to be made, using either geochemical or geophysical tools (Hwang et al. 2011; Foulger et al. 2013; Lustrino and Anderson 2015).

In this contribution we discuss, using observations from West Greenland and northeastern Canada, the predictions of the mantle plume hypothesis as the mechanism facilitating continental breakup and magmatism (Gill et al. 1992; Gerlings et al. 2009). We find that few of the predictions are confirmed. We suggest that breakup was, instead, predominantly driven by plate tectonic processes and that lithospheric structure in the neighbourhood of the Davis Strait was responsible for the excess Tertiary magmatism there that has traditionally been interpreted as the product of a mantle plume.

## CONTINENTAL BREAKUP AND MAGMATISM BETWEEN GREENLAND AND CANADA

The Labrador Sea and Baffin Bay (Fig. 2) opened as a result of divergent motion between Greenland and Canada (Srivastava 1978; Chalmers and Pulvertaft 2001; Abdelmalak et al. 2012; Hosseinpour et al. 2013; Delescluse et al. 2015; Alsulami et al. 2015; Peace et al. 2016). This separation occurred in three stages (Oakey and Chalmers 2012): 1) Paleocene separation between North America and Greenland while the latter was still attached to Eurasia, 2) continued Eocene separation between Greenland and North America as separation between Eurasia and Greenland (Greenland moving as an independent plate) began, and 3) since the Oligocene continued separation between Eurasia and Greenland, which again was attached to North America. Extension between Greenland and Canada resulted in oceanic spreading in the Labrador Sea (Chalmers and Laursen 1995) and most likely in Baffin Bay (Suckro et al. 2012) but not at the Davis Strait (Funck et al. 2012).

The earliest rifting, (possibly Triassic; Larsen et al. 2009) and the oldest and most extensive oceanic crust in the Labrador Sea–Baffin Bay area, occurs in the southern Labrador Sea (mid-Paleocene; Srivastava 1978; Chalmers and Pulvertaft 2001). The spatial and temporal extent of oceanic crust in Baffin Bay (Suckro et al. 2012) is less than in the Labrador Sea (Srivastava 1978). The Davis Strait is a bathymetric high linking the Labrador Sea to Baffin Bay and it is primarily underlain by continental lithosphere (Dalhoff et al. 2006) up to 20 km thick (Funck et al. 2012). The Ungava Transform Fault System (Suckro et al. 2013), a 'leaky' transform system

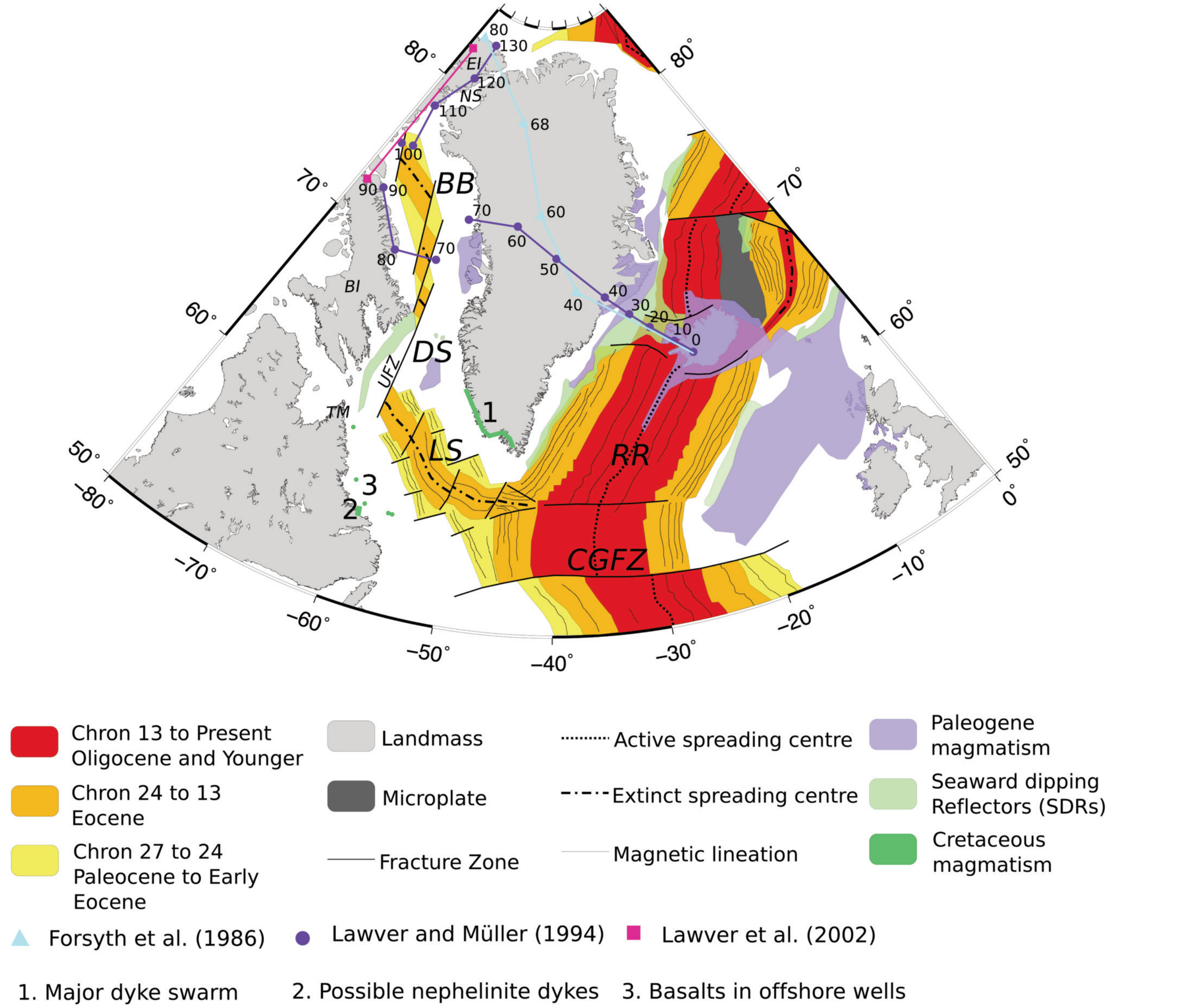


**Figure 2.** An overview of the North Atlantic oceanic spreading systems including the age of oceanic crust; major active and extinct spreading axes; oceanic fracture zones; proposed microplates; magnetic lineations and the spatial distribution of on- and off-shore flood basalts and seaward-dipping reflectors (SDRs) (Upton 1988; Larsen and Saunders 1998; Oakey and Chalmers 2012). The hotspot tracks of Lawver and Müller (1994) (closed circle), Lawver et al. (2002) (square) and Forsyth et al. (1986) (triangle) are also included, along with magmatic events in the Labrador Sea pre-dating proposed plume arrival including: 1) onshore West Greenland (Larsen et al. 2009), 2) onshore Labrador (Tappe et al. 2007), but disputed by Peace et al. (2016), and 3) offshore Labrador (Umpleby 1979). BB = Baffin Bay; BI = Baffin Island; EI = Ellesmere Island; DS = Davis Strait; LS = Labrador Sea; NS = Nares Strait; CGFZ = Charlie Gibbs Fracture Zone; RR = Reykjanes Ridge; UFZ = Ungava Fracture Zone; CN = Canada; GR = Greenland; IL = Iceland; UK = United Kingdom; IR = Ireland.

where small amounts of oceanic crust may have been produced in the absence of fully developed oceanic spreading (Funck et al. 2012), traverses the Davis Strait.

The earliest magmatism related to the opening of the Labrador Sea is possibly Late Triassic in age (ca. 220 Ma; Larsen et al. 2009). However, it is not until the Early Cretaceous that a strong extensional stress field is evidenced by the intrusion of coast-parallel dykes in West Greenland (ca. 150 Ma; Larsen et al. 2009) and possibly some debated equivalent dykes in Labrador (Tappe et al. 2007; Peace et al. 2016) along with a Mesozoic diatreme (King and McMillan 1975; Wilton et al. 2002; Wilton et al. 2016). Breakup occurred in the Paleocene (Chalmers et al. 1995), in addition to the eruption of flood basalt around the Davis Strait as four region-wide formations: the 62.5–61 Ma Vaigat Formation picrite, the 61–60 Ma Maligât Formation depleted basalt (also in the Hellefisk-1 offshore well), the 60–58 Ma Svartenhuk Formation less-depleted basalt and the Naqerloq Formation 56–54 Ma enriched basalt (Larsen et al. 2016). Furthermore, two less widespread basalt sequences include the 53.5 Ma Erqua Formation alkali basalt and the 38.7 Ma Talerua Member transitional basalt (Larsen et al. 2016).

## THE MANTLE PLUME HYPOTHESIS AND BREAKUP BETWEEN GREENLAND AND CANADA

A mantle plume (Morgan 1971) has been proposed as the causal mechanism for continental breakup and magmatism between Greenland and Canada (e.g. Storey et al. 1998; Courtillot et al. 1999; Nielsen et al. 2002; Funck et al. 2007; Gerlings et al. 2009; Altenbernd et al. 2015). It is postulated that initial rifting was relatively amagmatic (Nielsen et al. 2002; Altenbernd et al. 2015) and that the arrival of a mantle plume at ca. 62–60 Ma (Storey et al. 1998) led to the onset of seafloor spreading in the Labrador Sea (Gerlings et al. 2009) and widespread magmatism around the Davis Strait (Holm et al. 1993; Storey et al. 1998). The postulated plume is claimed to underlie Iceland presently (Tegner et al. 1998), and to have remained fixed with respect to other mantle plumes throughout its existence. This is suggested by various authors to have existed since ca. 250 Ma, depending on what basalt units are considered to comprise its associated 'plume-head' volcanic rocks (e.g. Lawver and Müller 1994). Figure 2 depicts three postulated plume tracks that are commonly cited as explanations for breakup and magmatism in West Greenland (Forsyth et al. 1986; Lawver and Müller 1994; Lawver et al. 2002). In this paper we primarily discuss the Lawver and Müller (1994) plume track as this is most complete and the one that approaches most closely the Davis Strait.

Observations in the Labrador Sea–Baffin Bay rift system that have been attributed to a mantle plume include:

1. The onset of seafloor spreading in the Labrador Sea (Gerlings et al. 2009);
2. Movement on the Ungava fault system (Storey et al. 1998);
3. Volcanism in West Greenland and Baffin Island (Chalmers et al. 1995; Larsen et al. 2016);
4. Interpreted underplating beneath the Davis Strait (Gerlings et al. 2009);
5. High $^3He/^4He$ (Graham et al. 1998; Dale et al. 2009);
6. Regional uplift patterns (Dam et al. 1998; Japsen et al. 2006); and
7. High melting temperatures estimated for picrite cumulates (Gill et al. 1992).

Despite this there are first-order disparities between the predictions of the mantle plume model and regional observations (Nielsen et al. 2007; McGregor et al. 2014; Peace et al. 2014). The mantle plume hypothesis requires that the earliest and most extensive uplift, magmatism and rifting occurred closest to the plume centre (e.g. Franke 2013; Fig. 3). However, this did not occur in the Labrador Sea-Baffin Bay rift system if the plume track of Lawver and Müller (1994) is assumed, as exemplified by the following:

1. Seafloor spreading started in the southern Labrador Sea before the north (Roest and Srivastava 1989);
2. Seafloor spreading was delayed and developed poorly in Baffin Bay (Suckro et al. 2012);
3. Seafloor spreading did not develop at all in the Davis Strait (Suckro et al. 2013), the location of the plume centre predicted by Lawver and Müller (1994); and
4. The predicted kilometre-scale uplift at the centre of the arriving plume did not occur (Redfield 2010; McGregor et al. 2013).

These points are discussed in more detail in the following subsections.

### The Labrador Sea

The Labrador Sea progressively opened from south to north (Oakey and Chalmers 2012; Delescluse et al. 2015), and although there is a consensus that spreading started no later than Chron 27 (Paleocene; Chalmers and Laursen 1995; Oakey and Chalmers 2012) some work suggests that spreading may have started as early as Chron 33 (Roest and Srivastava 1989; Srivastava and Roest 1999). Despite this debate it is clear that seafloor spreading started in the southern Labrador Sea considerably before the north (Roest and Srivastava 1989). This does not fit a model whereby a plume located to the north (Lawver and Müller 1994) initiated seafloor spreading (Storey et al. 1998; Gerlings et al. 2009). If seafloor spreading was initiated by mantle plume arrival it would be expected to start nearest to the plume and to propagate away from it (Fig. 3).

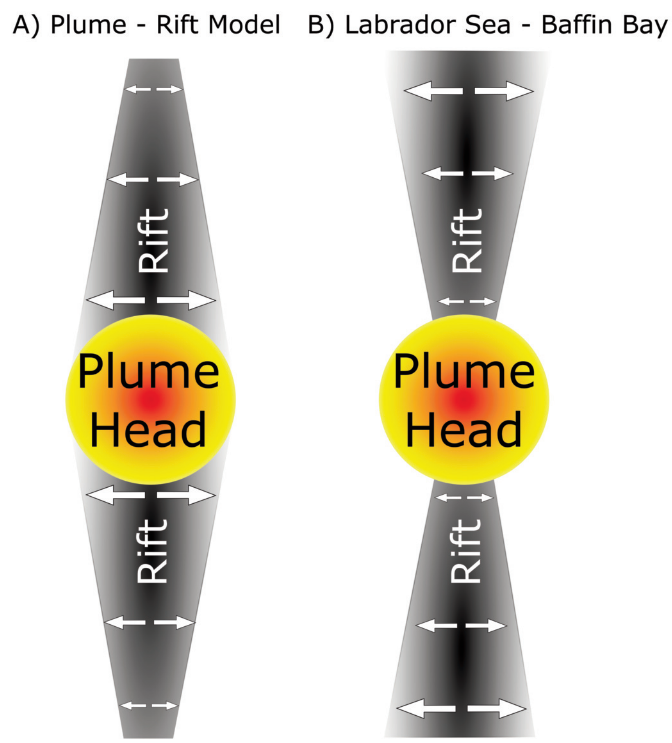


**Figure 3.** Arrows show A) predictions of rifting in response to a rising thermal anomaly in the mantle and B) observations in the Labrador Sea–Baffin Bay rift system. Modified from Franke (2013) whereby the original figure showed a similar example from the South Atlantic where observations of rifting and breakup again do not appear to fit the predictions of the mantle plume hypothesis.

### Baffin Bay

The nature of seafloor spreading in Baffin Bay is contrary to plume hypothesis predictions. First, it has been proposed that Baffin Bay is either entirely underlain by continental crust

(Kerr 1967; Van der Linden 1975) or that if oceanic crust is present it is less extensive than in the Labrador Sea (Jackson et al. 1979; Gerlings et al. 2009; Suckro et al. 2012; Hosseinpour et al. 2013). Baffin Bay is proposed to have been much closer to the plume (Lawver and Müller 1994) and so the reverse would be expected.

### The Davis Strait

In the Davis Strait seafloor spreading was never fully initiated as it was in the Labrador Sea (Srivastava 1978) and probably Baffin Bay (Suckro et al. 2012). Instead, a 'leaky transform' system developed (Funck et al. 2007). It is again not clear why a mantle plume should cause seafloor spreading in the Labrador Sea to the south (Storey et al. 1998; Gerlings et al. 2009) but not in the much closer Davis Strait. The Davis Strait is the focus of the West Greenland Tertiary volcanic province (Fig. 2; Storey et al. 1998; Gerlings et al. 2009; Larsen et al. 2016) and, although volcanic rocks are observed on Baffin Island (Clarke and Upton 1971; Geoffroy et al. 2001), rift-related dykes are also documented to the south on the margins of the Labrador Sea (Larsen et al. 2009). This disparity between a predicted time-progressive volcanic track as a result of plume passage (Lawver and Müller 1994) and the observations provides further evidence against a fixed mantle plume as the primary cause of the magmatism.

### Vertical Motion Studies

Low-temperature thermochronological studies (e.g. apatite fission track dating (AFT), helium isotopes and vitrinite reflectance) may be used to date vertical motions including possible plume-related exhumation. Results from West Greenland linking apparent uplift to presumed plume activity (Japsen et al. 2006) are controversial (Redfield 2010). Furthermore, results from Baffin Island suggest a slow and long-lived exhumation since the Late Proterozoic while Cenozoic uplift is not detected (Yaehne 2008; McGregor et al. 2013; Creason 2015). The Torngat Mountains in Labrador experienced rapid uplift in the latest Jurassic–earliest Cretaceous, but this is inferred to be rift-flank uplift (Centeno 2005). AFT ages from Ellesmere Island and along the Nares Strait show peaks in the Paleogene and Permo–Triassic, reflecting the complex tectonic evolution of the region (Arne et al. 2002; Grist and Zentilli 2005; Hansen et al. 2011). However, this is not when the postulated plume is predicted to have underlain the area (approx. 120–90 Ma). Apparent vertical motions along the West Greenland–East Canada margin are thus not consistent with the spatial and temporal pattern of vertical motions predicted for plume head impingement and a migrating plume tail.

### Plume Variants

Several variants of the plume hypothesis have been proposed to account for the mismatches between predictions and observations by Gill et al. (1992). These include: 1) a 'doughnut-shaped' plume; 2) a shift in relative plume position (migrating plume); 3) multiple, separate plumes; and 4) a non-axisymmetric plume head. Numerical modelling of the South Atlantic has been used to support the suggestion that plume-driven rift initiation may be offset from the proposed plume impingement location (Beniest et al. 2017), and that mantle contamination in combination with elevated temperatures near Iceland may explain igneous crustal thickness (Shorttle et al. 2014), concepts that may be applicable in the Labrador Sea–Baffin Bay area. Variants of the standard plume model are, however, not useful unless they make predictions of their own that can be tested – arbitrary *ad hoc* adjustments introduced merely to explain *a posteriori* observations that do not fit the simple model do not progress understanding of causative processes. It is clear that non-plume mechanisms for the Labrador Sea–Davis Strait–Baffin Bay region must be considered.

## THE ROLE OF LITHOSPHERIC STRUCTURE AND PROCESSES IN THE TECTONO-MAGMATIC EVOLUTION

Plate-related mechanisms provide candidate mechanisms for breakup and magmatism between Greenland and Canada (Foulger 2002; Nielsen et al. 2007; Peace et al. 2014; Foulger et al. 2015). In this section we discuss the role of lithospheric architecture in controlling breakup and associated magmatism between Greenland and Canada.

Beneath the Davis Strait (Fig. 2) the crust (Fig. 4 and 5A) is thicker than elsewhere in the Baffin Bay–Labrador Sea rift system (Laske et al. 2012; Welford and Hall 2013). According to a model of the depth of the lithosphere–asthenosphere boundary (LAB) (Schaeffer and Lebedev 2015; Schiffer et al. 2017; Lebedev et al. 2017) the lithosphere is also thicker (Fig. 5B). According to this LAB model the Davis Strait may be underlain by lithosphere ca. 150 km thick compared to the Labrador Sea and Baffin Bay which may have lithosphere as thin as ca. 50 km (Fig. 5).

Local mantle convection patterns may have been influenced by a lithospheric keel protruding into the asthenosphere (Fig. 6). Regions of thick lithosphere have been inferred to influence asthenospheric flow elsewhere, e.g. in southeast Brazil (Assumpção et al. 2006). Such structures may induce lateral thermal gradients leading to initiation of small-scale convection cells that boost adiabatic melting (Simon et al. 2009; Ballmer et al. 2010). Lateral temperature gradients beneath the Davis Strait may have varied, both spatially and temporally, because of variable crustal and lithospheric thinning (Suckro et al. 2013). Such lateral temperature gradients are expected particularly if small amounts of oceanic crust were produced along 'leaky' transform faults (Funck et al. 2007).

Thicker Davis Strait lithosphere (Fig. 5) could have had an insulating effect, causing large asthenosphere temperature gradients from north (Baffin Bay) to south (Labrador Sea) (Lenardic et al. 2005; Whittington et al. 2009; Heron and Lowman 2011) and therefore enhancing melting caused by other mechanisms such as edge-driven convection (e.g. Ghods 2002; van Wijk et al. 2008; Simon et al. 2009). Continental lithosphere persisted in the Davis Strait longer than elsewhere (Srivastava and Roest 1999). The Davis Strait is a considerably smaller region than others where insulation by continental lithosphere has been inferred to be influential, e.g. supercontinents (Lenardic et al. 2011), so this is likely to have been a minor effect.

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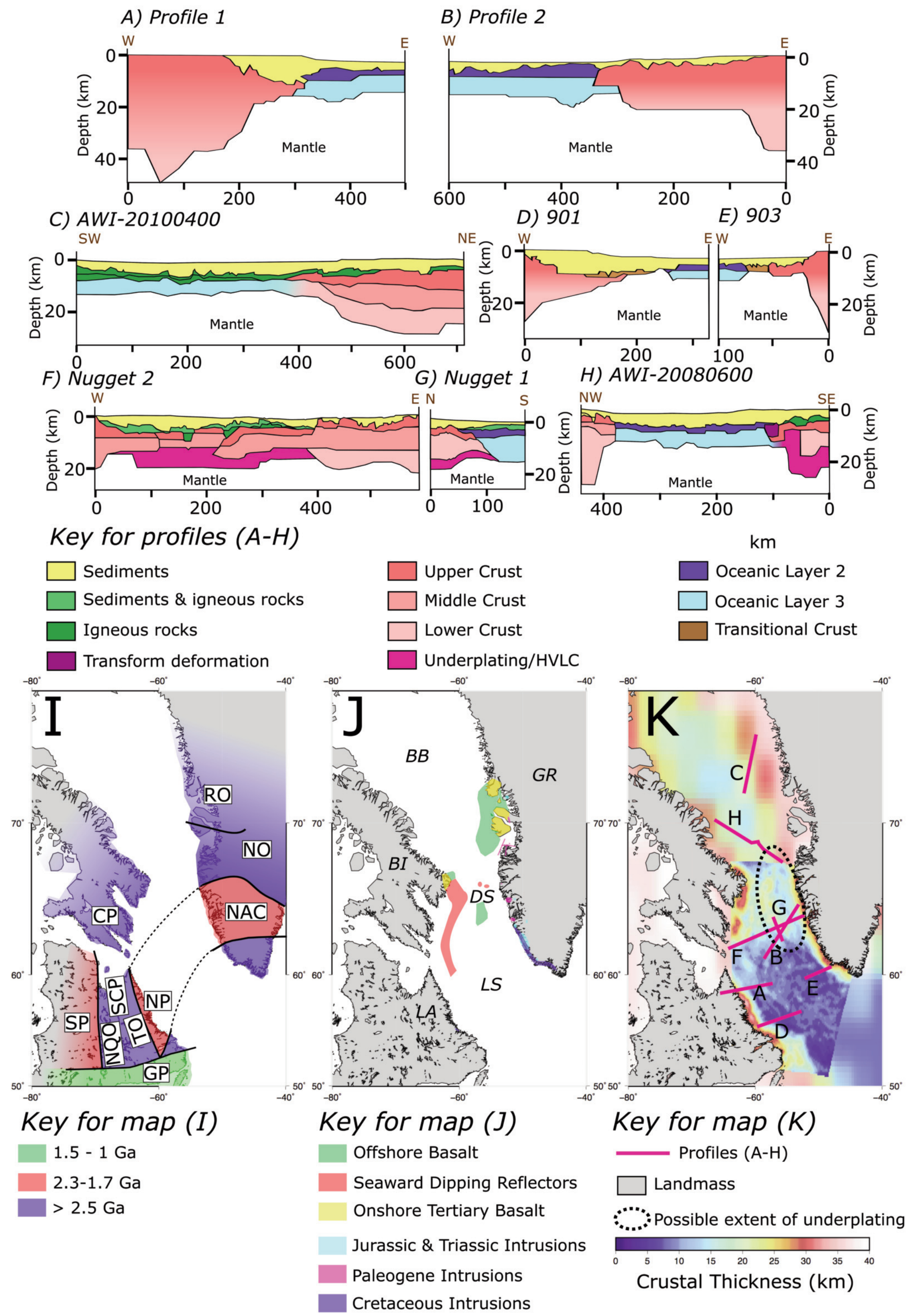


**Figure 4.** A compilation of crustal structure profiles (A–H) from the Labrador Sea–Baffin Bay rift system including: A) seismic reflection Profile 1 and B) and Profile 2 (Keen et al. 2012); C) seismic refraction line AWI-20100400 (Suckro et al. 2012); D) seismic reflection profiles 901 and E) 903 (Chian et al. 1995; Keen et al. 2012); F) seismic refraction NUGGET line 2 (Gerlings et al. 2009); G) Seismic refraction NUGGET line 1 (Funck et al. 2007) and H) seismic refraction line AWI-20080600 (Funck et al. 2012). Subfigure (I) depicts a simplified overview of basement units in northeastern Canada and Greenland modified from Kerr et al. (1997) and van Gool et al. (2002). Subfigure (J) shows the distribution of magmatism from the Triassic to the Tertiary (Park et al. 1971; Upton 1988; Larsen et al. 1992; Tegner et al. 1998; Tappe et al. 2007; Larsen et al. 2009; Peace et al. 2016). Subfigure (K) shows the calculated offshore crustal thickness using the global CRUST1.0 model (Laske et al. 2013) except in the Labrador Sea where the model of Welford and Hall (2013) is used. RO = Rinkian Orogen, NO = Nagssugtoqidian, CP = Churchill Province, NQO = New Quebec Orogen, SCP = Southern Churchill Province, SP = Superior Craton, TO = Torngat Orogen, HVLC = High-velocity lower crust, NP = Nain Province, GP = Grenville Province, NAC = North Atlantic Craton, BB = Baffin Bay, DS = Davis Strait, LS = Labrador Sea, GR = Greenland, BI = Baffin Island and LA = Labrador.

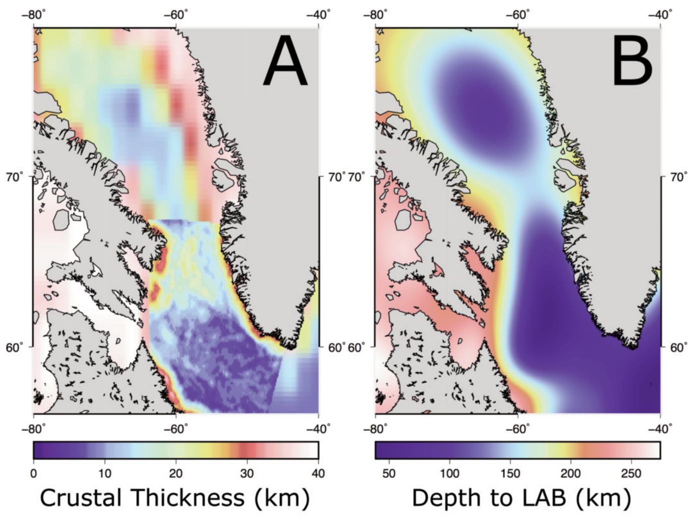


**Figure 5.** A) Calculated offshore crustal thickness using the global CRUST1.0 model (Laske et al. 2013) except in the Labrador Sea where the Welford and Hall (2013) grid is used. B) Depth to the lithosphere–asthenosphere boundary (LAB) using multimode waveform tomography (Schaeffer and Lebedev 2015; Schiffer et al. 2017).

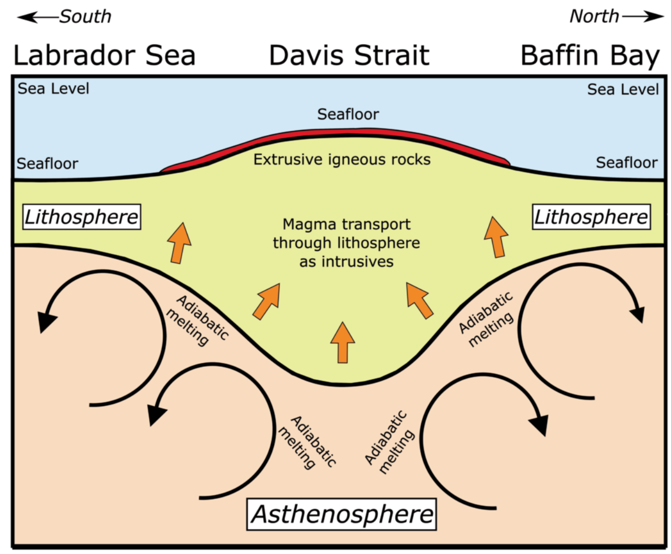


**Figure 6.** Schematic depiction of the model proposed herein. In this model the thicker crust and lithosphere in the Davis Strait, compared to the Labrador Sea and Baffin Bay (Fig. 5) where extensive thinning took place, could have induced small-scale convection (e.g. Simon et al. 2009). Small-scale convection in proximity to the Davis Strait could have resulted in adiabatic melting leading to the widespread magmatic rocks focused in this area. The reason lithospheric thinning in the Davis Strait was less than the Labrador Sea may have been due to the presence of pre-existing orogenic terranes that proved particularly resistant to thinning (Fig. 4I).

The thickness of the pre-rift continental crust has also been shown to be capable of exerting a significant influence on thinning and magmatic evolution during rifting and continental breakup (Audet and Bürgmann 2011; Petersen and Schiffer 2016). Previous work has shown that thick, warm, weak initial crust promotes dislocated extension and continental, pre-breakup melting whereas extension of thinner, colder, more brittle crust tends to be more localized, leading to quicker continental breakup in the absence of pre-breakup melting (Petersen and Schiffer 2016). The predictions of this model appear to be supported by observations of rifting in the Davis Strait as well as its location as the focus of the West Greenland Tertiary volcanic province.

The most important factor that boosted melt production at the Davis Strait region is probably the role the region played as a barrier to the propagating rift (Koopmann et al. 2014). Recent modelling suggests that such structural barriers retard rifting and enhance local melt production by restricting the area over which it can escape (Koopmann et al. 2014). Systematic variations in the abundance of magmatism are reported along the margins of the North and South Atlantic (Chalmers 1997; Franke et al. 2007; Skaarup et al. 2006; Elliott and Parson 2008; Blaich et al. 2009; Koopmann et al. 2016) with more abundant magmatism near 'transfer zones,' interpreted to have comprised barriers to rift propagation (Koopmann et al. 2014).

Numerical modelling shows that stress concentrations that encourage adiabatic melting can occur at ridge–transform intersections (Beutel 2005). This effect may explain instances of excess volcanism where ridge segments terminate at transform faults (Beutel 2005). Examples of volcanism produced in such a tectonic environment include the Foundation Seamounts (Hekinian et al. 1999), the Amsterdam and St. Paul Islands (Graham et al. 1999) and the Galapagos Islands. Two such ridge–transform intersections occur in the Davis Strait (Suckro et al. 2013), where two spreading centres terminate and melt produced will have found ready pathways to the surface through the transtensional segments.

Overall, a thicker continental lithosphere may have been conducive to enhanced melt production for a number of reasons including: 1) influencing asthenospheric flow; 2) providing additional insulation and thus enhancing other mechanisms; 3) comprising a barrier to rift propagation that was conducive to melt generation, 4) necessitating the development of a transform fault against which melt accumulated, increasing the magmatic volume locally, and 5) promoting dislocation extension with associated volcanism rather than abrupt breakup. Several crust and lithosphere-related effects thus predisposed the Davis Strait region to enhanced magmatism. The unusual magmatism there, traditionally attributed to mantle plume activity, may thus be explained by the interaction of a propagating rift and pre-existing lithosphere architecture.

## Preservation of Thicker Continental-type Crust and Lithosphere in the Davis Strait

Integral to the mechanisms we propose is the persistence of lithosphere near the Davis Strait that is thicker than Baffin Bay and the Labrador Sea. However, whether the crust and lithosphere in the Davis Strait and slightly farther north (Fig. 5) was thicker than the surrounding areas prior to rifting or only after preferential thinning in the Labrador Sea and Baffin Bay areas is relevant because this affects the feasibility of the mechanisms discussed above. The potential contribution of underplating (Gerlings et al. 2009) is also relevant.

The Davis Strait lies adjacent to the Paleoproterozoic Nagssugtoqidian (Connelly and Mengel 2000; van Gool et al. 2002; Kolb 2014; Engström and Klint 2014) and Torngat

(Funck and Louden 1999; Funck et al. 2000) orogenic belts (Fig. 4I) and thus the crust and lithosphere were almost certainly thickened prior to Mesozoic rifting. This suggests that the thick lithospheric keel we postulate was long-established prior to the onset of rifting.

Major structures in those terranes (Wilson et al. 2006) lay approximately perpendicular to the rift axis (e.g. Srivastava and Keen 1995; Abdelmalak et al. 2012) and may have thus resisted northward rift propagation (Fig. 4I) resulting in the reactivation of structures oblique to the extension direction (Peace et al. 2017b). The unfavourable orientation of pre-existing terranes may explain the failure of complete continental breakup locally between Greenland and Canada and have encouraged the transfer of opening to the Northeast Atlantic between Greenland and Eurasia. That rifting exploited more favourable Caledonian structures to the east of Greenland (Doré et al. 1997; Schiffer et al. 2015a, b, in press; Mjelde et al. 2016).

The large-scale geometry of the Labrador Sea–Baffin Bay rift system, that is a right-lateral step through the Davis Strait, may be a direct consequence of the presence of the Paleoproterozoic Nagssugtoqidian and Torngat orogens. This right-lateral step in the plate boundary geometry would have resulted in compression in the Davis Strait (Chalmers et al. 1993; Gregersen and Bidstrup 2008; Peace et al. 2017b) during later stages when Greenland moved north (magnetic Chron 24-13; Abdelmalak et al. 2012; Oakey and Chalmers 2012). This in turn would have allowed continued extension in the Labrador Sea and (probably) Baffin Bay but minimal thinning in the Davis Strait where transform tectonics continued to dominate.

Overall, the preservation of thicker continental-type crust and lithosphere in the Davis Strait is likely a combination of: 1) initial excess thickness, and 2) rifting not manifesting there as a result of the pre-existing orogenic belts that hindered rift propagation.

## CONCLUDING REMARKS

A suite of observations in the Labrador Sea–Baffin Bay rift system related to the geometry, spatial and temporal extent of rifting, seafloor spreading, rift-related magmatism and uplift do not fit the predictions of a model of breakup in response to the arrival of a mantle plume. This conclusion accords with the suggestion by Alsulami et al. (2015) that the role of a mantle plume has been overstated and that of Armitage et al. (2009, 2010) that elevated mantle temperatures alone cannot explain North Atlantic magmatism and rifting without the inheritance of previous structures.

The history of rifting, magmatism and seafloor spreading in the region are consistent with reaction to changing far-field stresses associated with plate tectonics. The observations can be explained without invoking a mantle plume. Tertiary volcanism in the Davis Strait results from local lithospheric structure. A thick lithospheric keel enhanced convection and comprised a barrier to the northerly propagating Labrador Sea rift, resulting in enhanced magmatism. This lithospheric keel is likely related to large-scale, pre-existing structures associated with the Paleoproterozoic Nagssugtoqidian and Torngat orogens. Pre-existing orogenic belts in the disintegrating continental lithosphere had first-order influences on the large-scale mode, timing and geometry of breakup across the entire North Atlantic region.

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# SERIES

## Economic Geology Models 3. Geological Contributions to Geometallurgy: A Review

**J.A. Hunt[1,2,3] and R.F. Berry[4]**

[1]*Mineral Deposit Research Unity (MDRU)*
*University of British Columbia*
*2020-2207 Main Mall, Vancouver, British Columbia*
*V6T 1Z4, Canada*
*Email: jhunt@eoas.ubc.ca*

[2]*Minerals Engineering, Materials and Environment (GeMMe)*
*University of Liege*
*Quartier Polytech 1, Allée de la Découverte 9, 4000, Liège, Belgium*

[3]*Centre of Excellence in Ore Deposits*
*University of Tasmania*
*Private bag 79, Hobart, Tasmania, 7001, Australia*

[4]*Australian Research Council Research Hub for Transforming the Mining Value Chain*
*University of Tasmania*
*Private bag 79, Hobart, Tasmania, 7001, Australia*

### SUMMARY
Geometallurgy is a cross-disciplinary science that addresses the problem of teasing out the features of the rock mass that significantly influence mining and processing. Rocks are complex composite mixtures for which the basic building blocks are grains of minerals. The properties of the minerals, how they are bound together, and many other aspects of rock texture affect the entire mining value chain from exploration, through mining and processing, waste and tailings disposal, to refining and sales. This review presents rock properties (e.g. strength, composition, mineralogy, texture) significant in geometallurgy and examples of test methods available to measure or predict these properties.

Geometallurgical data need to be quantitative and spatially constrained so they can be used in 3D modelling and mine planning. They also need to be obtainable relatively cheaply in order to be abundant enough to provide a statistically valid sample distribution for spatial modelling. Strong communication between different departments along the mining value chain is imperative so that data are produced and transferred in a useable form and duplication is avoided. The ultimate aim is to have 3D models that not only show the grade of valuable elements (or minerals), but also include rock properties that may influence mining and processing, so that decisions concerning mining and processing can be made holistically, i.e. the impacts of rock properties on all the cost centres in the mining process are taken into account. There are significant costs to improving ore deposit knowledge and it is very important to consider the cost-benefit curve when planning the level of geometallurgical effort that is appropriate in individual deposits.

### RÉSUMÉ
La géométallurgie est une science interdisciplinaire qui s'intéresse aux caractéristiques de la masse rocheuse qui influent de manière significative sur l'exploitation minière et le traitement du minerai. Les roches sont des mélanges composites complexes dont les éléments structurant de base sont des grains de minéraux. Les propriétés des minéraux, la façon dont ils sont liés entre eux, et de nombreux autres aspects de la texture des roches déterminent l'ensemble de la chaîne de valeur minière, de l'exploration à l'extraction à la transformation, à l'élimination des déchets et des résidus, jusqu'au raffinage et à la vente. La présente étude passe en revue les propriétés significatives de la roche (par ex. sa cohésion, sa composition, sa minéralogie, sa texture) en géométallurgie ainsi que des exemples de méthodes d'essai disponibles pour mesurer ou prédire ces propriétés. Les données géométallurgiques doivent être quantitatives et localisées spatialement afin qu'elles puissent être utilisées dans la modélisation 3D et la planification de la

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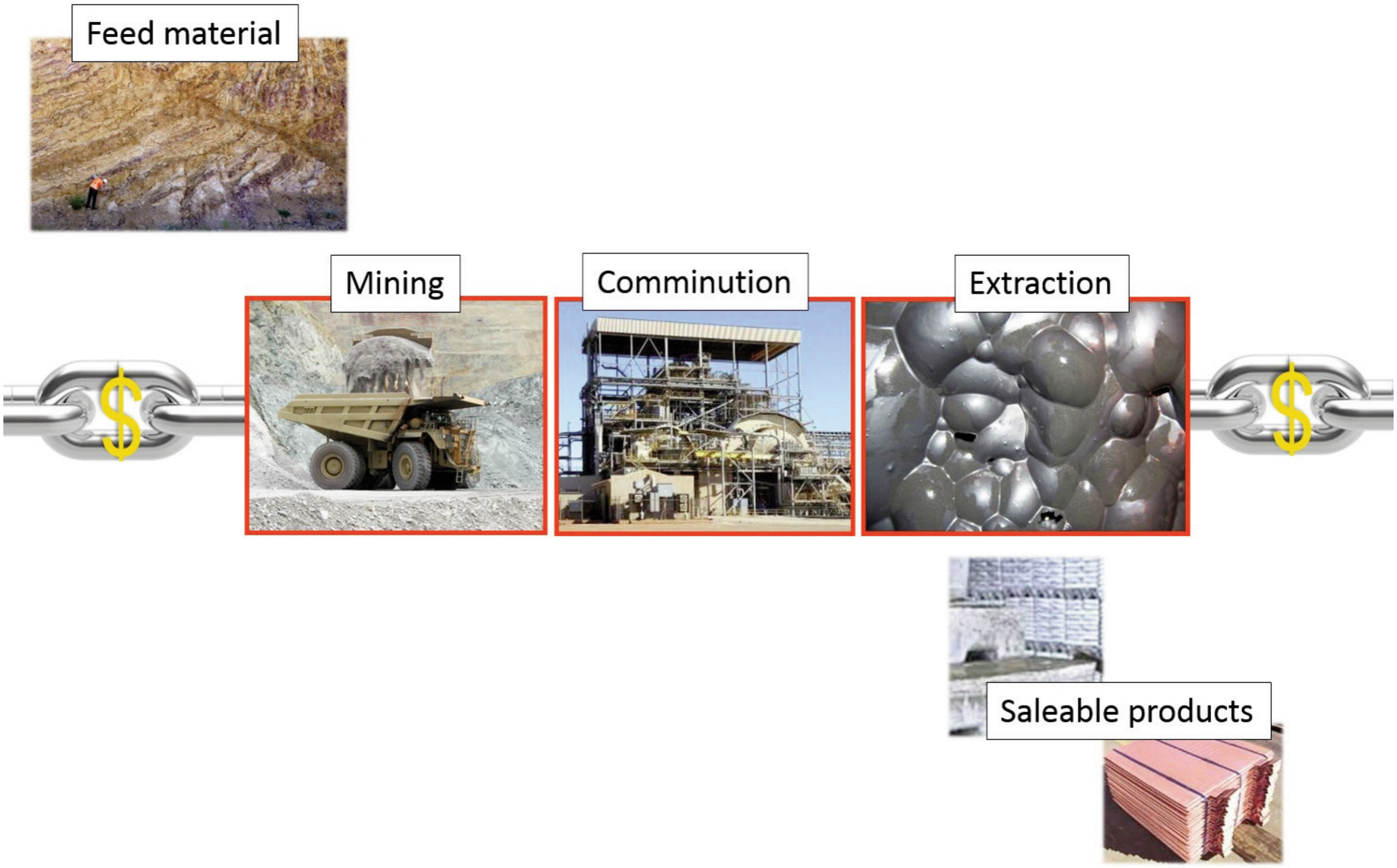


**Figure 1.** Example of the mining value chain (modified from Hunt and Berry 2015).

mine. Elles doivent également être peu couteuses afin d'être suffisamment nombreuses pour fournir une distribution d'échantillon statistiquement valide pour la modélisation spatiale. Une communication efficace entre les différents segments de la chaîne de valeur minière est impérative pour que les données soient produites et transférées sous une forme utilisable et que les duplications soient évitées. Le but ultime est d'avoir des modèles 3D qui montrent non seulement la qualité des éléments précieux (ou minéraux), mais aussi les propriétés de roche qui déterminent l'exploitation minière et le traitement du minerai, de sorte que les décisions concernant l'exploitation minière et le traitement du minerai peuvent être réalisées de façon holistique, c.-à-d. que l'impact des propriétés de roche sur tous les maillons de la chaîne des coûts du processus minier sont prises en compte. Les coûts d'amélioration des connaissances sur le gisement de minerai étant importants, il faut tenir compte de la courbe coûts-bénéfices lors de la planification du niveau d'investissement géométallurgique approprié pour le gisement considéré.

*Traduit par le Traducteur*

## INTRODUCTION

Geometallurgy is a team-based approach to documenting orebody variability in geology and mineralogy that affects the profitability of the mine (Fig. 1). Relevant performance parameters include comminution, (e.g. the transformation of ore, as transported to the mill, to mill feed by particle size reduction, through the use of crushing and grinding machines), metal recovery and environmental impact (e.g. Walters and Kojovic 2006; Walters 2011; Williams 2013). The aim is to generate a quantitative, spatially constrained database that can be integrated into 3D modelling and mine planning. It underpins a holistic approach to mine planning intended to optimize efficiency and profitability. Geometallurgy is also used to reduce the technical risk associated with new mine developments and/or the expansion of existing mines by reducing the difference between expected and actual mine performance in throughput, recovery, and value.

The ultimate aim is to value ore, not only on grade, but also on other factors, (e.g. throughput, recovery, tailings characteristics, product saleability, etc.) that better reflect the true value of each ore block. Geometallurgical data can also be used to compare prospects, in terms of real value, by taking into account processing parameters, such as hardness, (e.g. ease of crushing and grinding,) and mineralogy (e.g. minerals deleterious to processing, acid-producing minerals). It can be used during feasibility studies to assist with bulk sample selection and plant design for comminution (e.g. primary crushing followed by a semi-autogenous grinding (SAG) and ball-mill circuit with recycle crusher (SABC); three-stage crush, rod, and ball mill; or a crushing circuit including high-pressure grinding rolls (HPGR)), and processing options (e.g. gravity, flotation, and/or leaching). The data can also be used for optimizing long- and short-term block models, and mine scheduling (i.e. mine ore blocks in an order that produces the most value and least risk).

Geometallurgy is not new and has existed in various forms, (e.g. Mine to Mill) for at least 30 years (Holmgren and Marti 1984; McKee 2013). What is new, however, is the holistic view of the value chain and the strong team-based approach. It requires effective communication between what were traditionally information silos: isolated by specialization, business units, physical location, budgeting and management. Mine planning software has now been developed to make better use of the enhanced data that is becoming available (e.g. Carrasco et al. 2017).

We discuss the underlying character of rocks and then summarize typical rock and mineral factors that can affect the net present value of a deposit. The presentation is by no means exhaustive and the discussion is aimed at mine geologists. It emphasizes the most significant parameters that should/could be characterized based on drill core samples. The mine geologists' contribution to geometallurgy generally includes managing the mine database and deciding which small-scale geometallurgy proxies are relevant and practical. The geologists will probably work with the metallurgist to create models to predict metallurgical parameters from the available proxies. These models form the basis for 'transfer functions' (Deutsch 2013) that convert raw mine data into processing parameters suitable for geostatistical prediction across the ore reserves. This review only considers the applications of geometallurgy up to the hand over to the geostatistics group.

## ROCK PROPERTIES

It is relatively common for geologists to be asked to provide large 'representative samples' of average ore. However, ore deposits are complex with different zones of ore and gangue mineralogy and alteration. Each deposit has many unique features and is unlikely to be controlled by a single set of rock parameters. The mine geologist has little basis on which to select 'average' ore, and the selection invariably leads to biased results in pilot mill testing. The mineral process engineers (metallurgists) respond, in general, by over-engineering the mill to cover the sampling error historically associated with this selection. The following section looks at aspects of this in terms of inhomogeneous breakage behaviour and how a better representative sample of the rock to be mined can be achieved.

In discussions of the rheology of rocks, it is common to assume they are a homogeneous isotropic medium that can be modelled by an appropriate simplified model (e.g. elastic-plastic, elastic-brittle models; Jaeger et al. 2007). Mining operates across a range of scales where the anisotropic, heterogeneous and granular properties of the rock are important and, in general, brittle behaviour is dominant over ductile response. At the scale of mine stability and blasting, the mining is strongly affected by faulting and joints and geotechnical specialists have long recorded this level of heterogeneity (Little 2011).

**Table 1.** Types of structural damage that reduce the strength of rocks.

| |
|---|
| Fault zones, gouge, and cataclasite |
| Jointing: regional sets, local jointing and micro joints |
| Micro-cracks: inter-grain and intra-grain fractures |
| Grain boundaries |
| Porosity |

Quasi-brittle materials, such as rocks (Jiang et al. 2016), are also characterized by many other fine-scale structures (Table 1). They are composed of various minerals distributed in grains. Grain boundaries are weaker than the grains themselves. In addition, there are numerous randomly distributed micro-cracks and pores (Fig. 2) that contribute to the brittle response of rocks. In the crushing process, joints, micro-cracks, grain boundaries, and porosity are very important. The required energy for crushing changes dramatically as the

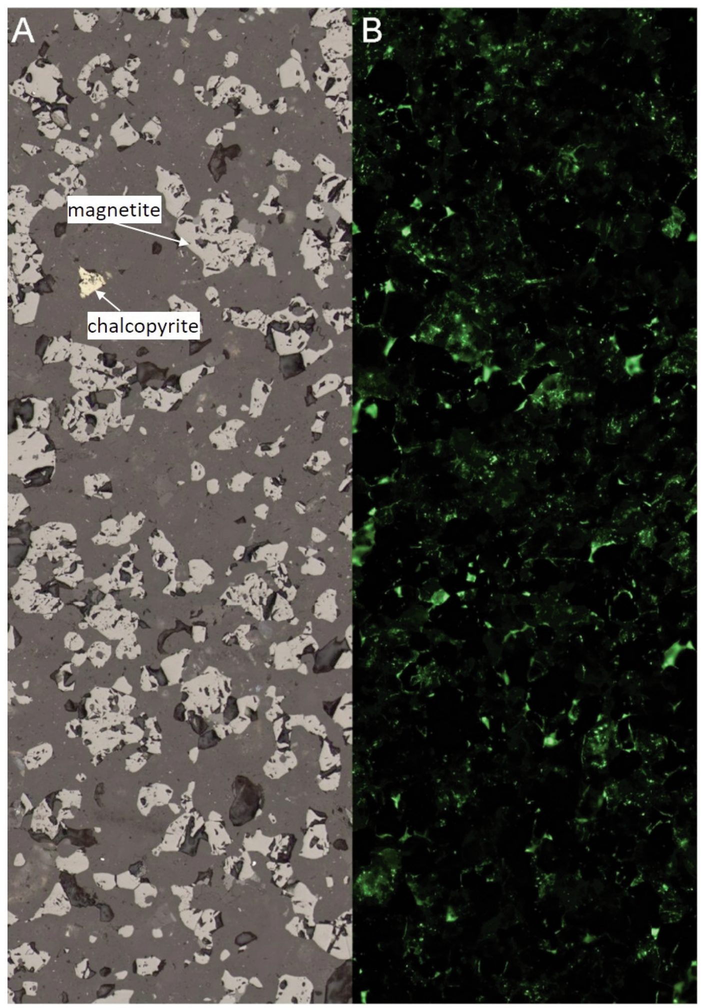


**Figure 2.** Microphotograph of iron oxide copper-gold (IOCG) ore. Field of view 0.9 mm wide. A. Reflected light image shows yellow chalcopyrite and slightly red-grey magnetite in a darker silicate gangue. B. Fluorescent light image shows doped resin decorating pores and microfractures.

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**Table 2.** Examples of typical values that reflect mineral hardness.

| | Mhos Hardness[1] | VHN(GPa)[2] | Fracture toughness[3] | Fracture toughness[4] | Cleavage[5] |
|---|---|---|---|---|---|
| hematite | 6 | 10.29 | 20.8 | | parting |
| magnetite | 6 | 7.25 | 12.9 | | none |
| pyrite | 6–6.5 | 14.8 | 6.14 | | poor |
| quartz | 7 | 12.1 | 5.35 | 1.5 | none |
| plagioclase | 6 | | 5.48 | | perfect |
| K feldspar | 6 | 6.9 | | 1.1 | perfect |
| chalcocite | 2.5–3 | | | | none/sectile |
| bornite | 3 | | | | none |
| chalcopyrite | 3.5–4 | 1.83 | | | poor/brittle |
| fluorite | 4 | 2 | 3.2 | 0.89 | perfect |
| calcite | 3 | 1.49 | | 0.39 | perfect |
| barite | 3–3.5 | | 1.2 | | perfect |
| *Comments* | *Abrasion/C.S.* | *Tensile strength* | *Tensile strength* | *Tensile strength* | *in preferred direction* |

Source: [1, 5]Hurlbut 1959; [2]VHN=Vickers Hardness: Whitney et al. 2007 and Broz et al. 2006; [3]Tromans and Meech 2002, 2004; [4]Whitney et al. 2007. C.S. = compressive strength

porosity and micro-fracture density increases (cf. Baud et al. 2014).

In blasting and crushing, rocks fail on the weakest zones with few mineral grains broken, and in many examples there is a low level of correlation of crushing energy with mineralogy (e.g. Schouwstra et al. 2013). Rocks with a coarse grain size are easier to crush than fine-grained rocks (Eberhardt et al. 1999). The uniaxial compressive strength of crystalline rocks is commonly much lower than expected from the strength of individual minerals. Noferesti and Rao (2011) argue this is due to the weak support for the grains and low interlocking factor.

During grinding, as size reduction continues, the particle size approaches the rock grain size and intra-grain fractures dominate over grain boundary fractures. During grinding the mineralogy is expected to be the major control on hardness. Typical values that reflect mineral hardness are shown in Table 2. In general, oxides, pyrite, quartz, and feldspar are hard, while sulphides, carbonates, sulphates, and phyllosilicates are soft. Martins (2016) reviewed the theoretical relationship between surface energy of a mineral, fracture toughness, and the Bond Ball work index. However, the response of real samples varies significantly from these predictions and the grinding response of variable mixtures of minerals can be even more difficult to predict (Ji et al. 2004; Tavares and Kallemback 2013; Csőke et al. 2013).

The toughest rocks are close to the mineralogical limit with grains tightly locked together and with low porosity and micro-fracture density. They have grinding hardness values (i.e. Bond Mill work indices, BMWi) that correlate at some level with the modal mineralogy. The grinding energy is not a simple linear function of the mineral abundance, but the mineral mode can be used as a proxy for BMWi in some deposits (e.g. Montoya et al. 2011; Hunt et al. 2013).

## Sources of Geometallurgical Data

### *Geotechnical Logging*

Geotechnical information is typically collected during the core logging process and includes rock quality designation (RQD), core recovery, and, in a few sites, geological strength index (GSI). RQD is an approximate measure of the degree of fracture (or jointing) in a rock mass and is measured as a percentage of the drill core in lengths of 10 cm or more (e.g. Deere 1964; Deere and Deere 1988). Core recovery is generally calculated as a percentage of the core run. GSI extends the concept of RQD to include the shape of the fragments and is most relevant in areas of weak rocks (Marinos and Hoek 2000).

Conventional geotechnical logging of strata for stability purposes typically concentrates on major structures, such as faults, and smaller structures may be ignored. For the purposes of blast design, the measurement of smaller structures, such as joints, foliations, and bedding are important as they can control blast fragmentation (Badal 1995; Scott et al. 1996). Scan line mapping can be used to record the properties of all discontinuities that cross it (e.g. Villaescusa 1991). This is typically done on an exposed rock face, but could also be carried out on oriented drill core. Typical properties recorded for the discontinuities are: location of the discontinuity along the scanline; dip and dip direction; trace length; type of discontinuity; roughness of the discontinuity surface; type (e.g. another joint, intact rock); and angle (low, i.e. $< 20°$; high, i.e. $> 20°$) of termination. For a rock face, sixty points are considered adequate to define the characteristics of a joint set (Scott et al. 1996). This information can be used to estimate *in situ* block size distribution (e.g. Villaescusa 1991), which can then be compared with the fragment size distribution expected at the primary crusher to determine the amount of breakage required from the blasting. This data can also be used in slope and bench stability analysis (Scott et al. 1996). Methods to automate geotechnical logging are being developed (e.g. Harraden et al. 2016).

RQD data can, in addition, be a significant input parameter in estimating rock strength and overall comminution performance as the abundance of fractures can influence the crushability and grindability of rocks. Burger et al. (2006) show the extensive use of RQD data in helping to improve predictions of throughput at Batu Hijau.


**Figure 3.** Example of point load testing of drill core. (image from Kojovic 2008). Force applied to the rock is gradually increased until the rock fails. The peak pressure applied is shown on the gauge.

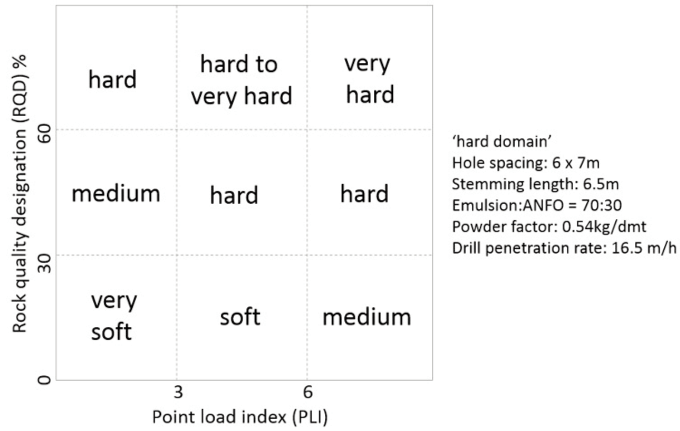


**Figure 4.** Left: point load index (PLI) versus RQD diagram developed for Batu-Hijau. Use of the diagram allows rocks to be divided into different strength domains each of which requires different drill-and-blast parameters. Right: example of drill-and-blast parameters developed for the 'hard domain'. ANFO = ammonium nitrate - fuel oil. Modified from Burger et al. (2006).

## *Rock Strength Testing*

Tests of uniaxial compressive strength (UCS), tensile strength, Young's Modulus, and Poisson's ratio are typically used to obtain information about the strength of intact rock (e.g. ISRM 1981; Napier-Munn et al. 1999). Lower cost tests that provide proxies for unconfined UCS include point load testing (PLT), sonic velocity, and rebound hardness (Verwaal and Mulder 1993; Meulenkamp and Grima 1999; Rusnak and Mark 2000; Sousa et al. 2005; Chang et al. 2006; Keeney et al. 2011; Momeni et al. 2015).

Point load testing (PLT) is relatively easy to carry out and can be done routinely on drill core (Fig. 3). PLT yields a strength index, referred to as *Is*, and is typically used in drill-and-blast and geotechnical fields as a quick and simple method to predict tensile and compressive strength (e.g. Broch and Franklin 1972; Brook 1985; Butenuth 1997). The point load index is also a useful guide to comminution behaviour. For example, at the Batu Hijau copper–gold porphyry in Indonesia, a large data base of PLT results were used, in combination with RQD data, to define hardness domains for the deposit. These domains were used in blasting (Fig. 4; Burger et al. 2006). They were also used to more accurately predict mill throughput.

Dynamic values of Young's Modulus and Poisson's ratio of a large rock volume *in situ*, can be obtained by seismic techniques in which the velocities of compression (*Vp*) and shear (*Vs*) waves are determined. In order to determine the elastic constants, the density of the rock must also be known (e.g. Scott et al. 1996). Similar information can also be collected from drill core using hand held (e.g. sonic velocity tester, Fig. 5) or bench-scale (semi) automated petrophysical techniques (e.g. Geotek logger, Fig. 5; Vatandoost et al. 2008; Hunt and Berry 2015).

Rock strength information can also be obtained from rebound hardness measurements collected on drill core (Fig. 6). This data is easy and quick to collect allowing almost continuous downhole measurements to be obtained. The device impacts under spring force with known energy and then rebounds; the hardness value is calculated from the ratio of impact and rebound speeds (Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/). Keeney et al. (2011) and Montoya et al. (2011) demonstrate that rebound hardness data can be used in modelling rock strength parameters that relate to crushing and grinding.

The point load index, sonic velocity, and rebound hardness largely correlate with impact (i.e. crushing) hardness (e.g. Burger et al. 2006; Vatandoost and Fullagar 2009). Point load test data can be used to predict about 50% of impact hardness of the material (Fig. 7). Sonic velocity has a similar correlation with impact hardness (Fig. 7b). The average rebound hardness value is less useful, but the 20% percentile of the measured range is a better predictor of impact hardness (Fig. 7d). For the range of deposits included in the AMRA P843A database, the correlation of these parameters with impact hardness is better on individual deposits than on the global database.

Grinding hardness, typically determined via Bond work index (BWI) testing, does not show a global correlation to UCS (Doll et al. no date). Similarly, there is no general correlation of point load, rebound hardness or sonic velocity with BWI (Fig. 8). However, these low cost tests along with bulk

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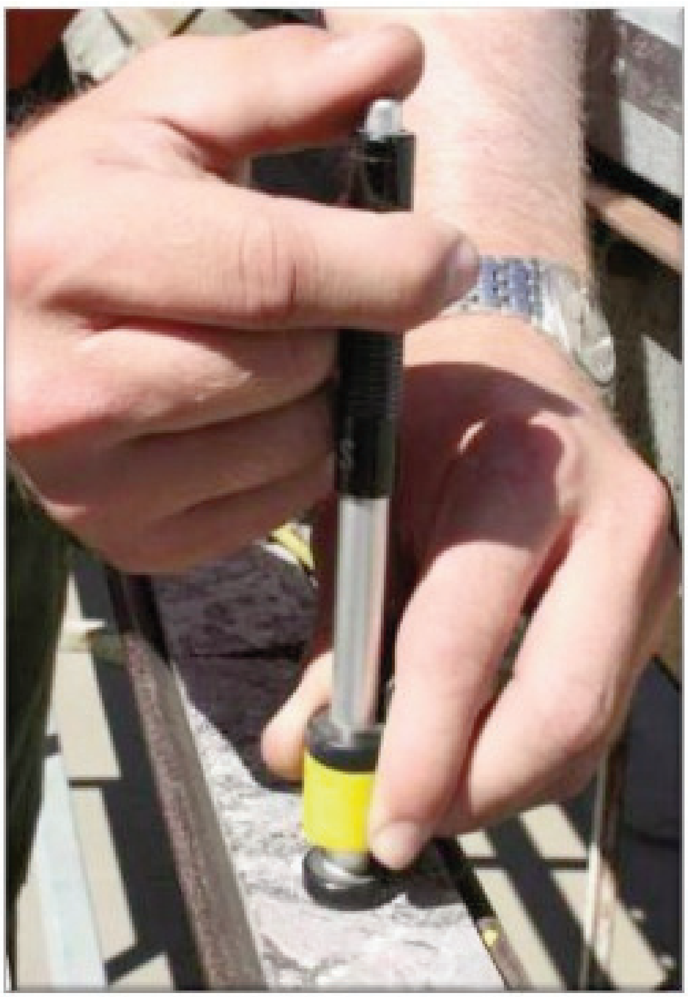
**Figure 5.** Left: example of hand-held measurement of drill core sonic velocity. Right: example of a Geotek multi-sensor core logger used for collecting petrophysical measurements (e.g. gamma density, *p*-wave velocity, resistivity, magnetic susceptibility, etc.) from drill core.



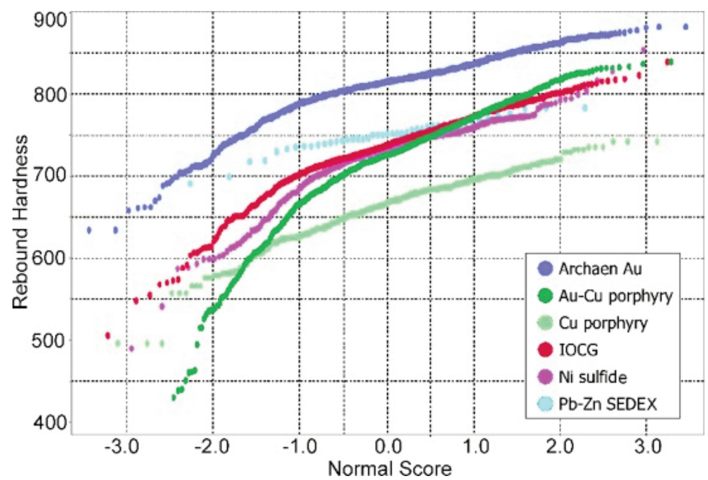



**Figure 6.** Left: example of collecting rebound hardness data from drill core. In this case the device being used is an Equotip (Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/). Right: Rebound hardness results from the AMIRA P843A database. 1500 m of drill core was measured at ~2 cm spacing for each deposit. Possible hardness values are 0 to 1000. IOGC = iron oxide-copper-gold ore.

mineralogy may act as weak proxies for grinding hardness in individual deposits (e.g. Keeney et al. 2011; Montoya et al. 2011). Better geometallurgical tests for grinding hardness are cut down Bond Work Index tests, such as the SPI (SAG Power Index), simplified Bond test (e.g. Kojovic and Walters 2012a), or by high-energy impact breakage such as the JKRBT Wi (JK Rotary Breakage Tester; Walters and Kojovic 2013).

In order to collect the large amount of data required so that results can be used as inputs for geometallurgical domain development and modelling, rock strength tests for geometallurgy need to be: rapid, low cost, relevant to comminution performance and rock texture, able to be used on a small sample size (i.e. drill core), and reproducible (precise). The aim is for comparative testing rather than highly accurate testing. Examples of geometallurgical tests suitable for large-scale rollout (i.e. 1000's of tests) across a deposit include: rebound hardness (e.g. Equotip), petrophysics (e.g. sonic velocity), and rock quality designation (RQD). Table 3 lists some of the common tests that can be carried out on drill core and their approximate cost

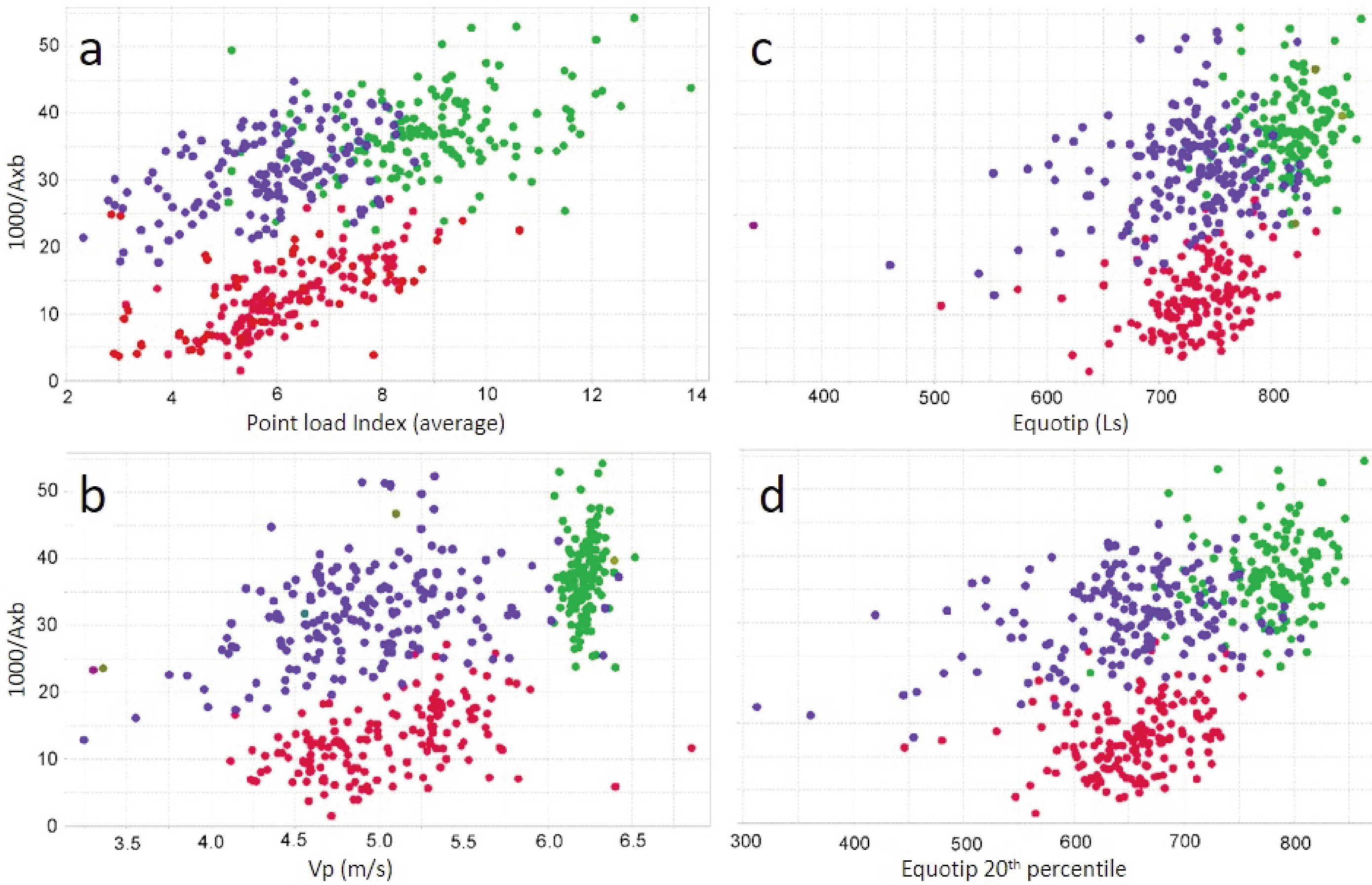



**Figure 7.** Comparison of small scale tests with inverse of Axb (JKMRC index for impact hardness) for a range of deposits in the AMIRA P843A database. *Vp* is compressional seismic velocity. Equotip (i.e. rebound hardness) results reported using Leeb hardness value (Ls; Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/) and 20th percentile of 100 individual Equotip readings over 2 m intervals. Each colour represents a different deposit style: red = iron oxide copper-gold ore (IOCG), green = porphyry Cu, blue = Archean Au.

along with issues to be considered. Measurement while drilling (MWD) techniques have the potential to be a major source of data, but adjusting for drill-rig variability remains problematic (Mwanga et al. 2015).

Harbort et al. (2013) discuss comminution test that can be used to domain an ore body. The classic metallurgy tests such as JK drop-weight test and JK rotary breakage test are used to measure impact hardness and require more than 50 kg of sample. The grinding energy requirement is provided by Bond Ball and Rod Mill tests that require at least 10 kg of material and are expensive. Typically, less than 100 of these tests will be carried out on a mine.

There are other tests that, although not suitable for rollout across an entire deposit because of cost and sample requirements, can be used for variability testing (i.e. 100's of tests). These tests are generally cut-down versions of bankable tests. A summary of the cut down tests is provided by Verret et al. (2011) and Mwanga et al. (2015).

### Chemical and Mineralogical Composition

Most drill core (at least in mineralized areas) is analyzed for elemental chemical content. Generally, drill core is divided into analysis intervals (e.g. 1m, 2m, 5m), split or cut in half, and one half sent for analysis. Results can include metal content (e.g. Cu, Pb, Zn, Au, Ag, Fe) and rock-forming elements (e.g. Si, K, Na, Ca). In terms of rock strength, an analysis method that involves complete digestion of the sample and provides information on rock-forming elements is most useful, for example four-acid digest with ICP-MS analysis (e.g. ALS: http://www.alsglobal.com/). Even better is full XRF analysis including loss on ignition (LOI) and $SiO_2$.

The abundance of constituent minerals (i.e. bulk or modal mineralogy in %) is not typically determined for routine assay samples of drill core. However, it is a key parameter in predicting performance characteristics in a mineral processing circuit, particularly in terms of geometallurgy. Modal mineralogy can be determined at relatively low cost using (semi-) quantitative X-ray diffraction (QXRD), as advances in instrumentation and application software have improved XRD throughput by an order of magnitude and analysis is now routine (e.g. Berry et al. 2011). The QXRD method is most applicable to major (i.e. rock forming) minerals and has limited application to minerals at low abundance. The nominal detection limit is 0.5%.

Bulk mineralogy can also be determined at low cost via calculation of mineralogy from chemical assay data (e.g. Berry et al. 2011). This method depends on the unique composition of


**Figure 8.** Comparison of small scale tests with Bond Work index (BMWi) for a range of deposits in the AMIRA P843A database. *Vp* is compressional seismic velocity. Equotip (i.e. rebound hardness) results reported by Leeb hardness value (Ls; Proceq: https://www.proceq.com/compare/equotip-portable-hardness-testing/) and 20th percentile of 100 individual Equotip readings over 2 m intervals. Each colour represents a different deposit style as in Figure 7.

**Table 3.** Examples of small-scale tests for rock strength.

| Test | Example | Example of speed | Example of cost | Comments |
|---|---|---|---|---|
| Fracture frequency | RQD | slow | | Generally already routinely done for geotechnical issues. |
| Rock appearance | Core description | | | Method exists to correlate with unconfined compressive strength. |
| Petrophysics | Sonic velocity; Density | 50 m of drill core /hour | ~ $5 per m | Best done on whole core. |
| Point Load | PLT | slow | ~ $50 per test | Slow, destructive. |
| Rebound hardness | Equotip | 30 m of drill core /hour; measurements every 2 cm | ~ $5 per m | Best done on whole core. Core needs to be stable. |

each mineral and problems can arise if the mineral compositions are ambiguous (e.g. solid solution series, polymorphic minerals, compositions not independent in assay space). However, it can be more accurate than QXRD when the correct minerals and mineral compositions are used.

If chemical assay data and QXRD results are available for all samples, the two datasets can be combined using weighted least squares methods to take advantage of the strengths of each technique when calculating modal mineralogy (e.g. Berry et al. 2011). In this case, estimates of high abundance minerals are controlled by QXRD measurements and low abundance minerals by chemical assay data. In a similar way spectral data (e.g. short wave IR (SWIR), thermal IR (TIR)), collected using hyperspectral scanners (e.g. Terraspec, Hylogger, Corescan, Geospectral, Specim, etc.) can provide less precise estimates of the abundance of some minerals and this can be combined with assays.

## APPLICATIONS OF GEOMETALLURGY

### Mine Stability

The availability of a comprehensive geological model is fundamental to any slope design (Hoek et al. 2000) and geological mapping techniques to classify rocks and to define the orientation and frequency of large- and small-scale discontinuities are essential in rock mechanics studies (Hustrulid et al. 2000). Hydrothermal processes that cause extensive alteration of the rock can significantly impact rock strength and discontinuities compared to surrounding less-altered rock. For example, studies at Chuquicamata have shown that potassic alteration has the least impact on rock strength, chloritic alteration has a significant impact, and sericitic alteration a major impact (Kazulovic personal communication in Hoek et al. 2000). Thus, a detailed map showing alteration type and intensity is also important for mine stability purposes. These should be continually updated as new information becomes available.

Data collected typically includes: information on structures and fabrics in the rocks, detailed core logs, images, and rock strength information. Connected to this are various forms of rock-mass classification including: rock quality designation (RQD), rock mass rating (RMR), geological strength index (GSI), and Q index (Barton et al. 1974; Hoek et al. 2000; Marinos and Hoek 2000; Barton 2006). The success of slope-stability analysis depends upon the level of understanding of the characteristics of the geological structure throughout the deposit (e.g. Nicholas and Sims 2000). The geological attributes that are most critical include: orientation, length, spacing, overlaps, and shear strength of faults and joints. Orientation and spacing of structures can be measured from surface exposures or oriented drill core. Structure length and overlap are best measured from surface exposures. Shear-strength data for structures can be obtained from surface exposures or from drill core samples. The strength that usually controls the behaviour of a fault is the strength of the material that is the weakest and comprises at least 20% of the fault zone (Nicholas and Sims 2000). It is important, particularly in open pits, to compare structural observations from diamond drill core (and underground exposures) to those from surface mapping to differentiate between natural fractures and those induced by blast damage to avoid underestimating the strength of the rock mass (Hoek et al. 2000).

The use of structural and strength data allows a deposit to be divided into 'engineering rock types' that are defined by intact rock and fracture shear strength. These may or may not match geological (i.e. lithological, alteration) boundaries. For example, at Grasberg, protolith, alteration type, RQD, and relative depth were used to differentiate engineering rock types (Nicholas and Sims 2000).

### Blasting

Blasting is the dominant method used for large-scale rock breakage in all but the weakest rocks and the goal is to convert an *in situ* rock mass into a muck-pile of an appropriate fragment size distribution (i.e. avoiding excess fines or oversize fragments) and of a suitable shape and looseness to suit available excavation and transport equipment (e.g. Scott et al. 1996). The properties of the intact rock and any discontinuities play a role in determining the amount of explosive energy needed to achieve the required breakage.

In terms of blasting, important rock mass information (e.g. Scott et al. 1996) is that related to strength properties (compressive, tensile, and shear strength), mechanical properties (Young's Modulus and Poisson's ratio), absorption properties (ability to transmit or absorb blast energy), structural properties (faults, jointing, bedding, foliation, cleavage and small scale fractures), and comminution properties (ease of crushing, grinding). To be incorporated into blast design, these properties must be measured or estimated in a quantified, consistent, and systematic manner.

Faults, jointing, bedding, foliation, cleavage, and small-scale fractures all affect the blasting behaviour (Little 2011). For example, discontinuities that are favourably oriented with respect to a blast hole will be preferentially extended by the shock wave produced during blasting. The surfaces of pre-existing fractures can act as surfaces for reflection and refraction of shock waves. Layered material introduces zones of different impedance and additional boundaries for shock wave interactions and attenuation. Interconnected structures may allow the early escape of explosion gases. The presence of a large number of fractures reduces the effort required to achieve fragmentation and the absence of discontinuities makes blasting more predictable. However, the presence of fractures spaced at the desired blasting spacing distance or the presence of strong rocks in a weaker matrix can lead to fragmentation problems. Horizontal planes of weakness or vertical planes parallel to the (pit) face are generally favourable to blasting (e.g. Badal 1995; Scott et al. 1996). Less predictable results can be achieved with dipping discontinuities.

### Comminution: Crushing and Grinding

Crushing and grinding of ore is used to partially liberate valuable minerals prior to separation in a mineral processing circuit. The way ore breaks is controlled by the properties of particles making up the ore, properties of minerals making up the grains and by the texture of the ore. Grain size, porosity, micro-fracture density, and modal mineralogy are considered to be the important characteristics that influence rock breakage (e.g. Malvik 1988; Petruk 2000).

During crushing and grinding, the main processes involved in grain size reduction are extension, abrasion, and compression, as illustrated in Figure 9. Failure can occur by tensile failure across the particle in unconfined compression and this is the most efficient process for reducing grain size (e.g. Tromans and Meech 2004). This type of failure is dominant in crushing. Less efficient processes are local zones of very high compressive stress that exceed the compressive strength of the material and also attrition during abrasion of particles.

Rocks fail on the weakest zones and rock elastic properties (e.g. Young's Modulus) are important in the propagation of

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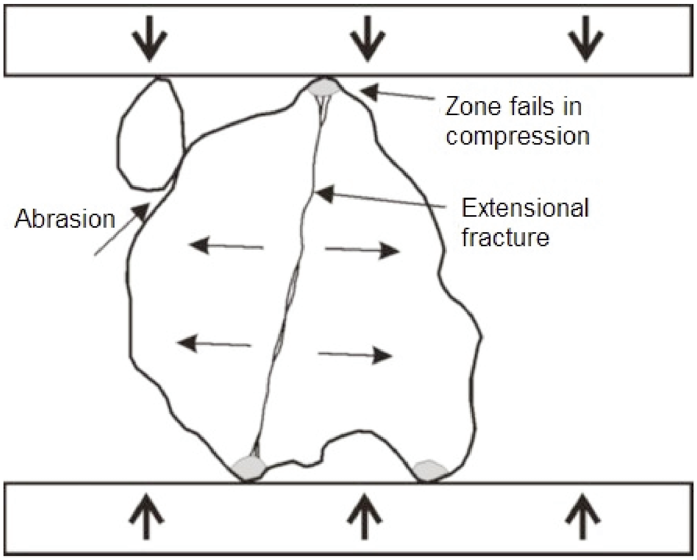


**Figure 9.** Three main processes in grain size reduction (after Wills and Napier-Munn 2006).

stress through the particles to the weakest point. Non-random breakage (Marino et al. 2016) may enhance the liberation properties that influence the behaviour of particles in the ensuing separation process(es). For example, breakage that exposes more of a valuable mineral at the particle surface may result in a significant improvement in the efficiency of separation processes that exploit surface properties (e.g. flotation) or provide access for fluids (e.g. leaching). Non-random breakage is more common when particle bed breakage devices are used (cf. Vizcarra et al. 2010; Runge et al. 2013).

## Recovery

A number of mineral properties are used to liberate and recover valuable phases, for example, electrical properties (e.g. recovery of zircon, rutile, ilmenite from mineral sands), density (e.g. gravity separation of gold, cassiterite, scheelite), magnetic properties (e.g. magnetite, pyrrhotite). Surface characteristics of minerals can also be important, for example, in flotation of sulphide minerals (Shuey 1975; Pridmore and Shuey 1976; Lotter and Bradshaw 2010; Rabieh et al. 2016). Leaching is strongly dependent on permeability and reactivity of the ore (e.g. Ghorbani et al. 2011).

Rock factors affecting liberation and recovery include size, shape, and association (deportment) and composition of the mineral grains. If the average grain size of minerals is coarse enough it may be possible to estimate the abundance and mode of occurrence of some minerals during drill core logging. This can be particularly important for valuable metal-bearing sulphides and pyrite. For example, Figure 10 illustrates some visually logged drill core attributes from a copper porphyry deposit. The occurrence of sulphides as disseminated or massive can affect their processing potential, generally in terms of liberation and estimations of required grind size to attain liberation. Massive sulphides can typically be liberated from host rocks at coarser grain sizes than finely disseminated sulphides. Mesotextures (e.g. massive, banded) identified in drill core can be of assistance in estimating metallurgical recoveries as demonstrated by Bojcevski (1998) for the George Fisher Ag–Pb–Zn deposit. Bojcevski (1998) shows that ores containing larger proportions of massive galena and massive galena–sphalerite generally have greater lead recoveries. This is due in part, as expected, to the higher lead content, but is also influenced by coarser grain size of massive galena. This results in increased galena liberation at the target grind size, along with less iron sulphide content that makes the separation process simpler.

Grain size is a key factor in the liberation of valuable minerals, but the definition of grain size must reflect the complexity of the grain shapes and the grain size distribution (Fig. 11). Easily liberated textures typically have a high average grain size as estimated by a volume weighted averaging process, such as phase specific surface area (Sutherland 2007). Ease of liberation can also be estimated by the use of simulated fragmentation where an image of a sample is divided into square domains (i.e. pseudo fragments) at a size close to final grind size. The level of apparent locked grains in these simulated fragments can then be measured (e.g. Hunt et al. 2011).

Grain association is expected to affect liberation. If easily floated minerals (e.g. pyrite and chalcopyrite) are closely associated, this improves recovery of the valuable component (Tungpalan et al. 2015). It is commonly observed that gold in silicates is more easily liberated than gold in pyrite (e.g. Zhou et al. 2004), although it is not certain this is due to association as there is also a grain size effect. Other examples of association control on liberation are hard to find.

In recovery models, especially for flotation, it is commonly expected that recovery will be a function of grade (e.g. Splane et al. 1982; Corrasco et al. 2008). At high grade the recovery percentage is fairly consistent, while at very low grade it falls to zero. For some deposits this non-linear shape can be matched to a simple model that has a small proportion of the valuable metal as non-recoverable in any sample.

$$\text{Recoverable } X = a^* (\text{total } X) - b \qquad \text{(Eq. 1)}$$

where $a$ is the proportion of $X$ recovered at high grade and $b$ is a fixed amount of $X$ that can never be recovered. A model such as this gives rise to the equation:

$$\text{Recovery \%} = 100^* (a - b/(\text{total } X)) \qquad \text{(Eq. 2)}$$

An example of the fit of this curve shape to small-scale batch flotation test data is shown as the red line on Figure 12. However, in many deposits the recovery is limited by other factors and a more complex relationship is observed (e.g. Sciortino et al. 2013).

It may also be expected that grain size is related to recovery; however, there are very few examples where a recovery-relevant estimate of the grain size distribution of the valuable mineral has been measured and is available for comparison (e.g. Hunt et al. 2011). Where the grain size has been measured, the recovery factor correlates better with grain size than it does with grade (Fig. 12). Producing a suitable grain size proxy remains difficult, however, and recovery proxies are largely

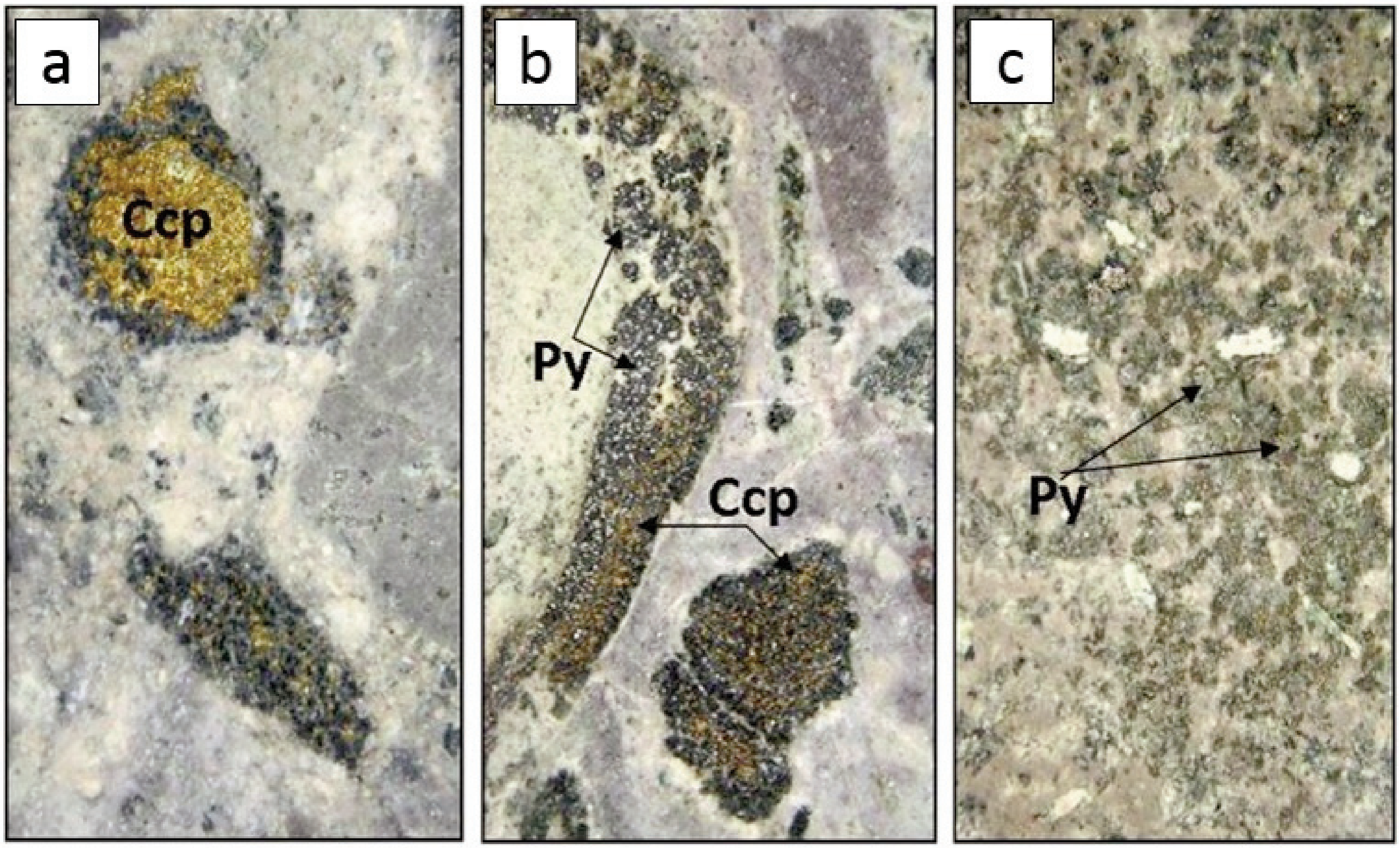


**Figure 10.** Examples of visually estimated chalcopyrite: pyrite ratios in drill core from a copper porphyry. a) 100:1, b) 60:40, and c) 0:100. Each image is of NQ drill core (NQ: ~48 mm diameter, inside core). Ccp = chalcopyrite, Py = pyrite. Modified from Bonnici (2012).

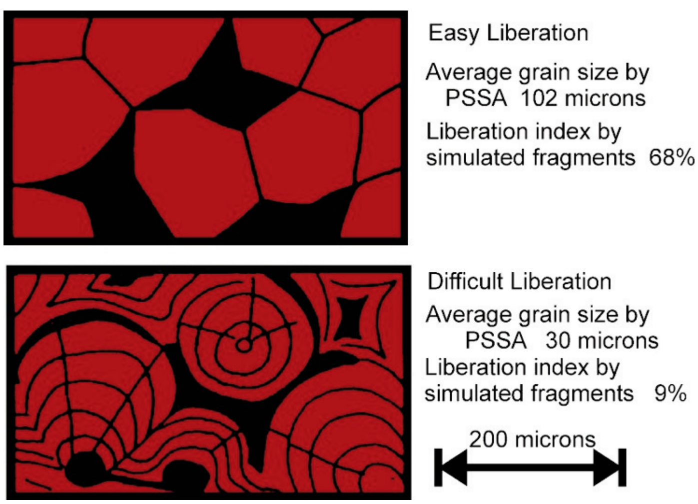


**Figure 11.** Grain size and liberation. Examples of textures for easy and difficult liberation redrawn from Craig and Vaughan (1981). Estimate of grain size of valuable phase (red) by phase specific surface area (PSSA). The images are also ranked in terms of percentage of simulated fragments (Hunt et al. 2011) that are 100% liberated at a fragment size of 20 microns.

limited to those from cut down tests whether for flotation (e.g. Chauhan et al. 2013; Runge et al. 2013) or leaching (Greet et al. 2015).

Lotter et al. (2016) provide a review of the flotation characteristics of copper sulphide minerals and point out the difficulties of floating different copper minerals with each having individual flotation characteristics. These authors also point out the added difficulties that occur if pyrite is present in sulphide ores, due to its natural tendency to float quickly and easily. In addition, if arsenic is present in the copper and iron sulphides, this can alter the flotation characteristics. Thus, the degree of mineral association and liberation (i.e. textural associations) between these minerals can be a complicating factor during the extraction of valuable phases and should be documented early in the mining value chain through mineralogical characterization of drill core (e.g. through complete chemical analyses, optical and SEM-based mineralogy).

### *Complicating Factors*

Gangue mineralogy can have significant direct impact on mineral processing. For example, talc and/or clay content can cause issues with pulp viscosity, entrainment and bubble 'clogging' in flotation (e.g. Farrokhpay et al. 2016). Carbonaceous material can make Au difficult to recover (e.g. Helm et al. 2009). The presence of deleterious elements (e.g. As, Bi, Cd, F, Hg) can reduce the value of concentrate or make it un-saleable (e.g. Goldie and Tredger 1991; Fountain 2013). Complex intergrowth textures can make it difficult to separate individual sul-

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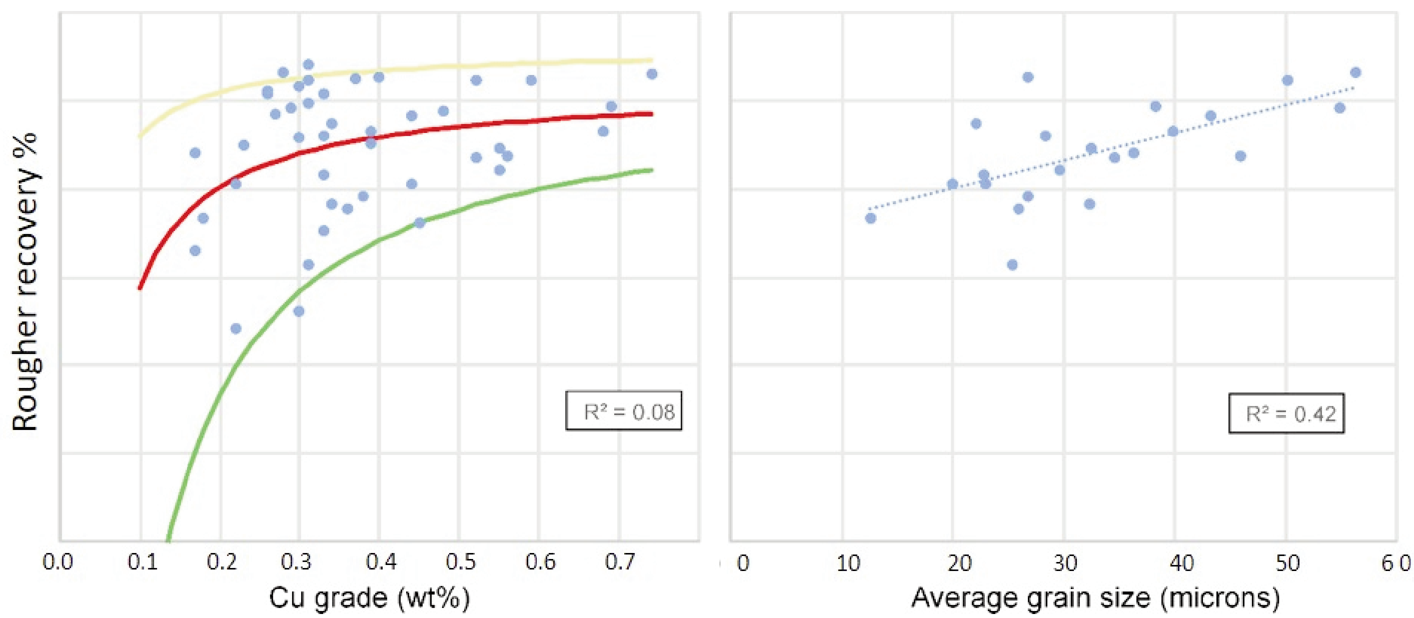


**Figure 12.** Recovery of Cu in a chalcopyrite dominated ore measured by small scale batch flotation and plotted against grade (left) and grain size of chalcopyrite (right). Best fit curve against grade is the red line (left graph). Yellow and green curves bound the distribution and reflect best and worst case grade recovery curves drawn using the equation form suggested in the text. Linear correlation coefficients ($R^2$) shown against grade and grain size.

**Table 4.** Examples of clay minerals and potential processing problems (cf. Cruz et al. 2013; Farrokhpay et al. 2016).

| Clay mineral group | Common minerals | Type of clay | Swelling potential | Effect on viscosity and yield strength | Problematic amount (wt.%) |
|---|---|---|---|---|---|
| Smectite | Montmorillonite, nontronite, saponite, beidellite | Bentonite, swelling clay, attapulgite clay | High (extreme, especially for montmorillonite) | Moderate – high depending on wt.% clay | > 5 % |
| Kaolin | Kaolinite, dickite | Kaolin, china clay, tonsteins | Low | Moderate – high depending on wt.% clay | > 10–15 % |
| Illite | Illite, glauconite | K-bentonites | Low | Moderate – high depending on wt.% clay | 1 to > 5 % depending on whether divalent cations are present |
| Interlayer clays | Illite – smectite | | Low to moderate | Moderate – high | |
| Vermiculite | | Zonolite | Moderate | Moderate | |
| Palygorskite | Palygorskite, sepolite | Fuller's earth, attapulgite clay | Low / none | Probably high (fibrous mineral) | Probably < 1 % |

phide minerals and necessitate expensive fine grinding (e.g. Jankovic 2003). The presence of mineralogy with the potential for fast oxidation, or the presence of highly soluble minerals, can require special handling to minimize potential problems (e.g. Wills and Napier-Munn 2006).

### *Texture and Gangue Mineralogy*

Several types of clays are known to cause problems with flotation and/or leaching as listed in Table 4. If test work indicates clays are likely to cause processing problems, then drill core can be routinely analyzed to determine the amount and type of clays present. This can be relatively easily and cheaply done using spectroscopy (e.g. SWIR) or semi-quantitative XRD (see Chemical and Mineralogical Composition section).

Disseminated versus massive textures of pyrite can be important in determining the acid rock drainage (ARD) potential of ore. Disseminated sulphides (i.e. low-sulphide-grade rocks) will likely have less exposed surfaces available for oxidation after size reduction steps (e.g. blasting or crushing), and thus less ability to produce acid (e.g. Parbhakar-Fox and Lottermoser 2017). The morphology of sulphides can also be important in production of ARD. For example, Weber et al. (2004) showed that euhedral pyrite is generally less reactive than framboidal forms. Galvanic effects can also affect the oxidation rate of pyrite if it is in contact with other sulphides, so it is also important to record this information (e.g. Parbhakar-Fox and Lottermoser 2017). In addition, the amount of acid formed, reaction rate, and resistance to oxidation vary between sulphide minerals and the reactivity is influenced by the Fe content of the sulphide mineral (e.g. Plumlee 1999; Lottermoser 2010). Generally, sulphides containing less Fe are less reactive.

The amount and composition of gangue minerals can also be important to ARD formation, as acid that is produced through oxidation of sulphides can be neutralized by reaction with gangue minerals (e.g. Parker 1999). The most effective neutralizing minerals are those containing calcium, magnesium, and manganese carbonate ($(Ca,Mg,Mn)CO_3$) (e.g. Parbhakar-Fox and Lottermoser 2017). Calcite is the most effective of these and, like the sulphides, reactivity of carbonates is affected by grain size and texture. Dissolution of some silicate minerals (e.g. olivine, serpentinite) and clays can aid in acid neutralizing; however, the rate of dissolution of silicates is typically much lower than that of carbonates, although this can be balanced by their greater abundance (e.g. Jambor et al. 2002). Chemical analysis can be used to help determine mineralogy (see below). Sulphur abundance correlates strongly with pyrite, and carbonate can be estimated if inorganic carbon (C) or loss on ignition is measured and these can be used to estimate the acid rock drainage potential (e.g. Berry et al. 2015).

### *Deleterious Elements*

The presence of excess fluorine (>1000 ppm) in a metal concentrate can make it un-saleable (e.g. Fountain 2013). If fluorite, or other potentially fluorine-bearing minerals (e.g. biotite occurs commonly in porphyry copper deposits and can contain > 1 wt.% F) are identified in drill core, samples can be further analyzed to determine if processing problems are likely to occur. If fluorine is identified as a possible problem, then F analysis can be included in routine analysis of drill core.

Other commonly problematic elements are As, Hg, Sb, and Bi (Fountain 2013). The zinc sulphide sphalerite (ZnS) can contain significant amounts of Fe, which in addition to reducing the Zn content of the concentrate, is also detrimental to the rate of sphalerite flotation and hence its recovery (Boulton et al. 2005). The presence of other additional metals in a concentrate (e.g. Pb, Zn in Cu concentrate; Cd in Zn concentrate) can add or detract from the value (e.g. Goldie and Tredger 1991).

Like clays and F-bearing minerals, the presence of carbonaceous material can also detrimentally affect mineral processing, particularly leaching and flotation (e.g. Goodall et al. 2005). Again, C is not typically part of a routine geochemical analysis but if carbonaceous material is identified in drill core then, C analysis (or at least LOI) can be routinely included in chemical analyses.

### *Grain Size Distribution*

Different minerals in an ore will grind to a different grain size distribution during comminution. Sulphide minerals (e.g. chalcopyrite, sphalerite, galena, nickel sulphides) often are finer grained after breakage than their host rock. This aspect of preferential grinding (Runge et al. 2013) can sometimes be exploited to increase the grade of mill feed streams by screening out low-grade (i.e. non-vein) particles. This tendency is being explored by the CRC ORE group in their 'grade engineering®' work (e.g. Carrasco et al. 2017), where they are designing innovative coarse separation technologies and modified circuits (CRC ORE: https://www.crcore.org.au/). In an example from a gold operation, belt cut material was screened into three sizes (+50 mm, 50–19 mm, -19 mm) and the grade engineering approach demonstrated: 1) 64% of the feed mass contains Au grades well below economic cut-off, and 2) 88% of the Au is contained in 36% of the mass in 'particles' below 19 mm. This provided the operation owners with information to make processing decisions about whether or not it is economic to process the +19 mm material through a comminution plant or should it go, as is, to leaching. The approach can also be used to recover higher grade material from feed streams destined for dump leach and re-direct them to mill feed.

## GEOMETALLURGICAL MODELLING

Geometallurgical modelling is carried out to provide information about deposit variability in terms of processing performance throughout the mining value chain. Unless the deposit is homogeneous, this typically involves the identification of geometallurgical domains with models developed for each domain. Quantitative, spatially constrained data collected from drill core logging and analysis can potentially be used as inputs to geometallurgical models. This typically includes conventional data, such as assay results, but can also include modal mineralogy and data from small-scale geometallurgical tests (e.g. Table 3) that provide proxies for geometallurgical parameters.

Strong proxies allow models to be built that are fundamentally sound and can, in some cases, work as a global model. For example, the relationship between RBT lite (Kojovic and Walters 2012b) and crushing hardness is robust and will work across a large range of rock types. However, many of the parameters available for modelling processing response are weak proxies that do not represent a direct measurement of the target parameter, but correlate with it inside a discrete domain. In these cases, the model will improve if the variability of the model domain is relatively small. Thus it is common to domain the orebody based on some parameter(s) and model each domain separately. The domains can be spatial, geochemical, and/or mineralogical. Batu Hijau (Burger et al. 2006) is an example where using average values for a number of domains solved the modelling problem. Other examples of geometallurgy models based on domains are described in Montoya et al. (2011), Keeney et al. (2011), Harbort et al. (2013), Hunt et al. (2013), and Hunt and Berry (2015).

Most geometallurgy modelling problems have the possibility to include a large number of weak proxies and it is important to simplify models as much as possible. Many model building programs fail if too many weak proxies are included in the calculation as they model the individual samples rather than trends in the data.

When considering how good a model is, it is important to remember that the samples are not typically independent.

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Many parameters are highly correlated and the training set does not come from a compositional space that covers all of the n-dimensional space, which the measured parameters can span. It is usual to select only one of each class of highly correlated parameters (Stone and Brooks 1990). Ordinary least-squares methods of modelling are numerically unstable and will play off highly correlated parameters to minimize the error in a way that models the training set, but ignores real trends in the data. Singular value decomposition is more stable (Press et al. 1986). Some papers have found partial least-squares methods suitable for this problem (e.g. Wells and Chia 2011), although these can make understanding the underlying driver of the solution difficult.

Standard statistical tests of goodness of fit may fail and it is good practice to keep a separate test data set. Measurement of error using cross validation can be used to identify unstable relationships (Witten and Frank 2005). The acceptable level of accuracy of the model will depend on the purpose of the model, the parameter(s) being modelled, and the sensitivity of the production chain. For example, a model that is able to estimate BWI values to ± 20% may be acceptable depending on the sensitivity of the comminution circuit, whereas a model that can predict fluorine content to ± 10% is not likely to be acceptable. It is also necessary to keep in mind the accuracy of the parameter that is being modelled. For example, reproducibility tests for the Bond test (BMWi) showed variances of up to 13% and a series of round-robin testing between commercial laboratories showed up to 9% variation (e.g. Kaya et al. 2002; Harbort et al. 2013). A model that reduces the difference between actual and predicted mill performance by 50% will be relatively easy to produce and will be sufficient in many cases. More accurate predictions will come at a rapidly escalating cost.

Parameters and estimates determined in geometallurgical modelling generally transition to geostatistical modelling at the point where transfer functions can be introduced that convert raw mine data into processing parameters (e.g. determining throughput from A*b and BWi values using software such as JKSimMet). However, care must always be taken to make sure that the relationships from small-scale samples match bulk sample testing. Blending in the mining process means that small samples test a wider range of compositions than will ever be seen in a mill. Indicated recovery problems in small-scale samples may result from these extreme compositions. For example, the results reported by Hunt et al. (2011) reflect the very high mica content of some small-scale samples and are not suitable for prediction of mill performance. The results do, however, indicate the importance of a blend model for the mill that includes more than just grade.

## CONCLUSIONS

Geometallurgy is an applied cross-disciplinary area. The most important contribution that geologists make to this field is in defining the spatial variability of the deposit in parameters relevant to mine performance. Propagating geometallurgical attributes into a resource model requires a large supporting data set depending on the variability and variography of the processing performance indicator of interest: throughput, recovery, acid drainage, etc. A key aim of this paper is to review the options available to generate a representative geometallurgical database at a mine. Once the data has been produced there are two further stages required: multivariate modelling to integrate and visualize the geometallurgical data, and integration of the models into the mine plan which starts with geostatistics.

It is very important to continually cross-check modelling and to continue sampling throughout the mine life. The weak proxies typically used in geometallurgical models can only be used for interpolation. As mining extends and new parts of the mine open up there is always the potential for ores to be included in the ore reserves that lie outside the original training set. You can only relax when the mine is closed!

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# PROFFESSIONAL AFFAIRS

## Geo-Ethics: What to do When Approval Authority Decisions Contradict Sound Science?

**Mark W. Priddle**

*Vice-President and Senior Geoscientist*
*McIntosh Perry Consulting Engineers Ltd.*
*RR3, 115 Walgreen Road, Carp, Ontario, K0A 1L0, Canada*
*E-mail: m.priddle@mcintoshperry.com*

### SUMMARY

Three case studies in Canada are evaluated where a regulatory authority ruled that measures considered by some professionals to be without scientific basis and less protective of human health or the environment were the required courses of action. The three projects were in the field of environmental geoscience. In all three cases, the solution proposed by a Professional Geoscientist (P.Geo.) was opposed by a representative of a regulatory body that held authority for approval. The final outcomes that were approved by the Regulator were less protective of human health (increased exposure to potential contaminants) and/or the environment (more resources used, higher contaminant exposure). In two of the three cases, the solutions were also more expensive to the client and the taxpayer.

This paper explores the practice of professionalism in geoscience versus regulatory authorities that hold jurisdiction over geoscience in a broad sense. In each of the three cases, the professional opinions and analysis of the P.Geo. working for a private sector client were overridden by a professional (P.Geo. or Professional Engineer) in an approval authority. These three studies highlight the ethical decisions required by professional geoscientists in the face of regulators who hold control over areas of geoscience. Although the training of professionals is similar, regulators appear to be influenced by perceived risk as opposed to actual risk based on scientific evidence. Similarly, some policies do not have a solid scientific basis. As a result, sound scientific reasoning and resulting rational decisions may be hindered in regulatory decision-making.

### RÉSUMÉ

Trois études de cas canadiens sont évaluées, où une autorité règlementaire a statué comme requises des mesures qui avaient été déclarées par des professionnels comme étant sans fondements scientifiques et moins protectrices pour la santé humaine ou les milieux de vie. Il s'agit de trois projets du domaine des géosciences des milieux de vie. Dans les trois cas, la solution proposée par un géologue professionnel (P.Geo.) a été contestée par un représentant d'un organisme règlementaire décisionnel. Les résultats définitifs approuvés par l'organisme règlementaire protégeait moins la santé humaine (augmentation de l'exposition aux contaminants potentiels) et/ou le milieu de vie (plus de ressources utilisées; augmentation de l'exposition aux contaminants). Dans deux des trois cas, les solutions étaient également plus coûteuses pour le client et le contribuable.

Le présent article explore la pratique professionnelle en géosciences par rapport à celle des autorités règlementaires qui ont juridiction dans le domaine des géosciences en général. Dans chacun de ces trois cas, les avis professionnels et l'analyse de P.Geo. travaillant pour un client du secteur privé ont été supplantés par celui d'un professionnel (P.Geo. ou ingénieur professionnel) œuvrant a sein d'une autorité règlementaire. Ces trois études mettent en lumière des décisions éthiques attendues de géoscientifiques professionnels face à des autorités règlementaires décisionnelles en certains domaines géoscientifiques. La formation de ces professionnels est similaire, mais il semble que les régulateurs soient influencés par le risque perçu plutôt que par le risque réel établi scientifiquement. De même, certaines politiques n'ont pas une base scientifique solide. Il s'en suit qu'un raisonnement scientifique solide et des décisions rationnelles qui en résultent peuvent être contrecarrés par une décision règlementaire.

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## INTRODUCTION

Three case studies in Canada are evaluated where a representative of a regulatory authority ruled that measures considered to be without sound scientific judgment and not necessarily protective of human health or the environment were the required courses of action. These case studies were in the field of environmental geosciences and took place in three different jurisdictions in Canada, involving at least one Professional Geoscientist (P. Geo.) and other professionals. This paper is based on a presentation given at the 35th International Geological Congress in Cape Town, South Africa, in August 2016.

### Case 1: Groundwater Pumping and Treatment

In this case, the environmental regulator required that treated groundwater be discharged to a sanitary sewer as opposed to being returned to the aquifer.

A chlorinated volatile organic compound (cVOC) plume in shallow overburden was to be remediated with an interim pump-and-treat system. A pumping well was installed with a large granular activated carbon treatment train (Fig. 1) to treat the contaminated groundwater. The consultant's pilot tests showed very high cVOC removal using this system. In fact, the water was typically, but not always, within drinking water standards for these cVOC compounds. It is noted that the formation was an unconfined aquifer in an urban setting where a law prohibited the use of groundwater as a potable source.

The only pathway for human impact from cVOCs was from groundwater via soil vapours seeping into buildings. The treatment was always to a level that would have prevented such impacts to indoor air. Transmission of cVOC to indoor air would only occur if concentrations in groundwater exceeded drinking water standards.

The P.Geo. recommended discharge of the treated groundwater to an infiltration trench downstream (Fig. 2) in order to minimize interruption to the natural groundwater flow system, enhance movement of clean water off-site, and blanket the plume with cleaner water to limit soil vapour impacts. The recommendations were also considered to reduce sanitary sewer loading and costs and allow uninterrupted discharge of treated water.

The Regulator did not allow discharge of the treated groundwater to an infiltration trench downstream, citing concerns that the treatment might be ineffective, or that the trench might become plugged. Questions were also raised about the commitment of the client to a long-term system, and uncertainties about where the infiltrated water would go.

The following responses were provided to the Regulator by the P.Geo. and client:

1. The system proved effective based on a pilot test. Regular monitoring of flow rates, effluent water quality and overall performance would be undertaken. In fact, there would be no issue if the system did not work perfectly as this would still be better than the *status quo*.
2. Plugging was highly improbable because dissolved solids were extremely low in the extracted groundwater and the water was fully oxygenated already (so metals would not be precipitated causing plugging) and there were no suspended solids in the raw and treated water. Also, the subsurface consists of coarse sand, gravel and cobbles, so the trench could be excavated and unplugged, if necessary.
3. Financial resources for the clean-up had been accrued, with money set aside for ongoing groundwater remediation at this site.
4. Groundwater modelling conducted to show the impact of pumping and recharge demonstrated that the plume was in a buried channel aquifer composed of coarse-grained material and that the flow direction remained consistent.


**Figure 1.** Treatment train for removing cVOCs from groundwater at the site in Case Study #1.


**Figure 2.** Possible location for discharge of treated groundwater to the aquifer (note the coarse-grained material in foreground).

In order to advance the project, the P.Geo. and the client agreed to the Regulator's demand to discharge treated water to sanitary sewer. The Regulator was represented by a Professional Engineer (P.Eng.) and supporting staff. The P.Geo. did not appeal this decision as there was pressure to start pumping groundwater as soon as possible. The benefit of pumping and controlling off-site movement of contaminated groundwater was positive. The system (Fig. 1) pumped clean water to the sanitary sewer at about 200,000 litres per day for about three years (i.e. a total of approximately 200 million litres of clean water was discharged to the sewer). The Municipality was compensated for the discharge by the client.

## Case 2: Nitrate Dilution in Groundwater

In this case, regarding an assessment for a septic system, the Regulator (conservation authority) provided approval based on less land area available for dilution than was originally proposed.

In parts of Canada, privately-serviced lots that use water wells and septic systems must be large enough to allow precipitation to dilute septic effluent (i.e. nitrate) in the subsurface to acceptable levels. The assessment takes into account precipitation, evapotranspiration, runoff and infiltration, hard surfaces and, of course, the available land area (Ontario Ministry of the Environment and Climate Change 1996a, b). The lot in question was divided by a watercourse which was a groundwater divide. The Regulator (conservation authority) was represented by a P. Geo. and supporting staff.

The consulting P.Geo. recommended a proposed severance located on the east side of the watercourse (Fig. 3; yellow-shaded area). However, the Regulator approved the larger lot that included the west side of the watercourse (Fig. 3; red outline). The approved lot was larger in area, but the area that was available for dilution of any septic discharge was smaller (0.32 ha) compared to the original proposal (0.40 ha).

The P.Geo. representing the Regulator stated that the proposed area was too small, and would therefore only allow the larger lot. However, this decision did not consider that much of the larger lot was not available for dilution, being on the opposite side of the creek from the septic system. Scientific reasoning suggests that the larger approved lot was potentially worse for the environment, in that the area would provide less water for infiltration to dilute the septic effluent.

The consultant (P.Geo.) did not object because the overall area (including land outside the severance) was sufficient for nitrate dilution and planning regulations did not allow for additional lots (and therefore septic systems) in the area around the severance. The client did not object because they obtained their severance. The Regulator (P.Geo.) was comfortable because the 'lot area' met the policy. Had the planning regulations not been in effect, the consultant would have had to decide on whether to accept the severance with the larger overall area but with a lower ability to dilute septic effluent or not.

## Case 3: Re-use of Excess Material

In this case, excavation and disposal of excess material (marginally contaminated soil) that posed minimal health risks was ordered to be completely removed from a site, which posed greater environmental risks than leaving it in place.

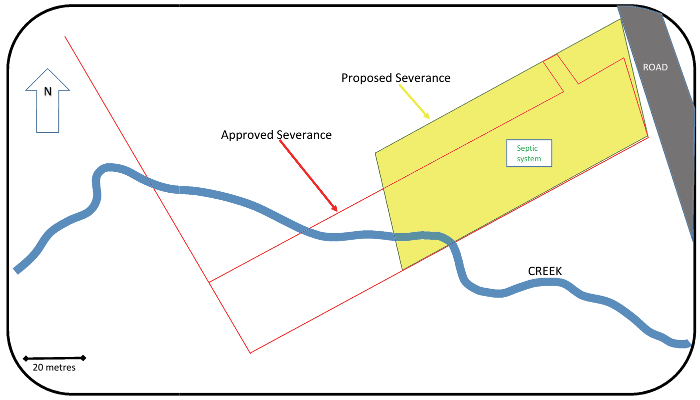


**Figure 3.** Outline of proposed severance (yellow shading) and approved severance (red outline) at the site in Case Study #2.


**Figure 4.** Example of test pit excavation to assess soil quality in the area of infrastructure renewal in Case Study #3.

Infrastructure projects typically generate excess soil when excavation for installation or renewal of buried services is required. In older urban environments, this material may be affected by various contaminants. Testing of material prior to construction is typically conducted (Fig. 4) to determine if it is 'contaminated' based on clean-up criteria and the numerical concentration values for potential contaminants in the soil. In some cases, the author has noted that there has been public pressure to remove all disturbed 'contaminated soil' despite there being no risk from leaving it onsite.

In environments where groundwater is not approved as a potable source there is typically limited risk in leaving marginally contaminated soil in the ground, but regulators sometimes require the removal of all contaminated soil (native or fill) from excavations associated with infrastructure renewal. The additional handling, testing, transport and disposal costs present a higher environmental risk compared to re-use of the soil in an area with no potential human or ecological risk, i.e. up to 5 metres below a paved street in a service trench (Fig. 5).

The consultant (P.Geo.) did not object to the requirement for removal and disposal of this marginally contaminated

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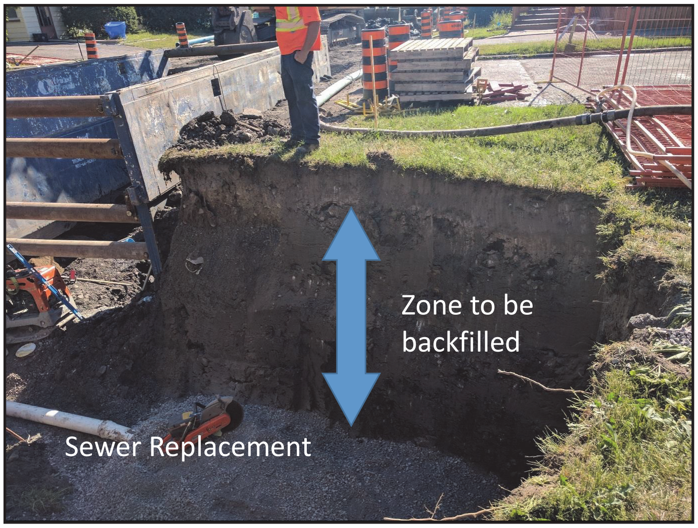


**Figure 5.** Typical profile in the area of infrastructure renewal showing zone of potential contaminated soils in excavation above services.

material, because human health and the environment was protected. However, there are additional fees and negative environmental impacts from transportation of soil and fill, and disposal of soil. These impacts include significant fossil fuel consumption during the transportation of materials from the site to the disposal facility and the extraction, processing and transportation of replacement soil from a source to the site. The professional for the Regulator was comfortable with the low risk of removal, and the client (land owner) concurred with soil removal as it appeared to be the most prudent method of dealing with material. The contractor concurred because it was simple and resulted in additional charges to the client.

It is noted that, subsequent to this case study, regulators (municipal and provincial governments) have been looking more closely at the possible re-use of excess materials in construction projects. This has been driven by more science-based discussions between regulators and practitioners and owners. Guidelines are being developed for a more rational evaluation of excess materials and possible re-use (*Excess Soil Management Policy Framework*, Government of Ontario, December 2016).

## COMMON THEMES

Several common themes are identified with these three case studies. In all cases, the Regulator and consultant (P.Geo.) did not agree on the approach. The consultant considered actual risk and practicalities, but the Regulator wished for no risk (either real or perceived), and a professional disagreement ensued.

### Geo-Ethical Implications

Geoscience is regulated in almost all jurisdictions in Canada. Regulation is on a provincial level and each professional association has its own legislation, processes, code of ethics and discipline procedure. Despite all this, professional geologists are independent and work within the bounds of professionalism and the laws of the jurisdiction in which they work. In many locations in Canada, there can be up to five levels of regulatory authority – Federal, Provincial, Municipal (two levels) and independent Boards or Authorities – all with authority over the opinions of consulting geoscientists.

The 'professional disagreements' noted in the above case studies indicate that regulators do not always evaluate risks in a similar manner to proponents or consultants who are professional geoscientists. Regulators are guided by policies in which guidelines are commonly taken as 'statutory', and not simply as guidelines; risk is sometimes only 'perceived risk', not 'real risk', but regulators are averse to either form. A Professional Geoscientist in a regulatory position may have other constraints on his or her decision-making beyond purely scientific judgments, and public perception may affect regulatory decisions.

### References to Code of Ethics

The following are excerpts from the Association of Professional Geoscientists of Ontario (APGO) Code of Ethics Regulation (Professional Geoscientists Act (Ontario) 2000). These pertain to the conduct of professional geoscientists and requirements for behaviour and interactions with others:

**Code of Ethics of Professional Geoscientists**
***Service and Human Welfare***

2. A professional geoscientist shall be guided in his or her professional conduct by the principle that professional ethics are founded upon *integrity, competence and devotion to service and to the advancement of human welfare* and by the conviction that his or her actions enhance the dignity and status of the profession.

***Duty to Others and the Environment***

5. (1) When acting in a professional capacity, a professional geoscientist shall at all times act with,
(b) *due regard to public needs*;
(2) A professional geoscientist shall,
(a) regard his or her duty to *public safety and welfare as paramount*;
(4) A professional geoscientist has a duty to *co-operate with other professionals with whom he or she is called upon to work*.
(5) A professional geoscientist shall *have proper regard for the natural environment* in his or her work.

The italicized items noted above are those which were considered in the three case studies discussed herein. The italics were introduced by the author for emphasis.

## RECOMMENDATIONS

A review of these three case studies provides an interesting insight into geo-ethical issues facing consultants and regulators. The following recommendations are made for situations where regulatory decisions contradict 'sound science.'

Do not over-ride a Regulator's decision (if they are a registered professional) *unless* there is an imminent danger to life, health of humans or the environment; however, in cases of imminent danger, the professional is *required* to object to such decisions. Professional geoscientists should ensure that their proposal is based on sound science and has been reviewed and documented. Regardless of differences in opinion, professionals should cooperate.

Furthermore, a record of *rational decision making* should be presented to the Regulator, and a post-project 'lessons-learned' evaluation specific to the difference in professional opinions should be undertaken. Finally, professional bodies should promote workshops or information-sharing sessions between professional geoscientists who are practitioners and those who are regulators.

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