BASIN SCALE COAL MAGMA MIXING WITHIN COALBED (CBM) METHANE RESERVOIRS, RATON BASIN, SE COLORADO, USA

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RESUMEN

La cuenca Raton de Colorado y Nuevo México alberga uno de los principales desarrollos de metano asociado a mantos de carbón (CBM) del mundo. Dentro del relleno de la cuenca, los reservorios de mantos de carbón del Cretácico tardío/Paleógeno temprano, están localmente intruídos por filones capa de poco espesor, (0,3 a 4,0 m), lateralmente continuos, del Oligoceno/Mioceno. Los paquetes individuales de sill-carbón son fácilmente rastreables en el subsuelo sobre áreas mayores a 100 km2. Los datos de afloramiento, coronas y petrografia demuestran que, durante el emplazamiento, los filones fluidizaron activamente a los carbones bituminosos de volumen medio, formando complejos caóticos que involucran a las rocas de caja frágiles y a los mantos de carbón fundido dúctiles, con muchas características que registran la inmiscibilidad líquido-líquido. Este proceso resulta en la formación de "thuiditas"; un término genético introducido aquí para describir los tipos de rocas resultantes de la fluidización térmica de rocas previamente consolidadas y litificadas. El rango del carbón, los macerales reactivos, el contraste geomecánico preferencial y la volatilización del carbón probablemente se combinaron para fluidificar de manera efectiva a la roca huésped durante el emplazamiento del magma, mientras que el desarrollo de una película de vapor y un caparazón de coque aseguraron una efectiva retención del calor, manteniendo la fluidez de la mezcla de carbón/magma. En este trabajo los autores delinearán los mecanismos de emplazamiento, documentando las complejas relaciones entre el carbón y el filón desde el afloramiento hasta el subsuelo, discutiendo cómo el sistema magmático y su emplazamiento regional han afectado el desarrollo del reservorio en muchas partes de la cuenca.

INTRODUCTION

The mechanics governing sill development and magma flow paths in sedimentary basins are inherently complex and an area of much recent research by both academia and the petroleum industry (Magee *et al.* 2016; Naviset *et al.* 2017; Witte *et al.* 2018; Spacapan *et al.* 2018; Rabbel *et al.* 2018; Galland *et al.* 2019; Magee *et al.* 2019; Schmiedel *et al.* 2021). Here we discuss and describe the key findings of a multidisciplinary study conducted by the authors during

2002-2004 which evaluated the distribution and emplacement mechanisms of high-level sill complexes intruded into coal seam reservoirs of the Raton Basin of SE Colorado (Figure 1).

The relationships of sill-coal mixtures and resultant rock types were studied throughout the basin from outcrop to the microscope; a program designed primarily to help predict subsurface sill distribution patterns aimed at assisting well siting and allowing for tailored cementing, drilling, and fracture completion practices. These proprietary studies ultimately proved crucial in understanding regional production trends.

The preferential intrusion of sills into a range of source rocks and reservoir types is well documented (Schutter 2003; Thomson 2007; Spacapan *et al.* 2018). This is particularly true of coals and coal seam reservoirs with numerous documented sill-coal occurrences in coal basins throughout the world, including Australia (Ward *et al.* 1989; Gurba and Weber 2001; Zhou *et al.* 2020), Antarctica (McClintock and White 2002; Sanders and Rimmer 2020), Botswana (Bulguroglu and Milkov 2020), Canada (Goodarzi and Cameron 1990), China (Yoa and Demang 2012; Chen *et al.* 2021), Indonesia (Guo *et al.* 2019), Poland (Kwiencinska *et al.* 1992), UK (Walker and Francis 1987; Murchison and Raymond 1989), India (Sarana and Kar 2011), South Africa (Gröcke *et al.* 2009) and the USA (Finklemann *et al.* 1998; Rimmer *et al.* 2009;

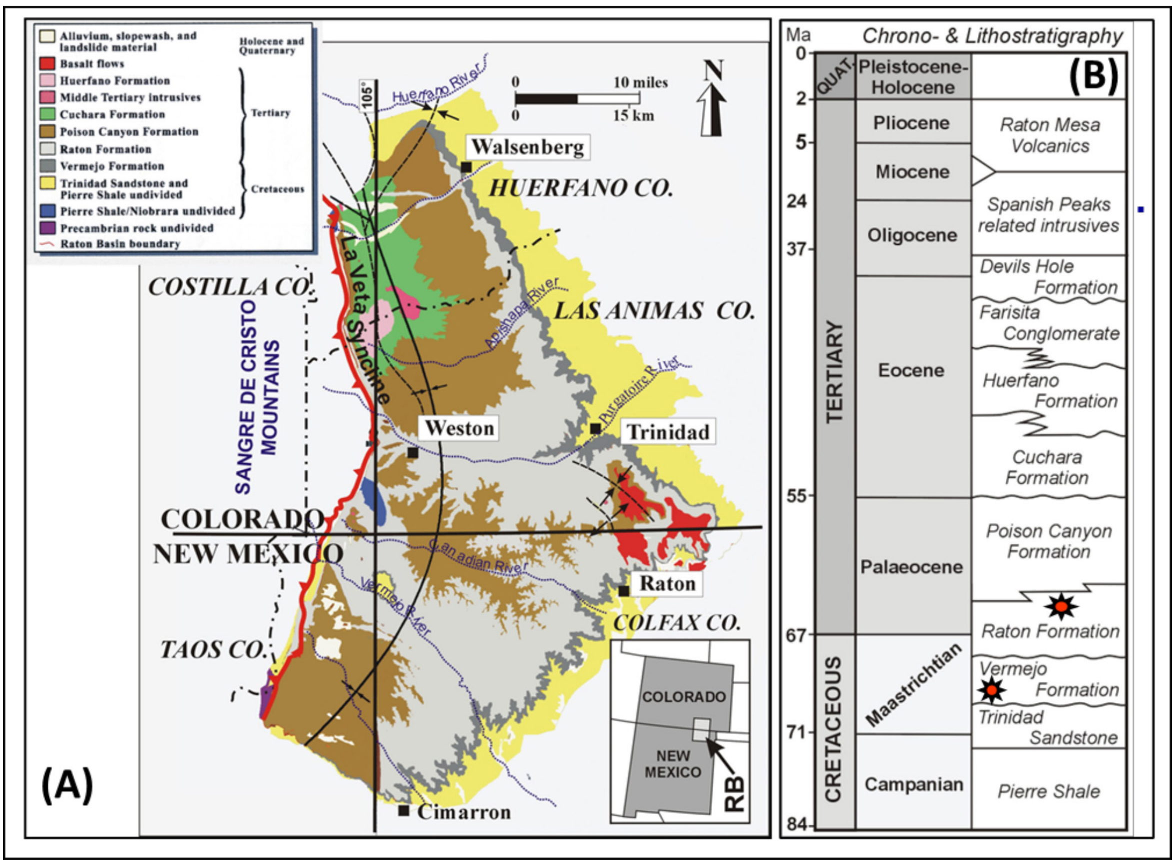

Figure 1. A) Location map of the Raton Basin with major geologic elements, redrawn after Flores and Badder 1999. B) Generalized stratigraphic column of the Late Cretaceous to Pliocene basin-fill. The Vermejo and Raton Formations are the principal coal bearing units (red stars).

Schimmelmann *et al.* 2009). Sills intruding coal seams and consequential release of CO_2 has even been invoked as a mechanism for the end Permian mass extinction (Ogden and Sleep 2011).

In most documented cases the interaction between the intruding magma and host coal show distinct similarities suggesting common operative processes, including textures typical of fluidization, brittle and ductile auto-brecciation, fragmentation, liquid-liquid immiscibility, and coking. It being clear that under a wide range of varying stress and PVT conditions the fluidization of consolidated "lithified" rock including coals (this study), carbonates (Jutras *et al.* 2006), shales (Rabbel *et al.* 2021) and sandstones (Jamtveit *et al.* 2004) is readily achieved by intruding magma; with the implications for basin-wide sill emplacement mechanisms being numerous (Spacapan *et al.* 2017; Galland *et al.* 2019).

REGIONAL GEOLOGY, SPANISH PEAK IGNEOUS COMPLEX, PRIOR COAL-SILL STUDIES

Covering an area over 6.000 km^2, the Raton Basin is one of five major late Cretaceous / early-Paleogene (+/- 71-55 million years) Coalbed Methane (CBM) basins in the Rocky Mountains. Exposed in a highly asymmetric synform (La Veta Syncline), the basin records the development of an overfilled coal-bearing retroarc foreland that evolved along the western margin of the Cretaceous interior seaway. Comprising over 5000 meters of various Devonian through Miocene sediments, the basin fill is crosscut by Oligocene to early Miocene intrusives of the Spanish Peak Igneous Complex (SPIC), which form part of the regional Rio Grande Rift extensional terrane that parallels the Sangre de Cristo Laramide thrust front (Cather 2004).

Preserving the K-Pg boundary layer (Orth *et al.* 1981), a complete Upper Cretaceous to early Paleogene coal-bearing stratigraphic interval is recorded by the Vermejo and Raton Formation's (Flores 1987; Pillmore and Flores 1987) (Figure 1b). Overlying extensive shallow shoreface sandstones of the Trinidad Sandstone Formation, Vermejo coals reflect deposition in a distal, laterally extensive fluvial dominated flood-basin, while Raton coals developed under complex alluvial plain conditions, dominated by high-sinuosity fluvial meander belts and episodic (non-coal forming) braidplains. Individual coals vary in thickness from 1-3 meters and are commonly continuous over distances of between 1-10 kilometers.

Rising over 4100 meters the regions topography is dominated by two stocks of the Spanish Peaks Igneous Complex (Figure 2 a & b). The Eastern Peak is primarily granite and granodiorite and the Western Peak a syenodiorite (Johnson 1961a; Woodward 1987). Over 500 individual dykes have been identified and mapped (Johnson 1968). Dykes radiate primarily from the Western Peak (Figure 2c) with a further set of regional cross-cutting dykes running mostly perpendicular to the basin axis (Figure 2c & 3a). Compositionally variable from basic through acidic and sourced from various crustal levels and melt types, radial dykes are syenite and monzonite porphyry, while sub-parallel dykes are generally deeper weathering sub-alkaline to alkaline lamprophyres (Figure 3a). In the absence of comprehensive chemical analysis, the sills described here are best regarded as fine-grained hypabyssal monzodiorites or diorites. We believe the sills where emplacement at depths < 3km based on observed regional coal rank (Figure 2.d) and the burial history modelling of the Raton Basin fill by Higley 2007. The entire igneous complex reflects multiple intrusive episodes dated variously by K-Ar (Stromer 1972) and high precision 40Ar/39Ar age techniques (Penn and Lindsey 2009) at between 21.3-26.6

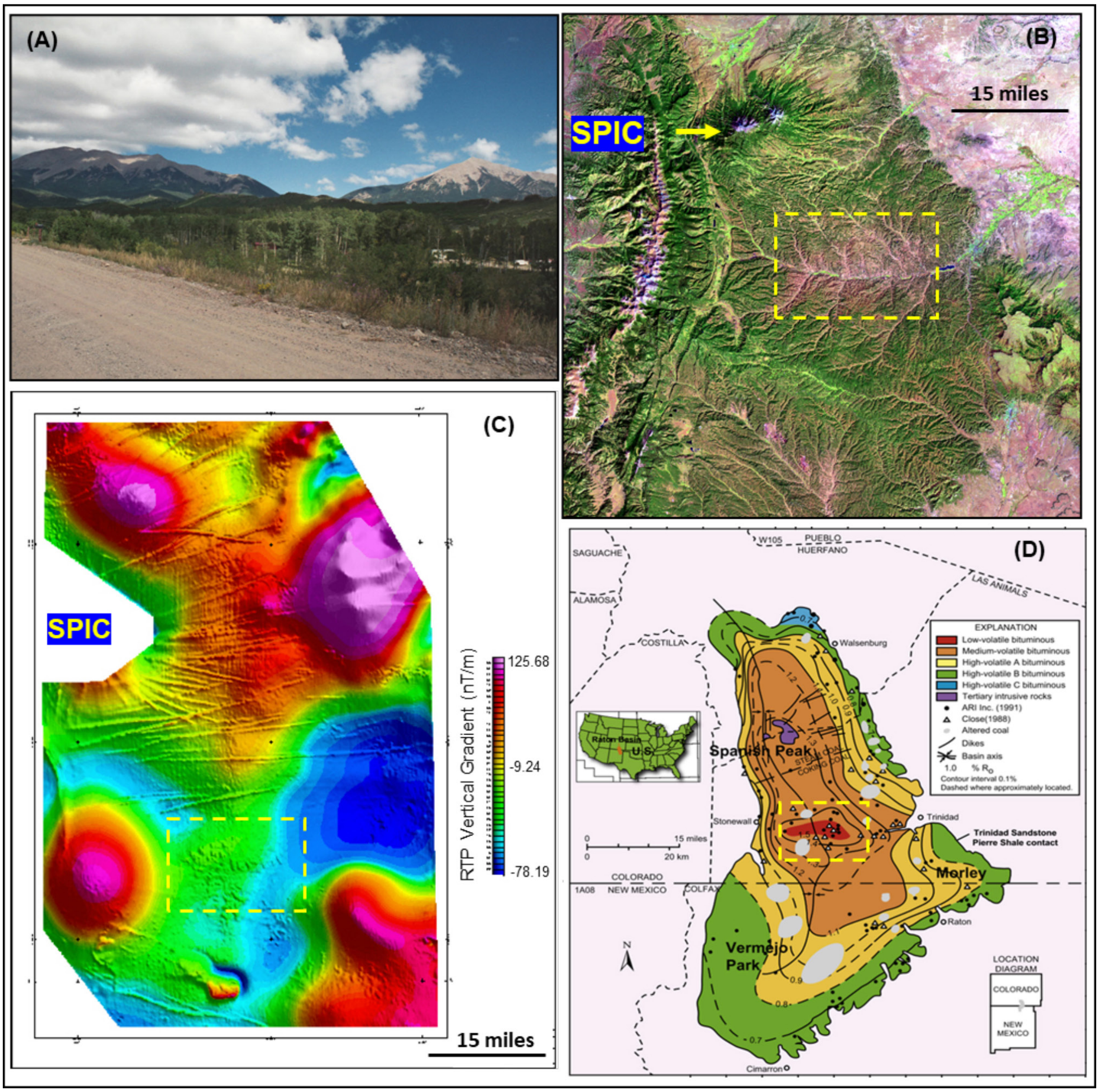

Figure 2. A) Panoramic view of the West and East stocks of the Spanish Peaks Igneous Complex (SPIC) B) False color satellite image showing the location of the SPIC with outlined study area. C) Regional high resolution aeromagnetic survey indicates that the two exposed peaks of the SPIC are just the surficial expression of a much larger deep-seated igneous complex. Note laccoliths, radial dyke swarms, and regional cross-cutting dykes. D) Coal rank map at the base of the Vermejo Formation, Raton Basin. Variation in vitrinite reflectance (percent Ro) is also shown (from Flores 2014).

Ma. Regional high resolution aeromagnetic data over the northern part of the basin flown in 2003 (Figure 2c), clearly demonstrates that the two exposed peaks are the surficial expression of a much larger regional igneous province characterized by numerous deep-seated stocks locally feeding higher level laccoliths and sill complexes. While coals are present throughout the basin, the principal CBM fields are south of the major dyked areas (Figure 2c).

Deep burial of the sedimentary pile resulted in high coal rank varying from low-volatile bituminous in the central parts of basin to high-volatile C bituminous along the basin margin (Fig 2d), with documented reflectance values ranging from 0.6-1.5 Ro and regional isovol patterns following for the most part original basin geometry (Tyler *et al.* 1995). The Raton coals are generally high-quality coking-coals; a coal type that when heated in the absence of air, will melt, vesiculate and harden into a spongelike mass of almost pure carbon (Crelling 2008). It has been suggested that local elevation of coal rank is observed along the central Purgatoire River Valley, attributed to hydrothermal fluid circulation associated with higher heat flow from the Spanish Peaks Igneous Complex (Dolly and Meissner 1977; Oldaker *et al.* 1993; Cooper *et al.* 2007).

Until the early 90's, intrusive within coalbeds of the basin had been of historic mining interest, primarily related to the distribution of mineable coals and the associated local degradation of coal quality to that of natural "coke" (Johnson 1961b; Dutcher *et al.* 1966; Crelling & Dutcher 1968). Podwysocki and Dutcher (1971) recognized the extreme influence imposed by intrusive rocks upon Raton Basin coals, documenting the formation of thin 'coal-dykes' which they attributed to the mobilization of coal and pyro-bitumen as a result of coal temperature reaching an estimated 375-550 C. More recently sills have been described from roadside outcrop with images of magma fingers (Fig. 3b) and fluidized contacts (Scofield *et al.* 2012; Magee *et al.* 2019) while coal metamorphism is discussed at length by Cooper *et al.* (2007).

In the late 90's, an understanding of the regions igneous history became increasingly important for Exploration & Production companies who were starting to develop the large CBM resource both in Colorado (Hemborg 1998; Close and Dutcher 2002; Carlton 2006; Osterhout *et al.* 2014) and New Mexico (Hoffman and Brister 2003, Hoffman and Jopnes 2005). Critical to almost all CBM developments is an appreciation of basin hydrology (Ayres *et al.* 1994; Kaiser *et al.* 1994; Pashin 1998) which largely controls reservoir pressure and coal seam gas content. In the case of the Raton Basin this is complicated by the highly fractured dyke complexes cross-cutting the coal reservoirs (Figure 3a), potentially acting as regional water corridors with infinite acting conductivity. We believe this is the single largest control on basin wide gas and water production.

RATON CBM RESOURCE, RESERVOIR CHARACTERISTICS AND WELL COMPLETIONS

The recoverable CBM resource within the basin is variously estimated at between 3-4 TCF, the likely in-situ resource being > 10TCF (Stevens *et al.* 1992). To date throughout the basin over 4000 vertical producing wells (Figure 3d) have been drilled to depths of between 200 m to 1150 m; below which coal permeability is generally too low to sustain economic production rates. Wells are typically drilled on +/- 40 acre spacing, allowing for the exceptional resolution of basin fill stratigraphy, coal depositional trends, fluvial architecture, and importantly sill distribution patterns. Individual coal seams and coal seam packages are generally traceable from well to well over a distance of 1 km. The Vermejo Formation has approximately 10 meters of net coal in thick continuous seams and the Raton Formation upwards of 15 meters of coal that show significant thickness variation and seam splits (Figure 3e).

Since 1997 basin-wide cumulative production is more than 2 TCF with an associated +/- 2 billion bbls of produced wastewater. At its peak in 2010, it is estimated that the entire basin was producing more than 140 BCF per year accompanied by +/- 100 million bbls of water. Average well EUR's are of the order of 0.5-0.8 BCF, with the best wells making +3.0 BCF associated with thick clean coals (Figure 3b). Typical wells make +/- 200 mscf/d with high-rate wells (> 350 mscf/d) generally clustering along small tip-line flexures which locally enhance permeability.

High levels of bright vitrinite (primarily telinite and collinite) and subordinate amounts of liptinite and inertinite generally characterize coal maceral types. High vitrinite content has promoted good to excellent blocky mm scale face and butt cleat development (Figure 3b) with initial coal permeabilities estimated to be in the range 3-30 mD; although it is highly likely that permeability increases during the life of wells reflecting matrix shrinkage. Ash contents are generally between 8-17% and sulphur value are < 1% reflecting the non-marine nature of the coal groups. Volatile matter ranges from 35-42%, fixed carbon from 45-55%, with heating values of between 12,750-15,000 BTU/lb. Gas is primarily thermogenic with $\delta^{13}C$ values averaging 44.0%. Produced gas is extremely dry with C1/C1-5 values of between 0.96/1.0 (nearly 100% pure methane).

The entire basin is under-pressured with a typical hydrostatic pore pressure of 0.38 psi/ft (8.6 kPa/m); nowhere has over-pressuring been observed and there is no evidence for a basin centered gas accumulation as inferred by Johnson and Finn (2001). All coals are 100% water saturated with no free gas; unlike conventional reservoirs gas is stored in the adsorbed state. Gas contents generally increase with depth varying from 100-450 scf/ton, with an average of 200-350 scf/ton. Throughout the basin gas content within individual coal seams is largely a function of reservoir/hydrostatic pressure, ash content, and adsorption capacity related to marcel type and its microporosity. The authors have found no evidence for increasing gas with proximity to igneous sills (Figure 3c); on the contrary coals intruded or directly adjacent to sills (+/-1 m) tend to be entirely coked and have little or no methane storage capacity. On one occasion a high-rate gas flow was encountered when drilling a likely fault-bonded sill, although in all other cases they act as local fractured aquifers and are avoided during completion. Most coals show very high rates of gas desorption, a testament to the high quality of the Raton coal reservoirs.

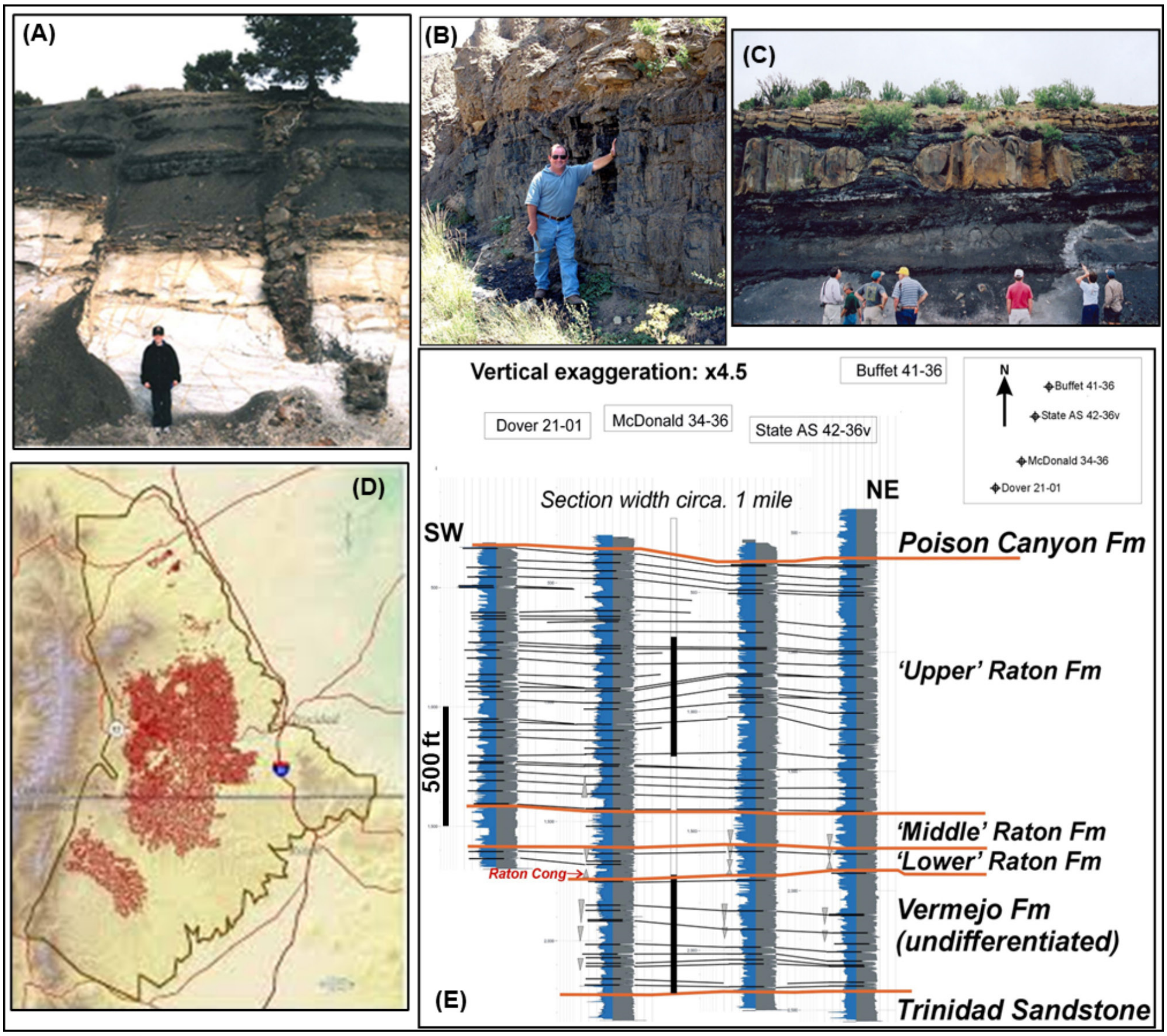

Figure 3. A) Faulted, thin lower Vermejo coals and over bank muds sitting on channel sandstones, and intruded by a highly fractured lamprophyre dyke, Trinidad. Such complexity typifies Raton CBM reservoirs. B) Thick (2m) well cleated clean lower Vermejo coals make for high quality CBM reservoirs, Berwind Canyon. C) Pillowed tubes (fingers) with connecting bridges intruded into Middle Raton Coals, Purgatoire River Valley D) Distribution pattern of over 4000 wells across the Raton Basin (from Osterhout *et al.* 2014) E) Typical coal correlation panel for individual coals from the Vermejo and Raton Formations. In general, most coals can be traced for distances of over 1 km. Individual coals >0.75m are selectively perforated and hydraulically fractured.

To counteract regional under pressure and the potential for formation damage by fluid invasion during drilling, over 95% of wells in the basin have been drilled with air or air-mist fluid systems. Low reservoir pressure and the inherently cleated nature (Figure 3b) of Raton coals lend themselves to high levels of damage from slurry dehydration resulting in tailored cementing systems with zero free-fluid, low density, high viscosity, thixotropic blends with selective fluid loss packages. In addition to coals, such blends have proved invaluable in cementing through sills and sill complexes, where cooling joints and fractures when combined with regional under pressure, can commonly lead to massive cement losses.

Individual coal seams greater than 0.75 meters thick are selectively perforated (4 spf) and hydraulic fracture completed with 70Q N2 foam, either via multi-stage bridge-plug/casing (3-5 stages catching 3-4 seams per stage) or selective placement via Coil Tubing (10-25 stages individually fracturing each coal); the use of nitrogen foam allowing for excellent proppant transport and placement while assisting in post treatment clean-up. Tracer's and the extensive use of BHP gauge data allows for evaluation of treatment effectiveness. In most all cases hydraulic fractures stay within individual coal seams, it being extremely rare to observe any significant fracture height growth between seams or across inter-seam lithologies. Based on diagnostic fracture injection tests (DFIT) and evaluation of several thousand post-frac instantaneous shut-in pressures (ISIP) coal fracture gradients are typically low, in the range 0.45-0.6 psi/ft. In almost all cases, commercial hydraulic fractures models significantly overestimate fracture height growth, and are generally not used. At no point are coal-sill packages hydraulically fractured as the inherent fracture network within the sills create extremely high-water flow rates, while associated coals carry little or no gas. Rod pump or PCP pumps are used throughout the basin to dewater completed coal seams. Water is disposed of in both surface ponds and deep disposal wells depending largely on produced water salinity from individual wells and well clusters.

Given the industrial scale development of the in-situ resource, the interaction between CBM development, hydraulic fracturing, basin hydrology, and micro-seismic activity associated with deep water disposal has been studied extensively by US government and state agencies (Geldon 1989; Topper *et al.* 2011; Wolfe *et al.* 2015; Nakai *et al.* 2017).

RATON BASIN SILL-COAL MIXTURES AND "THUIDITES"

Throughout the Raton Basin sills preferentially, although not exclusively, intruded both Vermejo and Raton Formation coals at numerous stratigraphic levels, largely reflecting lower Young's modulus and shear strength, lower fracture propagation pressures, and the relative ductility of naturally fractured cleated coal. Single sill bodies are readily traced from outcrop into the subsurface, commonly confined within the same coal bed over tens of square kilometers (Figure 7).

South of the main Spanish Peak igneous center, sill-coal packages are exposed at numerous localities along the Purgatoire River Valley allowing for three-dimensional observation of coal-intrusion mixtures and parental sill geometries. This information, when coupled with >1500 logged wells provides high-resolution (3D) coverage. Outcrop observations have been complimented by the intersection of numerous coherent sill-coal complexes in cores which has allowed for the close inspection of coal magma contacts, juvenile clast distribution, and fragmentation styles (Figure 5 & 6). Un-weathered cored surfaces have greatly aided petrographic interpretation. At all levels of observation, from outcrop, to core, to thin-section, coal-sill mixtures show a range of textures which clearly demonstrate fluid-fluid interaction and that previously lithified coals have undergone thermal fluidization during magma emplacement.

The resultant Raton rock types outwardly bear similarity to "peperite" (White *et al.* 2000; Skilling *et al.* 2002), a genetic term applied to a rock formed essentially by in-situ disintegration of magma intruding and mingling with unconsolidated or poorly consolidated sediment, often wet sediment. Covering a broad spectrum of magma compositions and types, peperite formation and associated complex magma – sediment mixtures has been the subject of much study and debate (Kokelaar, 1982; Busby-Spera and White, 1987; Brooks, 1995). Such deposits are recognized throughout rock record often forming the basis for paleoenvironmental reconstruction, recording the contemporaneous interaction and disintegration of extrusive and/or intrusive high-level magma via a range of disruption processes ranging from phreatic, pyroclastic, through autobrecciation and quench fragmentation (Kokelaar 1986; Hanson and Hargrove, 1999; Doyle 2000; Mueller *et al.* 2000; Németh *et al.* 2007; Jordan *et al.* 2008; Chen *et al.* 2013; McLean *et al.* 2016; Gihm and Kwan 2017). The majority of peperites are generally restricted to finer grained sediments where evidence for the contemporary nature of magmatism and sedimentation is often unequivocal based upon discordant host-sediment - magma morphology, dispersal patterns of juvenile clasts, autobrecciation textures, vesiculation patterns, and fluidal margins. In order to recognize the importance of "lithified" rocks in this process we are introducing the new term 'Thuidite'.

Thuidite – A New Term

Here we introduce the term "Thuidite" to describe the various coal-magma rock types observed in the Raton Basin. In a similar genetic sense to that of White et. al. (2001) when describing peperite, "Thuidite" describes consolidated "lithified" rocks that undergo thermal fluidization resulting in complex often chaotic host rock-magma mixing, commonly demonstrating liquid-liquid immiscibility and host melting. Outwardly resembling many of the features and textures typical of peperites (i.e., jigsaw fit auto-brecciation, mingling of sediment and juvenile clasts, flame structures, fluidized contacts) the Raton Thuidites reflect the in-situ disintegration of intruding magma following viscous liquefaction of coals approximately 30 million years after lithification. We believe the term Thuidite readily distinguishes between syn- and post-lithification thermal fluidization and may be appropriate to a wide range documented brittle and fluidal chaotic host-magma melt mixtures (e.g., lignite-tuffisites of Walker and Francis 1987; coal peperite of McClintock and White 2002; salt peperite of Schofield *et al.*

2014; carbonate peperite of Jutras *et al.* 2006; shale-dolerite breccia of Hoyer and Watkeys 2016; brecciated shale bitumen dykes of Rabbel *et al.* 2021; hydrothermal sandstone pipes of Jamtviet *et al.* 2004).

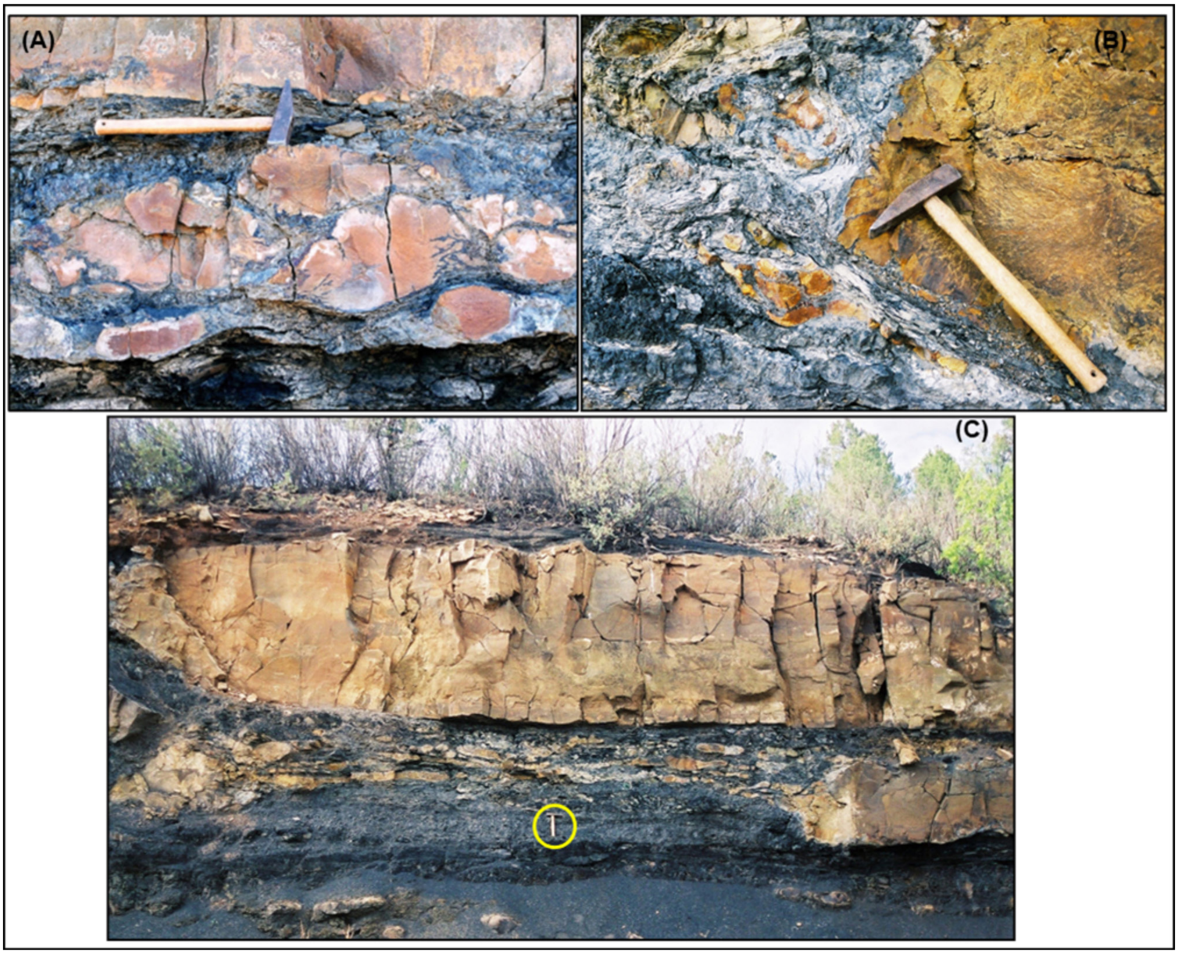

Figure 4. Exposures of pillowed bulbous sills, close-packed thuidites, dispersed thuidites and fluidized coal, middle Raton Formation, near the town of Weston. Photographs showing a wide range of typical coal-magma textures commonly observed in core. A) Closely packed thuidite domain. B) Fluidal and autobrecciated thuidite within flamed coal matrix. C) Weakly columnar tongue shaped bulbous tube underlain by weakly pillowed fragment breccias linked by dispersed globular thuidite juvenile clast trails. Hammer circled in yellow for scale.

OBSERVATIONS

Outcrop

Coherent sills intruding coals of the middle Raton Formation outcrop extensively along the Purgatory River Valley (Figure 4). Litho-bound and often confined within the same coal seam, it is not unusual for individual coal-sill complex's to be traced at outcrop along strike for several kms and through the subsurface over 30 kms (Figure 7) reflecting the high fluidity of the host magma. Intrusion style is characterized by the sequential emplacement of "tongue-shape" lobes and master tubes (i.e., tube width greater than 50m) with peripheral bulbous and frequently pillowed fingers, commonly linked by coherent and fragmented necks and thuidite juvenile clast trails (Figure 4c). Larger pillowed sills (>1m thickness) frequently show a weakly vesiculated hypocrystalline chilled margin, which may pass into a more deeply weathered crude columnar jointed and partially vesiculated holocrystalline core. The development of a discrete glassy hyalocrystalline carapace is generally absent or not discernable. Ragged and fragmented margins of individual bulbous tubes may show evidence for mechanical un-rimming along tensional and contractional cracks which are commonly filled in a flame like fashion with coked coal and may or may not grade into thuidite domains. Observed thuidites vary from closed packed to dispersed (Figure 4 a & b), characterized typically by lapilli to block size highly irregular mixed morphology clasts that show variation from brittle auto-brecciated pillowed fragments to fluidal 'non-graded' stretched planar orientated clasts which show limited evidence for hyaloclastization.

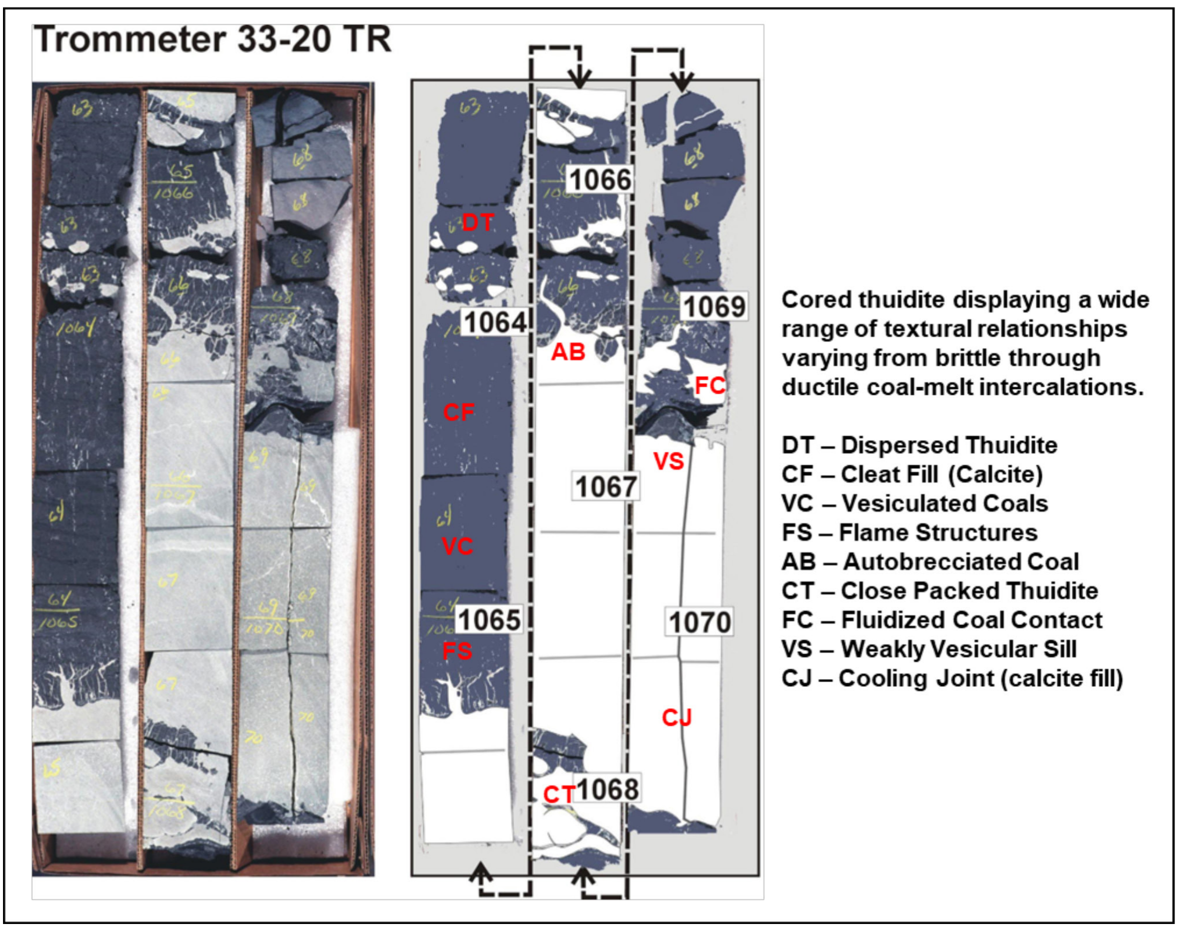

Figure 5. Core photograph of fractured sill and fluidized coal thuidites with annotated montage from the Trommeter 33-20TR well, 1062-1070 ft TVD. The core clearly shows a range of ductile and brittle coal-magma mixing textures commonly seen at outcrop.

Natural coking and surface weathering obscures small-scale coal-sill features, although coal vesiculation is locally evident and occasional weak fluidal coal flow textures close to juvenile clast contacts are highlighted by slight color variation afforded by non-reactive macerals (Figure 4b). At outcrop, coking of coal is generally confined to within 1 meter of intrusive contacts largely irrespective of sill size, with adjacent shales and sandstones showing little or no visual sign of alteration suggesting limited hydrothermal fluid circulation. Adjacent cleated coals commonly show calcite filling and calcite filled fractures reflecting the effects of coal shrinkage and resultant increased porosity during devolatilization and coking.

Core & Subsurface

Core from two CBM development wells (Trommeter 33-20TR & Reilly Canyon 21-29TR) intersected fine-grained sills and thuidite domains within coals of the middle Raton Formation (Figures 5 & 6). Both cores show a broad range of fluidal and autobrecciation structures and textures with a wide variation in clast dispersal patterns.

The Trommeter 33-20TR core (Figure 5) shows a 2.2 meter sill-coal thuidite mixture, which reflects the intersection of two thin bulbous fingers probably originating from the same tube. Contacts clearly show evidence for both brittle and fluidal mixing, with development of dispersed and closed packed thuidite. Autobrecciated, vesiculated, and flamed irregular tapered and ragged fluidal margins are common, while entrained coal xenoclasts show classic "jig-saw" fit textures. Delicate thin necks and tendrils commonly connect juvenile clasts forming mosaic patterns, while highly mingled contacts show viscous coal flow textures in close proximity (< 10 cm) to planar undisturbed bedding, demonstrating the localized nature of fluidization and mixing.

The Reilly Canyon 21-29TR core (Figure 6) shows a classic 1.3 meter dispersed thuidite, with no evidence for the intersection of the main intruding parental body. Juvenile clasts essentially float in a completely coked coal matrix, although the adjacent shale shows little visible evidence for extensive alteration. Juvenile clasts show mixed morphologies with both fluidal and sub-planar margins invariably orientated parallel to bedding. Both coal and diorite clasts show varying degree of quenching and autobrecciation, with wispy fluidal mixing and flame structures evident throughout. Coal vesiculation is locally intense near clast margins. Most cleats and fractures are filled with calcite.

Corresponding TOC and VR analysis across the Reilly Canyon core (Figure 6) clearly shows the coals are coked (60-80% TOC) with resulting high VR values (>2+). Outside of coked zones VR values return to background norms generally within a meter of individual sills with little on evidence for heat transfer beyond a thin thermal aureole. Such findings are typical of Raton coals (Crelling and Dutcher 1968; Cooper *et al.* 2007) and coal-sill mixtures elsewhere in the world (e.g., Goodarzi and Cameron 1990; Gurbra and Weber 2001; Chen *et al.* 2021) reflecting the low thermal conductivity of coked coal.

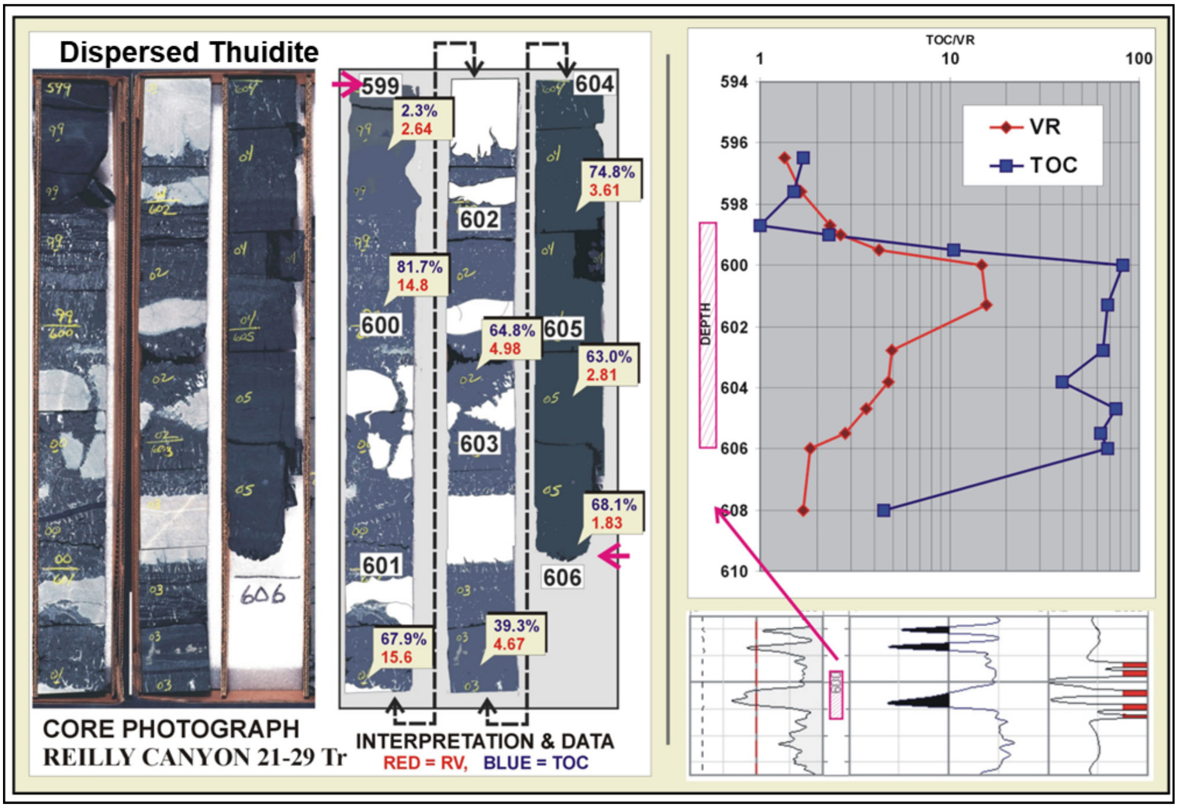

Figure 6. Core photograph of dispersed coal thuidite from the Reilly Canyon 21-29 TR well with accompanying VR values and TOC % (Total Organic Content) and corresponding GR, Density and Resistivity Logs. The use of resistivity logs readily allows for inter-well coal-sill package correlation.

In the subsurface electric logs record a slightly thicker (2-3 m) readily identifiable high-resistivity alteration aureole around coal thuidites which forms the basis for inter-well sill correlation (Figure 7); similar metamorphic contact aureoles having been studied around sills and organic-rich shales in the northern Neuquén Basin, Argentina (Spacapan *et al.* 2019). Typical open hole logging suites include GR, Caliper, Compensated Neutron-Density, and DIR Resistivity. Resistivity logs readily identify coal thuidite packages with DIR readings jumping from a baseline of 20-40 Ω-m to values reading off scale and generally greater than 2000 Ω-m (Figure 7a). The log response does not define discrete sills or margins (although SP logs can) rather it defines a highly resistive zone which we equate to a “hornfels’ effect. The exact physical-mineralogical rock properties behind such extreme values are generally not known and require further study. However, irrespective of causative reason, the high resistivity log response readily allows for correlation of coal-sill packages through the subsurface demonstrating the basin-scale thuidite phenomena (Figure 7 b & c).

Based on our observations from outcrop, core and the drilling of over 1000 wells in the central part of the basin to depths greater 1200m, we have found no evidence to support a "regional" hydrothermal overprint of coal rank associated with the SPIC. Rather we believe that an elevated geotherm recorded by the increase in coal rank along the Purgatoire River (Figure 2d) is likely a function of localized ponding of "stacked" sills sheets (Figure 7c).

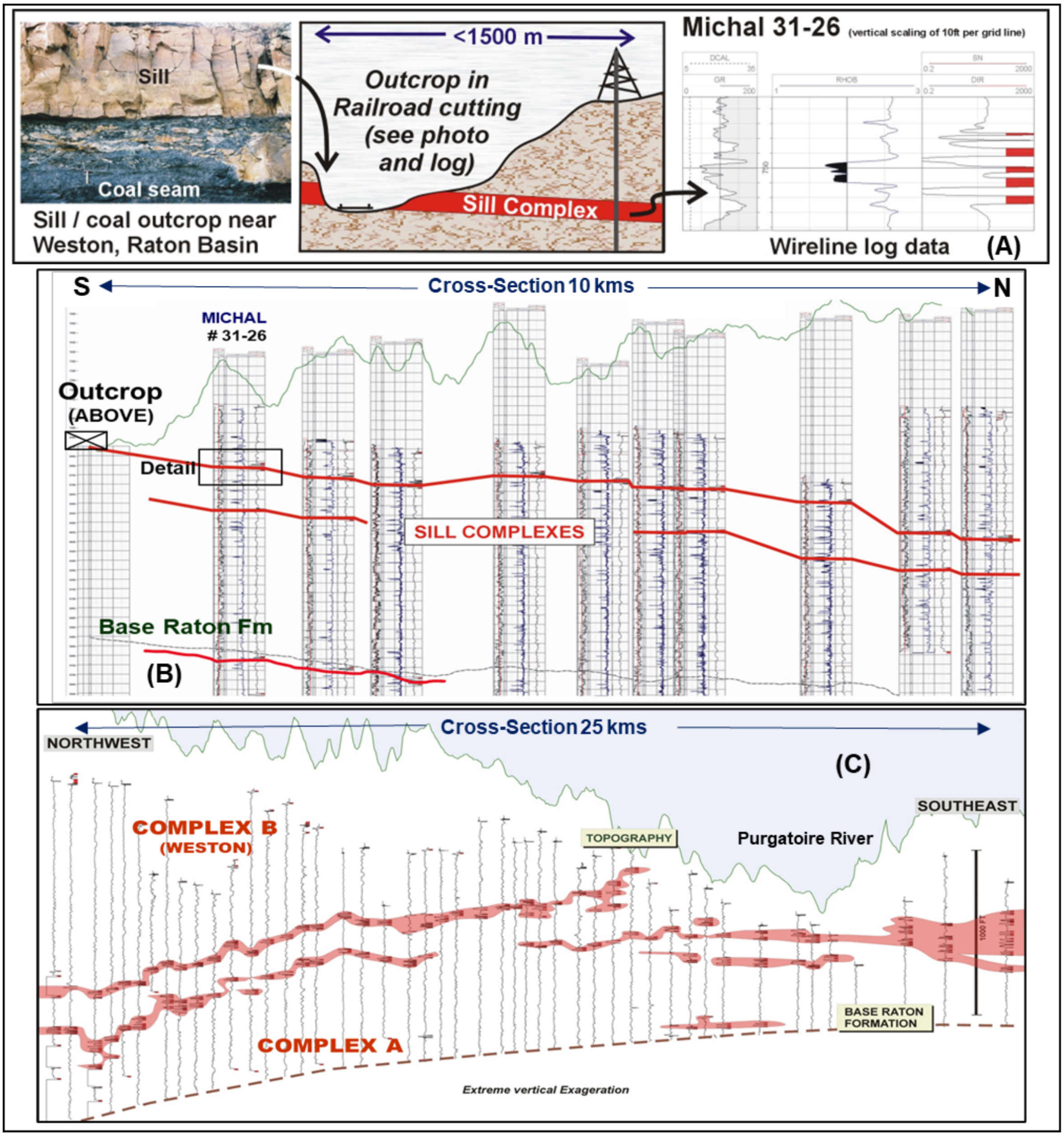

Figure 7. Coal – Sill Correlation panels using DIR logs. A) Sill – Thuidite complex at outcrop near Weston project down dip into the Michal 31-26 well 1.5 kms to the north (DIR Log Response over 200 Ω-m is red filled). B) Two discrete sill-coal complexes readily traced over 10 kms through the subsurface using DIR log response show the litho-bound character of Raton thuidite mixtures. C) Regional sill patterns showing multiple sill complexes developed throughout the basin; note increased sill stacking in the south-east near the Purgatoire River which may account for a localized increased in coal rank in this area.

Core Petrography

Petrographically, cored sills are best described as fine-grained evolved microcrystalline diorites or monzodiorites, comprised of seriate lath-shape columnar feldspars commonly showing aligned trachytic flow textures (Figure 8a). Larger pre-emplacement feldspar phenocryst

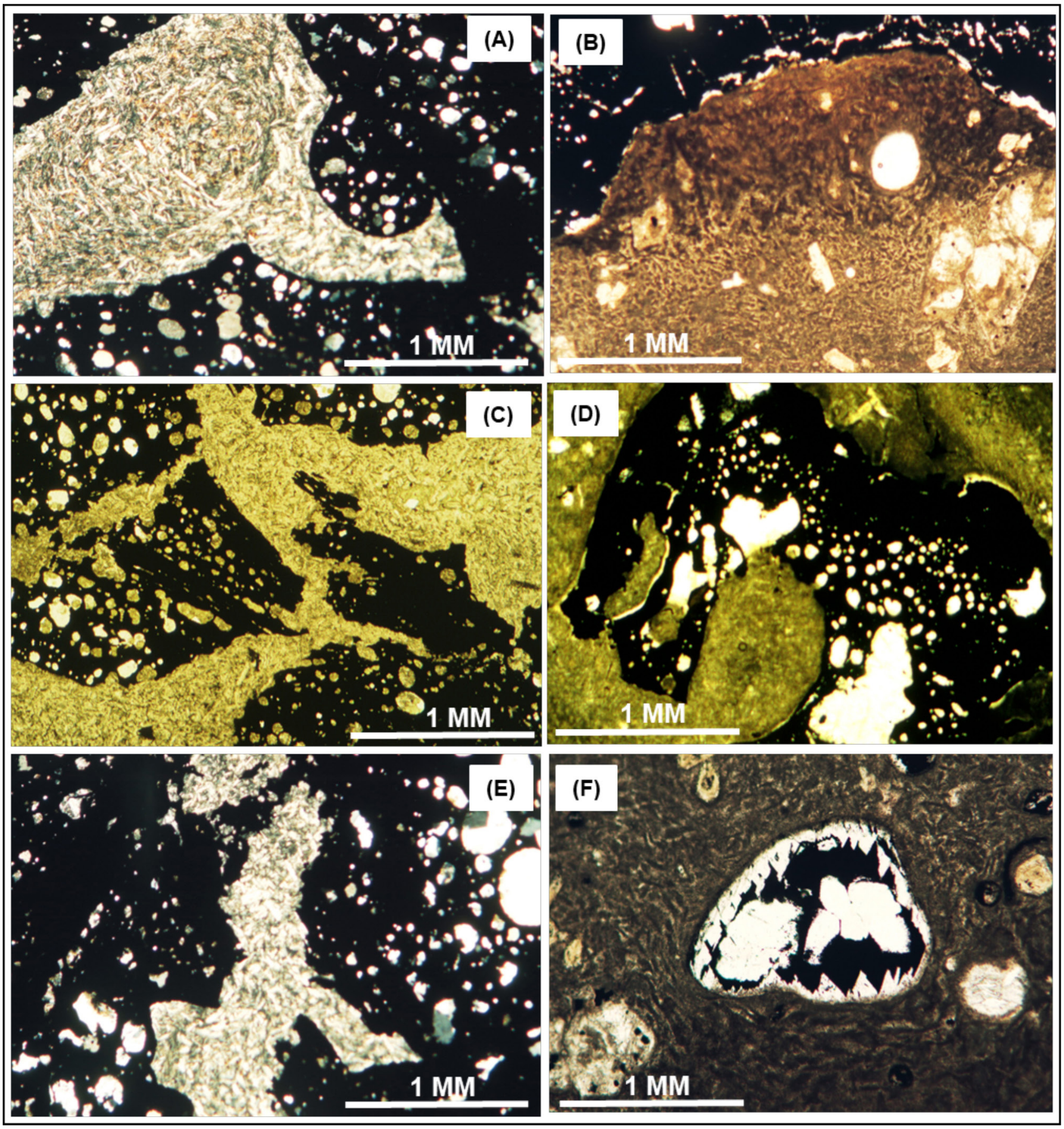

Figure 8. Coal thuidite photomicrographs. A) Hypocrystalline trachytic diorite and vesiculated coal with arcuate embayment and finely dispersed diorite clasts and blebs within coal matrix (XP). B) Coarse plagioclase phenocrysts frozen within microlitic hyalocrystalline chilled margin with thin elongate coal vesicular trails at the contact interface (PPL). C) Fragmented microcrystalline diorite with fine globular and frayed juvenile clast dispersion throughout weakly vesiculated coal matrix (PPL). D) Embayed globular magma/coal mixture, exhibiting amoeboid relationships and finely dispersed magma blebs in highly vesiculated coal (PPL). E) Highly vesiculated coal and fragmented microcrystalline diorite with dispersion of ragged diorite clasts throughout the coal matrix (XL). F) Diorite amygdale with coarse radiate dog-tooth calcite and quartz surrounding pyro-bitumen inclusion (PPL).

and glomerocryst clusters (Figure 8b) are common with limited resorption suggesting melt equilibrium, while intersertal chlorites may represent alteration of a palagonite precursor. Observed micro-morphologies exhibit a range of intricate brittle fracture through fluidal mixing textures (Figure 8c-e). At contacts, diorite texture may vary from hypocrystalline through glassy hyalocrystalline, the later often-persevering ghost-like microlite flow textures. Vesicles within diorite are rare, and when present are generally circular to ovoid, commonly filled with calcite-quartz admixtures which may contain coked coal (Figure 8f).

Diorite margins vary from brittle through ragged dispersions (Figure 8e) to arcuate embayments and smooth curvilinear surfaces. Isolated floating rounded and frayed juvenile diorite clasts are commonly formed through the coked coal matrix reflecting mingling and liquid-liquid immiscibility. Coked coal is invariably isotropic and shows intense matrix vesiculation as a consequence of devolatilization. Vesicles shapes vary from thin elongate trails along contact surfaces (Figure 8b) through flattened welded flow aligned vacuoles to dispersed rounded amygdales with various combination of calcite, quartz, pyrolytic carbon, and diorite melt fill (Figures 8a-f). Coals when heated in the coking process, begin to lose optical anisotropy at around 350°C. As the coal is heated between 350°C and 450°C, it progressively melts, devolatilizes, and vesiculates. In this range it usually reaches its maximum fluidity. In the 450°C and 550°C range it progressively loses its fluidity and hardens into coke (c.f. Crelling 2008). Textural characteristics observed in thin section clearly demonstrate that the Raton thuidites record various time-temperature stages of the viscoelastic coking process.

DISCUSSION

The laterally extensive intermittent mingling of sills and coal accompanied with the localized disintegration of partially evolved intruding microcrystalline magmas within the Raton Basin undoubtedly involved a multitude of processes which varied both in space and time. The formation of voluminous thuidites in Raton coals records magma fluidization of a lithified host-rock due largely to its abnormal thermal and rheological properties. From our observations it is evident that coal rheology played an extremely important role in the emplacement mechanics and resultant juvenile clast dispersal patterns. Sill accommodation space was likely achieved in part due to volatilization and release of vast quantities of water vapor and various gases including H_2, CO_2, CH_4, N_2 and a wide range of organic liquid byproducts, which may have accounted for up to 30% by volume of the host coal. The release of volatiles and liquids locally creating over-pressuring resulting in peripheral hydraulic fractures and small-scale features such as the coal-dykes of Podwysocki and Dutcher (1971).

The plasticity, fluidity, and swelling characteristics of coals under high temperatures are complex often coal specific phenomena, an understanding of which has developed primarily from the coke blending blast furnace industry (Loison *et al.* 1963; Diessel and Wolff-Fischer 1987; Diaz *et al.* 2007). The ability for coals to thermally mobilize, fluidize and potentially flow as a viscous media is well documented, and is governed by a wide range of properties, not least temperature, rank, reactive maceral composition and volatility (Ryan *et al.* 1998; Sciazko *et al.* 2020). In the context of the Raton Basin thuidites and their formation over tens of square kilometers, it is believed that the Raton coals had reached sufficiently high rank and possessed sufficient quantities of favorable vitrinite macerals, that during intrusion and subsequent carbonization (the process of heating coal in the absence of air) and volatilization, the reactive macerals passed through a liquid phase with simultaneous fluidization and the associated formation of a gas supported metaplast, possibly at temperatures between 360°- 480°C (Sciazko *et al.* 2020); values well within the range of 375-560°C postulated by Podwysocki and Dutcher (1971). Such liquification, devolatilization, and mobilization of plastic and viscoelastic coal is believed to account for many of the observed complex coal-magma relationships and coal vesiculation patterns; particularly as viscosity is time and temperature dependent prior to solidification above 480°C (Ryan *et al.* 1998). It is likely that the observed wide range of co-existing fluidal and blocky thuidite products reflect the effects of a broad time-space temperature spectrum (1-10 days at 360-1100°C) related to various stages of intrusion, mingling, and cooling.

The inferred fluidity of the dioritic intrusions indicates that the sill magma's retained sufficient heat and low viscosity to counteract the forces of cooling, quench fragmentation, and phreatomagmatic disruption on a large scale. The relatively evolved nature of the magma, as demonstrated by its microcrystalline trachytoid characteristics, does however suggest that the viscosity of the melt was likely at a level significantly above that of an aphyric glass. In order to retain fluidity, it is thought that high lithostatic load, cleat pore fluids, and fluid expulsion during devolatilization generated insulating stable vapour films at contact interfaces (Kokelaar 1982; Mills 1984), as possibly demonstrated by contact vesicle trails (Figure 8b). In addition, if temperatures passed into the coal solidification envelope above 480°C, that in combination with vapour film development the formation of a coked carapace likely reduced the deleterious effects of rapid cooling effectively insulating the evolved magma.

CONCLUSION

Outcrop, subsurface core and petrographic observations of sills intruded into coal seams within the Raton Basin, records evidence at a "basin-scale" for complex magma-sediment mixtures here termed 'thuidite" which clearly demonstrates fluidization and liquid-liquid immiscibility approximately 30 million years following lithification of the host coal. Raton thuidite assemblages resemble rock-types from a variety of volcano-sedimentary basins, and maybe a prevalent rock type in those basins where high rank coals and sills coexist. Raton intrusive sheet morphology developed in response to high-level magma preferentially intruding coals creating large extensive litho-bound coherent inter-fingering bulbous tube sill complexes and close packed and dispersed thuidite (Figure 9). It is believed that thermal heating of coal and its unique rheological properties during the carbonization process at temperatures in excess of 360ºC created liquefaction of the host, while the formation of a stable vapor film and surrounding coke carapace above 480ºC allowed magma heat retention, likely maintaining fluidity of the intruding bodies.

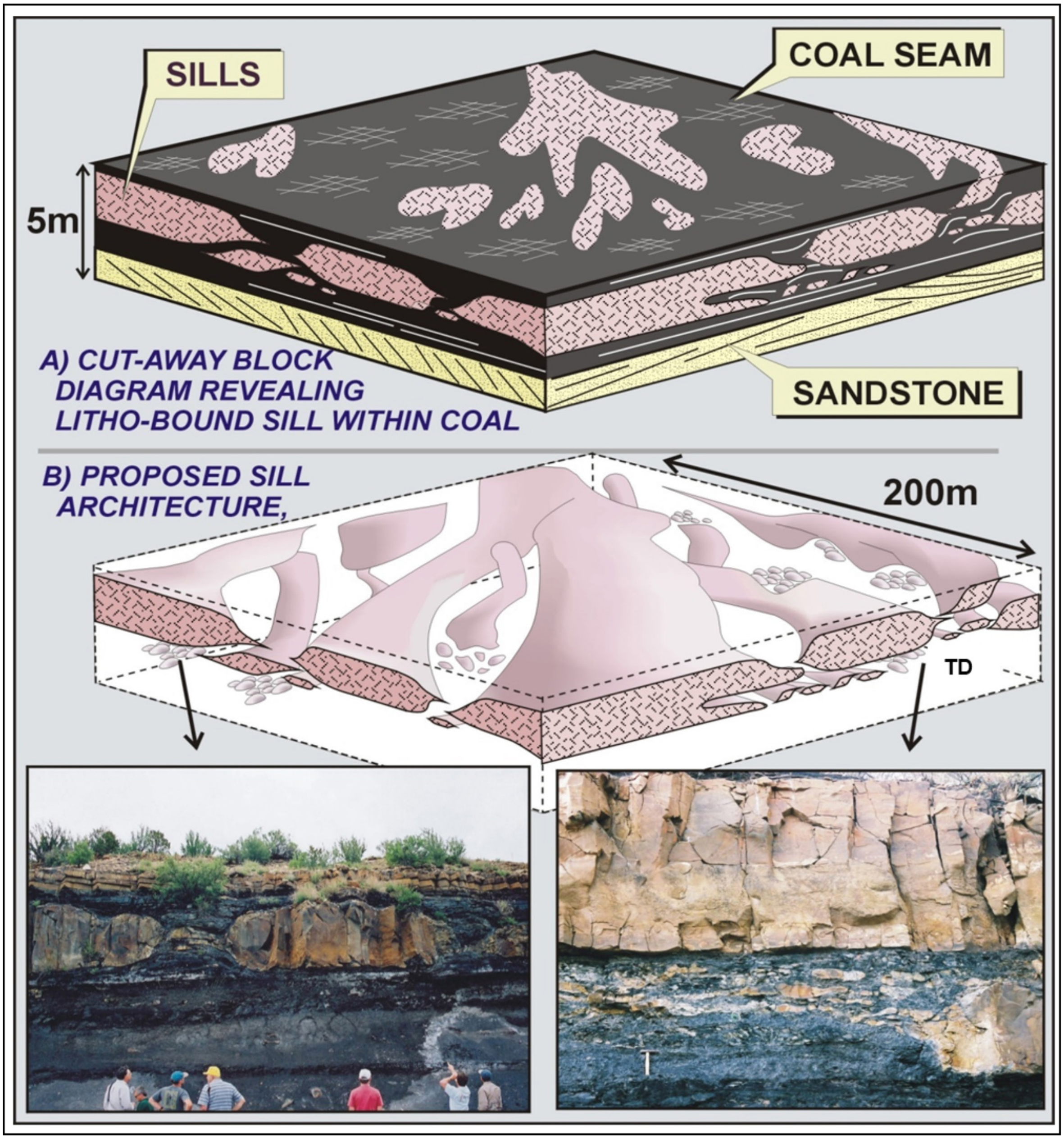

Figure 9. Sill emplacement model and thuidite generation. Due to inherent low modulus and naturally fractured nature, coal beds preferentially act as sill loci irrespective of overburden. Sill propagation is driven by feeder tube networks locally branching into fingers promoted by thuidite domain (TD) generation at margins and fronts causing ridged plugs having some similarities with a viscous indenter sill emplacement model (see Spacapan *et al.* 2017).

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