

## POTASH – RECENT EXPLORATION DEVELOPMENTS IN NORTH YORKSHIRE

**F.W. SMITH<sup>1</sup>, J.P.L. DEARLOVE<sup>1</sup>, S.J. KEMP<sup>2</sup>, C.P. BELL<sup>1</sup>, C.J. MILNE<sup>2</sup> AND T.L. POTTAS<sup>3</sup>**

<sup>1</sup> FWS Consultants Ltd, Merrington House, Merrington Lane Trading Estate, Spennymoor DL16 7UT.

<sup>2</sup> British Geological Survey, Nicker Hill, Keyworth, Nottingham. NG12 5GG.

<sup>3</sup> York Potash Ltd, 7-10 Manor Court, Scarborough. YO11 3TU.

### ABSTRACT

Polyhalite is not a rare mineral worldwide, but it rarely forms more than a minor component of evaporite sequences. York Potash Ltd is exploring an area of interest between Whitby and Scarborough, North Yorkshire, UK, in which an Exploration Target of 6.8 to 9.5 billion tonnes has been identified. Polyhalite exploration by York Potash has primarily been by drilling boreholes from surface, that are then cored through the Zechstein evaporite sequence. Assay samples have been analysed initially by quantitative X-ray diffraction, with subsequent analyses by Inductively Coupled Plasma Atomic Emission Spectroscopy.

The assay results reported in this paper for the weighted average ore zone sections range from 78 to 97% polyhalite, with high grade sections in places exceeding 99% polyhalite. The exploration results have led to a revised conceptual model for the Fordon Evaporites in North Yorkshire, in particular defining the differences between the three depositional environments of the Shelf, Basinal and intervening Transitional or Ramp facies and the occurrence of additional potash horizons in the region.

Of particular significance was the discovery of accessory or exotic minerals associated with the polyhalite. These include the extremely rare strontium mineral kalistrontite, and what we believe to be the first recorded occurrence in the English Zechstein of the boron-bearing minerals howlite, danburite and tourmaline.

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e-mail: jeremy@fwsconsultants.com*

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### INTRODUCTION

Polyhalite is not a rare mineral worldwide, but it rarely forms more than a minor component of evaporite sequences. North Yorkshire, UK, contains the largest reported resource of polyhalite in the world. York Potash Ltd, a subsidiary of Sirius Minerals plc., is exploring an Area of Interest (AOI) between Whitby and Scarborough (Figure 1), in which an exploration target of 6.8 to 9.5 billion tonnes has been identified.

Polyhalite is a hydrated potassium, magnesium, calcium sulphate evaporite mineral ( $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$ ) containing approximately 13% potassium and derives its name from the fact that it is composed of multiple (or poly) metals in the form of sulphate salts (or halites). It can either be marketed as a slow release fertilizer with no extra processing, or can be treated to generate potassium sulphate (SOP), magnesium compounds, and gypsum.

### BACKGROUND TO NORTH YORKSHIRE EVAPORITE STRATIGRAPHY

The Permian Zechstein sequence of North Yorkshire is well-known from the work of Smith (1980) and Smith et al (1986), in which five evaporite cycles were distinguished. These are the Z1 to Z5 cycles, three of which (Z2, Z3 and Z4) contain potash salts. Polyhalite is confined to the Z2 (Fordon Cycle) in the UK, but is known from other cycles in mainland Europe. Other potash minerals, principally sylvite (KCl) and sylvinites (a simple mixture of sylvite and halite), occur in the Sneaton and Boulby Seams in the Z4 and Z3 cycles respectively.

Polyhalite was discovered in Yorkshire in 1939 by a wildcat borehole drilled by the D'Arcy Exploration Company (a forerunner of British Petroleum), but it was passed over in the exploration boom of the 1950s and 60s, that focused mostly on the sylvite beds (Boulby and Sneaton Potash) in the Z3 and Z4 cycles. Most of what was known until recently about the Z2 polyhalite was



Figure 1. York Potash Area of Interest and location of exploration boreholes drilled and completed by September 2012.

from gas exploration, or gas storage exploration, and the works of Stewart (1949; 1963) and Colter & Reed (1980). These focused on the deeper basal sequence seen at Fordon, Atwick, and into the North Sea Basin, where the Z2 evaporites can be subdivided into the Upper, Middle and Lower subcycles (Figure 2), each containing identifiable mineral zones (Stewart, 1949; 1963). Colter & Reed (1980) later showed that these zones can be correlated over great distances within the Fordon Basin.

The Fordon Evaporites can also be divided into a condensed, western ‘shelf’ facies, comprising predominantly anhydrite; and an eastern ‘basinal’ facies characterised by the presence of thick basin-fill halite in the middle subcycle. A basin slope, or ramp, separates the two zones and runs irregularly north/south through York Potash’s AOI.

Polyhalite occurs in the basal sequence low down in the Middle Subcycle, as a complex banded seam, with significant high grades. It also occurs in the shelf sequence, immediately below the Upper Anhydrite (the basal unit of the Upper Subcycle).

### EXPLORATION TECHNIQUE

Polyhalite exploration by York Potash has primarily been by drilling boreholes from surface, that are then normally cored through the evaporite sequence. In two boreholes, SM3 and SM4, a second offset borehole was cored from the primary borehole to investigate the geological sequence approximately 50m from the primary borehole. These offset boreholes were labelled SM3A and SM4A. All boreholes were terminated within, or just above the Kirkham Abbey Formation. The

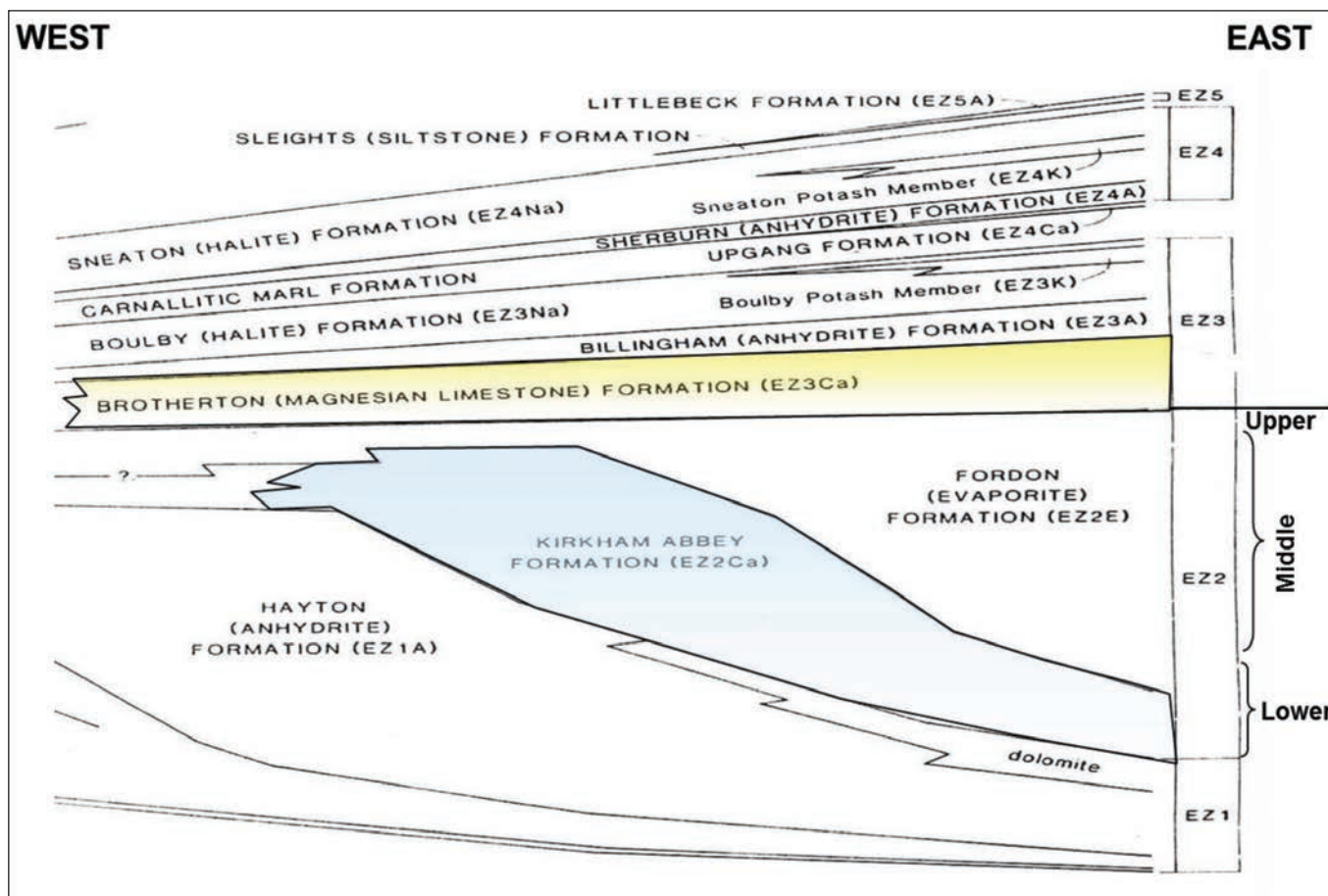


Figure 2. Stratigraphic relationships in the English Zechstein of Eastern England (from Smith et al., 1986).

boreholes have been logged using geophysical wireline logging. The areas between the exploration boreholes have been characterised by seismic data, based mostly on reprocessed legacy lines, but supplemented by a new 2D survey shot by York Potash.

The core was logged and photographed on site. Both geological and geotechnical logs were produced to assist with mineral exploration and mine planning. Cores from the potash zone were then sent to the British Geological Survey (BGS), cut in half, and one half cut into quarters. A detailed log of the potash-bearing core was prepared on the cut section, and the half core photographed. The coarse-grained Sneaton and Boulby (sylvite/sylvinite) seams, when cored, were assayed using the half core, whilst the finer grained polyhalite core was assayed using one of the quarter cores. Assay intervals were selected using a combination of the downhole wireline log results, hand-held core gamma logger results, and visual/geological observations. Any remaining core was archived at BGS (quarter core) and York Potash (quarter core for the Sneaton/Boulby seams and half core for the polyhalite seams).

Following crushing and milling of the assay samples, the polyhalite was submitted for initial quantitative X-ray diffraction (QXRD) analysis. This is a rapid analytical technique using the BGS state-of-the-art facility in the Mineralogy, Petrology and Microanalysis Facility. It has a fit-for-purpose level of accuracy using the Rietveld refinement technique. The results are compared with the down-hole geophysical wireline logs and show an excellent level of correlation. The principal advantages

of this method are the relatively quick turnaround time for the samples, and the ability to accurately identify and quantify a wide range of both ore zone and gangue minerals. It is critical for a project of this nature to know the detailed mineralogical make-up of the seams, as well as the elemental chemistry.

The polyhalite, and the Sneaton and Boulby sylvite/sylvinite seams, were also analysed at the BGS using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). This provides the 'industry standard' wet chemistry results. The sylvite/sylvinite seams were extracted using a simple aqueous leach and the polyhalite material was prepared using a lithium metaborate fusion, although it should be noted that the presence of borate minerals has the potential to cause significant interference with this method.

### EXPLORATION RESULTS

York Potash has drilled and reported on six exploration boreholes up to September 2012 (Figure 1).

The first borehole (SM1) was located within the main Fordon Basin, close to Robin Hoods Bay, and found basal facies, high grade polyhalite, low down in the Middle Subcycle, that correlated well with Units 2, 3 and 4 of Stewart (1963) and Colter & Reed (1980). A low-grade sylvite/sylvinite-bearing horizon was also located towards the top of the Middle Z2 subcycle (Figure 3). The Upper Anhydrite marker bed was absent, as a result of faulting.

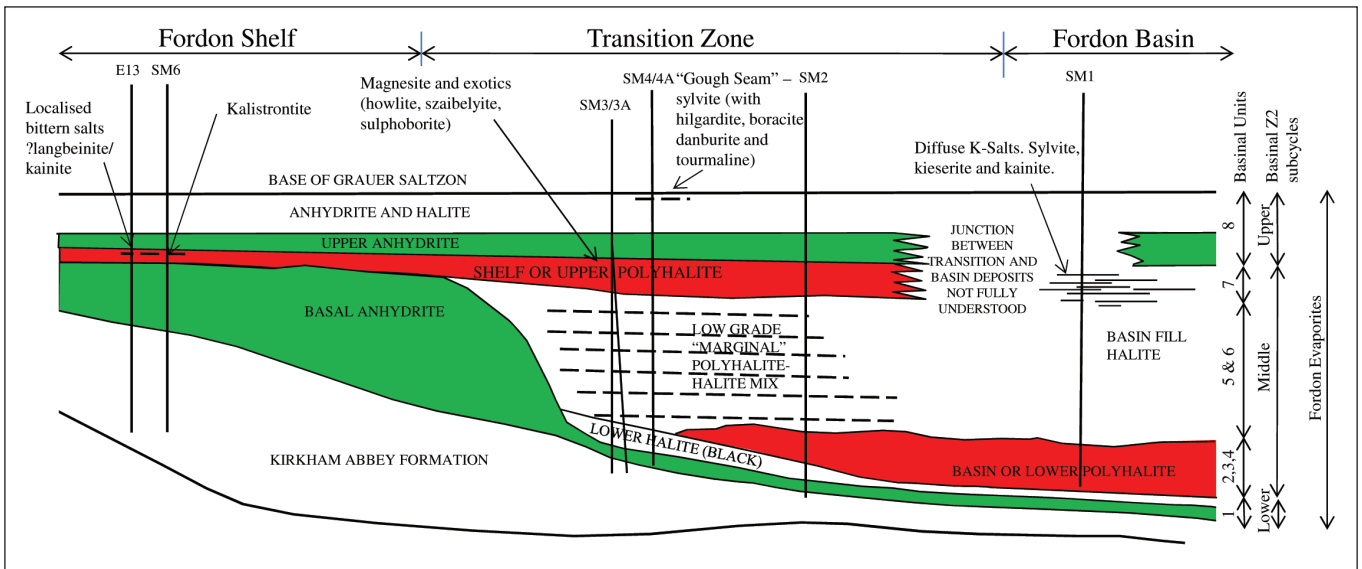


Figure 3. Revised conceptual geological model of the English Zechstein within the York Potash AOI from Whitby to Scarborough showing greater subdivision of the Fordon (Evaporite) Formation (EZ2 E).

SM2 was located just on the basinal side of the marginal ramp and found two seams – an upper (or Shelf facies) seam, just below the Upper Anhydrite, and a lower seam in broadly the same position in the sequence as the Basinal facies seam in SM1. Boreholes SM3 and SM4 found the upper (Shelf facies) polyhalite, whilst SM6 found the entire Z2 Middle subcycle to be a true, condensed, anhydritic shelf sequence. SM5 was terminated early without reaching the evaporites.

A sylvite/sylvinite-bearing unit was identified in borehole SM4 at the top of the Z2 Upper subcycle (Figure 3). This has been given the provisional name of the ‘Gough’ seam.

The results to date are helping to revise the stratigraphical sequence within the Z2 subcycle, and to define a Transition Zone in the vicinity of the Ramp where neither basin nor a true shelf sequence is found.

A summary of the published exploration assay results for polyhalite up to August 2012 is shown in Table 1. These show weighted average assay results for aggregated potential ore-zone sections ranging from 78 to over 97% polyhalite, that include high grade sections in places exceeding 99% polyhalite.

**DISCUSSION OF RESULTS**

The exploration results have led to a revised conceptual model for the Fordon Evaporites in North Yorkshire, in particular defining the differences between the three depositional environments of the Shelf, Basinal and intervening Transitional Zone, and the occurrence of additional potash horizons in the region. The revised conceptual model is shown in Figure 3.

The lateral correlation of the Shelf Polyhalite seam with the mineral zones of the basinal sequence is still under debate. The Shelf Polyhalite seam in the Transition Zone forms very clearly the lower part of the Upper Anhydrite (the lowest bed of the Upper subcycle). The unit of halite with K and Mg chlorides and sulphates (sylvite, kainite, and kieserite) within the main Fordon Basin lies at the top of the Middle subcycle, immediately

Borehole	Thickness (m)	% polyhalite	Assay*	Seam type/facies	Situation
SM1	23.3	95.0%	Weighted average	Basin	Fordon Basin
	11.1	97.1%	High Grade		
SM2	32.6	83.1%	Weighted average	Shelf	Transition Zone
	6.6	95.8%	High Grade		
	34.3	78.3%	Weighted average	Basin	
	6.8	99.2%	High Grade		
SM3	25.2	87.5%	Weighted average	Shelf	Transition Zone
	16.2	95.9%	High Grade		
SM3A	46.9	83.0%	Weighted average	Shelf	Transition Zone
	23.02	93.0%	High Grade		
SM4 SM4A**	5.1	89.4%	High Grade	Shelf	Transition Zone
	8.5	82.4%	Weighted average		
	5.7	86.2%	High Grade		
SM6	2.17	85.6%	High Grade	Shelf	Fordon Shelf

\* Assay is given as the weighted average for the quoted true seam thickness, within which the high grade section occurs  
 \*\* Wireline data result only

Table 1. Summary of published polyhalite assay exploration results.

below the Upper Anhydrite, from which it is clearly differentiated.

Polyhalite is believed to be predominantly a secondary, or replacement, mineral, being an early diagenetic replacement for anhydrite (or gypsum). It has, however, been reported that some of the basinal facies polyhalite deposits at Fordon and Atwick may be primary in origin (Stewart, 1963; Colter & Reed, 1980). Optical microscopy with backscattered scanning electron microscopy is being undertaken by BGS on polished thin sections to study the primary or secondary nature of the deposits. These data may also be used to assist seam correlation (through identification of trace mineral phases), and to establish the diagenetic history of the deposits.

QXRD provides a rapid and accurate quantification of the mineralogy of the core, and thus mineral assay results. Early results using the ICP-AES analytical method indicated potassium losses occurred during the lithium

metaborate fusion process, particularly where significant quantities of halite were present. The fusion process required some modification to remove these losses, and the final results were verified by thermal analysis, XRFs (X-ray fluorescence spectroscopy) and QXRD. These results highlighted the need to use multiple techniques to assay polyhalite, and demonstrated the value of the QXRD analytical methodology. The QXRD results have also highlighted the occurrence of a variety of trace, accessory and exotic minerals within this part of the English Zechstein sequence.

Stewart (1949 and 1963; and Stewart et al. 1954) and Armstrong et al. (1951) recorded a variety of minerals associated with the polyhalite, including principally kieserite and magnesite (in addition to halite, anhydrite and dolomite). A far more extensive range of accessory

or exotic minerals has been identified by the York Potash exploration programme to date, and are shown in Table 2. Some of these are fairly unusual, either because they normally only have a limited occurrence, or because of the quantities identified. Of particular interest in this paper are the strontium- and boron-bearing minerals.

### STRONTIUM-BEARING MINERALS

Stewart (1949) records celestine ( $\text{SrSO}_4$ ) in brecciated anhydrite and dolomite rock from 1445 m in the Lower Subcycle. Celestine was also recorded by Fowler (1944) in the Cleveland Hills borehole. Strontium borates have been recorded by Colter & Reed (1980) in the Upper Cycle of the Atwick 1 borehole, and trace amounts of celestine were reported by Stewart (1963) in the Upper

Mineral	Composition	Class (Strunz)	Sources
Magnesite	$\text{MgCO}_3$	Carbonate	A, B, Stewart (1949) and Armstrong et al. (1951)
Langbeinite	$\text{K}_2\text{Mg}_2(\text{SO}_4)_3$	Sulphate	A
Picromerite	$\text{K}_2\text{Mg}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$	Sulphate	A
Hexahydrate	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	Sulphate	A and B
Glauberite	$\text{Na}_2\text{Ca}(\text{SO}_4)_2$	Sulphate	A
Starkeyite	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	Sulphate	B
Ettringite	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	Sulphate	A
Uklonskovite	$\text{NaMg}(\text{SO}_4)\text{F} \cdot 2\text{H}_2\text{O}$	Sulphate	A
Celestine	$\text{SrSO}_4$	Sulphate	A and Stewart (1949)
Kalistrontite	$\text{K}_2\text{Sr}(\text{SO}_4)_2$	Sulphate	A
Gypsum	$\text{CaSO}_4 \cdot 2(\text{H}_2\text{O})$	Sulphate	A and B
Kieserite	$\text{MgSO}_4 \cdot (\text{H}_2\text{O})$	Sulphate	A and B
Epsomite	$\text{MgSO}_4 \cdot 7(\text{H}_2\text{O})$	Sulphate	B
Szaibelyite (ascharite)	$\text{MgBO}_2(\text{OH})$	Borate	A, B and Colter and Reed (1980)
Howlite	$\text{Ca}_2\text{B}_5\text{SiO}_9(\text{OH})_5$	Borate	A and B
Sulfoborite	$\text{Mg}_3[\text{B}(\text{OH})_4]_2(\text{SO}_4)(\text{OH},\text{F})_2$	Borate	A and Stewart (1963)
Boracite	$\text{Mg}_3\text{B}_7\text{O}_{13}\text{Cl}$	Borate	A and Stewart (1951)
Iron Boracite	$(\text{Fe}^{++}, \text{Mg}, \text{Mn})_3\text{B}_7\text{O}_{13}\text{Cl}$	Borate	Milne (1978) and Milne et al. (1977)
Ericaite	$(\text{Fe}^{++}, \text{Mg}, \text{Mn})_3\text{B}_7\text{O}_{13}\text{Cl}$	Borate	Milne(1978)
Parahilgardite	$\text{Ca}_6[\text{B}_5\text{O}_9]_3\text{Cl}_3 \cdot 3\text{H}_2\text{O}$	Borate	Milne (1978)
p-Veatchite	$\text{Sr}_2\text{B}_{11}\text{O}_{16}(\text{OH})_5 \cdot \text{H}_2\text{O}$	Borate	Stewart et al.(1954)
Hilgardite	$\text{Ca}_2\text{B}_5\text{O}_9\text{Cl} \cdot \text{H}_2\text{O}$	Borate	A
Danburite	$\text{CaB}_2\text{Si}_2\text{O}_8$	Silicate	A
Talc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	Silicate	A and B
Antigorite	$(\text{Mg}, \text{Fe}^{++})_3\text{Si}_2\text{O}_5(\text{OH})_4$	Silicate	A and B
Serpentine Group	$(\text{Mg}, \text{Fe})_3\text{Si}_2\text{O}_5(\text{OH})_4$	Silicate	B
Chlorite Group	$(\text{Mg}, \text{Fe})_3(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2 \cdot (\text{MgFe})_3(\text{OH})_6$	Silicate	A
Tourmaline Group	$(\text{Na}, \text{K}, \text{Ca})(\text{Li}, \text{Mg}, \text{Fe}, \text{Mn}, \text{Al})_3(\text{Al}, \text{Fe}, \text{Cr}, \text{V})_6(\text{BO}_3)_3(\text{Si}_6\text{O}_{18})(\text{O}, \text{OH}, \text{F})_4$	Silicate	A
Mica	Undifferentiated	Silicate	A and B
Sulphur	$\text{S}_8$	Element	B

<sup>A</sup> QXRD undertaken by BGS on behalf of York Potash Ltd

<sup>B</sup> Petrography undertaken by BGS on behalf of York Potash Ltd

**Table 2.** Accessory/exotic minerals identified from York Potash boreholes.

Cycle of the Fordon 1 borehole.

Celestine was identified by QXRD in the polyhalite cores from SM2 at the top of the Shelf facies polyhalite. Strontium can be accommodated at higher concentrations in the crystal lattice of gypsum than in anhydrite or polyhalite. When gypsum dehydrates to anhydrite (or polyhalite) some strontium becomes orphan and is either flushed away, or crystallises as celestine. Trace element geochemistry on polyhalite from boreholes SM1 and SM2 found between 655 and 1919 mg/kg Sr in polyhalite (mean 0.15% Sr in five samples).

Of particular significance was the discovery in borehole SM6 of significant amounts of kalistrontite ( $K_2Sr(SO_4)_2$ ) in the Shelf facies polyhalite seam (Figure 3). This is an extremely rare mineral, previously known from very few localities where it is associated with (a) reaction of sylvite with Sr-bearing solutions (Alshtan, Russia), (b) an alteration product of celestine (Pleismar, Germany), and (c) in a lake-bed evaporite (Omingwa Pan, Namibia). It contains 21.85% K, and 24.48% Sr. The sheer volume of kalistrontite in SM6 (up to 55% by volume in some samples) makes it a very unusual occurrence. The borehole is in the Fordon Shelf, where thick sequences of gypsum/anhydrite were deposited, but the source of strontium is unlikely to be mobilised from the gypsum, unless there is some mechanism for focusing all the strontium to this one point (although at present we do not know the full overall extent of this mineral in the region). A hydrothermal source is a further possibility.

## BORON-BEARING MINERALS

Most boron deposits in the world are derived from non-marine sources (e.g. hydrothermal or volcanic). Generally the level of boron in marine bitterns is not sufficient to create significant deposits or borate salts, particularly as the boron in marine evaporates is generally contained as a trace element in sulphates or clays, or remains in solution (Milne, 1978). Marine borates have been recorded in the Zechstein of Germany, the Lower Permian rocks of the Inder region of Russia, the Middle and Upper Permian rocks of Oklahoma and in the Upper Mississippian Windsor series in Nova Scotia and New Brunswick (Milne, 1978). Boron minerals have been recorded from the Boulby Potash and other horizons in the Zechstein (Stewart, 1949; Stewart et al. 1954; Colter & Reed, 1980; Milne, 1978; Milne et al., 1977). Some stratigraphic control is implied, since they appear to occupy preferred horizons. However, since the sequence has only been selectively studied, this conclusion remains open to debate.

No boron-bearing minerals were identified in borehole SM6 within the shelf deposits, although szaibelyite has been identified in historical borehole E11, and p-veachite in historical borehole E2. No boron-bearing minerals were identified in the basinal facies polyhalite in SM1 or SM2. Boron-bearing minerals were identified, however, in all the boreholes (including deflections) within the Transition or Ramp Zone for which we have data. The particular boron-bearing minerals within this Zone are howlite, szaibelyite and sulphoborite. We believe this is the first recorded occurrence of howlite in the English Zechstein. The vertical and lateral distribution of each mineral appears to be sporadic.

Boron-bearing minerals were also detected within the 'Gough' seam in SM4, including hilgardite, boracite, danburite and tourmaline. We believe this is the first recorded occurrence of danburite and tourmaline in the English Zechstein.

## CONCLUSION

The exploration results to date indicate that North Yorkshire has the world's largest known resource of polyhalite. The programme is revealing much new information about the Fordon Evaporite sequence, and is helping to refine understanding of the English Zechstein sequence in North Yorkshire. A new sylvite/sylvinite-bearing ('Gough') seam has been identified immediately beneath the Grauer Saltzon (Borehole SM4). A wide range of trace/exotic minerals have been identified, and specifically the first occurrence of kalistrontite in the UK and what is believed to be the first occurrence of howlite, danburite and tourmaline in the English Zechstein.

Since this paper was presented at the EIG Conference, more boreholes have been drilled. York Potash Ltd have declared a 1.35 billion tonnes inferred resource at a grade of 88.7% polyhalite, and is progressing towards defining an indicated resource and a world-class mining project.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Armstrong, G., Dunham, D. C., Harvey, C. O., Sabine, P. A. and Waters, W. F. 1951. The paragenesis of sylvite, carnallite, polyhalite and kieserite in Eskdale Boring Nos. 3, 4 and 6, NE Yorkshire. *Mineralogical Magazine.*, 29, p. 667 to 689.
- Colter, V. S. and Reed, G. E. 1980. Zechstein and Fordon Evaporites of the Atwick No. 1 borehole, surrounding area of NE England and the adjacent southern North Sea. *Contributions to Sedimentology*, 9, p. 115 – 129.
- Fowler, A. 1944. A deep bore in the Cleveland Hills. *Geological Magazine*, 81, p. 193 – 206 and 254 – 265.
- Milne, J. K. 1978. The potash deposits and their associates in the area of the Boulby Mine, Cleveland. PhD Thesis.
- Milne, J. K., Saunders, M. J. and Woods, P. J. E. 1977. Iron-boracite from the English Zechstein. *Mineralogical Magazine.*, 41, p. 401 – 406.
- Smith, D. B. 1980. The evolution of the English Zechstein. *Contributions to Sedimentology*, 9, p. 7 – 34.
- Smith, D. B., Harwood, G. M., Pattison, J. and Pettigrew, T. H. 1986. A revised Nomenclature for Upper Permian Strata in Eastern England. In, Harwood, G.M. and Smith, D.B. (Eds.) *The English Zechstein and related topics*. Geological Society of London Special Publication 22, p. 9 – 17.
- Stewart, F. H. 1949. The petrology of the Evaporites of the Eskdale No 2 boring. East Yorkshire: I – The Lower Evaporite Bed. *Mineralogical Magazine*, 28, p. 621 – 675.
- Stewart, F. H. 1963. The Permian Lower Evaporites of Fordon in Yorkshire. *Proceedings of the Yorkshire Geological Society*, 34, p. 1 – 44.
- Stewart, F. H., Chalmers, R. A. and Philips, R. 1954. Veatchite from the Permian Evaporites of Yorkshire. *Mineralogical Magazine*, 30, p. 389 to 392.