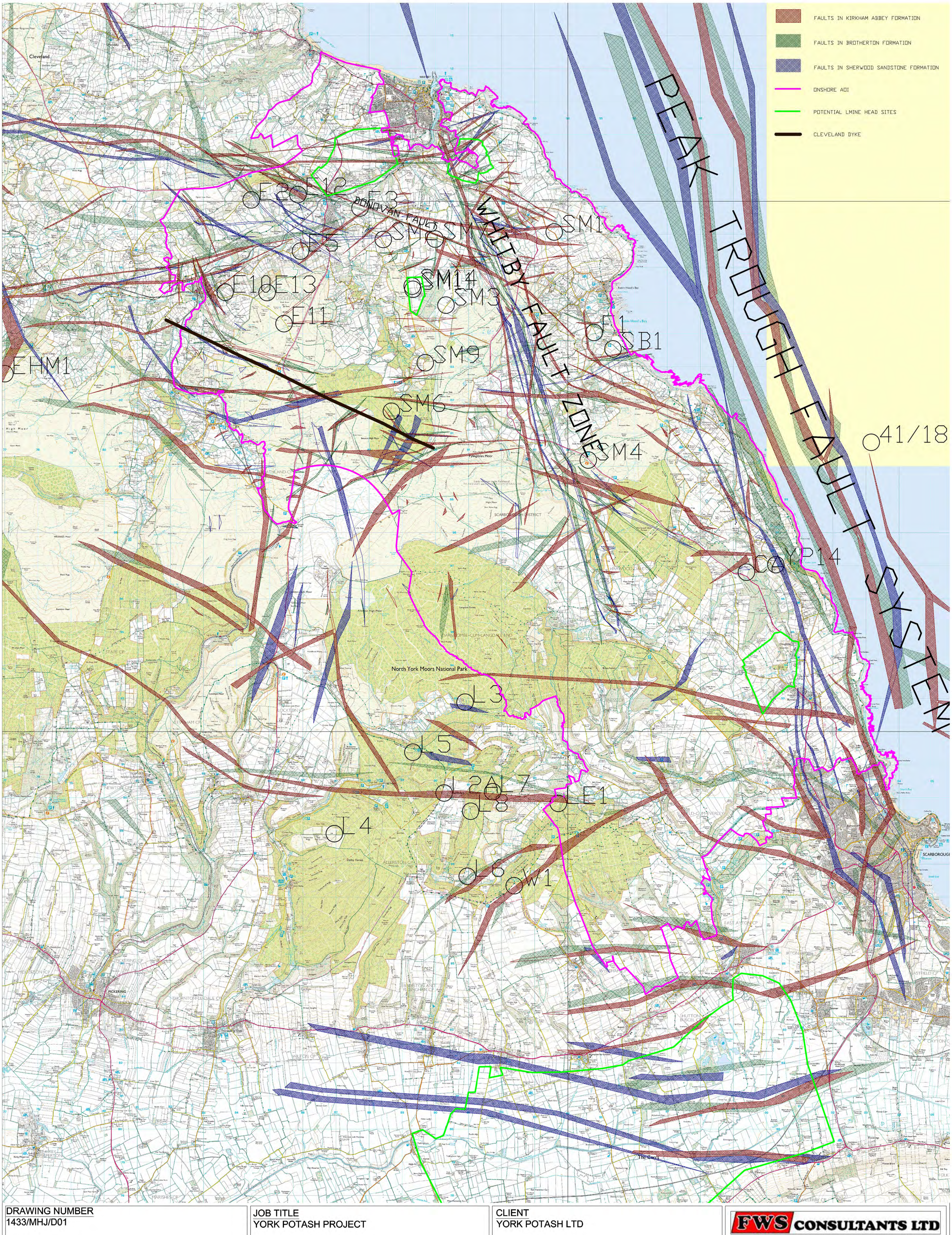

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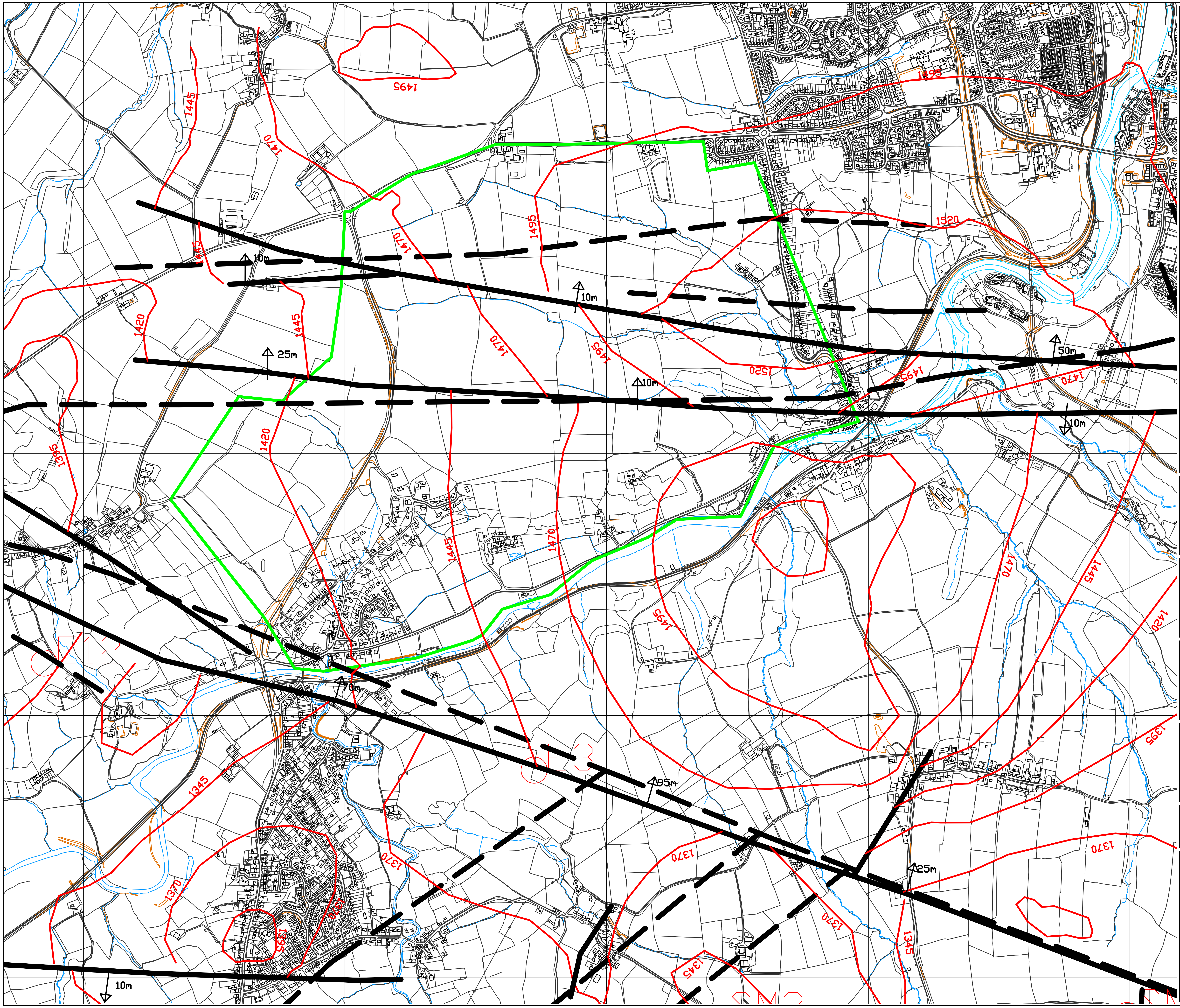

NOTES

CONTOURS ON BASE OF POLYHALITE (SHELF SEAM)
1500 DEPTH BELOW ORDNANCE DATUM (m)

FAULTS (KIRKHAM ABBEY)
FAULTS (BROTHERTON)
FAULTS (SHERWOOD SANDSTONE)
25m ESTIMATED THROW OF FAULT (m)

POTENTIAL MINE SITE

NOTE - ORDNANCE DATUM IS SEA LEVEL

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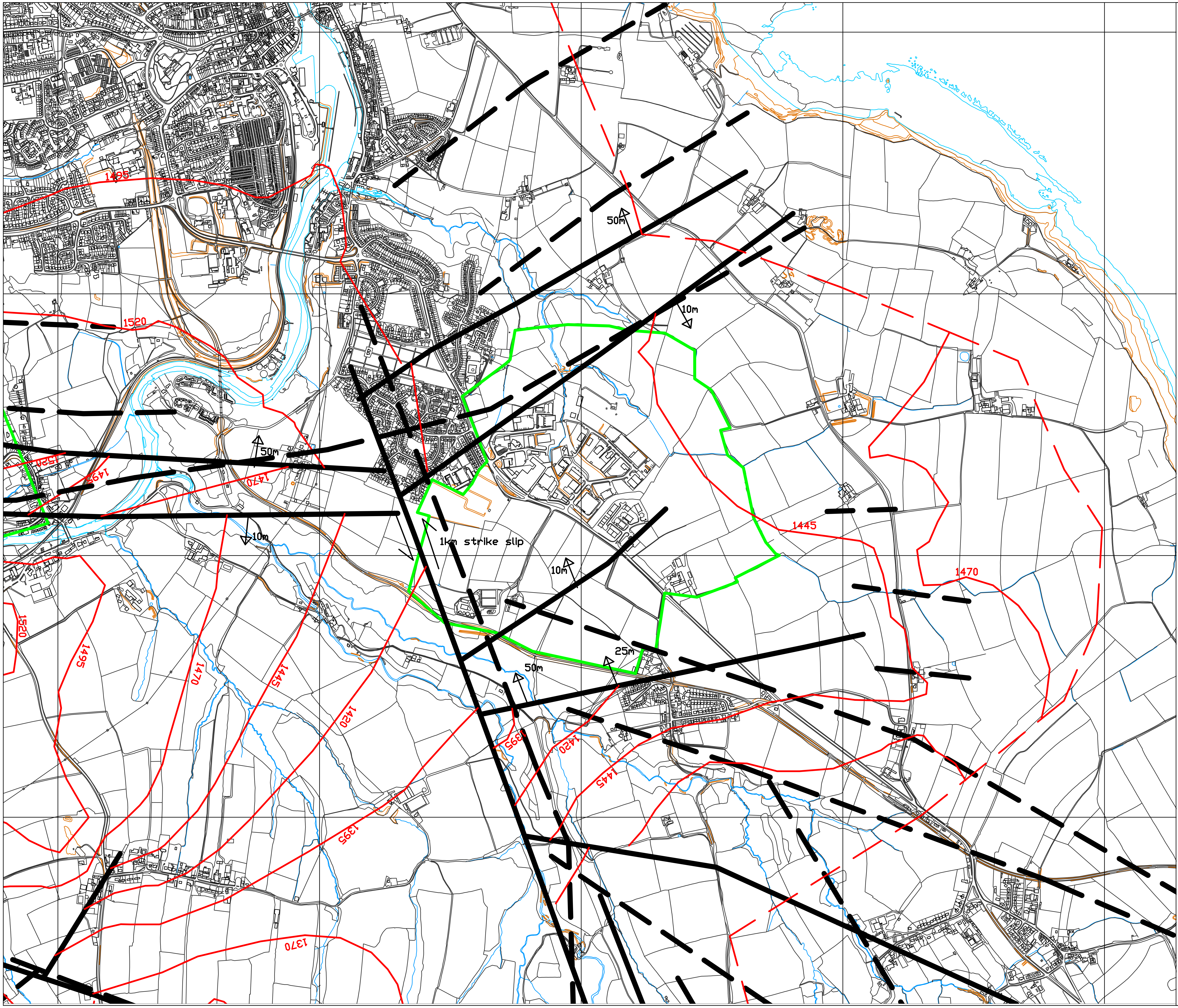

NOTES

- 🟥 CONTOURS ON BASE OF POLYHALITE (SHELF SEAM)
- 1500 DEPTH BELOW ORDNANCE DATUM (m)
- APPROXIMATE POSITION OF EASTERN EXTENT OF SHELF POLYHALITE SEAM
- FAULTS (KIRKHAM ABBEY)
- FAULTS (BROTHERTON)
- FAULTS (SHERWOOD SANDSTONE)
- 25m ESTIMATED THROW OF FAULT (m)
- 🟩 POTENTIAL MINE SITE

NOTE - ORDNANCE DATUM IS SEA LEVEL

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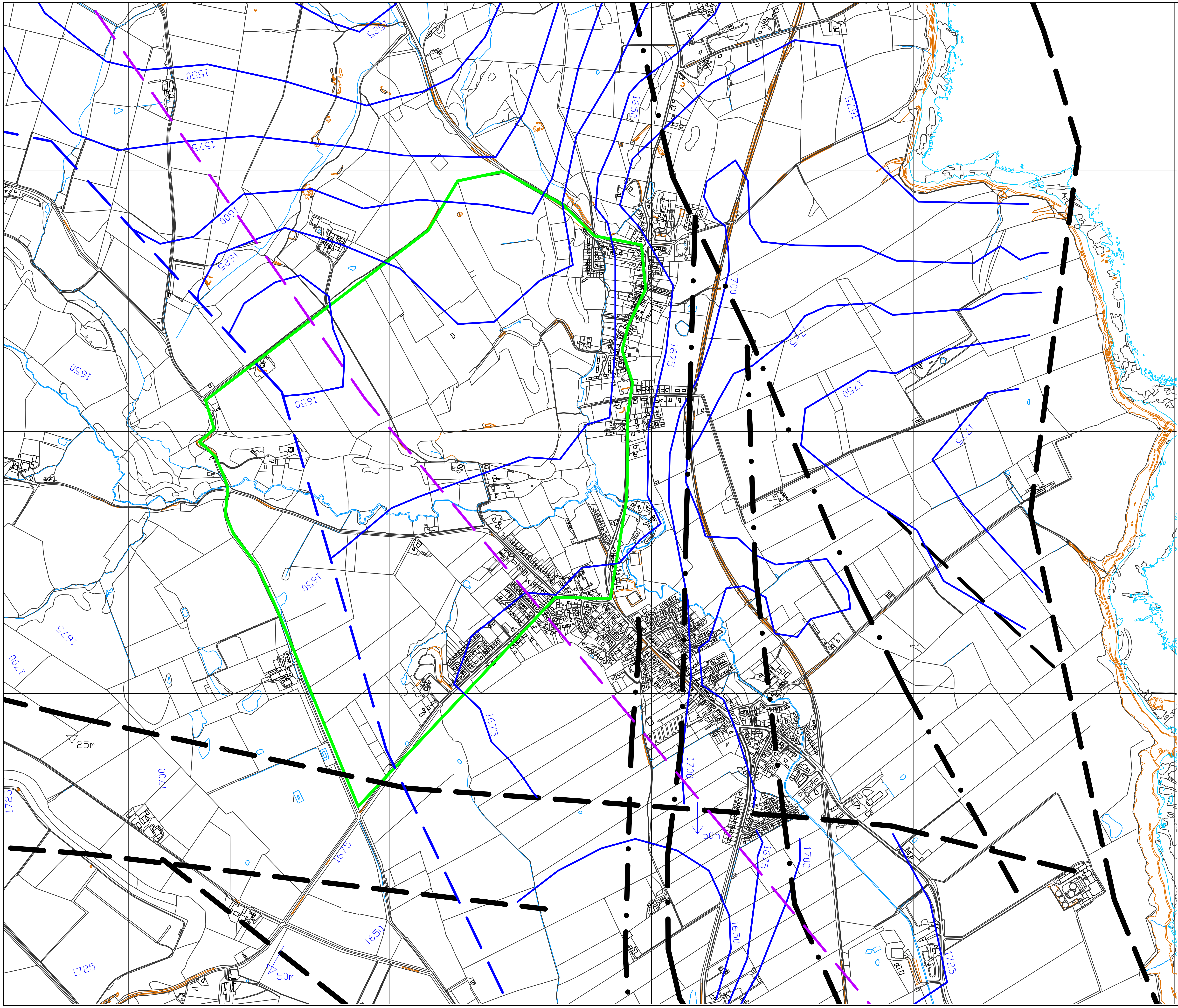

NOTES

- CONTOURS ON BASE OF POLYHALITE (BASIN SEAM)
- 1500 DEPTH BELOW ORDNANCE DATUM (m)
- WESTERN EXTENT OF BASIN POLYHALITE
- EASTERN EXTENT OF SHELF POLYHALITE
- FAULTS (KIRKHAM ABBEY)
- FAULTS (BROTHERTON)
- FAULTS (SHERWOOD SANDSTONE)
- ESTIMATED THROW OF FAULT (m)
- POTENTIAL MINE SITE

NOTE - ORDNANCE DATUM IS SEA LEVEL

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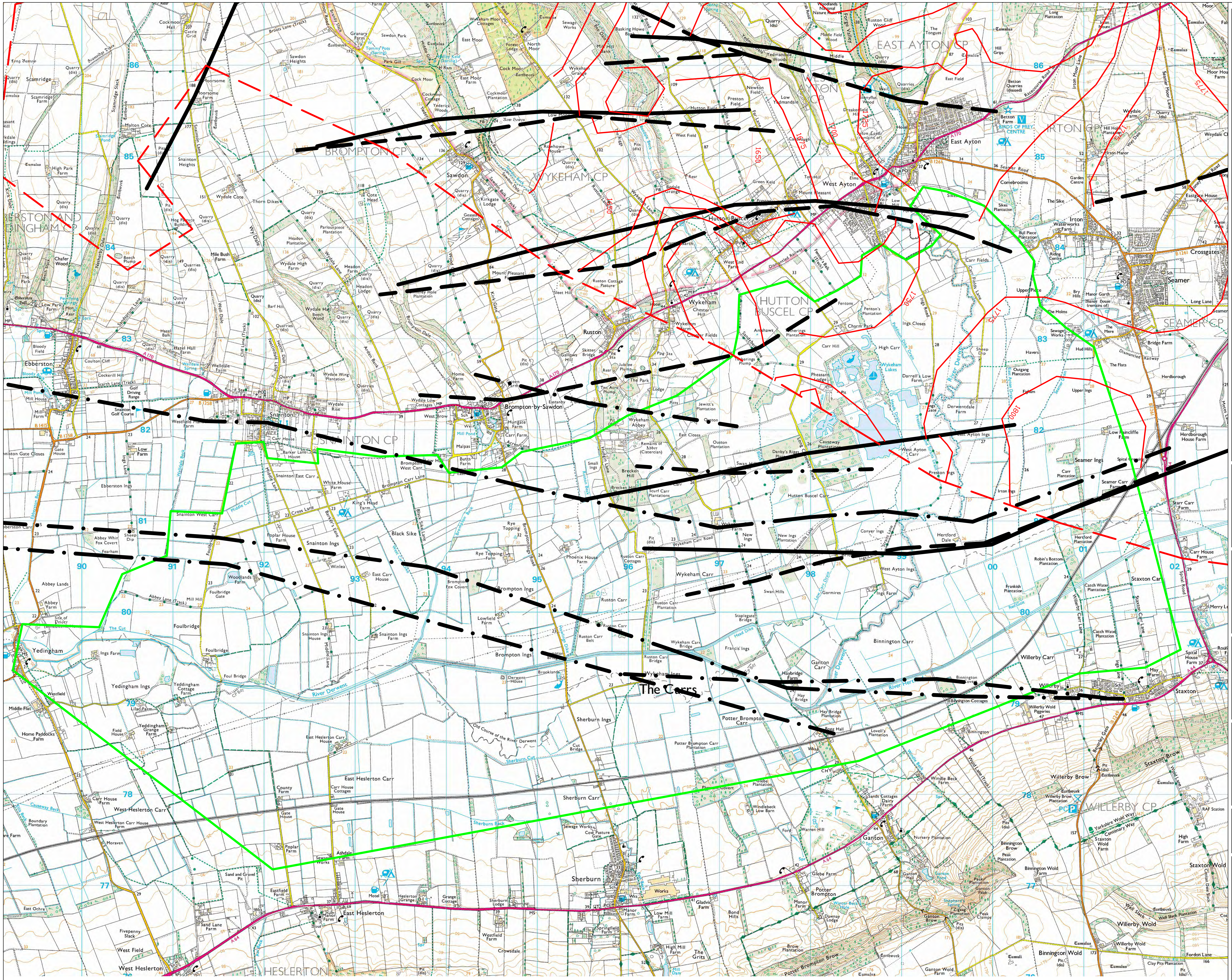

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— CONTOURS ON BASE OF POLYHALITE (SHELF SEAM)
1500 DEPTH BELOW ORDNANCE DATUM (m)
- - - APPROXIMATE EXTENT OF WORKABLE SHELF POLYHALITE

- - - FAULTS (KIRKHAM ABBEY)
— FAULTS (BROTHERTON)
-·-· FAULTS (SHERWOOD SANDSTONE)
↗25 ESTIMATED THROW OF FAULT (m)

— POTENTIAL MINE SITE

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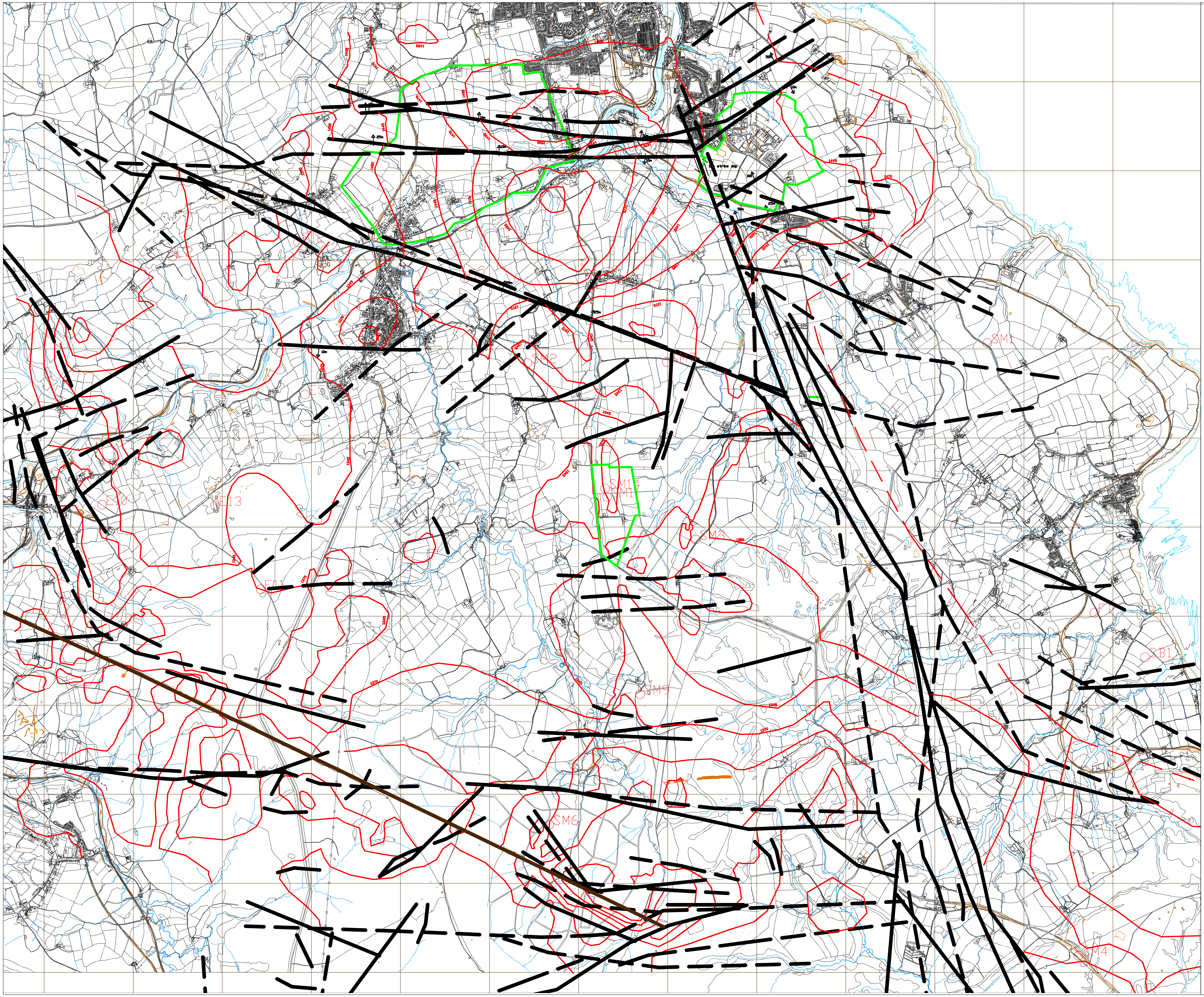

NOTES

CONTOURS ON BASE OF POLYHALITE (SHELF SEAM)
1500 DEPTH BELOW ORDNANCE DATUM (m)
EASTERN EXTENT OF SHELF POLYHALITE

FAULTS (KIRKHAM ABBEY)
FAULTS (BROTHERTON)
FAULTS (SHERWOOD SANDSTONE)
ESTIMATED THROW OF FAULT (m)

POTENTIAL MINE SITES

CLEVELAND DYKE

NOTE - ORDNANCE DATUM IS SEA LEVEL

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APPENDIX 2
LOCATION PLAN, BOREHOLES AND SECTION LINES

NOTE-BOREHOLES PROJECTED ONTO LINE IN APPROXIMATE PALEOGEOGRAPHICAL LOCATION

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Geol. Mag. **126** (6), *1989, pp. 699–705. Printed in Great Britain*

The Peak Trough – a major control on the geology of the North Yorkshire coast

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(*Received* 18 February 1988; *revised version received* 19 January 1989; *accepted* 23 January 1989)

Abstract – Although the Mesozoic sediments of the Cleveland Basin (North Yorkshire) have generally not been strongly faulted, several approximately N–S trending faults have been identified along the coast. New seismic data from adjacent coastal waters has allowed the offshore extension to the fault system to be examined for the first time. The coastal faults from Peak (Ravenscar) to Red Cliff (Cayton Bay) are shown to form part of a linked system defining a narrow graben only some 5 km wide, the *Peak Trough*. Faulting has been complex, with decollement levels apparently developed in weak layers at various horizons in the Triassic and Permian strata: fault geometries and regional considerations suggest that extension has been dominant. Movement occurred intermittently from Triassic to latest Cretaceous or early Tertiary times.

1. Introduction

The North Yorkshire coast, from Flamborough to Redcar (Fig. 1), includes some of the finest exposures of Mesozoic sediments in the British Isles. The sediments accumulated in the Cleveland Basin (the onshore extension of the Sole Pit Basin), a depositional area bounded to the south by a major east–west fault zone, the Howardian–Flamborough Fault Belt. Although faulting was much less severe within the basin, several approximately north–south trending faults cut the coast between Runswick Bay and Red Cliff (Cayton Bay) and influence the orientation of that part of the coastline. Most have westerly throws of not more than 60 m. However, the easterly downthrowing Peak Fault is more spectacular and has long attracted debate (see section 2, below). The discussion has focused principally on whether it moved during Jurassic time or is solely a Tertiary tear fault. There has been little consideration of its spatial or genetic relationships with other coastal faults, probably because of the lack of exposure inland and the difficulty of tracing the faults for more than a few kilometres. However, Kendall & Wroot (1924, p. 770) noted that the faults from Peak (Ravenscar) to Red Cliff were probably all part of the same system, while Alexander's (1986) idealized flow model for the Scalby Formation (Middle Jurassic) indicated a very shallow trough lying between Peak and White Nab.

Dingle (1971, p. 323) noted that the fault system continued northward from the present coastline and both he and Crosby (1981) mapped the Peak Fault for some distance offshore. Dingle's interpretation was based on seismic reflection profiles obtained using low-power sources which gave penetration of only a few hundred metres, generally insufficient for the mapping of any very distinctive marker horizons.

In 1986 JEBCO Seismic Ltd gathered seismic reflection data within a 30 km wide offshore zone extending from the Wash to Northumberland (Fig. 1) in anticipation of the UK 10th-round block allocations at the end of that year. This has allowed us to trace the main coastal faults for some distance offshore. Survey lines were set out on an approximately rectangular grid at 5 km spacing, with orientations parallel and at right angles to the general trend of the coastline. Lines at right angles to the coast were continued to within about 1 km of low-water mark, and some beach ties were made. Ties were also made to all released offshore wells within the area covered, synthetic seismic traces were computed and time-depth conversion plots were prepared. For commercial reasons, data processing was biased in favour of delineation of the sub-Permian strata and the sea-bed multiples which are a recognized problem in the area were only partially suppressed. Nevertheless, primary events can be distinguished even at shallow levels where there are contrasts in dip.

The profiles obtained show that the faults exposed from Peak to Red Cliff and their offshore continuation delineate a narrow graben trending obliquely to the present coastline, here named the *Peak Trough*. Although the bounding faults intersect the coast about 21 kilometres apart, the graben is only about 5 km wide (Fig. 1).

2. The Peak Trough onshore

The Peak Fault marks the more sharply defined western margin of the Peak Trough while the eastern margin is formed by step-faulting along the Scarborough–Cayton Bay and Red Cliff–Hunmanby lines. The Peak Fault cuts the cliffs at the south end of Robin Hood's Bay, where it has a maximum down-

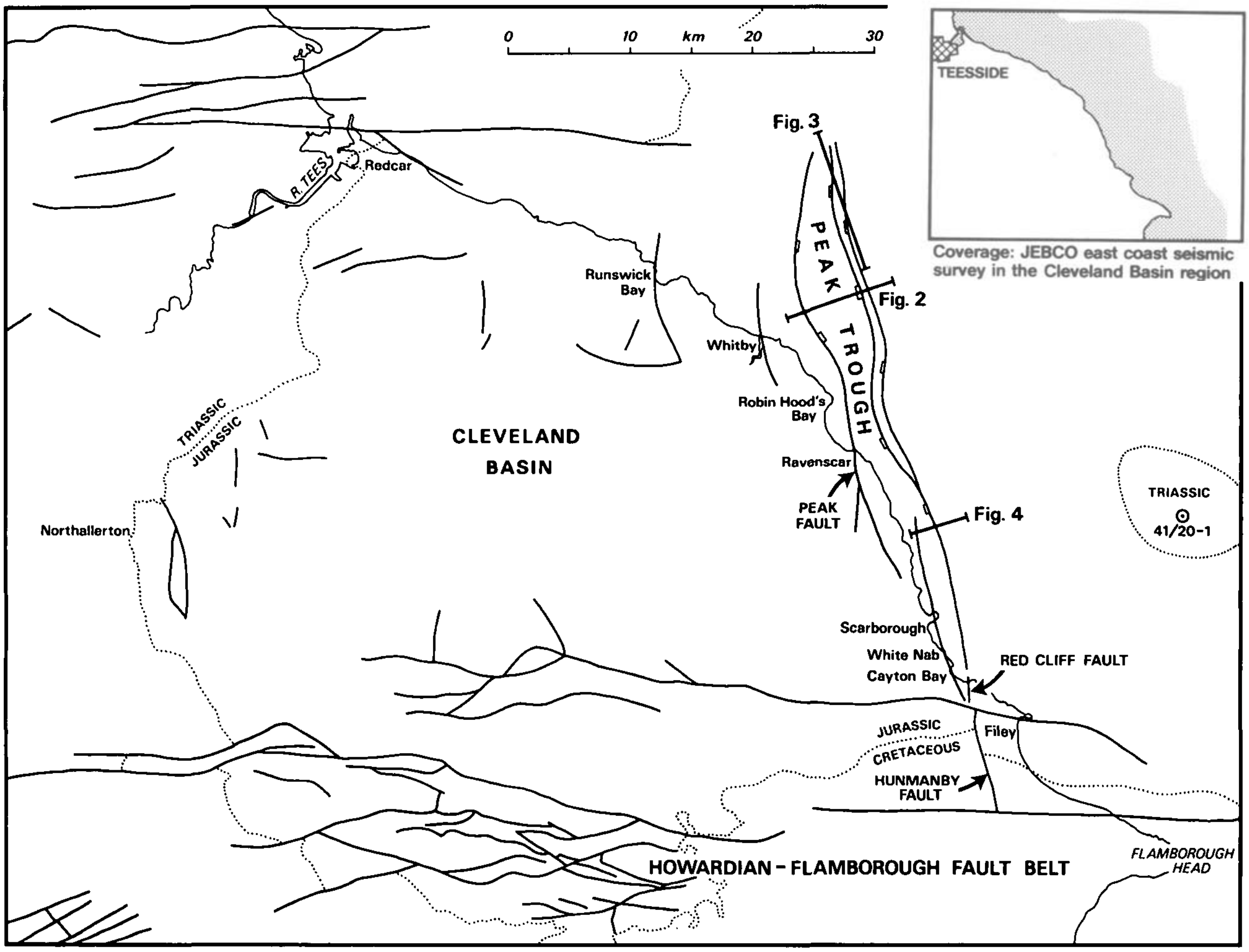

Figure 1. The North Yorkshire coast, showing locations of the Peak and Red Cliff faults and their offshore extensions. Offshore faults located at the base Jurassic level.

throw of some 150 m to the east. It forks northwards on the shore immediately below the Peak, and southwards from a point about 2.5 km inland: the two southerly branches have been mapped for several kilometres further inland (Fig. 1) and continue to downthrow to the east. The Red Cliff Fault downthrows about 37 m to the west (Fox-Strangways, 1904) and is probably continuous with the Hunmanby Fault further south.

Between the two faults, though lying closer to the Red Cliff Fault, is another fault line whose northern extremity is seen at Castle Hill, Scarborough. Here two faults converge on the northern part of the headland; the overall downthrow is to the east but the area between the branches forms a small horst (illustrated by Kendall & Wroot, 1924, p. 770). The fault probably continues beneath South Bay to link with the westerly downthrowing (60 m) fault at White Nab which branches south-southeastwards into a more complex faulted zone in Cayton Bay (Wright, 1968, fig. 9). At the north end of Cayton Bay the downthrow of the main fault appears to be over 150 m to the west, but the throw diminishes rapidly southward as the fault splits.

At outcrop the Peak Fault affects Lower to Middle Jurassic rocks, while the more easterly faults cut Middle to Upper Jurassic strata. Discussion on the age of the faulting has centred on the Peak Fault; Hemingway (1963, 1974) has argued that this is a Tertiary transcurrent fault with a dextral displacement of about 8 km while other workers have recognized Jurassic movement (e.g. Fox-Strangways, 1892; Kendall & Wroot, 1924; Ager, 1980).

Syn-depositional Jurassic movement is indicated by facies and thickness changes from flanking areas into the Peak Trough, though the surface expression of the trough may have been slight. The changes first become apparent in the Toarcian sequence (Lower Jurassic: Table 1), marked initially by minor lithological changes in the Jet Rock and Alum Shale members across the Peak Fault. The latter member also thickens slightly into the trough immediately southeast of the Peak (Howarth, 1962). Much more obvious is the preservation in the same part of the trough of younger Toarcian strata (Peak Member to Blea Wyke Formation); they are missing immediately to the west, where on the upthrow side of the Peak Fault Dogger Formation sands (Middle Jurassic) rest directly on the

STAGE / SUBSTAGE	LITHOSTRATIGRAPHIC UNIT		max thickness
LOWER OXFORDIAN (pars)	Lower Calcareous Grit Fm		42 m
	Oxford Clay Fm		30 m
CALLOVIAN	Osgodby Fm		25 m
	Upper Cornbrash		6 m
BATHONIAN	?	?	
UPPER BAJOCIAN	Ravenscar Group [mainly NM]	Scalby Fm [NM]	65 m
LOWER BAJOCIAN		Scarborough Fm	30 m
		Cayton Bay Fm 12 m > Cloughton Fm [NM]	85 m
		? Eller Beck Fm	4 m
AALENIAN		Hayburn Fm [NM]	57 m
	Dogger Fm		12 m
TOARCIAN	Blea Wyke Sandstone Fm		18 m
	Whitby Mudstone Fm	Fox Cliff Siltstone Mbr	11 m
		Peak Mudstone Mbr	13 m
		Alum Shale Mbr	37 m
		Jet Rock Mbr	31 m
		Grey Shale Mbr	14 m

Table 1. Subdivision of Toarcian to Lower Oxfordian sediments

Alum Shales Formation. The Dogger Formation itself is only 0.3–0.6 m thick west of the Peak Fault but thickens to as much as 12 m in the Peak Trough.

After deposition of the Dogger Formation fluviodeltaic sediments prograded over the area from the north to deposit the Ravenscar Group; interfingering with these predominantly non-marine sediments are some southerly-derived marine beds (Table 1). Fault movement continued to affect sedimentation (Farrow, 1966; Knox, 1973; Holloway, 1985; Alexander, 1986). Thus the Hayburn (or Saltwick) Formation thickens from 30 m west of the Peak Fault to 57 m in the trough (Hemingway, 1974). There is little evidence of any tectonic influence on deposition of the thin Eller Beck Formation (Knox, 1973) but the lower part of the Cayton Bay Formation (Millepore Beds) is thicker within the trough (Hemingway & Riddler, 1982). When the Scarborough Formation accumulated the Peak Fault acted as a hinge with progressive downwarping on the eastern side, where there is evidence of contemporaneous slumping in one bed only a few hundred metres from the fault (Farrow, 1966). Here the formation reaches its maximum thickness of 31.7 m, compared with a probable maximum to the west of 15 m (Fox-Strangways, 1982). It thins steadily south-southeastward across the trough from Peak to White Nab and then more rapidly over the Red Cliff Fault onto the eastern shelf at Low Red Cliff and Gristhorpe (Farrow, 1966, fig. 3). The latter sections lay well away from the Jurassic coastline and out of the reach of tractive currents (Farrow, 1966, p. 129).

Alexander (1986) suggested some tectonic control on deposition of the overlying non-marine Scalby Formation, though the faults probably failed to break surface and their topographic expression was never more than a metre or two. Her idealized flow model showed a trough between the Peak and Red Cliff faults, draining southward. Within the trough a meander belt developed (Nami, 1976) while over the eastern flank overbank deposits predominate south of Yons Nab (Alexander, 1986).

Following the early Callovian marine transgression, sedimentation of the Osgodby Formation was accompanied by extensive intraformational erosion. The most complete sequence occurs within the Peak Trough, while maximum erosion occurred on the shelf to the east of the Red Cliff Fault, at Cunstone Nab (Wright, 1968, fig. 2, p. 397). In early Oxfordian times an earthquake shock wave apparently produced the convolute bed in the Lower Calcareous Grit at the same locality (Wright, 1983, p. 257).

The Hunmanby Fault apparently continues the line of the Red Cliff Fault; it throws Upper Cretaceous Chalk against the Lower Cretaceous Speeton Clay, indicating an extended history of movement and supporting Hemingway's (1963) suggestion of Tertiary faulting in the area. This would have been generated during the major early Tertiary inversion of the Cleveland Basin (Hemingway & Riddler, 1982).

3. The offshore seismic sections

The JEBCO seismic sections show the expected intense deformation associated with the Howardian–Flamborough Fault Belt at the southern margin of the Cleveland Basin, but within the basin itself there is almost no faulting of Permian or younger sediments. The strong reflections associated with Zechstein carbonates, notably the Seaham Formation (Upper Magnesian Limestone/Plattendolomit), constitute excellent marker horizons, as they do through virtually the whole of the southern North Sea; they tie satisfactorily to the logs of all the released wells within the area covered by the JEBCO survey. North of Flamborough Head the Zechstein strata appear to be gently folded, with fold wavelengths of 10–20 km, and rise gradually to seabed subcrop in the area to the north of the mouth of the Tees. Considerable thicknesses of salt have been recorded in wells offshore from Scarborough (for example, 513 m of 'Stassfurt Halite' in the Lower Evaporites in Well 41/20-1) but there are only occasional indications of salt tectonism. The Zechstein reflectors tend to mask deeper horizons, but it is generally possible to identify structure in the Carboniferous rocks beneath the Variscan unconformity.

The simple regional pattern is disrupted locally by a narrow faulted trough which trends at about 330° and gradually converges on the coast from the north

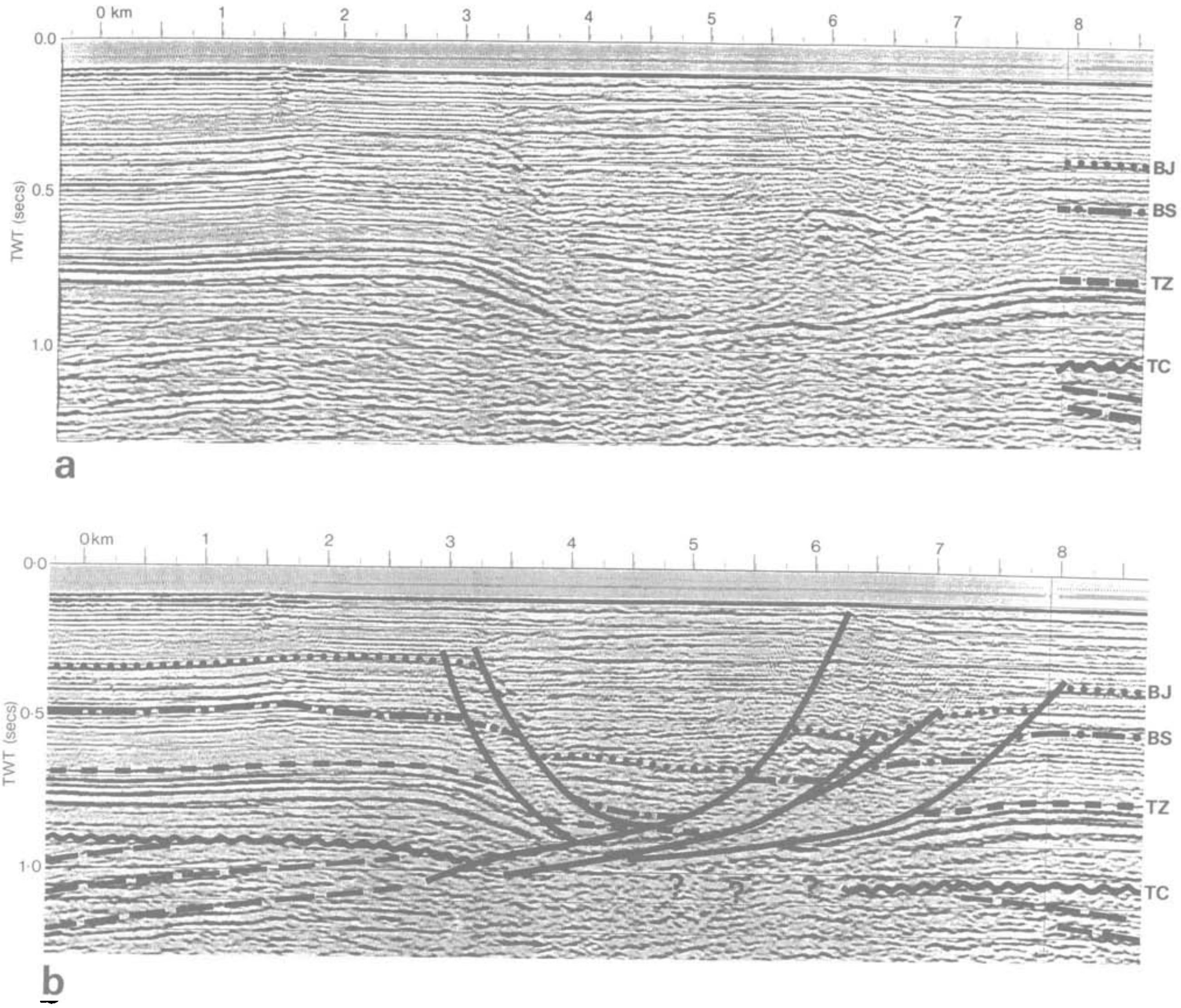

Figure 2. Migrated seismic section at right angles to the Peak Trough, offshore Whitby, uninterpreted (a) and interpreted (b). Dashed lines below the TC (Top-Carboniferous unconformity) indicate trends in Carboniferous reflectors. TZ is the top of the Zechstein evaporites, BS the top of the Bunter Shales and BJ the base of the Jurassic. Interpreted fault traces are displaced slightly from their most likely positions to allow display of some of the evidence for faulting. The thickening of the Upper Triassic interval at between 1.5 and 3 km on the distance scale suggests erosion of an uplifted graben wall, but this is only one possible interpretation of the consequences of movement in the region of minor faulting at about 1.5 km; if substantiated it would imply that some movements in the area pre-date Jurassic time.

(Fig. 1). The western boundary fault forms the natural offshore continuation of the Peak Fault, while the eastern margin can be extrapolated to link with the Red Cliff Fault. Other faults on the eastern side of the trough represent the Scarborough Castle Hill to Cayton system or its equivalents. Full analysis of the fault patterns would require three-dimensional imagery and the detailed problems presented cannot be solved using only the existing five-kilometre grid. Sediment masses must be assumed to have moved laterally into and out of the plane of section.

Eight seismic sections intersect the trough, although a number of these show only the eastern margin. Three are illustrated here. Critical analysis of the timing and amount of subsidence within the Peak Trough is limited by the absence of boreholes within it, the problem of recognizing reflectors younger than base Jurassic and the difficulty of correlating reflectors within and outside the trough because of changes in seismic character. However, the latter changes are in themselves some indication of fault movements having influenced Mesozoic sedimentation, and there may be sediments preserved within the trough that are absent elsewhere.

Figure 2 shows a migrated seismic section along a line which crosses the trough roughly at right angles about 10 km northeast of Whitby. The dipping reflection events seen at depth beneath the Zechstein beds on either side of the disturbed zone indicate that in this area at least the trough coincides with the apex

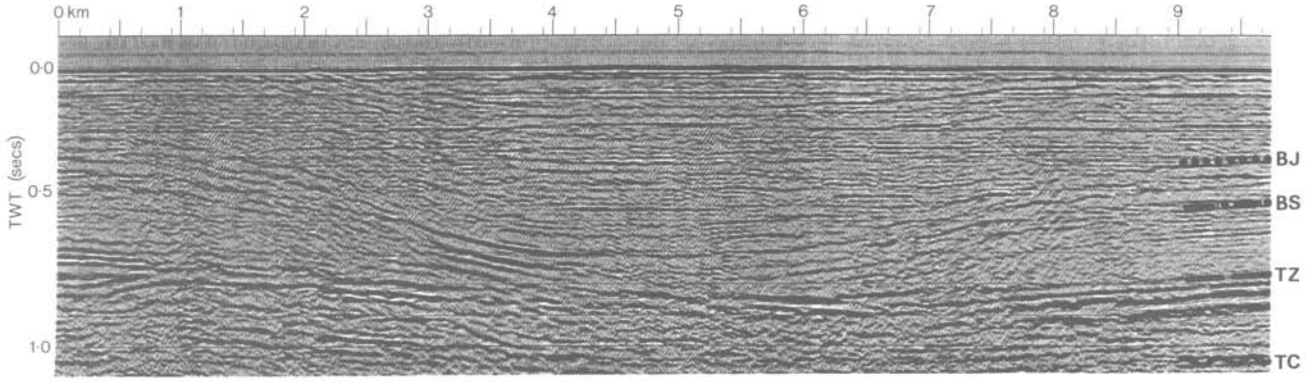

Figure 3. Migrated seismic section sub-parallel to the Peak Trough, near its northern end. Jurassic reflectors are synformal and cut across the strong multiple events which are a persistent problem in this area. Fault pattern is not indicated since a line with this orientation will not image meridional faulting accurately and the distortion will not be corrected by migration. Note that in this area the top of the Zechstein, although slightly disrupted by the faulting, has suffered almost no vertical displacement.

of a Carboniferous anticline. The Carboniferous events, and even the prominent and usually easily identified Zechstein reflectors, largely disappear within the disturbed zone, but the subsidence at Top Zechstein level amounts to at least 200 msec TWT. Although no wells have been drilled within the trough, and hence no time–depth relationship can be derived for the sediments within it, data from wells nearby suggests that this 200 msec is equivalent to more than 300 m of subsidence.

The pattern at Top Zechstein level outside the subsided zone is also interesting. The regional dip of this horizon is gently ESE, and indeed, were the data displayed in Figure 2 to be excised from the full section of which it forms a part, there would be no reason to postulate any significant changes of dip within the missing 9 km. However, about 3 km from the bounding faults, on both sides of the trough, the Top Zechstein bends noticeably upwards, this bend being sharply reversed at the margins of the subsided zone.

Apart from the rather slight peripheral changes in dip and some very minor faulting, deformation is confined to a zone approximately 5 km wide. The basic fault pattern is reasonably discernible along the margins of the trough, although where, and even if, the faults sole out is uncertain. There does appear to have been decoupling between deep faulting at sub-Zechstein level and extensive movements within the Mesozoic sediments, and low-strength layers along which such decoupling could have taken place are abundant. Salt may have played a significant role, and salt escaping from the Zechstein into higher regions could have lubricated faults in beds normally resistant to shear. The Triassic Bunter Shales/Saliferous Marls and much of the Jurassic strata also contain thick shales which could provide slip planes at a multitude of levels.

The existence of shallow decollements is confirmed by a section obtained along a line sub-parallel to the trough axis (Fig. 3). This is the only one of the NNW-directed set of JEBCO lines to enter the disturbed zone. Because it is sub-parallel to the trough axis and many of the events will have been generated by off-line reflections, the uninterpreted section is shown; it is not realistic to define fault locations on such a line. There seems to be very little displacement of the top of the Zechstein in this area, which is near the extreme northern end of the trough, but there are gaps where the normally strong reflectors virtually disappear. These may mark zones of faulting and possibly of salt escape. The synclinal nature of the overlying deformation is in part an artefact of line orientation but the dipping events indicated do at least allow the extent of subsidence affecting the Mesozoic sediments to be estimated. Again, 200 msec would seem to be a minimum estimate and must have been achieved almost entirely by shifting material southwards along the line of the trough, to areas where the Zechstein is also depressed.

The line illustrated in Figure 4 trends directly towards Cloughton Wyke and was the most southerly to show any part of the trough. The western margin (Peak Fault) lies west of the line-end and has passed onshore. The Mesozoic sediments are extensively faulted, whereas the Zechstein reflectors are merely downwarped, dip surfaces in the evaporites apparently providing decollements for rotational faults cutting the overlying sediments. It is hard to make an interpretation which does not involve at least the amount of downfaulting of the Bunter Sandstone and base Jurassic level shown in Figure 4, and the amount by which the Zechstein strata are depressed seems very clear. However, at the coastal outcrops in Cayton Bay only a few kilometres further south, the total displacement of the Middle to Upper Jurassic sequence is less than 200 metres. Displacements may be very different at base and mid Jurassic levels, suggesting an intervening Lower–Middle Jurassic phase of movement.

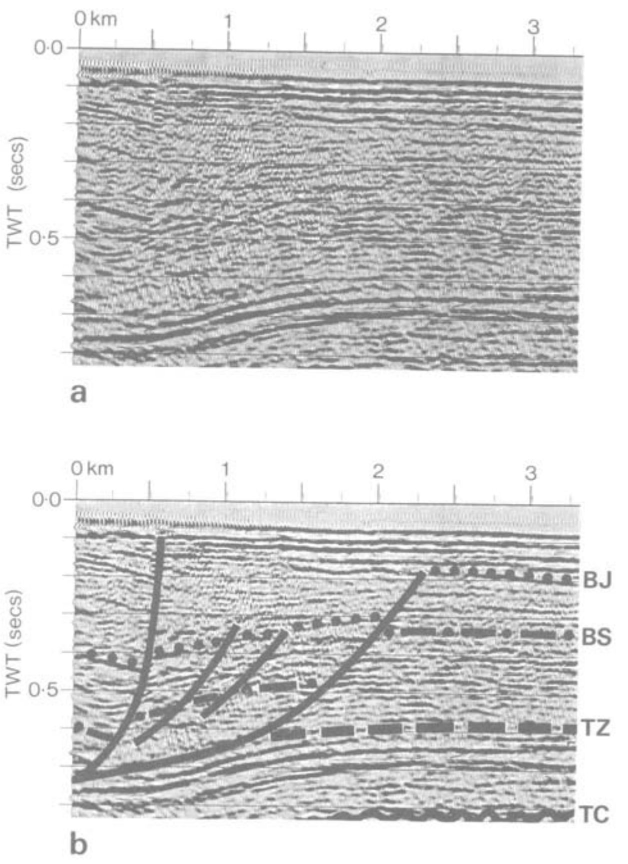

Figure 4. Migrated seismic section, offshore to the north of Scarborough, uninterpreted (a) and interpreted (b). This is the southernmost line from the JEBCO data to show any part of the Peak Trough. At this point the Peak Fault has already passed onshore, while the more easterly of the two main faults shown is maintaining a steady trend towards Red Cliff. Note the excellence of the markers provided by the Zechstein carbonates.

4. Discussion

The seismic sections illustrated define a complex zone of extensional faulting along and sub-parallel to the North Yorkshire coast. To the south the onshore extension of the trough would impinge almost at right angles on the Howardian–Flamborough Fault Belt, itself extremely complex (Kirby & Swallow, 1987). To the north, the faulting appears to die away a few kilometres beyond the seismic line illustrated in Figure 2 and the trough disappears; there is some indication that it may merely be offset to the east, and then continue northward out of the area covered by the JEBCO inshore survey. Its origin is not known, but some of the sections resemble those imaging flower structures associated with transtensional strike-slip faults. The variability in width of the trough could then be associated with variations in orientation of an underlying deep-seated fracture.

An interesting feature in its own right, the trough also has considerable regional geological significance. The nature of the Peak Fault has long been a matter for debate; it can now be seen to be merely a marginal fault to a zone which affects the coast southwards almost as far as Filey. The combined evidence from onshore and offshore areas indicates that there was active fault movement during Mesozoic times. This would fit the regional history of the North Sea basin, which is cut by several north–south trending Mesozoic grabens on various scales, of which the Peak Trough would be the most westerly.

Faulting of the Peak Trough apparently started during the Triassic period and was renewed in mid Jurassic time (mid Cimmerian movements), probably in latest Jurassic–earliest Cretaceous time (late Cimmerian movements) and again during the inversion of the Cleveland Basin in early Tertiary times. Such a long history of intermittent movement parallels the evolution of other grabens in the North Sea basins. Although regional considerations would suggest some transcurrent movement along the various faults during the inversion phase, a model invoking Tertiary lateral movement *alone* does not appear appropriate.

The implication of the new evidence is that the Jurassic rocks extensively exposed along the coast between the Peak and Red Cliff faults accumulated in an intermittently moving fault trough, and therefore the sedimentary infill is not necessarily typical of the major part of the Cleveland Basin. It may, on the other hand, provide an even closer model for comparison with the Brent Group of the Viking Graben than previously supposed.

Acknowledgements. We are grateful to JEBCO Seismic Ltd for making available their full seismic coverage of the Peak Trough, and for permission to reproduce the sections shown in Figures 2, 3 and 4. Janet Baker drew Figure 1 and annotated the seismic sections, while an anonymous referee made valuable improvements.

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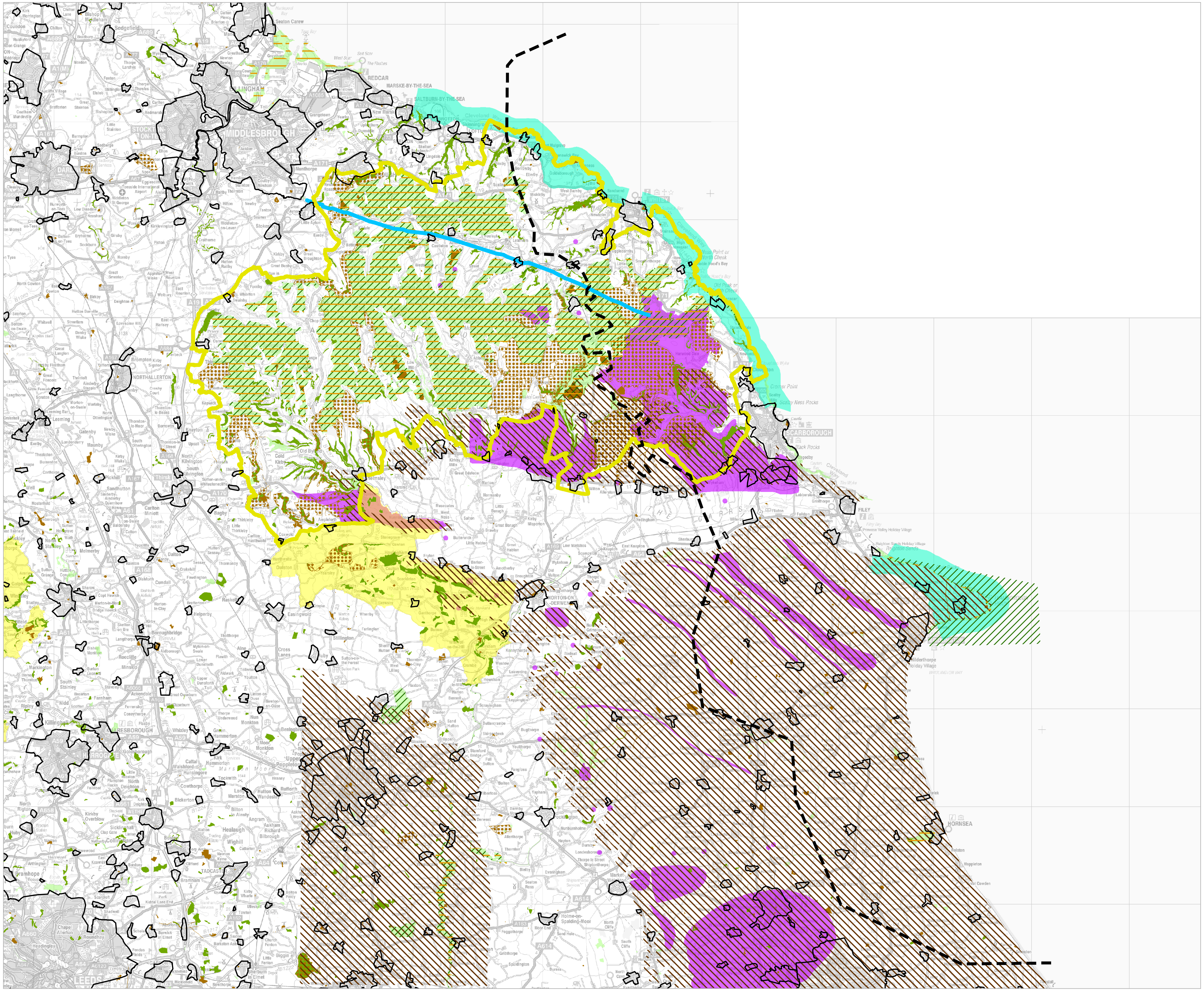
Appendix 12

ASA Environmental Constraints Mapping



Key

Environmental Constraints

- ▭ North York Moors National Park
- - - Estimated Extent of Onshore Polyhalite
- ▤ Special Protection Area
- ▨ Special Area of Conservation
- 🟩 Ancient Woodland
- 🟨 AONB
- 🟩 SSSI
- 🟦 Heritage Coasts
- 🟫 Scheduled Monument
- ▨ Principal Aquifer (Bedrock)
- 🟪 Source Protection Zone
- ━ Cleveland Dyke
- ▦ Forestry Commission Land
- ▭ Settlement Boundaries

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nlp Nathaniel Lichfield & Partners
Planning. Design. Economics.

Project Minehead Alternative Sites Assessment

Title Stage 2: Environmental Constraints Mapping

Client York Potash Limited

Date 10.04.2014

Scale -

Drawn by MAR

Drg. No GIS50303/04-07

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GIS Reference: S:\LE50274 - York Potash Minehead\LE50303-04 - York Potash Minehead - Environmental Constraints - Map 7 - 18.12.2013.mxd

Appendix 13

ASA Environmental Constraints Shadow Mapping
