Carboniferous exploration & development in the UK Southern North Sea

Successes and failures - a 30 year retrospective

Bernard Besly
Keele University / Besly Earth Science Ltd

https://t2m.io/44QfSBo7
Avant propos

Introductory comments and apologies

5 founding myths

Winding up comments

ACKNOWLEDGEMENTS

The following companies and individuals are thanked for discussion and material assistance over a period of many years.

UK activity since 1984

± 143 exploration wells with Carboniferous targets

± 37 discoveries
27 named fields placed on production
3.6 TCF recoverable gas

Gas generally contains high $\text{N}_2$ and in some cases high $\text{CO}_2$

Development slow

Some field performances disappointing

After c. 10 years perception that Carboniferous “difficult” and risky

In same period two significant gas discoveries in UK onshore
UK Southern North Sea; known unknowns

Published BGS analysis 2001

- 285 prospects > 500 acres
- 148 with P50 > 50BCF
- 127 in open acreage

Total unrisked P50 volume c. 17.5 TCF (7.8 TCF in open acreage)

- 72 base Permian closures
- 213 intra-Carboniferous traps

- 7 of the prospects in open acreage have since been drilled
- 4 discoveries
Carboniferous play elements

**HYDROCARBONS**
- Export to younger reservoirs

**RESERVOIRS**
- Westphalian red beds
- Fluvial / deltaic sandstones in Late Namurian to Westphalian
- Fluvial / deltaic sandstones in Early Namurian and Late Visean

**SEALS**
- Lacustrine Permian Sub-regional
- Multiple potential marine & lacustrine shale seals within Carboniferous

- Extremely thick succession (?) > 6.5 km
- Complex stratigraphy
- Nature of “Carboniferous play” different in different areas depending on subcrop
Founding myth 1

“The gas comes from Westphalian coals”

Maturity pattern dominated by effects of Mesozoic and Tertiary inversion

Many fields are remote from mature source in Carboniferous immediately beneath u/c

Some fields are remote from Westphalian subcrop
What source rocks? What maturities?

Carbon isotope data imply much of the gas is sourced from sapropelic source rocks at maturities of VR 2.0 – 2.5

Maturity / volatile matter relationships in coals show significant expulsion of gas in maturity range VR range 1.4 – 3.0
Results of North Yorkshire drilling campaign show that working gas charge does not depend on presence of coals

Abundant type III kerogen present as disseminated plant material throughout non-coal lithologies

TOC in thick shale units generally not $> 3\%$ (even in Lancashire ‘shale gas’ objectives)

Low TOC compensated by very large thickness

TOC and petrophysically-derived TOC from offshore well 43/21-2, Gent 2015
Founding myth 2

“Intra-Carboniferous seals are risky”

Potential seals within Carboniferous: thin marine shales or silty slope or delta top muds

- generally perceived to have high integrity risk
- silt content / vulnerability to minor faulting

Saltfleetby Field demonstrates that intra-Carboniferous seals can be effective

Intra Carboniferous traps are viable even where overlying Rotliegend is in non-seal facies

Image of geological section showing layers of rocks with labels for Permian, Zechstein, Rotliegend, Coal Measures, Amalae Marine Band (= SEAL), and Carb Limestone.
Intra-Carboniferous seals in combination traps

PEGASUS FIELD – 43/12 & 43/13
- Composite anticlinal trap requiring on both Silverpit and intra-Carboniferous seals; no closure at base Permian
- Multiple contacts and possibility of stacked pay
- Multiple reservoir/seal combinations can lead to unexpected trap geometries with stratigraphic component
Potential seals formed by Marine Bands, interdistributary bay fills, lacustrine shales
- Retention capacities up to 500 metres, more usually ± 300 metres
- Capacity may be impaired by presence of silt
- Not usually more than 15 metres thick - all potential seal facies vulnerable to erosion
Intra-Carboniferous seal integrity

- Marine horizon affected by soil formation – poor seal potential
- Thick marine horizon – no soil modification – 4 metres good seal potential
- Best seal: high GR, high RHOB, mod NPOR
- Thin heterolithic marine horizon – poor seal potential
- Poor seal: high GR, mod RHOB, high NPOR
Sub-seismic faulting and seal integrity - 1

Faults in 20 km² area proved by coal mining, Yorkshire Coalfield, filtered by maximum throw

Bailey et al. 2002

- Mining records show fractal distribution of faulting with large number of faults below seismic resolution
- 3D reservoir modelling of Yorkshire dataset implies fault juxtaposition significantly enhances sand body connectivity even in very low net:gross succession
- Sub-seismic faulting is major risk in intra-Carboniferous seal breach
- To reduce risk associated with intra-Carboniferous seals it would be desirable to demonstrate seals of suitable lithology having thicknesses of > 5 metres
Comparison of mining and offshore seismic datasets suggests lower limit of fault throw resolved by seismic is between 5 and 10 metres.

Yorkshire dataset, throw > 5 m

Faults in 20 km² area, SE Quad 44, mapped from 3D seismic

After Cameron et al 2005

Yorkshire dataset, throw > 5 m (black) + throw > 1 m (blue)

Faults imaged by coherency extraction, 20 km² area, NL Quad E

Ter Borgh et al 2018
Potential sealing lithologies abundant at all levels in Westphalian Coal Measures and upper part of Namurian

Almost all are extremely thin and vulnerable to minor faulting and/or incision

Potential seal horizons are present even in sections without marine flooding events
Thick shale units are preferentially developed in lower part of Westphalian A and in upper part of Namurian.

Already known to be effective seals in Pegasus, Cavendish, Kepler.

Define a fairway involving Carboniferous sealing in this part of Carboniferous succession.
Maltby Colliery, Yorkshire, Westphalian A coal seam
- VRe c. 0.65 – 0.8
- in footwall of Gainsborough Trough bounding fault
- known minor gas influxes associated with NW – SE trending fractures

Major 2012 gas influx where tunnel intersected gas-bearing fracture system within closure

Sub-regional in-situ stress data implies NW – SE fractures currently in extensional regime
Saltfleetby Field – a working intra-Carboniferous top seal

Base Westphalian A reservoir

Variscan structure, no Mesozoic modification, tilted during Tertiary

Seal formed by *G. amaliae* Marine Band – c. 8 metres thick

Most faulting parallel to present $\sigma_1$

Hodge 2003
Founding myth 3

"Carboniferous production is from fluvial reservoirs"

Porosity trend related to burial before Variscan inversion

Enhancement due to leaching at Variscan unconformity surface
Reservoir quality trends – older reservoirs

- Log analysis of two UK landwells supports Bailey *et al.* porosity model.
- Although sandstones in deeper parts of basin fill are generally very tight there are exceptions.
- Cut-off for 1 mD permeability at 10% porosity.
Formation damage skews perception of reservoir quality

Formation damage during drilling reduced by careful attention to mud system
Excess overbalance + imbibition of WBM filtrate in clay-prone reservoir creates excessive skin
Use of OBM leads to 10 x productivity increase

42/13-2 - 1997
Heavy salt brine mud
400psi overbalance
155 ft perf (5 intervals)
Max flow 3.0 MMscfd
Skin +47 (+24 - +175)
WBM filtrate invasion up 60 inches

42/13-3 - 2007
Oil-based mud
Minimal overbalance
110 ft perf
Max flow 17.6 MMscfd
Skin 0 - +2
Negligible invasion
Long-term performance of UK Carboniferous reservoirs has shown very wide departures from what was expected.

Boulton B and Schooner: faulting has increased connectivity
  • improved reservoir performance in Boulton B; deleterious in Schooner

Trent: reservoir thought to be petrophysically poor may have contributed to production + faulting may have increased connectivity
“Carboniferous production is from fluvial reservoirs”

What constitutes a Carboniferous reservoir objective?

Implications of unconventional gas exploration in UK onshore

Kirby Misperton Deep:
- unconventional resource contained within a ‘hybrid play’
- thin bedded heterolithics and tight turbidite sands
- naturally fractured silica-rich sandstones interbedded with organic-rich shales
- brittle lithologies suitable for fracture stimulation

Pay not recognised in conventional log analysis

Hughes et al. 2018
Founding myth 4

“Basin geometries are known”

Map of depocentres and highs in Carboniferous basin complex compiled from combination of seismic interpretation and gravity modelling

Most commonly presented map based on 3 sources:

- Fraser & Gawthorpe 2003 UK onshore
- Corfield et al. 1995 UK offshore
- Kombrink et al. 2010 Netherlands

Note that, away from well penetrations, base Carboniferous is poorly imaged in basinal areas
Founding myth 4

“Basin geometries are known”

Alternative interpretations put basinal depocentres in very different places.

No consensus even on position of southern edge of “Mid North Sea High”.

Features interpreted as granites from gravity data locally interpreted as basinal depocentres.
Founding myth 5

“Basins formed in rift and sag episode(s)”

Leeder 1982, 1988; Fraser & Gawthorpe 2003

Foreland thrust loading + dynamic topography (Kombrink et al. 2008)
Partitioned strain in long-lived regional transtensional regime (de Paola et al. 2006)

B Besly  Keele University

EBN Exploration Conference 2018  21 November 2018  26
Plays – timing

Leeds Basin (UK onshore)
- Variscan structure
- Neogene modification
- Base Namurian
- max burial in Variscan cycle
- Major Cret – Neogene uplift

Cleveland Basin (UK Q42)
- Variscan structure
- Modified in Cimm / Neogene
- Base Namurian
- max burial in Cret
- major uplift in Neogene

Silverpit Basin (UK Q44)
- Variscan structure
- Cimmerian modification
- Top Westph Coal Measures
- currently at max burial
Importance of quantifying pre-Permian exhumation

Alternative burial histories – Upholland-1 (UK onshore)

VR profile + modelled maturity profiles

Alternative burial histories – Upholland-1 (UK onshore)
Final comments

The Carboniferous is a complex system that needs to be unravelled

- hugely thick succession
- stratigraphic and palaeogeographic evolution mean that succession is very different in different parts of the basin complex
- multiple sub-basins
- complex histories of subsidence, fill and burial
- multiple source rocks – full of hydrocarbons

Nature of petroleum systems

- not a single play
- different fairways
- need for fine-tuned approach – more focussed recognition of specific play segments

Learning from past experience

- better drilling practices
- greater appreciation of the value of technical studies
- need to conserve knowledge and pass it on to new generations