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Direct hydrocarbon indicator mapping, offshore Nova Scotia [Project 400-111]

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prepared by

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Contents

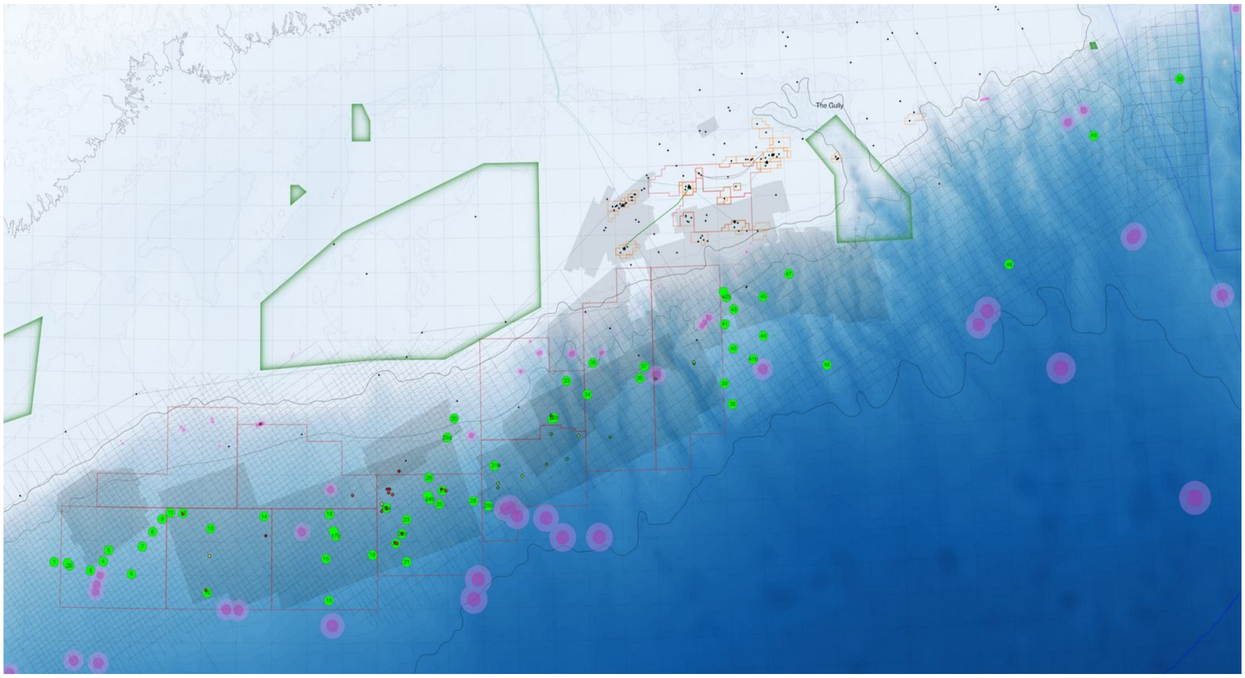
Project introduction

Direct hydrocarbon indicators (DHIs) — more properly thought of as seismic anomalies without some validation from wells — can help with all parts of the petroleum exploration process:

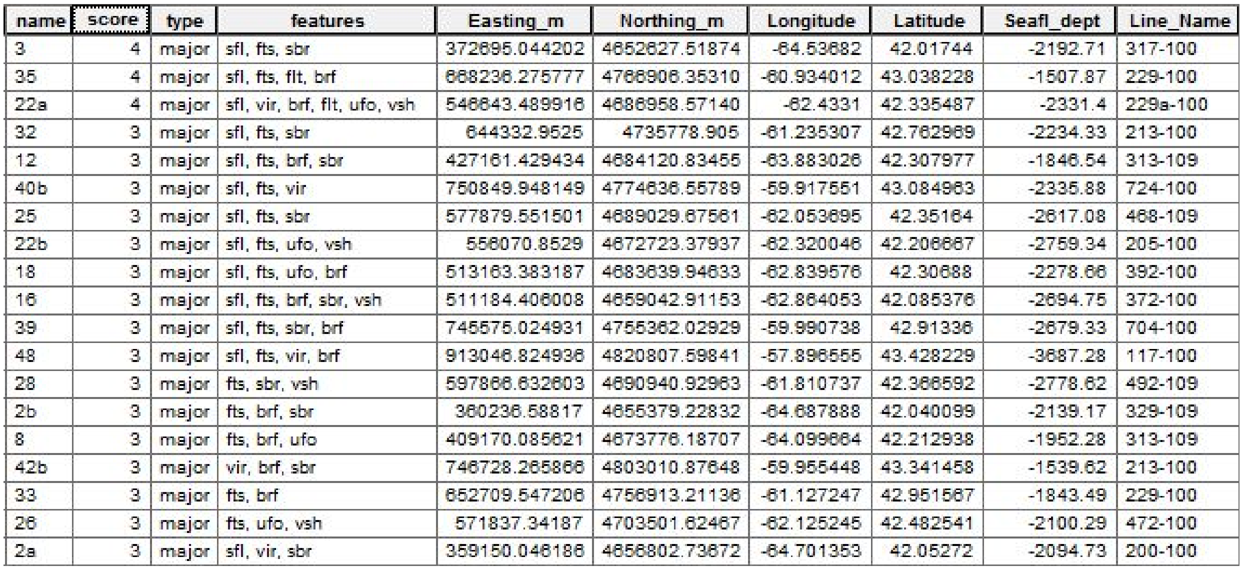
- Finding promising places to explore.
- Finding places to sample the seabed for leaking hydrocarbons.
- Calibrating rock physics models for seismic analysis (lithology and fluid prediction).
- Focus attention on promising areas for seismic reprocessing.
- Finding promising places to drill.
- Calibrating models of subsurface risk, especially with respect to source, migration, and trap risk.
- Mapping shallow drilling hazards.
- Finding promising places for field appraisal and development.

A few candidate direct hydrocarbon indicators were identified as part of the SW NOVA Extension project, published in June 2015. Plate 5.3.1.6 shows five candidate DHIs.

In the May 2015, Agile produced maps and a geodatabase of possible hydrocarbon leakage features offshore Nova Scotia:



Candidate hydrocarbon leakage features (green), and likely natural slicks (purple).



name	score	type	features	Easting_m	Northing_m	Longitude	Latitude	Seafl_dept	Line_Name
3	4	major	sfl, fts, sbr	372695.044202	4652627.51874	-64.53682	42.01744	-2192.71	317-100
35	4	major	sfl, fts, flt, brf	668236.275777	4766906.35310	-60.934012	43.038228	-1507.87	229-100
22a	4	major	sfl, vir, brf, flt, ufo, vsh	546643.489916	4686958.57140	-62.4331	42.335487	-2331.4	229a-100
32	3	major	sfl, fts, sbr	644332.9525	4735778.905	-61.235307	42.762969	-2234.33	213-100
12	3	major	sfl, fts, brf, sbr	427161.429434	4684120.83455	-63.883026	42.307977	-1846.54	313-109
40b	3	major	sfl, fts, vir	750849.948149	4774636.55789	-59.917551	43.084963	-2335.88	724-100
25	3	major	sfl, fts, sbr	577879.551501	4689029.67561	-62.053695	42.35164	-2617.08	468-109
22b	3	major	sfl, fts, ufo, vsh	556070.8529	4672723.37937	-62.320046	42.206667	-2759.34	205-100
18	3	major	sfl, fts, ufo, brf	513163.383187	4683639.94633	-62.839576	42.30688	-2278.66	392-100
16	3	major	sfl, fts, brf, sbr, vsh	511184.406008	4659042.91153	-62.864053	42.085376	-2694.75	372-100
39	3	major	sfl, fts, sbr, brf	745575.024931	4755362.02929	-59.990738	42.91336	-2679.33	704-100
48	3	major	sfl, fts, vir, brf	913046.824936	4820807.59841	-57.896555	43.428229	-3687.28	117-100
28	3	major	fts, sbr, vsh	597866.632603	4690940.92963	-61.810737	42.366592	-2778.62	492-109
2b	3	major	fts, brf, sbr	360236.58817	4655379.22832	-64.687888	42.040099	-2139.17	329-109
8	3	major	fts, brf, ufo	409170.085621	4673776.18707	-64.099664	42.212938	-1952.28	313-109
42b	3	major	vir, brf, sbr	746728.265866	4803010.87648	-59.955448	43.341458	-1539.62	213-100
33	3	major	fts, brf	652709.547206	4756913.21136	-61.127247	42.951567	-1843.49	229-100
26	3	major	fts, ufo, vsh	571837.34187	4703501.62467	-62.125245	42.482541	-2100.29	472-100
2a	3	major	sfl, vir, sbr	359150.046186	4656802.73672	-64.701353	42.05272	-2094.73	200-100

The attribute table showing the top (most likely) seep features.

Direct hydrocarbon indicators were a small component of that study, but only in the shallowest 1000 ms (about 800 m) below the seafloor, and only seaward of the shelf edge. Despite this, the work indicated that there are substantially more candidate DHIs in the area than the SW NOVA work suggested. Furthermore, the seismic data support mapping direct hydrocarbon features at much greater depth. We therefore proposed extending this work to greater seismic travel times and to the continental shelf.

The result of the work is a substantial and comprehensive database of recorded direct hydrocarbon indicators offshore Nova Scotia. We hope this will be useful and interesting to anyone exploring off Nova Scotia.

We further proposed using the project to inform an extended plan of sub-basin and/or field scale evaluation in 2016. We now propose using the insights from this project, in collaboration with Department of Energy and OERA staff, to focus such continued work.

Project summary

Workflow

Our approach was as follows:

1. To help establish that at least some anomalies are likely hydrocarbon related, build a well log database, then use seismic rock physics approaches, including log modeling and forward seismic models. This was a substantial amount of work, not least because the basic well data had to be collated, QCd, and reconciled with stratigraphic data before the modeling and analysis could be performed.

2. Build the Petrel project, seismic attributes, 'helper' horizons, etc. This took longer than anticipated because the Seeps project was no longer available at the Dept. of Energy.
3. Interpret candidate DHIs on the data using standard seismic interpretation techniques (chiefly horizon picking). This provided amplitude, apparent polarity, and anomaly size. Other attributes were computed from the interpreted data.
4. Export the data from Petrel to text and then to Python and shapefiles, using scripts we developed for the Seeps project.
5. Generate new attributes from the data, such as location, travel time below mudline, amplitude above background, and so on.
6. Spatially join the attributes to the features.
7. Produce an atlas, in the form of a geodatabase and shapefile, containing all of the results. This geodatabase would be fully quantitative, and reflect uncertainty as well as observation.
8. Provide recommendations for how to make use of this work in pursuit of OERA’s other goals, along with an extended plan of sub-basin and/or field scale evaluation in 2016.

Literature review

We have performed a literature review of the topic (see Bibliography). Compared to the related topic of hydrocarbon leakage, there is relatively little new research in the field, and almost no results on this geographic area. The lack of new research probably reflects the mature state of the research into amplitude and amplitude-vs-offset (AVO) anomalies in reflection seismic. The lack of results from the east coast of Canada is perhaps a consequence of this kind of work usually being proprietary. We will provide PDFs of the articles in the bibliography at the end of the project.

The chief outcome of the review has been to identify the following types of direct hydrocarbon indicator (after Brown, 1991):

Description	**Type of DHI**
Local increase in amplitude	Bright spot
Local decrease in amplitude	Dim spot
Discordant flat reflector	Flat spot
Local waveshape change	Polarity reversal
Low frequencies underneath	Attenuation shadow
Time sag underneath	Velocity sag
Lower amplitudes underneath	Amplitude shadow
Increase in amplitude with offset	AVO anomaly (see below)
P-wave but no S-wave anomaly	S-wave support (see below)
Data deterioration	Gas chimney (see below)

Of these, we anticipate that the following will be the most reliable indicators in this project, given the dataset and the geology; each carries some risk or uncertainty:

- Bright spots — potentially attributable to many other causes, e.g. tuning, low-saturation gas, cementation.
- Dim spots — can be hard to spot, especially in poor data.
- Flat spots and polarity reversals — rare because they need particular conditions.

Note that only the stacked data are available so we are unable to consider AVO effects and S-wave support.

Note also that gas chimneys were considered in the 'seeps' study in 2015, along with many other leakage-related phenomena. Rigorously reconciling the results of this study with the seeps study — for example by uplifting the seeps with their proximity to an anomaly — would be a good topic for a future study.

Rock physics project

We selected 16 out of the set of 20 wells used in the seismic calibration study (Chapter 5.2) of the 2011 Play Fairway Analysis (PFA) to perform a preliminary investigation of the effect of rock properties on seismic responses. We chose to focus only on siliciclastic lithologies, and excluded zones consisting mostly of carbonates or salt. Albatross B-13, Bonnet P-23, Glooscap C-63 and Shelburne G-29, which are present in the PFA compilation, were filtered out of the analysis. The wells we used were:

- Alma F-67
- Annapolis G-24
- Balvenie B-79
- Chebucto K-90
- Cohasset L-97
- Crimson F-81
- Dauntless D-35
- Evangeline H-98
- Glenelg J-48
- Hesper P-52
- Newburn H-23
- Shubenacadie H-100
- South Griffin J-13
- Tantallon M-41
- West Esperanto B-78
- Weymouth A-45

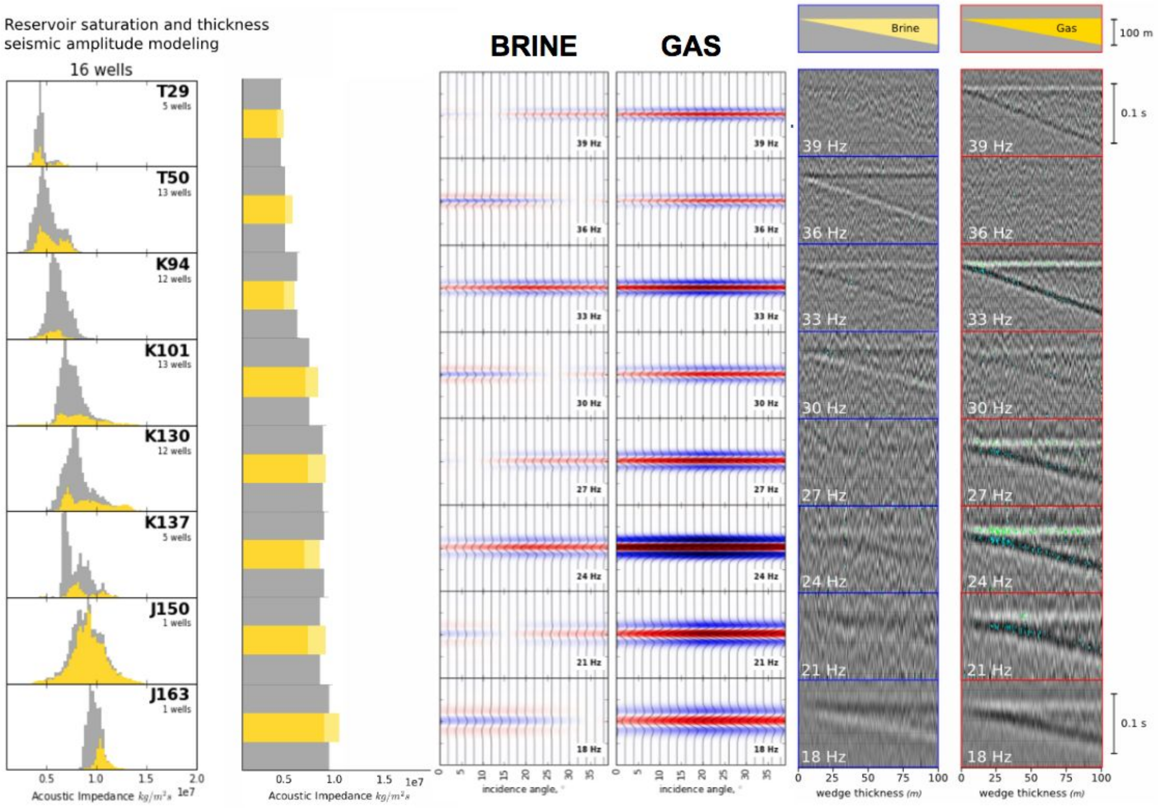
Using `striplog` and `welly` — open source software tools we developed for the Department of Energy — we performed the following workflow to characterize the sands and shales in the gross stratigraphic units:

1. Generated sand and shale interpretations.
2. Extracted velocity and bulk density data for each bed.
3. Grouped the beds by stratigraphic zone.

4. Produced statistics of acoustic and elastic properties for each zone.
5. Generate offset-dependant and thickness-dependent synthetics.

The purpose was to gain an understanding of the expected full-stack response of sands and shales at various thicknesses, fluid saturations, and depths. The interpreted lithology logs in the PFA were deemed too granular for meaningful statistics across the whole basin. However, these lithology classes will be valuable in any future rock property studies on a well by well basis.

The distribution of seismic rock properties grouped by zone allows us to make predictions about the seismic expression of gas-filled reservoirs versus wet reservoirs, thick reservoirs versus thin reservoirs, and whether prestack seismic analysis (so called amplitude versus offset methods) would be helpful in screening one type of fluid type from another. These predictions can be used to rank DHIs on a feature-by-feature basis, or play a part in a calibrating an automatic anomaly detection and screening.



Rock property modeling: impedance distributions and synthetic seismograms.

A word about tuning. Cursory analysis of the seismic parameters indicates that we should expect tuned beds at about 15 ± 2 m in the shallow section, and about 80 ± 15 m in the deeper section. Tuning can produce amplitude anomalies of up to about 50% of a bed's untuned amplitude, and is more geologically likely than hydrocarbons in some circumstances (such as in rifted mini-basins and

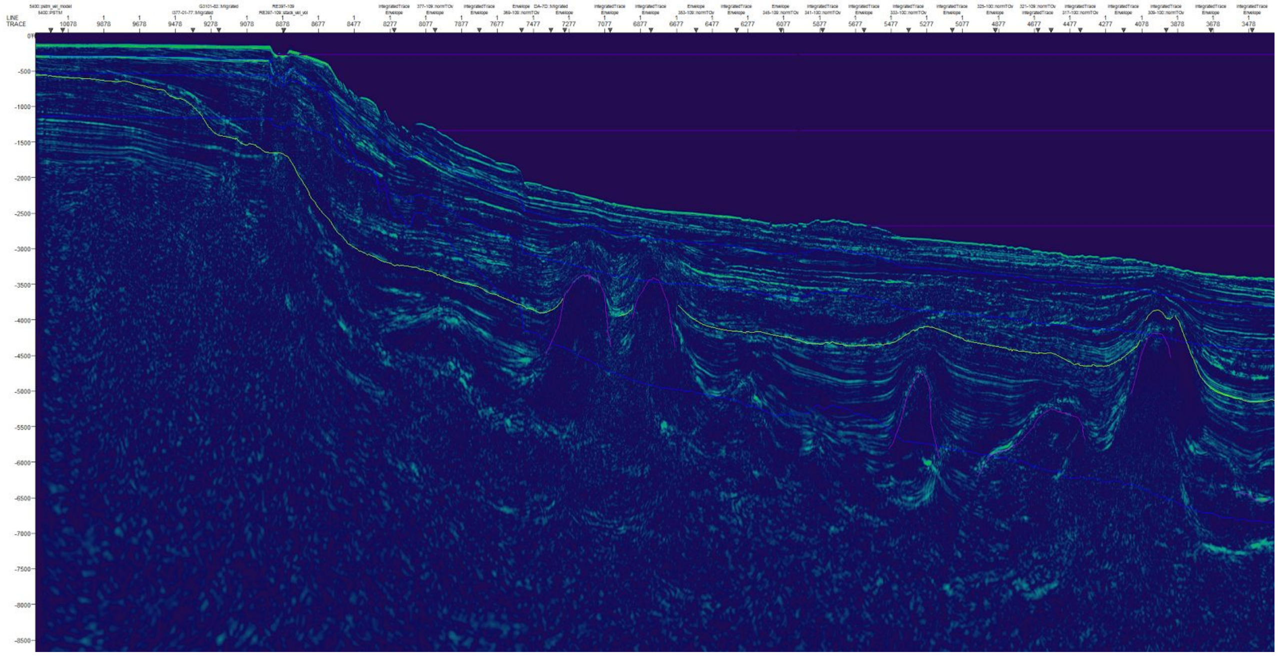
Interpretation project

An interpretation project in Schlumberger's Petrel has been set up on one of the interpretation workstations at OERA. The project is called *Agile_DHI*; it is not officially part of the deliverables, but the interpretation products themselves are included in the package.

We generated some seismic attributes known to be useful in amplitude analysis:

- Envelope (the Hilbert transform of the data)
- Sweetness (a sort of detuned version of the envelope)
- Relative acoustic impedance (the integrated trace, with a low cut of 10 Hz)

Of these, the envelope seemed to be the most useful, especially given the uncertain phase content of the data. (The phase content can only be reliably found by means of multiple well ties, which is too involved for this project.) The bright spots were picked on the envelope attribute



The envelope attribute (aka Hilbert transform, reflection strength or energy).

Our standard approach involves the creation of some seismic horizons — for example bathymetric contours, and models of the bottom-simulating reflector (BSR) and multiples. The horizons were generated in Petrel's pointset calculator from the pre-existing *SEABED* horizon — interpreted in the Play Fairway Analysis project — and have the same extent that it has. They were then cast back to Petrel horizons and also exported as Petrel-format ASCII files for import into Python and QGIS.

The figure below shows part of a single line from the envelope of the seismic amplitude volume. The bathymetric contours are shown in purple and the various model horizons in blue. It's clear that there are many features that one could interpret as 'anomalous'. For the time being, I am using the following criteria:

- The feature is anomalous relative to the local background. There's no single cut-off amplitude: 'bright' depends on the context.
- The feature is relatively continuous and signal-like.
- The feature is relatively isolated in time, reducing the chance of it being a processing artifact.
- The feature is geologically congruent with the local geometries. It can still cross-cut them, the point is that the geometries are reasonable.
- The feature is deeper than 1000 ms below mudline. I looked at shallower features for the Seeps study, and very shallow features are unlikely to be commercial (biogenic gas, low volumes, low pressures).
- In general, and where it was clear-cut, structural traps were favoured over stratigraphic traps.
- In general, I disfavoured anomalies at a strong contrast, e.g. T50, top salt, base salt.

After exporting the BRIGHT horizon to Petrel's ASCII format, and importing the data in to Python and then QGIS (an open source desktop GIS application), I was able to compute the following attributes of the interpretations:

- Water depth, assuming a velocity of 1485 m/s.
- Two-way time below the mudline (ie the seafloor).
- The apparent polarity.
- The relationship to the T29, T50, and K137 horizons, where possible

Since there were so few flat spots, I did not take the trouble to try measuring flatness.

After processing the interpretation by buffering to 500 m and thus merging many of the interpreted segments, I assigned scores to the segments as follows:

- Amplitude below 50th percentile: 0 points
- Amplitude above 50th percentile: 1 point
- Amplitude above 80th percentile: 2 points
- Size below 50th percentile: 0 points
- Size above 50th percentile: 1 point
- Size above 80th percentile: 2 points
- Polarity is undecided: 0 points
- Polarity is a peak or trough: 1 point
- Depth is > 4000 ms below mudline or > 2nd seabed multiple: 0 points
- Depth is > 3000 ms below mudline or > 1st seabed multiple: 1 point
- Depth is < 3000 ms below mudline and < 1st seabed multiple: 2 point

On inspection, two of the highest scoring anomalies failed one or more of the criteria and were arbitrarily downgraded by penalizing them by 2 points. I did not check any anomalies scoring less than 6 in this way, so if we expect the same 'reinspection failure' rate of 2/17 or 12%, then we might expect to downgrade about nine of those anomalies scoring 5.

Scientific objectives

The objectives were as outlined in the original proposal:

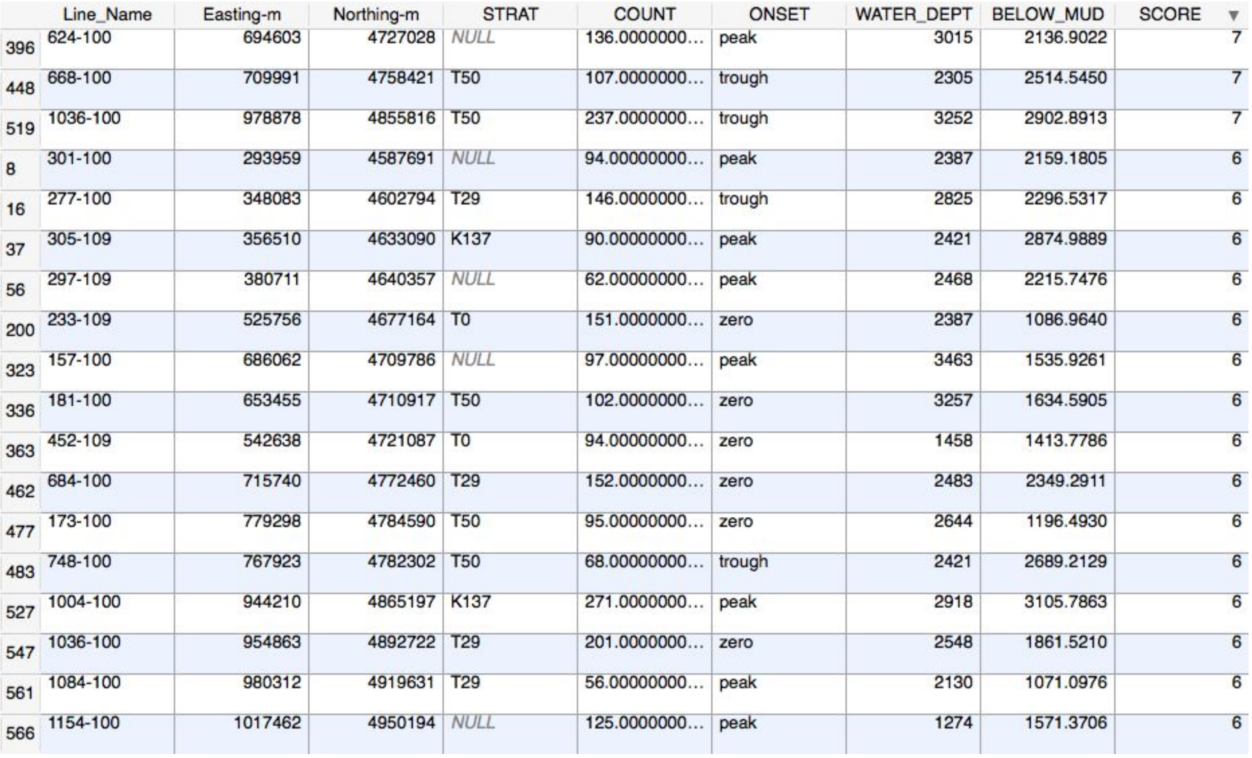
1. Produce a comprehensive geodatabase of direct hydrocarbon indicators on the available offshore seismic data. We would focus on areas of most interest, but aim to perform some screening everywhere there is seismic.
2. Provide recommendations, based on this research, for reprocessing the seismic data, addressing a specific objective of OERA (‘Seismic reprocessing and analysis’).
3. Provide recommendations for further study. For example, some detailed rock physics analysis might be needed to determine the cause of the anomalies, or there may be the substantial tracts of missing data. There may be sufficient data to attempt an automated anomaly detection approach, using the new DHI database as training data — such research would be of great interest to the global exploration community. These recommendations could help inform OERA’s future research programs.

We succeeded in meeting these objectives. The results are contained in the project deliverables, as outlined in the following section.

Project deliverables

1. A shapefile, `Agile_DHI_all_anomalies.shp`, containing all of the interpreted anomalies, with their scores and other metadata. The top 18 anomalies are shown in the figure below.
2. A PDF, `Agile_DHI.pdf`, of presentation-style slides containing a summary of the project and various figures. In particular, the file contains screenshots of the top 18 anomalies.
3. This report, `Agile_DHI_final_report.pdf`.

We are also including a copy of our working folder containing all our working files, other shapefile (eg from CNSOPB and DOE), Petrel exports, well data, and so on. This folder is not documented and is only included for completeness. However, the QGIS project file, `Agile_DHI.qgs`, should be fairly self-explanatory, and should 'just work' if the folder structure is undisturbed. It is about 6.6GB in size.



	Line_Name	Easting-m	Northing-m	STRAT	COUNT	ONSET	WATER_DEPT	BELOW_MUD	SCORE ▼
396	624-100	694603	4727028	NULL	136.0000000…	peak	3015	2136.9022	7
448	668-100	709991	4758421	T50	107.0000000…	trough	2305	2514.5450	7
519	1036-100	978878	4855816	T50	237.0000000…	trough	3252	2902.8913	7
8	301-100	293959	4587691	NULL	94.00000000…	peak	2387	2159.1805	6
16	277-100	348083	4602794	T29	146.0000000…	trough	2825	2296.5317	6
37	305-109	356510	4633090	K137	90.00000000…	peak	2421	2874.9889	6
56	297-109	380711	4640357	NULL	62.00000000…	peak	2468	2215.7476	6
200	233-109	525756	4677164	T0	151.0000000…	zero	2387	1086.9640	6
323	157-100	686062	4709786	NULL	97.00000000…	peak	3463	1535.9261	6
336	181-100	653455	4710917	T50	102.0000000…	zero	3257	1634.5905	6
363	452-109	542638	4721087	T0	94.00000000…	zero	1458	1413.7786	6
462	684-100	715740	4772460	T29	152.0000000…	zero	2483	2349.2911	6
477	173-100	779298	4784590	T50	95.00000000…	zero	2644	1196.4930	6
483	748-100	767923	4782302	T50	68.00000000…	trough	2421	2689.2129	6
527	1004-100	944210	4865197	K137	271.0000000…	peak	2918	3105.7863	6
547	1036-100	954863	4892722	T29	201.0000000…	zero	2548	1861.5210	6
561	1084-100	980312	4919631	T29	56.00000000…	peak	2130	1071.0976	6
566	1154-100	1017462	4950194	NULL	125.0000000…	peak	1274	1571.3706	6

The top 18 anomalies in the results, based on SCORE.

Conclusions

The key results of the project were:

- The seismic and well data were not trivial to locate and QC, slowing down the early stages of the project. Others are probably experiencing this issue. It may be hindering business development and innovation in the sector.
- A rock physics analysis of 16 wells showed that most wet sands are expected to be hard relative to the shales, and therefore expressed as peaks on zero-phase data.

- The well data also showed that we would expect a soft response from a gas sand, with a Class 3 AVO anomaly. This is typical for Cenozoic passive margin sands.
- We determined that tuning is a very plausible explanation for many of the anomalies, but without more detailed interpretation it is not possible to say more than this.
- We mapped over 1200 high-amplitude features on about 40,000 km of seismic lines; many of these were very small or very close to other, similar features. After further processing, we were left with 578 features.
- The features were assigned scores in four parameters: amplitude, size, polarity, and depth. Where possible, they were also assigned a stratigraphic interval.
- Twenty anomalies scored 6 or more. A further eighty score 5. The scores reflect the likelihood that the feature is a genuine anomaly, and that it has a geological explanation.

Challenges and limitations

There are several technical limitations of a study like this:

- The study lacked context and was not geologically interpretive. It was purely a high-level geophysical screening exercise.
- Amplitude anomalies can have many causes, including tuning, lithology, out-of-plane effects, and other non-hydrocarbon-related causes.
- The data are a near-offset stack only, so there's no support from offsets, which can be important in discriminating between hydrocarbons and tuning, for example.
- Structural conformance — an important criterion in evaluating amplitude anomalies on 3D data — is impossible to judge on 2D data.
- There is little well control so the rock types and their acoustic properties are highly uncertain.

Recommendations

Based on the results of this study, Agile makes the following recommendations:

1. **Long-term data plan.** The Department of Energy should partner with the Canada–Nova Scotia Offshore Petroleum Board, the Department of Natural Resources, and other relevant stakeholders, to formulate a long-term plan for data stewardship and accessibility. The current arrangements for data discovery and access are inadequate and have fallen somewhat behind what is available in other similar organizations. Related to this issue, and probably a prerequisite, is the adoption of an unequivocal statement of principles related to open, public data in Nova Scotia. *At its most ambitious, this would require a substantial and sustained effort — perhaps 4 to 6 person-years.*

2. **Short-term data fix.** The Department of Energy should continue with its data stewardship efforts to meet its short- to medium-term goals, including the support of

projects in the run-up to the 2017 Call for Bids. To the greatest extent possible, this should reflect the long-term needs as well. However, it need not require the adoption of open data principles or deep coordination with other organizations; it's really just a pressing practical issue. *This might require 3 to 6 person-months, depending mostly on the availability of data, the scope of the data types included, and the required products resulting from the work.*

3. **Comprehensive rock physics atlas.** Addressing the need for more quantitative geophysics in the offshore, the Department should construct a rigorous and comprehensive seismic rock physics catalog for offshore Nova Scotia. This would include treatments of the well data, rock property crossplots, and forward models of seismic responses, including their wet and hydrocarbon-saturated AVO responses. Such a world class atlas would be a valuable resource for potential explorers on this margin. *This would be a substantial undertaking and might require 2 to 3 person-years to deliver. In a better data environment, the enterprise would be much easier.*

4. **Focused geophysical evaluation.** In order to understand the geophysics of seeps and prospects in the Shelburne basin, we could extend these recent studies into one of the new 3D seismic surveys, especially if prestack data are available. This would help calibrate the regional-scale 2D-based studies with a better understanding of the geometries and spatial densities of the seep and amplitude anomaly features. *Depending on the desired outcomes, this could be a short-term project, on the order of 1 to 6 person-months, or a medium-term evaluation around 6 to 12 months in length.*

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