Spectral Noise Logging

SNL-5

Technical Overview

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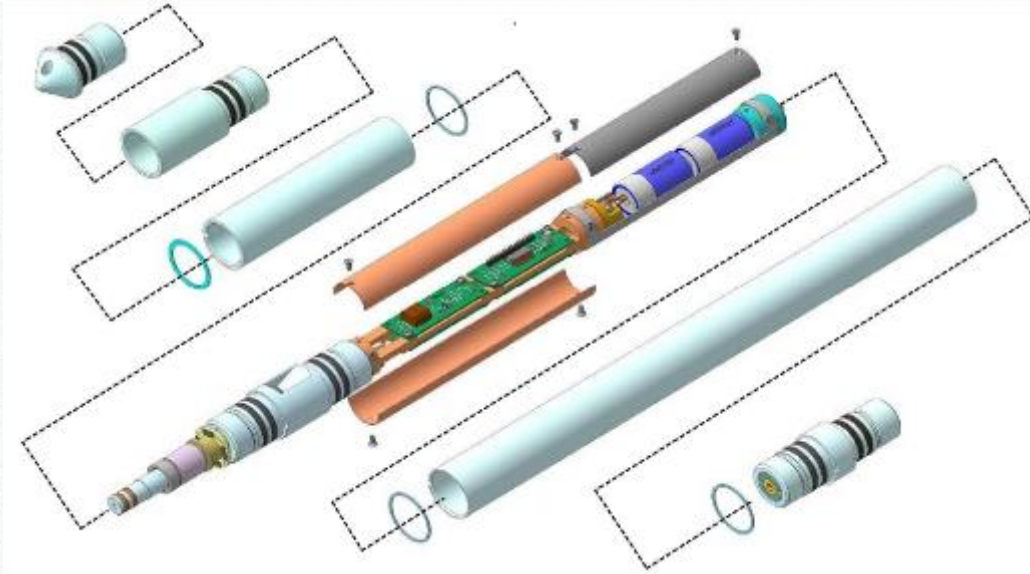
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Objective

To design a logging tool and data processing software which will capture the incoming noise in borehole and decode it into components related to reservoir flow and those emanated from completion elements and possible leaks.

Physics

When fluid/gas is moving through a media it produces an acoustic noise. This noise comes from both fluid itself and vibrating elements streamlined by fluid flow. The fluid noise is the result of internal friction and normally audible in high turbulent flows. It also can be produced by gas bubbling and slippage. The fluid noise spectrum and volume is strongly dependant on the fluid type, pressure, temperature and flowrate.

On the contrary, the console vibrations produce the noise which is not affected by pressure, temperature, flowrate and almost not affected by fluid type. The pitch of console's noise is defined by its size and console's material (stiffness/density – which can be also characterized by a sound velocity through a given material).

The simplest example of steady-pitch console is the tuning fork (see Fig. 1) which produces 1 kHz pitch irrespective to the air conditions: temperature, pressure, humidity, applied force etc. Obviously, the small size consoles produce high pitch noise while large consoles produce low pitch.

Fig. 1. Tuning Fork.

The downhole noise sources can be split into four categories:

Bore-hole vertical flow

This type of noise is produced by tubing/casing vibration induced by the borehole flow and normally occupies a frequency range below 1 kHz.

A turbulent borehole flow also produces noise in low frequencies. If borehole pressure goes below bubble point the saturated gas starts releasing and produces a noise with 5 kHz pitch which consequently changes down to 1 kHz while lifting towards surface.

The borehole noise is obviously produced within the borehole distance and has no vertical localization so that a noise spectrum as no clear vertical infrastructure. A borehole noise is normally quite audible for a human ear.

Completion elements

This type of noise is produced by perforations, X-Nipples, SSD, tubing shoe, gas mandrels, packer, and casing leaks. These elements normally fall down into the range between 1 kHz and 3 kHz.

Completion noise is localized in space within the borehole distance and can be located vertically as stand-alone high volume spots on the spectrum.
In practise they are not clearly localized in flowing conditions because of the masking effect of borehole noise residing in the adjacent frequency bandwidth. On the other hand the same elements are clearly seen on shut-in spectrums when the after-flow is strong at the moment of survey. Sometimes completion elements produce an unusually high pitched noise, such as a poor perforation or packer/casing leakage, which stand out on the regular bandwidth and are very noticeable on the spectrum. At the same time they may start messing up with reservoir fracture readings.

Channelling behind the casing

Channelling is the flow which occurs behind the casing through the fractured cement or fractured reservoir. It has clear boundaries (top and bottom) and is shows up on the spectrum as a narrow stand-alone vertical strip connecting two active streaks. The channelling noise can vary in pitch (deviate from vertical line) as the channel hole may change in size and structure. The channelling may periodically break when passing through the big holes (like absent cement) which shift the pitch into the low frequencies where it's masked by borehole noise.

Reservoir flow

Reservoir flow noise is produced by grains, pore throats and fracture vibrations of the reservoir fluid flow. It has clear vertical boundaries (top and bottom) but no radial localization. The reservoir fractures normally fall into the range between 3 kHz – 5 kHz but big fractures and caverns may go down to 1 kHz and mess up with completion noise. Some reservoir noise spectrums show two neighbouring bands of fractures associated with two fracture networks of different scales. The regular matrix flow produces a noise around 10 kHz – 15 kHz but may occupy a wider frequency range. The tight formations produce a noise in ultrasound range (> 20 kHz). In case of exceptionally tight formations with less than 1 mD permeability, only gas can percolate through these rocks and produces a noise in a wide range of frequencies (including those above 30 kHz).

Unlike borehole flow noise, a reservoir flow noise is mostly inaudible for the human ear because of the low volume and high pitch. This provides a key challenge for the SNL tool to capture reservoir flow noise.

Figure 2 shows the summary plot for typical subsurface noise sources.
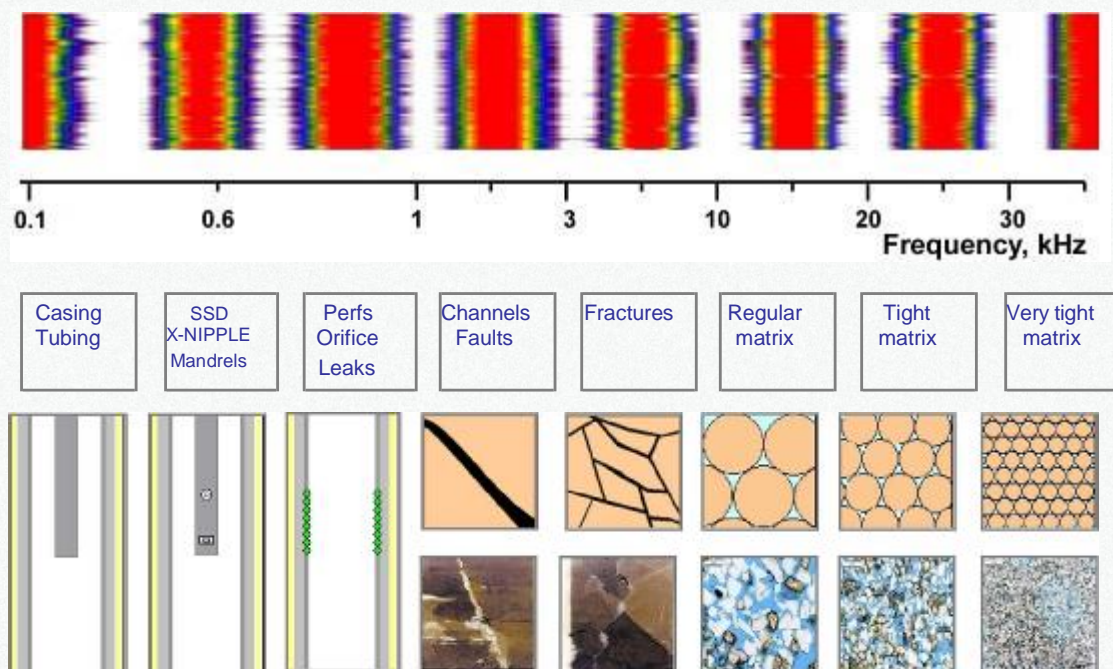

Fig. 2. Summary SNL Range.

The left side of the SNL panel is showing the low frequencies (down to 117 Hz) while the right side of the panel is showing high frequencies (up to 30,000 Hz).The noise volume is shown as rainbow color palette: with red color standing for high volumes, blue color standing for low volumes and white color standing for no noise (or noise below tool's threshold).

Effect of Rock type

Different rock types have different noise structure which is the key element of SNL analysis (see Fig. 3).

Fractured limestone

Double porosity limestone
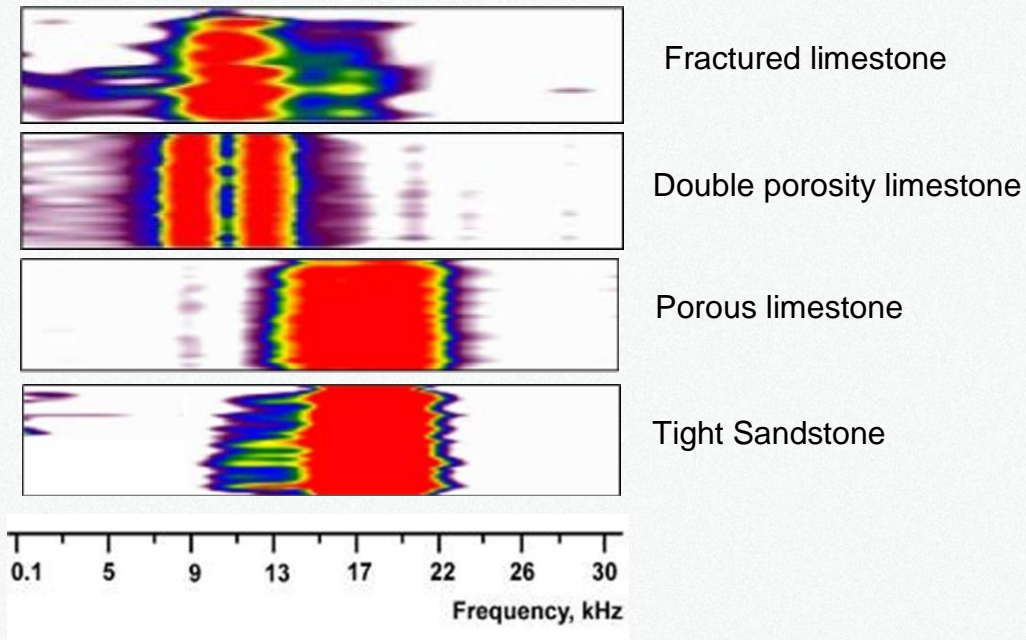
Porous limestone

Tight Sandstone

Fig. 3. Effect of rock type – laboratory experiment.

Effect of fluid type

The fluid itself does not seriously affect a noise spectrum. Either it's oil or water, the location and shape of the resonant peaks will be the same. But if rocks are highly fissured then gas will show a big difference as it will penetrate all fissures and produce a noise in a wide frequency range (see Fig. 4). Besides, gas is much noisier than liquids.
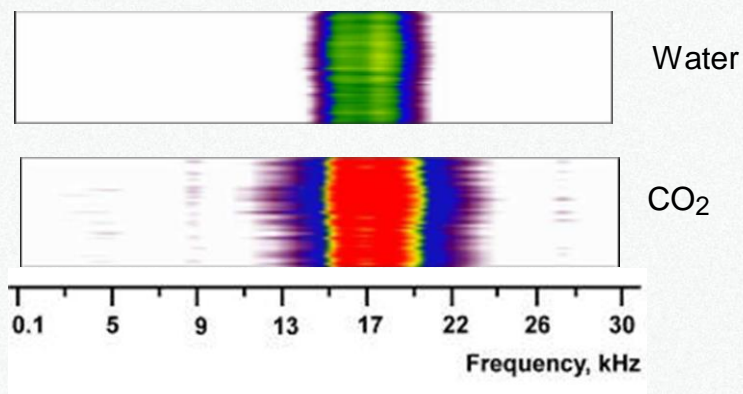

Water

CO_2

Fig. 4. Effect of fluid type – laboratory experiment.

Effect of flowrate

Laboratory experiments suggest that noise volume is monotonously growing along with increasing flowrate (see Fig. 5).

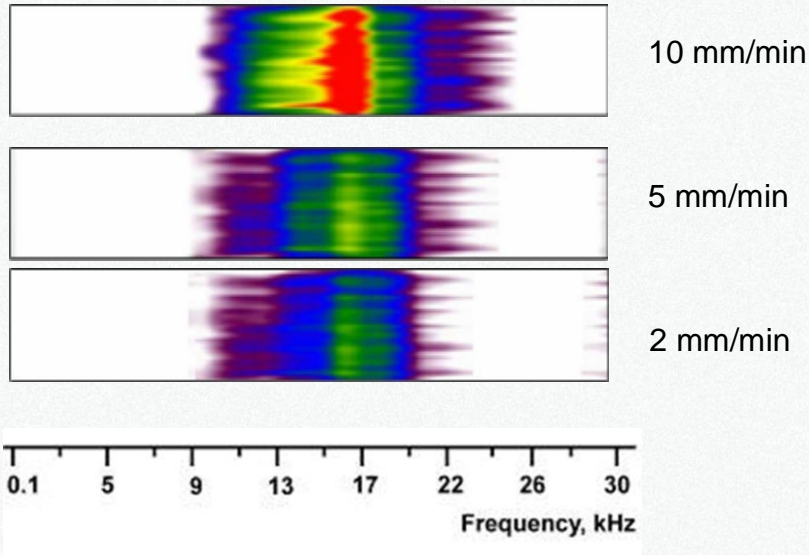

10 mm/min

5 mm/min

2 mm/min

Fig. 5. Effect of flow rate – laboratory experiment.

This can be used for indicative analysis for injectors or single-phase producers but in real practice the noise power log does not show a good correlation with flow rate.

Tool overview

The tools sensitive element is based on its hydrophone design: a piezo-crystal element placed in the oil-filled chamber. The tool is recording a noise sample every second. The table below provides specifications for the SNL-5 tool.

Maximum operating pressure	60 MPa (8,700 psi)
Maximum operating temperature	150 ºC (302 F)
Amplifier gain	77 dB
Quantization	12 bit
Dynamic range	68 dB
Data reading rate	1 sec
Frequency range (HP)	8 Hz – 60,000 Hz
Diameter	38 mm (1 ½ in)
Length	800 mm (2.6 ft)
Weight	5 kg (11 lb)

Every noise sample is digitized into 1024 time bins with 12 bit resolution and stored in 1 GB built-in memory. Once tool is retrieved on surface it can be connected to PC through standard USB interface and recognized by PC as external drive. The drive contains noise readings in the form of a binary file *snl.dat* which can be copied onto PC within about 10 minutes (or less if it was programmed for less operational time).

SNL Programmer software provides user-friendly facilities for programming the tool work schedule.

The *SNL Programmer* software is currently run under Windows XP, Windows Vista and Windows 7.

Logging procedure and data pre-processing

The noise data are acquired as 60-second stations every one meter. Normally two surveys are performed: one shut-in survey and one flowing.

The average logging time consumption is around 1 minute per meter which is similar to regular pulse neutron logging and high precision temperature logging. The SNL survey can be efficiently combined with either of them as the SNL tool is quite short.

After each survey tool is retrieved on the surface and the time-coded data is downloaded onto PC through USB interface. The recorded data is loaded into SNL Processor software where it's synchronized with depth counter and automatically checked for start/stop moments of tool movement which creates a set of sample station records at given depth (normally 60 records).

Every sample record is Fourier- transformed into a power spectrum. This efficiently results in capturing of 60 spectrums in 8 Hz – 60,000 Hz. *SNL Processor* will automatically process a set of 60 spectrums in order to derive the most "trustworthy" part of the spectrum set and the resulting spectrum is assigned to a given depth along hole and can be saved as a set of 2 x 512 logs (either binary or LAS 2.0 format). The decomposition is based on minimization of covariance between trend and drift components of spectrum set and employs regularization when solving the main set of equations.

Interpretation

Interpretation of SNL is quite straightforward.
The SNL log data file is loaded into *SNL* plug-in for *LogViz* software which allows visualization of SNL panels along with other logs on screen.

The SNL panel shows noise volume distribution from 8 Hz (left side of the panel) towards 60 kHz (right side of the panel)
.
The colour palette sets red for highest noise volumes then gradually goes through yellow, green, blue and violet for lower noise volumes with white denoting a noise below tool threshold.

The spectrums distinctly show matrix flow as noise peak around 15 kHz. They are often paired with one or two peaks around 3 - 5 kHz originating from the fracture flow.

Producers

Figure 6 shows production from reservoir A2 which is clearly seen on both spinner and SNL. The SNL readings elaborate more on the inflow structure – they show three streaks of matrix and fracture flow which are most probably communicating across fracture components. In closer look, one can see that SNL streaks are perfectly matched to the porosity/permeability streaks on volumetric rock model.
SNL also shows continuation of low frequency noise below perforation which is in line with a spinner showing the fluid lift from bottom of the survey.
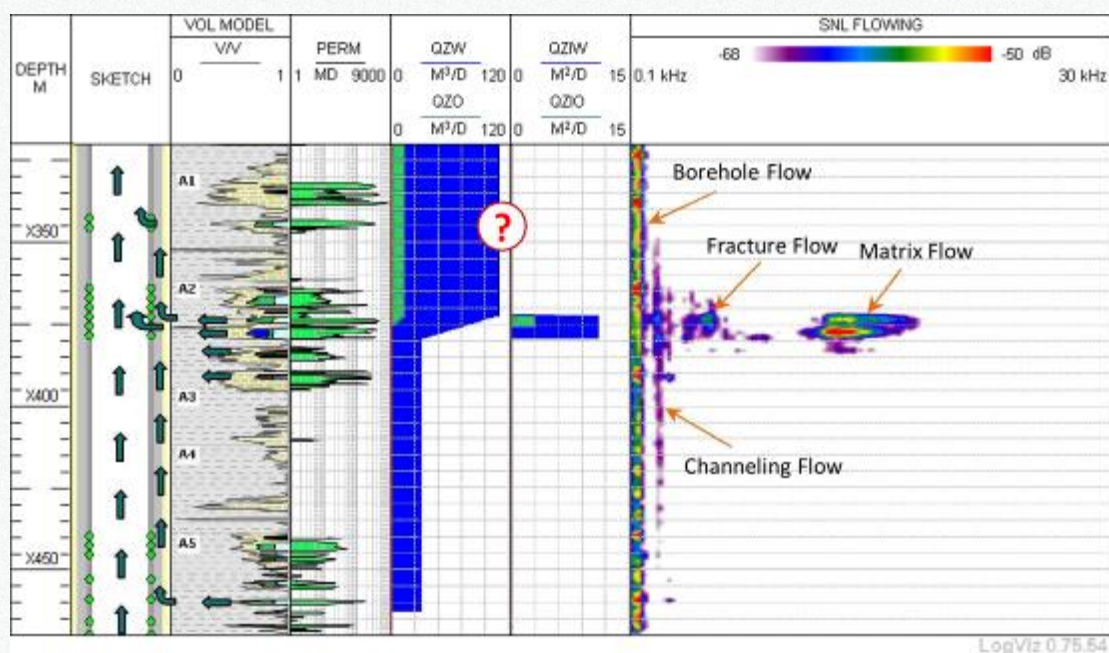

Fig. 6. SNL mostly shows a noise in the same zones as spinner except that spinner does not see the small inflow from upper perforations (red circle and question mark). Obviously spinner can not see a behind-casing channeling.

The next element on the Figure 6 is 2 kHz vertical satellite band which is clearly separated from borehole noise. This is channelling which starts along with inflow at the bottom of A5 and goes all the way up to the main producing interval in A2. SNL also indicates other channelling up to the upper perforations in A1, where the flow is small and spinner does not see the contribution.

Figure 7 shows a more complicated scenario. Both spinner and SNL show the inflow from bottom hole. The SNL suggests that the reservoir source of the bottom flow is very close to the bottom hole so one can see a reservoir flow structure of the noise. SNL shows a higher pitch spectral band which is behind-casing channeling.

SNL does not show noise across A7 (clearly seen on spinner) and suggests this inflow is sourced from the same bottom channelling – one can see that a channelling noise is reduced exactly across the top of A7 inflow zone. The A6 inflow is confirmed both from spinner and SNL justifying a regular radial inflow. Starting from this point and all the way up, there are no signs of borehole flow change from spinner readings. Meanwhile SNL clearly shows three flowing units: A3, A4 and A5 which run the flow behind the casing into the perforations in A6.
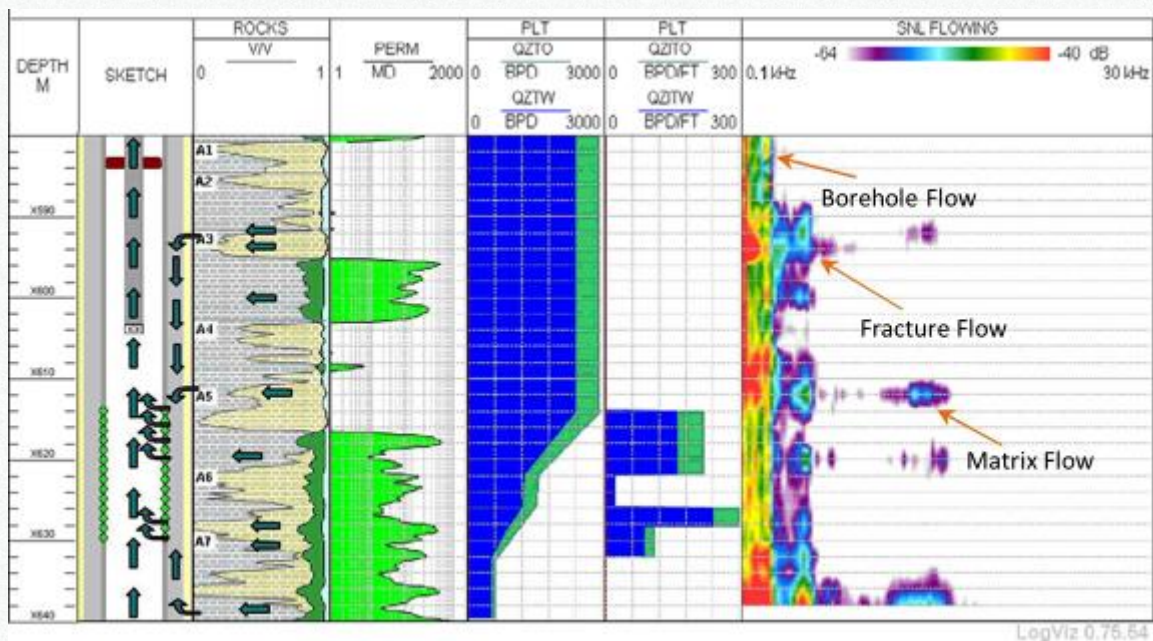

Fig. 7. SNL shows two extra flow units above perforations.

It should be noted that reservoir flow streaks have been captured while SNL tool was located inside the tubing – in noisy flowing conditions through tubing, annulus, casing and cement.

Injectors

Figure 8 shows regular injection into four perforated zones. SNL clearly shows a continuation of the low frequency noise below perforations where spinner suggests no flow. This continuation has a distinctive red colour band in a higher than borehole noise range – which is an indication of channelling. SNL also shows that the middle of A4 unit does not have a matrix flow noise component which means water sweeps through the fractures and does not penetrate the reservoir matrix.
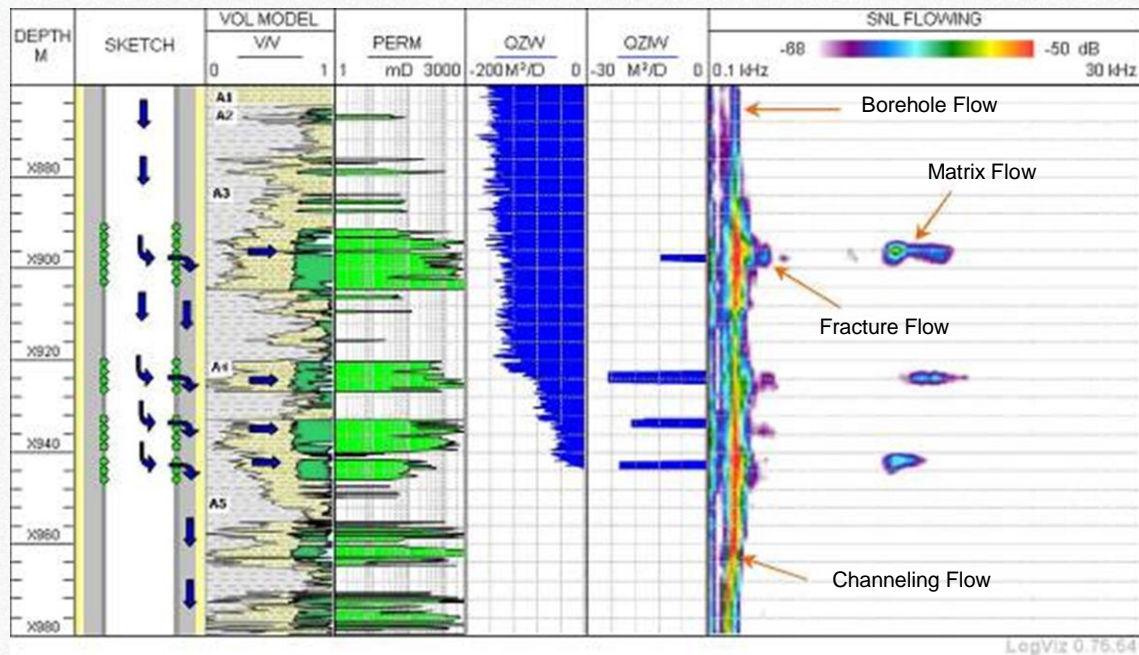

Fig. 8. SNL shows the same picture as spinner except the behind-casing down channeling below perforations.

Figure 9 shows regular injection though the tubing. Spinner shows that a small part of water is gone once the tool is out of tubing because tubing overhangs the top of perforations. SNL does not show a reservoir noise across the tubing shoe – which means that water is flowing somewhere else. Analyzing the through-tubing SNL readings above the pay zone one clearly observe three streaks of reservoir noise (the upper streak showing fracture noise only) which take the missing water at A7.

SNL confirms two bottom streaks but suggest a fracture extension of the flow in both cases. Both extensions are confirmed by temperature logs.
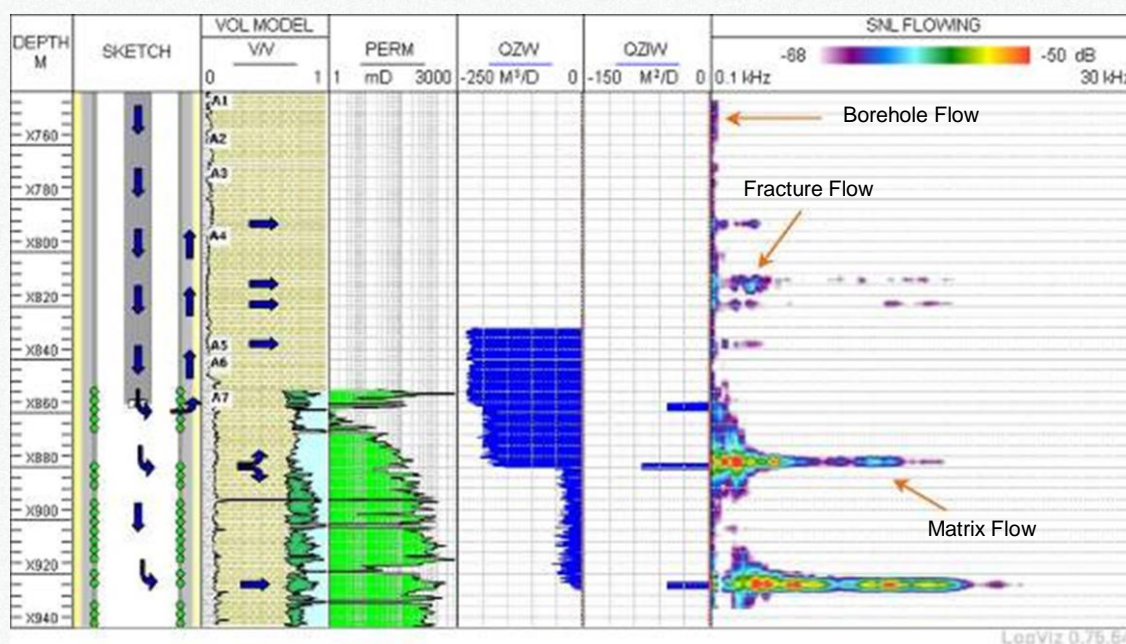

Fig. 9. SNL shows the same picture as spinner except the behind-casing channeling above perforations.

It should be mentioned that SNL tool was located in tubing and was streamlined by massive through-tubing injection and it was still able to capture a very low reservoir noise through the annulus, casing steel and behind casing channelling.

This example shows how SNL can seriously enhance the PLT survey with behind-casing analysis.

Observers

Figure 10 shows a regional reservoir flow noise in observer. The flow is also exposed on high resolution temperature log – right across the noise spot.
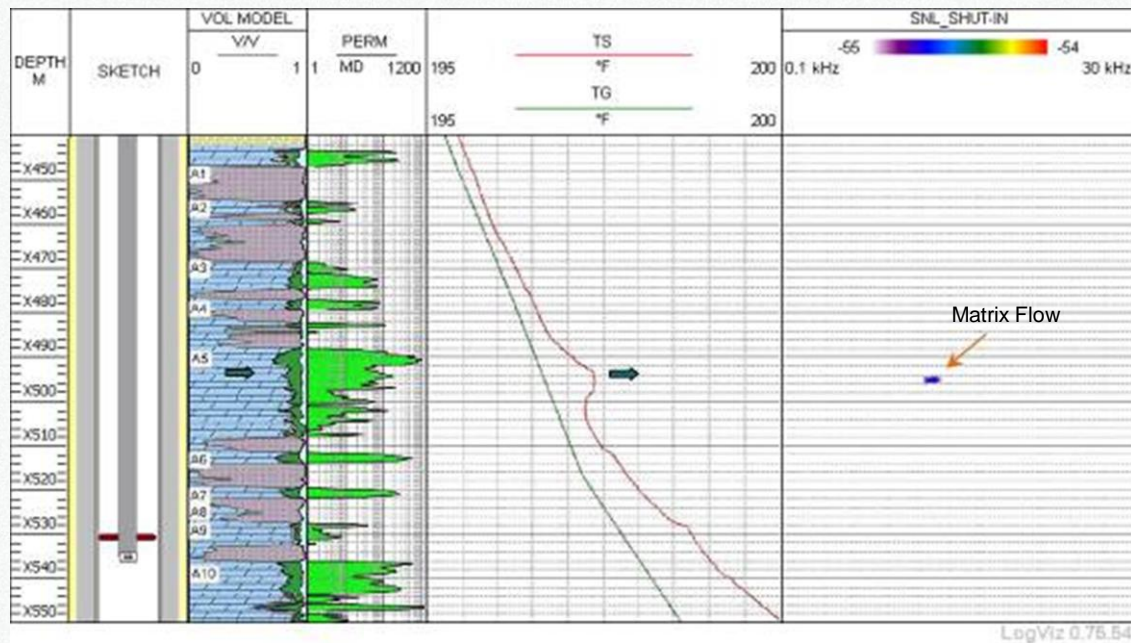

Fig. 10. High precision temperature log suggests invasion in A5 and SNL confirms that it's currently active.

This shows how SNL can be used in monitoring the regional vertical flow profile.

While temperature and pulsed neutron logging are great in capturing water/gas invasion zones they can not justify which units are currently active or inactive.

The SNL survey can help to sort this out.

Drilling wells

Figure 11 shows two SNL spectrums taken in newly drilled well before running the casing. The first panel shows active reservoir units emerging the communication between them. The second panel shows the second survey after the borehole mud was changed for heavier in order to kill active units. One can see that two bottom units have been completely killed while the upper three units were suspended in matrix but were still flowing through fractures.
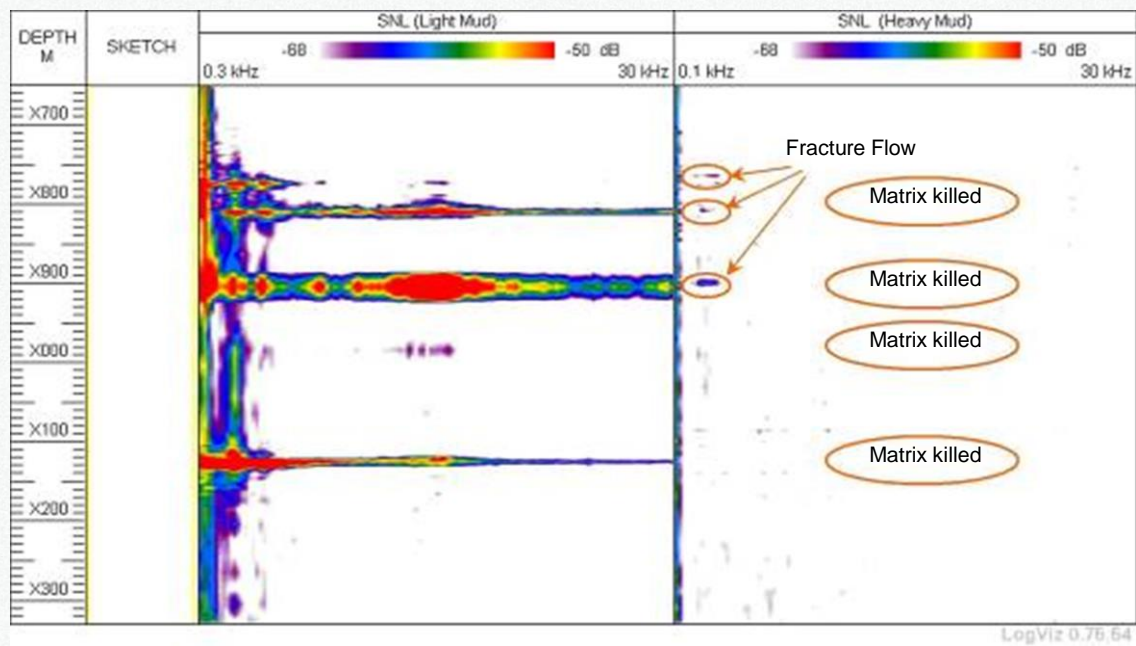

Fig. 11. SNL spectrum before and after changing for heavier mud.

Strength

1. Memory logging

The tool works in memory mode and takes readings at stations. This means that it's absolutely insensitive to the quality of slick-line unit and conveyance procedure.

2. Deep scanning radius

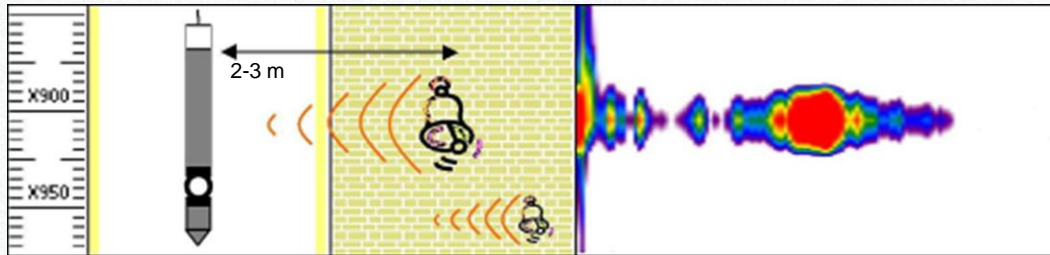Typical reservoir flow noise can be captured from up to 3 m away from wellbore.

Fig. 12. Noise log captures the reservoir flow noise from 2-3 m away from tool.

3. Scan through multiple barriers

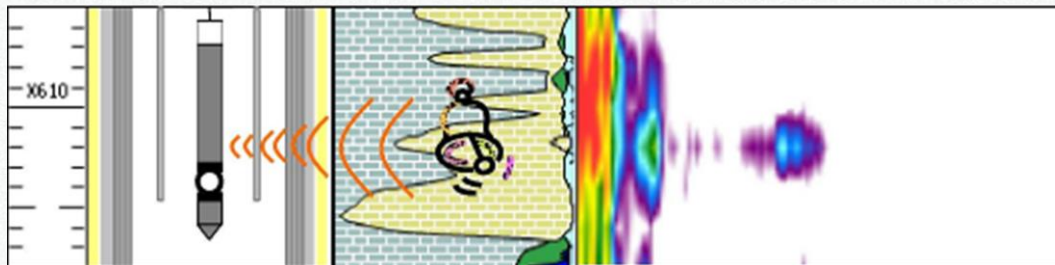Typical reservoir flow noise can be captured through multiple barriers – for example through tubing and casing.

Fig. 13. Noise log captures the reservoir flow noise through tubing, annulus, casing and cement bond.

4. Differentiation between flow elements

Spectral noise logging can differentiate between the noise emanating from matrix and fracture reservoir flow.
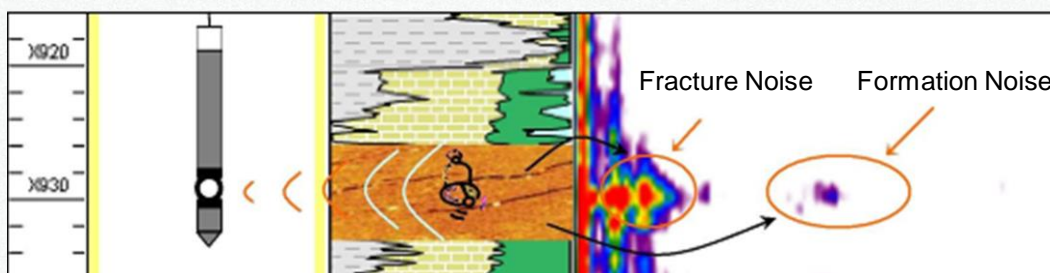

Fig. 14. Matrix and fracture flow components are clearly seen on the spectrum.

Limitations

1. Borehole gas bubbling

If wellbore pressure goes below bubble point the dissolved gas starts releasing from oil which normally produces a bubbling noise through the spectrum and masks the reservoir noise (see Fig. 15). However effective algorithms of digital filtering (1D and 2D wavelet thresholding) allow extracting the masked reservoir noise.
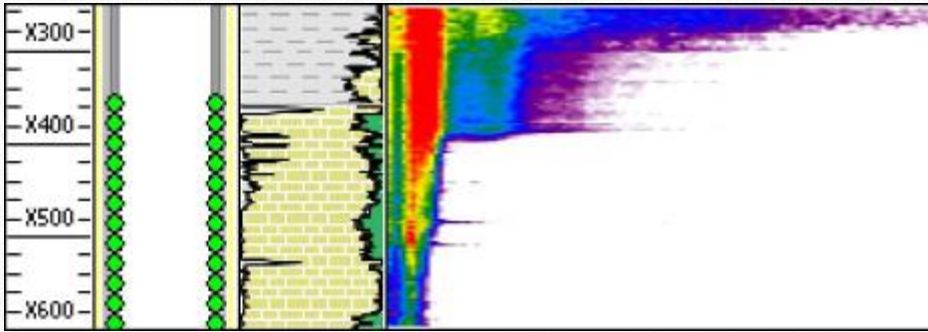

Fig. 15. One can see a gas breakthrough from top of perforations which covers the whole spectrum range and impedes the reservoir noise analysis above perforations.

2. Oil/water insensitivity

Different fluids differ in noise volume they produce while flushed through the porous media. But the shape of noise spectrum is not noticeably affected by the fluid type and mostly defined by the pore structure (see Fig. 16).
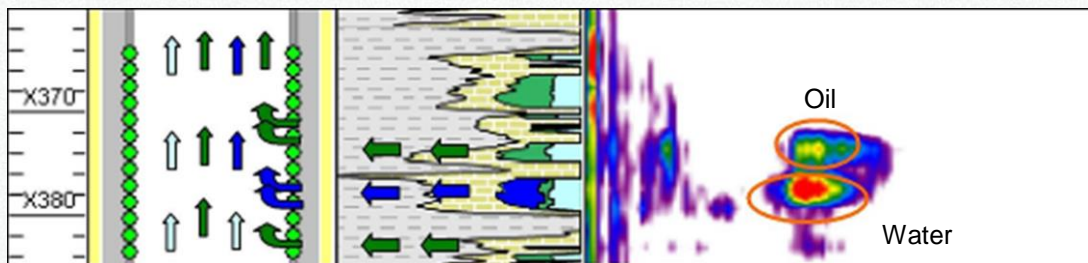

Fig. 16. One can see that oil flow unit A2 and water flow unit A3 are very close in spectrum.

Meanwhile the gas has its own spectrum signature which helps to identify it. Gas has much better penetrating abilities than liquids so that the gas noise covers the whole spectrum range as it induces the vibration of much wider range of rock grains and pore throats. That's why the gas flow is so clearly revealed on the spectrums (see Fig. 17).
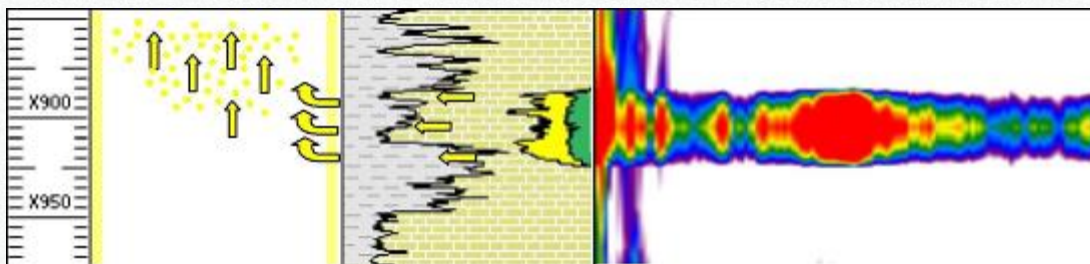

Fig. 17. Gas flow covers the whole spectrum range up and above 30 kHz.

Applications

- Drilling
  - o Capture the zones of mud circulation losses
  - o Monitor active flow units before casing run
  - o Monitor flow units after cement jobs
  - o Monitor flow units after perforation

- Production logging
  - o Identify active flow units behind casing in producers
  - o Identify active injection units behind casing in injectors

- Regional flow monitoring
  - o Monitoring vertical profile of regional subsurface flows through observers, including ecological zone

- Petrophysics
  - o Check reservoir units for matrix, fracture and double fracture
  - o Identify which fractures are active/non-active

- 3D flow simulations
  - o Use SNL-based injection units as vertical schedules for injectors
  - o Use SNL-based flow units to match the simulated flux profile in producers

FAQs

- Does SNL tool produce its own noise or use its own sound generator for scanning?
  No, SNL tool is absolutely dumb and only listening for surrounding noise.

- Does SNL capture reservoir flow noise through multiple barriers (like for example, tubing and casing or two casings)?
  Yes, this was the key point for developing super-sensitive SNL tool.

- Does SNL capture and identify reservoir noise through the very noisy borehole flow?
  Yes, because borehole flow produces a noise in different frequency range comparing to reservoir flow noise.

- Does SNL capture a reservoir flow noise through the long string in double completion?
  Yes. It can run in any of strings with the same result.

- Does SNL capture the after-shut-in flow in producers and injectors?
  Yes. The reservoir flow continues for some time after shutting-in a well and can be captured by SNL tool. Besides the shut-in flow scenario can vary from that of flowing because some units can start flow once the others are stopped. This gives indication of vertical pressure distribution and cross-unit communications.

- Does SNL capture a reservoir noise through non-perforated casing in shut-in wells (for example observers)?
  Yes. The regional flows of regular intensity produce a measurable noise. It's normally not audible for a human's ear but can be captured by SNL tool.

- Does well completion matter for SNL readings?
  Well completion may substantially damp the noise volume from reservoir flow – especially if borehole is filled with gas. It also affects a reservoir noise spectrum as different completion elements have different damping factor across the frequency range. But the shape of the spectrum is not seriously disturbed so that one can still clearly see the peaks of reservoir flow noise

- Is SNL applicable in gas wells?

  Yes. Despite of the high damping factor in gas-filled boreholes gas still produces much more noise than fluids so that eventually the SNL readings in gas wells are even noisier than in oil/water wells.

- Does SNL provide indication of fluid type in reservoir flow?

  No. But there is indirect indication of gas flow: it's higher in volume and extending to higher frequencies.

- Does SNL provide the direction of channelling?

  No. But in many cases there is indirect sign of channelling direction. For example, if the low frequency noise has dropped down at some depth and there is no sign of reservoir noise across then it is very logical that a part of the flow channels up behind casing.

- Is it possible to interpret SNL data in volume rates?

  Only relative sharing and quite roughly. The noise volume has a very good correlation with linear flow velocity through the core plugs in laboratory tests. But in practise one often deals with detrimental contribution from varying completion elements and varying fluid types. One can still asses a relative flow profile by integrating the noise volume in matrix frequency domain which will work for injectors and single-phase producers (gas producers, dry oil producers, high water cut producers). Meanwhile one should keep in mind that variation of completion design (for example, when tool goes out of the tubing) introduces distortion into the actual flow profile.

- Is it possible to run SNL tool at low speeds?

  Absolutely impossible. The tool is designed and tuned up for the super-sensitive noise readings and the smallest friction produces a huge noise in a wide spectrum which masks the faint signs of typical reservoir flow noise. There are some tools on the market which are mostly focused on low frequency analysis (for integrity purposes) and they can afford data acquisition at low speeds as the low frequencies stand out of the movement noise. But whenever one is challenged to capture a reservoir flow the data should be necessarily acquired at stations and then cleaned up from drifting noise.

- Are there any contraindications of using SNL tool along with other tools in one toolstring?
  The multiple experiments did not reveal any problems of using SNL tool along with PLT, high resolution temperature and pulsed neutron generator.

- If borehole is not cased then possibly there is no such an issue like channelling. Is SNL still viable?
  It depends on rock structure. If rocks are fractured there could be a fracture net behind the borehole walls which provides communication between different formation units and if active communication resides within 3 m around the wellbore then SNL will capture it.

- Is any difference in SNL logging/interpretation between vertical, inclined and horizontal wells?
  No, SNL is not directional.

- Given a vertically fractured reservoir and horizontal leg intersects fractures so that the inflow zones are captured by conventional PLT – is SNL be of any use? Yes. SNL will suggest if a given fracture is fed from matrix in well vicinity or not. This is obviously very important for planning workovers and reservoir simulations.