Nonlinear properties of vibrator-generated wavefields and their application to hydrocarbon detection

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Research on the seismic nonlinearity of rocks began in Russia in the 1980s. The first stage of this experimental and theoretical research established that the geologic environment is seismically nonlinear and the nonlinearity sufficient to be recorded by existing systems. However, this initial research did not focus on solving practical problems of reservoir analysis.

Consequently, the authors conducted field experiments, using standard vibroseis equipment, that focused on using the nonlinear component of field records for discovering hydrocarbon reservoirs and determination of their properties. We believe this is one of the first such experiments to be done or published.

Our results show that in porous, permeable, and oil-saturated rocks the following can be observed on the records of vibroseis surveys:

- The relationship of recorded wave amplitudes to source amplitudes is nonlinear.
- Several frequencies (harmonics) and combinational waves of subtractive and combined frequencies are present.
- Reservoirs are seismically active.

We feel that, because of these properties, using seismic nonlinearity should allow creation of more accurate reservoir models.

Background. According to Albert Einstein, any rigorous theory should be nonlinear. A linear approach to any physical process is a simplification which can be justified if it is sufficient from the practical point of view or if the experimental base cannot overcome its limitations. The linear approximation in seismic exploration was adequate in the past but does not satisfy the needs of new methods for studying the Earth's interior and, importantly, cannot explain a large number of recorded phenomena. A most promising evolution in vibroseis surveying is development of methods based on new, realistic subsurface models which consider energy activity and seismic nonlinearity of oil and gas reservoirs that sharply distinguish them from the host rock. A number of researchers have noted that the real geologic environment can change properties in time, can actively respond to probing by physical fields, and can be nonlinear. This is quite unlike the conventional models—constant, passive, linear—usually used in hydrocarbon exploration and production.

In the 1980s, sophisticated experimental and theoretical work on the nonlinearity of geologic sections was conducted in Russia. Nonlinear properties that resulted from harmonics and waves of combinational frequencies were studied in the frequency range of 10–300 Hz and at offsets of 1–2 km. It was established that the vibratory signal essentially changes characteristics of fluid-saturated rocks, including the layer pressure. The nonlinearity of a seismic wave can reach tens of percents. Analysis of experiments using a five-parameter nonlinear model showed that even small seismic vibrations can cause nonlinear distortions of a wavefield. The characteristics of the ground under a vibrator baseplate and in the near field were also investigated and it was specifically shown that velocities of ultrasonic waves correlate to a stress applied to a medium and vary from 10 to 25% depending upon the phase of the vibrator (stretching or compression) during which they were measured. The possibility that modulation of a high-frequency acoustic wave by a low-frequency wave indicative of fluid saturation was tested experimentally, and relationships between frequency variation and porosity and fluid type were obtained.

Mathematical models of microfractured media with nonlinear elasticity were developed. Modeling results showed that, with normal incidence of a wave on a boundary between nonlinear elastic half-spaces, the constant component of deformation is a result of nonlinear interaction

The Tyumen International Geoscience Conference and Exhibition in Western Siberia, co-sponsored by SEG and three other professional organizations, is fast approaching. It will take place in the scientific center of the Western Siberian Energy and Fuel Complex, on 4-7 December 2007. The three international organizations officially supporting the conference are SEG, the American Association of Petroleum Geologists, and the Euro-Asian Geophysical Organization. The fourth sponsor is Rosnedra, the Russian Federal Subsoil Use Agency.

The conference's plenary session on December 4 will feature presentations by representatives of the sponsoring societies which will reflect their views of the current state of the industry and their vision of the future of the applied geosciences.

The deadline for submitting abstracts for the Technical Program was 15 October 2007, but even you if missed it, you can still register and attend the conference. Abstracts received by the Technical Program Committee reflect a wide spectrum of "hot" topics in geology and geophysics and are from an impressively distinguished number of well-known experts who will be attending the conference. In recent years, a particular interest by the Russian geoscientists has been nonlinear seismics and the possible application of this emerging technology as a direct hydrocarbon indicator. This research, which began in the 1980s, has resulted in multiple industry publications in Russian and international journals. The accompanying article, which describes some very current experimental results of this research, is an excellent example of the quality of the presentations that will be offered at the conference in Tyumen.

I hope that you will enjoy reading about this work and that I will see you in Tyumen. More information is available at http://seg.org/meetings/tyumen2007.

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International Geoscience Conference

between the incident and reflected wave. Thus, within the time equal to the period of the incident wave, reflecting properties of the boundary change. Additionally, it has been found that the stress applied to the microfractured media influences wave velocities and depends on how widely fractures are opened; this can be used in hydrocarbon exploration. Another interesting result is that the media being probed seismically have significant stored energy, which interacts with the propagating wave and increases the degree of nonlinearity.

Some researchers have shown that nonlinear distortion of seismic and acoustic wavefields can occur as a consequence of interaction between media with differing inertial-elastic properties of fluid phases because of their out-of-phase movement in the wavefield. Considerable research has been devoted to seismic emission—the generation of wave energy by geologic objects. The suggested reading section at the end of this article shows that the phenomenon of nonlinearity in geologic media has been studied extensively and is an area of growing interest. The study of nonlinearity can help to obtain fundamental knowledge about the subsurface and provide tools for forecasting, exploring for, and monitoring hydrocarbon deposits. While the work described above is interesting, we must stress three points:

1) In all of this experimental work, the geologic section is treated as a single block and no attempts were made to correlate the observed nonlinear phenomena with particular geologic bodies (especially any of production interest).
2) Most often kinematic parameters are used, the nonlinear variation of which is often below the resolution of the recording equipment. However, nonlinear changes in the amplitudes of waves in complex media (oil- and gas-saturated deposits) can be significant.
3) There is always ambiguity about the source of nonlinear distortions in the seismic field; is the source in a deep geologic formation or is it a result of a strong near-field from the source or surface waves?

Therefore, the possibility of using nonlinear effects in seismic exploration for oil and gas was never specifically assessed. Furthermore, no unique theory was developed to explain the cause of nonlinear distortions in the rocks, but there are dozens of models which try to explain the interaction between seismic waves and the medium. Some of the most prominent models are:

1) Models that describe phase conversions (gas-fluid-gas) under weak deformations of the media. The essence of these models is the evaporation and condensation of the pore fluid and the forming and evaporation of gas bubbles on the pore surface in two- and single-phase fluid systems. The process of bubble disappearance from the pore surface is accompanied by an impulse sent to the pore wall at the bubble location. The characteristic frequencies of this field are defined by the characteristic times of the bubble's disappearance. Considering stability of the pore thermodynamic parameters and external fields, we can assume equilibrium between the bubble-forming processes and evaporation. This leads to a random, in time and space, homogeneously distributed isotropic force field. This force field produces acoustic energy emanating from the boundary of the hydrocarbon-charged layer. External acoustic energy accelerates the mechanism, leading to bubble evaporation which, in turn, creates energy in the low-frequency range.
2) Models that take into account the nonlinear character and deformation of fractured media. The common thread in this class of models is that different fracture configurations, when influenced by a seismic wave, make fractures close in different ways. For example, the extent of fracture closure under pressure is limited by its fully closed state; but when an opposite force opens the fracture, the amount of opening is, theoretically, unlimited. This redistributes stresses in the medium. The wavefront then changes and causes nonlinear effects.
3) Models that concentrate on the grain boundaries. An important observation is that a large stress gradient exists in an inhomogeneous (heterogeneous) medium with significant contrast in the matrix material (maximum on grain contacts and zero on the pore boundaries containing gas). Propagation of small-amplitude waves in media containing fluids is a two-scale process; there is, in addition to a large-scale field (varying considerably at distances equal to the wavelength), a small-scale fluctuating field, which changes at distances on the order of the grain size. The large-scale part of the field under stationary oscillations is described by a fourth-order equation of motion. However, some solutions are close to the solution of a simpler second-order equation. The ratio of fluctuation energy to the energy of the large-scale field depends on porosity and also on the pore surface. In contrast, in micro-inhomogeneous media attenuation of the large-scale field occurs (increase in the energy of fluctuation) and the attenuation depends linearly on frequency. Micro-inhomogeneous media include porous bodies saturated with fluids—i.e., hydrocarbon-bearing deposits. Generally speaking, we are dealing with small deformations. Taking into account the size of pores and stresses, the calculated nonlinearity should be small. But the stress between pores is concentrated in the contact area. If we consider the area of grain contact, the nonlinearity parameter will increase (second order); if we consider the volume, it will be fourth order. In microgranular multiphase media with sharp differences in elastic characteristics, oscillations could occur on different scales and lead to a nonlinear distribution in the energy spectrum.
4) Models that take into account irregular movement of matrix and fluid under seismic waves and occurrence of additional forces. As a result of a difference in elastic-viscous and inertial properties of fluids and matrix and in the case of permeability (fluids can move relative to matrix), irregular movement and dynamic interaction occur between fluids and skeleton in the seismic wavefield. Such movement generates additional forces in pore space, which create oscillations of a diffusional-relaxational nature to the extent of irreversibly displacing the fluid. These oscillations occur at every point of the pore space taking part in the oscillating process, propagate at velocities less than the wave velocities in matrix and fluid, and interact with the original field which created them. Interaction takes place not at the media boundaries, but along the wave path and is accompanied by oscillation changes which manifest themselves as nonlinear effects.
5) Models that include the generation of "natural" frequencies in the hydrocarbon reservoir under the influence of a probing seismic field. "Natural" frequencies depend on the inertial-viscous properties and relative volume of a pore fluid, and the size and depth of the reservoir.

All of these models have a certain physical justification. However, none can in itself explain the complexity of the non-

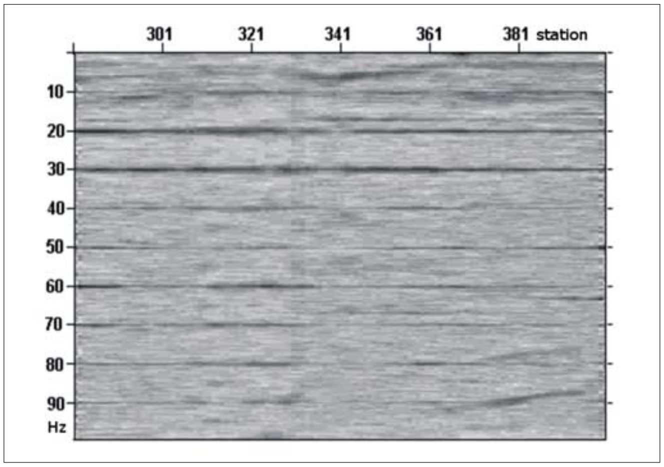

Figure 1. Example of a spectrogram for a wavefield acquired with two monochromatic signals: 20 and 30 Hz.

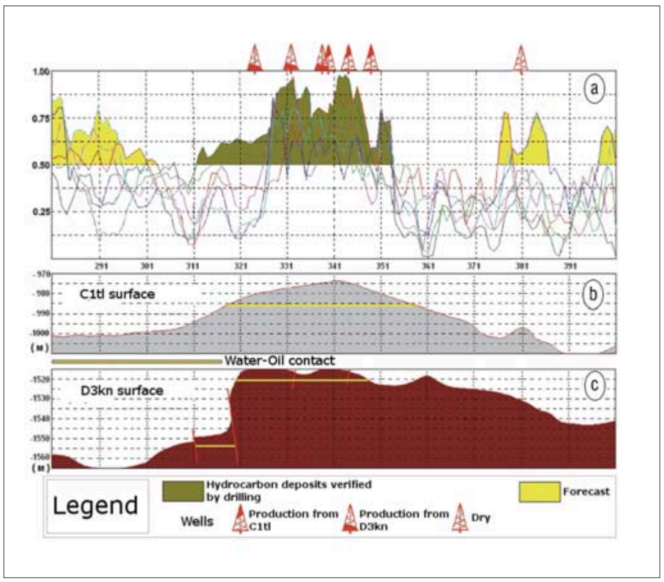

Figure 2. Amplitudes of a nonlinear component of the wavefield (a) with hydrocarbon-bearing horizons C1tl (b), and D3kn (c).

linear phenomena observed. This led to field experiments to explore and estimate nonlinear phenomena in seismic waves and their applicability to reservoir studies. Fundamental manifestations of seismic nonlinearity were as follows:

- Nonlinear dependence of recorded amplitudes excited by a seismic source.
- Existence of harmonic and combinational waves in reservoirs.
- Reservoirs are a source of seismic activity causing wave generation of a particular intensity and frequency (seismic emission).

Experimental results. This section summarizes the most interesting experiment results. The first group of experiments measured the amplitudes of harmonics and combinational frequencies with two signals of a single frequency excited by two groups of vibrators.

Signals f1 and f2 were generated at various distances from each other and at different points of the seismic line. Analysis of the nonlinear component distribution was carried out on spectrograms of the field records represented by amplitude-frequency spectra of uncorrelated field traces

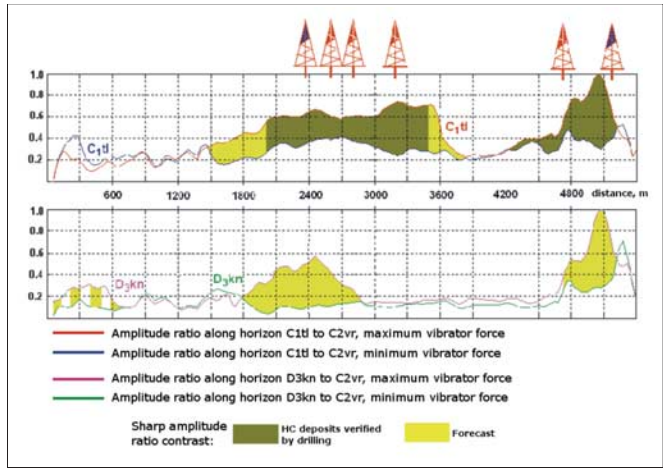

Figure 3. Variation in amplitude ratio of reflected waves for C1tl and D3kn to the amplitude of C2vr horizon with different forces at the source.

(vibroseis records) recorded at each point of the line. In the background noise, one can see extended horizontal lines corresponding to the frequencies generated by the vibrators and also the nonlinear components of the field (harmonics, combination and higher-order derivatives of these components). Note that the intensity of the nonlinear components does not always follow the intensity of the original frequencies. For example, a harmonic wave at 40 Hz (Figure 1), in the center of a profile, is not similar to the original 20-Hz wave. A harmonic at 60 Hz agrees better with the primary frequency of 30 Hz and has a maximum at the left edge of the profile. Waves of 10, 70, 80, and 90 Hz have maxima at stations 310–330; the maximum at 50 Hz is on the right side of the profile. These experimental data indicate wave interaction, meaning that the superposition principle—supposed to be satisfied in the linear theory—is not observed.

It was noticed during the experiments that the most intensive generation of nonlinear components is associated with hydrocarbon-bearing structures (Figure 2). One possible explanation is that the section of a profile responsible for the detected anomalies represents unconsolidated (loose) zones. Such unconsolidation can occur during tectonic deformation and be accompanied by fracturing, reduction of overburden pressure, increase in intergrain porosity, etc. Such zones exhibit nonlinear seismic properties.

As a result of our experiments, it is established that, in the real geologic environment, there are combinational frequencies and harmonic waves. Nonlinear field components and the surface structure of potentially productive reservoir blocks show correlation in amplitudes, meaning that deep layers of the subsurface are responsible for their occurrence. As stated above, the anomalies are associated with the presence of unconsolidated zones (i.e., potential hydrocarbon reservoirs) under the anticline folds.

The second group of experiments studied the dependence of the recorded amplitudes on the source amplitudes. The acquisition technique was based on exciting a linear sweep (f1-f2 Hz) by one vibrator with different baseplate pressure at various points of a profile, or sweeping with a varying number of vibrators working in phase. Very limited preliminary processing consisted in correlation of all vibroseis records with the same synthetic sweep and special band-pass filtering. All processing parameters, including amplitude recovery, remained strictly constant for all excitation modes. The aim of these experiments was to test the possibility that if for the same increase in source ampli-

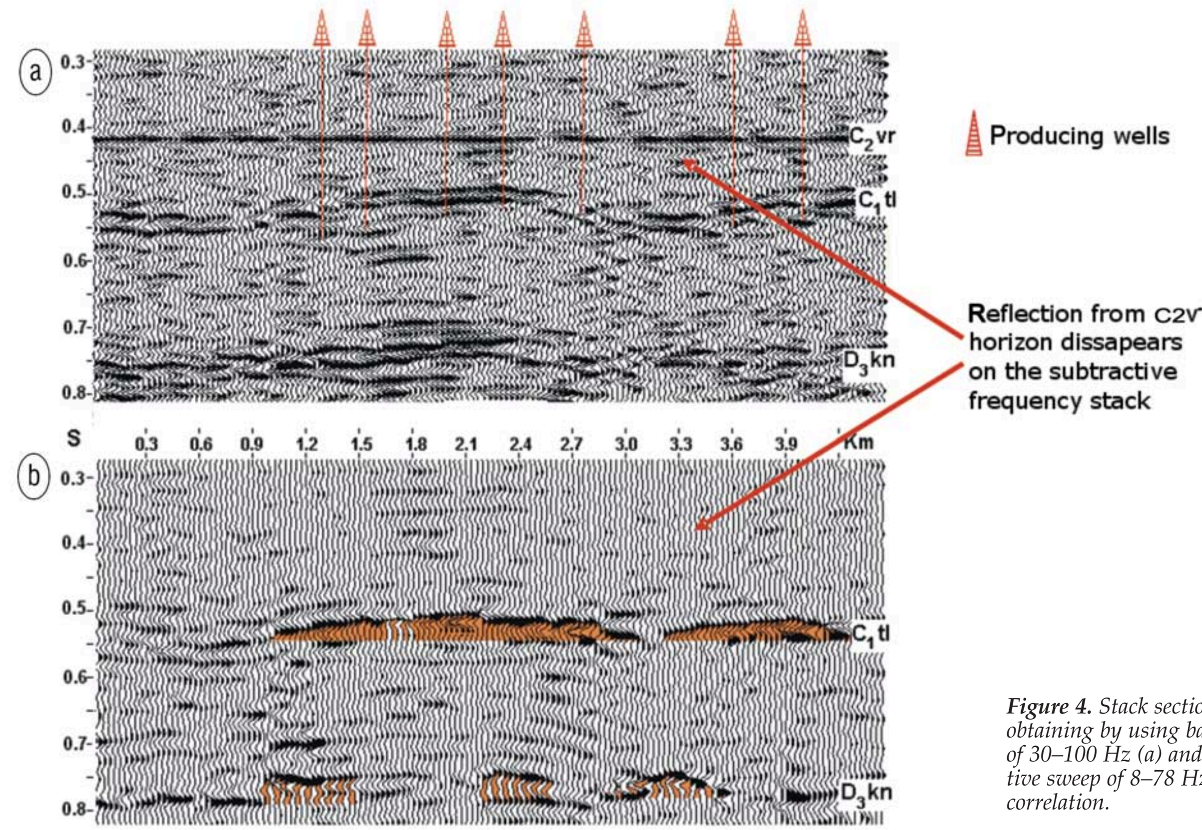

Figure 4. *Stack sections obtaining by using base sweep of 30–100 Hz (a) and subtractive sweep of 8–78 Hz (b) for correlation.*

tude, amplitudes recorded at two fixed locations vary in a different proportion, then at least one of the areas is seismically nonlinear. Therefore, the research objective was to analyze amplitude variation along the line versus the amplitude variation at the source.

The ratio of the amplitude intensity along a hydrocarbon-bearing horizon to the amplitude intensity along a nonproductive horizon for all vibrators modes is shown in Figure 3. In the case of linear acoustics, these ratios for different modes would coincide everywhere. However, the profile has sites where the ratios increase with growing intensity of the initial vibroseis signal. Correlation to well-test data (four wells) and well logs (two wells) verifies that the anomalous zones correlate to the oil-saturated sections of the corresponding horizons. As a result of this research, it is established that seismic wavefields in real geologic environments are nonlinear. Correlation with drilling results shows that this nonlinearity is associated primarily with oil-saturated reservoirs and it can be used as a hydrocarbon indicator.

The third group of experiments looked at the combination frequencies of simultaneous generation of a sweep and a single frequency. The acquisition technique is a simultaneous excitation of LFM sweep (f1-f2) by one vibrator or group of vibrators and a single frequency (fm, f1>fm) by another vibrator at each shot point. At different sites, the frequencies, recording duration, and sweep were varied but the receiver layout remained the same. Theoretically, fluid-saturated and complex formations with greater seismic nonlinearity should stand out in comparison with the background field on combination frequencies. Therefore, the purpose of the experiment consisted in determining any appearance in seismic records of waves of combination frequencies. To emphasize these combination frequencies, records were correlated with the main sweep (f1-f2), and combined (f1+fm)-(f2-fm) and subtracted (f1-fm)-(f2-fm) sweeps.

Accordingly, data processing in CMP imaging consisted of three types using corresponding signals for record correlation. All preprocessing parameters were identical for all stacks. The main processing goal was to preserve dynamic characteristics for subsequent analysis. From the analysis of all experimental material, it is apparent that sections of nonlinear frequencies exhibit considerable amplitude variation and, notably, that amplification zones correlate with areas of increased porosity and permeability.

Let us examine stacks obtained by correlating field records with the original sweep 30–100 Hz (Figure 4a) and with the sweep of subtractive frequencies of 8–78 Hz (Figure 4b). The reflection at 420 ms (Figure 4a) corresponds to layer C2vr. In this area, it is an unproductive layer of tight rocks. It is interesting to note that on the stack of subtractive frequencies (Figure 4b) this reflection is absent, while the reflections corresponding to the C1tl layer stand out as bright spots. Also there are some zones of increased amplitude for the reflection from the D3kn layer within intervals of 0.9–1.5 km, 2.2–2.6 km, and 2.8–3.5 km. It is possible that these zones are occupied by oil-saturated rocks. However, there are no well data for this interval.

It is important to note that obtaining adequate stacks when correlating with sweeps of subtractive frequencies proves that subtractive frequency is generated not by surface waves but in deeper part of the section. Thus, the distinguishing characteristic of the wavefield of subtractive

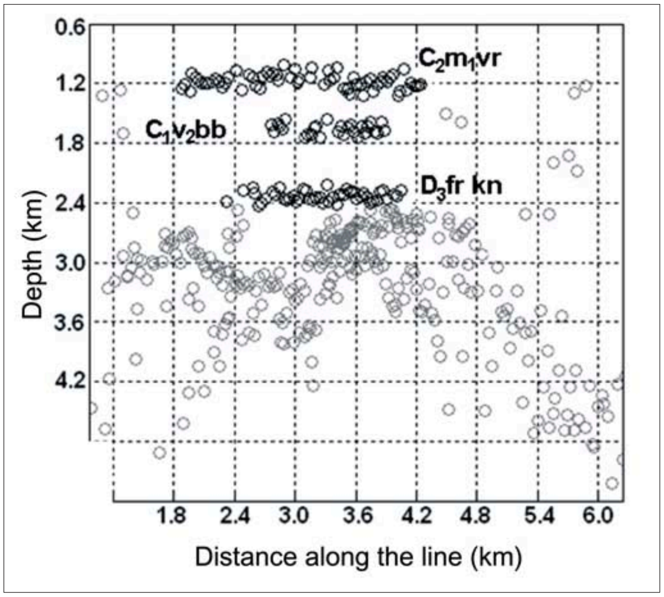

Figure 5. *Distribution of seismic emission sources in the lower half-space for frequencies 2.8–6.4 Hz.*

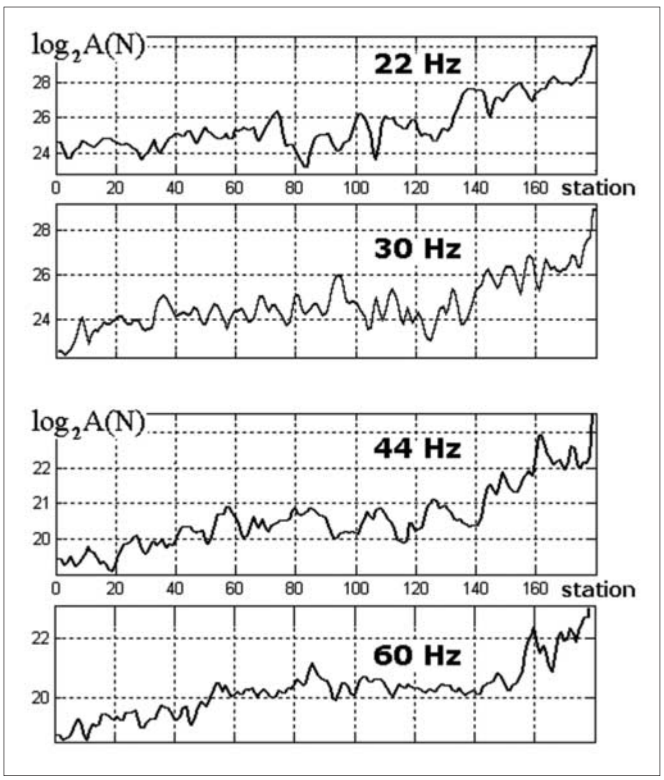

Figure 6. *Amplitude variation of the base frequency and its harmonics. Both groups of vibrators are close to each other and at the end of the line.*

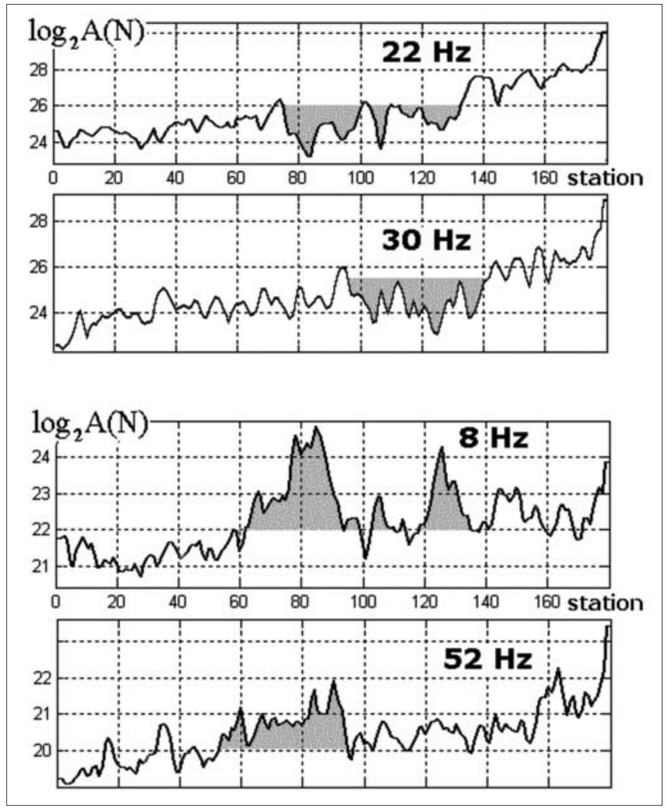

Figure 7. *Amplitude variation for base and combinational frequencies. Both groups of vibrators are close to each other and at the end of the line.*

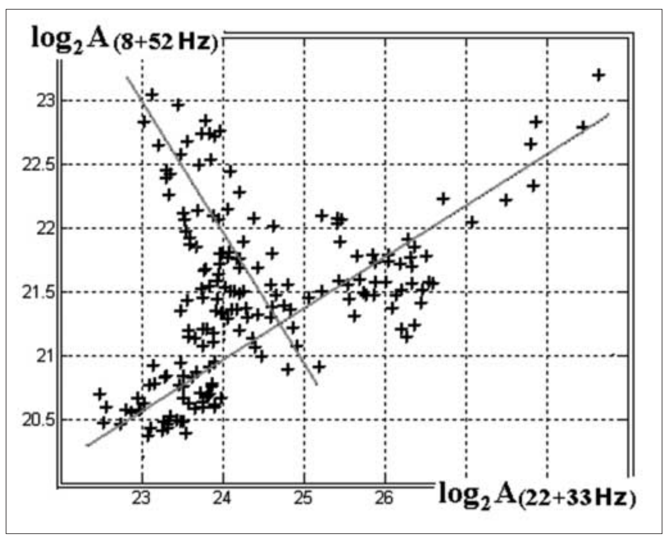

Figure 8. *Crossplot of source amplitudes and combination frequencies for the same station locations.*

frequencies is weak response from layers which do not contain porous rocks in contrast to the strong response from porous and permeable rocks. As a result, it is established that porous, loose, fractured, fluid-saturated rocks generate waves of combined, subtractive and harmonic frequencies. Moreover, on the stacked section such rocks expressed increased amplitudes for nonlinear frequencies while anomalies in wave amplitudes of the original frequencies are not observed (or are much lower).

The fourth group of experiments was designed to record microseismic energy. The work was related to research of "natural" noise in a geologic section and revealed relationships between the intensity and spectral characteristics of emission, and the presence of hydrocarbons. Broadband three-component receivers were used to record natural noise that did not contain any energy from active seismic sources. The results of processing and analysis of the recorded data are as follows:

1) The intensity of emission signals along a profile on X and Z components correlates with the location of hydrocarbons. Above hydrocarbon desposits, the amplitude

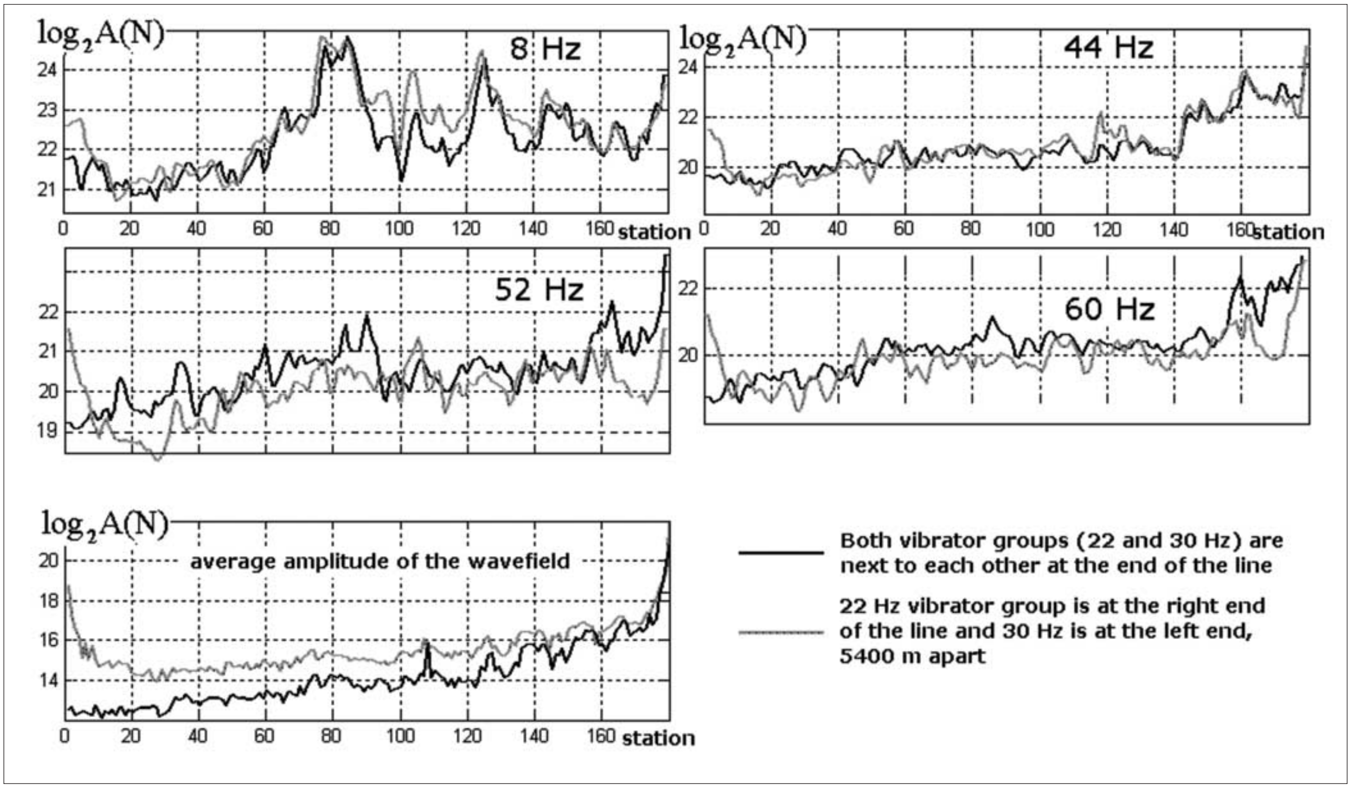

Figure 9. *Amplitude variation of the nonlinear wavefield component based on the vibrator group location.*

of the Z component is considerably larger than the amplitude of the X component.

2) Amplitude spectra of emission contain frequency intervals associated with various origins and positions and sources of noise.
3) Data analysis shows that better identification of the hydrocarbon location could be made with processing methods based on the principles of seismic tomography. The reason is that seismic tomography can localize areas of possible hydrocarbon deposits and fractured zones in the crystalline basement as areas of greatest noise emission (Figure 5). Several algorithms that transform noise fields into tomographic images of the subsurface could be used. One group of algorithms determines areas of concentration of noise "sources" in particular frequency ranges. Another group displays the intensity of noise emission at each point in a wide range of frequencies (1–100 Hz).
4) It appears possible to use records of conventional vibroseis seismic for tomographic analysis of emission if correlation was not applied in the field, and uncorrelated records were recorded. Special processing of seismic records allows constructing images analogous to the ones described above.

Discussion. As stated above, these experiments were conducted to determine what causes the appearance of nonlinear components on seismic records. Does the generation of nonlinear field components actually happen in the Earth or is it due to the admittedly nonlinear system of vibrator-ground and the vibrator near field?

The answer is partially evident, based on the obvious correlation of the anomalies of nonlinear field components with the presence of hydrocarbons. However, to confirm this conclusion, amplitude variations along a profile were analyzed for various arrangements of sources and the principle of reciprocity was examined. Figure 6 shows amplitude variations of base frequencies (22 and 30 Hz) and their harmonics when sources were next to each other (both pairs of vibrators are "bumper to bumper") at the right end of the profile.

In general, customary amplitude attenuation is observed as offset increases for all four frequencies. Deviations from a "smooth" exponential law are almost evenly distributed along the survey line. Because of the absence of additional data, it is impossible to deny the possibility that waves of harmonic frequencies originate near vibrators, are largely independent of medium properties, and remain approximately an order of magnitude weaker than the original signal. It is noticeable that all four curves include extended zones where curves dip under the level of the "smooth" exponent. These zones are between stations 80–90 and 140–150. However, less pronounced distortion of such "complicated" amplitude curves can be related, for example, to the soil property variation along the profile and ground coupling of the receivers.

Figure 7 compares the amplitude variations of combination (subtractive and combined) frequencies with the excited original frequencies. Then a different picture emerges. First, on the 8-Hz curve between stations 60 and 140, the amplitudes exceed the level of the smooth exponent by an order of magnitude. The anomalous attenuation of the original frequencies corresponds with this same section and this could not be explained by receiver-ground coupling because of the reversed sign of the anomalies. More likely wave energy from 22 and 30 Hz has been channeled into combination frequencies. This is illustrated by Figure 8 where the sums of the wave amplitudes of combination frequencies are compared to the sums of amplitudes of the excited vibrations. Two opposite tendencies are distinct. For some receiver points, the original (base) frequencies attenuate linearly and this accompanied by attenuation of combined and subtractive frequencies. For other receiver points, the opposite trend is observed and attenuation of the excitation frequencies is accompanies by amplification of combination frequencies.

Another explanation of this effect is possible within the framework of the linear approach. Waves of combination frequencies originate in a vibrator near zone but there exist geologic units with such thickness and such velocities that waves of 8 and 52 Hz frequencies resonate constructively within them. Conversely, waves of 22 and 30 Hz are summed incoherently and weakened. But this explanation demands additional constraints on the geology of such units. The presence of several geologic units is necessary, because our frequency set does have a common frequency. They have to be deep enough that at small incident angles, anomalies would appear in the central part of the profile. This is the only example shown but similar results were observed for different pairs of frequencies in other experiments. Trying to find the velocity-depth model "necessary" for such resonance each time is not feasible.

Finally, to solve the problem about the origin of the combination waves, it is enough to separate vibrator groups by a large distance (for example, position them at the different ends of a profile so that wave interaction in the near zone is not applicable) and excite different frequencies. The results of such an experiment are shown in Figure 9. The black curves correspond to a case when both groups of vibrators are at the right end of the profile. The grey curves represent 22 Hz at the right end of a profile and 30 Hz at the left end. The distance between the groups is 5400 m and the depth of the sedimentary layer is ~1600 m.

The amplitude change on the 8-Hz graph does not depend significantly on the vibroseis group arrangement. It unequivocally demonstrates that the "sources" of these vibrations are mainly not near the vibrators. The 8-Hz component has the largest values to the right of station 60. The combined 52-Hz frequency has more variations in amplitude (after moving the 30-Hz vibroseis grup to the left end of the profile) but good curve matching between stations 60–160.

The amplitude variations on the 44-Hz graph, on the contrary, are easily explained by the linear approach. The wave, originated at station 181, attenuates equally as station numbers decrease, irrespective of the 30-Hz vibroseis group location. This would seem to justify the "linear" point of view but the graph of the 60-Hz component behaves anomalously. It attenuates in the beginning or at least does not amplify as station numbers increase (up to stations ~40–45) and then it starts to amplify, achieving at the end of a profile almost the same amplitude values as those recorded for the 30-Hz vibroseis group when it was at this end of the profile! So the behavior of various multiple frequencies in the same section is different.

It is necessary to state that multiple nonlinear components of a vibroseis wavefield originate in the subsurface formation as well, although the contribution of the vibrator nonlinearity and the near zone is more significant for them than for the combination (combined and subtractive) frequencies.

Conclusions. The experiments described in this article show that the nonlinearity of seismic characteristics of reservoir rock is evident in such fundamental properties as:

- The occurrence of waves of combination frequencies (combined and subtractive) generated by the interaction of waves with the subsurface layers;
- The absence of linear correlation between the amplitude of the source and receiver.
- The phenomenon of seismic emission is present; tomography applied to passive seismic records allows localizing "noise areas" in the subsurface, including zones of hydrocarbon reservoirs.

Suggested reading. "Research of physicomechanical properties of a friable ground under a plate of the vibrator" by Aleshin and Smiths (in *Problems of Nonlinear Seismicity*, Nauka, 1987). "About some effects of vibrating influence on water-saturated environment" by Barabanov et al. (Proceedings of Academy of Science USSR, 1987). "Experimental researches of the nonlinear seismic phenomena" by Beresnev et al. (in *Nonlinear Seismology*, 1986). "Features of distribution of elastic waves in nonlinear elastic porous bodies" by Verbitskij (in *Problems of Nonlinear Seismic*, Nauka, 1987). "Harmonious and nonlinear components of seismic vibrating wave fields in porous, fractured, permeable, fluid-saturated environments" by Zhukov et al. (*Devices and Systems of Prospecting Geophysics*, Saratov, 2004). "Forecasting of filter-capacitor properties of collectors on the basis of use of nonlinear components of vibrating wave fields" by Zhukov et al. (in *Technologies of Seismic Prospecting*, Moscow, 2005). "Investigation of nonlinear seismic effects for hydrocarbons indication" by Zhukov et al. (*EAGE 2006 Extended Abstracts*). "Technology of hydrocarbon indication and delineation using nonlinear seismic effects" by Zhukov et al. (*SEG 2006 Expanded Abstracts*). "Application of non-linear seismic effects for hydrocarbon indication" by Zhukov et al. (*EAGE 2006 Extended Abstracts*). "Reservoir localizations with using of registration of seismic emission" by Zhukov et al. (*EAGE 2007 Extended Abstracts*). "Generation of seismic and acoustic waves sub harmonics in permeable saturated media with mobile fluid" by Zhukov et al. (*SEG 2007 Expanded Abstracts*). "The way of vibrating seismic prospecting a source of seismic fluctuations for its (his) realization" by Zhukov et al. (Russian Federation, patent 2181492). "Adaptive and nonlinear methods of Vibroseis prospecting" by Zhukov and Shneerson (*Nedra*, 1998). "Anchar technology: Method theory" by Kuznetsov et al. (GEOPHYSICS, 2003). "Interaction of plane waves with boundary of nonlinear-elastic environment" by Litvin and Tsvankin (in *Problems of Nonlinear Seismicity*, Nauka, 1987). "Nonlinear acoustic properties of porous permeable fluid-saturated environments" by Loginov et al. (in *Physical Bases of a Seismic Method*, Nauka, 1991). "Nonlinear seismicity and acoustics—a step in the future of oil and gas geophysics" by Loginov et al. (International Geophysical Conference SEG–EAGE). "Problems of nonlinear seismicity" by Nikolaev (*Science*, 1987). "Accumulation and chaotic development of nonlinear acoustic processes at dynamic stress of geological structures" by Robsman (*Acoustic Magazine*, 1993). "Natural lumpiness of rock" by Sadovskij (Thesis of Academy of Science of the USSR, 79, Volume 274). "Interaction of acoustic waves in gas-, oil-and water-saturated collectors" by Sergeev et al. (in *Problems of Nonlinear Seismicity*, Nauka, 1987). "Nonlinear reflecting properties of micro-nonuniform environments" by Sibiryakov (in Physical Fundamentals of a Seismic Method, Nauka, 1987). "Opportunities of amplification of nonlinear seismic waves" by Engelbreht and Hamidulin (in *Nonlinear Seismology*, 1986). "Elastic nonlinearity of reservoir rocks—a paradigm shift" by Khan and Khan McGuire (*CSEG Recorder*, 2005).