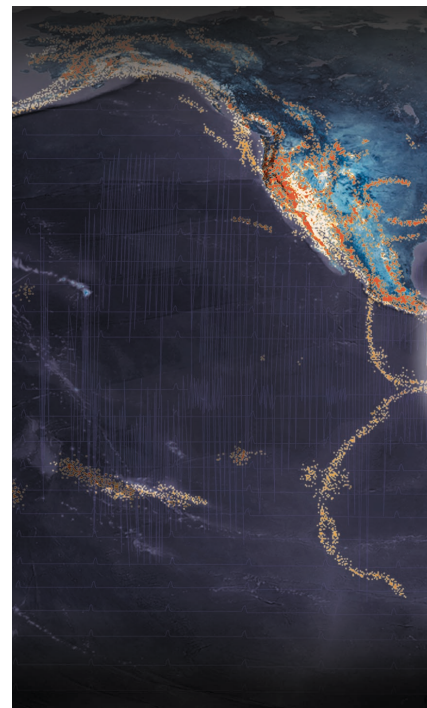


# Seismicity in the Oil Field

In some regions, hydrocarbon production can induce seismic activity. To help understand how production affects seismicity, a recording network was installed in a producing field in Russia. In a cooperative project between Schlumberger and the Institute of Dynamics of Geospheres at the Russian Academy of Sciences, scientists are analyzing the recorded data to help forecast seismic events, understand reservoir properties and monitor water injection.



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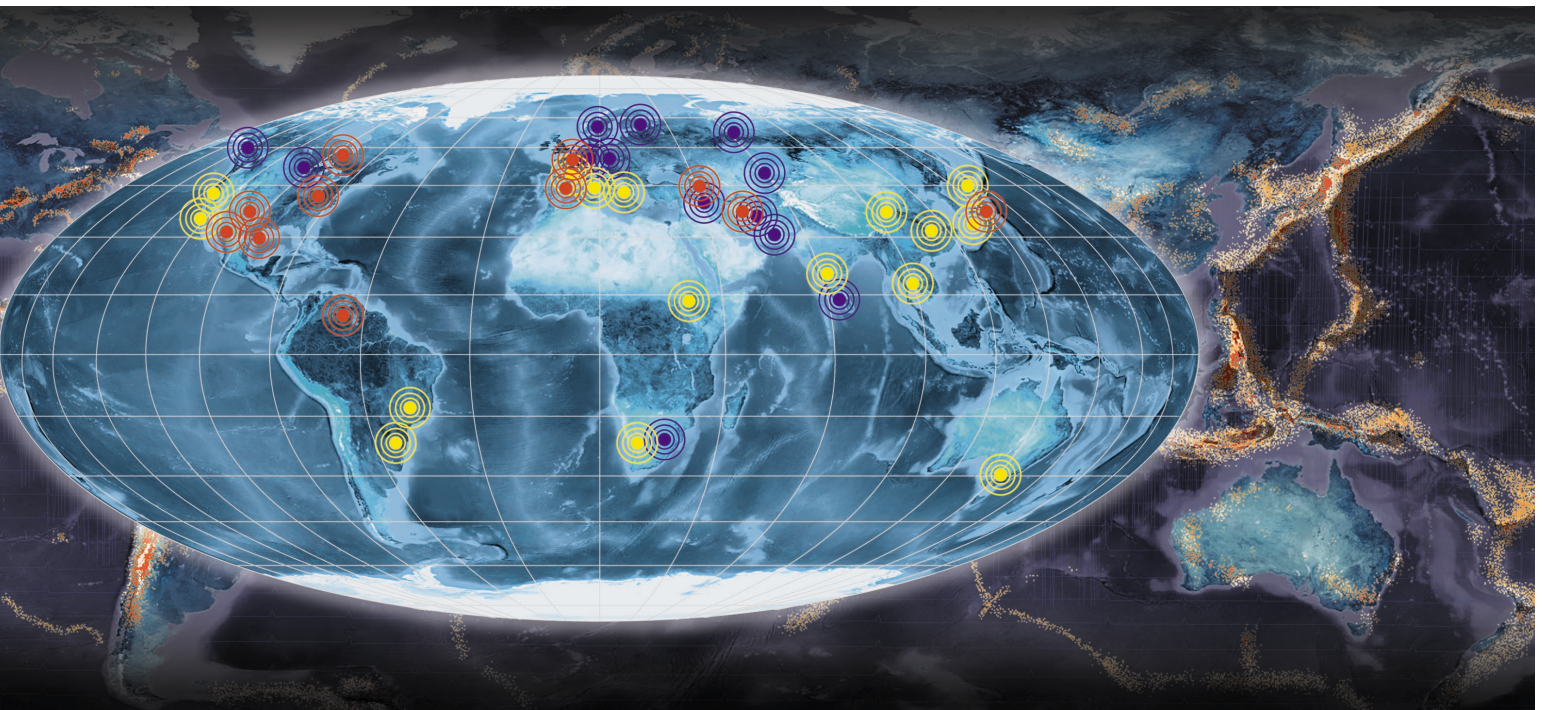
Scientists have observed that earthquakes can be triggered by human action. Induced seismicity, or seismic activity caused directly by human involvement, has been detected as a result of water filling large surface reservoirs, development of mineral, geothermal and hydrocarbon resources, waste injection, underground nuclear explosions and large-scale construction projects.<sup>1</sup> It is important to understand the conditions under which seismicity may be induced so that these operations can be performed safely.

The notion that human activity can provoke earthquakes is not new. In the 1870s, proposals for impounding water in man-made lakes across regions of southern California, USA, were rejected because of concerns that this might trigger earthquakes.<sup>2</sup> The hundreds of small earthquakes detected immediately after the 1936 filling of the Hoover Dam in Nevada and Arizona, USA, provided the first definite evidence of such an effect. Since then, more than 100 other cases have been reported around the world.<sup>3</sup> In some instances, the resulting seismic activity has been severe. Within four years of completing construction in 1963, the reservoir area surrounding the Koyna Dam near the west coast of India experienced several significant earthquakes, the largest being a major event of magnitude 7.0.<sup>4</sup> In

the nearby town of Koynanagar, masonry buildings were destroyed and 200 people died.

In the early 1920s, geologists in south Texas noted faulting, subsidence and earthquakes in the vicinity of the Goose Creek oil field. Houses shook and faulting broke the earth's surface.<sup>5</sup> A direct relationship was proposed between oil extraction and the onset of subsidence and seismic activity. At the time, subsidence associated with hydrocarbon extraction was considered rare, and this case was thought to be a unique occurrence in geological literature. Similar observations were then reported for the Wilmington oil field in Long Beach, California, USA, where six small earthquakes occurred between 1947 and 1955, and surface subsidence reached 9 m [30 ft] in 1966 after 30 years of oil production.<sup>6</sup>

By the 1960s, it became clear that deep injection of fluid could also cause seismicity. Early in 1962, waste-water by-products from the Rocky Mountain Arsenal near Denver, Colorado, USA, were injected into a disposal well in fractured Precambrian rocks at a depth of about 12,000 ft [3660 m]. Earthquakes up to magnitude 4.3 began occurring one month later, and continued for the three-year injection period. The frequency of earthquake occurrence was clearly related to the rate and pressure of fluid injection.<sup>7</sup>



⊙ Induced by dams    
 ⊙ Induced by oil and gas recovery    
 ⊙ Induced by mineral-deposit exploitation

Seismologists speculated that if the physical basis for triggering earthquakes by injection could be clearly established by field experiments, fluid injection or extraction might become a means of controlling earthquakes or preventing inadvertent seismic activity. Geophysicists and hydrologists designed an experiment to test the feasibility of controlled earthquake generation in the Rangely oil field in western Colorado. The field had been on waterflood since 1957, and an array of seismographs in the neighboring state of Utah had been recording small earthquakes in the field since its installation in 1962. In 1967, a portable array of seismographs was installed directly over the field. It began recording and locating seismic events along a subsurface fault in two areas where waterflooding had induced high pore

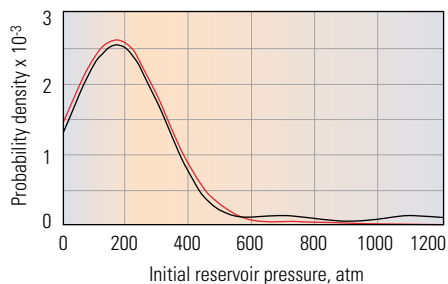
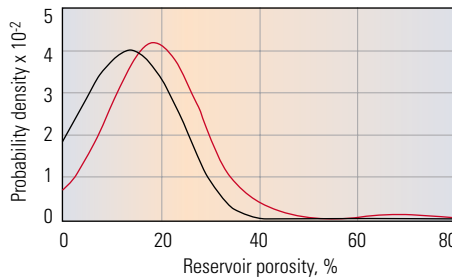
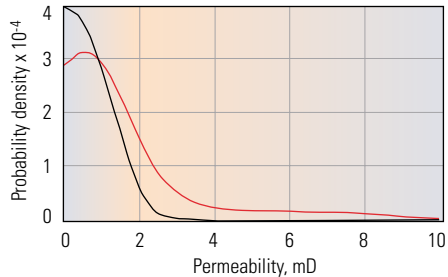
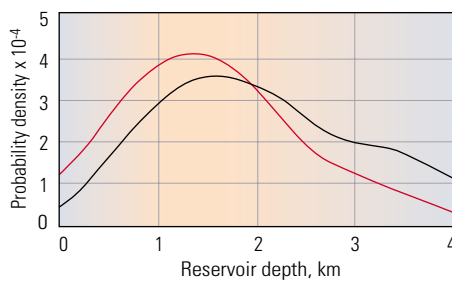
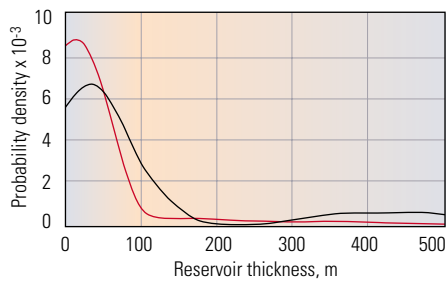
pressures.<sup>9</sup> The project successfully initiated seismic activity by injecting even more water and halted seismic activity by producing from near the fault. The report suggested the technique might be useful for controlling the timing and size of major earthquakes, and noted that up to that time, fluid injection for enhancing oil recovery had not triggered any damaging earthquakes.

In all these cases, the result of human interference was to change the state of stress in the surrounding volume of earth. If the stress change is big enough, it can cause an earthquake, either by fracturing the rock mass—in the case of mining or underground explosions—or by causing rock to slip along existing zones of weakness. The situation in regions of hydrocarbon recovery is not always well understood: in some places,

extraction of fluid induces seismicity; in others, injection induces seismicity. In many areas where the rock is not under large tectonic stresses, the seismic energy released during induced events is low—typically of magnitude 0 to 3—and not even felt on the earth's surface. However, if the rock mass is already under large tectonic stresses, the energy added by man's endeavors can have a destabilizing influence. Even minor actions can trigger strong seismicity.<sup>9</sup>

Long-term hydrocarbon exploitation can disturb conditions around oil and gas reservoirs in several ways, causing significant stress changes in the reservoir and the surrounding rocks. Injected fluid can propagate or filter into cracks and cause increased fluid pressure in pores and fractures, serving as a kind of lubricant in

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2. Bolt B: *Earthquakes: A Primer*. San Francisco, California, USA: W.H. Freeman and Company, 1978.
3. Guha SK and Patil DN: "Large Water-Reservoir-Related Induced Seismicity," in Knoll P (ed): *Induced Seismicity*. Rotterdam, The Netherlands: AA Balkema Publishers (1992): 243-266.
4. Earthquake magnitudes in this article are taken from a variety of literature sources. Magnitudes are usually calculated from the recorded amplitude of a seismic wave of specified frequency and calibrated for the distance from the earthquake and the magnification of the seismograph.
5. Pratt WE and Johnson DW: "Local Subsidence of the Goose Creek Oil Field," *Journal of Geology* 34, no. 7-part 1 (October-November 1926): 577-590.
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9. Simpson, reference 1.
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▲ A comparison of probability distributions for some key variables in hydrocarbon reservoirs. The black line represents data from 40 oil and gas fields with an observed increase in seismic activity due to hydrocarbon production; the red line corresponds to random-sample data on 200 reservoirs located in various regions around the world.

Average reservoir depth and thickness appear to be greater for oil fields with induced seismicity than average depth and thickness values for other hydrocarbon fields. Average porosity and permeability are lower for hydrocarbon fields with induced seismicity than for those without. Initial reservoir pressure has the same distribution in both cases.

Although there are examples of significant earthquakes related to reservoir development, and it is sensible to consider triggered seismicity as one of the possible hazardous consequences of production, it is rare for reservoir development to lead to earthquakes strong enough for people to feel. More often, induced seismic events are weak, and can be recorded only with the help of a sensitive seismometer network.

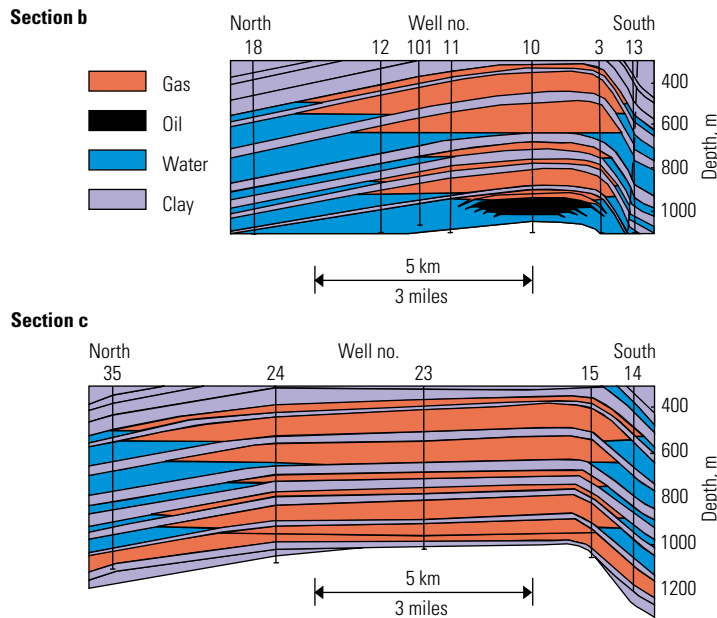
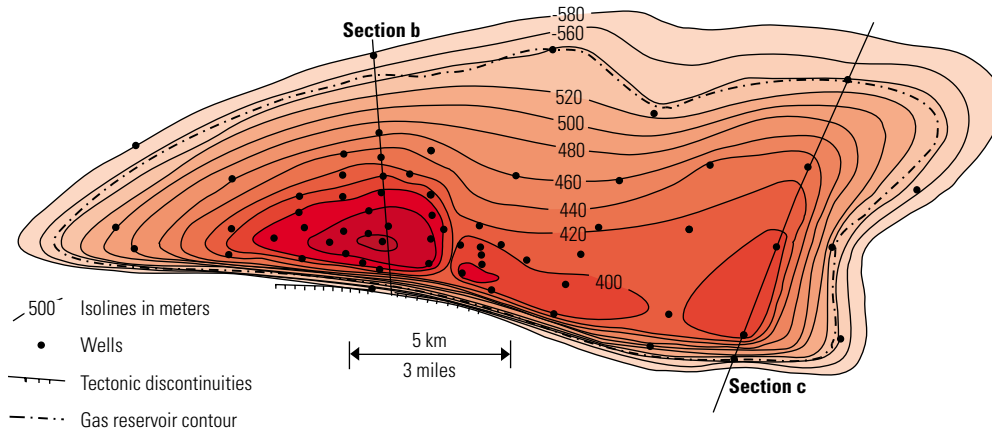
These feeble seismic events, induced ones as well as those caused by natural deformation processes, carry important information about the location of zones of weakness and seismically active faults in the rock. They also contain information about temporal changes in stress state

fractured zones. Three types of forces help initiate filtration-induced earthquakes as well as other man-made and tectonic earthquakes by causing motion of rock blocks along faults: First, poroelastic forces can force displacement along a fault in the surrounding rock mass. Second, hydrostatic forces can transfer pore pressure from an injection zone to a zone preparing for an earthquake through a fault or other permeable feature. Fluid migration in this case may be negligible. Finally, pressure differences can cause fluids to migrate from injection zones to zones of earthquake incipience.

Hydrocarbon field development always induces at least minor changes in the stress state of a reservoir. Sometimes this increases the level of small, background seismic events. The energy released depends on the properties of the reservoir and surrounding rocks, the level of heterogeneity and the rate at which they were deposited. Some 40 examples are known in which reservoir production caused significant changes in the seismic activity of a neighboring region. Comparison of data from these reservoirs with measurements from 200 other fields around the world shows which properties are most closely related to production-induced seismicity (above).



▲ Location of the Gazli field, Uzbekistan.



◀ Structural map (top) and cross sections from the Gazli gas field. The structural map shows well locations, contours of the uppermost horizon in meters, tectonic discontinuities, the locations of the cross sections and the limit of the gas reservoir. The cross sections show gas, oil, water and clay layers. [Adapted from Zhabrev IP (ed): *Gas and Condensate Deposits*. Moscow, Russia: Nedra, 1984 (in Russian)].

and other formation properties. Interpreting records of production-induced seismicity allows identification of active faults, delineation of fluid-contrast fronts and estimation of time variations of reservoir permeability and porosity. This information, in turn, may help to optimize the scheduling of hydrocarbon production, water injection and enhanced recovery operations.

In the following sections, we examine the relationship between recorded seismic events and the evolution of hydrocarbon exploitation parameters through two case studies. The first is a study of earthquakes in the region of the Gazli gas field in Uzbekistan. The second is an investigation of temporal and spatial characteristics of seismicity in the region of the Romashkino oil field in Tatarstan, Russia.

### Gazli Earthquakes

The Gazli gas field is located in Central Asia about 100 km [63 miles] northwest of Bukhara, Uzbekistan (previous page, bottom). The field structure consists of Jurassic, Cretaceous, Paleocene and Neocene formations overlapping Paleozoic basement in an asymmetrical anticline with dimensions 38 by 12 km [24 by 7.5 miles] (above). The thickness of sediments is about 1000 m [3300 ft], reaching a total depth of 1600 m [5200 ft].

The field has 11 accumulations—10 gas and condensate, and one oil—all located in Cretaceous sediments. Producing horizons consist of sandstone and clay beds. Porosity of the sandstone is high and averages 20 to 32%. Permeability of all but one producing horizons ranges from 675 to 1457 mD. Produced gas consists mainly of methane (93 to 97%) with condensate in the lower horizons (8 to 17.2 g/m<sup>3</sup> [67 to 144 lbm/gal]).

The gas field was discovered in 1956 and production began in 1962. Over the next 14 years, roughly 600×10<sup>6</sup> m<sup>3</sup> of water, or 10<sup>6</sup> ton per km<sup>2</sup>, were injected. In spite of the water injection, subsidence was detected at the surface. The subsidence rates averaged 10.0 mm/a [2.5 in./yr] in the period 1964 to 1968 and 19.2 mm/a [5 in./yr] from 1968 to 1974. Subsidence was observed to be associated with reduction in formation pressure: when formation pressure dropped by 1 atm [101 kPa], the central part of the field subsided by 2 mm.<sup>10</sup>

Beginning in 1976, a series of large earthquakes was recorded. The first significant earthquake occurred on April 8, 1976 at a distance of

10. Piskulin VA and Raizman AP: "Geodesic Investigations of the Earth Surface Deformation in Epicentral Zones of Gazli Earthquakes in 1976-1984," *Proceedings of 7th International Symposium on the Earth Crust Modern Motion*. Tallinn, 1986.

20 km [12 miles] from the Gazli gasfield boundary. The earthquake magnitude measured 6.8. Just 39 days later, on May 17, 1976, another severe earthquake occurred 27 km [17 miles] to the west of the first one. The magnitude of the second earthquake was 7.3. Eight years later, on March 20, 1984, a third earthquake occurred 15 km [9 miles] to the west of the second earthquake, with a magnitude of 7.2. The hypocentral depths of all three were 25 to 30 km [16 to 18 miles], all within the 32-km [20-mile] thick earth crust in the region. Aftershocks occurred in a volume surrounding the three hypocenters. These earthquakes are the strongest of all the known earthquakes in the plain of Central Asia.

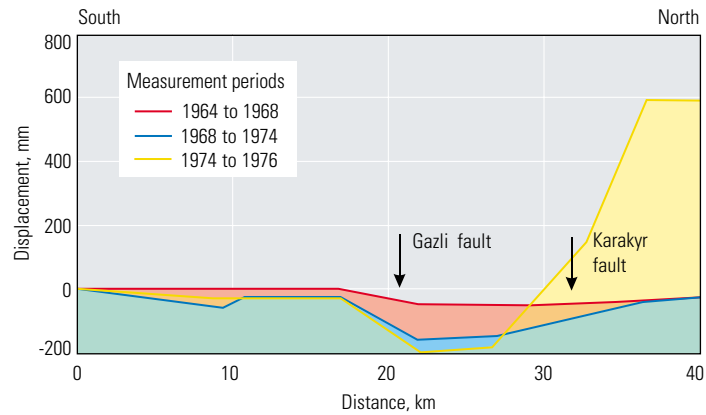
There was no clear relationship between the location of the earthquake hypocenters and any previously known active tectonic structures. Closer investigation showed that the earthquakes had created new faults.<sup>11</sup> Analysis of the fine-scale structure of the aftershock zone indicated an initial state of tectonic activation.<sup>12</sup> The orientation of the fault plane, the direction of fault-block displacement and the trend of the aftershock zone correspond to the regional stress field and orientation of regional-scale faults.

Geodesic measurements were made after each large earthquake (below). The area that had previously subsided was found to have subsided an additional 230±8 mm [9 in.] after the 1976 earthquakes (above).<sup>13</sup> In the vicinity of the earth-

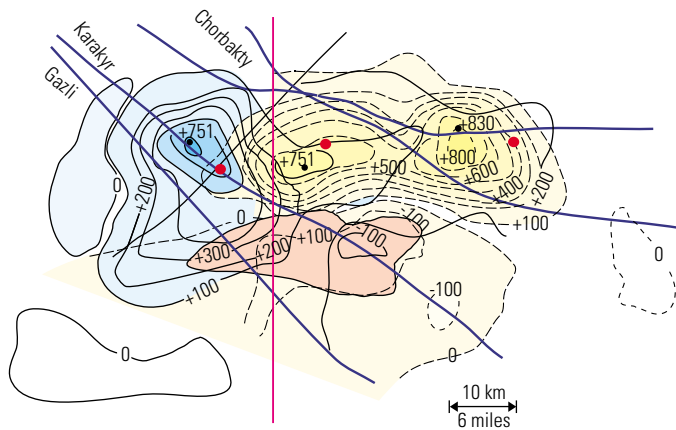
quake epicenters, an upward displacement of the surface was detected: up to 830 mm [33 in.] near the epicenter of the April 1976 earthquake, up to 763 mm [30 in.] near the epicenter of the May 1976 earthquake, and up to 751 mm [29.5 in.] near the epicenter of the March 1984 earthquake. Horizontal displacements of up to 1 m [3.3 ft] were detected and found to be directed mainly away from the epicenters.

The amassed data indicate that the Gazli earthquakes were triggered by exploitation of the gas field.<sup>14</sup> High tectonic stresses are typical for

border regions of young platforms such as the Turan plate. These stresses cause accumulation of significant tectonic energy. Depletion of the gas field served as a trigger for the release of accumulated tectonic energy in the form of significant seismic events. Field production was undertaken without consideration of the possibility of production-induced seismicity. Some geophysicists, including the authors of this article, believe that if the natural tectonic regime had been taken into account during the planning of hydrocarbon recovery, the earthquakes might have been avoided.<sup>15</sup>



▲ North-south profile of vertical displacement after the Gazli earthquakes. The region between the Gazli fault and the Karakyr fault subsided, while north of the Karakyr fault, upward displacement was measured.



- Vertical displacement after the earthquakes in 1976, in mm
- Vertical displacement after the earthquakes in 1984, in mm
- A boundary of gas accumulation
- Epicenters of the earthquakes on April 8 and May 17, 1976 and March 20, 1984
- Tectonic faults
- Position of surface vertical displacement profile

◀ Surface deformation following the Gazli earthquakes of 1976 and 1984. Maximum vertical displacements are shown as black dots, and earthquake epicenters as red dots. Dashed lines mark the vertical displacement following the 1976 events; and solid lines mark the vertical displacement following the 1984 event. The gas field is shaded in light red. Tectonic faults are shown as thick black lines. The red vertical line marks the position of the cross section displayed (above). [Adapted from Piskulin and Raizman, reference 10].

## The Romashkino Oil Field

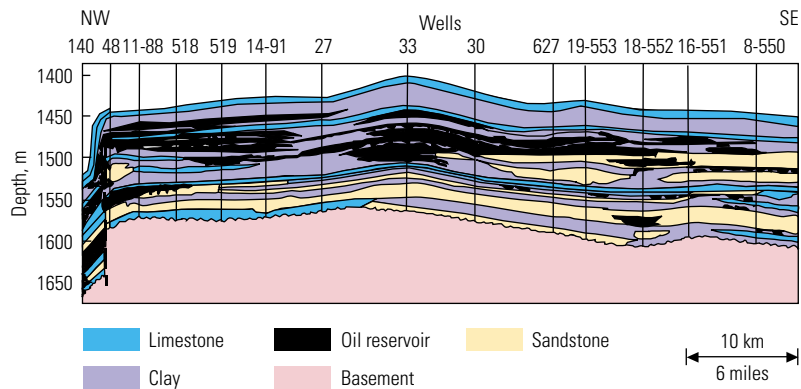
The Romashkino oil field is the biggest oil field in Russia (right). It has a maximum dimension of about 70 km [44 miles], a structural height of 50 to 60 m [164 to 197 ft] and a reservoir depth of 1600 to 1800 m [5200 to 5900 ft].<sup>16</sup> The deposit is a succession of 10- to 30-m [33- to 100-ft] thick oil-bearing Devonian sandstones and carbonate rocks (below). The main productive formation contains thinly bedded sandstones and clays. Permeability of the sandstone layers is 200 to 420 mD, porosity is 18.8 to 20.4% and oil saturation is 69.4 to 90.5%. Initial reservoir pressure was 160 to 180 atm [16.2 to 18.2 MPa].

Geological exploration in this region began in 1933. In 1947, exploration drilling commenced, and in 1948 Romashkino produced its first oil.<sup>17</sup> Water injection began in 1954, but for the first several years, injection did not compensate for fluid extraction. In 1958, for the first time, the volume of fluid injected that year exceeded the volume of fluid extracted, and by 1963 total injected and extracted fluid volumes balanced. By 1975, the total volume of fluid injected in the program reached  $2.13 \times 10^9$  m<sup>3</sup>, or 104.7% of total extracted fluid. Suggested maximum pressures for water injection were 200 to 250 atm [20.2 to 25.3 MPa], but actual injection pressures sometimes were higher.

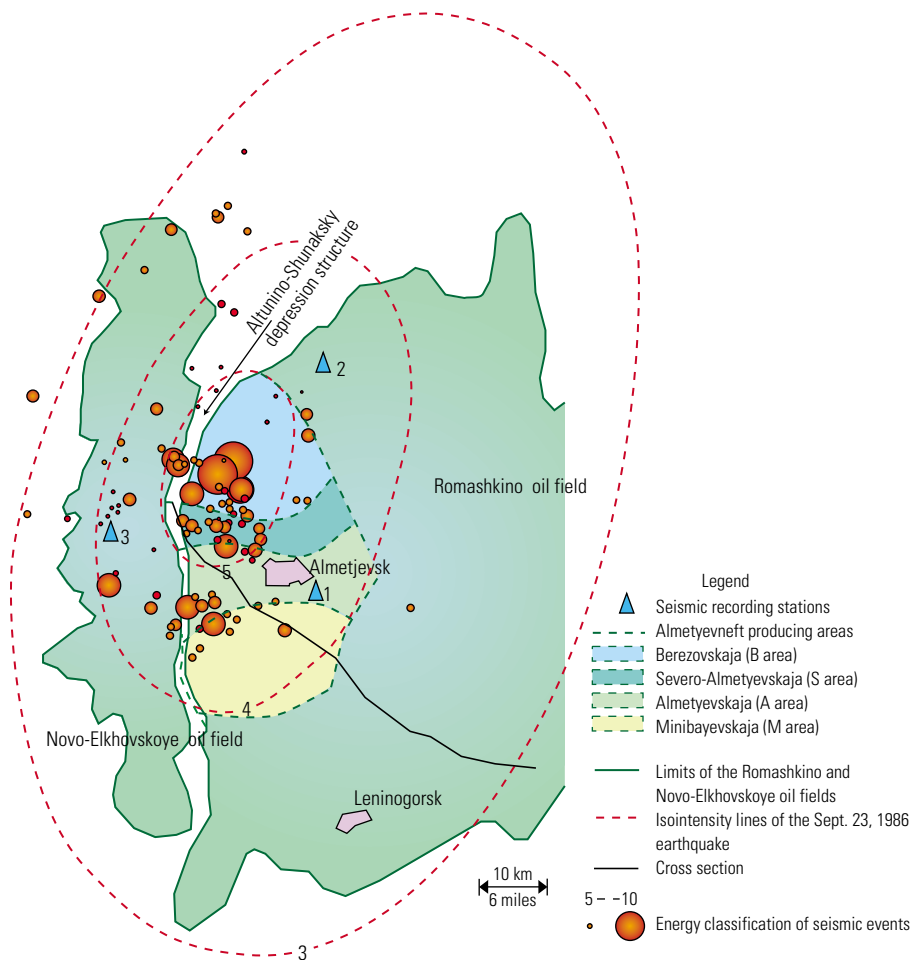


^ Location of the Romashkino field, Russia.

11. Shteinberg VV, Grajzer VM and Ivanova TG: "Gazli Earthquake on May 17, 1976," *Physics of the Earth 3* (1980): 3-12 (in Russian).
12. Turuntaev SB and Gorbunova IV: "Characteristic Features of Multi Fracturing in Epicentral Zone of Gazli Earthquakes," *Physics of the Earth 6* (1989): 72-78 (in Russian).
13. Piskulin and Raizman, reference 10.
14. Akramhodzhaev AM and Sitdikov B: "Induced Nature of Gazli Earthquakes, a Forecast of Earthquakes of Gazli Type and Prevention Measures," *Proceedings of Workshop on Experience of Gazli Earthquakes Study Further Investigation Directions*. Tashkent, Uzbekistan: FAN (1985): 59-60 (in Russian).  
Akramhodzhaev AM, Sitdikov BB and Begmetov EY: "About Induced Nature of Gazli Earthquakes in Uzbekistan," *Geological Journal of Uzbekistan 4* (1984): 17-19 (in Russian).  
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Mavlyanov GA (ed): *Gasli Earthquakes in 1976 and 1984*. Tashkent, Uzbekistan: FAN, 1986 (in Russian).
15. Akramhodzhaev et al, reference 14.
16. Bakirov AA (ed): *Geological Conditions of Oil and Gas Accumulation and Location*. Moscow, Russia: Nedra, 1982 (in Russian).
17. Muslimov RH: *An Influence of Geological Structures Distinguish Features on an Efficiency of Romashkino Oil Field Development*. Kazan, Russia: KSU, 1979 (in Russian).



^ Geologic profile of the Romashkino field. [Adapted from Muslimov, reference 17].



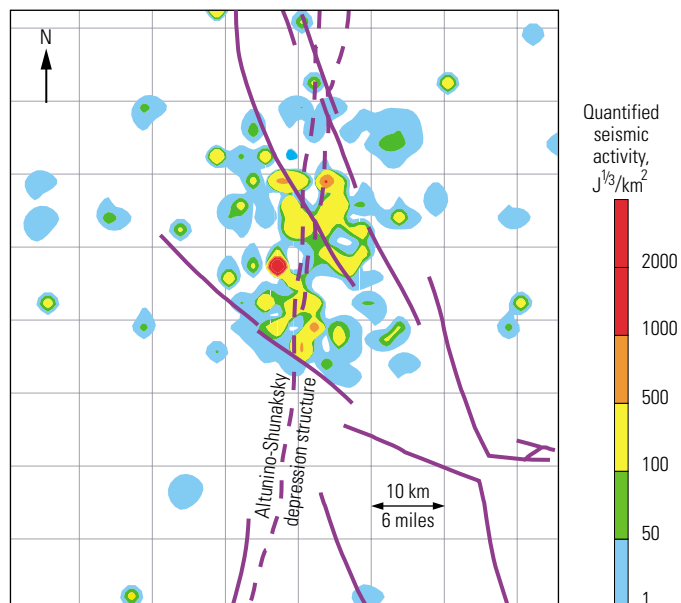
### Characteristics of Romashkino Seismicity

According to seismic zoning maps, the southeast part of Tatarstan in the region of the Romashkino oil field is considered a seismically quiescent area. But in 1982 and 1983, after decades of production and injection, citizens in the vicinity of the town of Almetjevsk began noticing moderate seismic events. In 1985, the “Tatneftegeophisica” seismic service installed a local seismic network that recorded numerous earthquake epicenters in the region of the Romashkino oil field (left). Most of these are in the western part of the field on the Altunino-Shunaksky depression, the structural boundary between the Romashkino and Novo-Elkhovskoye oil fields.

From 1986 to 1992, the network recorded 391 local earthquakes with magnitudes up to 4.0. Three time intervals showed noticeable increases in seismic activity—at the end of 1986, in the middle of 1988 and at the end of 1991. The largest episodes were an earthquake on September 23, 1986, with magnitude 3.8 and another with magnitude 4.0 on October 28, 1991, in the region of the town of Almetjevsk.<sup>20</sup>

^ Seismic activity in the region of the Romashkino oil field. Seismic recording stations are triangles, seismic epicenters are dots or circles, with the size depending on the amount of energy released. The dashed red ellipses are contours of intensity of the September 1986 earthquake. The black line positions the cross section displayed (previous page, bottom). The four producing areas of the Romashkino field that exhibit the most seismicity are delineated (B, S, A and M) and discussed in later sections of the article. [Adapted from Iskhakov et al, reference 20.]

For exploitation convenience, the Romashkino oil field is divided into more than 20 areas. In these areas, various methods of injection are used: injection through a line of wells, local injection wells and pattern waterflooding. In several areas, well density is three to five wells per km<sup>2</sup>. However, overall, the density of well coverage and geometry of well location appear to be the result of a complicated development history defined by objective factors as well as random ones.<sup>18</sup> Methods of nonstationary injection were used in a number of areas. That is, water was injected through one injection line for one month, then the first line was switched off and water was injected through another line, and so on. Injected water migration velocity varies from 100 to 1500 m/a [330 to 4900 ft/yr].<sup>19</sup>

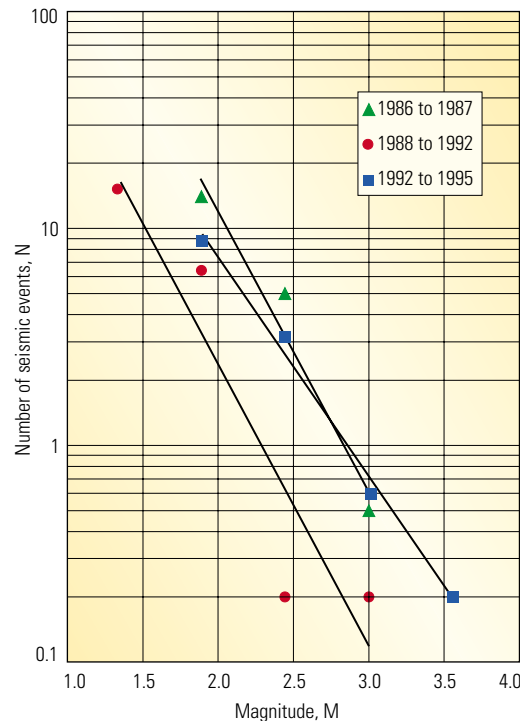


^ Distribution of quantified seismic activity (color coded) in the region of the Romashkino oil field. Quantified seismic activity is the sum of the cube root of seismic-event energy occurring in one square km<sup>2</sup>. The distribution of seismic activity is related to tectonic faults (solid purple lines) and the Altunino-Shunaksky depression structure (dashed lines).

The recorded activity can be examined in several ways to compare it to reservoir parameters. A map of seismic activity in the region of the Romashkino oil field shows spatial variations in the level of activity (previous page, bottom). A quantitative measure of seismic activity was computed for each km<sup>2</sup> by summing the cube roots of the energies in all earthquakes occurring there during the 1986 to 1992 period of observations.<sup>21</sup> Most of the seismic activity quantified in this way is situated along the Altunino-Shunaksky depression, with some corresponding to mapped tectonic faults.<sup>22</sup>

Before the recorded seismic activity can be used more quantitatively, the quality of the data must be assessed. Seismic recording networks have sensitivity limitations in the magnitude and distance of events they can record. Extremely small events can go undetected, as can distant events. Also, since large events do not occur often, shorter seismic recording intervals are less likely to record the larger earthquakes. For all earthquakes in a given region, a linear relationship exists between the magnitude of seismic events recorded in a time interval and the logarithm of the number, or frequency, of events of that magnitude. If the frequency-magnitude plot shows deviations from a linear trend, the earthquakes being plotted are not representative of all the seismic activity in the region. A deviation from linear on the low-magnitude end indicates that the seismic network is not sensitive enough to weak events, while a deviation on the high-magnitude end usually shows that the observation period was not long enough.

In the case of the seismic activity recorded from the Romashkino network, the frequency-magnitude plot is mostly linear (above). Only those events that were listed in the 1986 to 1995 catalogs of instrumentally recorded seismic events were plotted. Remote events with epicentral distances of more than 70 km [44 miles] were not considered. During the observation period,



< Relationship between the logarithm of the number of seismic events and the magnitude of the events in the region of the Romashkino oil field.

different catalogs used different methods of seismogram interpretation. To ensure consistency, frequency-magnitude relations were plotted separately for three different time intervals: 1986 through 1987, 1988 through 1992, and 1992 through 1995. Also, an average annual number of events for these time periods was considered.

For the earlier time interval—up to 1987—only the events with magnitude greater than 2 are representative for this particular seismic network: not enough events with lower magnitude were recorded. After 1987, because of a change in the seismic network, events with magnitude 1.5 become representative, and so can be included in further calculations.

For all three time intervals, the slopes of the frequency-magnitude plots range from  $-1.02$  to  $-1.3$ , considerably more negative than the value for natural seismicity, which is  $-0.75$  to  $-0.9$ .<sup>23</sup> The slopes of the Romashkino plots reach values typical of induced and triggered seismicity, as measured elsewhere in the world.<sup>24</sup>

### Change in Quantified Seismic Activity with Time

Quantified seismic activity is one of the most useful parameters for characterizing seismicity.<sup>25</sup> It provides a way to transform the display of seismic events from a discrete system to a continuous one: the point-by-point representation of seismic events described by three spatial coordinates plus the event time and energy converts to a continuous plot in a different coordinate system. The selected quantitative measure of activity was described earlier as the sum of the cube roots of the energies in all events occurring in a km<sup>2</sup>. To minimize the influence of an arbitrary choice in the way the area is divided into squares and in the selection of a beginning time interval, activity values were computed for overlapping areas and time intervals. The amount of overlap depends on the smoothness of the obtained distributions of activity.

18. Muslimov, reference 17.

19. Sultanov SA: *A Control of Water Injection in Oil Reservoirs*. Moscow, Russia: Nedra, 1974 (in Russian).

20. Iskhakov IA, Sergeev NS and Bulgakov VYu, *A Study of Relation Between Seismicity and Oil Fields Development. A report of OMP 50/81*. Bugulma, Russia: Tatneftegeophysica, 1992 (in Russian).

21. Energy is calculated through a formula based on the square of the amplitude of seismic waves of specified frequency content measured at a standard distance from the event source.

22. Belousov TP, Muhamediev ShA, Turuntaev SB, Junga SL, Ischakov IA and Karakin AV: "Active Faults, Stresses State and Seismicity of South-East Tatarstan," *Seismicity and Seismic Zones of Northern Part of Eurasia, part 2*. Moscow, Russia: Nauka (1994): 90-108 (in Russian).

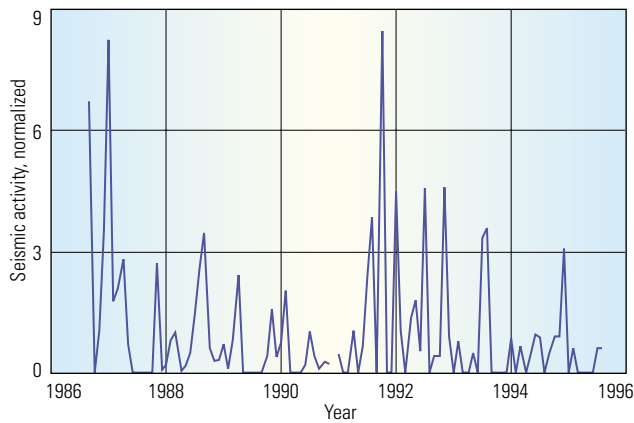
23. Sadovsky MA and Pissarenko VF: *Seismic Process in Block Media*. Moscow, Russia: Nauka, 1991 (in Russian). Isacks B and Oliver J: "Seismic Waves with Frequencies from 1 to 100 Cycles Per Second Recorded in a Deep Mine in Northern New Jersey," *Bulletin of the Seismological Society of America* 54, no. 6 (1964): 1941-1979.

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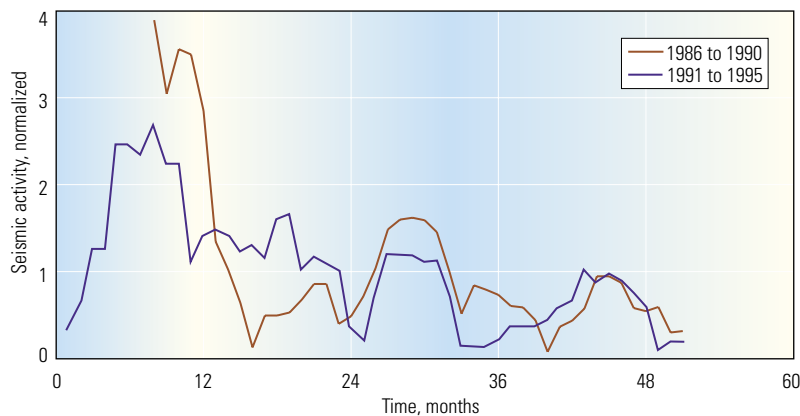
Nurec Dam," in *Seismological Investigations in the Regions of Large Dam Constructions in Tajikistan*. Dushanbe, Tajikistan: Donish (1987): 101-119 (in Russian). Turuntaev SB: "An Application of the Weak Seismicity Catalog for Detection of Active Faults in Rock Massif," in *The Monitoring of Rock Massif State During Long-Time Exploitation of Large-Scale Underground Works*. Appatity, Russia: KFAS, 1993 (in Russian).

25. Ponomaryov VS and Teitelbaum UM: "Dynamics Interactions Between Earthquakes Focuses," in: *Regional Investigations of Seismic Regime*. Kishinev, Moldova: Shtinita (1974): 79-92 (in Russian).





^ Seismic activity variation in the Romashkino region. The amplitude was calculated by summing the cube root of energies from all events occurring in that month.



^ Comparison of two cycles of seismic activity in the region of the Romashkino oil field.

Initially, the temporal and spatial components of activity change were calculated separately. The variation over time was examined on a monthly basis by summing the cube roots of energies of events that took place during a month. The resulting temporal series was normalized by the average value for that time period (above, top). Two strong peaks and several smaller ones are evident in this plot, but periodicity, if it exists, is not obvious. The seismic activity also may be displayed in other ways to try to extract any underlying periodicity. These methods involve transformation to phase coordinates (see "Another Dimension in Seismic Activity," page 12). Looking at the data in the new coordinate system led to the following results.

Over the observation period, seismic activity in the Romashkino oil field occurs in two cycles. Both cycles start with the strongest earthquakes for this region and each cycle lasts for about five years. The two cycles of activity variations

from 1986 to 1990 and from 1991 to 1995 can be smoothed and superimposed so that their first maximums coincide (above, near). An intriguing qualitative agreement of the curves appears, presenting evidence of some kind of regularity in seismic activity oscillations.

The existence of a regular component to the sequence of seismic events carries information about the energy state of the rock. It seems possible that when the level of energy accumulated in the rock from both natural and human sources reaches a certain value, energy is released by seismic events that are structured in space and time. This is similar to the behavior of a fluid being heated: for certain values of the rate of energy supplied to the fluid, its laminar movement changes to a chaotic flow, and then to a regular flow with convection cells.

In a rock formation undergoing oil production and water injection, there is an increased possibility of a large earthquake, regardless of the release of natural tectonic deformation energy in the form of seismic events. This is because the energy transferred to the rock through hydrocarbon exploitation will continue to increase. The existence of quasi-periodic oscillations in the level of seismic activity suggests that the input energy is rather large. Understanding this relationship between seismicity and exploitation regimes may allow seismicity to be controlled by a more careful scheduling of production and injection.

### Spatial Characteristics of Romashkino Seismicity

The seismic behavior of the Romashkino oil field exhibits an interesting characteristic: a high number of earthquakes occur in pairs, with a short time between members of a pair. For example, about 60 paired events with magnitude less than 1.0, or about 50% of the total number of events with such magnitude, occurred within 24 hours of one another. One can suppose that events grouped in time are somehow also connected in space. Examples of this can be seen in laboratory studies of seismic signals generated during crack growth in block models of rock.<sup>26</sup> Under certain conditions of crack development, a seismic impulse is generated at the moment a crack reaches the block boundaries. The locations of the event pair define the limits of the episodic movement along the crack, or fault.

Connections between epicenter pairs in the Romashkino field generally show north-south alignment, trending with the longitudinal Altunino-Shunaksky depression (next page, top). This direction also corresponds to the model of the regional stress field.<sup>27</sup>

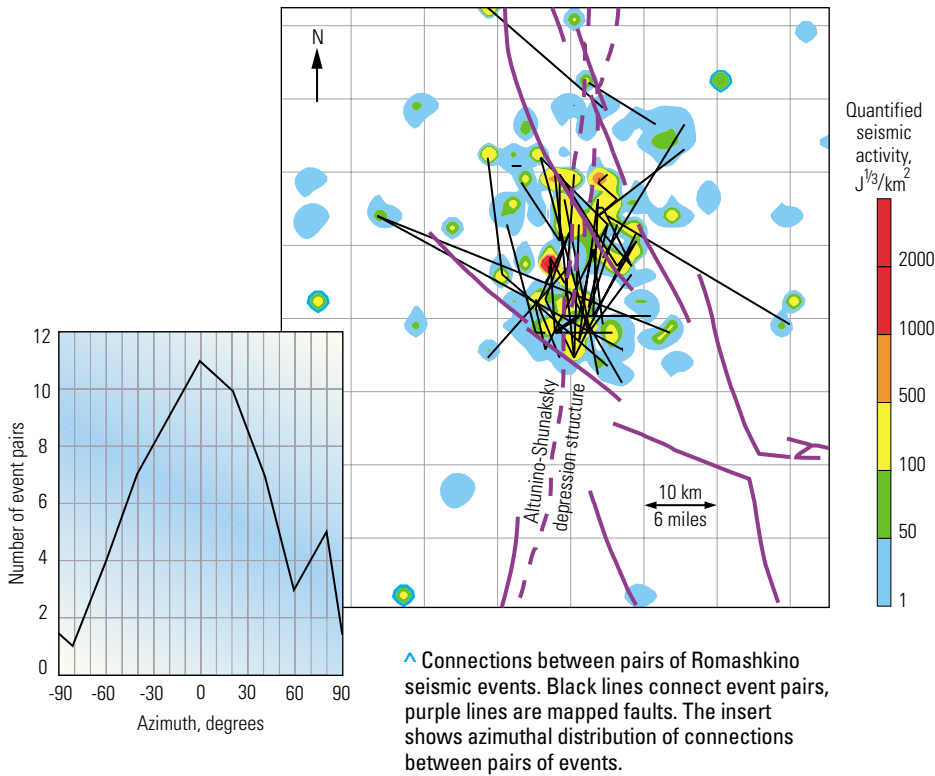
### Correlating Seismic Activity with Hydrocarbon Exploitation

It is always difficult to know whether seismicity is the result of human modifications in the region or if it is natural seismic activity related to tectonic processes; timing could be the key to knowing the difference. In general, the answer might be obtained if a regional seismic network had been installed in advance of the hydrocarbon development, dam construction or mining operation. The seismic network could record a background level of natural seismicity and quantify its

26. Turuntaev SB: "A Study of Various Model Waves Sources in Application to Seismology," PhD Thesis, Institute of the Physics of the Earth, Moscow, Russia, 1985 (in Russian).

27. Belousov et al, reference 22.

28. Mirzoev et al, reference 24.



to 1992 for the four most seismically active areas of the Romashkino oil field: Almet'yevskaja (A), Severo-Almet'yevskaja (S), Minibayevskaja (M) and Berezovskaja (B).

With these values, a pseudocatalog was constructed to tabulate the monthly extracted and injected volumes and the volume imbalance, or the difference between the volumes of injected and extracted fluids. These values were assigned a date (middle of a month), time (middle of a day), coordinates (approximate center of the considered area), and depth (1 km). Arranged in this format, the production data closely resembled the standard form for seismic catalogs, but listed fluid volume instead of seismic energy.

The previously described procedure for calculating quantified seismic activity was applied to the volumes in the pseudocatalog, but this time a "quantified exploitation activity" was calculated (below). The quantified exploitation activity was also analyzed using a 6-month moving average: 6-month averaged values of extraction, injection and imbalance were calculated, then the interval was shifted by a month and calculated again. The results were normalized by the overall average.

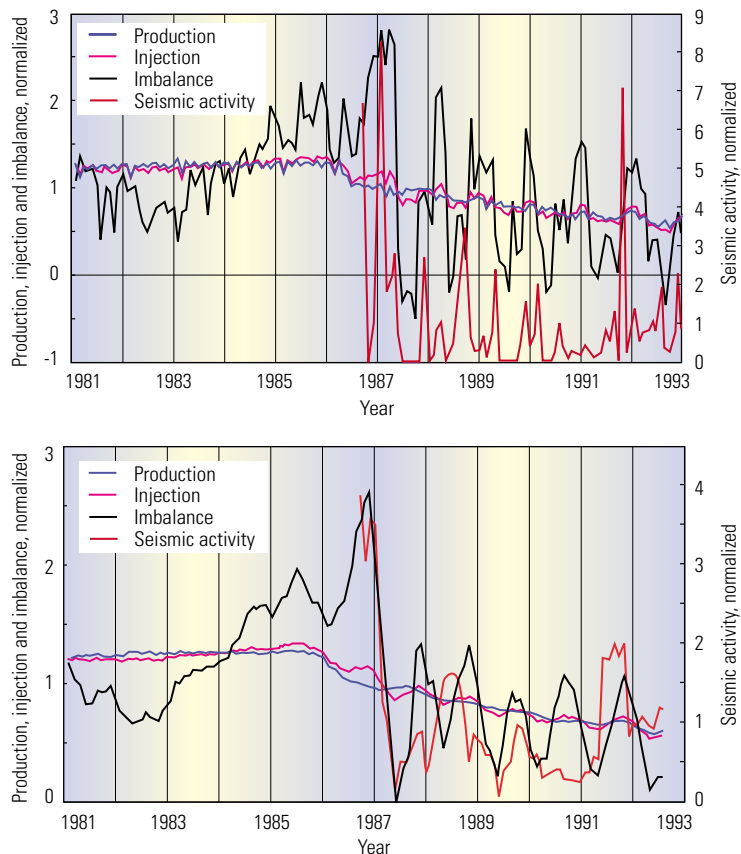
(continued on page 14)

characteristics. If, after the beginning of human action, a significant change in seismicity character is recorded, it could reasonably be interpreted as a seismic reaction of the rock formation to man's intervention.

Installation of seismic recording networks and assessment of background seismic activity are already common practice in regions where the level of natural seismicity is high.<sup>28</sup> However, in stable areas without a history of natural seismicity and where no sizeable earthquakes are expected, an advance seismic background study usually is not performed. In the absence of an advance study, the question may be resolved by two methods: first, to compare characteristics of the observed seismicity with those of known natural seismicity and those of induced seismic activity; and second, to look for correlation between the natural seismic and human activities.

In the first method, as was shown above, the slope of the magnitude-frequency plot for seismicity in the region of the Romashkino oil field has a value more typical of induced than natural seismicity. But the low number of recorded events indicates this result may not have high statistical significance.

The second method involves comparing the recorded seismicity with the exploitation schedule of the Romashkino oil field. The relevant production data are the values of the monthly volumes of fluid extracted and injected from 1981



▲ Top: Comparison of monthly values of seismic activity (red) with variations in total volumes of injection, production and imbalance in the four central areas (combined) of the Romashkino field. Bottom: Comparison of smoothed values of seismic activity (red) with variations in volumes of injection, production and imbalance in the four central areas of the Romashkino field.

## Another Dimension in Seismic Activity

For many natural processes, periodicity is evident from a simple plot of observation versus time. For example, the periodicities of ocean tides, phases of the moon, earth-surface temperature, hours of daylight and several other phenomena are easily recognized from observations or simple plots.

However, some processes may have so many forces at work that periodicity is not obvious. One way to analyze a time-varying observation called  $A(t)$  is to write it as a sum of three components

$$A(t) = A_p(t) + A_r(t) + A_t(t)$$

where  $A_p$  describes the high-frequency random oscillations of the activity,  $A_r$  is the regular component, and  $A_t$  represents slow variations, or a trend.

To find a regular component in the behavior of the function  $A(t)$ , we can change coordinates from  $A(t)$  and  $t$  to phase coordinates  $A(t)$  and its derivative,  $dA(t)/dt$ . The new coordinates can be thought of as the activity and the rate of activity variation.

For the seismic example, a point in the new, phase-coordinate system defines a state of the seismic process at some instant of time and the velocity of change of this state. A set of points, or a trajectory, defines a change of the system with time.

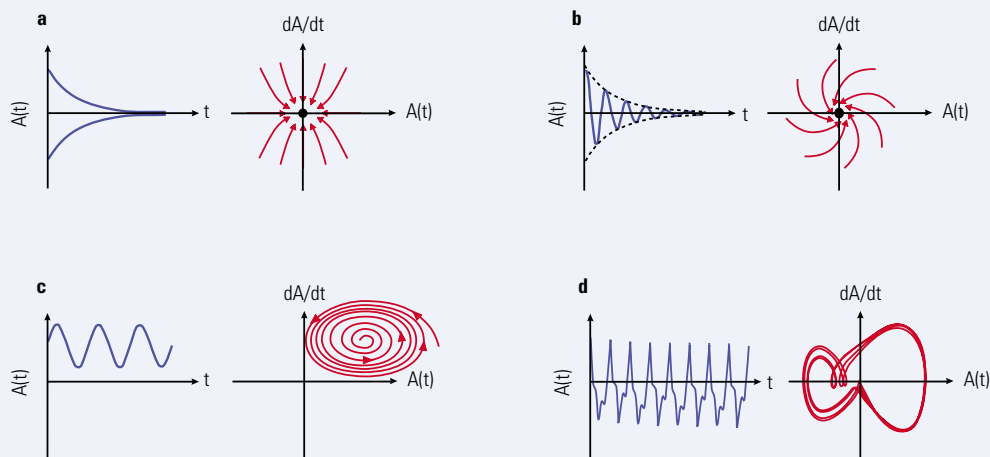
It is known that if a system's behavior can be described with certain types of equations, then special points, lines and areas in phase coordinates exist that "attract" the neighboring trajectories. These points, lines and areas are called "attractors."<sup>1</sup>

If the system is one of a monotonous decrease, the corresponding attractor is known as a node (below). For any starting time, the system moves in a direct line toward that node in phase space. In a system of damped oscillations, the attractor is known as a focus, toward which the system will move. A system of decreasing or increasing oscillations will have a corresponding, elliptically shaped, limit-cycle attractor in phase space. Highly irregular oscillations can still exhibit some regularity in phase space and be drawn to multiple attractors.

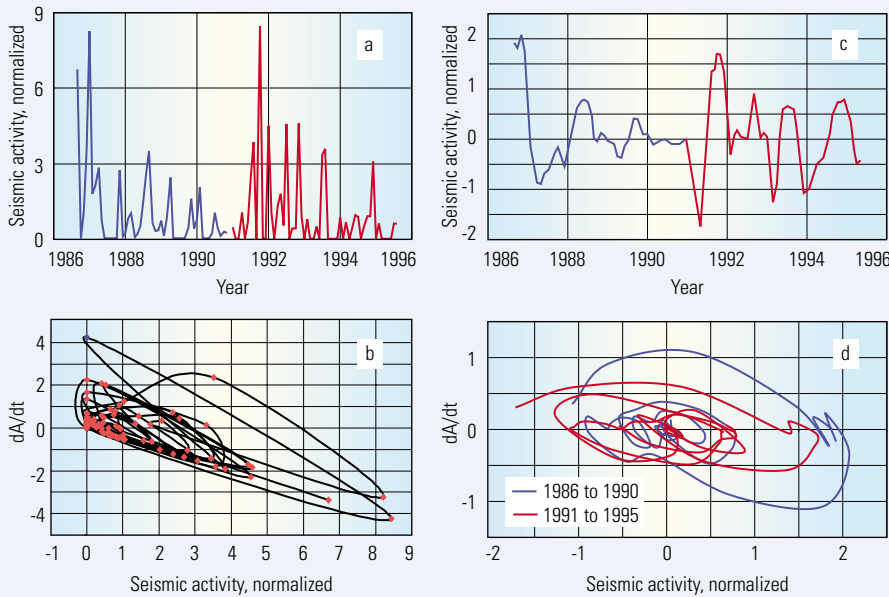
When there is a change in the parameters defining the system evolution, the set of possible solutions of the corresponding equations can change too. That may result in a change in the types of attractors in phase space. Such a change in attractor type is called bifurcation. The simplest examples of bifurcation are from one node (or focus) to two nodes (or foci), a bifurcation from focus to limit cycle, or bifurcation from one limit cycle to two limit cycles.

Expressing seismic activity in terms of phase coordinates is useful for several purposes:

- Two basic characteristics of the seismic process (its activity and rate of activity variation) are considered and transformed as independent values.
- The resulting phase portrait, or map, is more sensitive to procedures like smoothing and trend removal, which simplifies the selection of a time period for the calculation of activity, a smoothing type, or further coordinate transformation.



▲ Time-varying functions (left member of each pair) and corresponding types of attractors (right member of each pair) in phase space. a) node; b) focus; c) limit cycle; d) limit cycle with multiple attractors.



^ Seismic activity variations in the Romashkino region. Amplitude of seismic activity (*top left*) was calculated by summing the cube root of energies from all events occurring in that month. These data were displayed in phase coordinates (*bottom left*) to see if periodicity could be identified. The seismic activity data were then smoothed and detrended (*top right*) to extract a regular component. The phase portrait (*bottom right*) of the smoothed, detrended regular component shows some similarities to the phase portrait of a limit cycle on previous page, part c.

- The standard procedure of Fourier analysis is not effective if applied to quasi-harmonic oscillations with changing frequency and amplitude. In phase coordinates, such changes can still be analyzed in terms of attractors. For example, an increase in the amplitude of oscillations up to a constant value will look like a growing limit cycle and a decrease in amplitude to zero will look like a point-type attractor.

- After transforming the phase portrait to a form that allows a mathematical description, one can carry out the reverse transformation and obtain a mathematical description of the regular component of the original seismic process. This may allow estimation of future seismicity. The statistical significance of this prognosis depends on the value of the random, or unpredictable, component of seismic activity and of rate of activity variation, and it also depends on the ability to recognize bifurcation points in phase trajectories (points of change of seismic regime type).

### Phase Characteristics of Romashkino Seismic Activity

The time variation of quantified seismic activity in the region of the Romashkino oil field (*left, part a*) can be described by a phase portrait (*left, part b*). At first glance, the activity-state trajectory in phase coordinates looks chaotic. However, the random component can be removed by moving-window smoothing and the trend can be removed by a linear transformation similar to axes shift and rotation (*left, part c*).

The resulting phase trajectory (*left, part d*) starts at an initial point then spirals in; at a certain moment the trajectory comes back to the outer part of the spiral and then spins in again. All the while, the trajectory remains within a certain area.

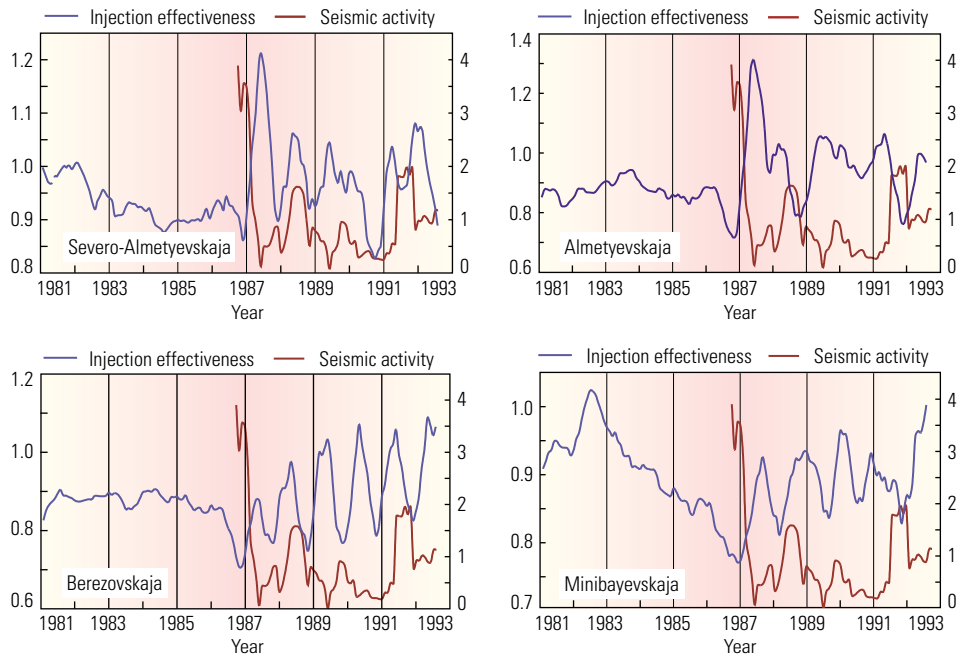
This phase portrait resembles the limit cycle displayed on the previous page, part c for an oscillator under the action of an external force.

An outward motion of a spiral trajectory generally corresponds to an increase in amplitude of seismic-activity oscillations, while an inward motion corresponds to a decrease of activity oscillations. Shape and dimensions of the obtained cycles can yield additional information about the seismic process, and should be studied further. One observation already is that oscillations of the seismic activity are not strictly sinusoidal; the period tends to oscillate with an average value close to 12 months.

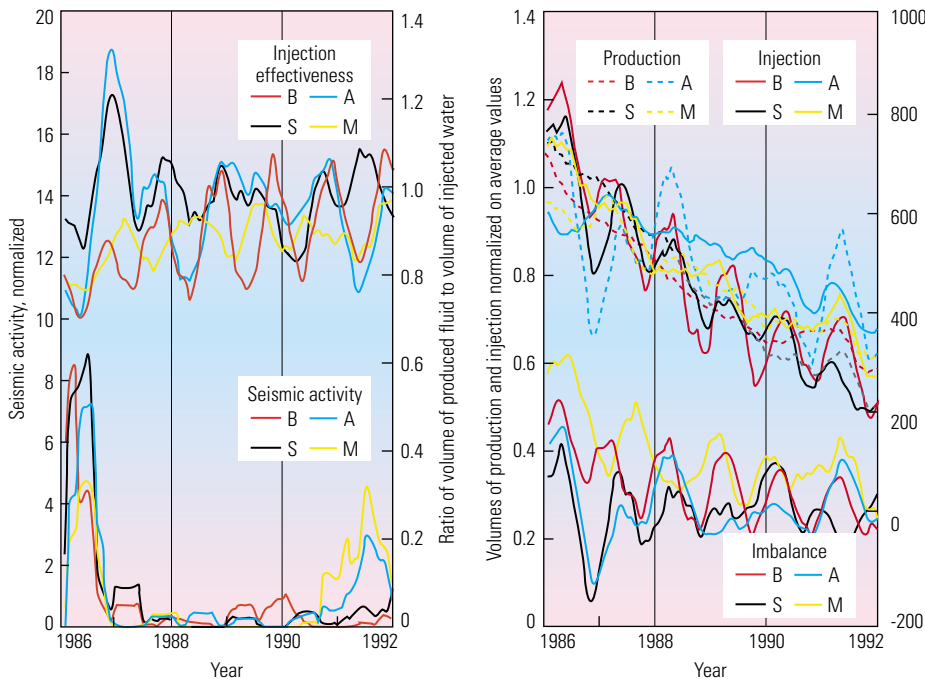
1. Haken H: *Advanced Synergetics. Instability Hierarchies of Self-Organizing Systems and Devices*, Springer series in Synergetics. Vol 20. New York, New York, USA: Springer-Verlag, 1983.

An injection effectiveness, or ratio of produced fluid to injected water volumes, was calculated for the four most seismically active areas (right). Comparing these to the quantified seismic activity in the region of the Romashkino oil field shows an inverse relationship in the oscillations of seismic activity and effectiveness of injection. In 1986, the time at which the seismic activity data become available and show a marked drop from extremely high to low, the character of time variation of the production parameters changes considerably.

In Area A, injection effectiveness begins to oscillate with significant amplitude opposite to the oscillations of seismic activity. In Area S, the onset of injection-effectiveness oscillations is also observed, but they are less synchronized with the seismic-activity oscillations. In Area B, even clearer, quasi-harmonic, injection-effectiveness oscillations are observed with a period close to 12 months and a regular amplitude. In Area M, a trend of decreasing injection effectiveness changes in 1986 to an increase with oscillations, roughly opposite in sign to the oscillations of seismic activity.



▲ Comparison of overall Romashkino seismic activity with variations of injection effectiveness for the four different areas of the field. In each case, the scale of the left vertical axis is injection effectiveness and the scale of the right vertical axis is normalized seismic activity.



▲ Comparison of seismic activity variations (bottom left) with injection effectiveness (top left), production and injection (top right) and volume imbalance (bottom right) for the four most seismically active areas of the Romashkino field.

To some extent, the features observed in the temporal variations of injection effectiveness are related to a change to a new fluid-injection technology in 1986. One of the results of such a change was a decrease of the injected volume in summer. In winter, injection was maintained to avoid freezing in the flow lines. This introduced a seasonal component to the effectiveness oscillations and more economical water injection in general. At the same time, it is impossible to assert that all the variations are due to injection-technology differences.

The injection effectiveness for the A, S, M and B areas can be compared with the variation in quantified seismic activity in each area (left). For completeness, the seismic activity changes are also compared with the extracted and injected fluid volumes.

A notable feature is the increase of injection volumes that took place four months before the two most considerable increases in seismicity—at the beginning and at the end of the studied time period in Area A. It is also remarkable that production decreased in these periods of increasing seismic activity, even when injection

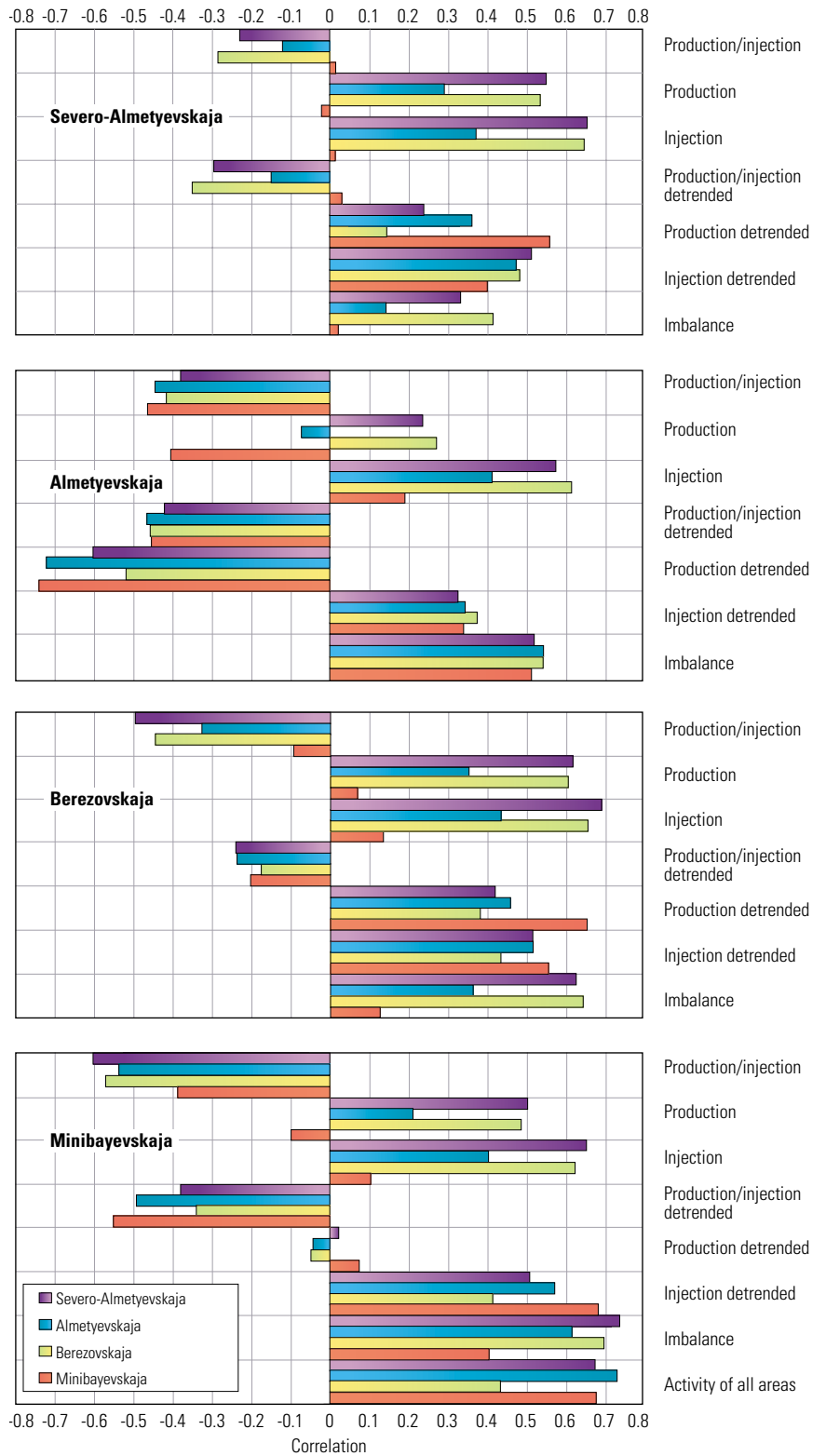
increased. Later on, even weaker increases of the seismic activity are always accompanied by a decrease in total fluid production in Area A. It is also interesting that, for example, during the 1991 to 1992 increase of seismic activity in Area M, both injection and production increase, but injection effectiveness decreases at the same time.

Regression analysis shows a statistically significant relationship between the seismic-activity variations in the four studied areas and production and injection regimes for these areas. The confidence level of the relationship is 99%.

Crosscorrelation coefficients were computed to help understand the relation between seismic activity in the four most seismically active areas of the Romashkino oil field and some characteristics describing the exploitation process, such as extracted and injected fluid volumes, imbalance and injection effectiveness. During the period of study, the volume of injected fluids and the volume of produced fluids both decreased for economic reasons. For completeness, correlations were computed between the seismic activity and detrended values—removing a linear trend from the values—of injected and produced volumes.

Correlation between the exploitation parameters in one area and the seismic activities in all four areas can be shown graphically (right). The correlation with the seismic activity of each region is depicted as a horizontal bar. Longer bars indicate better correlation, and bars to the left show negative correlation.

It is remarkable how well the seismic activity and exploitation parameters correlate, not only within an area but also between areas. The injected and produced volumes in every area and their detrended counterparts correlate positively with the seismic activity in all four areas, with few exceptions (correlations between seismic activity in Area A and production in every area are negative). The injection effectiveness (produced/injected) in every area correlates negatively with seismic activity in all four areas while imbalances correlate positively. The highest absolute values of correlation are observed between the detrended production in Area A and the seismic activity in Areas A and M (which is near A); and between the imbalance in Area M and the seismic activity in Areas S and B. Absolute values of these correlation coefficients are greater than 0.7.



^ Correlation between exploitation parameters and seismic activity for the four production sectors. The exploitation parameters are listed at the right. The correlation with seismic activity in each of the four areas is shown as a colored horizontal bar. For example, at the top, the correlation coefficient between the production/injection ratio in the S sector and the seismic activity in the A sector (blue bar) is -0.12.

The correlation between seismic activity and hydrocarbon exploitation means the two are related, but it does not indicate which one is the cause, which one is the effect, and how long it takes the cause to create the effect. Shifting the data series in time relative to each other, recomputing the correlation, and tracking the lag that results in the best correlation gives the best statistical estimate of the time lag between cause and effect (right and next page). Positive lags correspond to positive time shifts of the seismic-activity series relative to other data series. The most interesting are the plots for Areas M and A, which indicate that changes in exploitation parameters precede changes in seismic activity. For these areas, maximum correlation is observed when lags are positive and equal to one to two months. Correlation coefficients reach 0.8 for Area M (correlation between seismic activity and injection) and 0.7 for Area A (correlation between seismic activity and imbalance, and between seismic activity and production).

The maximum correlation for Area B corresponds to zero or negligible time shift.

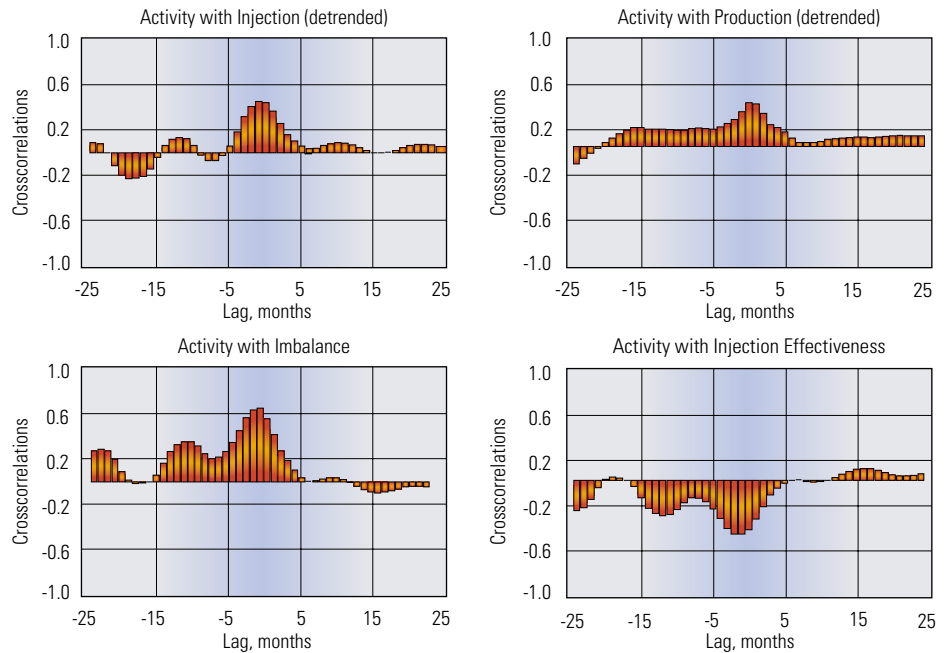
It was a surprise that for Area S, the maximum correlation occurs when the time shifts of seismic activity relative to most parameters are negative and equal to six to seven months. This means that the change in the seismic activity precedes the change of exploitation parameters.

### Exploiting Seismicity

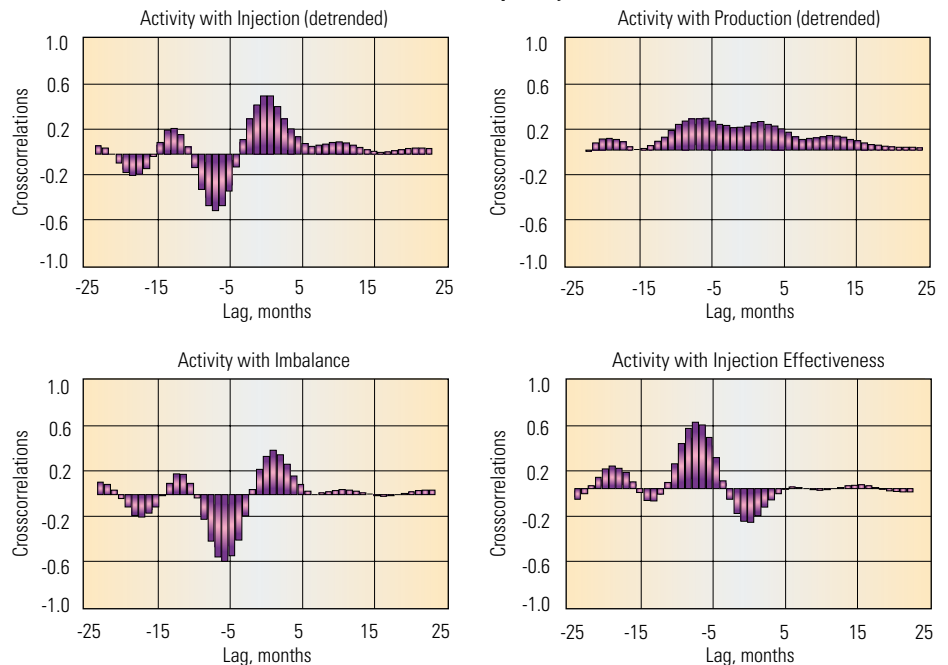
Few will deny that there is a relationship between hydrocarbon recovery and seismic activity, but exactly how strong a relationship exists has yet to be determined. Furthermore, what can or should be done about it sparks another debate.

In regions of high tectonic potential energy, hydrocarbon production can cause severe increases in seismic activity and trigger strong earthquakes, as in Gazli, Uzbekistan. In regions of lower tectonic stress, earthquakes of that magnitude are less likely, but relatively weak earthquakes could occur and damage surface structures.

### Berezovskaja area

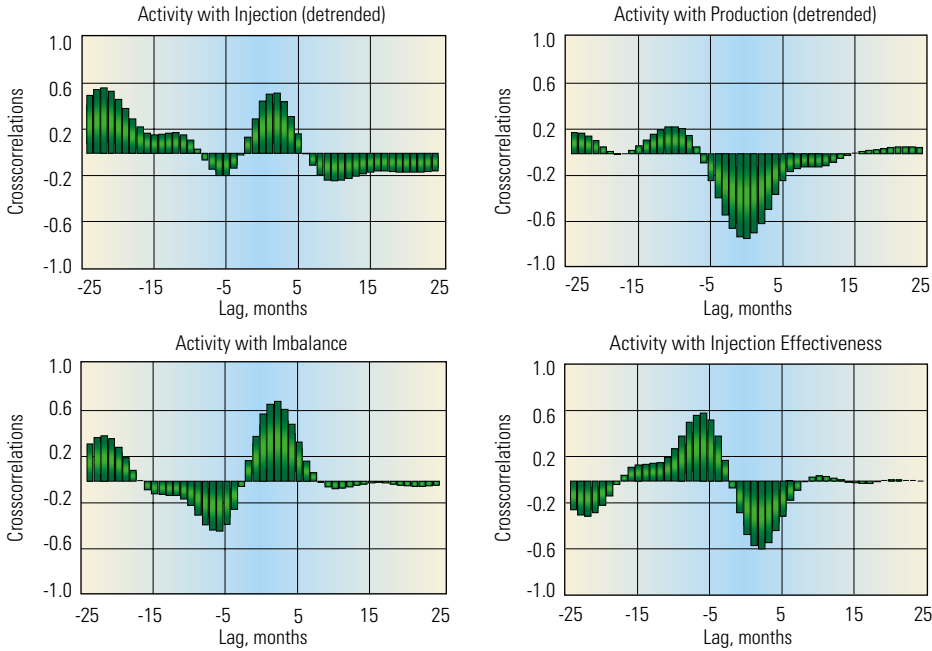


### Severo-Almetyevskaja area

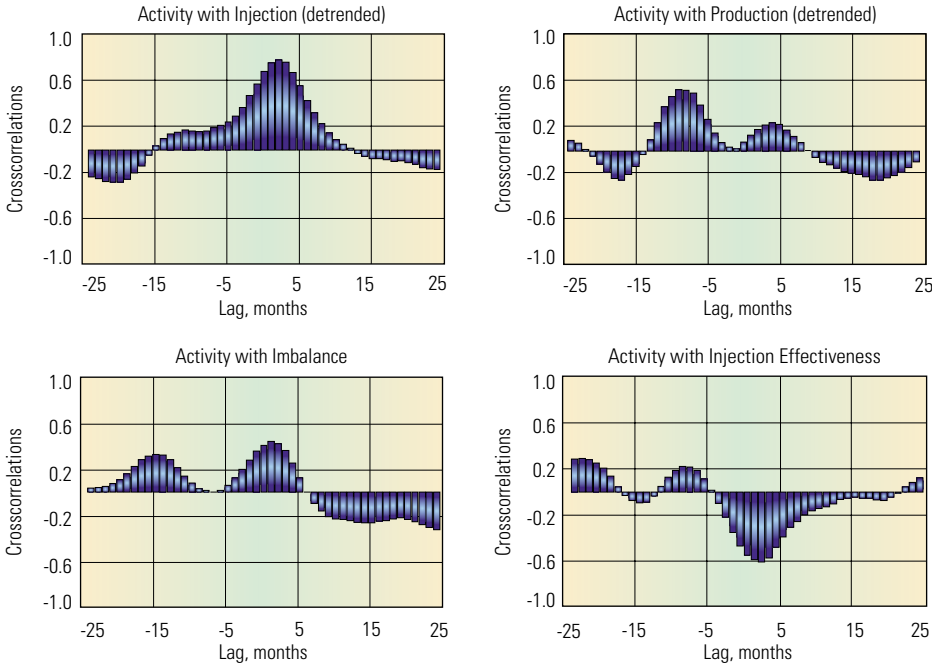


^ A change of correlation coefficients (between seismic activity and detrended production, injection, imbalance and injection effectiveness) due to shift of data series in time relative to each other. A positive lag, as seen in the cases of the A and M areas, indicates that the changes in field exploitation parameters precede changes in seismic activity. A negative lag indicates that changes in seismic activity precede changes in exploitation parameters.

### Almetyevskaja area



### Minibayevskaja area



Analysis of data on temporal and spatial characteristics of seismic activity can provide useful information on the deformation processes occurring in reservoirs and surrounding rocks. Zones of active faulting that also have high permeability can be delineated. If acquired over sufficient periods of time, this information may help forecast hazardous increases of seismic activity and evaluate recovery methods. For example, in the Romashkino oil field, water-injection effectiveness decreased during periods of increased seismic activity and increased during periods of low seismic activity. It may be that faults that become activated during periods of seismic activity also develop higher permeability. This could decrease injection effectiveness.

Installing a local permanent seismic network in advance helps quantify the level of background seismicity so that changes can be detected. This helps unravel the mysteries of the relationship between production and seismic activity. Experience shows that to estimate the values of temporal and spatial parameters of seismic deformation processes in the region of hydrocarbon fields, it is advisable to record the data for one or two years in advance of any production. However, more recording and analysis should provide further insight. The results published here are the preliminary findings of the cooperative project between Schlumberger and the Institute of Dynamics of Geospheres in Moscow. Other groups are also actively pursuing surface monitoring of seismic activity that may be related to hydrocarbon exploitation. For example, the Koninklijk Nederlands Meteorologische Instituut (KNMI) has a program to monitor seismicity in The Netherlands. Several other groups are monitoring seismic activity with borehole sensors. All of these efforts will improve the industry's understanding of the effects of production on our surroundings. —LS