The field test confirms the prognosis of the location of giant oil and gas fields in the Andes of South America made in 1986

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Abstract

1986 saw the publication of a prognostic map for discovering giant oil and gas fields in the Andes in South America based on the recent block structure of the Earth's crust. The model assumes that petroleum moves to the traps through permeable channels created at the intersection of deep faults. The technology of creation that the prognostic maps use involves (1) maps of morphostructural zoning, which outline the morphostructural knots (intersections of faults), and (2) a pattern recognition program that identifies knot-containing giant oil/gas fields. It was forecasted that, in the Andes of South America 11 knots, which had not been developed at that time, contain giant oil or gas fields. These 11 sites covered only 15% of the total area of all the Andes basins. Since then, six giant oil/gas fields have been discovered in the Andes region: Cano-Limon, Cusiana, Capiagua, and Volcanera (Llanos basin, Colombia), Camisea (Ukayali basin, Peru), and Incahuasi (Chaco basin, Bolivia). All these discoveries were made in places shown on the 1986 prognostic map as promising areas.

Keywords Oil/gas exploration · Structure of the crust · Prognostic map · Giant fields · Field test · Andes (South America)

Introduction

Here, we describe the effectiveness of pattern recognition technology in generating prognostic maps for the discovery of giant oil and gas fields. Giant fields (500 million barrels of ultimately recoverable oil or gas equivalent) account for 40% of the world's petroleum reserves. The success rate of discovering giant fields in exploration drilling consistently declined in the twentieth century: "After 1940 the quantity of oil that was discovered in giant fields declined precipitously" (Menard 1982). It reached the level 1:300 in the 1980s (Kronman et al. 1995), and continue to drop down in the twenty-first century: "Oil and gas discoveries dry up to lowest total for 60 years, and large fields are harder to find" (Crooks 2017).

The success rate of discovering giant oil and gas fields in South America in the 1980s was low: only 0.3% of the total number of wildcats discovered a giant field (Kronman et al. 1995). The exploration of the East Andes started in 1944 and proceeded until the 1980s in three waves of activity with no significant success. During this period, the activity migrated from the East part of the Llanos basin (at the border with oil-rich Venezuela) to the West, to the foothills of the East Andes. The history of discovery of the first big oil in the area (the giant Cano Limon) was described by the "father of Cano Limon" the chief geologist at Occidental C. McColough:

At the month of June 1983 an elite panel of eight Colombian geologists was called back from jobs overseas to assess the oil situation in the country. The focus was on the Llanos Basin where the reserves of Intercol's (Exxon's) deep Arauca field discovery were suspected to be closer to 3 million barrels than the 100 million barrels estimated initially, and Ecopetrol's Apiay discovery was being recognized as questionably commercial. On June 21, the panel presented its findings to the President of Colombia. The next day El Tiempo, the leading newspaper, carried the story under the headline "Petroleum Expectations in the Llanos Collapse."

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Ironically, unknown to the panel, Occidental's Cano Limon1 was at the time drilling ahead in the Cretaceous, after having penetrated 174 ft (53 m) of net oil pay in the Eocene Mirado sands in what was to become a super giant field (McCollough 1987).

Another critical aspect that downgrades the expectations of the foothills of the East Andes was the common conclusion that “the age of the structures being considered to be post-migration. Consequently, it was not surprising that the industry preferred to pursue the traditional Llanos Basin foreland play for the next 10 years” (De'Ath 1995). It also delayed the discovery of the next giant in the foothills of East Andes–Cusiana–Capiagua.

Right at this time (at the beginning of 1980s), an oil exploration project was initiated that focused on finding the giant oil and gas fields based on the pattern recognition technology described above.

The technology for forecasting giant oil/gas fields is based on:

1. *Morphostructural zoning* revealing block structure of upper crust developed by Rantsman and Glasko (2004).
2. The idea of Pikovskiy that oil and gas stream to places of accumulation through permeable “pipes”—intersections of neotectonic deep faults (Guberman and Pikovsky 1984).
3. Computer technology of *pattern recognition* developed by S. Guberman for solving geophysical problems (Guberman et al. 1964), improved by a Russian–American team of outstanding scientists including mathematician Gelfand, and geophysicists Press and Keilis-Borok, and applied to predicting location of future earthquakes and mineral deposits (Gelfand 1976; Press and Briggs 1975; Briggs and Press 1977).

The geological base of the project—the morphostructural map of the Andes—was created in 1981 for a seismological project (see Fig. 1) (Zhidkov 1981).

This paper presents the technology that can dramatically improve the search for giant oil and gas fields.

Method

The technology uses (1) the map of morphostructural zoning of the Andes, which outlines the morphostructural knots (intersections of neotectonic faults), and (2) a pattern recognition program that identifies knot-containing giant oil/gas fields.

Morphostructural zoning

The technique of morphostructural zoning for mountain regions was developed in the 1960s and the 1970s by Rantsman (1979). Morphostructural zoning builds a hierarchical model of a recent block structure of the Earth's crust. It consists of (1) morphologically homogenous areas (*blocks*); (2) linear zones between blocks (*morphostructural lineaments*); (3) areas of intersection or attachment of the lineaments (*morphostructural knots*). The knots consist of small blocks, and they are more movable zones compared to relatively stable large blocks, and, therefore, are also areas of high density of tectonic traps.

The model establishes a hierarchy of the blocks: the homogenous groups of blocks are to be united into mesoblocks, and mesoblocks in turn into macroblocks in accordance with certain rules (Rantsman 1979). The hierarchy of blocks determines the hierarchy of lineaments dividing them: first rank, second rank, and third rank. The higher the rank of a block boundary, the stratigraphically deeper the roots of that boundary in the Earth's crust. The morphostructural zoning of the Andes of South America is given in Fig. 1.

Pattern recognition

Pattern recognition was first applied to geological problems by Guberman et al. (1964). The problem of recognition was represented in the following form: a set of objects is given, and each object belongs to one of two classes. The goal of pattern recognition is to find the formal rule, which determines to which of two classes each object in question belongs (examples of classes are healthy and sick patients, oil containing and dry traps, etc.). Each object is described by the answers to a questionnaire (the parameters). The first step in recognition is the “learning phase”: Using examples of objects of each class, a set of characteristic features of objects and their combinations for each class are found. The second step is the “recognition phase”. In this phase, the characteristic features are applied to the objects which did not participate in learning, and the class to which each object belongs is decided.

Objects of recognition

We defined the object of recognition as the morphostructural knot, which is the area around the intersection of lineaments. The idea to use a morphostructural knot as an object of prognosis in oil/gas was first tested in the Andes of South America: we found that 16 out of 17 large oil/gas fields are located within the morphostructural knots (at a distance of

Fig. 1 Original prognostic map of the Andes of South America (Northern part) (Guberman et al. 1986). Morphostructural lineaments: 1—deep-sea trench, 2—continental slope, 3—first rank lineament, 4—main strike-slip faults, 5—second rank lineament, 6—

transverse lineament of third rank, 7–9 highly promising knots in 1986; 7—highly promising knots, 8—highly promising knots where giant oil/gas fields were discovered after 1986

less than 45 miles from the center of the knot) (Guberman et al. 1986).

The goal was to separate all morphostructural knots in the area into two parts: the knots which contain large oil fields, and those that don't. To achieve the goal, we needed

to find a set of features (or combinations of features) which are common for the knot-containing large oil/gas fields (the “oil set”), and then apply them to the rest of knots and determine which knots are most similar to the knots in the “oil set”. This will indicate the knots for future discoveries.

Each knot was described by a number of parameters, which were used by the pattern recognition program for characterizing the classes of knots with (class I) and without (class II) giant oil/gas fields. The parameters are as follows:

1. altitude in the center of the knot;
2. maximum difference of the altitudes inside the knot;
3. number of knot-forming lineaments;
4. highest rank of lineament in the knot;
5. thickness of sedimentary basin in the knot;
6. contact of relief types in the knot (mountain–mountain, or mountain–foothill, or mountain–plain);
7. the position relative to the global system of seismotectonic latitudinal belts (Guberman 2008).

Most parameters describe the level of tectonic activity of the knot in the past.

Learning

For the learning process, we must choose the representatives (examples) of objects of both classes (I and II). Nine morphostructural knots in the Andes basins with known giant oil/gas fields were used for the learning process as examples for class I. The set of examples for class II contained 63 knots located in the Andes, in which giants at that time (1984) were not discovered. As a result of the learning process, the program picked three class I criteria and three class II criteria. This set of criteria forms the decision rule. The result of recognition using this decision rule was as follows.

The criteria correctly recognized 14 out of 15 knots, which contained giant oil/gas fields known in 1986. In the rest of the knots (63 in total), which had no giant oil/gas fields discovered at the date of prognosis (1986), the program found 11 knots that promise great discoveries in the

future. These 11 sites covered only 8% of the total area of all the Andes basins. Figure 1 shows a summary of the results (for the North Part of the Andes, where all discoveries made after 1986 are located).

Results

After the prognostic map was prepared, the first giant discovered in the Andes of South America was Cano Limon—the largest oil discovery of the 1980s in Latin America. Before this discovery, 71 exploration wells were drilled in the Llanos basin with very little success (namely two fields with total reserves of about 20 million bbl of light oil and one field with reserves of 90 million bbl of 13.6° API oil—none of which were commercial) (McCollough 1987). The estimation of the foothills of Andes was very pessimistic within the world’s geological community, and even by the owner of the prospect Occidental Petroleum. Oxy’s efforts to farm out the Cano Limon prospect failed after showing it to almost 60 industry E&P companies. Cano Limon was, as stated by Taylor and McCollough, the result of an “exploration approach unconstrained by past experience and models” (Gabela 2011).

During the 32 years following the publication of this forecast, six more giant oil/gas fields were discovered in the Andes: Cano-Limon, Cusiana, Capiagua, and Volcanera (all in the Llanos basin, Colombia), Camisea (in the Ucayali basin, Peru), and Incahuasi (Chaco basin, Bolivia) (see Table 1).

All the discoveries were made in places shown on the prognostic map as promising (see Fig. 1). Moreover, all the oil and gas discoveries were located in basins without the existing big oil or gas fields at the time of prediction. Each promising site is a circle with a radius of 45 miles.

The rate of success was estimated to be at least 0.75, and the reliability of the predictions was checked through a set of special statistical and logical tests similar to the tests described in Gelfand (1976).

It has to be noted that all examples of giant oil/gas fields used by the pattern recognition program to find

Table 1 Oil and gas fields discovered after publication of the prediction 1986

Knots	Field	Fluid	Basin, Country	Age	Depth ft	Reserves of oil, m. barrels, of gas, TCF	Discovery
CE6	Cano Limon Matanegra. La Yuca	Oil	Llanos, Colombia	E ₂ , K	7600	1050	1984–1987
CE7	Volcanera	Gas	Llanos, Colombia	E ₂ , E ₁ , K	19,100	5	193
CE7	Cupiagua	Oil	Llanos, Colombia	E ₂ , E ₁ , K	16,807	500	1992
CE7	Cusiana	Oil	Llanos, Colombia	E ₂ , E ₁ , K	15,590	1500	1988
EL5	Camisea, Kinteron, Sagari	Gas	Ucayali, Peru	K	8100–9700	10–15	1986–2012+
EV9	Incahuasi	Gas	Chaco, Bolivia	PZ	18,400	2.5	2004

Table 2 Recognition of promising knots in different geological provinces

	West Siberia	North Sea	California
Number of promising knots	23	13	21
Part of basin area occupied by the promising knots	0.16	0.15	0.16
Number of giant fields	17	26	19
Number of giants inside promising knots	14	24	17
Level of success	82%	92%	89%

characteristic features for giant oil/gas fields were located in the western part of the Andes (Cordillera Occidental) in the subduction zone at the border between Pacific and South America tectonic plates. It is remarkable that these *characteristic features* successfully predicted the location of giant oil/gas fields in the foothills of the East Andes (Cordillera Oriental) located in substantially different geological conditions—on the border between mountain provinces and great plains. This initiated an attempt to investigate how universal these *characteristic features* can be. The test was conducted on some well-established prolific oil provinces in the world possessing different geological and morphostructural settings: Western Siberia (plains), California (piedmont and intermountain depressions), and the North Sea (continental shelf). All these provinces were well developed, and it was reasonable to assume that the number of undiscovered oil/gas giants is small. The results of the tests in these regions are presented in Table 2.

This was an important control experiment, since the data from new regions were completely unrelated to the criteria found for the giant oil/gas fields in the Andes. For each region, criteria for finding the biggest oil/gas fields in the province were applied to each morphostructural knot. To adjust the parameters describing the knots to the differences in absolute heights between Siberia (hundreds of feet) and the Andes (tens of thousands of feet), the parameters were expressed in relative units.

The results of these tests showed the following:

1. They confirm and augment the reliability of the methodology.
2. The level of success is equal to or more than 0.75.
3. The decision rule obtained is invariant despite the different geological conditions (on-shore or off-shore).

The technology described above not only directs the exploration drilling to the right place, but also avoids drilling at the wrong sites. In Colombia, during the 30 years following the publication of the prognostic map, three huge discoveries were mistakenly announced: Anaconda-1 by Chevron, Coporo-1 by Ecopetrol, and Gibraltar-1 by Occidental, with estimates of more than 1 billion barrels of oil at each location. All of them are located outside the areas predicted by pattern recognition technology in 1986. All

three wells turned out to be failures. The total cost of these projects reached \$200M.

To show just how effective the technology is, let us follow the history of *Occidental's* drilling in the Eastern Plains of Colombia (Llanos basin). From 1981 onwards, 32 dry wells were drilled in a row in the Llanos basin until the giant Cano Limon was found. All 32 wells are located outside the promising sites. The first well drilled inside the promising circle was a great discovery—the Cano Limon field. If Occidental had followed their strategy of exploration drilling but applied it only to areas recommended by the prognostic map, the giant Cano Limon field would have been hit by the first well. It contains 95% of the total oil reserves found by Occidental in the Llanos basin so far.

Conclusion

The 30-year-long field test showed the high reliability of the prognostic map for the discovery of giant oil and gas fields in the Andes of South America, created by the technology described above: all six giant oil/gas discoveries made in the Andes after the publication of the prognosis are located in sites predicted by the prognostic map in 1986. It makes highly attractive another seven sites in the Andes, which were recommended by the prognosis, but still remain underdeveloped.

High reliability of the forecast allows a sharp increase in the return on investments (developing only 15% of a sedimentary basin and receiving 90% of reserves of hydrocarbon of the basin), and to reduce the time of the return (the giant will be discovered first).

Preparing prognostic maps demands, in addition to topographical maps of different scale, only general knowledge about the tectonic structure of the sedimentary basin, and can be prepared at the early stages of exploration—even before bidding for licensing rounds and geophysical works.

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