Mathematical Geology, Vol. 22, No. 8, 1990

Improving Reservoir Description by Using Geostatistical and Multivariate Data Analysis Techniques[1]

Henrique Garcia Pereira,[2] António Costa e Silva,[3] Amilcar Soares,[2] Luis Ribeiro,[3] and Justino de Carvalho[3]

In order to improve the reservoir description phase in extensively recognized oil fields, a methodology, combining geostatistics, multivariate data analysis, and appropriate geological reasoning, was developed. This methodology involves several steps: (i) Splitting the variable set available on each well into two subsets, with different intrinsic meaning—the "principal" and the "supplementary" variables. The former summarize oil-quality distribution, and supplementary variables are chosen to reproduce some geological/petrophysical characteristics of the reservoir. (ii) Application of Correspondence Analysis to the disjunctive table recoding all data in categorical form, using arbitrary class limits for quantitative variables. (iii) Selection of "final" class limits by visualization of supplementary projections onto the factorial plane and by contiguity analysis of groups in the well-location map. Groups of wells are arranged in decreasing order of their average oil-quality distribution, given by an index, which is the projection onto factor 1 of correspondence analysis. (iv) Establishment of Reservoir Quality Zones (RQZ), being a zone defined as a set of embedded groups, displaying spatial contiguity. The oil-quality index of a given zone is greater than a certain limit, which is related to fluids saturation, spatial distribution of net oil column and petrophysical characteristics of the zone. (v) Estimation of boundaries for each zone through Transitive Kriging of indicator data. (vi) Oil-in-place volume calculation for each zone, combining the geometrical estimation approach with Universal Kriging. Steps (i)–(iv) are applied interactively, using a case study for illustration purposes. Some consequences of horizontal zonation on production planning are discussed, focusing on the improvement of the reservoir description phase, brought by the proposed methodology.

KEY WORDS: oil, correspondence analysis, transitive kriging, universal kriging, horizontal reservoir zonation.

INTRODUCTION

For production-planning purposes, a critical step of the modeling process of a reservoir is the knowledge of its internal architecture. Oversimplification of this

---

[1] Manuscript received 23 January 1989; accepted 13 February 1990.

[2] CVRM, Technical University of Lisbon, IST, Av. Rovisco Pais, 1096 Lisboa Codex, Portugal.

[3] Partex CPS, Av. 5 de Outubro, 160, 1000 Lisboa, Portugal.

feature usually entails expensive running of black-box simulation programs, based on history-matching procedures. The reservoir characterization parameters that feed such programs are currently initialized by some average values, which are subsequently modified using blind trial-and-error procedures.

The point to be raised here is that a combination of multivariate statistical techniques, geostatistics, and appropriate geological reasoning can provide a reliable basis for improving the overall modeling process and the field-development strategy, via the refinement of the reservoir description phase.

Reservoir description involves a critical assessment of all geological, petrophysical, and production data, in order to define meaningful hydraulic zones in the reservoir and assign quantitative geological parameters to inter-well areas, at the appropriate scale for the the fluid-flow simulation.

Most reservoirs exhibit strong heterogeneities, linked to complex variations in the pore space pattern, which influence relevant properties like porosity, permeability and capillary pressures. The heterogeneity problem is approached here by a tesselation of the reservoir into ''pay zones,'' denoted in the sequel Reservoir Quality Zones (RQZ).

Once established, the reservoir framework, which includes the overall deposition system, the number and distribution of layers (vertical zonation), and the recognition of different lithologies and facies, it is now possible to perform the Reservoir Quality Zonation, as the next step in the reservoir description process. The objective of this step is to determine, within each layer, the lateral variation on rock properties and fluids saturation, as well as the areal extent of such characteristics.

This subdivision into RQZ can easily be set up by using multivariate statistical techniques, which must reflect the current understanding of correlations involving the available geological and petrophysical information.

Obviously, the segmentation of statistical units into groups is not unique, depending on the selected attributes and on the assumptions and rationale behind the data analysis algorithm. Therefore, a careful criticism of the groups obtained by multivariate statistics must be performed by the geological/production team. This task relies strongly on the graphical representation of groups obtained in the previous step, and is guided interactively by the production planning objectives. In particular, correlation of RQZ predicted by data analysis with facies distribution seems to be a promising feature, aiming to provide new insights into such problems as reservoir continuity, recovery efficiency, and fluid-migration paths.

Once decided, combining expert advice with results of multivariate statistical techniques, which samples belong to each ''final'' group, the boundaries from zone to zone must be estimated, in order to define the geometry of the RQZ. This problem is approached here by using the geostatistical technique known as ''transitive kriging of indicator data,'' which accounts for the geometrical structure of the RQZ, via the transitive variogram.

Inside each one of the RQZ, the oil-in-place volume is calculated using the Universal Kriging method, applied to the variable net oil column (thickness · porosity · oil saturation).

In fact, in a previous study regarding the same data set (Pereira et al., 1989), the conclusion was reached that Universal Kriging gives better results than alternative techniques (intrinsic random functions of order *k*, trend surface analysis, median polish of the drift, etc.), provided that a reliable structural analysis is performed.

In the framework of the above-outlined methodology, application of reservoir quality analysis to the prediction of zonal continuity, prior to planning secondary and tertiary recovery projects, can be a useful tool for improvement of the reservoir description phase. Some practical consequences of this analysis on reservoir development strategy and on residual oil recovery are reported in the sequel, for a case study concerning an extensively recognized field, as preliminary results of a research project granted by the Hydrocarbons Division of the EEC (''Development of a Geomathematical Model Applied to Oil Reservoirs'').

AVAILABLE DATA

The Middle East oil field, which was selected to test the above-outlined methodology, produces from porous limestones of Lower Cretaceous age; and a great amount of information related to geological, petrophysical, and production data is available.

The general morphology of the reservoir is an elongated, domed anticline, divided vertically into layers by four main stylolitic intervals, evaluated from core descriptions, neutron, and induction logs data.

The layer selected for this case study is the main producing unit of the reservoir, with an average thickness of 30.4 ft. Early test and pressure data were used to find the original fluid levels. The elevation of 7950 ft was taken as a preliminary value for the oil–water contact.

Based on lithology (namely, limestone, clay, and dolomite), fossil content, and log analysis, facies were established by the geological team. Variation of facies within the reservoir was originated in coastal-marine and open-marine shelf environments, linked to sedimentary cycles driven by eustatic sea level changes.

Within the relevant layer, four different facies were determined (from top to bottom):

F1—A rudist facies composed by interbedded, vuggy rudistic debris packstones and wackestones with extensive cementation associated with the stylolitic zone.

F2—A miliolitic pellet facies composed by fine grains and well-sorted grainstones and packstones in well-bedded units.

F3—A rudist facies, similar to the first one, but with negligible cementation.

F4—A miliolitic, algal-lump facies composed by interbedded coarse and fine sediments, with predominant grainstones in the upper part.

Apart from facies and lithology, measurements of elevations, thicknesses, porosities, permeabilities, and water saturations are available at each well, for the relevant layer. The total number of wells, at the final stage of development of the field, is 181, including producers, injectors, and water-supply wells. From these, a set of 172 wells was used in this case study, distributed in space according to the well-location map of Fig. 1. Regarding the reservoir fluid data, a single suite of PVT data is recommended, and the oil formation volume factor (Bo) is 1.60 RB/STB at the initial reservoir conditions.

RESERVOIR-QUALITY ZONATION

In a great reservoir where the main layers are separated by stylolitic intervals acting as vertical barriers, such as the one previously described, the lateral heterogeneities can play an important role in oil recovery; and the importance of areal zonation, as a basis for the understanding of reservoir continuity, is fully acknowledged.

Essentially, the objective of this horizontal zonation procedure is to highlight lateral variations on fluid saturation and rock properties, splitting the available set of wells into groups that display similar characteristics. Since vertical zonation was performed in a previous step, the problem addressed here consists on finding, within the selected layer, the areal extent of homogeneous zones, in order to improve the interwell scale of reservoir description, by taking into account lateral heterogeneities affecting fluid saturation and oil recovery.

For the purpose of areal zonation or tesselation of the field, several multivariate statistical methods can be applied. In this paper, the factorial method proposed by J.-P Benzécri, denoted Correspondence Analysis, was selected (Benzécri, 1973; Teil, 1975; Greenacre, 1984). This method has been used in the oil industry in rather different contexts (Bertrand et al., 1981; Bonham-Carter et al., 1986). Nonetheless, for the objective of the present research, it seems also to be appropriate, since it provides the projection of wells and variables onto the same factorial space and accounts, jointly, for qualitative and quantitative information, bridging the gap between purely descriptive approaches and numerical models. In this case, facies and lithology are categorical data, which call for correspondence analysis application.

Another useful feature of the correspondence analysis technique, to be ap-

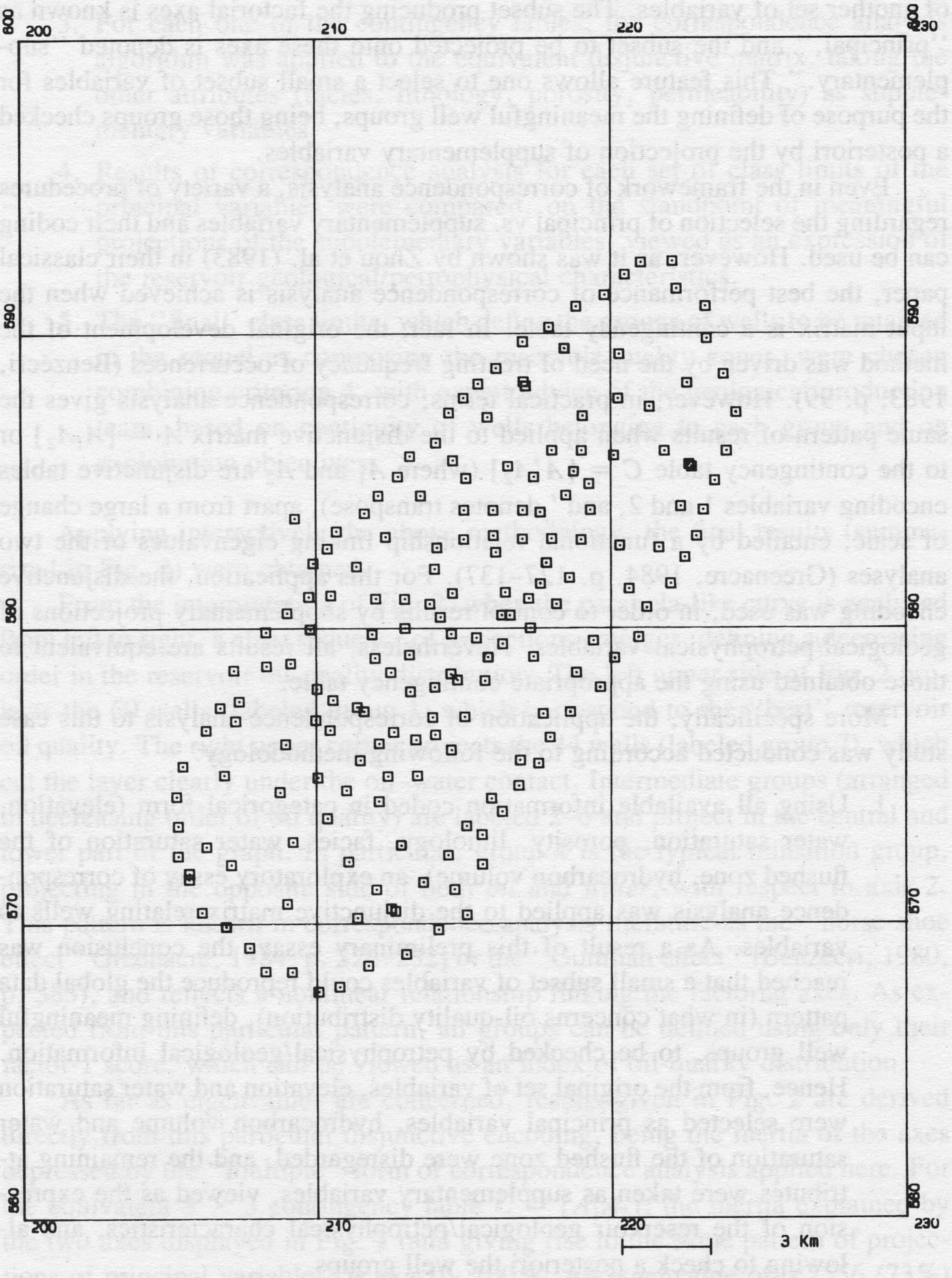


Fig. 1. Well-location map of the field used in the case study.

plied in the sequel, is that a subset of variables can be projected onto an existing display of a factorial plane, which has been previously obtained on the grounds of another set of variables. The subset producing the factorial axes is known as "principal," and the subset to be projected onto these axes is denoted "supplementary." This feature allows one to select a small subset of variables for the purpose of defining the meaningful well groups, being those groups checked a posteriori by the projection of supplementary variables.

Even in the framework of correspondence analysis, a variety of procedures regarding the selection of principal vs. supplementary variables and their coding can be used. However, as it was shown by Zhou et al. (1983) in their classical paper, the best performance of correspondence analysis is achieved when the input matrix is a contingency table. In fact, the original development of the method was driven by the need of treating frequency of occurrences (Benzécri, 1983, p. 99). However, in practical terms, correspondence analysis gives the same pattern of results when applied to the disjunctive matrix $A = [A_1 A_2]$ or to the contingency table $C = [A_1' A_2]$ (where A_1 and A_2 are disjunctive tables encoding variables 1 and 2, and $'$ denotes transpose), apart from a large change of scale, entailed by a functional relationship linking eigenvalues of the two analyses (Greenacre, 1984, p. 127–137). For this application, the disjunctive encoding was used, in order to control results by supplementary projections of geological/petrophysical variables. Nevertheless, all results are equivalent to those obtained using the appropriate contingency table.

More specifically, the application of correspondence analysis to this case study was conducted according to the following methodology:

1. Using all available information coded in categorical form (elevation, water saturation, porosity, lithology, facies, water saturation of the flushed zone, hydrocarbon volume), an exploratory essay of correspondence analysis was applied to the disjunctive matrix relating wells to variables. As a result of this preliminary essay, the conclusion was reached that a small subset of variables could reproduce the global data pattern (in what concerns oil-quality distribution), defining meaningful well groups, to be checked by petrophysical/geological information. Hence, from the original set of variables, elevation and water saturation were selected as principal variables, hydrocarbon volume and water saturation of the flushed zone were disregarded, and the remaining attributes were taken as supplementary variables, viewed as the expression of the reservoir geological/petrophysical characteristics, and allowing to check a posteriori the well groups.
2. Using different class limits in the selected principal attributes, a series of two-way contingency tables was built. Each contingency table is a bidimensional histogram containing the absolute frequency of co-occurrences of wells which fall within the current class limits for both

variables. The coding of the selected quantitative variables was performed accordingly.

3. For each one of the contingency tables, the correspondence analysis algorithm was applied to the equivalent disjunctive matrix, taking the other attributes (facies, lithology, porosity, permeability) as supplementary variables.
4. Results of correspondence analysis for each set of class limits of the principal variables were compared, on the standpoint of meaningful projections of the supplementary variables, viewed as an expression of the reservoir geological/petrophysical characteristics.
5. The ''final'' class limits, which define the groups of wells to be retained in the sequel as composing the reservoir quality zones, were chosen combining criterion 4. with expert advice of the geological/production team, based on contiguity of wells belonging to each group and on exploitation objectives.

Applying interactively the above methodology, the final results (summarized in Fig. 2) were obtained.

From the interpretation of Fig. 2, when the parabola-like curve is analyzed from left to right, a clear sequence of projections emerges, defining a decreasing order in the reservoir oil-quality distribution. The left upper side of Fig. 2 projects the 60 wells (labeled group 1) which correspond to the ''best'' reservoir oil quality. The right upper corner projects the 44 wells (labeled group 7), which cut the layer clearly under the oil–water contact. Intermediate groups (arranged in decreasing order of oil quality) are labeled 2–6 and project in the central and lower part of the graph. In particular, group 4 is the typical transition group, projecting in the opposite side of both *oil* and *water*, with respect to axis 2. This pattern is known in correspondence-analysis literature as the ''horse-shoe effect'' Greenacre, 1984, p. 226–232) or the ''Guttman effect'' (Benzécri, 1980, p. 383), and reflects a nonlinear relationship linking the factorial axes. As expected from this particular pattern, all groups can be defined using only their factor-1 score, which can be viewed as an index of oil-quality distribution.

As far as eigenvalues are concerned, results given in Fig. 2 are derived directly from this particular disjunctive encoding, being the inertia of the axes depressed by the ''multiple'' form of correspondence analysis applied here. For the equivalent 3 × 3 contingency table $C = [A_1'A_2]$, the inertia explained by the two axes displayed in Fig. 2 (and giving rise to the same pattern of projections of principal variables) is exactly 100%. An eigenvalue of 0.7556 (73%) is assigned to axis 1, and of 0.2812 (27%) to axis 2.

The spatial two-dimensional arrangement of groups is displayed in Fig. 3, and their characterization, in terms of supplementary variables, is given in Table 1.

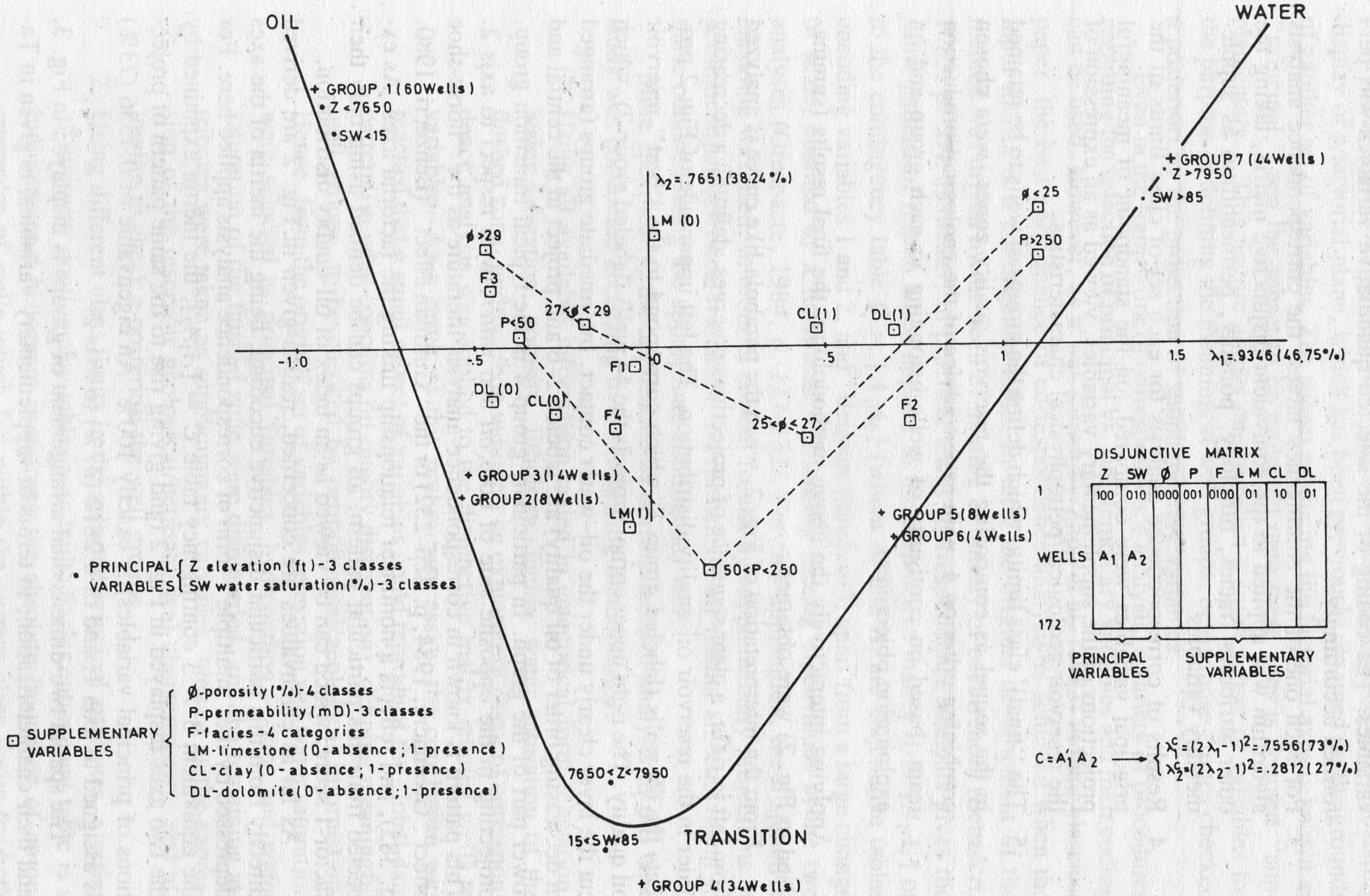


Fig. 2. Summary of results of correspondence analysis.

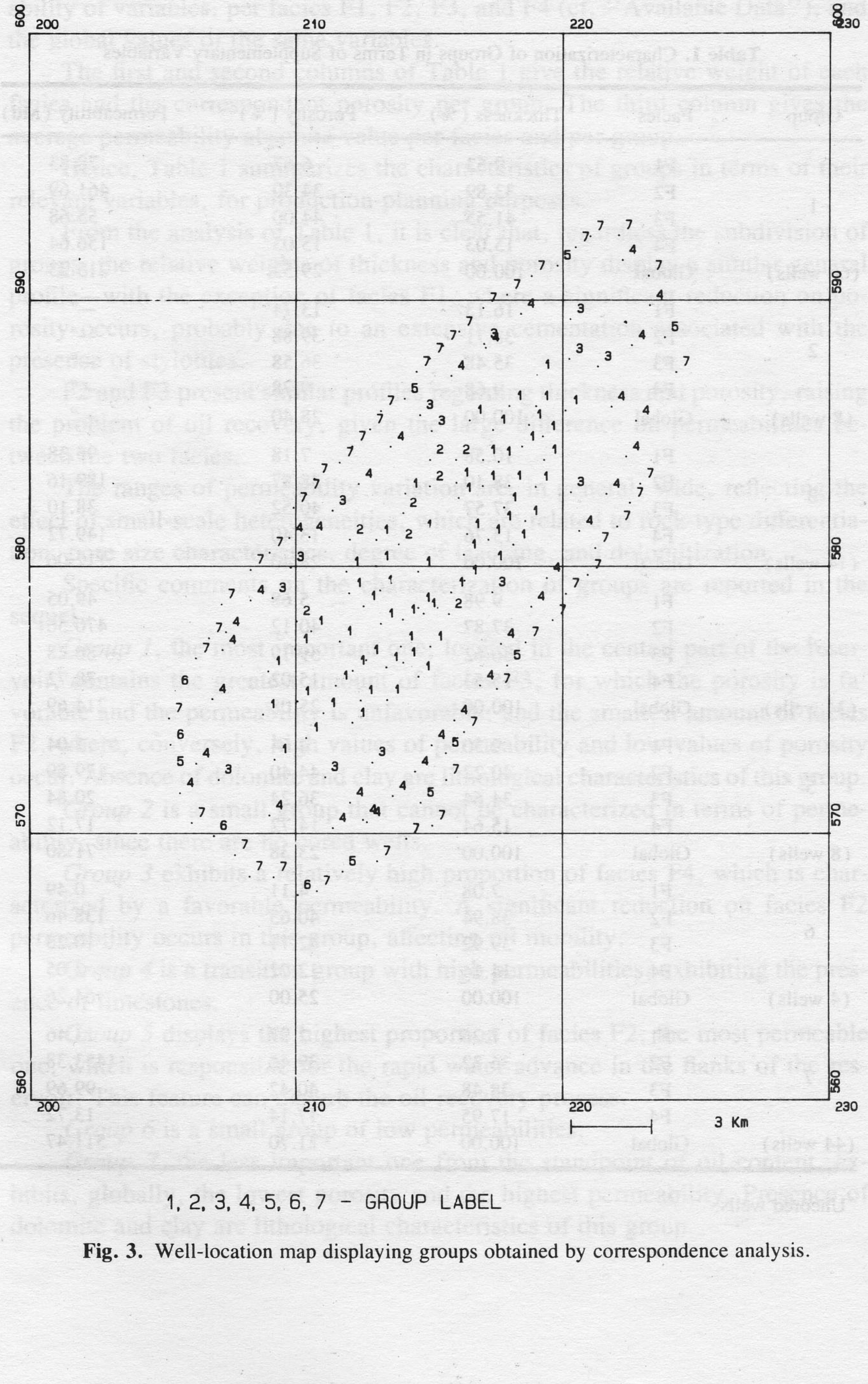


Fig. 3. Well-location map displaying groups obtained by correspondence analysis.

Table 1. Characterization of Groups in Terms of Supplementary Variables

Group	Facies	Thickness (%)	Porosity (%)	Permeability (Md)
1	F1	9.53	6.67	78.83
	F2	33.89	34.30	461.69
	F3	41.55	44.00	55.68
	F4	15.03	15.03	156.64
(60 wells)	Global	100.00	29.53	215.23
2	F1	16.13	13.74	—[a]
	F2	38.71	39.88	—[a]
	F3	35.48	36.58	—[a]
	F4	9.68	9.78	—[a]
(8 wells)	Global	100.00	28.40	—[a]
3	F1	10.58	7.18	95.38
	F2	38.10	38.87	189.16
	F3	37.57	40.52	38.10
	F4	13.76	13.40	149.72
(14 wells)	Global	100.00	28.40	112.06
4	F1	9.98	5.68	49.05
	F2	37.87	40.12	470.56
	F3	36.62	39.19	86.28
	F4	15.53	15.02	78.72
(34 wells)	Global	100.00	25.08	214.69
5	F1	9.50	4.64	1.04
	F2	40.22	44.40	179.89
	F3	34.64	36.24	20.84
	F4	15.64	14.72	17.12
(8 wells)	Global	100.00	23.38	71.80
6	F1	7.08	4.11	0.49
	F2	38.94	40.65	138.46
	F3	39.92	42.71	10.23
	F4	14.14	12.72	2.05
(4 wells)	Global	100.00	25.00	64.26
7	F1	7.26	2.97	13.46
	F2	36.32	39.46	1453.38
	F3	38.48	40.42	99.69
	F4	17.95	17.14	13.72
(44 wells)	Global	100.00	21.70	511.47

[a] Uncored wells.

Table 1 gives, for each group, the average thickness, porosity, and permeability of variables, per facies F1, F2, F3, and F4 (cf. ''Available Data''), and the global values of the same variables.

The first and second columns of Table 1 give the relative weight of each facies and the correspondent porosity per group. The third column gives the average permeability absolute value per facies and per group.

Hence, Table 1 summarizes the characteristics of groups in terms of their relevant variables, for production-planning purposes.

From the analysis of Table 1, it is clear that, regardless the subdivision of groups, the relative weights of thickness and porosity display a similar general profile—with the exception of facies F1, where a significant reduction on porosity occurs, probably due to an extensive cementation associated with the presence of stylolites.

F2 and F3 present similar profiles regarding thickness and porosity, raising the problem of oil recovery, given the large difference on permeabilities between the two facies.

The ranges of permeability variation are, in general, wide, reflecting the effect of small-scale heterogeneities, which are related to rock-type differentiation, pore size characteristics, degree of leaching, and dolomitization.

Specific comments on the characterization of groups are reported in the sequel.

Group 1, the most important one, located in the central part of the reservoir, contains the greatest amount of facies F3, for which the porosity is favorable and the permeability is unfavorable; and the smallest amount of facies F2, where, conversely, high values of permeability and low values of porosity occur. Absence of dolomite and clay are lithological characteristics of this group.

Group 2 is a small group that cannot be characterized in terms of permeability, since there are no cored wells.

Group 3 exhibits a relatively high proportion of facies F4, which is characterized by a favorable permeability. A significant reduction on facies F2 permeability occurs in this group, affecting oil mobility.

Group 4 is a transition group with high permeabilities, exhibiting the presence of limestones.

Group 5 displays the highest proportion of facies F2, the most permeable one, which is responsible for the rapid water advance in the flanks of the reservoir. This feature can disturb the oil-recovery process.

Group 6 is a small group of low permeabilities.

Group 7, the less important one from the standpoint of oil content, exhibits, globally, the lowest porosity and the highest permeability. Presence of dolomite and clay are lithological characteristics of this group.

Once characterized as the groups provided by the correspondence analysis technique, a new concept—the *reservoir quality zones* (RQZ)—was introduced, in order to define properly the group morphology. In fact, some groups (e.g., 2, 5, and 6) are poorly represented, and do not allow a separate morphological identification. On the other hand, groups 1–7, arranged in decreasing order of reservoir oil quality, are located in space in such a way (cf. Fig. 3) that a RQZ labeled by X can be defined as the area representing the union of wells belonging to groups indexed from 1 to X.

Formally, the RQZ X is given by:

$$X = U_{i=1,X}\, G_i$$

where G_i denotes the group of wells of order i.

Group 7 was not considered as oil, given its low quality; however, it intervenes in the sequel by bounding zone 6 (composed as the union of all groups indexed by 1–6).

Hence, for estimation purposes, the reservoir is split into six embedded zones. Taking only zone 1, the highest oil quality is obtained. If zone 2 is considered, group 2 is added to zone 1, and the overall oil quality decreases. Finally, zone 6 contains the global amount of exploitable oil in the reservoir.

ESTIMATION OF ZONE BOUNDARIES

The boundaries of each zone and the respective area are calculated by kriging an indicator variable. This indicator variable $I_X(x)$, attached to zone X, is defined by:

$I_X(x) = 1$ if the well located in x belongs to zone X

$I_X(x) = 0$ if the well located in x does not belong to zone X

where X is each one of the previously defined zones (1–6).

The set of wells available is contained in an area $A = X\ U\ X^c$, which bounds the entire field.

Since the wells belonging to a certain zone ($I_X(x) = 1$) are surrounded by its complementaries ($I_X(x) = 0$), each zone can be viewed as a deterministic compact set and, therefore, the theoretical assumptions of the transitive kriging method are met.

The practical implementation of transitive kriging is similar to the stationary version of kriging, requiring only the models for the transitive covariances or variograms (Alfaro et al., 1976; Matheron, 1978).

The transitive covariance $K(h)$ is the following measure:

$$K(h) = \text{meas. } [X \cap X_{+h}]$$

where h is a vector of displacement. Also, the transitive variogram is given by:

$$1/2\ g(h) = \text{meas. } (X) - K(h)$$

The transitive variogram reveals the geometrical structure of the zone and is the basis on which the transitive kriging procedure relies.

Using as input the indicator data, the estimated values $I_X^*(x_0)$ are obtained in an unsampled dense grid of M points x_0, by solving the transitive kriging system, which provides the weights w_i of each sample located in x_i.

The kriging estimator $I_x^*\ (x_0) = \Sigma\, w_i\, I_X(x_i)$ rank between 0 and 1, and can be interpreted as the probability that a sample, located in x_0, belongs to X.

In order to select, from the M points, a subset belonging to X, the probability values $I_X^*(X_0)$ are sorted in descending order and the first N points x_0 are retained, being N defined as:

$$N = M\ I_{X,A}^*\ (x)$$

where $I_{X,A}^*\ (x)$ is the global estimator of the indicator for the zone X, in the entire area A, which contains M points of the grid.

The above-outlined methodology was applied to zones 1–6. In Fig. 4, the relative variograms $g'\ (h) = g(h)/\text{meas. } (X)$ are displayed.

The experimental values of $g'\ (h)$ were fitted by a power model, the parameters of which are given in Table 2, as well as the kriged global estimators $I_{X,A}^*(x)$, which are the relative measures of X. Based on these values, the indicator point kriged maps were converted in binary maps, representing the six zones, as shown in Fig. 5.

ACTUAL OIL-IN-PLACE CALCULATION

In order to quantify the volume of oil contained in each one of the reservoir quality zones and provide an estimation error, the geostatistical methodology described below was applied.

Given a certain zone, limited in 2D by the boundaries exhibited in Fig. 5, the oil-in-place contained in that zone is given by the product of the area by the mean kriged value of the variable net-oil column (thickness · porosity · oil saturation), calculated inside the same boundaries.

Superimposing the previously defined zonation to the distribution of the variable net-oil column, Fig. 6 was obtained. In Fig. 6, two important net-oil column areas can be recognized, which are contained, obviously, in zone 1. Low values of the variable are found in the northern and southern parts of the reservoir, as well as in the eastern flank, which was expected from groups 5 and 7 of correspondence analysis. The exception goes for group 6, where no

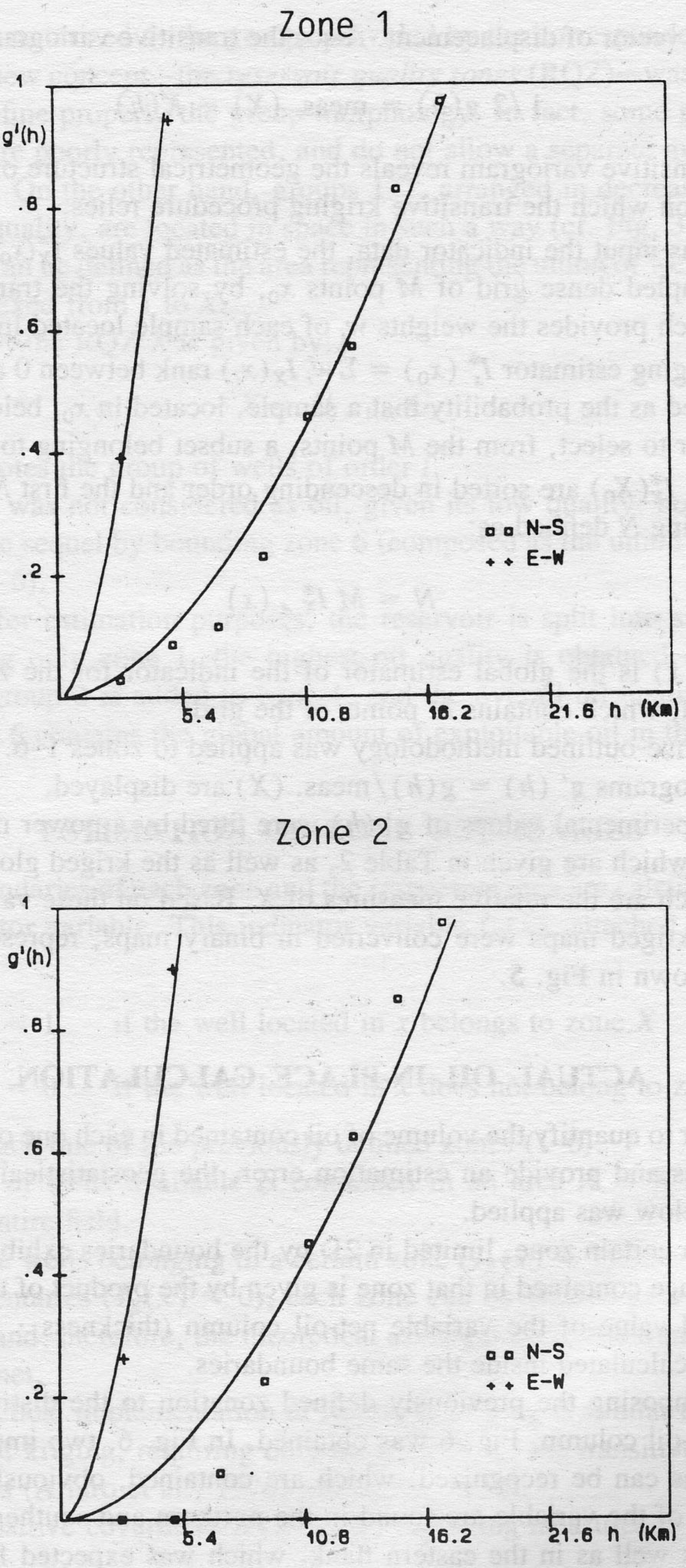


Fig. 4. Transitive variograms per zone and fitted-power models.

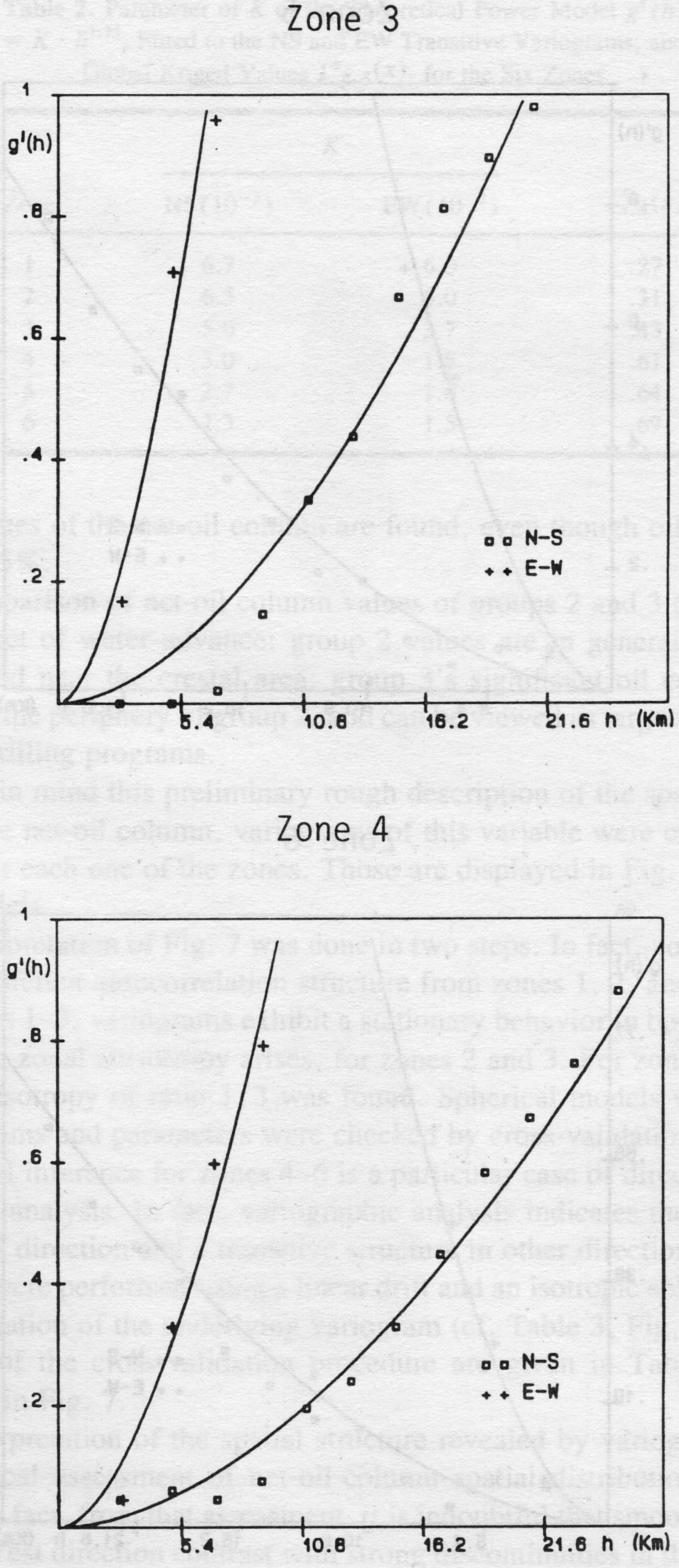
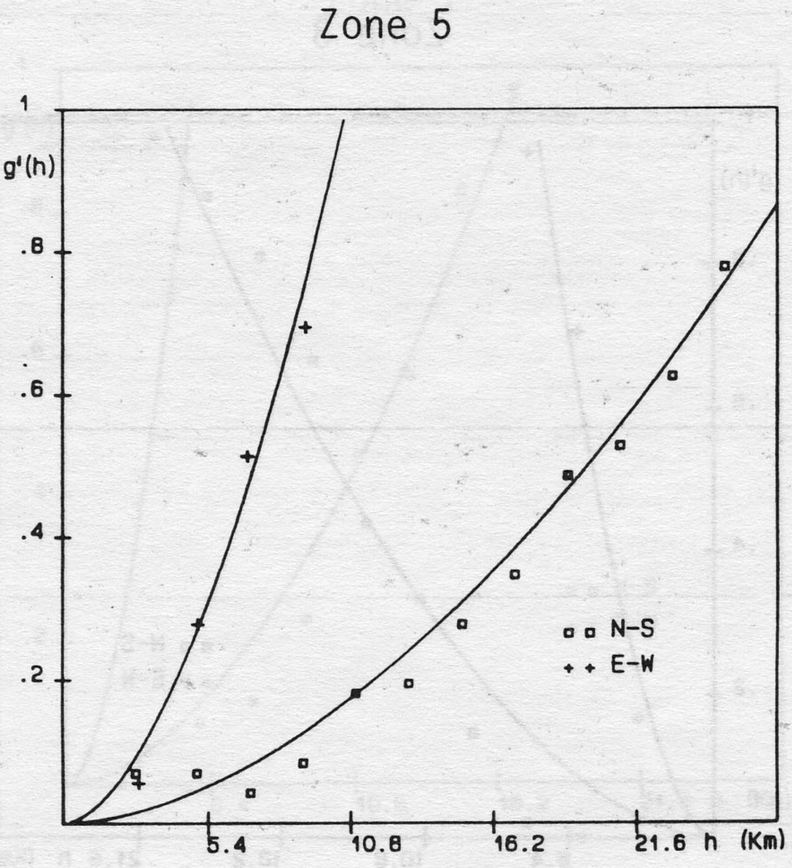


Fig. 4. Continued.



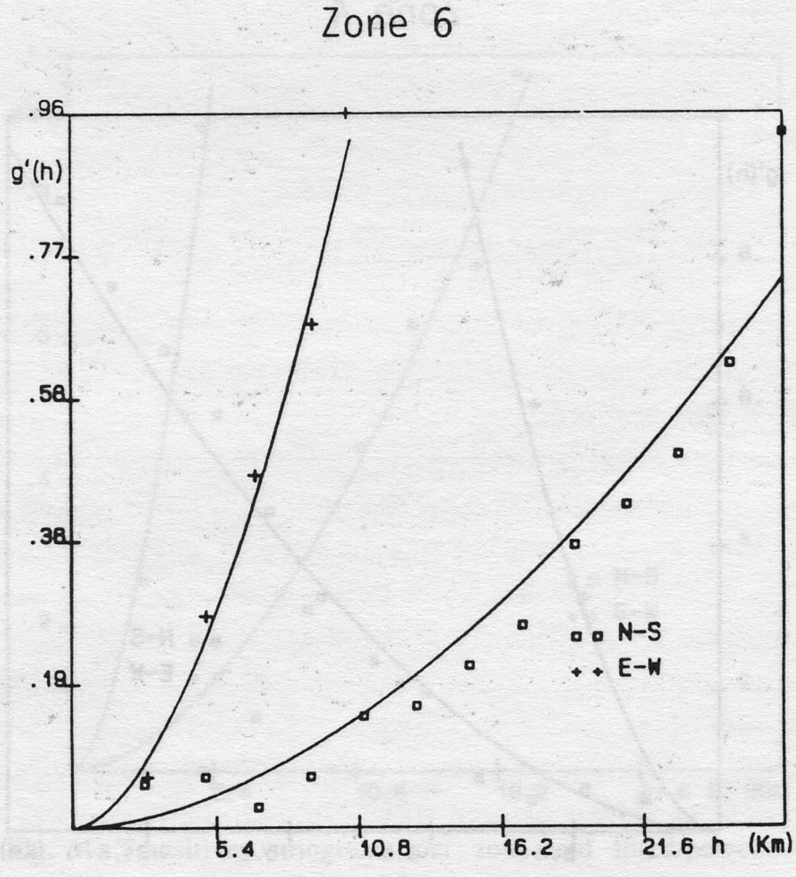


Fig. 4. Continued.

Table 2. Parameter of K of the Theoretical Power Model $g'(h) = K \cdot h^{1.75}$, Fitted to the NS and EW Transitive Variograms, and Global Kriged Values $I^*_{X,A}(x)$, for the Six Zones

	K		
Zone	NS(10^{-3})	EW(10^{-2})	$I^*_{X,A}(x)$
1	6.7	6.0	.27
2	6.5	5.0	.31
3	5.0	3.7	.43
4	3.0	1.8	.61
5	2.7	1.6	.64
6	2.3	1.5	.69

important values of the net-oil column are found, even though oil saturation is higher than 15%.

The comparison of net-oil column values of groups 2 and 3 (Fig. 6) illustrates the effect of water advance: group 2 values are in general lower, even though situated near the crestal area: group 3's significant oil concentrations are located in the periphery of group 2, and can be viewed as targets for eventual future infill drilling programs.

Bearing in mind this preliminary rough description of the spatial behavior of the variable net-oil column, variograms of this variable were calculated and interpreted for each one of the zones. Those are displayed in Fig. 7, as well as the fitted models.

The interpretation of Fig. 7 was done in two steps. In fact, zones 4, 5, and 6 display a different autocorrelation structure from zones 1, 2, and 3.

For zones 1–3, variograms exhibit a stationary behavior in both directions, even though a zonal anisotropy arises, for zones 2 and 3. For zone 1, a simple geometric anisotropy of ratio 1 : 3 was found. Spherical models were fitted to those variograms and parameters were checked by cross-validation.

Statistical inference for zones 4–6 is a particular case of direct nonstationary structural analysis. In fact, variographic analysis indicates the presence of a drift in N–S direction and a transitive structure in other directions. Universal kriging tests were performed using a linear drift and an isotropic spherical model as a representation of the underlying variogram (cf. Table 3, Fig. 7).

Results of the cross-validation procedure are given in Table 3, for the models fitted in Fig. 7.

The interpretation of the spatial structure revealed by variography agrees with the critical assessment of net-oil-column spatial distribution previously performed. In fact, from that assessment, it is indoubtful that smooth transitions in the East–West direction contrast with strong discontinuities in the orthogonal one. Hence, stationary variograms arise in the former direction, even though a

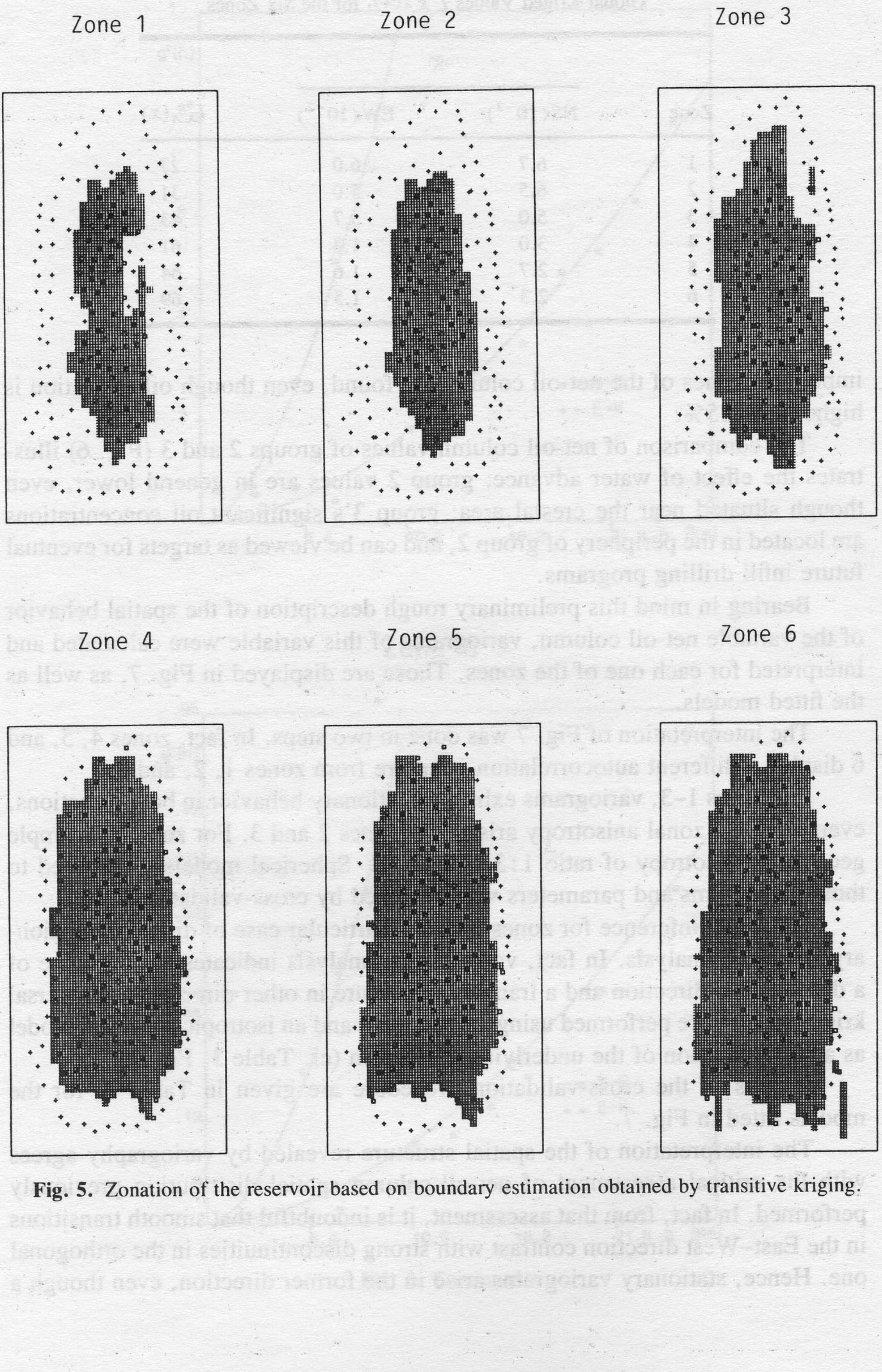
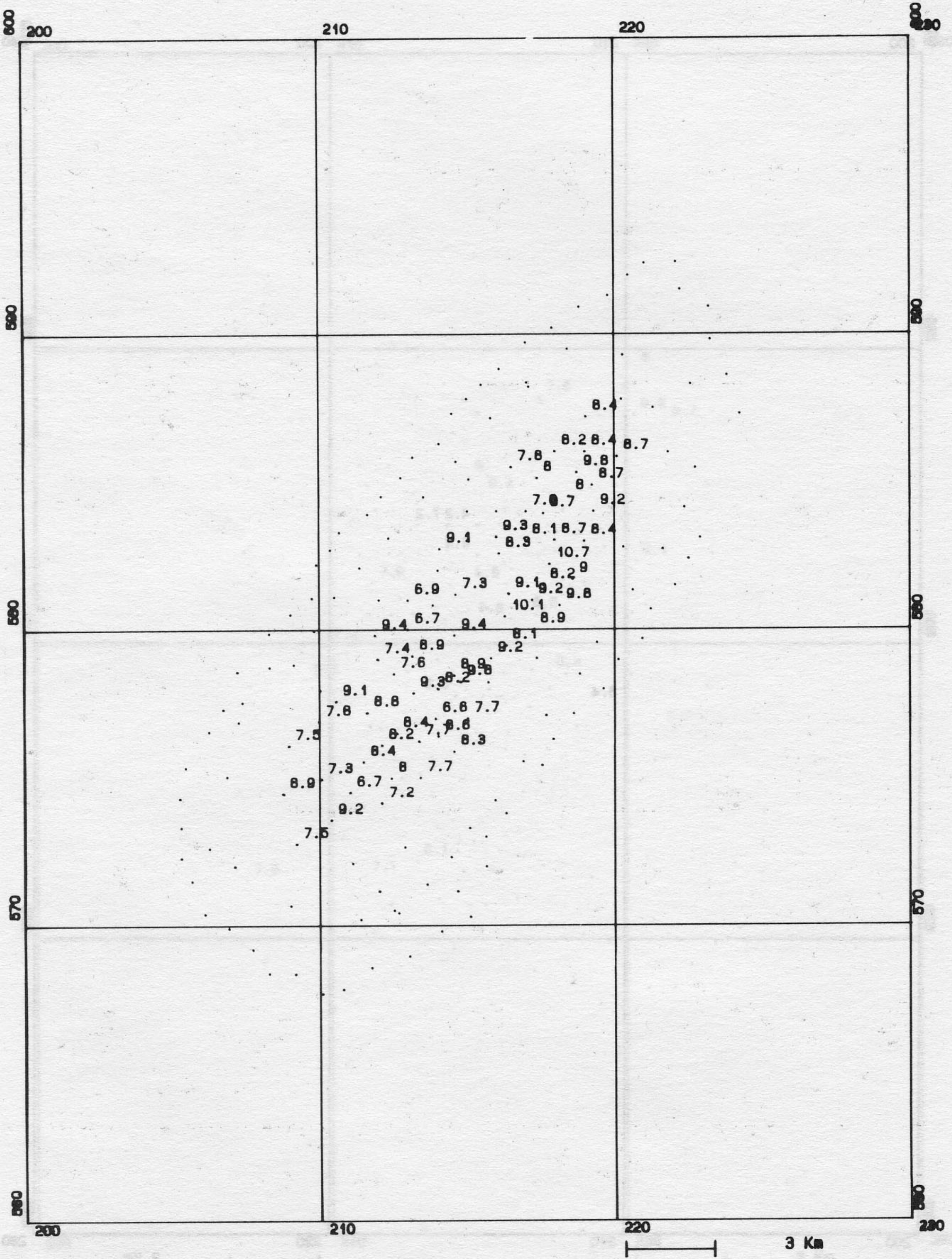
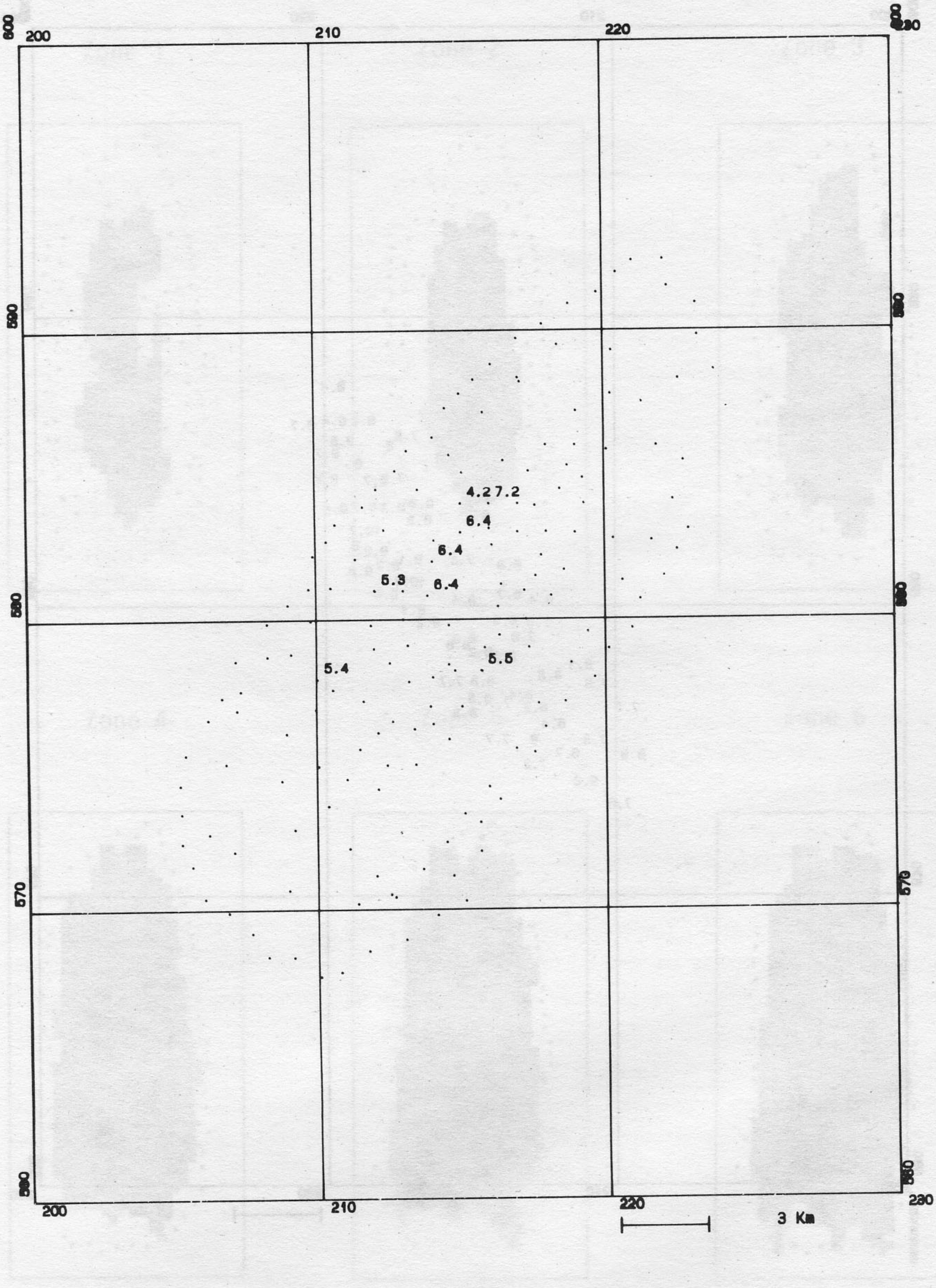


Fig. 5. Zonation of the reservoir based on boundary estimation obtained by transitive kriging.



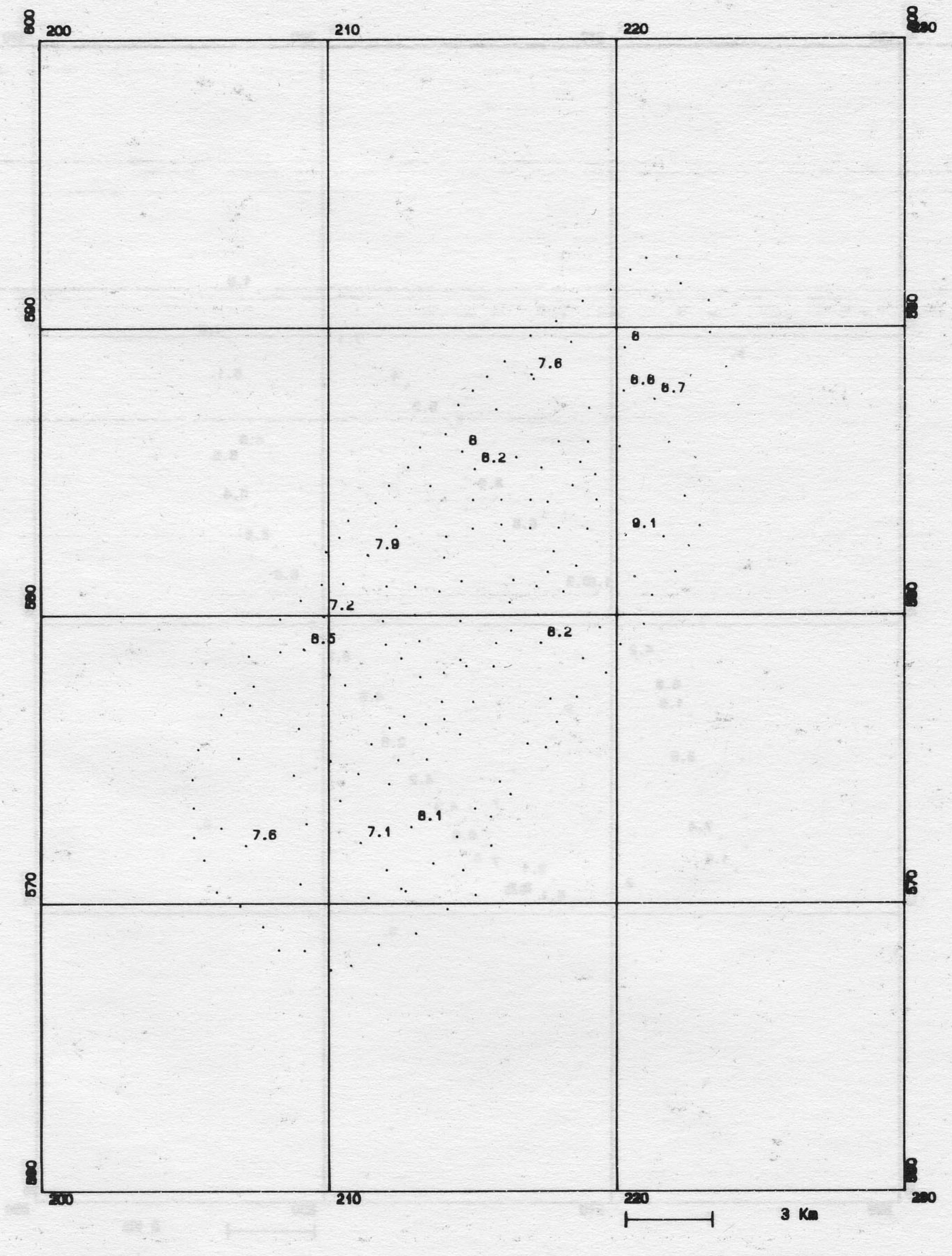
GROUP 1

Fig. 6. Net oil column distribution per group.



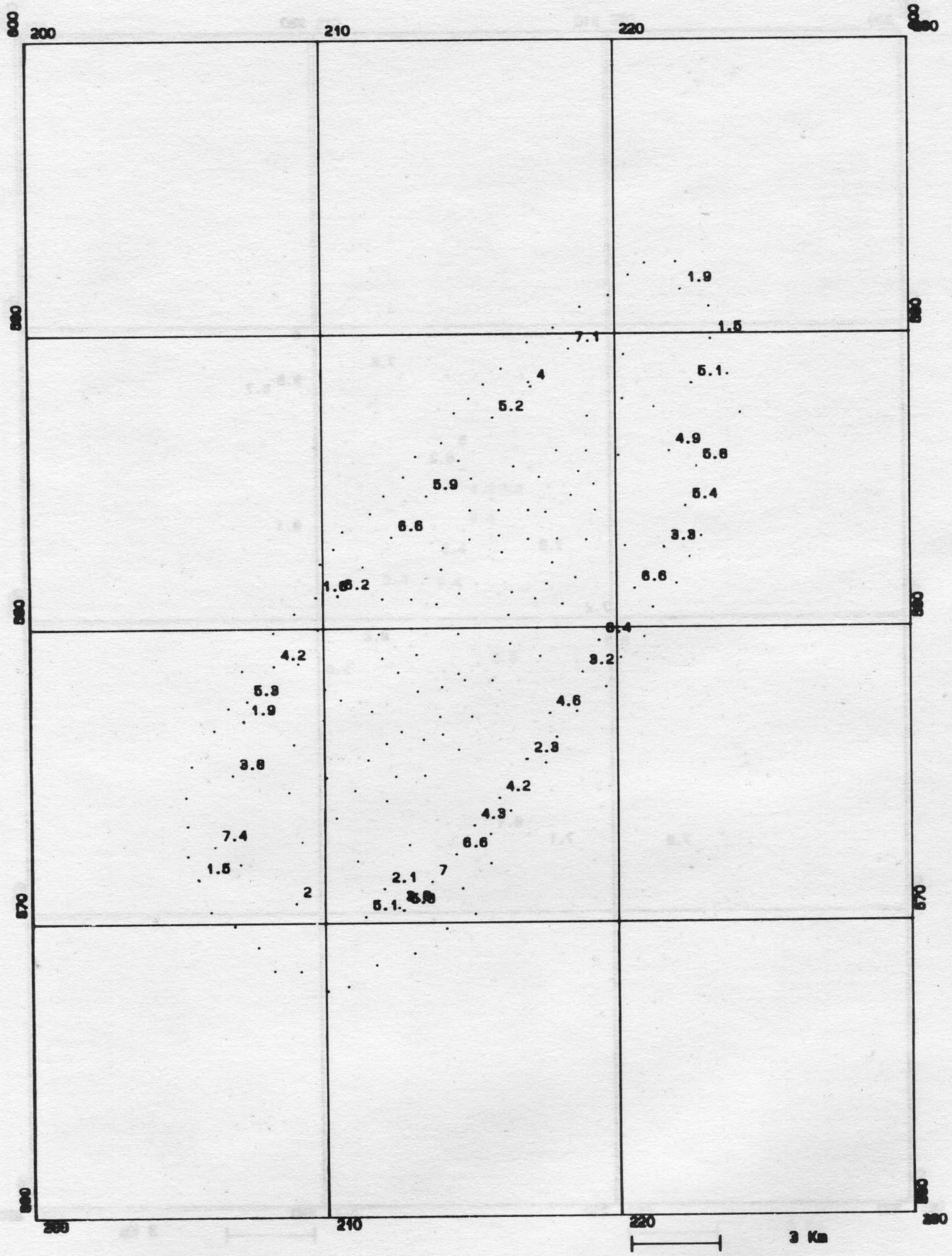
GROUP 2

Fig. 6. Continued.



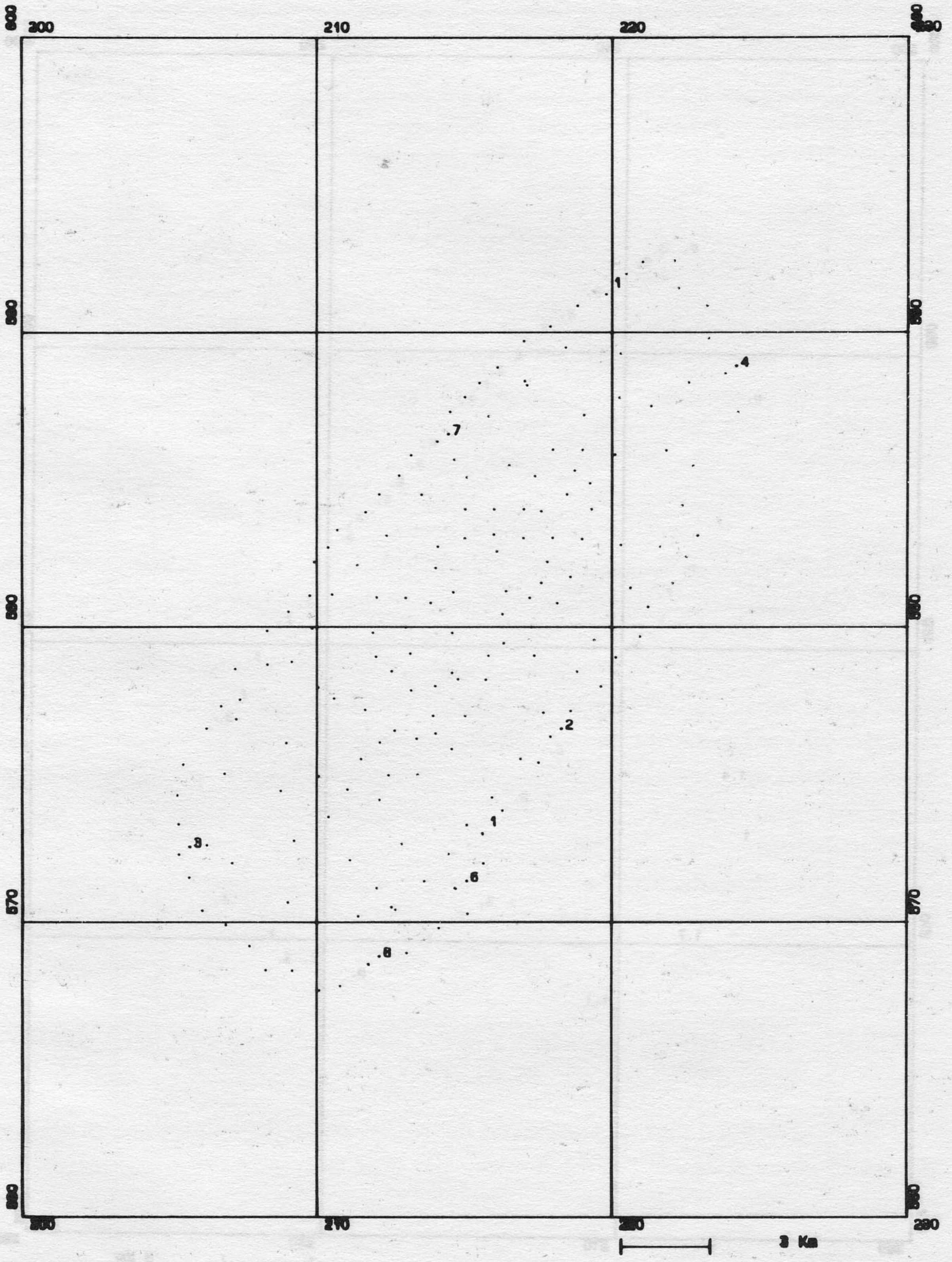
GROUP 3

Fig. 6. Continued.



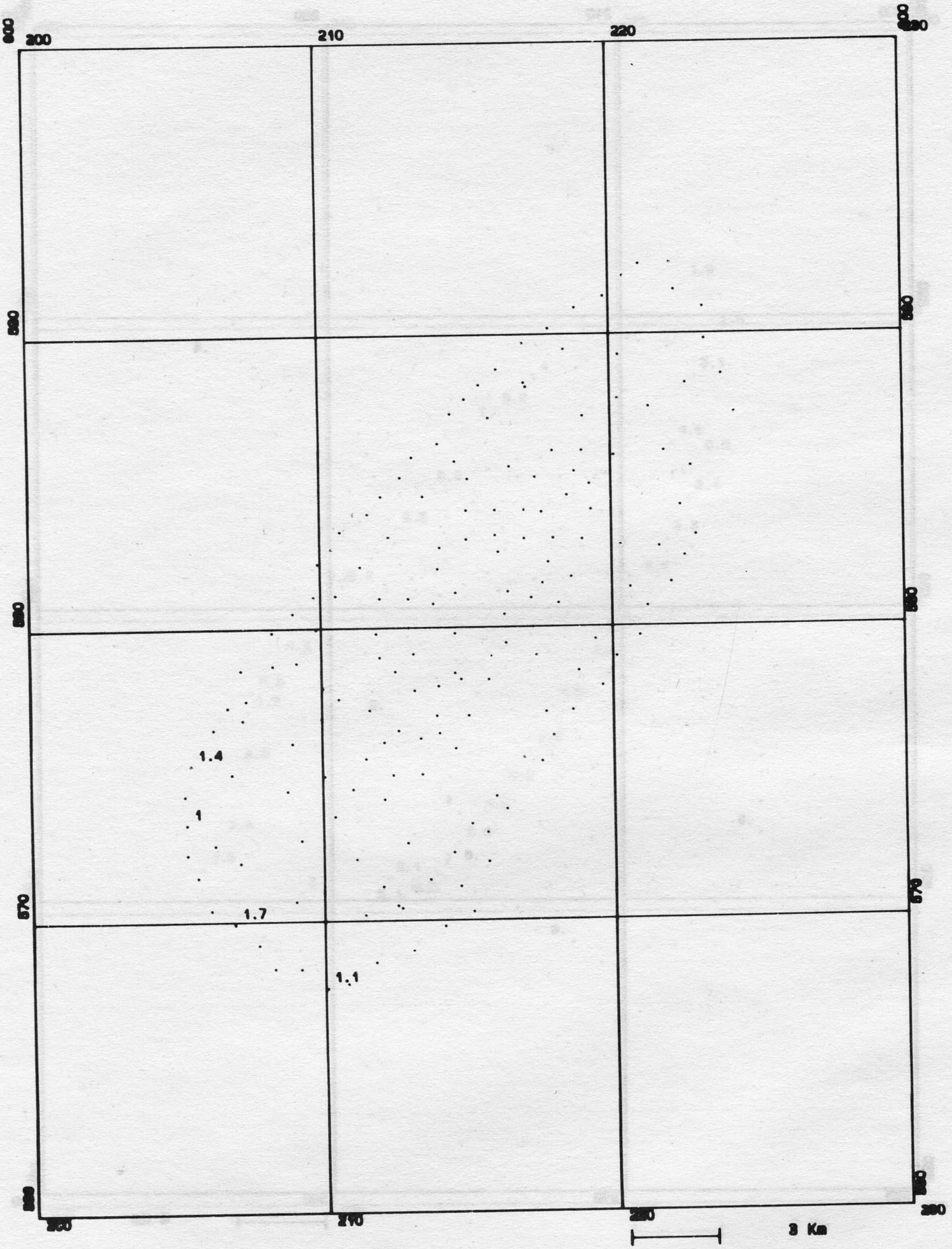
GROUP 4

Fig. 6. Continued.



GROUP 5

Fig. 6. Continued.



GROUP 6

Fig. 6. Continued.

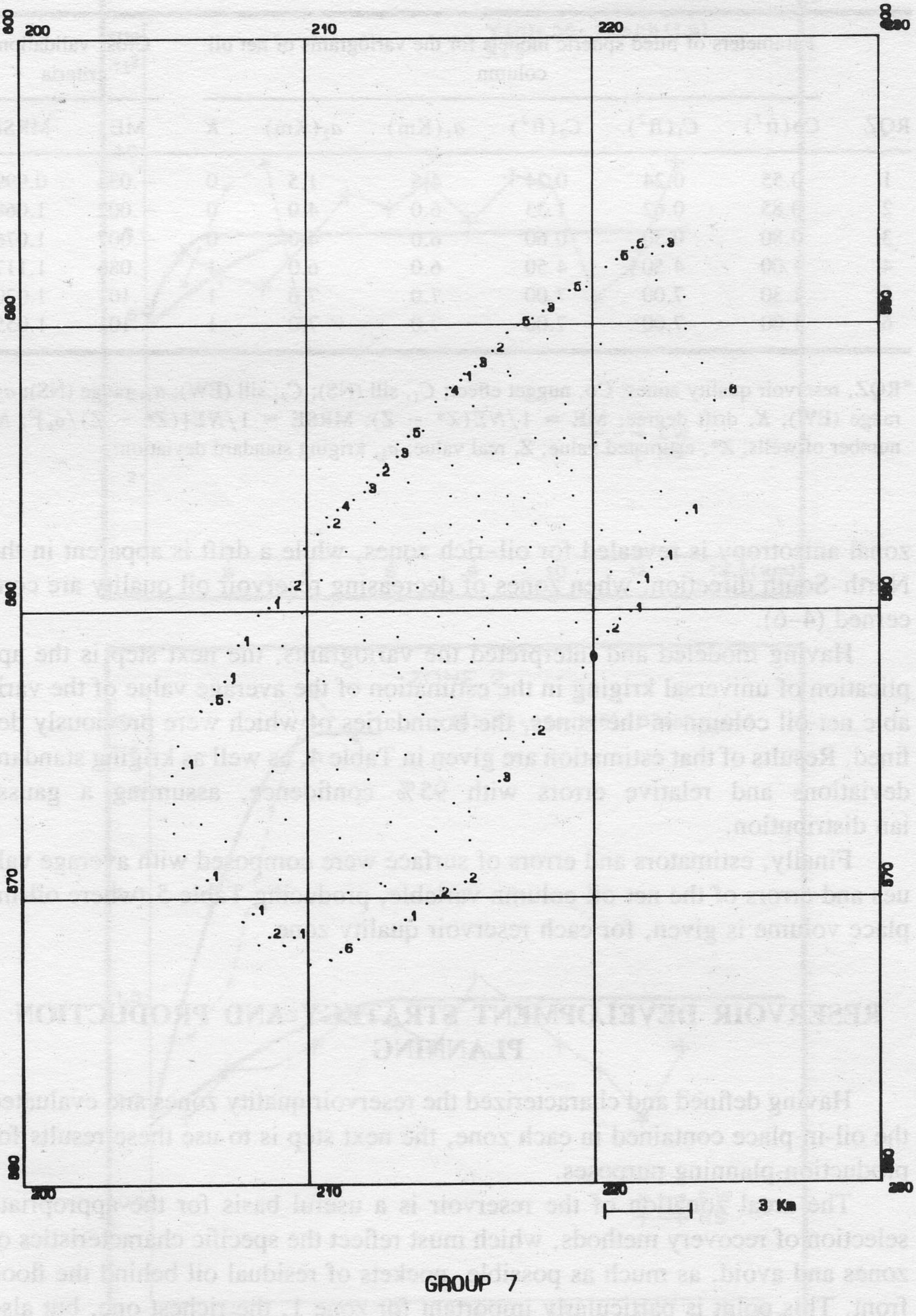


Fig. 6. Continued.

Table 3. Cross-Validation Results for Selected Variogram Models of Variable Net Oil Column[a]

	Parameters of fitted spheric models for the variograms of net oil column						Cross-validation criteria	
RQZ	Co(ft^2)	C_1(ft^2)	C_2(ft^2)	a_1(Km)	a_2(Km)	K	ME	MRSE
1	0.55	0.24	0.24	4.5	1.5	0	−.034	0.999
2	0.85	0.62	1.33	6.0	4.0	0	−.002	1.068
3	0.80	0.50	0.60	6.0	4.0	0	−.007	1.076
4	1.00	4.50	4.50	6.0	6.0	1	.086	1.117
5	1.30	7.00	7.00	7.0	7.0	1	.101	1.020
6	1.00	7.00	7.00	7.0	7.0	1	.101	1.055

[a] RQZ, reservoir quality zones; Co, nugget effect; C_1, sill (NS); C_2, sill (EW); a_1, range (NS); a_2, range (EW); K, drift degree; ME $= 1/N\Sigma(Z^* - Z)$; MRSE $= 1/N\Sigma[(Z^* - Z)/\sigma_k]^2$; N, number of wells; Z^*, estimated value; Z, real value; σ_k, kriging standard deviation.

zonal anisotropy is revealed for oil–rich zones, while a drift is apparent in the North–South direction, when zones of decreasing reservoir oil quality are concerned (4–6).

Having modeled and interpreted the variograms, the next step is the application of universal kriging in the estimation of the average value of the variable net-oil column in the zones, the boundaries of which were previously defined. Results of that estimation are given in Table 4, as well as kriging standard deviations and relative errors with 95% confidence, assuming a gaussian distribution.

Finally, estimators and errors of surface were composed with average values and errors of the net-oil column variable, producing Table 5, where oil-in-place volume is given, for each reservoir quality zone.

RESERVOIR DEVELOPMENT STRATEGY AND PRODUCTION PLANNING

Having defined and characterized the reservoir quality zones and evaluated the oil-in-place contained in each zone, the next step is to use these results for production-planning purposes.

The areal zonation of the reservoir is a useful basis for the appropriate selection of recovery methods, which must reflect the specific characteristics of zones and avoid, as much as possible, pockets of residual oil behind the flood front. This point is particularly important for zone 1, the richest one, but also for zone 2, especially in the flanks. Moreover, in zone 4, careful attention is required in the recovery of its southern part, exhibiting significant oil saturations (cf. Fig. 6).

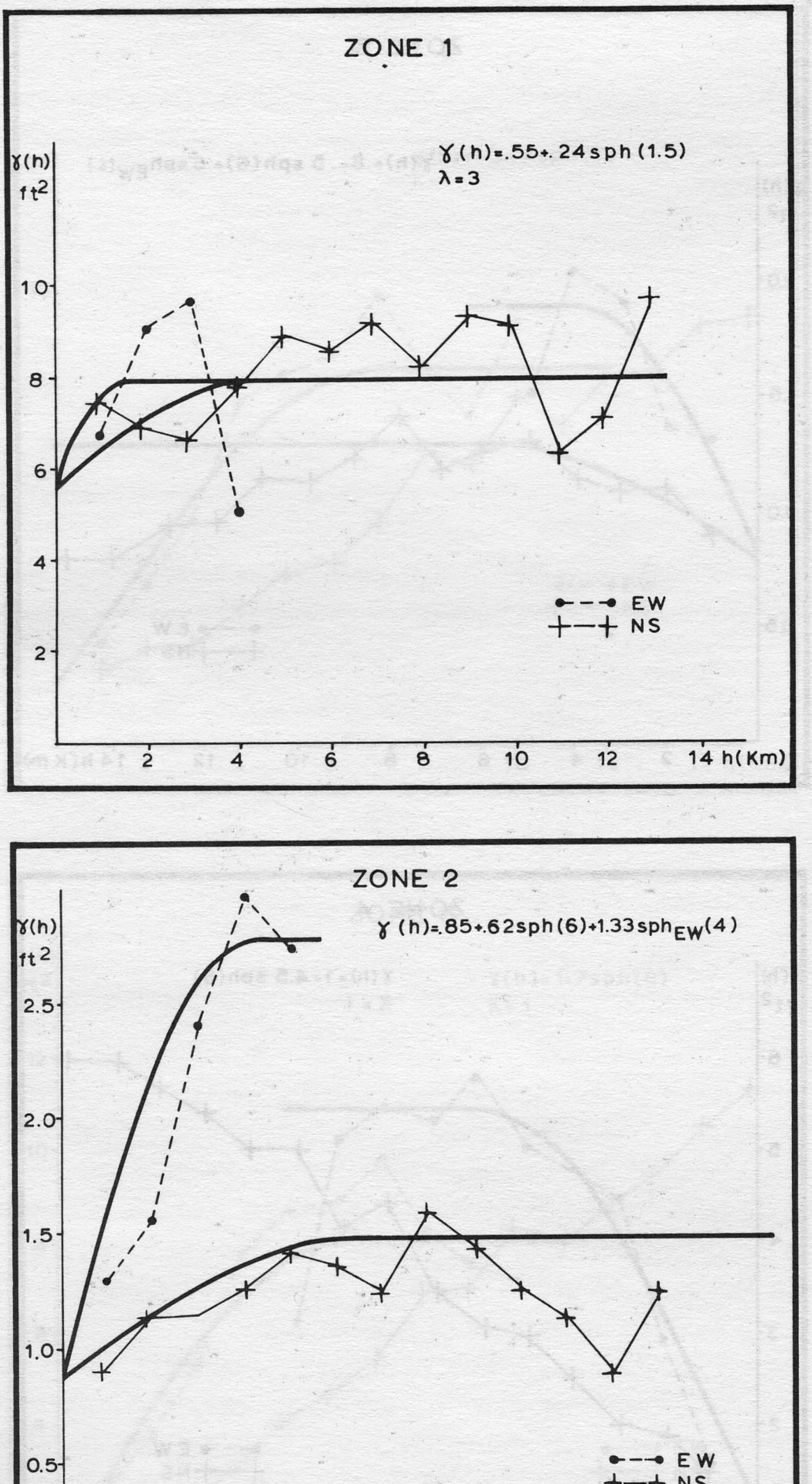


Fig. 7. Variograms and fitted models for the variable net oil column in each zone.

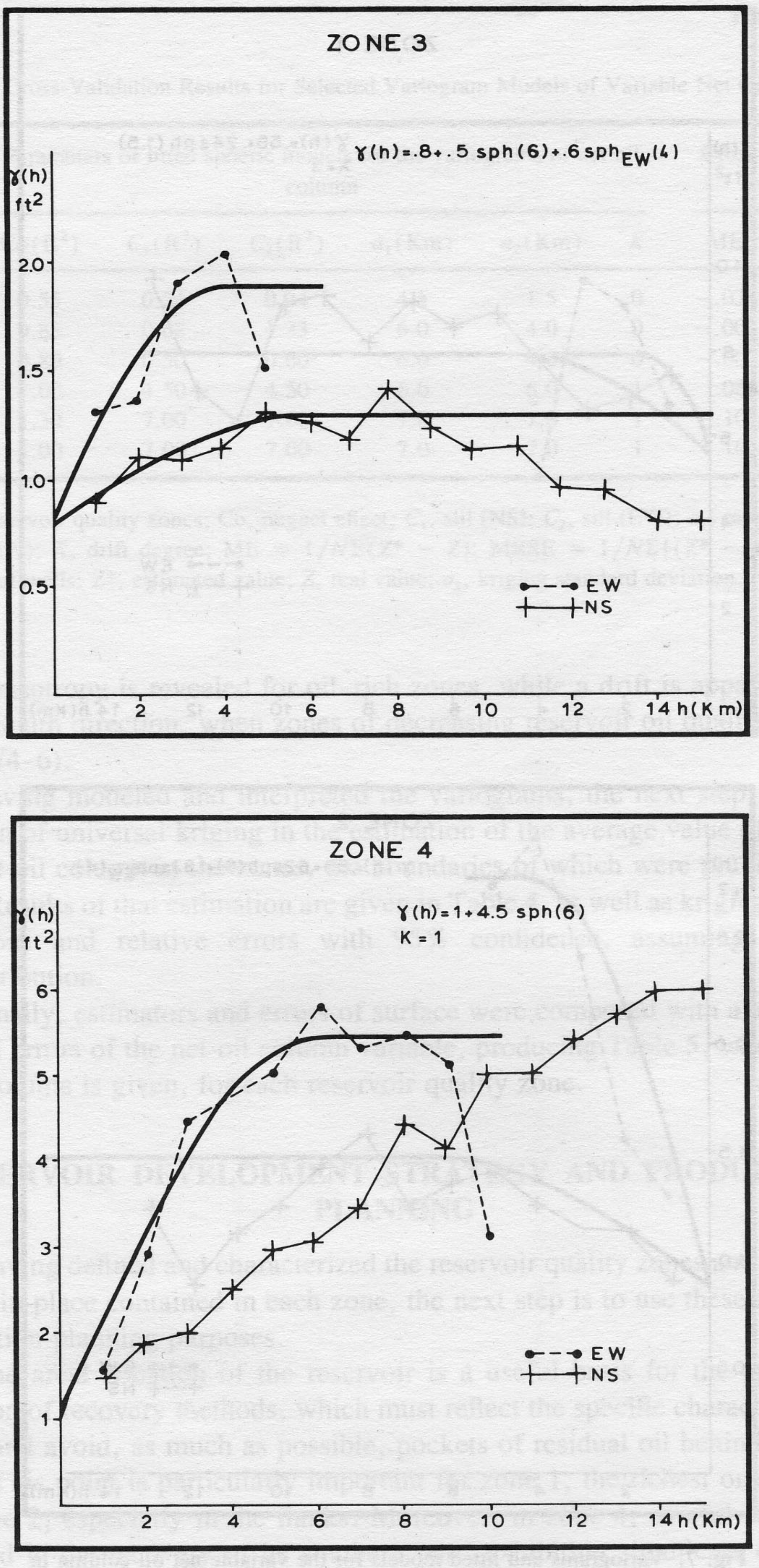


Fig. 7. Continued.

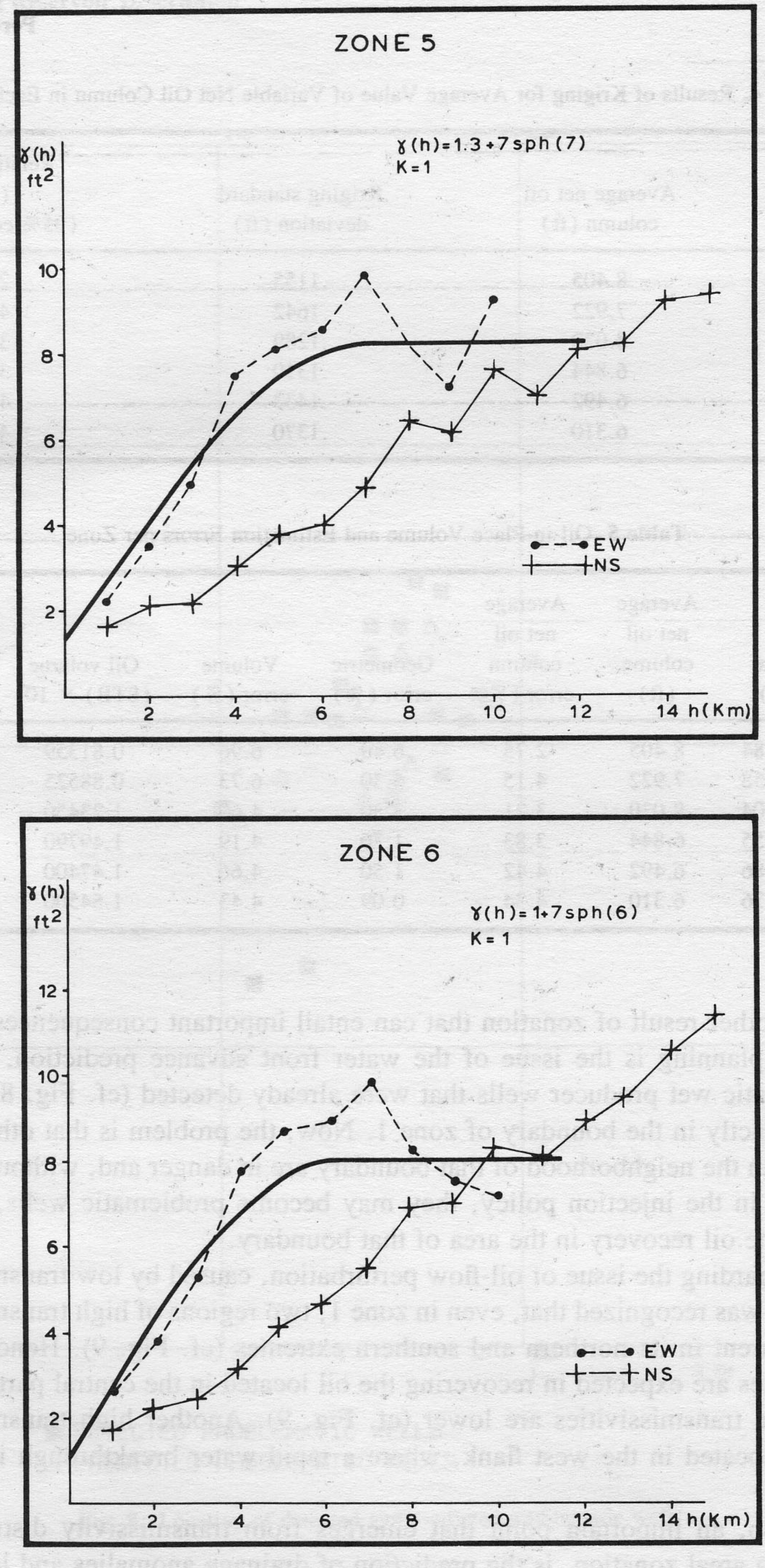


Fig. 7. Continued.

Table 4. Results of Kriging for Average Value of Variable Net Oil Column in Each Zone

RQZ	Average net oil column (ft)	Kriging standard deviation (ft)	Relative error (%) (95% confidence)
1	8.405	.1155	2.75
2	7.922	.1642	4.15
3	8.030	.1289	3.21
4	6.844	.1310	3.83
5	6.492	.1433	4.42
6	6.310	.1370	4.34

Table 5. Oil-in-Place Volume and Estimation Errors per Zone

RQZ	Area $(km)^2$	Average net oil column (ft)	Average net oil column error (%)	Geometric error (%)	Volume error (%)	Oil volume (STB) × 10^9	Percentage of total oil in place (%)
1	80.784	8.405	2.75	6.40	6.96	0.81359	52.60
2	93.258	7.922	4.15	5.30	6.73	0.88525	57.20
3	128.304	8.030	3.21	3.30	4.60	1.23450	79.90
4	182.655	6.844	3.83	1.70	4.19	1.49790	96.95
5	189.486	6.492	4.42	1.50	4.66	1.47400	95.40
6	204.336	6.310	4.34	0.09	4.43	1.54500	100.00

Another result of zonation that can entail important consequences in production planning is the issue of the water front advance prediction. In fact, problematic wet producer wells that were already detected (cf. Fig. 8) are located exactly in the boundary of zone 1. Now, the problem is that other wells located in the neighborhood of that boundary are in danger and, without drastic changes in the injection policy, they may become problematic wells, jeopardizing the oil recovery in the area of that boundary.

Regarding the issue of oil-flow perturbation, caused by low transmissivity areas, it was recognized that, even in zone 1, two regions of high transmissivity are apparent in its northern and southern extremes (cf. Fig. 9). Hence, some difficulties are expected in recovering the oil located in the central part of zone 1, where transmissivities are lower (cf. Fig. 9). Another high transmissivity area is located in the west flank, where a rapid water breakthrough is recognized.

Also, an important point that emerges from transmissivity distribution, linked to areal zonation, is the prediction of drainage anomalies and local difficulties in fluid flow. Examples of such problems, arising from a detailed anal-

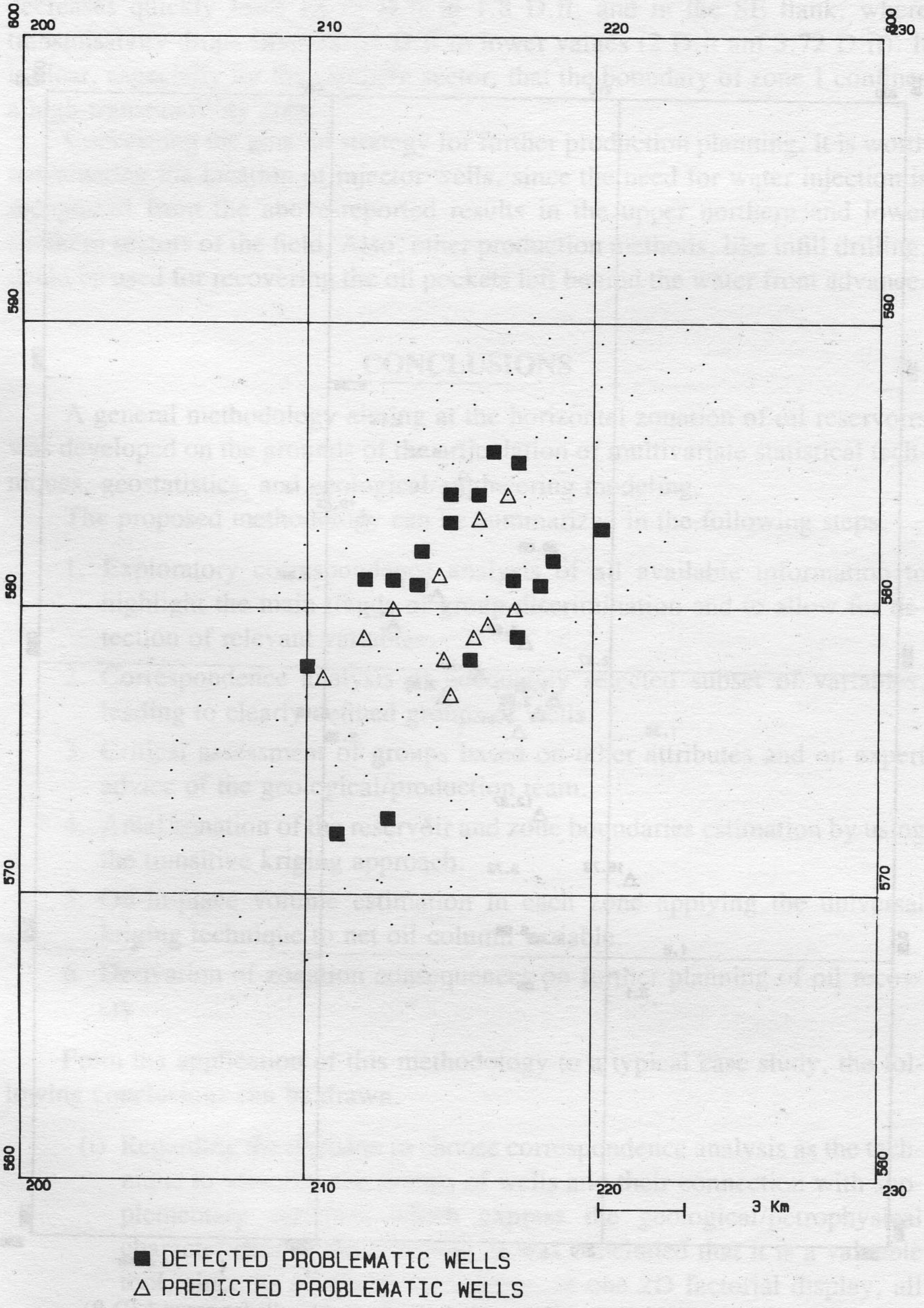


Fig. 8. Location of detected and predicted problematic wells.

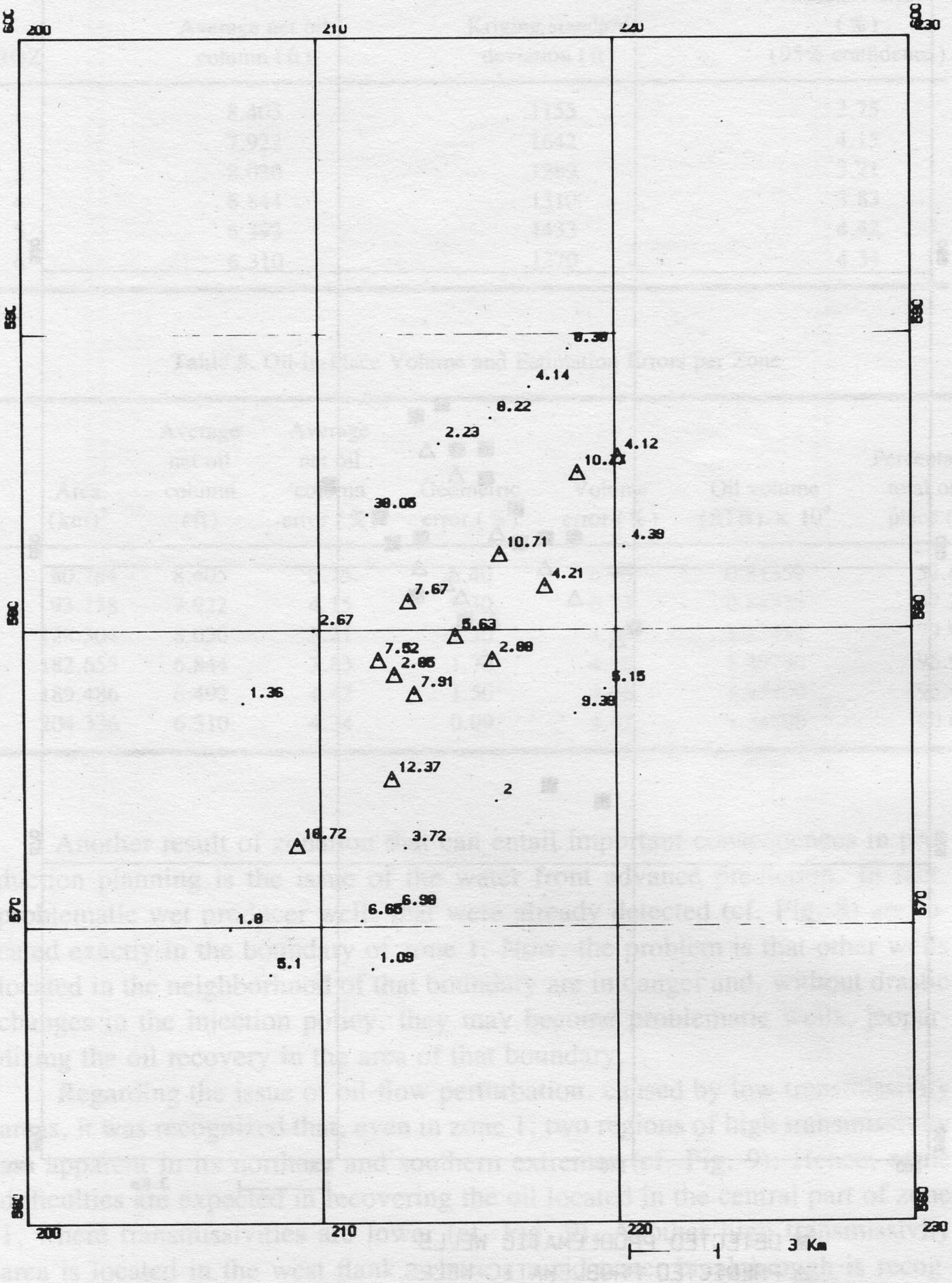


Fig. 9. Spatial distribution of transmissivities in cored wells for group 1 (D.ft).

ysis of Fig. 9, can be picked in the SW part of the field, where transmissivity decreases quickly from 18.72 D.ft to 1.8 D.ft, and in the SE flank, where transmissivity drops from 12.37 D.ft to lower values (2 D.ft anf 3.72 D.ft). It is clear, especially for the southern sector, that the boundary of zone 1 confines a high-transmissivity area.

Concerning the general strategy for further production planning, it is worth reevaluating the location of injector wells, since the need for water injection is recognized from the above-reported results in the upper northern and lower southern sectors of the field. Also, other production methods, like infill drilling, could be used for recovering the oil pockets left behind the water front advance.

CONCLUSIONS

A general methodology aiming at the horizontal zonation of oil reservoirs was developed on the grounds of the articulation of multivariate statistical techniques, geostatistics, and geological/engineering modeling.

The proposed methodology can be summarized in the following steps.

1. Exploratory correspondence analysis of all available information to highlight the main trends of group discrimination and to allow for detection of relevant variables.
2. Correspondence analysis of adequately selected subset of variables, leading to clearly defined groups of wells.
3. Critical assessment of groups based on other attributes and on expert advice of the geological/production team.
4. Areal zonation of the reservoir and zone boundaries estimation by using the transitive kriging approach.
5. Oil-in-place volume estimation in each zone applying the universal kriging technique to net oil-column variable.
6. Derivation of zonation consequences on further planning of oil recovery.

From the application of this methodology to a typical case study, the following conclusions can be drawn.

(i) Regarding the decision to choose correspondence analysis as the technique to visualize the groups of wells and their connection with supplementary variables which express the geological/petrophysical characteristics of the reservoir, it was concluded that it is a valuable tool, since its allows to summarize, in one 2D factorial display, all relevant information, linking groups of wells arranged by decreasing order of an index of oil quality to supplementary projections of geological/petrophysical variables.

(ii) The initial groups obtained by any segmentation method must be criticized on the grounds of the geological/reservoir engineering context, and validated by external information on facies and rock types distribution.

(iii) Once found a reliable zonation of the reservoir by combining groups of wells exhibiting a decreasing oil quality, the transitive kriging approach is the appropriate technique for boundary estimation, providing, for each zone, its area and respective error.

(iv) Since an accurate structural analysis is possible, the universal kriging approach gives the best results in the estimation of the average net oil-column per bounded zone.

(v) The horizontal zonation of the reservoir is a valuable basis for further planning purposes.

More specifically, the improvement on reservoir description brought by zonation has an important impact on production planning, as follows from the sequel:

(a) The zonation allows the detection of the water front advance, problematic wells and facies prone to water invasion. It is felt that such studies in earlier stages could avoid some inconveniences of the water front advance. Furthermore, it seems that average water saturation maps currently used in the industry are not adequate to cope with this type of problem.

(b) The zonation, when combined with accurate transmissivity maps, can provide a good basis for avoiding residual oil pockets, via the appropriate injector wells planning and/or use of special recovery methods, and as infill drilling.

(c) The zonation, when correlated with facies distribution, allows to detect drainage anomalies and fluid flow perturbations, and can be taken as a basis for the control of the injection profiles.

(d) It is required to complement the zonation studies with transient pressure tests, in order to carry out injection and production optimization, specially for zones where oil recovery is more complex (e.g., zones 1 and 3); identification of depleted and by-passed reserves in such areas using GR and Natural or Pulse Neutron logs is essential for spotting residual oil saturation.

(e) It is required to quantify carefully the benefits of the developed methodology in production planning, especially in what concerns the initialization of dynamic reservoir models.

ACKNOWLEDGMENTS

Critical review of the manuscript by M. Greenacre, R. Olea, and J. C. Davies was greatly appreciated. Their suggestions were very useful contributions to the improvement of the final form of the paper.

REFERENCES

Alfaro M., Miguez, F., 1976, Optimal Interpolation Using Transitive Methods: *in* Guarascio et al. (Eds.), Advanced Geostatistics in the Mining Industry. Reidel, Dordrecht, Holland, p. 91–99.

Benzécri, J.-P, 1973, L'Analyse des Données, tome 2, L'Analise des Correspondences: Dunod, Paris, 619 p.

Benzécri, J.-P., 1980, Pratique de l'analise des données. Abregé Théorique, Cas Modéle, Vol. 2: Dunod, Paris, 466 p.

Benzécri, J.-P., 1983, Histoire et préhistoire de l'analyse des données: Dunod, Paris, 159 p.

Bertrand, R., Desjardins, M., and Kubler, B., 1981, Application de l'analyse factorielle des correspondences aux gas adsorbés de l'offshore du Labrador: Can. J. Earth Sc., v. 18, p. 509–517.

Bonham-Carter, G., Gradstein, F., and D'Orio, M., 1986, Distribution of Cenozoic Foraminifera from the Northwestern Atlantic Margin Analysed by Correspondence Analysis: Comput. Geosci., v. 12, p. 621–635.

Greenacre, M., 1984, Theory and Applications of Correspondence Analysis: Academic Press, London, 364 p.

Matheron, G., 1978. Estimer et Choisir, CGMM, Fontainebleau, 175 p.

Pereira, H. Garcia, Costa e Silva, A., Ribeiro, L., and Guerreiro, L., 1989, Estimation of Reserves at Different Phases in the History of an Oil Field: *in* Armstrong, M. (Ed.), Geostatistics, Vol. 2, Kluwer Academic Publishers, p. 543–555.

Teil, H., 1975, Correspondence Factor Analysis: An Outline of the Method: Math. Geol., v. 7, p. 3–12.

Zhou, D., Chang, T., and Davis, J. C., 1983, Dual Extraction of R-Mode and Q-Mode Factor Solutions: Math. Geol., v. 15, p. 581–606.