APPLICATIONS OF SCANNING ELECTRON MICROSCOPE AND X-RAY MICROANALYSIS TECHNIQUES IN THE EVALUATION OF RESERVOIR QUALITY AND PETROLEUM PRODUCTION PROBLEMS

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SUMMARY

This report summarises the findings of an introductory program to test the application of the scanning electron microscope (SEM) energy dispersive X-ray microanalysis system (EDX) for geological investigation of reservoir quality and petroleum production problems. The three SEM techniques used were:

1. secondary-electron imaging (SEI),
2. backscatter-electron imaging (BEI), and
3. cathodoluminescence (CL).

Analysis by SEI provides three dimensional images of pores and grain surfaces, from which the following may be defined:

- pore geometry,

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- the distribution of pore-throat blocking phases,
- phases capable of damaging the reservoir, and
- evidence for paragenetic timing.

BEI analysis by SEM provides detail of compositional differences and is therefore principally of use as a tool for assessment of diagenetic problems. This technique is also of use in examination of pore systems and provides a means of direct comparison wich optional microscopy studies.

CL-imaging by SEM is as yet an unproven technique, but has potential for analysis of carbonates and possibly quartz cements.

The SEM, when used in conjunction with standard thin section microscopy, X-ray diffraction analysis, core analysis and sedimentalogical data provides a highly sophisticated but readily masterable tool for interpreting the geological controls on reservoir properties and predicting the lateral variation that may be expected in a reservoir.

INTRODUCCION

Ecopetrol-ICP, Ecopetrol's centre for research and development, have recently acquired a Cambridge instruments S240 Scanning Electron Microscope (SEM) with a Link Analytical Instruments/85S energy dispersibe X-ray microanalysis system (EDX). These, in conjunction with other techniques, will be used for technical analysis by petroleum geologists, petroleum engineers, and petrochemical and refining engineers in order solve petroleum exploration, production and refining problems.

This report provides the results of a program to evaluate the applicability of the SEM and EDX as tools for geological investigations of petroleum reservoirs. The study, which was requested by Ecopetrol-ICP, was undertaken at Badley, Ashton & Associates Limite, Spilsby, U.K. by Ecopetrol-ICP personnel under the technical guidance of Cambridge Instruments and Badley, Astton personnel.

Aims of the study

The project was initiated to test the applicability of secondary-electron image (SEI), backscatter-electron image (BEI), and cathodoluminescence (CL) analysis in assessing reservoir quality and formation damage. This work was supplemented by optical microscopy and X-ray diffraction analysis (XRD), for the purpose of providing further data applicable for petrographical analysis of this type.

Data base

The study was undertaken on selected samples from the Colombian wells Casabe 1044, Casabe 1045 and Tibu 649-C. The samples were prepared in the following manner:

- five thin-sections (TS), impregnated with dyed resin and stained for calcite and dolomite, and for K-feldspar, and supplied by GAPS, London, U.K.

- nine polished blocks, prepared by the Department of Geology, University of Hull, Hull, U.K.

- thirteen core-chip fragments mounted on SEM stubs and carbon-coated, prepared at Cambridge Instruments,

- eight gold/palladium-coated TS, prepared by Ecopetrol-ICP. only three of these stamples were examined due to time constraints.

All samples, core analysis data, and core plug material were selected and supplied by Ecopetrol-ICP personnel.

Personnel

Assessment of the geological applications of the SEM and EDX techniques was undertaken by Ecopetrol-ICP personnel, Rafael Reyes (Geologist) and Pablo A. Pinzón (Physicist, Mc. of Science). Assistance in the use of the SEM and EDX was provided by John Parry of Cambridge Instruments, and geological guidance was supplied by Dr. Ross Garden, Dorothy Payne and Dr. Michael Ashton of Badley, Asthton & Associates Limited. XRD data were supplied and interpreted by Dr. Arthur Fraser, University of Hull.

Conditions of geological guidance

The study supervision, by Badley, Ashton and Associates Limited, was undertaken with the agreement that data collected was not intended to be of any interpretive value, due to the restricted sample data base, and the limited time allocated to the project.

SEM AND EDX TECHNIQUES AND THEIR GEOLOGICAL APPLICATIONS

The samples examide for this project were studied on the SEM by SEI, BEi and CL, each technique being used in conjunction with X-ray microanalysis, using EDX. The principal geological applications of these methods of investigation are provided in Figure 1.

Analysis by SEI

This technique is capable of providing information concerning three-dimensional relationships between graints, and the pore structure of rock samples.

Sample type and preparation

The ideal sample type for SEI is a rock fragment taken from a core plug and approxi-

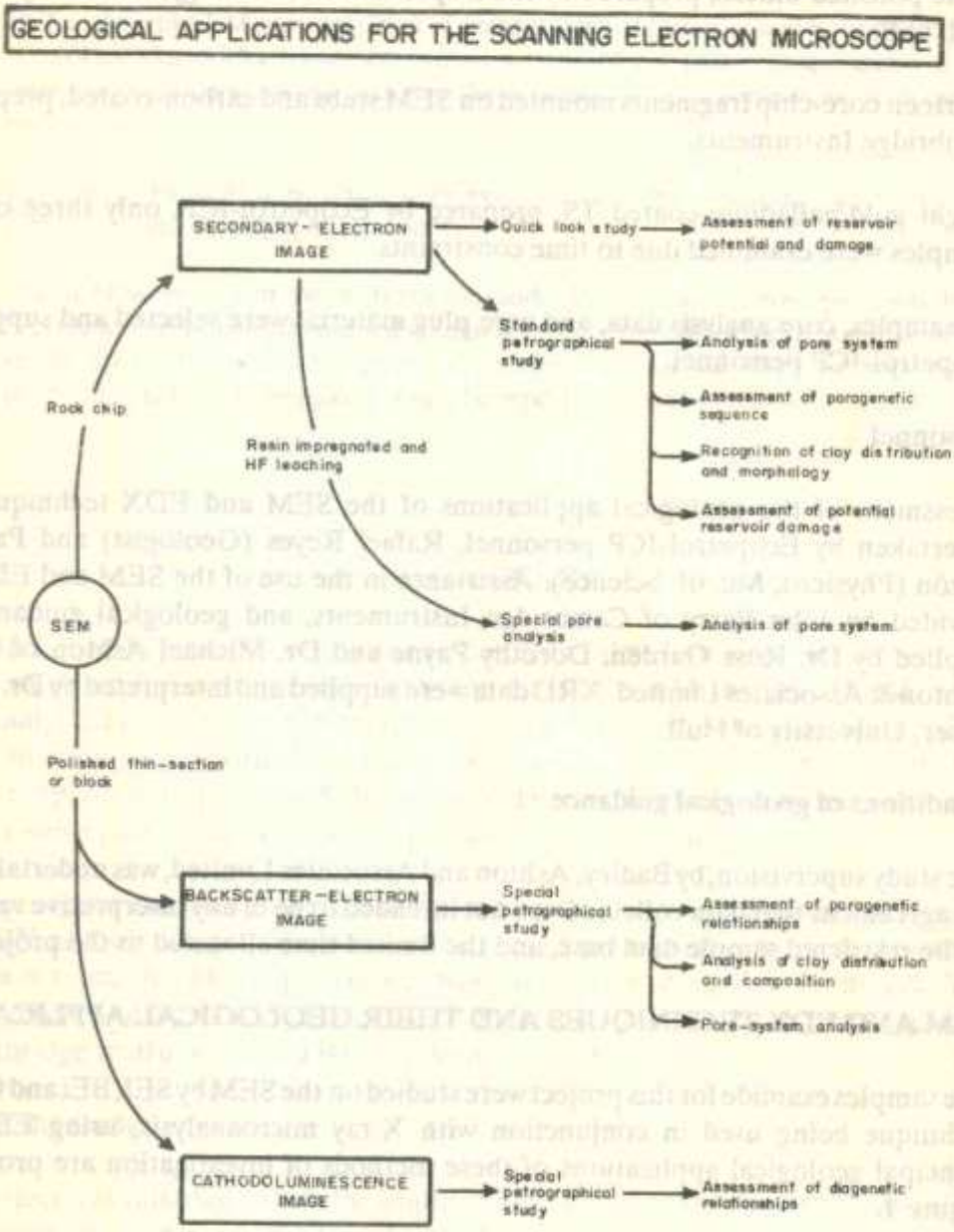


FIGURE: 1 POTENTIAL GEOLOGICAL USES FOR THE SEM DURING THE EVOLUTION OF RESERVOIR CHARACTERISTICS

mately 1 cm in diameter (= diameter of a standard SEM stub). The sample is attached to a SEM stub by epoxy resin with an approcimately flat surface, broken perpendicular to lamination, being uppermost. Once the resin has set, the sample is coated by carbon or gold-palladium and then a conductive strip of silver dag, extending from the upper surface of the sample to the top of the stub, is drawn. Typically 2-3 coats of carbon or adequate dissipation of excess electrons from the sample surface. Before placing any sample in the SEM chamber, the surface should he gently blown to remove any potentially conductive dust particles.

Applications of SEI

The principal purpose of analysis by SEI is to provide three-dimensional images of pores and grain surfaces for the use in the assessment of:

- pore geometry,
- the distribution of pore throat blocking phases,
- phases potentially capable of damaging the reservoir during production, and
- relationships indicative of paragenetic timing.

Particular emphasis needs to be paid to the study of clay and carbonate composition, morphology and distribution and the effect of grain dissolution on development of the pore system.

Acquisition of results

Analysis of rock samples by SEI should provide details, supplemented by ilustrative photomicrographs, of the following features:

1. texture, indicating grain size, sorting, grain orientation and clay distribution,
2. authigenic phases and diagenetic features, providing evidence for paragenetic timinig and the effects on the pore system.
3. pore types, illustrating pore size, pore throat size, and the distribution and abundance of porosity and permeability-controlling phases.
4. the pore system, indicating the overall interconnectivity of pores and the effectiveness of the system for fluid flow,
5. the distribution of fines capable of migrating under adverse conditions during reservoir production.

Limitaions of SEI analysis

The use of a broken rock surface presents two principal restrictions for analysis; these are:

1. internal features of cements, replacements and grains cannot be determined, therefore limiting the ability of this technique to define diagenetic relationships,

2. EDX results on uneven surfaces are of varying quality or may even be unobtainable due to;

- the scattering of the electron beam on surfaces adjacent to that under analysis, or
- the shadowing of the point of analysis, in deep pores or behind grains, from the detector.

Analysis by BEI

BEI analysis by SEM provides a means for visual differentiation of compositionally distinct phases and therefore its principal applicability is in diagenetic analysis.

Sample preparation

In standard practice, BEI samples are prepared as polished TS or polished resin-mounted blocks, in which the sample may or may not be resin impregnated. Polished TS are preferable seince samples may also be analysed by optical means. However, resin-mounted blocks commonly prove more easy to polish and therefore provide better BEI results. Both polished TS and resin-mounteed blocks are carbon or gold palladium coated and treated with silver dag in a similar manner to SEI samples (see above), however only one or two coats may be needed.

Applications of BEI

Atomic number differences, depicted as brighteness variations by BEI, define compositional contrasts between mineral phases and can therefore be as distinctive as differing optical properties under transmitted light. The principal application of BEI is, therefore, in the analysis of authigenic phases and diagenetic relationships. Additionally, the use of two-dimensional surfaces enables analysis of replacive as well as cementing fabrics, a feature in contrast with SEI studies and in direct comparison to optical microscopy studies.

A second application for BEI studies is as a means of pore system analysis, and examination of pore-throat occluding phases. This technique is complementary to optical microscopy but has the advantages that investigation may be undertaken at high magnifications, and that semi-quantitative chemical analysis may be obtained by EDX.

Acquisiton of results

The types of results collected from BEI are similar to those for SEI. This technique has the advantage that chemical analysis by EDX can be calibrated to provide semi-quantitative results since analysis by EDX can be calibrated to provide semi-quiantitative results since analysis is undertaken on flat surfaces from which there is only minor

electron interference from phases adjacent to that under investigation.

Limitations of BEI analysis

The principal limitation of SEM analysis by BEI is that it provides only limited addtional data from that which may be obtained by optical microscopy. Additionally, sample-preparation is a relatively time consuming process.

Analysis by CL

This technique is as yet unproven as a means of analysis of clastic reservoirs, although preliminary studies have been undertaken (Hogg et al. 1987). In contrast, the use of CL in carbonate rocks is well documented.

Samples are prepared in the same manner as those for BEI analysis.

At present two principal applications of CL analysis with the SEM are recognised; these are:

1. the study of carbonate cements, in order to determine paragenetic timing and basin wide correlation of authigenic phases, and

2. the investigation of quartz cements, in order to provide data concerning their volumetric extent, and distribution within pores. Additionally, CL may also provide evidence for multiple phases of quartz cementation.

Uses of X-ray microanalysis by EDX

This technique provides an invaluable method of mineral identification during all types of SEM analysis. However, it is noteworthy that the technique is at best semi-quantitative and ideally, mineralogical identification should be made in conjuction with morphological information.

Limitations of EDX analysis

On irregular surfaces (ie. those typical for SEI), X-ray microanalysis is prone to provide spurious results due to reflections from phases adjacent to the area of analysis. This effect will be of less importance on flat samples (ie. those typically used for BEI and CL). A second limiting factor is the ability of the electron beam to pass through the sample for analysis and to result in X-ray omissions from materials deeper in the sample. It is particulary important to consider this factor when analysing thin materials such as clays.

Applications of TS microscopy and XRD analysis

SEM analysis provides a means of assessing three-dimensional features and some

compositional variations in clastic reservoir rocks but, as noted above, each technique has a number of limitations. In addition, detailed analysis using the SEM are time consuming and limit the general availability of this expensive item of equipment. It is therefore advisable for SEM studies to be carried out in conjunction with other petrographical techniques, principally TS microscopy and XRD analysis.

Purpose of TS microscopy

The principal importance of TS microscopy in analysis of reservoir quality are that it enables:

- modal analysis, which provide semiquantitative mineralogical and porosity data,
- textural analysis, giving semi-quantitative assessmento of grain size and sorting, and
- subjective analysis of pore systems, the distribution of porosity and permeability controlling phases, and the extent and timing of diagenetic reaction.

The principal limitation of this technique is its inability to determine accurately finelycrystalline phases. It is, however, relatively quick and requires the use of relatively inexpensive equipment.

Purpose of XRD analysis

XRD analysis is normally undertaken on both bulk-rock and clay-fraction ($<4\mu$m) samples. Whole-rock analysis provides:

- semi-quantitative mineralogical data, which should be comparable to modal analysis data from TS, and
- identification of finely-crystalline phases not discernible from TS microscopy.

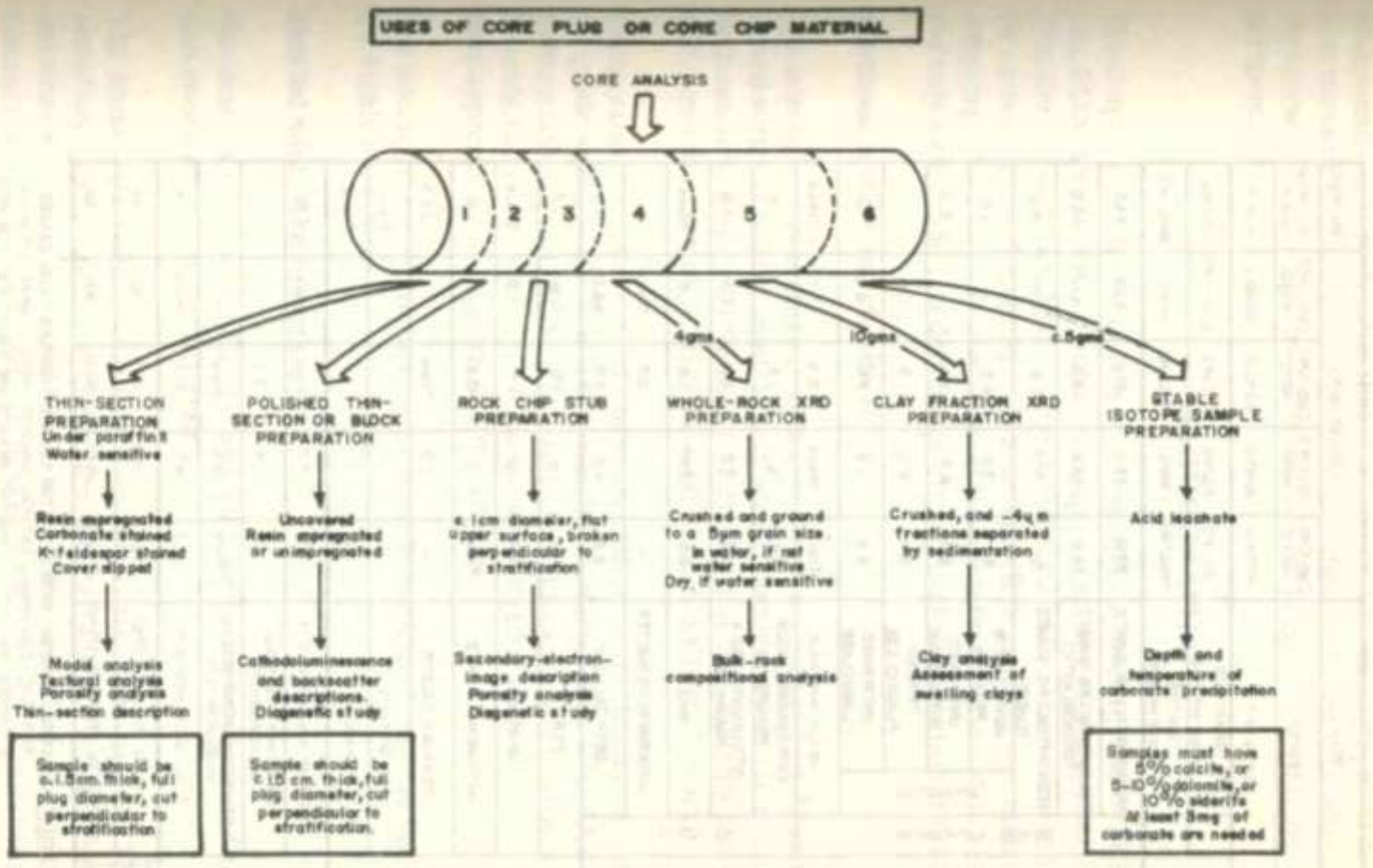
Clay-fraction analysis is of importance for the:

- accurate determination of clay species, and
- assessment of the proportions of exandable clays, potentially capable of damaging the reservoir.

The limitation of XRD is that it provides no information concerning the spacial distribution of the phases identified, and therefore their importance as controls on reservoir properties. This technique also requires expensive equipment, and the interpretation of the data is relatively timeconsuming.

Material for investigation

In the petrographical investigation of clastic reservoir by TS microscopy, SEM and XRD, the samples should be taken from conventional core plug material, or if this is not available, from core chip material taken adjacent to the position of a core plug. The



A DIAGRAMMATIC ILUSTRATION OF THE POSSIBLE PETROLOGICAL USES OF STANDARD CORE PLUG OR CORE CHIP MATERIAL, FOLLOWING CORE ANALYSIS.

FIGURA 2.-

WELL				CASA BE-1045				TIBU-469C
SAMPLE				CSB-1045 4078	CSB-1045 4087	CSB-1045 4252	CSB-1045 4460	TIBU-469 616.5
DEPTH (F T)				4078.0	4087.0	4252.0	4460.0	616.5
TEXTURE		GRAIN SIZE (visual estimate)		MS/FS	FS/MS	FS/VFS	C.SH/VFS	CS/MS
		SORTING (visual estimate)		MWS/MS	MWS	MWS/VFS	MWS	MWS/WS
DETRITAL PHASES (%)	FRAMEWORK GRAINS	MONOCRYSTALLINE QUARTZ		32.0	36.0	37.0	33.5	43.5
		POLYCRYSTALLINE QUARTZ (GRANOBLASTIC)		16.5	14.0	16.5	4.0	16.0
		POLYCRYSTALLINE QUARTZ (CHERT)		6.0	3.0	5.5	1.0	4.0
		FELDSPAR	MICROCLINE & PERTHITE	6.0	7.0	4.5	-	1.0
			UNTWINNED K-FELDSPAR	9.0	8.5	11.5	-	5.0
			TWINNED PLAGIOCLASE	3.0	2.5	1.5	1.0	-
			UNTWINNED PLAGIOCLASE	5.5	2.5	7.5	8.0	-
		HEAVY MINERALS		Trace	Trace	2.5	1.0	Trace
	DUCTILES	EXTRABASINAL ROCK FRAGMENTS		7.0	5.0	1.5	-	1.5
		INTRABASINAL ROCK FRAGMENTS		5.0	7.5	2.0	0.5	1.5
		MICA		6.5	7.5	1.5	1.5	Trace
		CARBONACEOUS MATTER		-	-	0.5	Trace	-
		DETRITAL CLAY		2.5	4.5	6.5	48.0	0.5
AUTHIGENIC PHASES (%)		PYRITE		-	-	1.0	Trace	0.5
		ANATASE		0.5	1.0	-	1.5	Trace
		AUTHIGENIC QUARTZ		Trace	-	0.5	-	1.0
		FERROAN CALCITE		-	1.0	Trace	-	25.5
		SIDERITE		-	-	-	-	Trace
		KAOLINITE		0.5	-	-	-	Trace
MODAL POROSITY(%)		PRIMARY MACROPOROSITY		8.5	7.7	10.9	Trace	0.5
		SECONDARY OVERSIZED MACROPOROSITY		1.8	1.4	2.2	-	-
		SECONDARY INTRAPARTICLE MACROPOROSITY		Trace	0.4	Trace	-	-
		TOTAL MACROPOROSITY		10.3	9.5	13.1	Trace	0.5
CORE ANALYSIS		HELIUM POROSITY (%)		32.5	26.9	18.9	NA	NA
		HORIZONTAL PERMEABILITY(mD)		2072.0	167.0	38.0	NA	NA

TABLE 1.- MODAL ANALYSIS RESULTS FOR THE SELECTED SAMPLES FROM CASABE 1045 AND TIBU-469C. TEXTURAL ANALYSIS RESULTS WERE VISUALLY ESTIMATED AND MODAL ANALYSIS RESULTS ARE CALCULATED FOR 200 MINERAL COUNTS, EXCLUDING POROSITY COUNTS.

importance of using core plug material is that results may be calibrated against core analysis data, enabling accurate determination of the controls on reservoir porperties. Additionally, it is preferable that alla samples for petrographical analysis are taken from the same rock fragment to reduce the influence of sedimentalogical variability on the data set. The principal uses of standard core plug (after core analysis) are presented in Figure 2.

PETROGRAPHY

This chapter provides the details of petrographical investigation by SEM (SEI, BEI and CL), EDX, TS and XRD of selected samples from wells Casabe 1044, Casabe 1045 and Tibú 469-C. Modal analysis was only conducted on five resin-impregnated TS, stained for carbonates and K-feldspar (Table 1). XRD analysis was undertaken on three samples (Table 2). The limited data set renders interpretation of the results inadvisable and only a guideline to a detailed petrographical investigation is presented here.

Sandstone texture and classification

The selected samples range from coarse-silt to coarse-sand grade and are moderately to well sorted (visual estimate). They are predominantly fine to medium-grained and moderately well-sorted (Plates 1 and 2). Detrital clay contents are typically low (< 6.5%) except in sample CSB 1045-4460 which is a silt-grade wacke.

Compositionally, the selected sandstones fall in the lithic arenite field except for the silt-grade wacke (CSB 1045-4460) which is subfeldspathic (Fig. 3A). Replotting with polycrystalline quartz at the feldspathic, subfeldspathic and quartzose fields (Fig. 3B). Notably, two samples from the Casabe 1045 well (CSB 1045-4078;and CSB 1045-4087) have appreciable non-quartzose lithic contets.

The selected samples are therefore texturally moderately mature but compositionally are highly immature.

Detrital mineral composition

The detrital suite of the Casabe and Tibú wells can be separated into two groups; framework grains and ductile grains.

The framework suite is dominated by monocrystalline quartz (32.0-43.5%), with subsidiary granoblastic polycrystalline quartz (4.0-16.5%), plagioclase (5.0-9.0%, untwinned > twinned, except in sample Tibú 469-616.5, in which plagioclase is abscent), K-feldspar (6.0-16.0%), untwinned K-feldspar > microcline and perthite) and chert (1.0-6.0%). Heavy minerals are moderately common (trace-2.8%) and include zircon, epidote, apatite monazite, sphene, rutile and ilmenite.

The ductile grain suite is dominated by rock fragments (0.5-12.5%), with subsidiary mica (trace-6.5%) and carbonaceous matter (< 0.5%). The rock fragments are com-

posed principally of altered volcanic clasts and mudclasts with only minor amounts of granitic fragments.

Detrital clay is typically a minor component < 6.5%) but is particularly abundant in sample CSB 1045-4460 (48.0%), in which it plugs pores and occludes porosity. Notably, the clay fraction in this sample also includes appreciable quantities of swelling clays including possible swelling chlorite (Table 2).

Variations in detrital composition

The principal variations in the samples from Casabe 1045 result from grain size differences. The silt grade sample (CSB 1045-4066) has a lower abundance of feldspar, polycrystalline quartz and rock fragments. the sample for well Tibú 469-C is notably different from those Casabe 1045 in having negligible plagioclase and relatively low abundances of rock fragments and mica.

Authigenic mineral composition

The Casabe samples are notable for their general scarcity of authigenic phaes. Recognisable authigenic include ferroan calcite (< 1.0%), pyrite (< 1.0%), anatase (< 1.5%) and quartz overgrowths (< 0.5). In contrast sample Tibú 469-616.5 is extensively cemented by ferroan calcite (25.5%), and has minor or trace amounts of authigenic quartz, pyrite, anatase, siderite and kaolinite (Table 1).

Calcite: coarsely-crystalline sparry cement, filling primary and secondary pores (Pls 4-1, 5-1, 5-2, 5-3 and 5-4).

Quartz: minor overgrowths lining pores, overlain by ferroan calcite in Tibú 469-616.5

Pyrite: scattered framboids, engulfed by ferroan calcite (Pls 4-1, 5-1).

Siderite: locally-developed, microspherulites forming at pore margins. The sperulites were partially dissolved and corroded prior to ferroan calcite cementation (Pl. 4-1).

Kaolinite: sparsely-developed booklet at pore margins and pore throats (Pls 4-2 4-3).

Indicators of sediment provenance

The small data set, size prevents determination of sediment provenance in the three study wells but the principal indicators of sediment provenance are rock fragment chert, heavy minerals and feldspar.

Rock fragments: include abundant volcanic fragments, and lesser amounts of mudclasts and granitic fragments.

Chert: chert of sedimentary or volcanic origin, and chert with carbonate inclusions of

WELL		CASABE-1045		TIBU 469C
SAMPLE		CSB 1045-4078	CSB 1045-4460	TIBU 469-616.5
DEPTH (FT)		4078.0	4460.0	616.5
WHOLE-ROCK ANALYSIS (%)	QUARTZ	67.71	70.74	68.72
	PLAGIOCLASE	8.12	9.13	-
	K-FELDSPAR	11.15	3.7	2.6
	MICA/ILLITE	5.9	6.10	≤1
	KAOLINITE	≤2*	2.6*	≤1
	CHLORITE	Trace	Trace	-
	CALCITE	-	-	22.26
	HALITE	-	-	0.5-1.5
CLAY-FRACTION ANALYSIS (%)	ILLITE	29-33	12-16	10-14
	KAOLINITE	49-53	63-67	75-79
	SMECTITE	1-5	14-18°	-
	CHLORITE	13-17+	3-7+	9-13

* Includes halloysite ° Contains 15-20% interstratified chlorite

+ Include unspecified amount of halloysite

TABLE 2.- XRD Analysis results for the selected Casabe 1045 and Tibu 469C samples.

probable sedimentary origin are include in the detrital suite.

Heavy minerals: include zircon, epidote, rutile, ilmenite, monazite, apatite and sphene. Notably, there is a high abundance of epidote (1.0%) in sample CSB 1045-4252.

Feldspar: the Casabe samples contain abundant feldspar of both plagioclase and alkali compositions, whereas the Tibú sample is dominated by K-feldspar.

Paragenesis

The limited development of authigenic phases and the small sample data base restrict the interpretation of a paragenetic sequence for the Casabe and Tibú wells. In all three wells the paragenetic sequence can be rationalised into three chemical diagenetic stages which occurred concurrently with mechanical diagenesis. Although unlikely to have similar diagenetic sequence the Casabe and Tibú wells are treated together here for convenience.

Mechanical diagenesis

Physical alteration of the selected sample on burial is separable into two phases; these are:

1. **plastic deformation of ductile grains** (mica, mudclasts, volcanic clasts), causing flexure or splaying of mud and volcanic clasts (p.1 3-3). This effect is common to both the Casabe and Tibú samples.
2. **fracturing of framework grains** prior to ferroan calcite cementation (Pl. 3-3). Evidence of this event is only present in well Tibú 469-C.

Chemical diagenesis

Chemical modification of the sandstones is separable into three stages:

1. **early reducing and alkaline diagenesis** is marked by sphurulitic siderite and framboidal pyrite precipitation (Pl. 4-1). Spherulitic siderite is recognised only in the Tibú 469-C well, whereas pyrite is common to all three wells.

2. **acid diagenesis** forms a complicated sequence of events including quartz overgrowth and kaolinite (Pls 4-2, advanced feldspar dissolution (Pl. 5-1). Feldspar dissolution is succeeded by anatase precipitation (Pl. 5-1).

This essentially acidic phase is probably related to the phase of siderite dissolution (Pl. 4-1). However this reaction cannot be accurately timed.

Evidence of this diagenetic stage is limited in the Casabe wells, which have very low kaolinite and quartz abundances (Table 1), and some indication of feldspar dissolution.

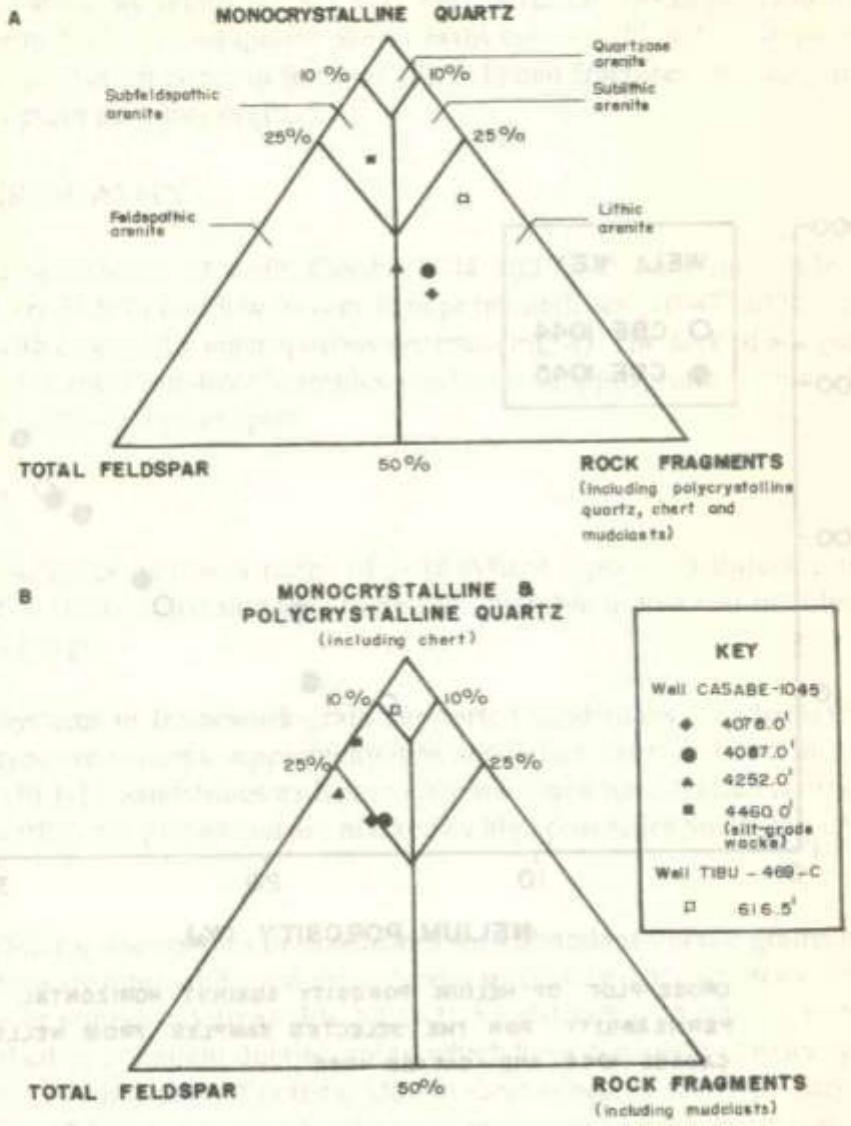
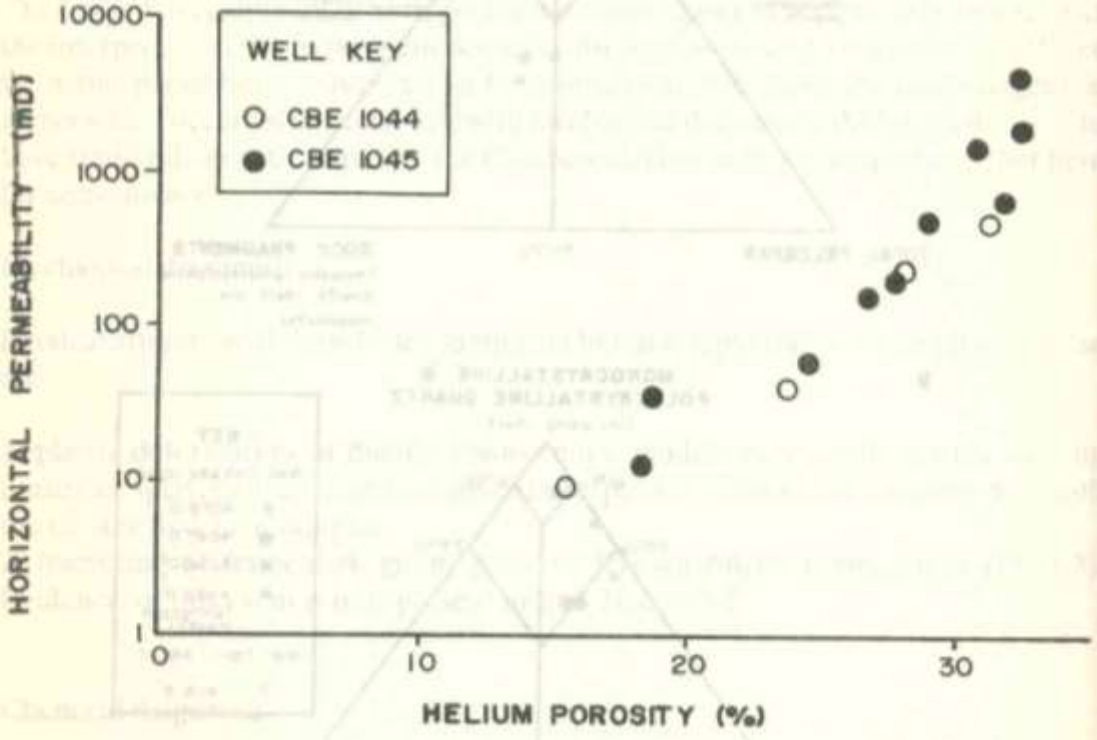


FIG. 3.- SANDSTONE CLASSIFICATION (A. AFTER DOTT 1964) AND CHEMICAL-STABILITY DIAGRAM (B) FOR SAMPLES SELECTED FOR MODAL ANALYSIS.



CROSS-PLOT OF HELIUM POROSITY AGAINST HORIZONTAL PERMEABILITY FOR THE SELECTED SAMPLES FROM WELLS CASABE 1044 AND CASABE 1045

In contrast, quartz cementation and feldspar dissolution are moderately well develop in sample Tibu 469-616.5.

3. **late alkaline diagenesis** is market by ferroan calcite cementation in the Casabe 1044, 1045 and Tibu 469-C wells (Pls 5-2, 5-3, 5-4). Ferroan calcite in sample Tibu 469-616.5 overlies siderite (Pl. 4-1) and quartz overgrowths siderite (Pl. 4-1) and quartz overgrowths fills dissolution pores in feldspar (Pl. 5-1) and fractures (Pl. 3-3), and postdates grainto-grain dissolution (Pl. 5-3).

RESERVOIR QUALITY

The selected sandstones of wells Casabe 1044 and 1045 have moderate to high porosities (15.6-32.5%) and low to very high permeabilities (10-477mD), typical for sandstones with essentially macroporous systems (Fig. 4). The lack of adequate core analysis data for the Tibu 469-C samples renders it inappropriate to consider their reservoir properties in this chapter.

Pore systems

The Casabe samples display a range of pore system types with differing reservoir properties. For the selected samples, these are separable in two end-members and a third mud-rich type.

Macropore systems in framework-grain supported sandstones are characterised by primary macropore systems supplemented by secondary oversized and intraparticle macropores (Pl 1-1). Sandstones with pore systems of type have relatively little ductile material or authigenic phases and are marked by high porosities and high permeabilities.

Macropore/Micropore systems in sandstones with abundant ductile grains have isolated or tortuously interconnected primary and secondary macrospores dispersed in microporous or nonporous areas (Pls 2-1, 2-2). Sandstones with pore systems of this type are typified by abundant ductile grains, which have deformed plastically to form pseudomatrix. Abundances of detrital clay in sandstones of this type may be low. Ductile-rich sandstones are expected to have moderate to high porosities but low permeabilities.

Sandstones and siltstones with abundant detrital clay are essentially non-porous or have isolate porous laminae (Pls 1-3, 1-4). Porosity is low, having been occluded by pore-filling detrital clay, and permeability is therefore also expected to be low.

Pore-system evolution and geological controls

This sections is not intended to be interpretive and observations are only drawn from the study set. The selected Casabe samples have undergone only minor authigenic modification but have been affected, to varying degrees, by compaction. On burial,

compaction resulted in deformation of ductile grains causing the destruction of primary porosity and the blocking of pore throats. The extende of this effect is presumed to be proportional to the ductile abundance in the sandstones. The only chemical diagenetic effect to influence the reservoir is the partial dissolution of feldspars, but this will have only slightly altered reservoir properties.

Reservoir sensitivity and formation damage

The study of selected samples from Casabe 1044 and 1045 has indicated that the two principal areas of potential reservoir damage are:

1. migration of fines, notably detrital clay, fragments of partially dissolved feldspar, splayed mica and plastically deformed grains, and kaolinite platelets. This may result in the blockage of pore throats causing increased flow path convolution.

2. swelling of expandable clay will potentially block pore throuts and decrease interconnectivity between macropores.

CONCLUSIONS

The principal conclusions of this training study are:

1. SEI, in conjuctions with EDX analysis, of rock-chip samples provides the best means of studying reservoir sandstones using the SEM. This technique provides a better understanding of pore-system geometry, the distribution of cement phases and the whereabouts phases with of potential for damaging the reservoir. Additionally, it will provide evidence of paragenetic timing that will supplement optical microscopi studies.

2. BEI, in conjuction with EDX analysis, is essentially a tool for diagenetic studies and is less suitable for the routine study of petroleum geology. However, because it provides a technique, complementary to TS microscopy, it is also of importance as a means of analysing pore systems and porosity and permeability controlling phases.

3. the SEM, when used in conjunction with TS microscopy, XRD analysis, core analysis and sedimentological interpretation of the cored and uncored intervals provides a highly sophisticated tool for interpreting the geological controls on reservoir properties and predicting the lateral variation that may be expected in the reservoir.

RECOMMENDATIONS

It is recommended that:

1. a series of comprehensive petrological studies, attempting to solve geological

reservoir problems should be undertaken with the aim of training Ecopetrol personnel in the methods of such data with TS and XRD data.

2. the use of CL-imaging using the SEM is as yet an unproven technique but has potential applications for the petroleum geologist. This method should be examined further to determine its true potential.

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