VOLCANIC ROCK FRAGMENTS OF PARANÁ BASIN PROVENANCE IN THE UPPER CRETACEOUS SANDSTONES OF SANTOS BASIN, EASTERN BRAZILIAN MARGIN

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Resumo – Arenitos turbidíticos e plataformais das formações Itajaí-Açu e Juréia (Santoniano-Maastrichtiano) são os principais reservatórios de hidrocarbonetos da Bacia de Santos, offshore da porção sudeste da margem continental brasileira. Estes arcóseos e arcóseos líticos são ricos em fragmentos de rochas vulcânicas (FRV). A preservação da porosidade nestes reservatórios em profundidades comumente superiores a 4000 m é atribuída à inibição da dissolução por pressão e da cimentação de quartzo por franjas de clorita. A alteração diagenética dos FRV é a principal fonte para a precipitação de clorita. Um estudo petrográfico de proveniência foi executado sobre 230 lâminas de amostras coletadas em testemunhos de 12 poços distribuidos ao longo da bacia para avaliar a distribuição dos FRV e prever a distribuição de clorita. A distribuição disseminada de FRV ácidos e básicos, bem como as texturas granofíricas dos FRV ácidos, indicam que a principal proveniência dos FRV da Bacia de Santos foi a erosão das vulcânicas toleíticas do Cretáceo inferior da Bacia do Paraná (Formação Serra Geral). O vulcanismo alcalino que ocorreu ao longo da parte norte da bacia durante o Cretáceo superior parece ter atuado apenas como fonte local de FRV para os arenitos. O decréscimo no teor de FRV do Santoniano para o Maastrichtiano concorda com o interpretado retrocesso erosional da escarpa do platô vulcânico da Bacia do Paraná em direção ao oeste, relacionado ao soerguimento da Serra do Mar durante o Cretáceo superior.

Palavras-chave: proveniência; arenitos marinhos; fragmentos de rochas vulcânicas; reservatórios profundos

Abstract – Marine turbidite and shelf sandstones of the Itajaí-Açu e Juréia formations (Santonian-Maastrichtian) are the main oil reservoirs in the Santos Basin, offshore eastern Brazil. These arkoses and lithic arkoses are rich in volcanic rock fragments (VRF). Porosity preservation in these deep reservoirs (commonly >4000 m) is ascribed to the inhibitory role of chlorite rims on quartz cementation and pressure dissolution. Diagenetic alteration of VRF is the main source for chlorite precipitation. A petrographic provenance study was performed over 230 thin sections sampled from 12 boreholes cored throughout the basin, in order to understand the distribution of VRF and to predict the distribution of chlorite in the basin. The basinwide distribution of basic and acidic VRF and the granophyric textures of the acidic VRF, indicate that the main provenance of Santos Basin VRF was the erosion of the Lower Cretaceous tholeiitic volcanics of the Paraná Basin (Serra Geral Formation). The alkaline volcanism, which took place along the northern part of the basin during Late Cretaceous seems to have acted only as a local source for VRF in the sandstones. The decrease in the amount of VRF from the Santonian to the Maastrichtian sandstones agrees with the interpreted erosional westward retreat of the scarp of Paraná Basin volcanic plateau due to the uplift of eastern Brazil coastal range during Late Cretaceous.

Keywords: provenance; marine sandstones; volcanic rock fragments; deep reservoirs; chlorite

1. Introduction

The Santos Basin, the largest among eastern Brazil offshore marginal basins, is located in southeastern Brazilian continental margin, limited to the northeast by the Cabo Frio Arch and to the southwest by the Florianópolis Platform (Fig. 1; Pereira and Feijó, 1994). The main targets for petroleum exploration in the basin are Upper Cretaceous, marine turbidite and shelf sandstones, up to 60 meters thick. They present anomalously high porosity (in places higher than 25 %), considering their present depths between 4000 and 5000 m. Pore-lining chlorite is the most abundant diagenetic constituent of these sandstones, and is interpreted as the main factor of porosity preservation though the inhibition of quartz cementation and pressure dissolution. The sandstones are rich in volcanic rock fragments (VRF), which alteration and dissolution is interpreted as the main source of Fe, Mg, Si and Al ions for the observed chlorite authigenesis (Sombra, 1990; Anjos et al., 2003). A petrographic study was conducted over 230 thin sections prepared from blue epoxy-impregnated samples, with the objective to recognize the provenance and the distribution of VRF in these Upper Cretaceous sandstones, in an attempt to understand and predict the distribution of chlorite in the reservoirs. The identification of paleovolcanic *versus* neovolcanic and extrabasinal *versus* intrabasinal provenance of VRF in clastic rocks is a complex, yet important issue for the understanding of the evolution of sedimentary basins and their source terrains in general, and particularly of Santos Basin.

2. Geological Setting

The Santos Basin was originated during the Lower Cretaceous South Atlantic rifting. The structural and stratigraphic evolution of the basin during the rift stage is poorly constrained. During the Aptian, at the end of rift stage, an about 1000 m thick evaporitic sequence was deposited in a narrow proto-oceanic sea under transitional conditions. The salts were covered in the Albian by a wide marine carbonate platform. The subsequent sedimentation was dominantly clastic marine. The main clastic reservoirs of the basin are Santonian to Maastrichtian, shallow and deep marine sandstones, respectively of the Juréia Formation and the Itajaí-Açu Formation (Ilhabela Member). Intense deformations related to the halokinesis of the Aptian evaporites initiated already in the Albian, originating large structures in the deep part of the basin and influencing the Upper Cretaceous sedimentation patterns. Basic alkaline magmatism occurred during late Cretaceous in the northern part of the basin and in the adjacent margin, mostly along the Cabo Frio Arch (Fig. 1; dated at 92 ± 9 to 87 ± 12 Ma; Mizusaki, 1992). This intrabasinal, coeval magmatism is represented by olivine basalts and diabases, which were initially assumed as the main sources for the VRF that commonly occur in the sandstones. However, an about 1 km thick succession of tholeiitic floods covered most of the adjacent intracratonic Paraná Basin during early Cretaceous (Fig. 1; Serra Geral Formation; Mantovani, 1985; Rocha-Campos *et al.*, 1988).

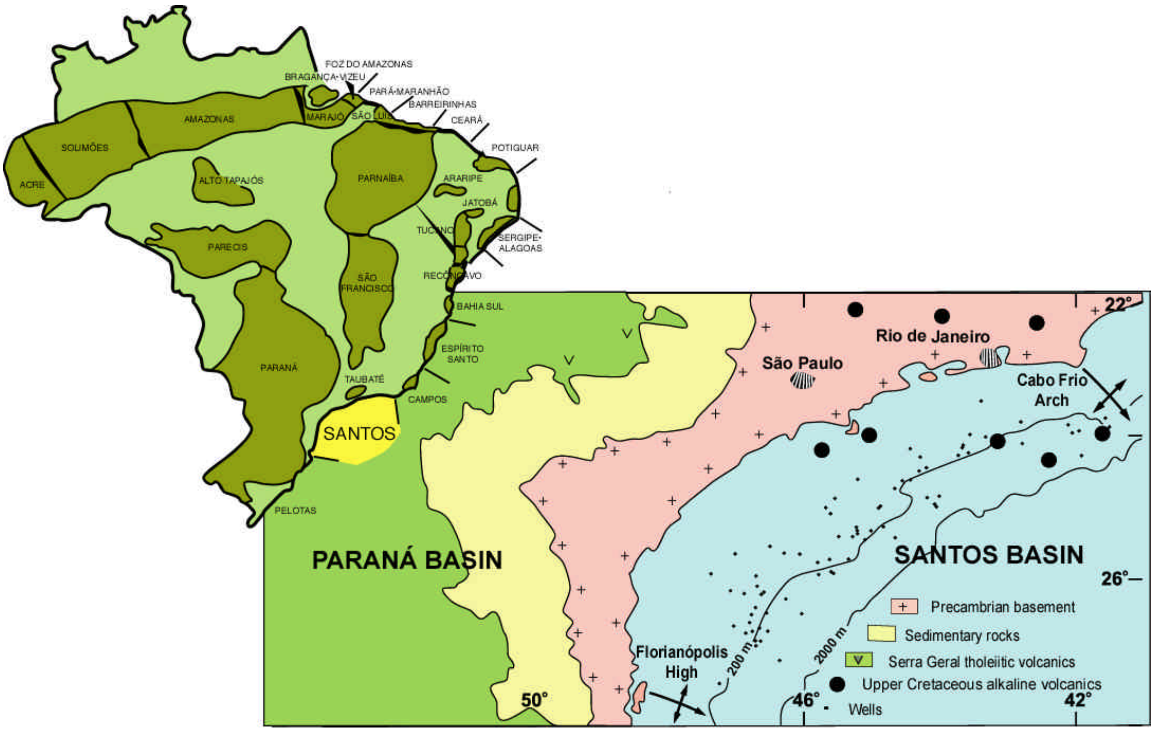

Figure 1 - Location of Santos Basin in offshore southeastern Brazil, showing studied wells, main occurrences of the upper Cretaceous alkaline volcanism, and outcropping areas of Precambrian crystalline rocks, of the Paraná Basin sedimentary rocks and Serra Geral lower Cretaceous volcanics.

3. Petrography

The Santonian and Campanian Ilhabela turbidite sandstones are medium to coarse-grained and moderately to poorly-sorted, frequently showing amalgamated cycles which are interpreted as high-density turbidity current deposits accumulated in chanellized lobes (Sombra, 1990). The Maastrichtian turbidites are fine-grained and well-sorted, and interpreted as distal, low-density deposits from non-chanellized lobes. The Juréia shelf sandstones are fine to coarse-grained and represent platform bar, tidal channel, shore-face and beach deposits (Sombra, 1990). The sandstones are arkoses and lithic arkoses, rich in basic and acidic volcanic rock fragments (Fig. 2).

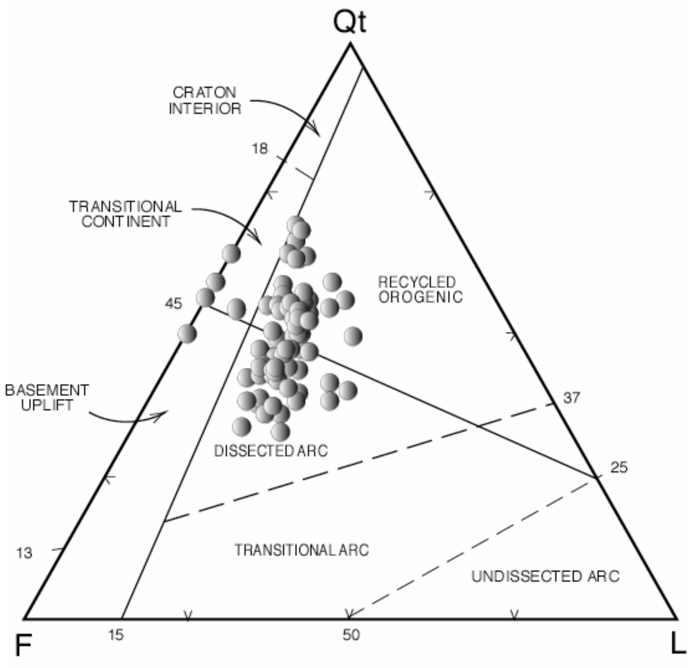

Figure 2 - Major detrital composition of the Santos Basin Upper Cretaceous sandstones, plotted in Dickinson (1985) diagram. Rock fragments are essentially volcanic.

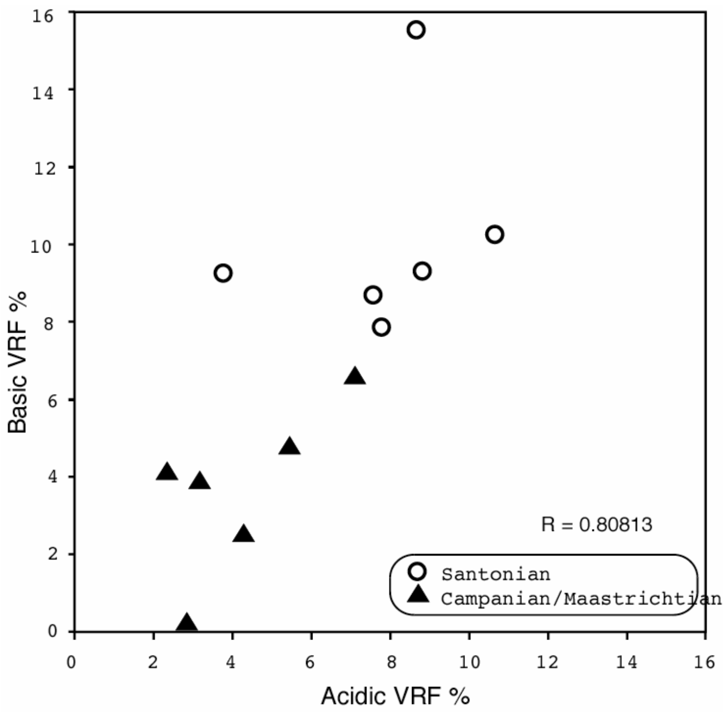

Figure 3 - Average contents of basic and acidic volcanic rock fragments in Santos sandstones of Santonian and Campanian/Maastrichtian ages. The fairly good correlation indicates a common source, of decreasing supply with time.

Basic VRF (av. 6 %, max. 20 %) and acidic VRF (av. 6 %, max. 12 %) occur distributed basinwide in samples from every facies and age. The average content of basic and acidic VRF presents a good correlation in sandstones from Santonian to Maastrichtian and throughout the basin (Fig. 3). The basic VRF are texturally characterized according to the proportion in original content of volcanic glass and crystals into holohyaline, hemicrystalline and holocrystalline types (Figs. 4a, b, c). They are commonly extensively, yet heterogeneously altered to chlorite and TiO_2 (Figs. 4c, d). The acidic VRF are all holocrystallyne, commonly with micrographic textures (granophyric; Fig. 4b) and were substantially less affected by diagenetic alteration processes than the basic VRF. The average content of total VRF does not show any systematic variation in geographic distribution throughout the basin. However, a stratigraphic variation is observed in VRF content, with sandstones of Santonian age showing larger amounts of VRF than those from Campanian and Maastrichtian (Fig. 3).

Intrabasinal grains include clay intraclasts, which are commonly compacted to pseudomatrix and chloritized, and occur more commonly in the turbidites. Carbonate bioclasts of mollusks, foraminifers and ostracods, and microcrystalline intraclasts are recrystallized and dissolved in variable degrees, and are more common in the shallow marine sandstones.

The porosity and permeability of Santos clastic reservoirs are strongly controlled by diagenesis. The main diagenetic processes identified are mechanical and chemical compaction, dissolution and alteration of VRF to chlorite, and precipitation of smectite, chlorite, calcite and quartz. Chlorite, mostly as coatings and rims, is the main diagenetic constituent in the deep Ilhabela turbidite reservoirs (Fig. 4c, d), while quartz overgrowths are more abundant in the Juréia shelf sandstones. Dolomite occurs in shallow marine sandstones, as pre-compactional pore-lining and pore-filling cement, in places associated to coarsely-crystalline anhydrite (Fig. 4b). Compaction is remarkably limited for such deeply-buried sandstones, what is demonstrated by an average intergranular volume of 27 %, but chlorite-poor shelf sandstones consistently show stronger compaction and smaller IGV values.

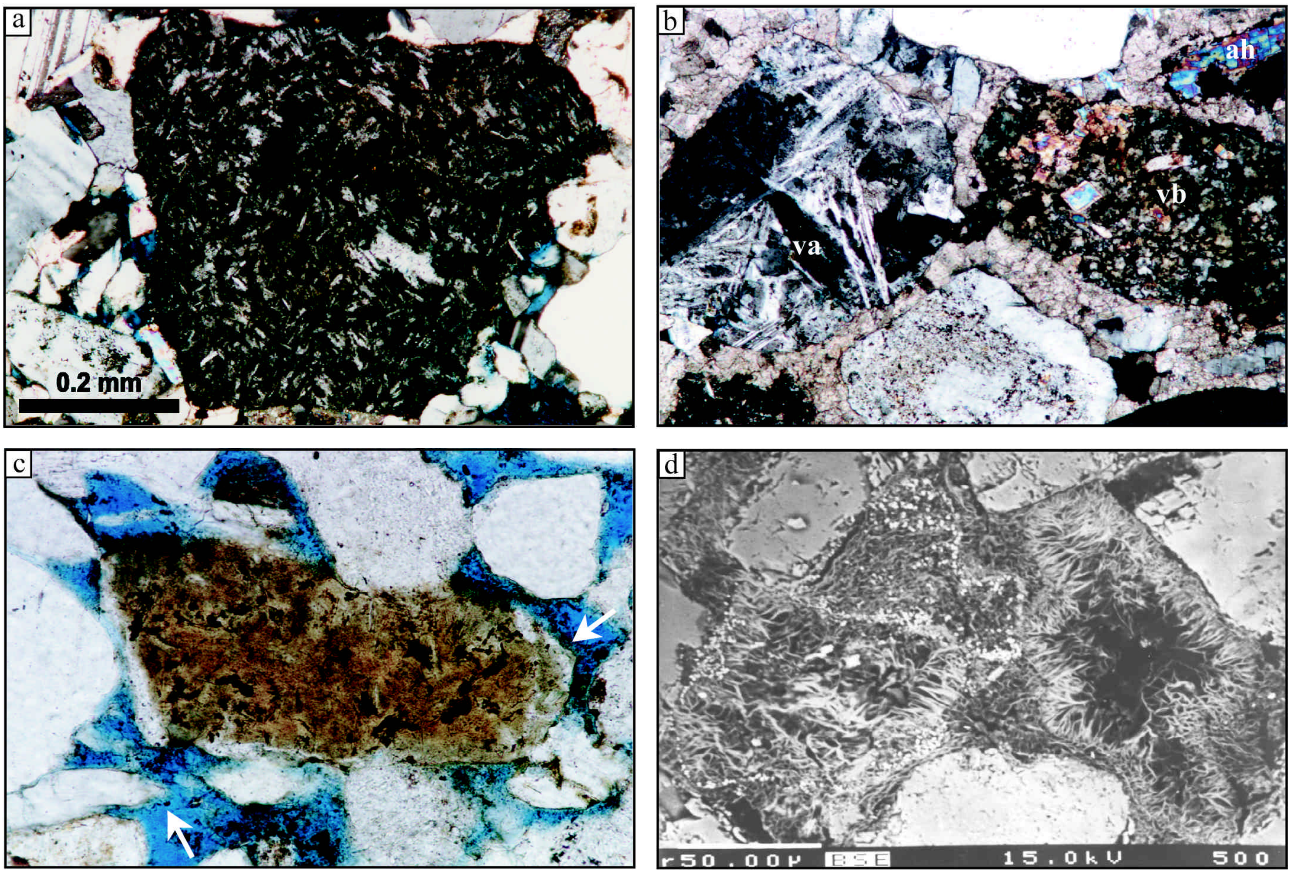

Figure 4 - a, b and c: Optical photomicrographs of Santos Basin sandstones: **(a)** basic holocrystalline fragment partially altered to iron oxides; crossed polarizers (XP); **(b)** acidic VRF with granophyric texture (va) and basic holocrystalline VRF (vb), cemented by precompactional pore-filling dolomite and anhydrite (ah); XP; photo field is 0.9 x 1.35 mm; **(c)** hemicrystalline basic volcanic rock fragment intensely replaced by chlorite titanium and iron oxides; chlorite pore-linings (arrows); uncrossed polarizers (//P); field 0.45 x 0.67 mm **(d)** backscattered electrons (BSE) photomicrograph of thick authigenic chlorite rims lining the pores, and chaotic mesh of chlorite and anatase (white) replacing altered VRF.

4. Discussion

The possible source terrains of the volcanic fragments in the Upper Cretaceous sandstones of Santos Basin include the penecontemporaneous, intrabasinal basic-alkaline volcanism, concentrated along the northern part of the basin, and the Lower Cretaceous, extensive tholeiitic Serra Geral volcanics of the adjacent Paraná Basin (Fig. 1). Since that the intense alteration of the VRF prevent their dating through radiometric methods, or even the recognition of their petrogenetic affiliation through chemical analyses, the characterization of their provenance must be achieved from their petrographic features and their distribution. Petrographic criteria for the characterization of paleovolcanic *versus* neovolcanic, and extrabasinal *versus* intrabasinal provenance of VRF in clastic rocks suggested by (Zuffa, 1985, 1987) are an useful guide for the complex task of differentiating the provenance classes of volcanic fragments and understanding their distinct paleogeographic implications in such a complex basins/source area system as that of Santos Basin. It is quite obvious that the successful recognition of paleovolcanic *versus* neovolcanic grains depends on the degree to which diagenetic processes have obscured the original features (Zuffa, 1991). The distinction may be quite difficult in sequences containing both extrabasinal paleovolcanic and neovolcanic grains subjected to strong diagenesis. Considering the criteria proposed by Zuffa (1985, 1987), Santos VRF are predominantly characteristic of an extrabasinal, paleovolcanic provenance, considering that they show grain size and roundness similar to the associated siliciclastic grains, extremely variable composition and textures, and that several fragments show alteration to iron oxides, suggestive of subaereal weathering (Fig. 4a, c). This indicates the tholeiitic Serra Geral plateau volcanics as their major source. No systematic geographic variation is observed in VRF content, but rather a stratigraphic variation, with sandstones of Santonian age showing larger amounts of VRF than those from Campanian and Maastrichtian (Fig. 3). Higher amounts of VRF should occur concentrated in the proximity of the intrabasinal centers located along the northern part of the basin if the upper Cretaceous volcanics were the main source of VRF in the sandstones. The granophyric textures of the observed acidic VRF (Fig 4b) are very similar to the textures of the acidic volcanic rocks which cover the basalts in the Serra Geral Formation (Mantovani, 1985). These acidic granophyric rocks show no resemblance in texture and composition to any product of the intrabasinal alkaline volcanism. Acidic volcanics presently show a limited distribution in the northern part of Paraná Basin, where they were extensively eroded, but are thick and extensive in the southern half of the basin (Mantovani, 1985). The average content of basic and acidic VRF for each studied well presents a good correlation (Fig. 3), suggesting that the two types of fragments have the same provenance. Palinspatic reconstructions indicate that the extension of the Serra Geral volcanics and of the whole Paraná Basin were substantially larger than the present (Almeida, 1998). The epeirogenic uplift of the eastern Brazil coastal range (Serra do Mar) during late Cretaceous and Paleogene produced a generalized erosion and westward retreat of the Serra Geral Formation scarp and of the eastern boundary of the Paraná Basin (Fig. 1; Almeida, 1998). The larger amount of VRF in the Santonian sandstones relative to the Campanian/Maastrichtian sandstones is probably the reflect of a gradual reduction of VRV supply to Santos Basin, due to the westward erosional retreat of the Serra Geral scarp during late Cretaceous uplift.

5. Reservoir Implications

Due to the wide regional supply of the basic and acidic VRF from the Serra Geral plateau, their amounts are correlative and similar throughout Santos Basin. However, the volume of authigenic chlorite in the sandstones varies largely and without relation with the amount of VRF. This indicates that other parameters control chlorite authigenesis and thus reservoir quality of the sandstones, such as the timing and intensity of VRF alteration, the patterns of circulation and the composition of pore fluids, and the thermal and burial histories within the basin (Anjos, 2003). Therefore, the dominant provenance of VRF from the Serra Geral volcanics of Paraná Basin implies that models designed to predict the quality of Santos Basin sandstone reservoirs will have to incorporate and consider the interplay of complex diagenetic parameters, and not mostly local variations in VRF supply. The coeval, intrabasinal alkaline volcanism has an apparently minor and local role on VRF distribution, although some local, thermal and fluid flow effects on reservoir quality may have occurred. The objective of this specific provenance study was to supply information and orientation to the evaluation and prediction of the quality of the reservoirs and their controlling parameters, with the aim to decrease exploration uncertainties and risk. A much wider provenance study on course will unravel the patterns of sediment supply and infill throughout the basin during upper Cretaceous and lower Tertiary.

6. Acknowledgements

The authors thank PETROBRAS for access to samples, data, information, and for the license to publish this work. Special thanks are given to A. Roisenberg for information on the Cretaceous magmatism. L. F. De Ros acknowledge the support of Brazil National Research Council (CNPq).

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