# [PS]Mineralogical and Geochemical Characterization of the Miocene-Oligocene Santos Shale, Southern San Joaquin Valley, California*

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## Abstract

The Santos shale is a 29 ~ 20 Ma member of the Temblor Formation located in the southwest corner of the San Joaquin basin. It was deposited in an ocean basin along the slope and the basin plain. The Santos outcrops in the Temblor range along the western perimeter of the San Joaquin valley, where it dips and thins eastward into the subsurface under the valley. The goal of the study is to characterize the Santos shale through its mineralogical and geochemical properties to better understand depositional environment and its potential as a source rock or fractured shale reservoir. Forty samples were used for this study from the wells along the crest and the flank of the Belgian anticline, ranging in depths of 1,061' in the west and 14,970' in the east. XRD analyses revealed that the bulk composition of the average Santos is composed of 45% clays, 29% quartz, 15% carbonates and 11% feldspar. In the clay size fraction, the clays are on average composed of 45.5% smectite, 43.3% illite, 8.2% kaolinite and 3.0% chlorite. LOI reveals the Santos has an overall high TOC content that ranges from 1.4 to 15.8 wt.%, with an average of 7.7 wt.%. Geochemical analyses from XRF and ICP-MS indicate the Santos was deposited in a well oxygenated marine environment based on relationships between iron, TOC and total sulfur; and low trace element ratios used as paleoredox proxies such as Ni/Co vs. V(V+Ni), V/Sc vs. V(V+Ni), and V/Cr vs. Ni/Co. Redox conditions upon burial are indicated by enrichment in Ni, V and U within the Santos samples. High TOC content is attributed to the oxic ocean environment with productive paleo waters. The preservation of the organic matter is due to redox conditions upon burial at the ocean-sediment interface where the oxygen is quickly depleted from settling organic matter. High TOC values in the Santos imply very good potential for fracture development.

# Mineralogical and geochemical characterization of the Miocene-Oligocene Santos shale, Southern San Joaquin Valley, California

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## INTRODUCTION

The Santos shale is a 29 ~ 20 Ma member of the Temblor Formation located in the southwest corner of the San Joaquin basin. The goal of the study is to characterize the Santos shale through its mineralogical and geochemical properties to better understand depositional environment and it's potential as a source rock or fractured shale reservoir. Forty samples were used for this study from the wells along the crest and the flank of the Belgian anticline, ranging in depths of 1,061' in the west and 14,970' in the east.

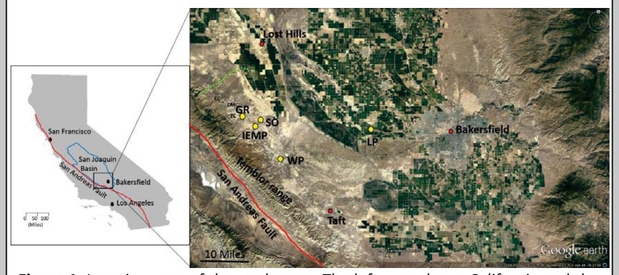


**Figure 1**. Location map of the study area. The left map shows California and the major geologic regions related to this study, including the San Joaquin basin outlined in blue and the San Andreas fault traced in red. The Google Earth image above shows a detailed view of the study area. Wells where samples came from are noted in the yellow dots and cities for regional reference are noted with red dots. There were a total of 40 samples taken from five different wells; Anderson 26 (GR) had 9 samples from 1,061'-1,944', Westpet 57-29 (WP) had 14 samples from 4,063'-4,887', Carrec 86-22 (SO) had 13 samples from 4,983'-5,234', McDonald-Purdy had 1 sample at 6,505', Tenneco West 31-5 had 3 samples from 14,910- 14,970'. Type location outcrops are marked by CC- Carnerous Creek, CMC-Chico Martinez Creek and ZM-Zemorra Creek. Dashed green line represents southernmost distribution of continuous Agua sandstone. Southeast of the line, there is sporadic isolated pockets of Agua sandstone and is interpreted to be a sediment-starved outer shelf or shelf break around 25 Ma by Bent (1985).

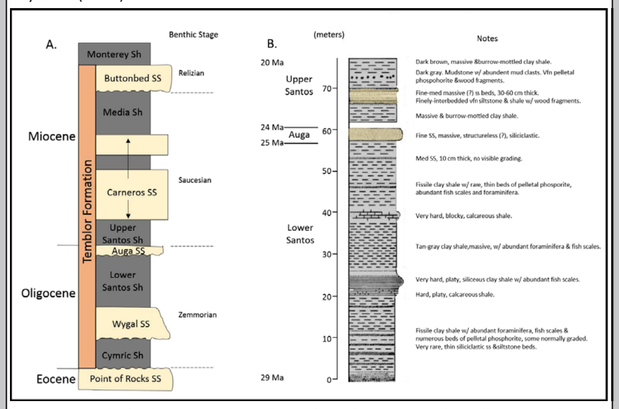


**Figure 2**. Redrafted stratigraphic column from (Carter, 1985). A. illustrates the stratigraphy of the Temblor Formation. B. is measured section of the Santos from High Zemorra Trench, Kern County. Ages taken from (Scheirer and Magoon, 2007).

## METHODS

- 40 Samples obtained from the California Well Sample Repository at CSUB
- Standard XRD sample preparation protocols followed for Bulk and Clay size fraction (<2 microns)
  - Main minerals and accessory minerals identified/measured using a MacDiff software
  - Relative abundances calculated using conversion factors from Biscaye (1965) for clay fraction and Cook et al (1975) for bulk size
  - Determined expandability and % illite in the I/S mixture layer by following Inoue et al (1989)
  - Broke out Kaolinite and Chlorite peaks following methods from Guo and Underwood (2011)
- Total Organic Carbon was determined by using Loss On Ignition (LOI) method
- X-Ray Fluorescence (XRF) was performed at the China Geosciences University Beijing to determine major oxides and some trace element concentration
- Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) was performed to determine trace element concentration

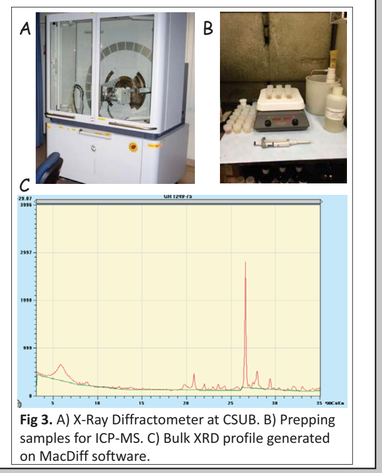


**Fig 3.** A) X-Ray Diffractometer at CSUB. B) Prepping samples for ICP-MS. C) Bulk XRD profile generated on MacDiff software.

## RESULTS and INTERPRETATIONS

### ALL WELLS MINERALOGICAL COMPONENTS

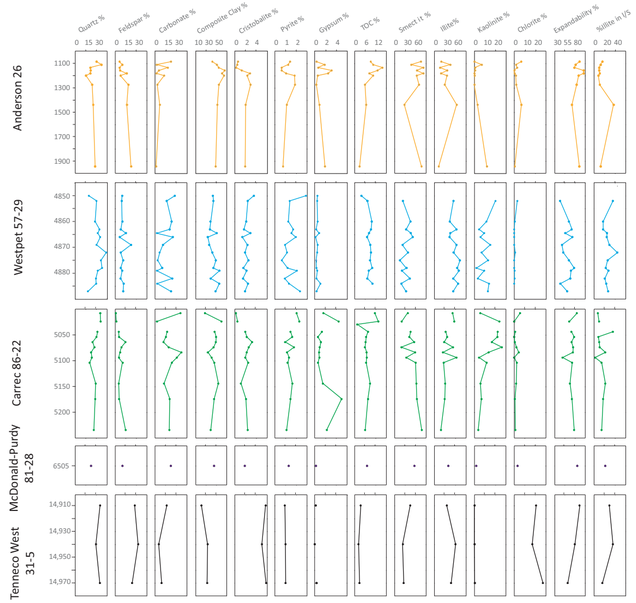


**Figure 4.** Bulk and Clay assemblage, along with TOC content plotted versus depth. The average bulk composition is composed of 45% clays, 29% quartz, 15% carbonates and 11% feldspar. The clays are on average composed of 45.5% smectite, 43.3% illite, 8.2% kaolinite and 3.0% chlorite.

### REDOX and PALEOPRODUCTIVITY

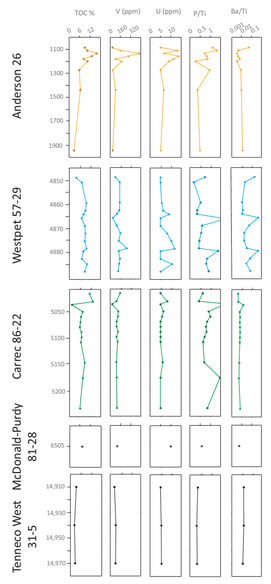


**Fig 5.** Redox (V, U) and paleoproductivity indices (P/Ti. Ba/Ti) plotted along TOC wt.%

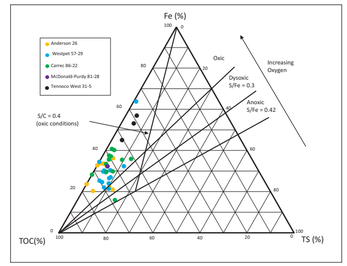


**Fig 6.** Ternary plot of relationships of Iron (Fe), total Sulphur (TS) and total organic carbon (TOC) suggest samples were deposited in an oxic environment. Deep samples (Tenneco-West 31-5) are enriched in Fe relative to the other samples.

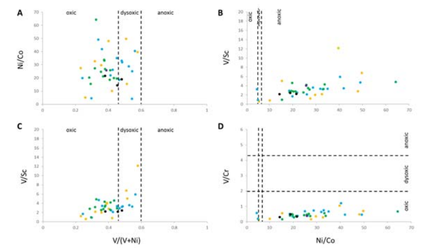


**Fig 7.** Cross plots of trace element ratios used as paleoredox proxies. A: Ni/Co vs. V(V+Ni), B: V/Sc vs. Ni/Co, C: V/Sc vs. V(V+Ni), and D: V/Cr vs. Ni/Co (Chen, et al., 2016 and references therein). Note one sample (Westpet 57-29, 4850') plots of the scale on the V/Sc axis, with a ratio of 150, and is not represented on these plots.

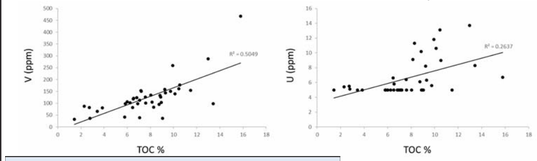


**Fig 8.** Correlations of redox proxies (V and U) with TOC. The preservation of the organic matter is likely due to redox conditions upon burial near the ocean-sediment interface.

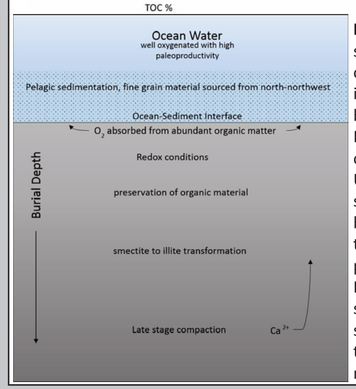


**Fig 9.** Depositional model of the Santos shale. Fig 6 and 7 suggest ocean waters in this time were well oxygenated ocean conditions with high paleoproductivity (Fig. 5), which is in agreement with past interpretation that noted abundant bioturbation, diatoms, fish scales and bone fragments. Productivity may have played a major role on influencing the change of oxic ocean conditions to reducing sediments. Under productive sedimentary conditions, organic matter is supplied to the sediment, subsequently increasing the biological oxygen demand and raising the redox boundary to the sediment water interface. Redox conditions upon burial played a major role in preserving organic matter (Fig. 8). Between 4,000' and 5,200', this sample set shows that smectite decreases and illite increases (Fig. 4), implying smectite to illite transformation. Late stage compaction leads to the albitization of plagioclase and source of calcium for mass transport.

## CONCLUSIONS

- XRD analyses revealed the bulk composition of the average Santos is composed of 45% clays, 29% quartz, 15% carbonates and 11% feldspar. In the clay size fraction, the clays are on average composed of 45.5% smectite, 43.3% illite, 8.2% kaolinite and 3.0% chlorite.
- Geochemical analyses from XRF and ICP-MS indicate the Santos was deposited in a well oxygenated marine environment based on relationships between iron, TOC and total sulfur; and low trace element ratios used as paleoredox proxies such as Ni/Co vs. V(V+Ni) and V/Sc vs. V(V+Ni).
- High TOC (average 7.7 wt. %) content is attributed to the oxic ocean environment with productive paleo waters. The preservation of the organic matter is due to redox conditions upon burial at the ocean-sediment interface where the oxygen is quickly depleted from settling organic matter.
- Diagenetic effects can be seen at different burial depths. The shallow burial depths are dominated by sulfate reduction. The intermediate burial depths are characterized by incipient smectite to illite transformation and the deep burial depths by late stage compaction.
- The high quartz and TOC values are likely the main contributors to the highly fractured nature of the Santos noted in conventional and sidewall cores.
- The zones with the highest TOC and quartz values would likely make the best zones for hydrocarbon prospects within the Santos as an unconventional fractured shale reservoir.