RESERVOIR CHARACTERIZATION USING IMAGE ANALYSIS OF CORE-EXAMPLES FROM THE GEYSERS GEOTHERMAL FIELD

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1. ABSTRACT

Digital imaging can improve the efficiency and accuracy of collection, interpretation and archiving of reservoir data. Digital images of whole or slabbed core can replace traditional photography and offer means of quantitative analysis that were not previously available. Images with the resolution of conventional photographs can be collected using either a still or video imaging camera and then analyzed using image processing and Geographic Information System (GIS) software. The images can be annotated to describe lithology and identify important features. Color enhancement techniques can be used to classify important features such as mineralogy, rock type, vein distribution, and fracture or matrix porosity. This digital data may be used to establish the statistical distribution of these features in the core. Image analysis also can be accomplished at the microscopic level. This approach has been used to document the character of porosity in core from The Geysers geothermal field and simulate the process of adsorption. Once digital images are collected, they can be archived in a GIS database. The large size of data files produced by imaging suggests that CD-ROM is the preferred media for long-term storage. The GIS data basc also allows other information, such as porosity and permeability measurements or geophysical logs, to he combined with the core images.

2. INTRODUCTION

Core from a geothermal reservoir is aften crucial for understanding the hydrothcrmal alteration and structural and lithologic aspects of permeability control. However, core is expensive to collect, is often under utilized, and is commonly lost or destroyed after some period of time. In addition, the quality of core logs is highly dependent on the skill and training of the geologist doing the logging.

Recent developments in digital cameras and image analysis can he applied to improve archiving and analysis of core. This paper discusses the use of digital core images in conjunction with image processing and Geographic Information System (GIS) software to improve cataloging and archiving core and to analyze lithologic and structural features.

This paper will he organized first to indicate the procedures for archiving core, followed by some aspects of detailed image analysis that can be applied to the core. Core from The Geysers geothermal system will he used to illustrate the techniques.

3. CORE IMAGING

Core was prepared for imaging by slabbing with a rock saw. This step required some care in that saw marks cause difficulty in later analysis. If needed, the contrast between mineralogic and lithologic components can be enhanced by spraying the core with an acrylic matte finish or by polishing.

The procedure for digitally imaging, capturing, and archiving rock core is shown graphically in Figure 1. The first step in the imaging process is to position half of the split core in a box. A box, 165 cm long X 20 cm wide X 20 cm deep, was constructed to hold a typical 152 cm run of drill core. The box was placed on a metal roller assembly which allowed the core to be easily moved beneath the fixed imaging camera. A fine-grained, tan-colored sand was used to fill the box to about 7-10 cm from the top. The core was then placed an tap of the sand layer, and more sand added to fill in the areas between the core and the box, as well as the cracks between core pieces. The sand allowed the core halves to he held in a stable position with the slabbed surfaces of different pieces at the same level. Black cloth was used to outline the core and reduce reflections.

Core images were recorded using a Sony ProMavica MC-7000 Professional Still Video Camera. This camera produces high quality color video pictures with a horizontal resolution of 500 or more TV lines during recording and playback, The images were recorded on a 47 mm Sony MP-50 video floppy disk which has the capability of staring up to 25 high-resolution images, and can he erased and reused.

The core imaging was done in a studio that was painted flat black to reduce reflected light. Two professional photographer's lamps were arranged so that light was evenly dispersed on the core. After adjustment of the white balance *so* that the images would he recorded in natural color tones, several different aperture and F-stop settings were tried. The settings of 110 ISO and F2.8 were found to be most useful in producing a good quality image of light to medium gray-colored rock core. With the camera raised about *35* cm above the core, each image recorded slightly over 30 cm of care. The camera was connected to a high-resolution video monitor which aided in positioning the core and focusing the camera. A 15 cm scale was photographed with each piece of core and toothpicks were used lo mark the beginning and end of each depth interval. These toothpicks were later used to help stitch the individual images into one scene of the entire core. Depth intervals were also recorded on each image

After recording the image, the camera was attached to an IBM-compatible 486 personal computer. The floppy disk was played hack using the camera and the images were captured using a Matrox Video Presentation Plus board and software. The images were then enhanced using Aldus Photostyler and HiJaak Pro software. Photostyler is used to first orient the core images so that they are vertical instead of horizontal. Some images required simple brightness/contrast adjustments and this was also accomplished using Photostyler. The images were saved as Targa Uncompressed files and then loaded into HiJaak Pro graphics software, which was used to convert from Targa format (*.tga) to Tag Image File Format (*.tit). The TIFF files can be read by ERDAS image processing software which was used to further enhance the imagery and stitch the individual core images together to form an image of the entire core.

4. CORE IMAGE ANALYSIS & GIS DEVELOPMENT

Image analysis can take several forms. The most basic annotates the image to producc a corc log. Thus, the image replaces the conventional graphic log through the addition of descriptive text. Second, vectors may be drawn on the image to highlight features of interest or those that may be too subtle to he recognized on the image. Third, a rudimentary spectral analysis may be done; an example of this is outlined below.

The digital analysis of core can be done using two methods that are overlapping and often indistinguishable from one another: image processing and Geographic Information Systems (GIS). During the image processing phase, the data is processed for color, contrast, and brightness corrections and enhancements, and then subjected to statistical analysis to produce digital data for input into the GIS.

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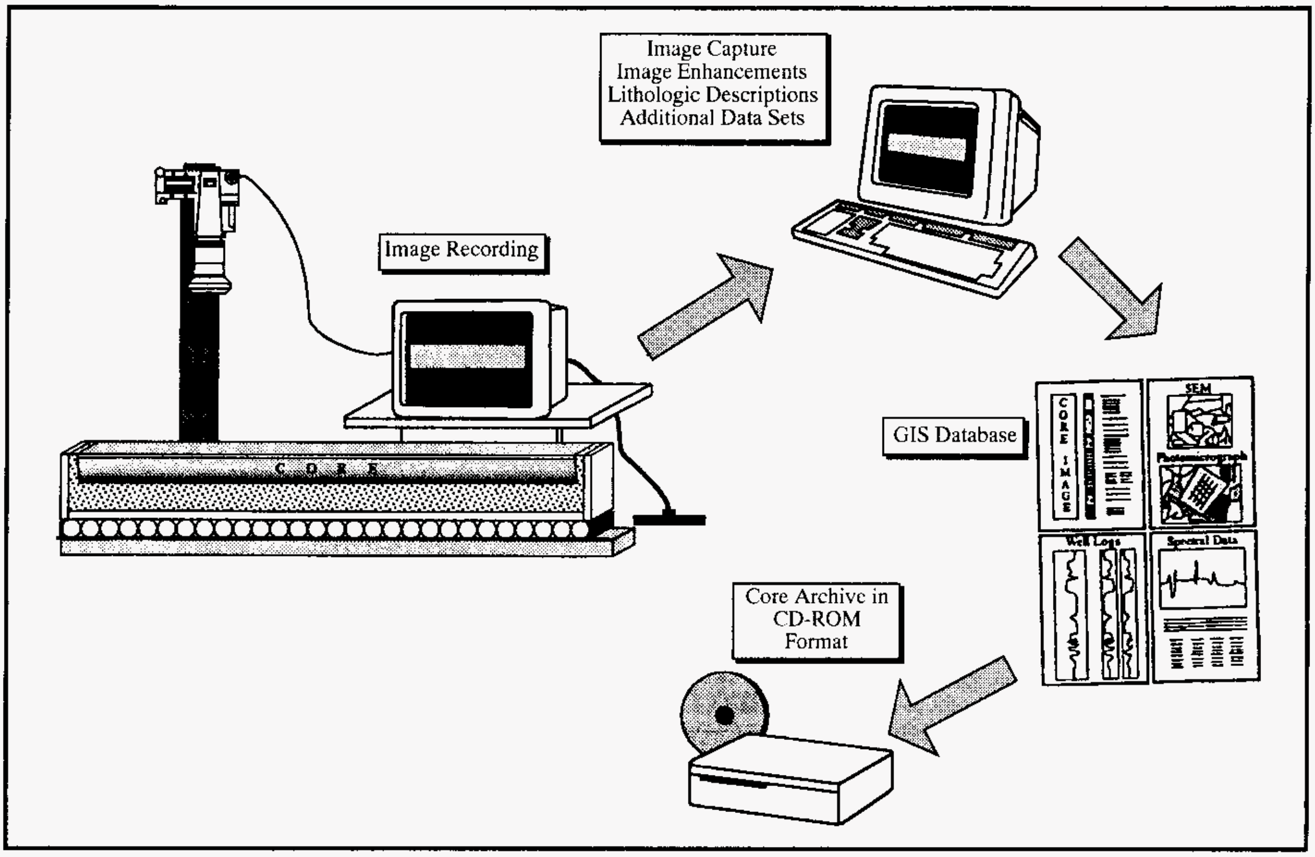

Figure 1. **Procedures** for imaging, capturing **and** archiving **core**

In the GIS environment, further statistical analysis, the incorporation of ancillary data, assigning descriptive attributes to each feature, and archiving is achieved. Analysis is enhanced in the GIS environment by the use of multiple data layers. The core image can be placed on the computer screen for reference, and interactive overlays developed. These overlays can include classified raster GIS data, such as lithologic descriptions; raster image data, such as SEM and confocal microscopy images; and vector GIS data, such as well logs. For this paper, ArcView software was used to integrate and view multiple data sets created by Arc/Info and ERDAS GIS and image analysis software.

The first step in core database development is lithologic characterization at a resolution that is comfortable to work with on the computer screen. The image is reduced or enlarged from its default scale to allow different perspectives. At the macro-scale both visual and digital characterization can be accomplished. Enhancements, such as directional filtering, can also be applied to bring out the structure of the rock.

To illustrate this method, we have used a piece of core from well CA 1862-4 in The Geysers field. The sample is from 1360 m, below the first lost circulation zone at 1293 m and immediately above a steam entry at 1381 m. In the upper portion of the reservoir, calcite is an important constituent. According to the mud log of CA 1862-4, calcite disappears at a depth of 1493 m. The dissolution of this phase forms porosity that is an important component of reservoir storage (Hulen et al., 1992). The image of this core is shown in Figure 2a.

The initial digital analysis involved the use of an ERDAS sequential clustering algorithm to create a raster GIS file consisting of unnamed spectral classes. Each class contains pixels that are spectrally homogeneous. The cluster algorithm works by measuring the spectral distance between pixels based on the brightness values of the red, green, and blue bands. This procedure is basically a test of the homogeneity of the data. Input parameters include the maximum number of clusters to be considered, the minimum spectral distance that will separate the means of two clusters, a distance parameter used when merging clusters, the number of pixels that are analyzed between merged clusters, and a cluster elimination threshold percentage (ERDAS, 1991). Pixels that exceed a predetermined threshold are placed into new classes.

For this study, 60 classes were generated. Since cluster analysis is an unsupervised method of classification, the resultant classes are of an unknown character and, therefore, need to be assigned to the rock and mineral types that they represent. To accomplish this, the classes were overlain on the image of the core one at a time. The lithologies overlain by the different pixel classes were determined, and proper class names were assigned. The core (Fig. 2a) is composed primarily of calcite, quartz, argillite, graywacke, black shale, and chert, which became final class names.

Class 1 is made up of calcite, which appears white on the image. Class 2 consists of quartz that also appears white on the image, thus making it visually confusing with calcite. The confusion was eliminated by the use of Alizarin Red S to stain the calcite red before imaging. Class 3 contains argillite that appears as homogeneous units ranging from light olive green to gray on the image. Class 4 consists of graywacke with relatively abundant quartz grains. This class appears as mottled gray to olive green on the image. Class 5 represents black shale and appears black on the image. Class 6 is comprised of chert that ranges from gray to light-olive green on the image. Minor pyrite is also present, but the grain size is too small to be digitally detected at this scale, so it is not included in the classification procedure. The original 60 classes were recoded to fit this classification scheme.

The recoded classes were compared to the core to determine their accuracy. It was found that confusion existed between several of the classes. Gray chert clasts were often confused with graywacke, as was olive green chert with olive green argillite. Calcite was also occasionally confused with black shale where the Alizarin Red S appeared exceptionally dark. Much of the confusion was quickly edited to the proper classes using the ERDAS Imagine raster editor. Overall, the lithologic characterization took much less time than logging by hand.

After recoding and editing the data to the final classes, the raster polygons were assigned colors to allow them to be easily distinguished on the computer screen. Statistics were generated for the percentage and area of each of the classes. These data are attributed to each class and can be interactively queried on the screen or as a tabular hardcopy output product. A GIS overlay and database queried statistics for the core can be seen in Figure 2b. This data can now be

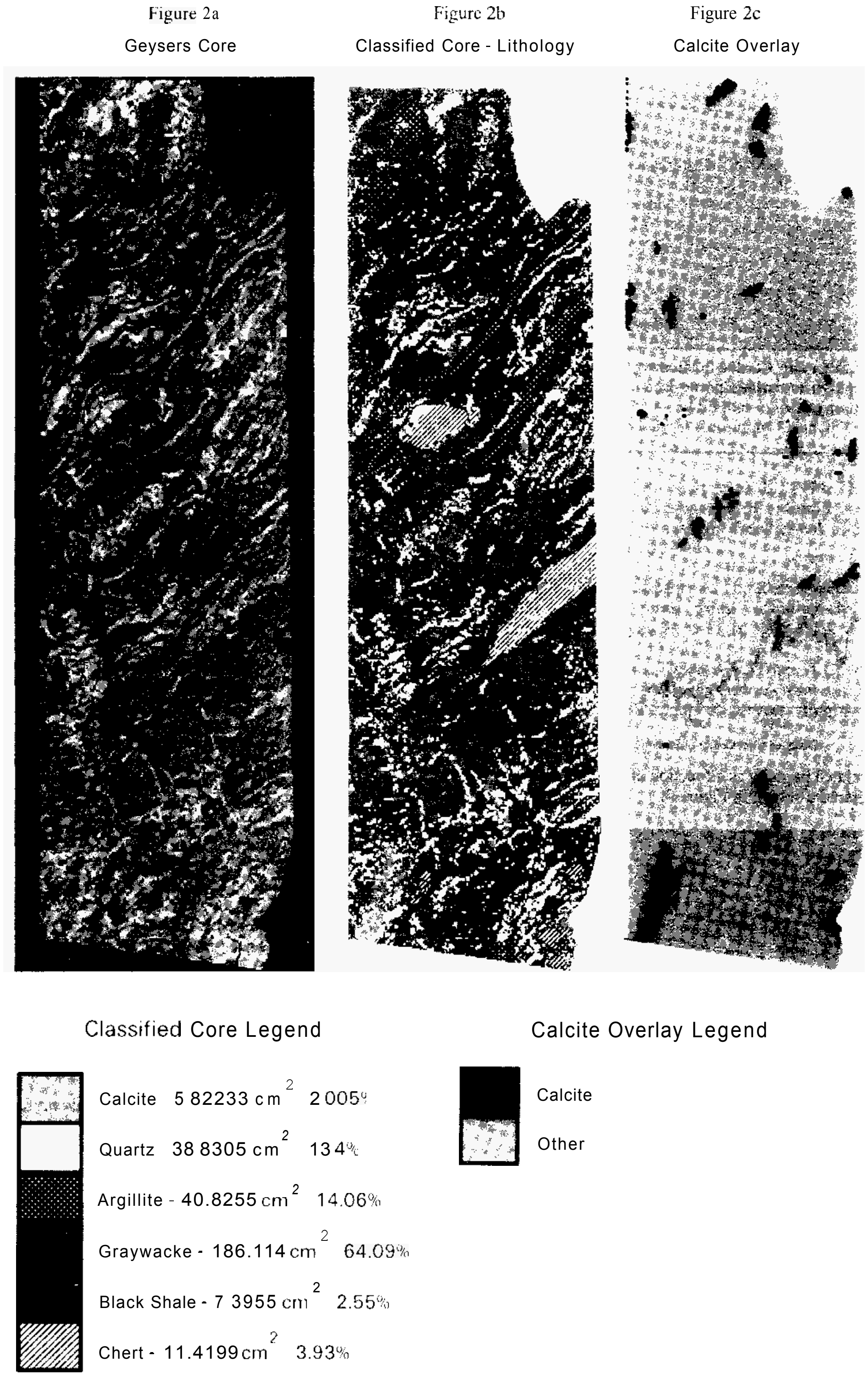

Figure 2. a) Image of core from well CA 1862-4. b) Processed image showing spectral classes and their lithologic designations. c) Isolation of calcite in core.

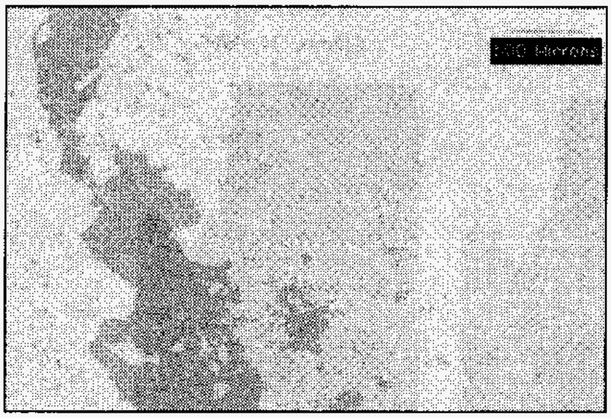

Figure 3. **Laser** Scanning Confocal **Microsope** images of core from well NEGU-I 7 that differentiates **pore** space (dark **pattcrn)** from rock matrix (light pattern).

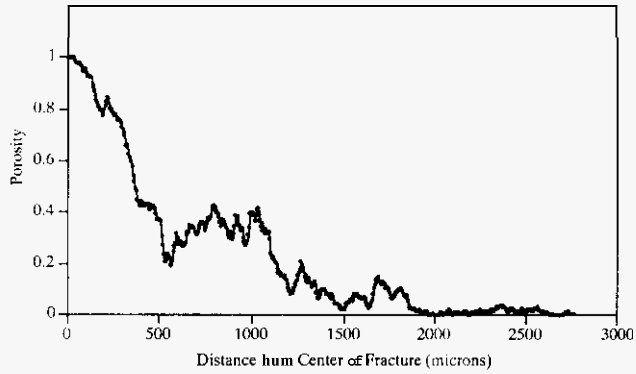

Figure 4. Calculated porosity **as** a function of distance from the cen ter line nf the fracture shown in Figure 3.

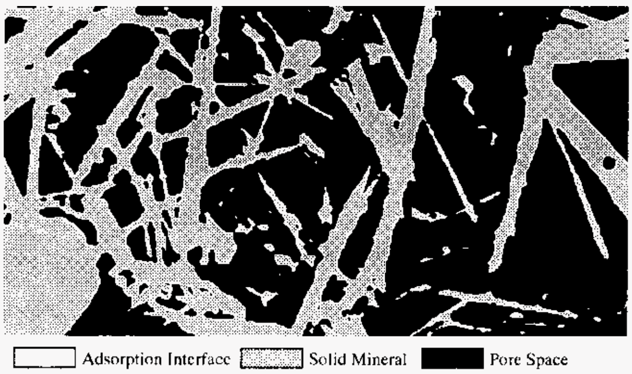

Figure **5**. Digitized SEM image of an actinolite-filled vug from well Prati-State 12 classified to show pore, mineral and simulatcd adsorbed water with a thickness of 7575 angstroms.

combined and interactively used with other GIS database compo nents, such as microscopic images or petrophysical measurements.

5. MICROSCOPIC IMAGE ANALYSIS

The observation of complex textures in core samples suggests that total porosity measurements on core samples only partially describe the relationships necessary to understand reservoir storage. The pore size and distribution will determine how effective the porosity is in contributing fluid **reserves** to the production **zone,** and **surface** areas of minerdls within the pore space will influence adsorption and capillarity.

Two different techniques have **bcen** used to characterize porosity on a microscopic scale. Measurement of the distribution of pores within **a** sample has utilized a technique known **as** Laser Scanning Confocal Microscopy (LSCM). The application of this technique requires that the sample be injected with an epoxy doped with a fluorescent dye. LSCM utilizes a laser to fucus at different layers of the sample, allowing three-dimensional imaging of the pores. **A** convenient aspect of LSCM is that the data arc rccordcd digitally. Scanning Electron Microscopy (SEM) has been used to image the mineral-void relationships inside **pores.** It has the advantage **of** not disturbing the fine textural **features** while being capable **of** higher magnification than the LSCM method. The fallowing examples illustrate applications **of** these techniques.

5.1 Distribution of Fracture Porosity

Porosity and permeability within most high-temperature reservoirs arc formed principally by fracturing and faulting related to tectonic, magmatic and hydrothermal processes. Fluid flow paths and storage capacity **are** related to **fracture** geometry, development of gouge, and secondary precipitation and dissolution of hydrothermal mineral species.

A sample of core from **well** NEGU-17 from The Geysers was selected for its well-developed fracture porosity. This core has been described in detail by **Hulen** el **al. (**1992**)**, who have also emphasized the importance of calcite dissolution on the control of porosity. The sample was from a steeply dipping vein that had **been** sealed by quartz and calcite, with most calcite subsequently removed by dissolution. The LSCM image (Fig. **3)** of the sample differentiates pore **space** and **rock** matrix. The image clearly shows the "dual porosity" character of the sample with interconnected porosity along the fracture and isolated **pores** distributed around the fracture

A computer program **was** written to calculate the distribution of porosity as a function **of** the distance away from the center line of the fracture. The results **of** this analysis are shown in Figure **4.** Although the fracture width does vary, it **averages** about ***500*** microns. The porosity distribution is somewhat bimodal, but decays to nil approximately four fracture widths from the center line.

One of the tenets of structural geology holds that minor structures mimic major structures. At this point, **Figure 4** represents our concept ofthe distribution of fracture porosity in the reservoir. The main fracture is through-going and could be expected **to** carry steam. The non-conncctcd porosity adjacent to the fracture would contain the liquid reserves. The **access of** the matrix porosity to the fracture would **be** through **cracks** that are out **of** the plane **of** the image or through those that would develop **as** a result of imposed **pressurc** differentials between the crack and the fluid-filled **pores.** The hypothesis that these minor fractures and associated matrix porosity mimic the larger structures will be tested in The Geysers when core becomes available from **well** SB-15D from The Geysers Coring Project (Hulen et al., 1994). Whole-core imaging, as describad in sections 3 and **4** ai this paper, will be done to document the character of the larger fractures and surrounding matrix porosity.

5.2 Adsorption

In order to quantify porosity distribution and surface area available for adsorption in The Geysers geothermal reservoir, Scanning Electron Microscope (SEM) images were analyzed using ERDAS software. This software allows us to classify the images **as** either crystal or **pore** along scan lines and then to accumulate data on pore sizc. total porosity and surface area of the mineral-purr interface. The measurements of pore characteristics are based on the methods describad in Krohn and Thompson **(**1986**),** hut we have modified their image analysis techniques to enable us to calculate mineral **surface** area **as** well as pore volume.

Digital image processing of SEM data **was** approached as a microscalc remote sensing and geographic information system (GIS) problem. This consisted of digitizing SEM images to incorporate 256 gray-scale **levels** to be used in the classification of **pore** space by albcdo. Classifications were made by digitally overlaying GIS files, consisting of maps of the gray-scale images quantified by albedo, onto the original gray-scale images. Details of the image analysis procedures are given in Nielson et al. (1993).

In this example of analyzing SEM data, we have used core samples from well Prati-State 12, located in the northwest Geysers. The **sample** contains a pore wherc calcite has been removed and a complex fabric of actinolite precipitated. Image processing **was** used to determine pore-space area, pore-space perimeter, solid-mineral area, the total length of the interface between the pore **space** and solid mineral, and the total **area** of the image. Figurc 5 is a processed image showing solid mineral as stippled, pare **space** as black, and an adsorbed water layer as white. At this **scale,** the adsorbed phase is one pixel thick which is equivalent to 7575 Angstroms.

The objective of this research was to estimate the potential adsorbed liquid reserves. The lengths of chords that traverse **pare space** and the length of the boundary between the solid and pore were measured. Relative volume calculations of the percent adsorbed fluid assumed that the images represent slices of rock that **arc** the thickness of **the** adsorbed layer. It is also assumed that the total pore **space** is filled with water resulting in a simple two phase water adsorbed-water relationship. The calculated relative volume of adsorbed water is a function of the magnification of the image. **The** calculated volume percents were plotted against magnification and then extrapolated to 0. It was found that, duc to different surface **areas** resulting from mineral habit, the actinolite-filled **pares** had a slightly higher adsorption capacity than epidote-filled pores. The actinolite assemblages supparted a 0.005% volume adsorption at **an** assumed adsorption thick**ness** of 10 Angstroms, 0.05% **at** 100 Angstroms, and 2.5% at 5300 Angstroms. It was concluded from this **work** that adsorption can not account for significant fluid **reserves** in The Geysers reservoir.

6. SUMMARY

This papcr has given three examples, at three different scales (whole **core,** microscopic, and electron microscopic) of the application of digital imaging techniques to the characterization of geothermal reservoirs. **These** techniques can provide significant improvements in our ability to archive data as well **as** perform statistical analyses on the distribution of mineral phases and porosity. **The** applications are only limited by the imagination of the researcher and the imaging techniques available. As the technology for building hyperspectral **scanners** is now available, we foresee the **use** of high-resolution scanning spectrometers for the future characterization of core. The increased spectral resolution will result in significantly better lithologic and mineral identification than is possible with the equipment we have described here.

7. ACKNOWLEDGEMENTS

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