MAJOR ADVANCE IN SAMPLING AND PRESERVING UNCONSOLIDATED RESERVOIR CORE

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Abstract Accurate prediction of reservoir performance depends on good input data. Much of this data is obtained from core measurements, and so preservation of reservoir character in core is fundamental. A major obstacle to obtaining good core from poorly consolidated (weakly cemented) reservoir formations has been the lack of a method which consistently preserves both rock structure and wettability.

A new wellsite preservation technique, which uses a vacuum manipulated elastomer sleeve to seal and apply a small confinement to core, has been developed. The increase in shear strength which results from this confinement is analysed in terms of the Mohr-Coulomb failure criterion. Sealing properties of the selected elastomers are described. Sleeved core samples are protected in an integrated packaging system for transport.

The method has clear advantages over commonly used freezing and resin injection methods of preserving poorly consolidated core. It is especially applicable to light oil or gas bearing sand which cannot be preserved by freezing. Questionable contact with liquid resins, and temperature cycling are avoided.

The apparatus used is simple, self contained, portable, and has been proven in a number of field operations for a variety of rocktypes and locations. The effectiveness of the technique for structural preservation has been clearly demonstrated by means of detailed X-ray CT study. Protection against core fluid loss, oxidation, and other contamination is as least as good as any other known technique. The substantial improvements in core quality yielded by the technique can increase the reliability of data from poorly consolidated core, to the benefit of reservoir evaluation.

INTRODUCTION

Unconsolidated (weakly cemented) sand bodies are found at shallow depth where temperature and pressure have been insufficient to cement sand grains into solid sandstone. Mineralogy and grain shape vary, but porosity and permeability tend to be high, hence unconsolidated sands offer good reservoir potential. Substantial quantities of oil are located in unconsolidated formations.

Unfortunately, these valuable resources present special obstacles to economic production of oil. One of the chief areas of concern is the validity of data extracted from core which is used to predict reservoir performance. Petrophysical data from core depends strongly on the size and shape of intergranular porosity, and for core data to be representative of reservoir properties, the relative positions of constituent grains must be preserved during coring, handling and analysis.

Coring

During coring, rapid sediment penetration using polycrystalline diamond compact bits minimises opportunity for structural disturbance and flushing. Low friction fibretube inner core barrels are most commonly used to ease core entry. Tripping of the full core barrel to surface is done slowly and smoothly to prevent hydrocarbon expansion and mechanical shock from disaggregating the core.

At the surface, the full fibretube inner core barrel is removed intact and carried from the drillfloor for cutting into manageable lengths. The fibretube is braced to prevent flexure during this process and special handling techniques are applied to avoid damage. Conventional steel inner barrels which discharge loose core are plainly unsuitable for unconsolidated core. Rubber sleeve core barrels which were specially designed for unconsolidated core are also inferior to the fibretube system. Entry friction is high, and the rubber sleeved whole core is difficult to handle without bending and damage. Small variations in rubber or core properties lead to "necking down" of core.

Preservation

The three most common techniques for preserving fibretube cored unconsolidated sand are; (1) Core bearing fibretube is cut into lengths (about 1m) and sealed with plastic or rubber caps alone; (2) Cut and capped fibretube core is cooled so that pore fluids freeze and cement structure; (3) The space between cut core, fibretube, and endcaps is filled with a quick setting liquid, usually a low viscosity resin (Worthington et al. 1987).

Capping and sealing alone (1) allows core to move within the fibretube during transport, and offers little protection from structural damage. Freezing core (2) using refrigerated containers or dry ice works well in some instances, but is inefficient if liquid saturations are low, or freezing points of liquids are below temperatures which can easily be achieved at the wellsite. The possibility of freezing affecting core and fluid properties cannot be discounted, and the cost of storing large amounts of core at low temperature can be prohibitive. The resination technique (3) prevents gross movement of core within the fibretube, if resin accesses all the void space (annulus and fractures, not pore space). Long term storage is much less expensive than for frozen core. Chemical contamination of core by resin components however, means that wettability and fluid property measurements on resinated core are of uncertain representativeness.

Review of the available techniques showed a clear need for a method which could be easily applied at the wellsite, would avoid the uncertainties of chemical contamination and freezing, would work on all unconsolidated sands regardless of fluid type and saturation, would be compatible with the popular fibretube coring technique, and would provide a low cost long term storage facility. The technique described here meets all of those criteria, and is based on the application of precision made rubber sleeves and endcaps using a novel Soft Sediment Tool (SST).

EQUIPMENT DEVELOPMENT - ELEMENTS OF THE NEW TECHNIQUE

The SST technique preserves structure of unconsolidated core by application of a confining stress. Short lengths of cut core plus matched diameter rigid endcaps are displaced into expanded rubber sleeves, which are then allowed to contract onto the core. This confinement results in an enhanced shear strength in the material sediment, and hence resistance to damage.

In addition to confining and strengthening core , the sleeves and endcaps also provide a barrier to drying and oxidation.

Elastomer Sleeves

The base elastomer selected is a high grade non-staining medium acrylonitrile butadiene rubber. To achieve proper vulcanisation and elastomeric properties it has an admixture of furnace black reinforcing agent, zinc oxide curing agent, a delayed action organic accelerator and sulphur crosslinking agent. Plasticiser and anti-oxidant which could leach back and contaminate the fluids in the preserved core have been omitted.

The absence of anti-oxidant in the rubber requires the sleeves to be stored in a cool dark atmosphere prior to use. The sleeves should be used preferably within one year of manufacture. (Wax dipping of sleeved cores described later in the paper serves a double purpose of protecting both core and rubber from oxidation. Elastic properties of the rubber are estimated to last for at least five years after wax dipping).

The rubber used to manufacture SST sleeves is therefore a "clean" elastomer with very low order of non-reacted components. These can be further extracted by acetone refluxing, if desired, for extremely critical applications. Hardness and specific gravity at room conditions are 60^{o} +/- 4^{o} IRHD (International Rubber Hardness Degree) and 1.15 +/- 0.02 respectively. Currently there are three sizes of sleeve to suit the most commonly used fibretube and core sizes, but any new size could easily be produced.

TABLE 1 **Sizes and Application of Currently Available SST Rubber Sleeves.**

Nominal Size of Fibretube core barrel (Inches)	Actual Internal Diameter (mm)	Sleeve Internal Diameter (mm)	Sleeve Wall Thickness (mm)
5.25	140	120	3.0
4.38	115	102	4.0
4.00	108	89	4.0

The sleeves are made on fine turned hard chrome plated mandrels which impart a very smooth internal surface finish, for efficient sealing to the serrated edge end caps - see next section. The wall thickness is controlled to +/- 0.125mm in the moulding process and by external grinding.

Sample Retaining/Sealing End Caps

The advanced plastic selected for the caps is a 90°-95° IRHD polyetherurethane elastomer without plasticiser, and care is taken to have all components stoichiometrically reacted together to form a low contaminant residue product.

The caps are cast in precision made moulds to form 15mm thick discs with a +/- 0.5mm 90° serrated side to form a "labyrinth seal" in contact with the inside of the sleeves under pressure. The serrations also increase friction between the sleeve wall and the caps to keep them in close contact with the sample end faces and help to maintain the axial extension induced in the sleeve by the vacuum operated expander. The dimensions of end caps to suit the SST sleeves currently in use are as shown in the following table.

TABLE 2 **Sizes of Endcaps for SST Preservation.**

Endcap Outside Diameter (mm)	Sleeve Inside Diameter (mm)
138.5	120
113.6	102
106.5	89

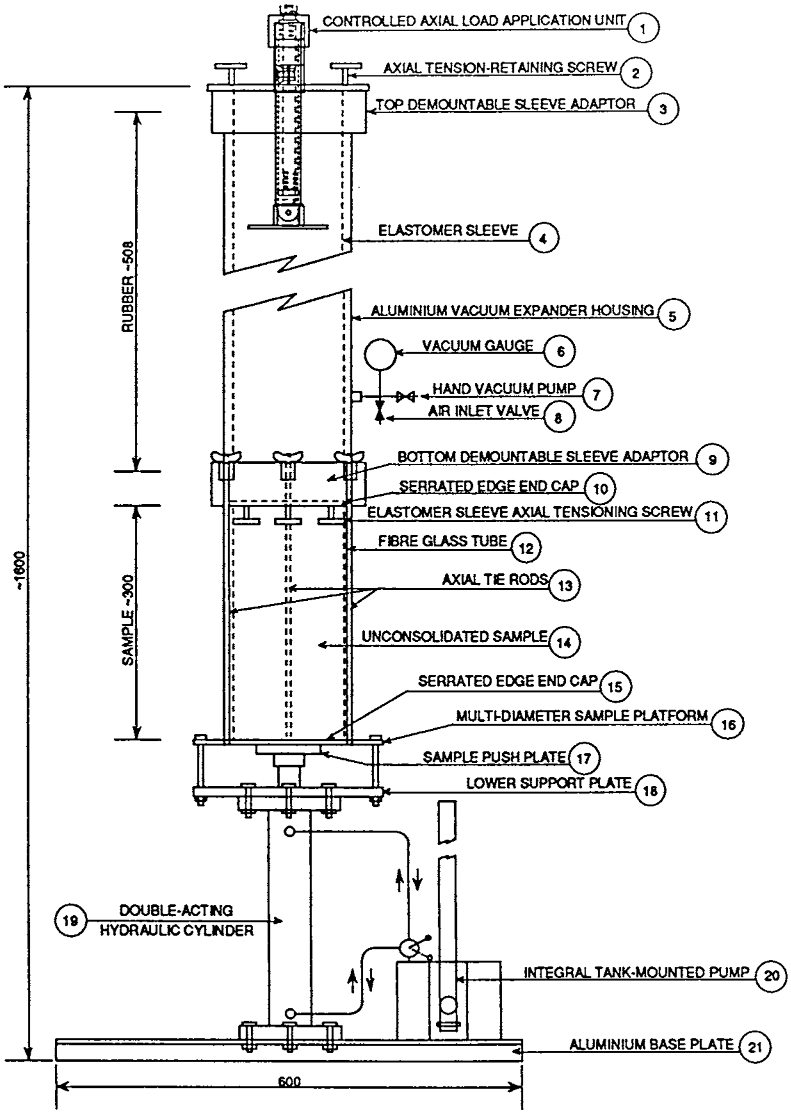

FIGURE 1 **Assembled Soft Sediment Tool.**

Polyetherurethane has outstanding hydrolytic stability and good resistance to oils and many chemicals. It also possesses high tensile strength, is abrasion resistant and resilient.

Sample Extruder and Vacuum Operated Sleeve Expander.

The assembled apparatus is shown schematically in Figure 1, and operational procedure is discussed in the next section.

The apparatus is easily dismantled for transport and reassembled with minimal tools. It packs into a light weight case with compartments cut from thick polyethylene foam.

FIELD APPLICATION OF THE SST TECHNIQUE

Over the past two years, the SST has been used at a number of offshore and onshore wells. Because of the compact portable nature of the equipment, accommodation has never been a problem, Figure 2. Unpacking and setting up the SST can be completed in under an hour.

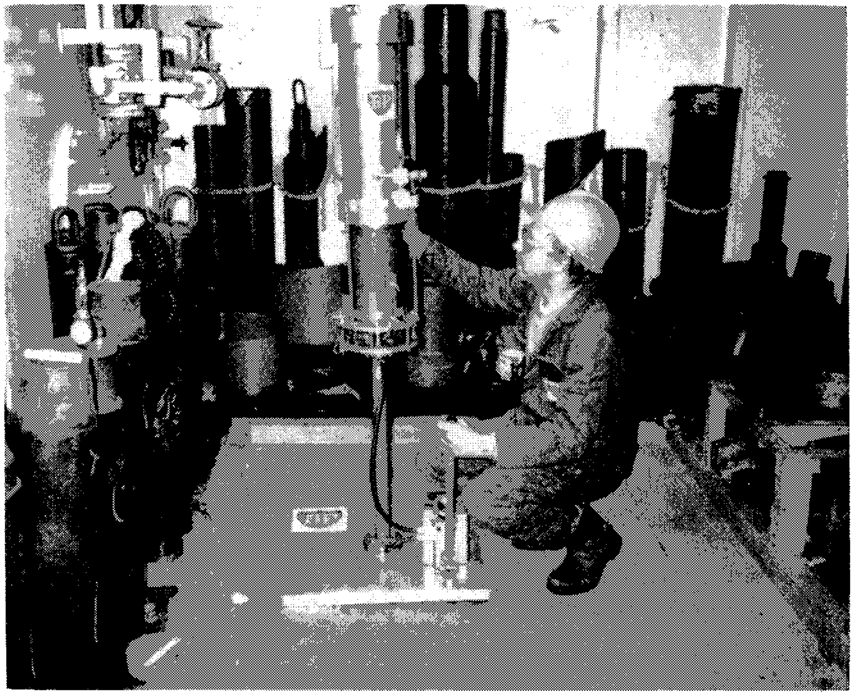

FIGURE 2 The Soft Sediment Tool set up in the field

Selection Of Samples For SST Preservation

Samples of unconsolidated core are selected and prepared for SST preservation during the process of marking and cutting up of the fibretube inner core barrel. Flat, square cut faces are essential for proper confinement of the SST sample, and the following procedure is used. Location of 0.3 m preserved samples is determined, and as soon as the first face of the sample is cut, it is supported with a rigid endcap. The 0.3 m sample is then carefully supported during cutting of the second face. The second cut face is also protected by a rigid endcap.

Endcaps are marked with depths, and the samples placed vertically to allow drilling mud to drain from the core annulus. The SST sample is most prone to damage during the cutting and capping process. A well designed whole core handling and cutting system as well as careful handling are essential.

Sleeving Samples Using The SST

As soon as samples have drained of mud, they can be sleeved. The length of core in fibretube with caps taped in place is lifted onto the push plate (17) and sample platform (16) of the SST, Figure 1. A sleeve (4) is then loaded into the vacuum expander (5), and expanded to the same inner diameter as the fibretube (12). The vacuum expander is then clamped onto the top of the core and fibretube using the tie rods (13), and the core jacked into the mid region of the sleeve. Because the components of the SST are all built to conform to the fibretube dimensions, the core is fully supported during this process, and only a thin smear of core is lost (approximately 5g). When the core and endcaps are in place in the expanded rubber sleeve, a small axial load is applied to the core (either manually, or by means of the axial load device (1)), air is allowed into the expander vessel through the valve (8), and the sleeve contracts onto and confines the core.

The expander vessel containing the sleeved core is then unclamped and carefully lifted from the fibretube. The sleeved core is removed, the sleeve secured to the endcaps by stainless steel bands, and the sleeve trimmed to length and marked with the sample identification, Figure 3.

Packaging Sleeved Samples

Sleeved core samples are quite firm due to the confinement of the rubber sleeve, and can be carefully handled without risk of damage. Individual samples are packed in bubble wrap, and placed upright in robust polyethylene foam lined shipping crates. Each crate can accept upto six samples. Crates are secured within a shipping container for transport to the laboratory.

If sleeved samples are to be stored for any length of time, they are wax dipped immediately on arrival at the laboratory. The wax layer increases the barrier to core drying and oxidation, and also increases the life of the rubber sleeve by preventing oxidation. The dipped samples are repacked in bubble wrap and placed upright in foam lined storage crates. For economy, the storage crates are of a lighter construction than shipping crates.

FIGURE 3 **Trimming SST sleeves to length**

ANALYSIS OF STRESSES APPLIED TO SAMPLES BY THE TECHNIQUE

The unstretched sleeve is restrained in the expanding tool prior to the vacuum being applied. The sleeve is therefore subjected to plane strain and goes into axial tension, due to the Poisson effect, when expanded diametrally under external vacuum.

The sample and endcaps are then jacked into the central portion of the expanded sleeve. Endcaps form a tight sliding fit within the sleeve, and maintain good contact with the cut faces of the sample.

As vacuum is reduced, and the sleeve is relaxed onto the sample and endcaps, lateral and axial compression is applied to the sample by the rubber sleeve. Axial tension in the sleeve is transferred as axial compression to the sample via the end caps (and to some degree as shear at the boundary of the sample). This compression is maintained by the friction between the sleeve and serrated edge of the end caps, and the mechanical interaction between the relaxed sleeve inside diameter and the outside sharp edge of the end caps.

It is imperative that the end caps are always in close contact with the sample faces. If they are not, axial tension is expended in bedding the end caps to the sample, and not applied to the sample.

One of two basic assumptions is required to compute the confinement provided by the sleeve. Either the sample is not deformed by the confining stresses provided by the sleeve, and the specimen dimensions remain constant; or the sample is compressed by the sleeve.

Field observation and the magnitude of partial vacuum required to expand the sleeve over the sample (less than 0.1MPa (15psi)), suggests that the magnitude of confinement provided is too small to cause any significant deformation in the sample.

Consequently the axial and lateral confining stresses may be computed from the measured dimension of sleeved core and the initial sleeve dimension listed in earlier sections.

Using Lame's elastic theory for thick wall cylinders in axial plane strain, neglecting torsional effects and regarding the elastomer as an isotropic linear elastic body, with tensile modulus E_o = 4.45 MPa and Poisson's ratio $\nu = 0.3$, a typical calculated radial stress on a 102 mm diameter sample sleeved with an 89 mm internal diameter sleeve is 0.062 MPa (9 psi) and the axial stress is 0.028 MPa (4.1 psi).

These values show that there is an anisotropic confinement acting on the sample which may be a cause for very weak specimens to fail under lateral compression. Also pre-existing failure surfaces, weakness surfaces, or natural fissures tend to exhibit reduced shear strength, and these may offer preferred locations for potential failure.

Shear compression failure will occur if the difference between the lateral and the axial confining stresses causes the strength of the material to be exceeded. Evidently the worst situation for this occurs during the sleeving process when lateral confinement only is applied (ie when endcaps are not properly bedded onto the sample surface before the sleeve is relaxed onto the sample).

Lateral failure may be interpreted in simple terms using the linear Mohr-Coulomb failure criterion (Craig, 1978). Assuming no significant influence of the intermediate principal stress on the strength of the sample, this criterion may be expressed as:

Shear strength $\tau = C + \sigma_n \operatorname{Tan} \phi$

where C = cohesion of material or surface
σ_n = normal stress acting on surface
ϕ = angle of interal friction

putting:

axial restraint = minor principal stress = 0
lateral restraint = major principal stress

and expressing this as a Mohr diagram, failure occurs if any part of the Mohr's circle of stress lies above the failure envelope of the material. When axial restraint is applied, the effect is to reduce the diameter of the circle such that the tendency for failure is reduced, Figure 4.

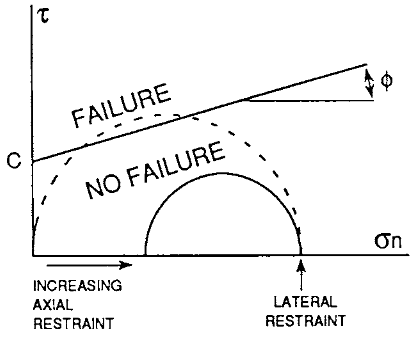

FIGURE 4 Mohr diagram, conditions for lateral failure.

Thus the importance of applying a small axial load before allowing the sleeve to relax onto the core, and of ensuring good contact between endcaps and cut end faces of the core sample is clearly shown.

Considering typical values for an unconsolidated sand of C = 0.035 MPa (5 psi) and $\phi = 30^{\circ}$, and the calculated axial and lateral restraints applied by the rubber sleeve and endcaps; Figure 5 shows that lateral shear failure of SST samples during sleeving is unlikely to occur.

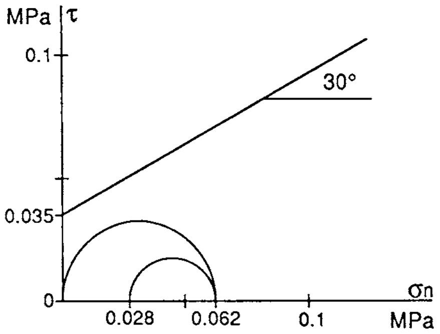

FIGURE 5 Mohr diagram, stresses applied to typical unconsolidated sand sample by SST sleeves.

Recent Modifications to the SST Technique

A new design of vacuum expander vessel is currently being evaluated. The new vessel is designed to enable more rapid loading of rubber sleeves, and will also allow axial and lateral restraints to be exactly balanced throughout core sleeving operations. The new vessel will therefore remove any potential for lateral shear failure during sleeving, even when completely cohesionless core material is packaged.

EVALUATION OF THE SST FOR PRESERVING UNCONSOLIDATED CORE

Comparison With Other Preservation Techniques

The SST technique has been designed to preserve high quality core samples for special core tests, not for preservation of the entire core. On a foot for foot basis, SST is slower than freezing or resin injection. However where approximately 10% of the whole core is preserved by SST, SST sampling keeps abreast of bulk core preservation methods.

The SST technique has none of the safety hazards associated with low temperature work, asphyxiating gases, or solvent vapours.

Once samples have been sleeved, active confinement by the rubber maintains core structural integrity. Although resin is also permanent once set, complete filling of the annulus between fibretube and core is not always achieved, leaving space for the core to expand and collapse. Freezing preservation requires a continuous supply of dry ice, or power supply to a freezer container, and so is subject to logistical problems and power cuts.

Efficiency Of The SST Technique For Fluids Preservation

The rubber sleeve and polyurethane endcaps totally encapsulate and seal the core sample at the wellsite, so drying and oxidation effects are minimised early in the life of the core sample. By following up with wax dipping as soon as core arrives in the laboratory, a second line of protection is applied. Fluids preservation in SST samples will therefore be an improvement on any conventionally preserved wax dipped core because of the additional protection given by the rubber.

Efficiency Of The SST Technique For Structural Preservation.

The efficiency of structural support and preservation given by the SST technique has been determined by X-ray Computed Tomographic (CT) examination of preserved core samples. Adjacent samples of similar whole core have been preserved at the wellsite by SST and freezing. The X-ray CT scanner was then used to compare the structural quality of samples after transportation to the laboratory.

Figures 6 and 7 show X-ray CT sections of two whole core pieces. Darker areas in these figures indicate denser material cut by the X-ray CT section. Fractures appear either as low density or high density features. The former are air filled, open and probably originated post core surfacing; the latter are drilling mud filled and originated down hole. The sample in Figure 6 was preserved by freezing, the sample in Figure 7, by SST. Both samples came from a massive unconsolidated sand section, and were handled in a similar manner. The X-ray plates clearly show many open fractures in the frozen sample. The SST sample has one fracture which is drilling mud filled, and which therefore must have been present in the sample before preservation. To date, samples have been inspected for structural integrity after routine transportation by land, sea, and air from a number of locations. No evidence of post preservation sample damage has been seen. The small anisotropy of confining stresses applied to SST samples during sleeving, does not appear to have caused lateral shear failure in any samples yet examined. SST sample structural quality has always been as good as, or better than, frozen or resinated samples.

CONCLUSIONS

The SST technique can be applied to preserve fibretube cut unconsolidated core at the wellsite. Equipment is self contained and compact.

The structural quality of core preserved by the SST to date has been as good as, or better than, core preserved by any other technique.

SST sampling avoids core freezing, and contact with resins, both of which might alter core or fluid properties.

The anisotropy of confining stresses applied by the SST rubber sleeves has not caused lateral shear failure of any core preserved to date. A modified vacuum expander vessel currently under test, allows axial and lateral constraints to be balanced during sleeve application, thus removing potential for lateral shear failure.

The active confinement applied to SST samples by the rubber sleeves means that samples can be stored for extended periods, without the uncertainty and cost of frozen storage.

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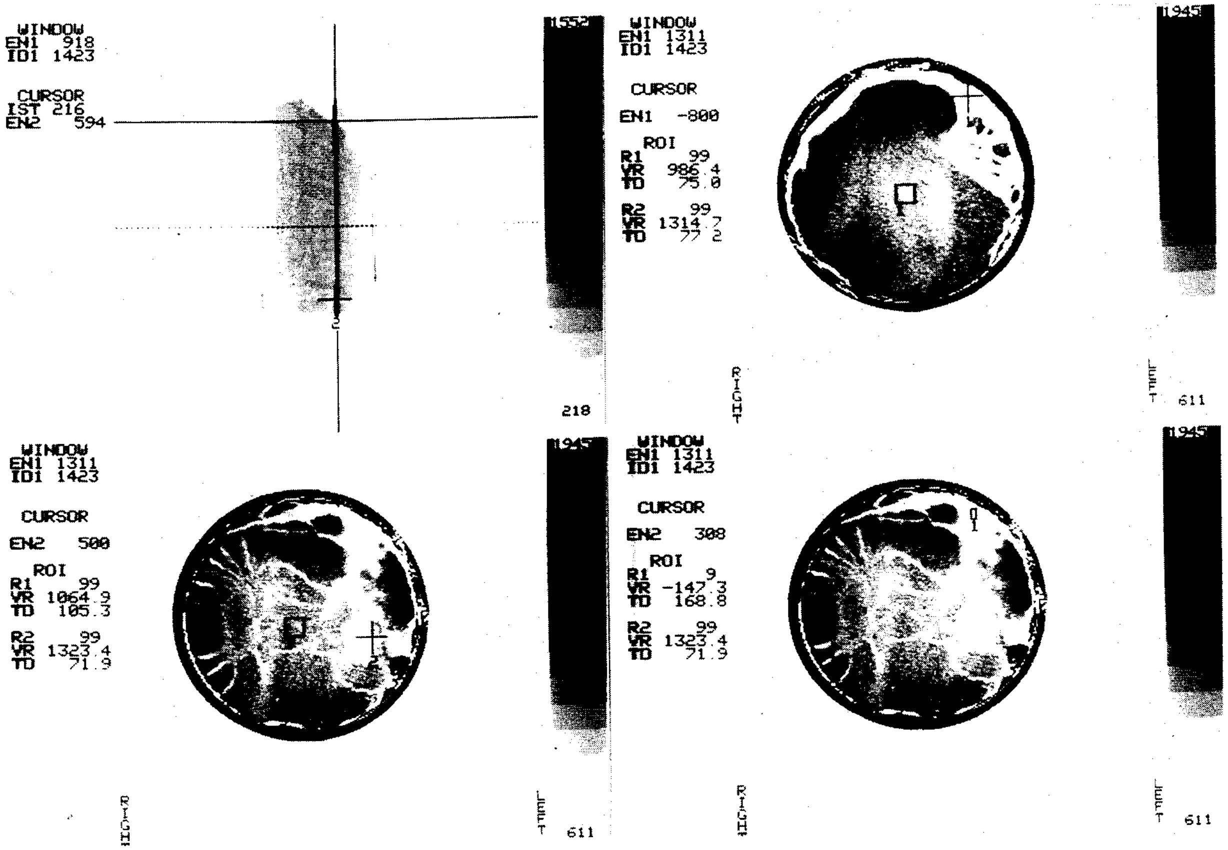

FIGURE 6 X-ray CT plates of frozen preserved core.

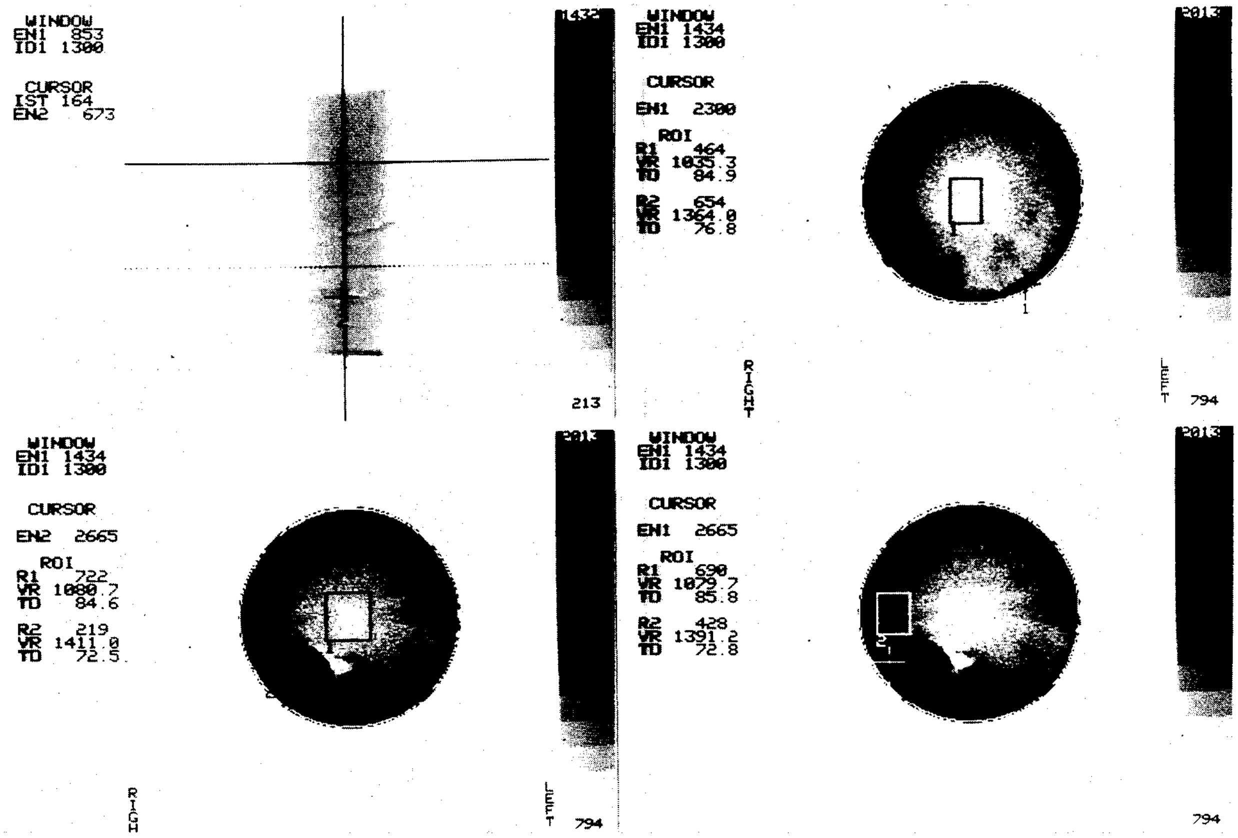

FIGURE 7 X-ray CT plates of SST preserved core.

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