EUG XI

Symposium SS03

Applications of Computerised X-Ray Tomography in Geology and Related Domains

Convenors

Patric Jacobs
Rudy Swennen
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Wednesday PO Session

SS03 : WEpo01 : PO

Characterization by Computed X-Ray Tomography of the Water Absorption in a Limestone used as Building Stone in the Oviedo Cathedral (Spain)

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Water plays a fundamental role in rock weathering processes and its penetration and movement inside rocks greatly influences the nature and intensity of the damage produced. Computed X-ray Tomography (X-ray CT), as a Non Destructive Technique (NDT), is very useful in mapping water penetration. In the present paper this technique has been used to study the internal structure and to characterize the water movement inside the Piedramuelle Stone, a Cretaceous limestone used together with other carbonate rocks as building material in the Oviedo Gothic Cathedral (N of Spain) and in many other historical buildings of the city.

X-ray CT provides good images of the internal structure of the samples: the sedimentary layering due to differences in composition and porosity is clearly seen in CT images as well as other textural characteristics. The movement and penetration rate of water has been followed up by X-ray CT during standard free absorption water tests (ICR-Normal 7/81); the obtained images clearly show the difference between dry and wet zones in the interior of the sample. The water movement is related to the petrographic characteristics of the rock, mainly to the sedimentary layering that controls the direction of water penetration. Using the Hounsfield numbers a quantitative approach to the penetration rate of water has been done. Preliminary results show that the penetration of water is fast only in the outer layer, the first millimetres, of the sample.

SS03 : WEpo02 : PO

3-D Visualization by Computed X-Ray Tomography of the Internal Damage due to Freeze Thaw Cycling Tests in a Dolomitic Rock used in Historical Buildings in Oviedo (Spain)

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Samples of the “Laspra Stone”, a tertiary dolomitic rock used as building stone in the Oviedo Cathedral (N of Spain) and in other historical buildings of the city, have been studied by Computed X-ray Tomography (X-ray CT); the obtained images show the textural characteristics of the rock: layers of different pore size and sedimentary structures like bioturbation.

After the initial characterization the samples were subjected to standard freeze-thaw ageing tests. The progress of decay was followed up by X-ray CT after each cycle. In some cases, damage was observed in the third cycle and the internal depth and disposition of damage could be seen by X-ray CT. The 3-D reconstructed images show the relationship between the produced fissures and the textural characteristics of the rock.

SS03 : WEpo03 : PO

Positron Emission Tomography Studies of Physico-Chemical Processes in Sandstones

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Positron emission tomography (PET) is a tomographic imaging technique utilising the characteristic radiation of positron emitting radionuclides. PET, originally applied in nuclear medicine for in vivo non-invasive medical research (T. Jones et al., 1996), allows to monitor absolute positron emitter concentration (Bq/ml) at well-defined time and locations. Here, we highlight the potential of PET to study non-destructively in-situ physico-chemical processes in building materials.

Although discoloration of natural stones is often observed in sandstones and marbles, there is no consensus about its causes (diffusion moisture and metal ions, air pollution, ...) and its effects. Analytical techniques allow to detect trace elements in low concentrations in the bulk or on the surface, but correlation with phenomena like surface discoloration is complicated mainly due to the inhomogeneous distribution of trace elements. A PET study investigated the migration of ^{55}Co-EDTA (a water-soluble tracer) in a porous homogeneous Ledian (Belgian Tertiary) sandstone core (5x5x6 cm). ^{55}Co is a long living positron emitter ($t_{1/2}$ =17.5 h) (H. Sarma et al., 1986; P. Goethals et al., 2000). The PET experiment was completed in three stages: 1. Transmission scan of the experimental set up using an external 511 keV gamma source (^{68}Ge/^{68}Ga homogenous ring source) to correct for gamma attenuation. 2. ^{55}Co-EDTA (7.5 MBq) is absorbed on the bottom of the core and after the first emission scan brought in contact with the surface of an EDTA/water solution. Scans of the dynamic emission experiments (10 min) were recorded at fixed intervals (0.50, 100, 150, min) during the migration of ^{55}Co-EDTA in the sandstone core. 3. The emission scans are reconstructed using the pre-recorded transmission scan for attenuation correction. The brightness of each picture point (pixel) is a measure of the activity concentration and can be quantitatively expressed as Bq/ml.

The scan images clearly demonstrate that the adsorption of ^{55}Co on the bottom of the core shows a homogeneous pattern. During the diffusion process the ^{55}Co-EDTA migrates with the waterfront. Reproducible results were obtained indicating that under normal circumstances the migration of water in sandstone ranged between 7-8 mm/h. Analogue results were obtained with R-^{18}F, also a water-soluble tracer.

PET in combination with suitable tracers can contribute substantially to the in-situ study of slow dynamic processes. Since PET is complicated and needs a cyclotron and a radiochemical division, work is now in progress to evaluate if X-ray CT and H-MRI can obtain the same results.

Jones T, *Eur. J. Nucl. Med*, **23**, 207-211, (1996).
Sarma H, Zweit J, Smith AM et al, *Appl. Radiat. Isot*, **37**, 105-109, (1986).
Goethals P, Volkaert A, Vandewielle Ch et al, *Nucl. Med. Biol*, **27**, 77-81, (2000).

SS03 : WEpo04 : PO

Rock Drying Tests Monitored by Computerised X-Ray Tomography: Visualisation of the Water Location – Importance of the Initial Water Saturation Value

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Three stages are identified during experimental drying-procedures of porous media. They depend on the physical state of the water and therefore on distinct transfer mechanisms : capillarity or vapour diffusion. In both mechanisms, the porosity structures are determinant, particularly the bulk volume of the voids, the pore dimensions, and the network connectivity. The liquid-vapour limit controls the distribution of salts precipitation. The position of this limit with respect to the porous network is an essential data as salts precipitation causes strong damages on building stones. The computerised X-ray tomography (CT) allows to visualise this limit.

The studied stones are the Fontainebleau sandstone and the Lourdines micrite, both constituted of only one mineral species : respectively quartz and calcite. Their porous structures are greatly different, and they are obviously related to the ordering and dimensions of the constitutive grains. The diameter of the quartz grains is about 300 µm whereas that of the calcite grains is only a few microns. Porosity and threshold are respectively 12% and 12 µm for the sandstone, and 26% and 0.12 µm for the micrite.

The CT is a 3D non-destructive method of investigation tool measuring the X-ray attenuation of a sample with respect to its radiological density. This technique permits to follow the fluid saturation evolution in a stone sample. In our approach the CT analysis of dry samples gives directly images of the porosity because these stones contain only one mineralogical species. Then, the CT analysis of a partially water saturated sample allows to visualise the water.

Two kinds of drying tests have been performed: first, drying tests of samples where the porosity was initially partially water-saturated (by capillary absorption); secondly, drying tests of samples where the porosity was initially totally water-saturated (under vacuum). The CT analysis shows that during the second and the third drying stages, the water location is the same whatever the initial saturation. But it shows too that the initial water saturation is an important factor controlling the water repartition in the voids during the first drying stage. If drying follows a partial saturation, the water repartition is homogeneous in the sample, whatever the structures porosity, whereas after a total saturation, the water repartition is greatly controlled by these structures : the largest voids are more rapidly empty than after a partial saturation even if the measured flux is unchanged.

The CT analysis of drying stones shows that the emplacement of the transition between liquid and vapour with regard to the porous structures depends on the value of the initial water saturation during the first drying stage of stone samples but not during the two last stages.

SS03 : WEpo05 : PO

Application of CT Scanning for Three-Dimensional Visualization of Fractures in Rock Test Samples

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Mining and tunneling, especially at great depths, involves excavation of rock from a highly jointed and faulted rock mass that is under high initial stress conditions. The resulting blocky nature of the rock mass surrounding the mine leads to potential rock fall hazards and extremely damaging rockbursts may occur as a result of the failure of the solid rock or due to slip on pre-existing geological discontinuities. Numerical modeling provides a means for understanding these phenomena and predicting the future stability of a mine or excavation. The challenge has been to develop models that can model the solid rock and pre-existing discontinuities as well as to be able to predict the onset of rock failure and subsequent rock response.

A number of numerical models have been developed to model rock failure, based on boundary element, finite element and particle flow methodologies (Napier et al. 1996). Modern computers facilitate the analysis of complex situations, but the results of the studies will depend significantly on the rock fracture models that are used. Selection for the correct models and verification of the material parameters must be done by comparison with experiments conducted under controlled conditions.

A series of experiments have been conducted in cubic blocks of quartzite to simulate the response of deep level mine excavations. Cuts are made into he block to represent simplified mine layouts and the blocks are loaded with increasing vertical loads up to 100 MPa and with a confining pressures of 20 MPa. The resulting fracture patterns are three dimensional in nature and cannot be reconstructed from surface views alone. This must also be compared with the results of numerical modeling and the locations of acoustic emissions, monitored during the test.

XRAY Computerized Tomography proved to be an ideal method for obtaining a view into the samples and to provide digital reconstructions of the fracture pattern. The samples were scanned and software written to automatically differentiate the lower density fractures from the surrounding rock. The fracture patterns from the automatic processing are compared with those from manual delineation methods. Three dimensional visualization software enables the comparison of the fracture patterns derived from CT scanning, numerical modeling and acoustic emissions, and has produced remarkable insights into three dimensional fracture processes.

Napier JAL, Daehnke A, Hildyard MW, Kuijpers JS, Malan DF, Sellers EJ and Turner, PAT, *J. SAIMM*, **97**, 119-134, (1997).

SS03 : WEpo06 : PO
X-Ray Tomographic Studies of Lake Sediment Drill Cores

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Since 1997, cores taken from lake sediments for the identification of sedimentary structures indicative of geological events such as earthquakes in Switzerland have been investigated. These cores were logged by conventional geological techniques but the nature of the sediments makes the identification of the fine details of the internal structure macroscopically difficult, hence x-ray techniques were applied, in many cases with success. The first cores to be investigated were from Lake Seewen in the Swiss Jura Mountains using both radiograms and tomography. Radiograms reveal features such as dropstones, organic masses, fractures and sand dykes. X-ray tomography scanning at intervals of 3 mm reveal details of soft-sediment deformation at event horizons, which have been proven to be caused by earthquake shaking. Subsequently, in Lake Bergsee in the southern Black Forest, cores of gyttja, a soft jelly-like virtually structureless deposit, were investigated using x-ray tomography to identify macroscopically undetectable structures, such as fractures and sudden changes in the density which could be caused by collapse under conditions of earthquake shaking. When combined with geotechnical measurements, high-resolution density profiles were constructed using tomographic data acquired by scanning at 4 mm intervals along a ten metre section of core. Changes in density detected within the profile down to a depth of 7 m are negligible which suggest that the normal consolidation which reaches a maximum of 4% has not taken place. In the section below 7 m the general increase in density seen from 1.03 to 1.11 g/cm^3 represents the expected consolidation in this type of lake deposit. This approach indicates that x-ray tomography scanning can be a powerful tool in the investigation of structures and the physical properties in sediments.

SS03 : WEpo07 : PO
Perm Reduction Function Derived from CT-Based Pore Network Modeling

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Permeability is the most important but the least predictable parameter in petrophysics. While permeability of clean sandstone has been studied extensively and well understood, the relationship between permeability and porosity for shaly sandstone lacks fundamental understanding. To quantitatively understand the effect of clay deposition on perm reduction, recently we have developed some clay deposition models on the CT-based pore-network. A novel scaling function of perm reduction is obtained through the model calculations. Applying this scaling function to estimates of perm for an extensive sample set, we found without exception that both the accuracy of perm estimation and correlation of porosity to perm increase significantly when compared with the conventional Coates-Timur model.

SS03 : WEpo08 : PO
X-Radiographic Computed Axial Tomography: New Tool for Paleo/Astro/Geo-Biology?

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X-radiographic computed axial tomography [CT; including both medical CT (macroCT) and research-grade microscopic CT (microCT)] has been used to investigate a variety of geologic sample types where invasive techniques are unsuitable. In paleontology, macroCT has been used to investigate the nature of vertebrate remains, with emphasis on construction of isosurface maps of bones/teeth which have been extracted from their surrounding matrix. More recent work has focused on examining the internal structure of these fossils, as well as resolving the spatial distribution of embryonic skeletal elements within fossilized eggs.

Neither type of CT has been used extensively in other realms of paleontologic investigation, particularly where fossils are still entombed in matrix. A variety of matrix-embedded fossils representing a spectrum of biotas (ranging from invertebrates to trace fossils), a spectrum of preservational modes (ranging from soft-bodied biotas to organisms with biomineralized skeletons), and a spectrum of size scales (ranging from decimeter-sized scyphomedusae to decimicron-sized microbiotas) were analyzed using CT. For macroscopic fossils analyzed with macroCT, slice resolutions of 250 µm yielded relatively robust images of decomposing tissues within matrix-embedded soft-bodied fossils, as well as biomineralized support structures encased within biomineralized exoskeletons. Such insights have potential to augment our understanding of the paleobiology of key intervals of Earth history, such as the earliest putative metazoans. For example, most of the earliest metazoans consist of simple discoidal structures preserved on the soles of sedimentary rocks; lack of diagnostic anatomical structures on fossil-bearing surfaces and lack of a biomineralized skeleton has led to intense controversy over their taxonomic affinity, and in some cases controversy over their biogenicity. Yet analyses of rocks containing the discoidal Ediacaran fossil *Aspidella* yield clear images of stalks within the rock - these subtle density contrasts shed light on the medusoid- vs. pennatulacean-affinity of these fossils, and hence our understanding of the biology and preservation of early metazoans. Similarly, for smaller fossils, microCT slices as small as 8 µm thick yield robust images of individual skeletons within coquina grainstones, as well as zoning within secondarily mineralized skeletal elements. Although internal anatomical details are not visible at size scales below 800 µm^3, variations in skeletal morphology and biomineralization have been noted in phosphatized, pyritized, clay-replaced, calcified, agglutinated, and silicified microfossils.

SS03 : WEpo09 : PO
In-Situ Visualization of Advection Fluid Image within Deformed Rock by X-Ray CT during Permeability Testing

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Many laboratory-based permeability measurements have been performed on reconstituted fault derived from crystalline rocks. However, the previous experiments treat averaged bulk permeability values derived from the pressure or volume difference between inflow and outflow at any methods (e.g., constant head, flow pump and transient pulse methods). The heterogeneity within samples was, that is, out of consideration on the studies. The aims of this research was specified as follows: 1) To visualize the advecting fluid image during permeability testing. 2) To elucidate the relationship between fluid flow property within fault related rocks and their deformation mechanism. In order to achieve these aims it was necessary to develop apparatus with the capability of not only measuring permeability but also visualization of fluid advection. The X-ray computerized tomography (CT) medical scanner was used as a tool to noninvasively image three-dimensional flow patterns during permeability testing. Experiments were carried out using the permeameter machine made from acrylic plastics, which was sit in X-ray CT. KI solution was used as a contrast medium, because it has much advantage of high X-ray attenuation and innocuousness for human.
X-ray CT image has been successful applied to this study of fluid advection in laboratory permeameter. High-resolution, three-dimensional fluid flow distribution was measured for fault-related rocks. The fault zone of independent particulate flow mechanism play a role as conduit to fluid flow while cataclastic fault zones act as barriers. In sheared rock including some cracks, the only connected cracks can function as fluid conduits. The localized permeabilities along permeable fault zones and fractures, calculated by fluid front rates, are two-orders higher than averaged bulk permeability derived from the pressure or volume difference between inflow and outflow in permeameter.

SS03 : WEpo10 : PO
Prediction of Solute Transport at the Column Scale by Accounting Explicitly for Soil Structures

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The inability to predict the flow and transport behaviour in soils based on a priori information demonstrates the lack of knowledge we currently have concerning transport-relevant properties or processes, or both. Since soils are heterogeneous porous media, knowledge of the spatial structure of hydraulic properties is a prerequisite to predict flow and transport behaviour. We present an approach where the effective solute transport behaviour at the scale of a soil column (10 cm) is predicted by taking into account the spatial structure of the hydraulic properties at the local scale (1 mm). An undisturbed soil column, 10 cm high and 16 cm in diameter, was taken from the upper A-horizon of a silty agricultural soil (Orthic Luvisol). The spatial structure of the parameter field was estimated from medical X-ray tomograph recordings. The greylevels of the images obtained by the CT-scanner are related to the local x-ray absorption coefficients which themselves are linearly related to the local bulk density within the water saturated soil column. By postulating that bulk density is a proxy for hydraulic properties, i.e. regions with the same density have the same hydraulic properties, the x-ray images can be interpreted as a representation of the three-dimensional spatial parameter structure of hydraulic properties within the entire soil column. As a first approximation, the x-ray image was partitioned into two different density classes separating the dense aggregates and the less dense matrix. The three-dimensional structure of the two density classes was implemented in a model of flow and transport. The local hydraulic properties were derived from directly measured pore-size distribution and pore-connectivity. For the simulations it is assumed, that Richards' equation and the convection-dispersion equation are valid at the local scale. For validation purpose, model simulations were compared with a measured breakthrough curve of a conservative tracer determined on the same soil sample. Considering that the local hydraulic properties and parameter structure were determined independently with respect to the breakthrough experiment, good agreement was found. Predictions of solute transport at the column scale were sensitive to the difference in saturated hydraulic conductivities of both materials, but not to the local dispersivities. The simulations demonstrate that (i) assuming validity of the Richards' equation and the convection-dispersion equation on the local scale leads to a good description of the effective flow and transport behaviour at the column scale without making any assumptions about the governing processes at that scale, (ii) the dispersion parameters, which are notoriously difficult to determine, need not be determined since their effect is included explicitly, and (iii) local absorption coefficients can be used as a local proxy for the parameter field of the hydraulic properties.

SS03
Applications of Computerised X-Ray Tomography

SS03 : WEpo11 : PO
Quantification of 2D and 3D Air Apertures in Undisturbed Soil Samples in Relation to Hydraulic Properties

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In the past visualisation techniques (colouring dyes, impregnation waxes, ...) were used to explain the occurence of fast-conducting flow paths in porous materials. However, visualisation itself cannot be used for modelling purposes in 3D porous media. X-ray CT analysis is a very promising tool for a rapid and non-destructive quantification of soil properties such as macropore characteristics. This paper will try give an overview of some research topics related to the quantification of porous structures of undisturbed soil columns that were carried out in the past.

In this research, a SOMATOM PLUS4 X-ray CT scanner was used to derive 2D and 3D porous structures in a quantitative way. The occurence of beam hardening using this CT-tool however, limited a full quantitative approach of porous dense media. Therefore a pre-correction algorithm based on the theoretical calculation of the mono- and polychromatic attenuation values was implemented before further processing 2D images. Next, a calibrated relationship between air aperture sizes and cutoff values was derived for glass samples and sandy loam material. This relationship can be used to withdraw pixels that are part of pre-defined air apertures of certain sizes within undisturbed soil material. The sequential 2D CT images can then be used to obtain a 3D binary image representing a 3D rendering image of a certain pore space with new image analysis methods. Three soil cores (10 cm diameter, 15 cm long) exhibiting preferential flow during hydraulic outflow experiments were used for this analysis. Computer algorithms were developed to simulate the soil hydraulic properties on the base of the 3D pore space. These simulated values were compared with measured hydraulic properties from laboratory experiments. Conductivity values at saturation matched very well but could be coincidental and further experiments should be carried out.

However, whatever the flow model becomes, the problem of the resolution of the images (with use of medical scanners) remains crucial to obtain pore networks with a high connectivity level. Therefore, the application of microfocus X-ray CT can be very helpful to quantify and characterise more detailed 3D porous networks which could be used for modelling purposes and can be validated with measured hydraulic properties.

SS03 : WEpo12 : PO
Derivation of Soil Hydraulic Properties and Characterisation of the Porous Soil Structure using Microfocus X-Ray Computed Tomography

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Characterisation of the soil structure and the pore network is essential for understanding macroscopic hydraulic phenomena such as water flow and solute transport in soils. X-ray computed tomography (CT) provides a non-destructive and non-invasive technique to visualise the different soil phases being the soil matrix, fluids and air. However, in order to link macroscopic hydraulic properties to soil structure, good quantitative CT data are necessary. In the past the Laboratory for Soil and Water of the K.U. Leuven succeeded to derive quantitative data of macropore networks from medical CT scanners. The use of a microfocus CT scanner will provide higher resolution data due to a decreasing focal spot size. Prior to the quantitative characterisation of soil structure and the pore network of undisturbed soils, preliminary research is conducted on more homogeneous porous media.

The macroscopic hydraulic properties (the water retention and the hydraulic conductivity curves) of a series of 100 cm^3 (5 cm x 5 cm^2) homogeneously packed sand samples of known bulk density are determined in a multistep outflow experiment. At known overall water contents the samples are scanned using an AEA microfocus CT scanner (with a maximum energy of 160 keV and an optimal resolution of about 10 µm). X-ray attenuation coefficients determined at two energy levels (dual energy approach), is applied to obtain a 3D visualisation of the moisture/air and density distribution within the sample. Mean volumetric water contents are calculated and compared with the overall water content of the sample.

Further use of microfocus CT will be very helpful in the quantitative characterisation of pore networks. Artificially created pores down to 0.5 mm in diameter are now clearly visualised on CT slices. Visualisation of smaller pores is certainly a realistic goal for the future. Image analysis will extract further information on geometric properties of the pore network such as pore volume, area and pore connectivity. Incorporation of these parameters in a pore network model and simulation of flow using the model will help us to better understand macroscopic flow phenomena.

SS03 : WEpo13 : PO
Porosity and Fluid Flow Characterization of Granitic Material by Capillary Test Under Tomodensitometry RX

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To study the relationship between porosity-mineral distribution and the connectivity -permeability parameters, we develop a methodology using tomodensitometry RX and capillary imbibition test. The apparatus used is a medical scanner with a voxel size around 1 mm^3 (0.7x0.7x2 mm) and a set of 40 cross section is used to build a 3D image of the sample. The fluid flow during the capillary test is followed with a several set of 40 cross-sections aquired at different step of tests. The radiological density is used to build 3D maps of the mineralogy, porosity, and fluid location. During the test, radiological density is used to infer hydraulic radius following the Laplace equations. This value is relative to the flow capacity of the material. Different sizes of volume are defined the core size (100 cm^3), the section size (cm3) and the mineral size (few mm^3). With this set of data, the direction of flow, the location vs the mineralogy or the structure are tested and characterized with the definition of the hydraulic radius. A 3D-map of the permeability is inferred, and used to recognize the contribution of each part to the mean permeability measured at the sample scale. Two cores of granite are tested. They are cored in the same block and in two perpendicular directions. This test shows the role of the felsdpar and micas mesch on the network used by the fluid. The hydraulic radius involves on three orders of magnitude (from 10^{-10} to 10^{-13} m), at the mineral scale, with K-feldspar as faster. In this granitic sample the continuity of the K-feldspar mesh controle the fluid flow at the sample scale with an inferred hydraulic radius for the core similar to the K-feldspar one. Comparison between results obtained on the two cores shows the effects of the low structuration induced by tectonic strain. For one core, thick quartz bands perpendicular to the general flow direction reduce the hydraulic radius by one order of magnitude whereas the hydraulic radius inferred at the mineral scale are the same in both case. The used of tomodensitometry RX and capillary test show clearly different permability values appendant on the tested volume size, the mineralogy and the interaction between the general flow direction and the structure of the material.

SS03 : WEpo14 : PO
3D Characterization of a Variable Aperture Fracture in Crinoidal Limestone using Microfocus CT

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The ultimate objective of our research is to model fluid flow in fractured media using network and discrete approaches. Therefore, a detailed knowledge of fracture apertures is necessary. We use microfocus CT as a tool to measure the apertures of a fracture in a cylindrical sample of crinoidal limestone. In a first step, a homogeneous sample is scanned and the images are corrected for artefacts, the most important of which is beam hardening. A linearisation technique is used in order to correct the images for beam hardening. This technique transforms the polyenergetic CT-data into monoenergetic ones, which requires knowledge of CT-data as a function of object thickness. In a second stage, a calibration is performed on phantom objects of crinoidal limestone to investigate the relationship between missing attenuation and fracture aperture. The phantom objects consist of two perfectly polished halves of a cylinder, which are fixed at certain distances, reproducing different known fracture apertures. In analogy to previous research, a linear relationship between fracture aperture and integrated missing attenuation is developed. In a third stage, a sample of crinoidal limestone with a variable aperture fracture is scanned and the obtained calibration relation between fracture aperture and attenuation coefficient is used to derive the fracture aperture throughout the sample. A correction procedure is used to determine the perpendicular distance of each fracture part in three dimensions. Finally, a validation of the CT technique is performed by measuring part of the fracture aperture by a classical microscopic technique. Microscopically measured fracture aperture data are compared to the corresponding microfocus CT profiles.

SS03 : WEpo15 : PO
Construction of a Microfocus Computer Tomography (µCT) Simulator for a Quantitative Exploitation of µCT in Material Research

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Objective of the Kemit project is to apply X-ray µCT in applied and fundamental material research in a quantitative way. µCT is an ideal technique for the non-destructive characterisation of internal features in a wide class of materials, such as fractures in rocks, the structure of trabecular bone, metal foams and composites. The quantitative knowledge of the internal material geometry is an essential input for the numerical modelling of material behaviour or for the prediction of the permeability of fractures.

However, reconstructed µCT images show artefacts, due to e.g. beam hardening, noise and scatter. To enhance the quality of the quantitative µCT data, the precise causes of the artefacts have to be identified. Simulation of the physical and technological phenomena occurring in the µCT offers the possibility to more thoroughly understand and to optimise the acquisition and reconstruction process. Therefore, a simulator used for medical CT is adapted to the µCT equipment at the KULeuven. An important prerequisite for the simulator is the knowledge of the hardware characteristics of the different µCT-components, such as the emission spectrum of the X-ray source, the size of the focal spot.

In this paper, the development of a 2D-µCT simulator is presented. To validate the acquisition process in the µCT-simulator the 'real' µCT-resolution is compared to the simulated one. Resolution is characterised by the 'full width of half maximum' of the 'line spread function'. The 'line spread function' is the differential of the 'edge response function' which is determined by measurements on cubes with strong attenuation (copper). Measurements are performed using the µCT equipment at the KULeuven. Finally, as an example, we compare reconstructed images of a copper cube using the simulated and measured data.

Bastiaens W, J Nuyts, R Swennen, *"Constructie van een µCT-simulator voor geologische doeleinden.", Ms thesis, KULeuven*, (2000).
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SS03 : WEpo16 : PO
Computerised X-Ray Tomography as a Powerful Tool in Single Grain Zircon Study

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Our previous applications of X-ray computerised microtomography (mCT) has shown a great advantages of this technique in revealing of internal structure and morphology of single mineral crystals. Moreover the importance of mCT information is a quite compatible to results of optic, SEM (BSE) and CL methods.

We used Skyscan 1072 microtomograph having <8 µm X-ray beam and 2 µm spot resolution. The mCT provides the high-resolution density information of the crystals internal microstructure non-destructively and without specimen preparation (Van Dyck, Sasov, 1999). Computer interface allows to get 2D images in any direction desired as well as full 3D images of the bulk sample. In addition, the 3D reconstruction of internal structure details could be done even for separate domains within single grain.

Our recent mCT study revealed the density inhomogenity of different zircon crystals caused by the presence of cores, overgrows, rims and different inclusions. So far the most dense discrete outer zone (up to 5 µm) has been found in all studied crystals. Some of the grains contain less dense core and more dense overgrowth whereas another grain shows more dense central part and less dense rim. However these details of internal structure are not detectable by optic and BSE.

The mCT studies of zircon and monazite grains of different morphologies, ages, origin and mode of crystallisation having distinctive internal structures and individual features are in progress.

We would like to emphasise the following advantages of mCT technique: 1. Absence of special preceding sample preparation, mechanical and chemical disturbance of the original sample that is of great importance for future comparative studies. 2. High resolution of mCT allowing to observe very fine details of crystals internal structure making this method compatible to popular cathodoluminescence.

SS03 : WEpo17 : PO
A Method for Numerical Solution of the Integral Equation of the Computerized Tomography and its Application in Geophysics

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In the first part of this paper is given a review of characteristic features, achievements and unsolved problems of the computerized neutrino geotomography. Computerized neutrino geotomography (more precisely: computer-aided neutrino geotomography), is a section of the computerized tomography characterized by the fact that the attenuation of neutrino beams which pass through the Earth in different directions have to be measured. Having this information, with the formulae from computerized tomography, the density distribution of the Earth can be calculated. In the second part of this paper is given a method for numerical solution of the specific integral equation of the computerized tomography. The problem of solving this equation is an ill-posed one and could be treated with some methods developed to cope with such problems. We applied a version of the method of optimal regularization. Our method, which is based on Cormack's formulae, is worked out for material media: 1)with central symmetry and 2)with noncentral symmetry. This method is applied to study the possibilities for investigating the interior of the Earth by means of neutrino experiments, i.e. by means of computerized neutrino geotomography. The preliminary results of the research performed show that the precision of measuring the Earth's density depends mainly on the precision of measurment of the neutrino fluxes.

SS03 : WEpo18 : PO
Assessment of Landslide Hazards using Geophysical Tomographies

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Landslides are among the major natural and man-made hazards affecting mankind and yet their causes, their consequences for human life and property, and possible strategies for mitigating their effect are not very well understood. We will note, that only in Bulgaria there are over thousand active landslides on populated and health resort areas. The material and social losses have not been calculated yet. But in preliminary data they are enormous. Numerous and dangerous are the landslides in opencast coal-mines too.

In this paper we offer methods for combined application of high resolution electrical (resistivity) tomography and seismic ray tomography for characteristic of landslide hazards and unstable ones.

The major aim here is to predict where and when landsliding will occur, establishing their variability in space and time, and appraising their impact on the natural and socio-economical environment. The above methods are applied for studing of concrete landslides in Bulgarian Black Sea Coast and some unstable slopes in an opencast coal-mine of Maritza-Iztok area, Bulgaria. This combined application of electrical and seismic tomographies for assessment of landslde hazards is very useful.

Thursday PM Session

SS03 : THpm21 : F4
Simulation of 3-D Chemical Transport in Heterogeneous Soil Cores using X-Ray CT

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Heterogeneities are common in natural porous media. They are present on different scales. Using X-ray computed tomography (CT), the small-scale porosity distribution and chemical transport in nondestructive soil cores were measured. Three computer codes were developed: one for calculating the small-scale porosity distribution in natural soil cores from CT measurements; one for estimating the parameters of water and contaminant transport in porous media including values of small-scale hydraulic conductivity, dispersivity and adsorption coefficient for certain organic chemicals; and one for predicting three-dimensional chemical transport in porous media using a hybrid Lagrangian-Eulerian finite element method. The models were applied to a series of heterogeneous soil cores taken from a field near Columbia, Missouri. The input data consisted of CT scan data collected during breakthrough experiments using an iodide tracer. A series of laboratory experiments were conducted to establish an empirical formula between hydraulic conductivity and porosity. This formula along with six other empirical formulas from the literature were utilized to estimate the hydraulic conductivity distribution within the soil core by using the porosity distribution calculated from the CT data. Also calculated, using porosity data, were dispersivity and the adsorption coefficient in each volume element throughout the soil core. Comparisons between model predictions and laboratory measurements of effluent concentrations were made. Also compared were the resulting relative frequency distributions for porosity, pore water velocity and hydraulic conductivity within each core. This approach quantifies the spatial variation of transport parameters on a macropore scale rather than on a core-averaged scale. The comparisons of chemical transport in natural soil cores suggest that small-scale heterogeneities cause the departures between the measured and simulated solute breakthrough curves, and that a smaller grid size is needed to improve the comparisons.

SS03 : THpm22 : F4
Study of the Microgeometry of Porous Materials using Synchrotron Computed Microtomography

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A series of measurements of the structure of a variety of porous materials have been made using synchrotron computed microtomography (CMT). The work was carried out at the Brookhaven National Synchrotron Light Source, Argonne Advanced Photon Source, and European Synchrotron Research Facility. The experiments at Brookhaven and Argonne were carried out on bending magnet beam lines using area detectors to make tomograms based on determination of the sample x-ray absorption coefficients. The work at the ESRF used an undulator beam line, a pencil x-ray beam, and an energy dispersive x-ray detector to make tomographic sections of trace element distributions. The spatial resolution employed was determined in large part by the sample size. Most of the work was done with a pixel/voxel size ranging from 0.002 to 0.010 mm. Analysis of the data was performed to derive values for porosity, permeability, connectivity, conductivity, etc. We examined a suite of samples in order to obtain a set of values describing their microstructures that could be useful in fluid flow calculations relevant to petroleum recovery or transport of environmental contaminants. We examined the structure of unconsolidated sediments since their structure is relevant to transport of contaminants in rivers and estuaries. Fluorescent tomography was used to ascertain whether or not metals were concentrated on the surface or throughout the volume of a single sediment particle. Studies of different types of sandstones, carbonates, and limestones were made to catalog their microgeometry properties. Finally, measurements were made on sandstone samples that had been subjected to high-pressure compression to investigate the relation between the microgeometry and the magnitude of the applied pressure.

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SS03 : THpm23 : F4
Using Various Scales and Systems for X-Ray Tomographic Imaging of Multi-Phase Flow Processes

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X-ray computed tomography (CT) allows non-invasive measurement of phase distribution and species concentration and therefore offers significant advantages to studying fundamental physical processes of water movement and contaminant transport in porous media. We present results obtained with two different CT systems and for various sample sizes and porous media. The two systems used were: (i) a tube x-ray system of the Non-Destructive Evaluations Group at Lawrence Livermore National Laboratory providing resolution on the order of 400 microns; and (ii) a micro-tomography system located at the synchrotron facility of the Advanced Photon Source at Argonne National Laboratory, providing resolution on the order of 10 microns. The samples varied in size from 76 mm to 1.5 mm. The synchrotron radiation is monochromatic, making it possible to scan at a specific energy, for instance at the absorption edge of a chemical dopant. We added 2 mol-percent KI to the water phase and thereby enhanced the contrast between air and water phases. Using the synchrotron-based system we were able to obtain high-resolution images in which we could detect individual pores and grains as well as phase distributions. Using image processing techniques the phases can be separated and phase distribution and movement can be quantified. With the polychromatic tube x-ray system average values of saturation for the porous medium were obtained, providing water saturation information on the macroscopic scale.

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SS03 : THpm24 : F4
Heavy Oil Solution Gas Drive Reservoirs: An Experimental Study

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Some heavy oil reservoirs located in Canada and (Smith 1986, Metwally and Solanki, 1996) and Venezuela (Mirabal et al. 1996), under solution gas drive, show higher than expected production rates, low produced gas-oil ratio and high recovery. The reasons for this behavior are not clear. A series of computerized-tomography-monitored, heavy-oil natural depletion experiments were carried out to examine the core scale behavior of the heavy oil solution gas drive process using high pressure/high temperature experimental setup. Heavy mineral oil and 9° API heavy crude oil from the Hamaca region of the Orinoco Belt, Venezuela were used. A visualization cell attached to the outlet of the sand pack allowed monitoring of bubble size and shape as bubble exited the sand pack. Conventional solution-gas-drive behavior was observed in the experiments conducted with the heavy mineral oil. However, in the heavy crude oil experiment, gas bubbles entrained in the crude oil flowed together. Thus suggesting a possible effect due to the high asphaltene content and large viscosity of Hamaca crude oil. Moreover, for both experiments, critical gas saturation was observed to be around 3%.

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SS03 : THpm25 : F4
An X-Ray CT Study for the Assessment of Basic Rock Properties in Deforming Samples

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The character of the reservoir rocks is uncertain and variable at the depths where they are subjected to different tectonic forces and pressure changes due to drilling, well stimulation and production operations. The way that a porous rock behaves is different than a solid material under these conditions and, its elastic response after a change in the stress condition largely depends on the porous structure and the heterogeneity, even in the microscale. The stress- and time-dependent deformation of the porous structure is expected to change the behavior of the most important properties of the rock, such as porosity, and permeability. Although, porosity of the reservoir rock can be determined in-situ by using different logging tools, the determination of permeability is more complicated and can be done either by well testing or laboratory flow measurements. Well testing is a costly operation to determine permeability. Laboratory measurements, on the other hand, are performed the core plugs taken from full diameter cores and should be run under representative stress field to imitate the in-situ conditions. Thus, measuring the permeability and porosity in the deforming medium is important to obtain a representative data.

In this study, we demonstrate the use of X-ray CT to investigate the porosity and permeability changes of the rock during deformation in a triaxial cell. We have performed the experiments in a specially designed X-ray transparent triaxial test cell, which enables to apply stress as well as making flow measurements. We used limestone samples.

Since the presence and value of confining pressure changes the deformation behavior of the rock, we applied different constant confining stresses on the samples to change the deformation regime. As we increased the axial load, we scanned the samples at different locations to determine the stress dependent local changes in porosity. We also measured the absolute permeability during the deformation.

Results showed that the stress condition applied to the porous medium changes the rock and fluid transport properties compared to the sample measurements done without stressing the sample. X-ray CT enabled us to quantify the local porosity changes during different modes of deformation.

SS03 : THpm28 : F4
X-Ray Fluorescence Micro-Tomography of Geological Samples

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Imaging three-dimensionally the elemental distributions within a specimen represents a challenging analytical task, well achieved using X-ray fluorescence micro-tomography. Accordingly, this analytical in-situ technique, stemming from the synchrotron radiation, allows newly developed approaches to be applied for characterizing heterogeneous geological samples.

Three-dimensional element-specific imaging can be performed by acquiring transmission tomograms above and below the absorption edge of an element or by collecting its characteristic fluorescence. This last procedure combines fluorescence signal retrieval and 2D tomographic reconstruction algorithms. This refers to the cross-sectional elemental imaging of an object from fluorescence data collected from a series of projections formed by rotating this object in the X-ray beam. This finally allows mapping out non-destructively the internal volume of a specimen with micrometer resolution.

We present here the first attempt at imaging multi-phase fluid inclusion samples, synthesized in quartz at high pressure and temperature, by collecting the characteristic fluorescence of the enclosed elements at the microprobe instrument of ID22 beamline, European Synchrotron Radiation Facility, Grenoble, France. The results demonstrate the possibility of accurately visualizing the cross-sectional distribution of elements within a single fluid inclusion, as well as examining their spatial relationship. By acquiring numerous slices, three-dimensional reconstruction of the entire sample, with a resolution equivalent to the beam spot size, can be obtained. Combining conventional computed microtomography measurements which provide the 3D attenuation distribution for the whole sample, would allow a better correlation between elemental distribution and phase occurrence within the fluid inclusion. Employed in the field of fluid inclusion studies, element-sensitive tomography can finally offer great promise to generate new data for documenting and understanding the composition, properties and evolution of geological fluids. Further investigations will be dedicated to the characterization of microphases in diamonds.

SS03 : THpm29 : F4
Numerical Simulation of Random Walks and Magnetic Relaxation of Protons in Complex 3D Pore Space of Rocks

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Detailed geometry of pore space is one of the key elements controlling the fluid motion through it and is probed in many disciplines. In the oil exploration, for example, magnetic resonance (MR) has become widely employed in probing pore space of rocks and pore-filling fluid configuration. The information on the pore shape is extracted from extra relaxation of polarized spins occurring on the pore boundary or through restricted diffusion in the presence of applied field gradient.

The mathematics governing the former case is a classic example of restricted diffusion under an absorbing boundary condition. There is an extensive literature on cases with simple boundary shapes. On the other hand, real life data come from various types of rocks, often with poorly characterized, yet complex pore space. One of the pressing challenges is to extract relevant characteristic length scales from a limited set of data and simple theoretical models. Even if this task is accomplished, extrapolation from the static length scales to transport properties and fluid configuration is not guaranteed. Yet, elucidation of pore geometry apart from chemistry of its filling fluid and grains is a necessary step in understanding various properties of complex fluids confined to a complex porous media.

In addition to developing novel experimental techniques (Song et al, 2000) and theoretical models (Ryu, 2001), we employ large scale numerical simulations of magnetic relaxation of random walking molecules inside a realistic 3D pore structure provided by microtomography. The immediate benefit of using a 3D tomography data (Auzerais, 1996) as a basis is that the geometrical details of rock/pore can be comprehensively analyzed independently. The evolution of random-walking, spin-carrying molecules is simulated inside the multiply linked chambers (voxels), typically of 10^5-10^6 in numbers. From this, various MR measurements as well as 1D, 2D- diffusion propagators are numerically obtained and their interpretation based on analytic models for simpler geometry is compared against the thoroughly examined geometrical parameters.

This way, we can bridge the gap between elegant, but simple-minded interpretation models and extremely complex experimental data in an unambiguous manner. One can also deform the original structure in a variety of manners to test hypotheses which aim to correlate aspects of pore structure with measured properties. We will demonstrate how theory, experiment and numerical simulations come together to provide a coherent body of knowledge through an extensive use of 3D microtomography data. Representative movies on the topic are available from: http://www.physics.ohio-state.edu:80/~ryu/nmr.html

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SS03 : THpm30 : F4
Analogue Models Analyzed by Single- and Multi-Slice Spiral X-Ray Computerized Tomography

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In the late 1980s the non-destructive X-ray computerized tomography (CT) technique was introduced in geology to produce cross-sectional images of sandbox models. The number of cross-sectional slices that could be obtained of a particular stage in the evolution of the model was mainly a function of the X-ray dose intensity needed for proper visualization, and the performance of the X-ray source. The time between consecutive runs was dictated by the required cooling of this source below a certain threshold value. Because of the time involved in CT data acquisition and the long cooling duration of the X-ray source, early medical scanners could only record a limited number of cross-sectional slices. Another limiting factor was the computational capacity needed to calculate images from projectional raw data profiles. Periodic acquisition of sections at similar positions during deformation made it nevertheless possible to follow the 2-D evolution of structures in time. However, the time-consuming recording of closely spaced sequential cross-sectional slices, necessary for a full 3-D analysis of the model, was generally not carried out until the end of the experiment.

Recent technological improvements of X-ray tubes, acquisition systems and computation capacity have resulted in more powerful X-ray CT techniques. We performed analogue model experiments within the investigation field of single- and multi-slice spiral X-ray CT scanners. The acquisition system of spiral scanners revolves around the model as it moves in the longitudinal direction through the scanning plane. In this manner, 3-D volume raw-data of analog models are easily acquired. An unlimited number of closely-spaced serial cross-sections can be calculated retrospectively from the raw data. Data acquisition time for such a 3-D data set depends on the X-ray dose necessary to adequately penetrate analog materials (i.e. material composition and thickness), detector quality, and performance of entire acquisition system (e.g. single or multi-slice system, rotation time, table speed, data transfer and computation speed). Slice spacing will only affect the postprocessing time. Such analyses are especially valuable when trying to understand complex geological structures where lateral changes in 3-D geometry are common.

Periodic acquisition of such volumetric data sets makes it possible to follow the 3-D evolution of models from the initial undeformed stage to the final deformed stage. This opens new and exciting perspectives for a complete 4-D analysis (3-D geometry through time) of analogue models The digital data also allow the reconstruction of any desired section be it, horizontal, longitudinal or oblique. Examples are shown of 4-D analysis of analogue models simulating structures in shortening (Schreurs et al., in press), extension and inversion (www.earthsci.unibe.ch/tectonics/Research.html).

Schreurs G, Hanni R & Vock P, *Geol. Soc. Am. Special Paper*, **193**, (in press).

SS03 : THpm31 : F4
The Use of Computerised Tomography (CT) in the Investigation of the Settlement Behaviour of Soils

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The use of computerised tomography (CT) has become a standard diagnostic radiographic technique in modern medicine. Its potential as a non-destructive testing technique is being realised in the geosciences but only very slowly in geotechnical engineering. A joint project between Sheffield Hallam University and the University of Sheffield is attempting to exploit the method to investigate the long-term settlement of opencast coal mine backfills.

The material used in the restoration of opencast coal mines is the same material as that excavated to expose the coal seam, and is made up predominantly of mudrock. The process of excavating the overburden material and re-compacting it subsequent to the coal extraction results in a material that is made up of particles ranging in size from <60μm to >60 mm nominal diameter. Post-compaction settlements due to compression of the void spaces between particles can be very large and often significantly reduce the development potential of restored opencast sites. Movements tend to occur rapidly initially as the ground-water regime becomes re-established, and more slowly thereafter. Conceptually, these movements are usually referred to as 'collapse' movements followed by 'creep' compression, though their causes and mechanics are poorly understood.

Many hypotheses have been advanced explaining the mechanisms of creep settlement in soils. Most of these suggest that the primary mechanism is the rotation and/or crushing of particles, but verification of this has been hampered by the reliance that has had to be put on external measurements and on comparisons of indices. A key feature of this research project is the use of CT scanning together with markers fixed to individual particles, which will allow the observation at the soil particle level the physical processes associated with settlement of opencast fills and their changes with time.

The preliminary results from a series of CT scans on a number of large scale specimens will be presented, and the importance of this visualisation of soil behaviour will be outlined. The quantitative data extracted from the images may lead to a probabilistic approach to the prediction of settlement by these mechanisms being adopted and this possibility is discussed. The potential for the use of CT in the investigation of other mechanisms of settlement of granular materials will be discussed also, as will be the the possible utilisation of Magnetic Resonance Imaging (MRI) in the research of inundation problems of granular soils. The paper will conclude by outlining other work currently underway and its expected outcomes.

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A Sampling of Applications of X-Ray Computed Tomography using a Scanner Optimized for Geological Imaging

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To image the broadest possible range of geological specimens and materials, an X-ray computed tomographic (CT) scanner must be capable of optimizing trade-offs among penetrating ability, spatial resolution, density discrimination, imaging modes, and scan times. An industrial CT scanner custom-designed for geological applications, in operation since 1997 at the University of Texas at Austin, offers significant advantages over medical scanners and desktop microtomographs. Two tungsten-target X-ray sources (200-kV microfocal and 420-kV) and three X-ray detectors (image-intensifier, high-sensitivity cadmium-tungstate linear array, and high-resolution gadolinium-oxysulfide radiographic line scanner) can be used in various combinations to meet specific imaging goals. Available imaging modes are second-generation (translate-rotate), third-generation (rotate-only; centered and variably offset), and cone-beam (volume CT). Control over the translational positioning of the specimen between the fixed sources and detectors ensures that maximum resolution can always be achieved. Specimens as small as about1 mm on a side, and as large as 0.5 m in diameter and 1.5 m tall, can be accommodated.

Applications in petrology and structural geology include measuring crystal sizes and locations to identify mechanisms governing the kinetics of metamorphic reactions; visualizing relationships between alteration zones and abundant macrodiamonds in Siberian eclogites to elucidate metasomatic processes in the mantle; characterizing morphologies of spiraled garnet-inclusion trails to test hypotheses of porphyroblast rotation during synkinematic growth; measuring vesicle size distributions in basaltic flows for determination of elevation at the time of eruption to constrain timing and rates of continental uplift; analysis of the geometry, connectivity, and tortuosity of migmatite leucosomes to define the topology of melt flow paths, for numerical modeling of melt extraction during anatexis; and visualizing and quantifying the deformation of continuous 3-D plagioclase-chain networks in slowly cooled basalt flows to evaluate differentiation by compaction of a crystal mush. Meteoritical research includes measuring sizes of chondrules and metal-troilite particles in chondritic meteorites to test hypotheses of sorting during condensation of the solar nebula; visualizing paths of migration for molten metal in rare lodranite meteorites to gain insight into processes of core segregation in the terrestrial planets; and imaging of metal/clast relationships in a brecciated chondrite to demonstrate impact-induced metamorphism, metal fusion, and brecciation on the meteorite's parent body.

Paleontological studies include analysis of fossil jaws of Mesozoic marsupials to establish the antiquity of distinctive patterns of tooth replacement and reproductive strategies seen in modern marsupials; comparisons of the internal cranial anatomy of mammals and their closest extinct relatives to pinpoint the evolutionary origin of the mammalian neocortex, the locus of advanced sensory perception; and description of the evolution of the avian brain and braincase from those of non-avian dinosaurs, from data on skulls of the oldest known dinosaurs and complete skeletal analysis of the world's second-oldest bird.

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Porosity Measurements by Means of Microfocus X-Ray Computer Tomography (μCT)

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The use of medical CT scanners for porosity measurements has been illustrated by different authors e.g. Géraud et al. (1992), Klobes et al. (1997) and Hellmuth et al. (1999). However, the medical CT scanners have a limited resolution. With Microfocus Computer Tomography (μCT), optimal resolution in the order of 10 micrometers in three dimensions can be achieved. The most annoying artefact for both techniques is undoubtedly beam hardening (Joseph, 1981). This artefact can be minimised by the use of hardware filters (Van Geet et al., 2000). These have the advantage being useful for heterogeneous materials, but have the disadvantage of lowering the contrast. Apart from this approach a linearisation procedure can be developed for homogeneous materials, enabling complete exclusion of the artefact. For limestone reservoir rocks, for example, the linearisation procedure, which will not lower the contrast, can be used. Consequently, enhanced image quality is achieved. Once a good image quality is obtained, the extraction of quantitative information is possible.

Here, the possibilities in extracting porosity information will be discussed. First, the extraction of μCT-derived porosity measurements of carbonates will be illustrated, whereby the obtained information will be correlated with classical reflected microscopy observation. The μCT-technique, however, has the advantage of integrating 3D-information. Also microporosity, being below resolution of the technique, can be quantified. Apart from a bulk porosity measurement, a 3D-visualisation of the meso- and macropores by means of thresholding is possible. This information might enhance the interpretation of any porosity/ permeability characteristic. Second, the use of μCT in visualising and quantifying fracture porosity will be illustrated. A thorough calibration with artificial fractures has been performed, allowing a precise fracture aperture measurement. This has, subsequently, been applied on a natural rock sample, enabling a 3D-visualisation of the fracture network and a quantification of the fracture aperture. The latter quantitative data have been checked with a classical microscopy technique. Consequently, the technique of μCT enables 3D porosity measurements and the differentiation of a dual porosity system.

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Characterisation of Petrophysical Rock Properties Through Monitoring with Computerised X-Ray Tomography: Core Flood Experiments of Boom Clay Backfill Material

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CT is a fast, reliable, quantitative non-destructive technique, easy to operate, and thus pre-eminent for core flood experiments for determining petrophysical rock properties through uninterrupted monitoring of porosity-governed (fluid- or gas-)flow experiments. It allows easy processing and visualisation of data for comparison and analysis.

Natural Boom clay (of Rupelian, Oligocene, Tertiary age) showed tomographic densities up to 1624 HU (±53 HU), falling at the upper extreme of the range of tomographic densities from 1005.7 HU to 1624.2 HU, determined for natural clays by De Waele (1991). These values confirm the consolidated to overconsolidated nature of the Boom clay, as reported from triaxial stress path tests by Bouazza et al. (1996). Granular Boom clay backfill material consists of Boom clay powder and artificially compacted Boom clay pellets in a 50/50 mixture with an overall density of 1.7 g/cm^3. Compacted pellets with a density of 2.1 g/cm^3 yielded tomographic densities of about 1700 HU. Air-filled Boom clay backfill material generated tomographic density values of 1032.3 HU, while these 50/50 mixtures with an overall density of 1.7 g/cm^3 showed tomographic density values of 1186.5 HU. Tomographic density ratio of pellets versus backfill material (1700 HU over 1186.5 HU = 1.43) confirms the density ratio (2.1 g/cm^3 over 1.7 g/cm^3 = 1.23) for a mixture consisting for 50% of pellets.

CT has also been successfully applied for the study of the hydration properties of granular Boom clay backfill material through core flood experiments. The hydration of the granular material is quite fast and a good homogeneity is ascertained. Hydraulic conductivities of $3x10^{-11}$ to $9.8x10^{-12}$ m/s and swelling pressures of 0.2 to 0.6 MPa are obtained. Core flood experiments illustrate the swelling nature of the Boom clay backfill material through restoration of initial porosity, partially due to decompaction of the previously artificially compacted pellets and partially due to the swelling nature of the constituting clay minerals like smectite. Uninterrupted monitoring of core flood experiments enables quantification of porosity-related rock properties, that are crucial for the assessment of nuclear waste host rock characteristics.

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