BRITISH GEOLOGICAL SURVEY

Natural Environment Research Council

TECHNICAL REPORT
Hydrogeology Series

Technical Report WD/94/1

Porosity variations near a hydraulically active fracture in the Upper Chalk, Hampshire, England.

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January 1994

Abstract

This Technical Report details work presented as a poster at the Annual General Meeting of the Tectonic Studies Group of the Geological Society, held at Trinity College, Dublin, December 13th to 15th, 1993.

The Chalk is the principal aquifer in southern England, however it has an unusually complex void structure. It is commonly regarded by hydrogeologists as a dual-porosity medium. The groundwater storage characteristics of the Chalk aquifer are usually attributed to the intergranular porosity (water is thought to be held virtually immobile in the chalk matrix by capillary forces) and the flow or transport properties of the aquifer are usually attributed to the fracture porosity (the transmissivity of the Chalk is relatively large, of the order of $1000m^2/day$). The flow and transport properties of the aquifer are known to be particularly sensitive to fracture orientation, length and aperture frequency distributions (flow rate is proportional to the cube of the aperture). However, there have been few physical observations of chalk fractures and adjacent pore structures.

The present study addresses this last problem. A study of a hydraulically active joint from the Upper Chalk is described. Hydraulic activity across the joint surface is inferred from the clay lining (predominantly smectitic clays) and iron staining seen on the clay surface in hand specimen. SEM studies indicate that dissolution and precipitation processes are localized by the microtopography of the joint indicating possible channel-like flow across the fracture surface. Carbonate precipitation in the chalk matrix adjacent to areas of dissolution is inferred to be due to the mixing of supersaturated fracture brines with relatively static saturated matrix brines.

Acknowledgements

I would like to thank Jonathan Pearce for his help in obtaining the SEM images and for performing the image analysis on images 13, 14 and 15.

Contents

1.0 Introduction

The Chalk is the principal aquifer of southern England, however it is atypical in that it is a dual porosity medium. The Chalk in southern England has a porosity of approximately 35 to 40% with about one porosity percent attributable to fracture porosity and the remainder due to matrix, or intergranular, porosity (Price 1987). Pores in the Chalk matrix are of the order of 1 micron in size. Consequently, water is held virtually immobile in the matrix by capillary forces and the matrix porosity makes only a negligible contribution to flow in the aquifer. In contrast, due to their relatively large apertures (from tenths of a millimetre to tens of centimetres) fractures give rise to the characteristically large transmissivities (typically 1000m^2/day) seen in the Chalk.

Fracture aperture size is important in determining the rate of flow in the aquifer as, for a given potential (hydraulic) gradient, the flux through a given fracture is normally found to be proportional to the cube of the fracture aperture (Barker 1991). Field evidence from the unsaturated zone of the Chalk indicates that fracture aperture can be greatly enhanced by dissolution, however fracture dissolution is a complex process in that it is known to be dependent on a number of variables including groundwater carbonate saturation, Eh, pH and the partial pressure of CO_2 as well as the major ion speciation of the groundwater (none of these variables are satisfactorily constrained to date).

Both flow and pollutant transport within the Chalk aquifer have been modelled by treating the aquifer as a dual-porosity medium consisting of discrete porous, but relatively impermeable, blocks of specified dimensions separated by planar fractures with a given size distribution. These models by necessity assume discrete boundaries between blocks and fractures. Is such a representation reasonable or does the Chalk exhibit hydrodynamically significant pore structures that are not accounted for in the dual-porosity models?

1. 1 Scope & Aims

This report presents some qualitative observations of porosity characteristics adjacent to a single joint surface (assumed to have been hydraulically active, as evidenced by iron oxide staining in hand specimen) from the Upper Chalk at Twyford Down, Hampshire. The sample was collected as part of a more extensive investigation of temporal and spacial variations in iron and manganese oxide mineralisation on fracture surfaces associated with groundwater flow in the Upper Chalk.

A stub and a resin impregnated polished thin section (perpendicular to the fracture surface) were prepared for use in the study. A Cambridge Stereoscan 250 Scanning Electron Microscope was used to image the samples (run at 20 kV) and image analysis was performed using an IBAS Kontron image analyzer.

The aim of the present work is to assess whether the Chalk exhibits hydrodynamically significant pore structures that are not accounted for in the present dual-porosity models.

2.0 The Figures

The following section presents nine SEM images obtained from a stub (SEM - secondary emission mode) and a thin section (SEM - backscattered mode) of Upper Chalk from Twyford Down, Hampshire. The resin impregnated thin section was obtained approximately perpendicular to the fracture surface being investigated. The preliminary results of an image analysis study of intercrystalline porosity are also presented.

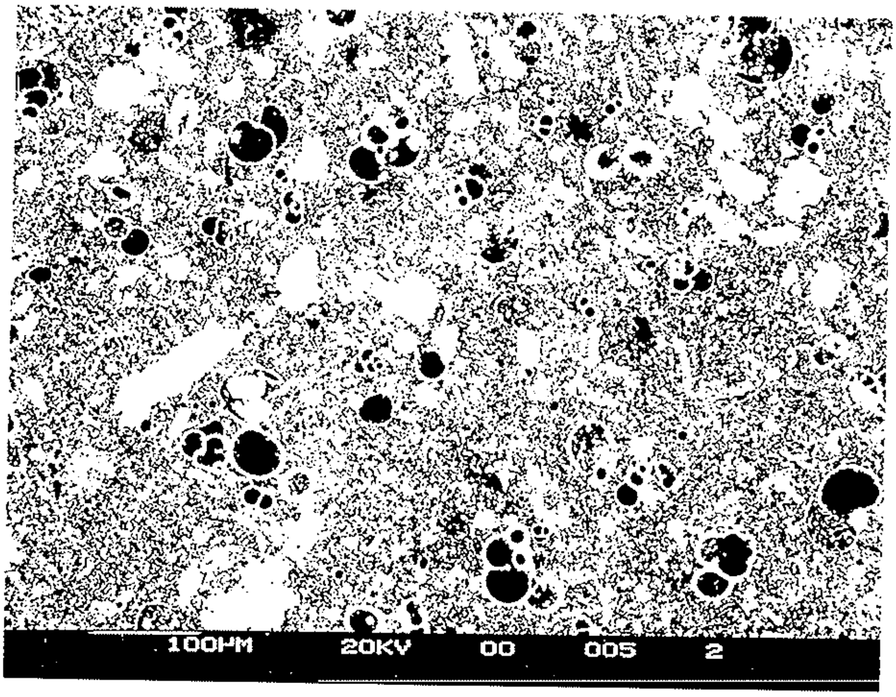

Figure 1. SEM image (backscattered mode) of the chalk matrix approximately 15 mm from the fracture surface. Matrix porosity is typically a combination of sheltered, or shelly, porosity (predominantly non-interconnected) and intercrystalline porosity (predominantly interconnected). It can be seen that the intercrystalline porosity is locally reduced by the patchy development of authigenic carbonate overgrowths (up to approximately 100 μm in size). Image magnification is given by the scale bar in the lower left hand corner of the figure.

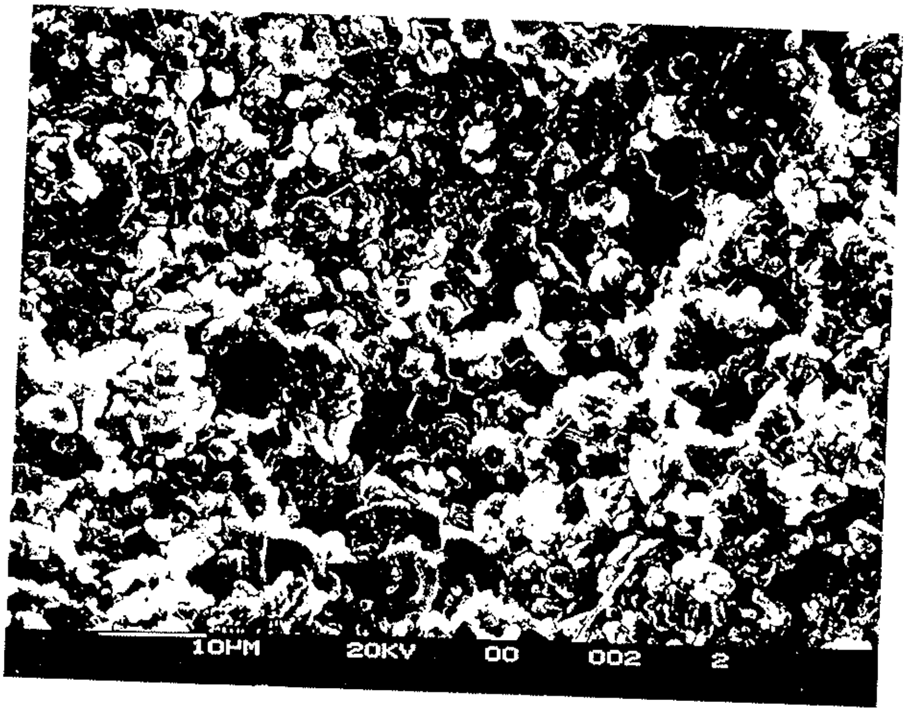

Figure 2. SEM image (secondary emission mode) of chalk matrix approximately 6 mm from the fracture surface. Intercrystalline porosity can be seen to be associated with loosely packed coccospheres and coccolithic fragments (the relatively undeformed coccospheres are typical of the Upper Chalk of southern England). Intercrystalline pore sizes are generally in the range < 0.1 μm to approximately 10 μm. Image magnification is given by the scale bar in the lower left hand corner of the image.

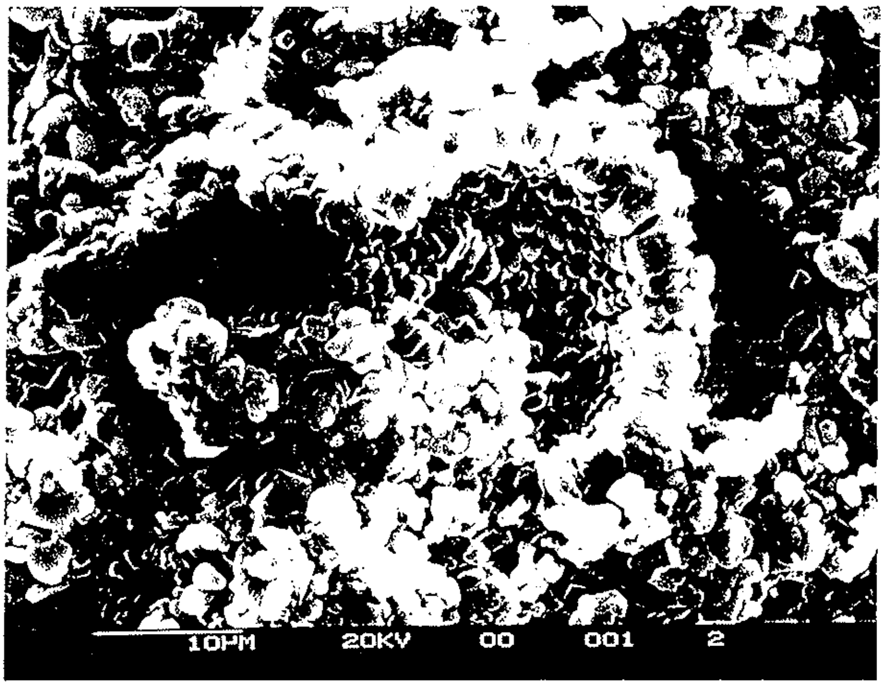

Figure 3. SEM image (secondary emission mode) of a foraminifera test within the chalk matrix approximately 6 mm from the fracture surface. Sheltered porosity is associated with intact foraminifera tests and large pieces of shelly material. The sheltered porosity may contain limited authigenic carbonate overgrowths and very limited deposits of smectitic clays (both not shown in Figure 3.) Typical pore sizes for the sheltered porosity are in the range 10 μm to approximately 50 μm. Image magnification is given by the scale bar in the lower left hand corner of the image.

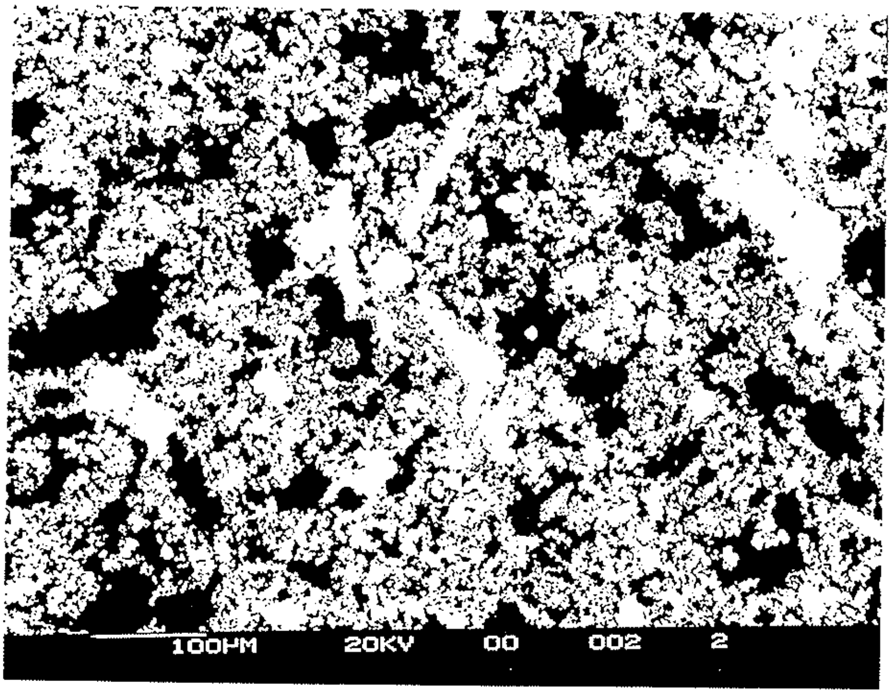

Figure 5. SEM image (backscattered mode) of the zone of 'enhanced' porosity less than 1 mm from the fracture surface. The sheltered porosity has been entirely removed (foraminifera tests and shelly material is absent - contrast with Figure 1, unmodified chalk matrix pore structure) and the intercrystalline porosity greatly enhanced. However, the authigenic carbonate overgrowths have been relatively well preserved. Image magnification is given by the scale bar in the lower left hand corner of the image.

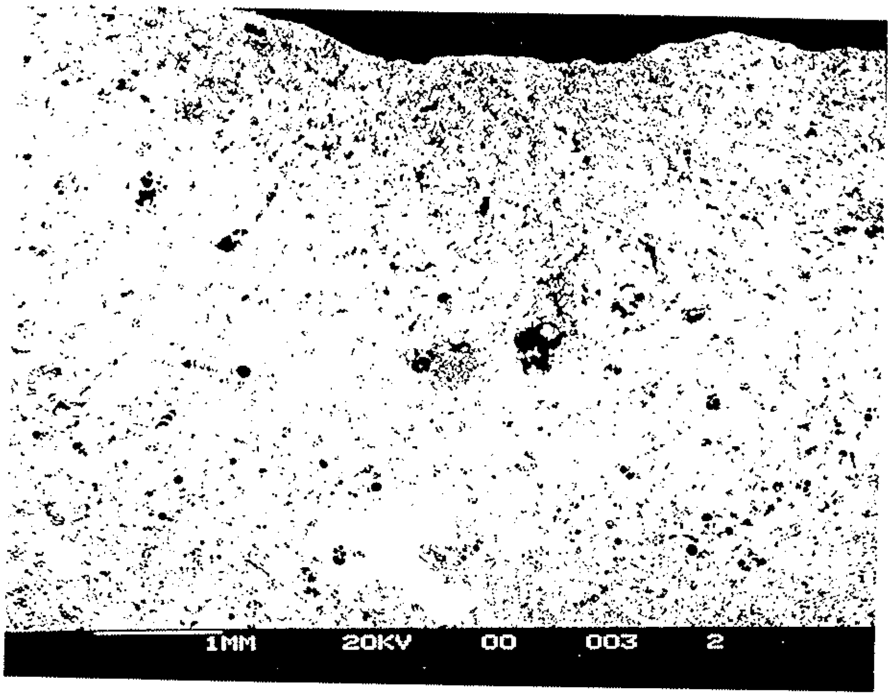

Figure 4. Low magnification SEM image (backscatter mode) of a chalk fracture surface (seen at the top of the field of view) and concentric, roughly semi-circular, zones of modified porosity, apparently associated with a topographic low in the fracture surface. A zone of greatly 'enhanced' porosity can be seen adjacent to the fracture surface (Figure 5 is a higher magnification image of this area). The zone of 'enhanced' porosity has a radius of approximately 1 to 1.5 mm. Behind the 'enhanced' porosity zone is a zone of 'reduced' porosity, with a radius of approximately 2.5 to 3 mm. Within the zone of reduced porosity the sheltered porosity appears to be relatively unmodified (visual inspection shows that the incidence and character of the formainifera tests in this zone are similar to those of foraminifera in the chalk matrix away from the fracture surface), however the intercrystalline porosity appears to be greatly reduced. The fracture surface is coated with a relatively homogeneous layer (approximately 20 μm thick) of smectitic clays rich in iron oxides (not seen in Figure 4). The zone of 'enhanced' porosity is interpreted as being due to localized solution (controlled by channel-like flow across the fracture surface). Re-precipitation of carbonate material away from the fracture surface will be due to local (pore scale) carbonate supersaturation of groundwater. The supersaturation may be a consequence of transient local gradients in Eh, pH, groundwater speciation or CO_2 partial pressure (the latter possibly being sensitive to the expected local gradients in flow rate near the fracture). Image magnification is given by the scale bar in the lower left hand corner of the image.

2.1 Image analysis discussion

Image analysis of the intercrystalline porosity proved problematic. Three images of the unmodified chalk matrix porosity (13, 14 and 15 - Figures 6.1 and 6.2) were analyzed but gave unexpectedly low bulk porosities and image 16 (Figure 6.2), from the zone of enhanced porosity, proved to be unanalyzable (too few pores were sampled and larger pores were truncated by the field of view).

Analysis of images 13, 14 and 15 gave porosities of approximately 12.5%, 27% and 21.5% respectively. These values are relatively low for the Upper Chalk where a porosity of approximately 35% is more typical. It is thought that a combination of poor photographic resolution and imaging of calcite material out of the analysis plane contributed to the relatively low porosity observations. Image 16 (zone of enhanced porosity) has a porosity of between 50 and 60 % (visual estimate).

The pore size distributions for the three analyzed images (Figure 7) have forms similar to those of typical sigmoidal chalk pore size distribution curves (obtained by direct measurement techniques). However, Figure 7 should be regarded only as a qualitative observation given the previously mentioned reservations regarding the accuracy of the image analysis.

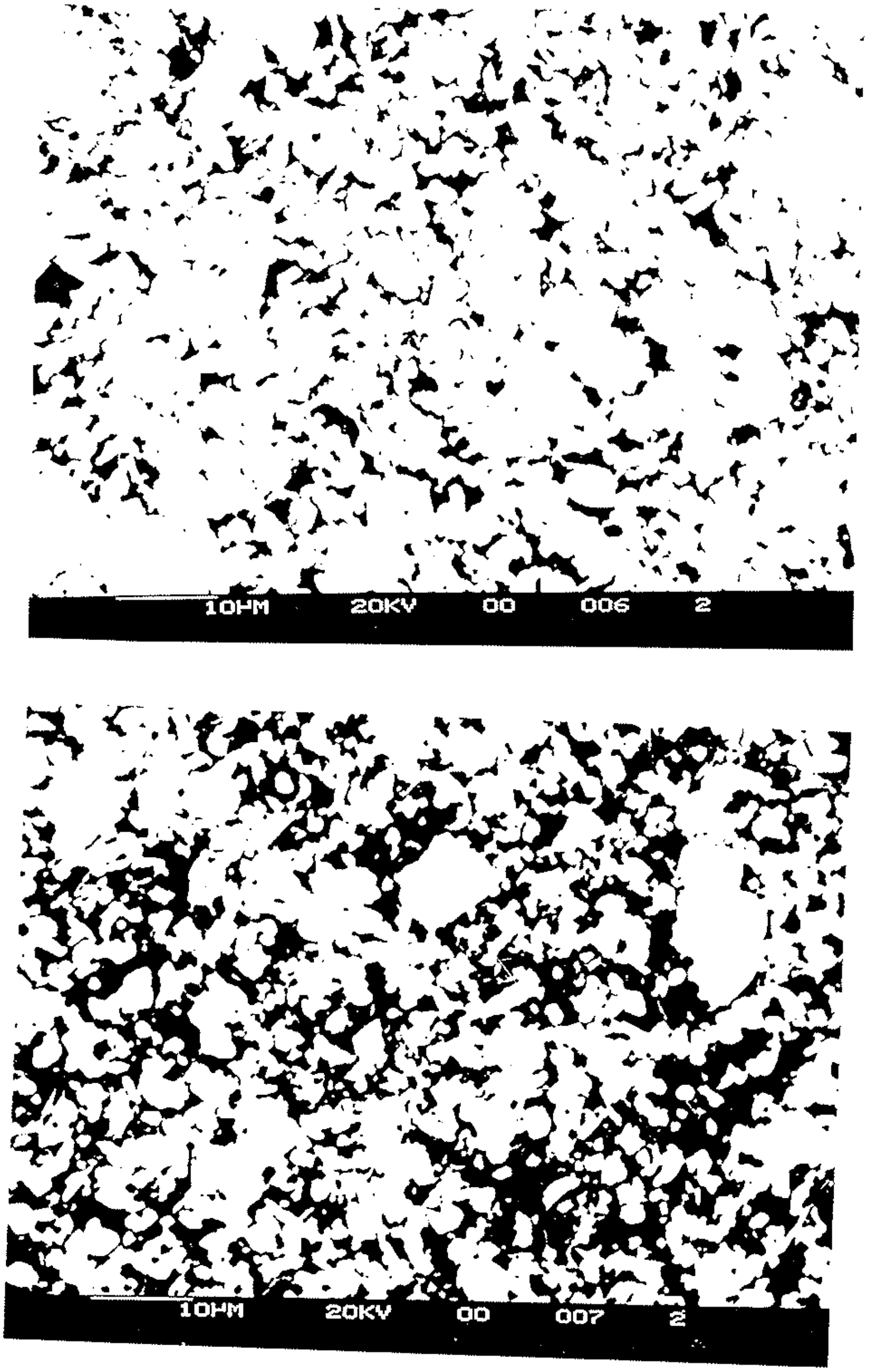

Figure 6.1. Two SEM images (top image 13, bottom image 14) used in the image analysis. The images (obtained in backscattered mode) are of areas of intercrystalline porosity which were thought to be unaffected by authigenic carbonate overgrowths. Image 13 was obtained approximately 15 mm from the fracture surface and image 14 was obtained approximately 6 mm from the fracture surface. Both images were obtained away from the areas of modified porosity identified in Figure 4.

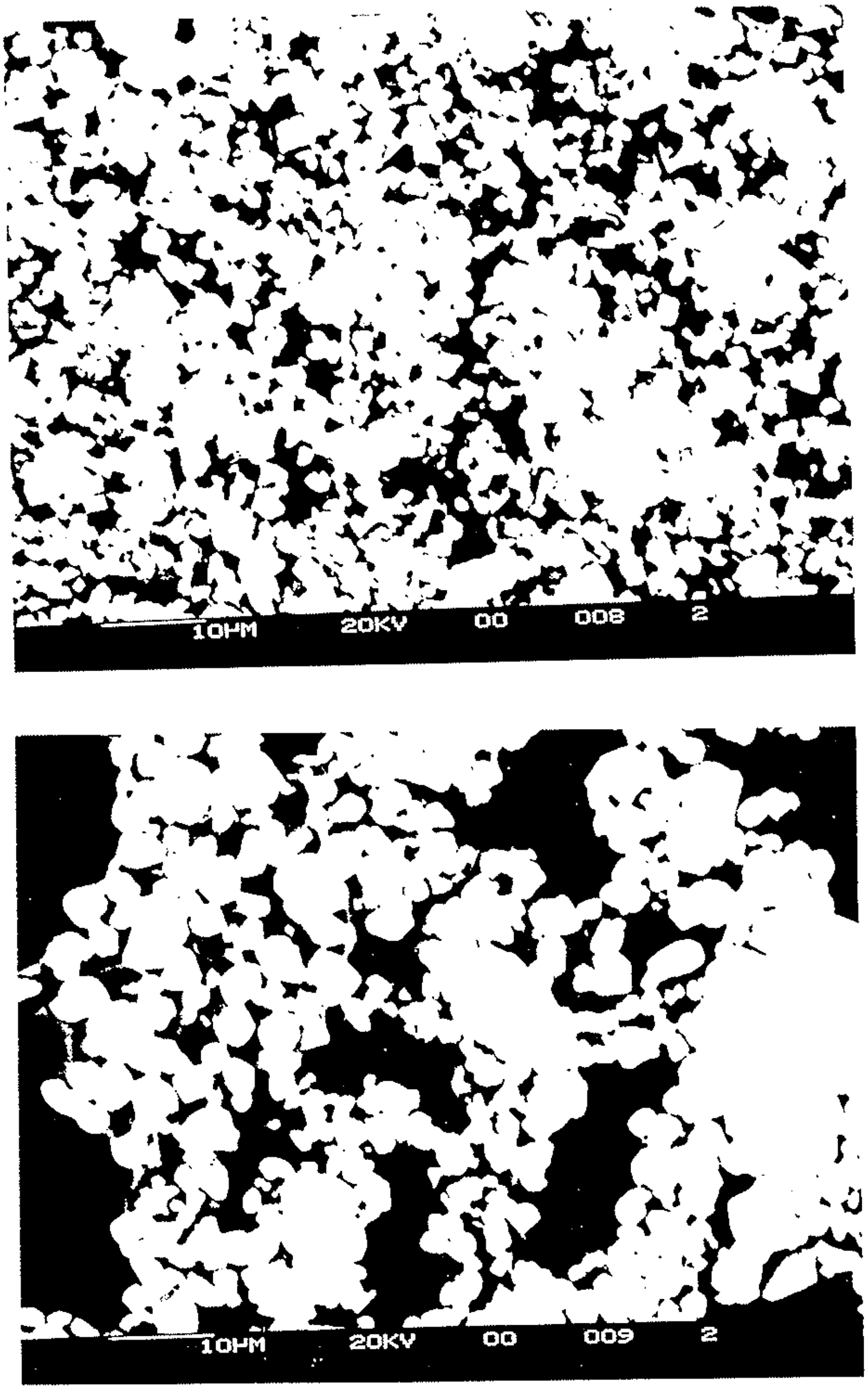

Figure 6.2. Two SEM images (top image 15, bottom image 16) used in the image analysis. The figures (obtained in backscattered mode) are of areas of intercrystalline porosity which were thought to be unaffected by authigenic carbonate overgrowths. Image 15 was obtained approximately 1 mm from the fracture surface. Images 15 lies outside the areas of modified porosity identified in Figure 4. Image 16 was obtained from the centre of the of enhanced porosity, less than 1 mm from the fracture surface.

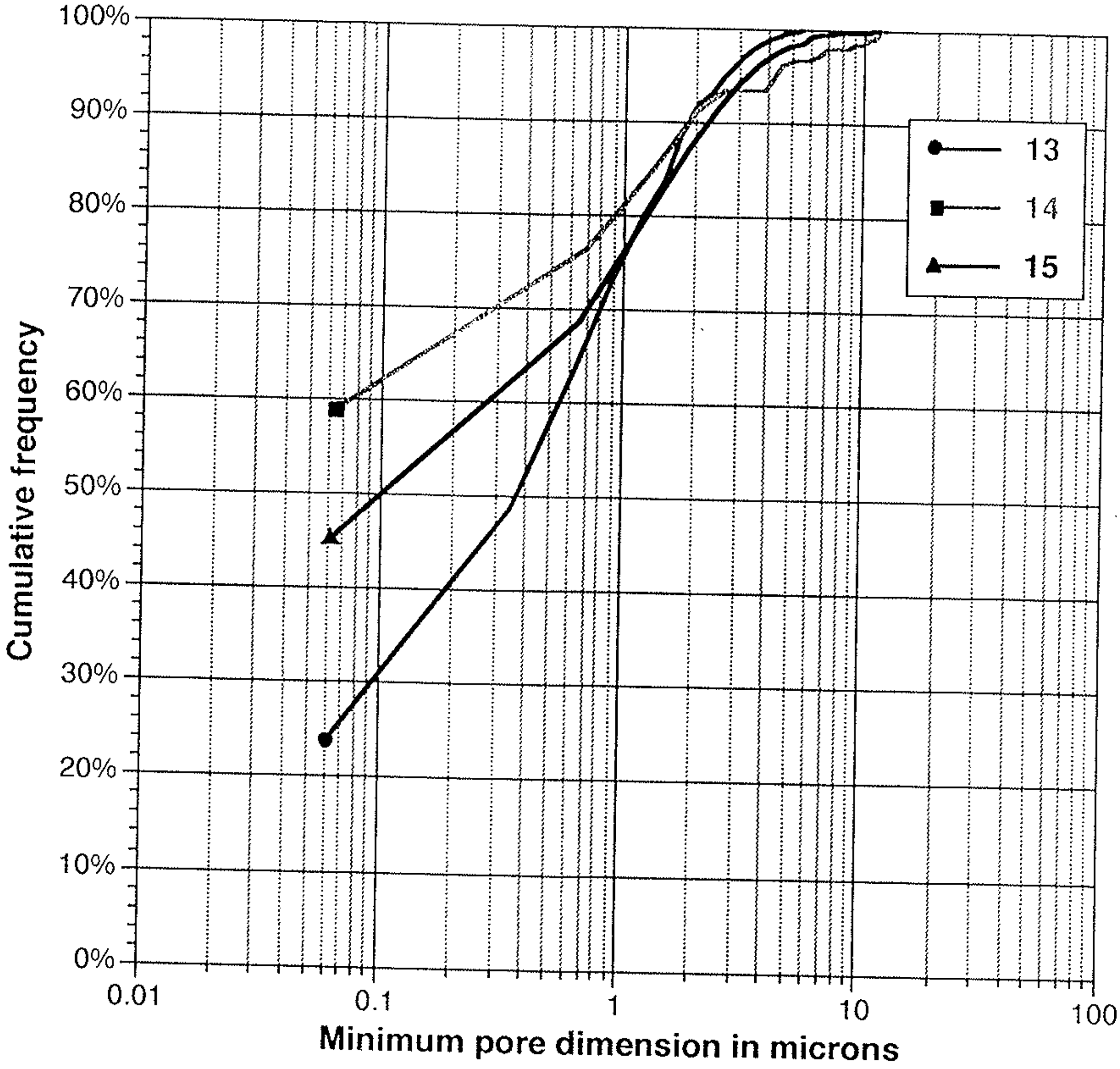

Figure 7. Cumulative frequency distribution of the minimum dimension of individual pores (μm) for images 13, 14 and 15, the full curves are not shown. The lower limits to the curves are a consequence of the limited resolution of the image analysis technique. This figure is analogous to 'standard' capillary pressure or pore size distribution curves obtained by direct measurement of pore size distributions (*eg*. MICP plots).

3.0 Hydrogeological implications

This is a preliminary study of a single fracture surface. However, a number of significant implications for hydrogeological processes can be identified if modification of chalk pore structures can be shown to be common, *eg*.

1. The modified pore structures may be interpreted as indicating channel-like flow across fracture surfaces. The relative intensity of channelled (as compared to distributed) flow within fractures will affect the transport characteristics of the aquifer.

2. Rates of diffusion of potential pollutants into the chalk matrix are expected to be reduced due to the presence of anomalously low porosity zones between fracture surface and unmodified chalk matrix.

3. Enhanced porosity adjacent to fracture surfaces may provide a 'pathway' for slow flow within the chalk, *eg*. nitrate migration at 0.6 ma^{-1} in the unsaturated zone (to date there is no adequate physical explanation for this and similar observations).

4. Porosity enhancement adjacent to fracture surfaces increases the effective surface area of the chalk blocks and so increases the area available for sorption.

3.1 Summary

A. Two concentric zones of modified pore structure have been identified associated with a topographic low in the fracture surface. B. A semi-circular zone of enhanced porosity adjacent to the fracture (estimated porosity of 0.5 to 0.6) is interpreted as having been developed by solution processes. Re-precipitation of carbonate material more distal to the fracture surface has led to zone of reduced porosity. C. Local (pore scale) gradients in carbonate saturation may be associated with gradients in flow rates near the fracture. Possible driving forces for the re-precipitation of carbonate material are transient local gradients in groundwater Eh, pH, major ion speciation or CO_2 partial pressure. D. The geometry of the concentric zones of modified pore structure suggest that during their formation flow across the fracture surface was localized, *ie*. 'channel flow'.

References

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