Compaction localization in high porosity sandstones with various degrees of heterogeneity: insight from X-ray computed tomography

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High resolution X-ray computed tomography imaging (with voxel size 48 μm) was conducted on various sandstone samples with different initial degrees of heterogeneity. All samples were imaged intact, and some after having developed localized compaction features in conventional triaxial experiments at high confining pressure, i.e. in the shear enhanced compaction domain (Wong et al., 1997).

Our analysis of heterogeneity from X-ray CT data is based on the use of the coefficient of variation $\delta = \sigma / \mu$ (σ being the standard deviation and μ the average value). The coefficient of variation was shown by Otani et al. (2005) to be a convenient indicator of material heterogeneity in CT images of experimentally deformed sand piles. The authors reported differences in δ before and after their experiments, and interpreted these differences as the effect of grain crushing resulting in more even material distribution within the voxels, hence in lower δ values. The same concept was used by Louis et al. (2006) to image contrasts in δ values throughout a volume of rock that had developed compaction bands in triaxial laboratory testing, knowing that the bands that had formed could be identified by visual inspection but not on the X-ray CT images. This study resulted in a radically enhanced image of the discrete compacted zones within the CT-scan series, whereby more deformed areas showed relatively low values of coefficient of variation due to grain crushing and pore collapse, as compared to nominally undeformed areas.

In the present work, we extended the use of the coefficient of variation to undeformed rock samples in order to tentatively relate initial heterogeneity to compaction localization. As already been suggested by several experimental studies (Klein et al., 2001; Baud et al., 2004) and theoretical simulations (Katsman et al., 2005 ; Wang et al., 2008), mechanical heterogeneity may constitute a first order controlling parameter, together with porosity, for the development of localized compaction features such as compaction bands. The coefficient of variation was calculated over sliding blocks of 3*3*3 neighboring voxels in all available CT volumes of undeformed sandstones. In order to observe the effect of the image resolution on this local value of the coefficient of variation, we also performed the same calculation for stepwise decrease of the resolution, which was achieved through successive reductions in image size. Figure 1a presents the results of such calculations for all the sandstones studied. In every case, δ increases and reaches a peak value, before the increase in voxel size progressively homogenizes the volume considered. This characteristic pattern, where the voxel size at δ_{max} is likely related to the dominant spatial frequency, and the δ_{max} itself carries information on the pore size distribution and mineralogical composition, provides a mean to compare the different sandstones. We chose to extract δ_{max} for every rock to use as an indicator of rock heterogeneity and plot it against the measured porosity in order to provide a potentially predictive diagram for the type of compaction observed eventually in the deformed samples. Such plot is showed in Figure 1b, and the type of compaction actually observed is specified after the name of each sandstone. '*CB'* stands for compaction bands and corresponds to the formation of an array of well defined compaction bands, '*diffuse CB'* denotes the presence of zones of preferred compaction with ill-defined boundaries (Baud et al., 2004), and '*no CB*' denotes the absence of localized compaction features (homogeneous compaction). Figure 1b suggests that discrete compaction features may form when the two conditions of high porosity and low δ value are met.

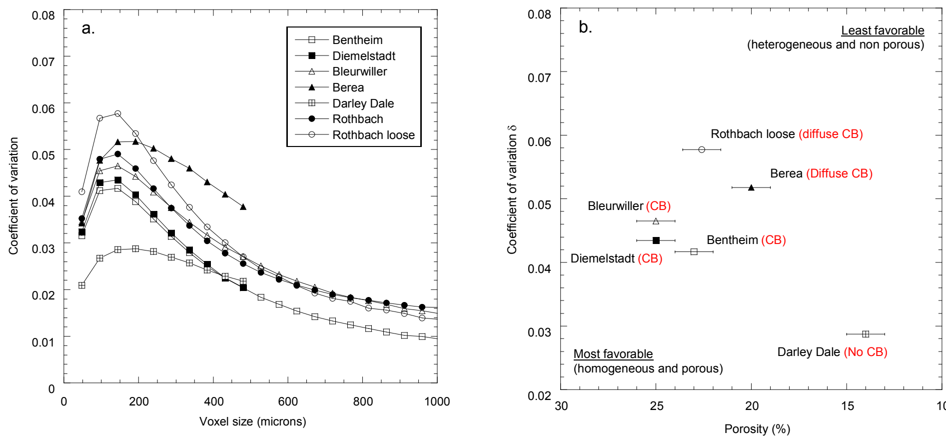

Figure 1. a. Average local δ value as a function of voxel size in the sandstones studied. b. Type of compaction as a function of porosity and heterogeneity. Compaction bands develop in more homogeneous and more porous samples.

Our results suggest that 3D X-ray CT data can readily provide a local indicator of heterogeneity that is likely to play a significant role in the formation and propagation of compaction bands in porous sandstones. The coefficient of variation as second controlling factor after porosity may explain why, for instance, rocks with comparable porosity exhibit distinct compaction patterns. In situations where porosity was not measured beforehand or can not be obtained, the same X-ray CT data, through proper X-ray attenuation/density calibration, may be used to retrieve that porosity as well, making this tool potentially powerful for the prediction of localized compaction.

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