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A true triaxial experimental study on porous Vosges sandstone: from strain localization precursors to failure using full-field measurements

Cyrille Couture and Pierre Bésuelle Univ. Grenoble Alpes, CNRS, Grenoble INP, 3SR, 38000 Grenoble, France

Abstract

This study systematically investigates the effect of deviatoric loading paths on diffuse and localized deformation developing during the mechanical loading of a high porosity (20%) Vosges sandstone (Eastern France). Laboratory scale experiments are performed using a high pressure true triaxial apparatus, designed to provide access to full-field surface kinematics at high spatial and temporal resolutions during the loading phase. The true triaxial experiments, with independent control of the three principal stress, are conducted at two constant mean stresses, in the brittle-ductile transition regime, and at five prescribed Lode angles, from axisymmetric compression (ASC) to axisymmetric extension (ASE). First, the transition from diffuse towards localized deformation is analyzed in different loading increments and shows an intermediate step of early strain localization, characterized by a large number of early deformation bands developing well before the stress peak and with a predominantly dilatant behavior. Secondly, the evolution of the mechanical behavior and localization patterns, such as deformation band angles and localized dilatancy, indicate a transition from the brittle regime to the ductile regime that is not only dependent on an increase in the mean stress, but also on a decrease in the Lode angle. The analysis of fullfield measurements also provides insights into the emergence and evolution of local strains, as deformation structures coalesce or relocate and different failure modes develop depending on the prescribed stress paths.

Keywords: true triaxial experiments, strain localization, full-field measurements, localization precursors, Lode angle, sandstone, porous rock

¹ 1. General context

The development of strain localization in confined geomaterials is recognized as a fundamental deformation mechanism which generally relates to an evolution in the mechanical response and failure. In high porosity sandstone, this phenomenon is most often apparent in the form of a unique or series of parallel and conjugated deformation bands, characterized by extended structural deformations in narrow and linear zones of concentrated deformation [e.g., 1, 2, 3].

In studies performed under controlled laboratory settings, the manifes-9 tation of deformation bands leading to failure in stressed rock samples has 10 been demonstrated to be sensitive to the loading path and the mechanical 11 response of the underlying micro-structure. A well studied phenomenon in 12 high porosity rocks is the transition into a ductile regime with an increase in 13 the first invariant of the stress tensor, i.e. the mean stress [e.g., 4, 5]. The 14 conventional triaxial apparatus, where a stress deviator is applied in the ma-15 jor principal direction while the confining pressure is applied on a jacketed 16 cylindrical specimen, is well suited to assess the role of the mean stress. In 17 such experimental conditions, the apparatus-sample contact boundaries are 18 well defined, by the superposition of a confining fluid and a deviatoric loading 19 using an axial unidirectional rigid piston. Nonetheless, the lack of indepen-20 dent control between the radial stresses limits the imposed stress paths to 21 axisymmetric compression and extension conditions, leaving an intermediate 22 broad spectrum of the octahedral (deviatoric) plane unexplored. 23

To circumvent this limitation, different variations of the true triaxial ap-24 paratus (TTA) have been developed in various experimental laboratories, 25 aiming to investigate the role of alternative stress paths to the classical ax-26 isymmetric cases [6]. The most prominent method for mechanical testing of 27 rocks in true triaxial conditions consists in performing loading experiments 28 at different minor and intermediate principal stress levels, while the major 29 principal stress evolves with incremental axial strain. As such, the design ad-30 vancements of the TTA have enabled to demonstrate the important role of 31 the intermediate principal stress on the deformation and failure mechanisms 32 in various types of rocks. In terms of the resulting stress invariants during 33 this type of loading, while intermediate values of the Lode angle, between 34 0° and 60° , can be achieved, the Lode angle continuously and systematically 35 decreases in conjunction with an increase in the mean stress (σ_m). There-36 fore, the independent effect of the stress invariants on the evolution of the 37

material response cannot be directly assessed. Additionally, their continu-38 ous and simultaneous evolution during loading, inherent to principal stress 39 controlled loading, results in the distribution of stress states at failure to be 40 scattered in certain regions of the meridian and octahedral planes. Figures 41 1a.-l. illustrates this effect for selected data sets retrieved from the literature 42 for principal stress controlled testing of various rock samples, where values 43 of the peak octahedral stress, as defined in equation 1, are represented as 44 projections on a single octahedral plane. 45

An alternative experimental approach consists in systematically investi-46 gating different stress paths with prescribed invariants of the stress tensor, 47 by imposing an incremental relation between the principal stresses. Ex-48 periments performed under this type of loading procedure provide valuable 49 insight on the independent effect of isotropic and deviatoric loading paths on 50 the mechanical response and deformation mechanisms. Ingraham et al. [13] 51 performed a series of experiments under such loading conditions on samples 52 of a high porosity sandstone, by imposing two independent invariants during 53 the loading phase: the mean stress (σ_m) and the Lode angle (θ) , as defined 54 in equation 1. The peak stress recorded for each test are thus organized on 55 selected meridian and deviatoric planes (see Figure 1.m). Ma et al. [14] have 56 followed a similar methodology, for a mixed loading mode at a constant minor 57 principal stress and constant Lode angle in two different porous sandstone 58 samples. The results from these two studies have consistently shown a mea-50 surable effect of the Lode angle on failure and localization patterns analyzed 60 in post-mortem observations. Nonetheless, experimental data on the subject 61 are scares and many questions remain open as to the mechanisms involved 62 during the deformation process of porous rocks subjected to general stress 63 paths. 64

It is thus essential to further study the effect of different loading condi-65 tions in terms of the mechanical response, but also in their relation to the 66 emergence and development of localization structures in porous rocks. The 67 purpose of the present experimental campaign is therefore to systematically 68 explore the effect of different invariant controlled stress paths on the me-69 chanical response, combined with a unique full-field measurement technique 70 to characterize the diffuse and localized deformation in laboratory samples of 71 a Vosges sandstone, a high porosity quasi-isotropic model sedimentary rock. 72



Figure 1: Representation of stress state at failure in the octahedral plane, arranged by experimental campaigns retrieved from the literature: Dunham dolomite (a), Inada granite (b), Manazuru andesite (c), Mizuho trachyte (d), Orikabe monzonite (e), Solhofen limestone (f), Yamaguchi marble (g) [from 7]; Yuubari shale (h), Shirahama (i) [8] [data from 9]; Westerly granite (j) [10]; KTB amphibolite (k) [11]; Taiwan siltstone (l) [12]; Castlegate sandstone (m) [13]; Coconino sandstone (n), Bentheim sandstone (o) [14]. The color scale indicates the mean stress level reached at the deviatoric stress peak, the value of the maximum mean stress being specific to each study.

73 2. Methods and material

74 2.1. Experimental setup

The high pressure true triaxial apparatus (TTA) used for this experimen-75 tal campaign has been designed and assembled at Laboratoire 3SR (Greno-76 ble) for the specific purpose of testing rock samples in biaxial and true tri-77 axial loading conditions [15]. The apparatus is designed to accommodate 78 prismatic samples of $50 \times 30 \times 25 \text{ mm}^3$ inside a specially fabricated soft mem-79 brane installed in the main confining chamber. The loading mechanism of 80 this apparatus relies on a combination of direct fluid pressure and a pair of 81 rigid pistons to apply stresses at the surfaces of the prismatic samples. The 82 mixed boundary conditions aligned with the surfaces of the sample are thus 83 imposed by a combination of rigid stainless steel and sapphire glass contacts 84 in the major (1) and intermediate (2) directions, respectively; and a soft 85 contact through the jacket in the minor (3) direction. The loading device 86 is rated for a maximum isotropic confinement of up to 100 MPa, applied by 87 increasing the fluid pressure inside the confining chamber hosting the iso-88 lated sample. The stress deviators, decoupled in the major and intermediate 80 directions, are applied by the means of pressure controlled hydraulic pistons 90 (self-equilibrated with respect to the cell pressure). In the major direction 91 1, a set of sliding pedestals transfer the load on the surface of the specimen 92 while accommodating displacements in the orthogonal direction. For the 93 specified sample dimensions and through the effect of the balanced ram, the 94 stress deviator, in both the major and intermediate directions, can reach up 95 to 670 MPa and 530 MPa, respectively. A detailed description of the ap-96 paratus is given in [16]. A recent modification consist in the manufacturing 97 of urethane molding rubber to produce soft reusable jackets, making them 98 adaptable to strain gauge installation by passing cable through sealed con-90 duits; an essential improvement to obtain direct surface strain measurements 100 in the out-of-plane (non-visible) direction 2 [17]. 101

102 2.2. Loading Procedure

Using linear relationships between the principal stress values (σ_1 , σ_2 and σ_3), a loading procedure was developed for the control system of the apparatus to perform true triaxial loading experiments with imposed loading paths based on the invariants of the Cauchy stress tensor. While any combination of mutually independent set of invariants are suitable to objectively define general stress state increments, the Octahedral-Lode invariants is preferred as it describes a convenient polar coordinate system around the trisectrix, or
isotropic stress state line, in the principal stress space. The selected invariants are thus defined as

$$\sigma_{av} = \frac{1}{3} [\sigma_1 + \sigma_2 + \sigma_3]$$

$$\tau_{oct} = \frac{1}{3} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right]^{1/2}$$

$$\theta_{\sigma} = \arctan\left[\sqrt{3} \frac{\sigma_2 - \sigma_3}{(\sigma_1 - \sigma_2) + (\sigma_1 - \sigma_3)} \right]$$
(1)

where σ_{av} is the average stress, and τ_{oct} and θ are respectively the octahedral 112 stress and Lode angle, measuring independently the deviatoric stress mag-113 nitude and orientation in the octahedral plane (see Figure 2). The strain 114 invariants $(\epsilon_{av}, \gamma_{oct}, \theta_{\epsilon})$ are equivalently defined in terms of the principal 115 values of the strain tensor. In the adopted solid mechanics convention, com-116 patible with the presented full-field measurements, both principal stresses 117 and strains are positive in tension. To simplify the discussion of results, the 118 invariants along the trisectrix of the principal stress and strain space are pre-119 sented in terms of the mean stress, $\sigma_m = -\sigma_{av}$, and the volumetric strain, 120 $\epsilon_v = 3\epsilon_{av}$. Therefore σ_m is positive in compression and ϵ_v is positive during 121 dilatancy. The Lode angle, as defined in equation 1, spans from 0° in axisym-122 metric compression (ASC, $\sigma_2 = \sigma_3$) to 60° in axisymmetric extension (ASE, 123 $\sigma_1 = \sigma_2$). It is a measure of the deviatoric stress orientation in the stress 124 space, and can be intuitively interpreted as an indication of the intermediate 125 principal stress magnitude, with respect to the magnitude of the minor and 126 major principal stresses at a given mean stress. 127

For the presented experimental campaign, a consistent procedure was 128 followed for each experiment performed at prescribed loading paths: (1) a 129 sample alignment phase is initiated to insure centering of the contact between 130 the pistons, pedestals and the sample surfaces in directions 1 and 2; (2) a 131 subsequent isotropic monotonic loading phase consists of increasing the cell 132 pressure at a rate of 2 MPa/min, until the prescribed mean stress is reached; 133 (3) finally, a deviatoric loading phase consists in monotonically increasing the 134 octahedral stress while maintaining σ_m and θ at constant values. During this 135 last loading phase, a PID controller feedback loop prescribes the hydraulic 136 pressure to update the intermediate and minor principal stresses, in terms of 137 the major principal stress, according to the relationship: 138



Figure 2: A graphical representation of the cylindrical Lode coordinate system in the principal stress space (a), based on the three invariants σ_m , τ_{oct} and θ . In (b), the octahedral plane (normal projection on a plane perpendicular to the isotropic state line) and the meridian plane (τ_{oct} vs. σ_m) provide complementary 2D information of the stress state.

$$\sigma_2 = \frac{3\tan\theta - \sqrt{3}}{2\sqrt{3}} (\sigma_1 - \sigma_m) + \sigma_m$$

$$\sigma_3 = \frac{-3\tan\theta - \sqrt{3}}{2\sqrt{3}} (\sigma_1 - \sigma_m) + \sigma_m$$
(2)

obtained from a simple algebraic rearrangement of equations 1. The hy-139 draulic syringe pumps are controlled based on this set of equations, while 140 including additional proportionality parameters to calibrate the hydraulic 141 pressure in the piston according to the sample surface stresses and frictional 142 correction terms. These linear correction terms take into account the varia-143 tion in the dynamic friction effect between the piston shaft and the seals with 144 the variation in hydraulic pressure in the main confining chamber, which is 145 equal to σ_3 . The correction of σ_1 ranges from 4.6 MPa to 9.7 MPa and the 146 correction σ_2 from 3.2 MPa to 9.3 MPa, for values of σ_3 between 0 MPa and 147 -90 MPa. 148

Due to significant non-linear elastic deformation of the apparatus during the deviatoric loading phase, the vertical strain rate could not be explicitly prescribed based on the measurements from the external LVDT linked to the control system. The exact strain measurements are therefore a priori

Table 1: Mineral characterization of Vosges sandstone

mineral composition	93% quartz
	5% microcline
	2% mica and kaolinite
porosity	21%
grain size	150-450 $\mu \mathrm{m}$
mean grain size	$300 \ \mu \mathrm{m}$

unknown during the experiments, since applied corrections from the sample 153 boundary displacement are obtained by digital image correlation during the 154 post-experimental analysis. Instead, the monotonic loading in the major 155 principal direction is controlled at a constant injection rate (1.5 cc/hr) in 156 the vertical piston chamber, resulting in a mean vertical strain rate for all 157 the experiments of $4.2 \times 10^{-7} \,\mathrm{s}^{-1}$ at the beginning of the deviatoric loading 158 phase and $2.3 \times 10^{-6} \,\mathrm{s}^{-1}$ at the end of the hardening phase. This strain rate 159 evolution during the experiment is a function of the compressibility of the 160 injection fluid, an hydraulic oil with entrapped air pockets, and the stiffness 161 of the true triaxial apparatus. 162

163 2.3. Material

A total of ten samples has been prepared using a single block of Vos-164 ges sandstone originally retrieved from the Woustwiller quarry, in Eastern 165 France. The mineral composition and micro-structural characterization of 166 this sedimentary rock, reported here in Table 1, were documented by Bésuelle 167 et al. [18] in an earlier experimental study on this particular porous sand-168 stone. The initial porosity for each of the retrieved sample has been measured 160 at $21\% \pm 1$, showing a satisfactory consistency between sampling locations 170 of the block. 171

The prismatic samples, of approximate size $50 \times 30 \times 25$ mm³, are pre-172 pared as to have symmetric boundary conditions on opposite surfaces of the 173 geometry by performing successive iterations of machining, polishing and 174 later applying watercolor paint coatings. The allowable tolerance on the 175 parallelism is ± 0.02 mm for each pair of surfaces in contact with the hard 176 platens (hardened steel in direction 1 and sapphire glass in direction 2) and 177 ± 0.03 mm for the pair of surfaces in contact with the urethane membrane, af-178 ter the strain gauge installation. The surfaces in contact with the platens are 179 finally lubricated using a thin coating of a stearic acid and vaseline mixture, 180

effectively minimizing end friction effects under high confining pressures [19]. This thin lubricant coating being translucide, the visual aspect of the fine speckle pattern applied over the surface is maintained after an homogeneous contact is established between the sample and the sapphire glass.



Figure 3: Intact prismatic samples of Vosges sandstone showing (a) the natural porous surfaces and (b) prepared surfaces with horizontal strain gauges, painted surfaces and the monochromatic speckle. Orthogonal vectors mark the spatial directions associated with the principal stress space.

185 2.4. Instrumentation and measurements

The unique conception of the TTA used in this study enables the monitoring of full-field surface kinematics, using digital image correlation (DIC), from photographs of one of the sample surface during the loading phase. The out-of-plane strains are also measured directly on the sample surface using strain gauge instrumentation.

The full-field photographs of the sample surface are captured through a sapphire viewport, oriented in the 1-3 plane (orientation as in Figure 3). The digital imaging system, a single-lens reflex (DSLR) 36 Mpx Nikon D800E camera, provides a spatial pixel size of 7 microns over the entire surface of the sample. In the camera configuration used to minimize noise and shutter vibrations, photographs were taken at regular intervals with a minimum time period of 3 seconds/image.

On the white painted and polished visible surface of the sample, a fine 198 monochromatic speckle pattern is applied by paint atomization, using a pre-199 cision airbrush, to create a random deposition of black watercolor droplets 200 over the whole region of interest (ROI) (Figure 3b). This process enhances 201 the optical texture and uniqueness of local zones of interest (ZOI) from the 202 natural texture created by the surface heterogeneity on the surface of the 203 porous sandstone. The DIC algorithm relies on the conservation of optical 204 flow during the deformation process. Therefore, the spatial resolution, con-205 vergence and systematic error in the process rely on the quality of the optical 206 texture in each ZOI. The texture quality is assessed for each created speckles 207 by computing the autocorrelation function [20]. The autocorrelation radius 208 is a scalar measurement of the pixel displacement where the autocorrelation 209 function of a ZOI reduces by half, indicating the level of self similarity of 210 the texture around this area [21, 22]. Measurements of the autocorrelation 211 radius in the vertical and horizontal directions are shown in Figure 4a and 212 4b respectively for a typical surface ROI. For DIC, a speckle pattern with an 213 autocorrelation radius of around 2 pixels is considered to provide an optimal 214 texture quality which is independent of the acquisition noise. 215

The DIC algorithm used to performed the image analysis is the open 216 source Software for Practical Analysis of Materials (Spam) developed as a 217 collaborative and open source project [23]. The correlation algorithm, de-218 signed for 2D and 3D analysis, is based on a two step approach: an initial 219 correlation to the nearest pixel, generating an approximation of the defor-220 mation field by tracking large rigid body motions, and subsequent iterations 221 consisting in a sub-pixel correlation based on the initial approximation ob-222 tained from the first step. This latter operation allows for all possible affine 223 (six degrees of freedom in 2D) transformations of the ZOI, to accurately track 224 the local displacement at each node. One of the purposes of the displacement 225 field obtained from DIC is to apply corrections to the sample's boundary 226 displacement in the 1-3 visible plane, providing accurate global strain mea-227 surements. The strain in the horizontal direction 3 is computed from the 228 horizontal displacement of DIC points at the two vertical boundaries. In the 229 vertical direction 1, the external LVDT measurement is corrected at regular 230 intervals using accurate DIC measurements, compensating deformation ar-231 tifacts from the compliance of different parts of the apparatus (loading cell, 232 surface contact interfaces) measured externally. The contribution of in-plane 233 deformation to the global volumetric deformation of the sample is calculated 234 from the sum of averaged outward displacements at each boundary. This 235



Figure 4: Assessment of speckle quality and measurement error in sample G16, at $\sigma_m = 60$ MPa and $\theta = 0^\circ$, showing: the fields of autocorrelation radii in the vertical (a) and horizontal (b) direction, and image correlation of two photographs in the same deformation state (c), compared to the increment 1-2 reported in Figure 7.

method is equivalent to the computation of the contour integral for smalldeformation gradients.

Additionally, the two-dimensional fields of incremental local strain, cal-238 culated from the spatial first order derivative of the displacement field, are of 239 clear interest in identifying localization patterns and their evolution. Nonethe-240 less, due to reduced continuity compared to the discrete displacement field, 241 the local strain field is more sensitive to the errors in the image acquisition 242 process and selected DIC parameters (acquisition noise, choice of ZOI size, 243 convergence error resulting from the DIC process). It is thus necessary to ap-244 ply local corrections and filtering of the displacement field to obtain a better 245 representation of the derived strain field. First, the field of correlation resid-246 uals, quantifying the correlation error and non-linear deformation, is used 247 to mask the displacement field; the values at poorly correlated nodes are 248 replaced by a weighted interpolation of surrounding converged nodes. Sec-249 ond, a sequential median and mean convolution of the nearest neighbors is 250 performed to render a continuous field by eliminating isolated singularities, 251 at the expense of degrading the local pixel-scale deformation measurements. 252

From the resulting filtered displacement field, a local strain tensor is calculated based on the displacement of 4 neighboring nodes using a regular grid layout and linear finite element shape function interpolations. This procedure yields a spatial map of the local deformation gradient tensor at the center of each cell. Since large rotations and strains may develop locally, large transformation formalism is used for the local deformations derived from the incremental displacement field (see Appendix A).

To assess the effect of acquisition and correlation errors on the strain 260 measurements, Figure 4c shows a deviatoric strain field calculated using two 261 photographs acquired in the same deformation state, at the beginning of 262 the deviatoric loading phase (at photograph 1). In the deformation range of 263 interest, the strain measurement error is seen to be only slightly more im-264 portant in regions of the sample surface where the the autocorrelation radius 265 is higher. However, this error remains negligible in comparison to the mag-266 nitude of localized deformation observed in selected subsequent increments 267 of the deviatoric loading phase (increment 1-2 is illustrated in Figure 4d for 268 comparison). 269

To measure the out-of-plane deformation in direction 2, strain gauges were 270 installed horizontally at mid-height on both sides of the sample surfaces in 271 contact with the soft membrane. For the axisymmetric compression experi-272 ments, where $\sigma_2 = \sigma_3$, it was observed that strain gauges in direction 2 and 273 DIC measurements in direction 3 were in good agreement until pronounced 274 localization effects start to develop. This reveals a good correspondence be-275 tween different measuring techniques as well as strain homogeneity despite 276 different types of boundary conditions with different end-friction and possi-277 ble bulging effects developing in independent directions 2 and 3. The global 278 volumetric strain is represented as to take into account the full three dimen-279 sional in-plane and out-of-plane components in each of the three principal 280 strain directions. 281

282 3. Experimental Results

Guided by the study of Bésuelle et al. [18] in which axisymmetric compression (ASC) and extension (ASE) loading experiments were performed on samples of the Vosges sandstone (extracted from the same initial block), the range of mean stress was selected to investigate deformation mechanisms associated with the brittle-ductile transition regime. The present experimental campaign thus consisted of ten monotonic loading experiments following

σ_m^{peak} [MPa]	θ^{peak} [°]	$-\sigma_1^{peak}$ [MPa]	$-\sigma_2^{peak}$ [MPa]	$-\sigma_3^{peak}$ [MPa]	$ au_{oct}^{peak}$ [MPa]	β [°]
61.1	0.0	128.7	27.2	27.3	47.8	50
61.7	16.0	121.0	46.8	17.3	43.6	56
62.3	29.6	110.6	61.9	14.5	39.3	61
61.9	45.4	96.9	75.1	13.7	35.2	64
62.0	59.9	87.9	87.8	10.4	36.5	64
90.0	0.0	169.0	50.4	50.4	55.9	43
90.1	15.1	166.4	69.8	34.0	55.9	47
$90.0^{[2]}$	$14.9^{[2]}$	168.7	68.9	32.6	57.5	-
91.4	32.4	148.8	94.2	31.2	48.1	54
90.0	44.9	136.9	107.1	26.2	46.8	56
89.9	59.9	122.8	122.7	24.1	46.5	56

Table 2: Summary of stress states and angle β at $\tau_{oct}^{peak[1]}$ for each of the 10 loading paths

[1] The *peak* superscript designates the moment when the octahedral stress reaches its maximum value.

[2] Duplicated experiment at $\sigma_m=90$ MPa and $\theta=15^{\circ}$ not represented in subsequent Figures.

invariant controlled loading paths at five prescribed Lode angles (0, 15, 30, 45 and 60°) at two mean stresses (60 and 90 MPa).

A summary of the peak principal stresses and corresponding stress invari-291 ants is presented in Table 2. In this Table, a duplicated data point at $\sigma_m=90$ 292 MPa and $\theta = 15^{\circ}$ is provided. Since only the stress values for this additional 293 experiment are available, it is not represented in subsequent Figures, but 294 helps to consolidate the result for this loading path. Due to differences in 295 the correction terms applied to Equation 2, embedded in the servo-controlled 296 loading program (constant for tests at $\sigma_m = 60$ MPa; linear dependency with 297 σ_3 for tests at $\sigma_m = 90$ MPa) and in the post-experimental correction func-298 tions (linear dependency with σ_3 for all tests), there is a slight discrepancy 299 between the mean stress and Lode angle initially prescribed and the peak 300 values of the controlled invariants reported in Table 2. The importance of 301 the correction terms dependence on the cell pressure (σ_3) was only assessed 302 after the first part of the experimental campaign. The deviation is however 303 not significant compared to the mean stress and Lode angle intervals between 304 the different selected stress paths. Therefore, the closest prescribed values 305 will be used to reference the different loading paths. 306

307 3.1. Mechanical response

The evolution of global octahedral stress (τ_{oct}) and volumetric strain (ϵ_{vol}) 308 during the deviatoric loading phase is reported for each experiment against 309 the octahedral strain (γ_{oct}) in Figure 5. A first comparison of the different 310 mechanical responses at the two studied mean stresses indicates that, irre-311 spective of the Lode angle prescribed for each experiment, an increase in the 312 mean stress, from 60 MPa to 90 MPa, favours a slower bending of the octa-313 hedral stress versus strain curve during the pre-peak regime, while the initial 314 stiffness is essentially the same. Consequently, the peak octahedral stress is 315 found to increase with the mean stress, a classical result often reported in the 316 literature for experiments following ASC loading paths. While the increase 317 in the peak stress with the mean stress is more pronounced at a Lode angle 318 of 15°, the variation in this increase with the Lode angle remains moderate 319 and appears to become relatively constant between experiments at higher 320 Lode angles of 30° to 60° (Figure 6). 321

At each of the two investigated mean stresses, loading paths following 322 different Lode angles in the octahedral plane also promote a significant vari-323 ation in the mechanical response during the late pre-peak regime. During 324 this stage of loading, the octahedral stress level along the stress-strain curves 325 is consistently lower at higher Lode angles. A noticeable difference in the 326 stress-strain response is also apparent between the lower $(0^{\circ}, 15^{\circ})$ and higher 327 $(30^{\circ}, 45^{\circ}, 60^{\circ})$ values of the Lode angle (mostly apparent at $\sigma_m = 90$ MPa). 328 This marked difference in the octahedral stress evolution during the pre-peak 329 regime results in a consistent decrease in the peak octahedral stress with in-330 creasing Lode angle, while the octahedral strain corresponding to the peak 331 stress tends to increase. Between the two prescribed mean stresses, this in-332 fluence of the Lode angle on the peak stress occurs over a different range of 333 Lode angles. In Figure 6a, it is seen to steadily decrease from 0 to 45° at 334 $\sigma_m=60$ MPa and over a shorter range of 15° to 30° at $\sigma_m=90$ MPa (con-335 solidated by the additional data point in Table 2). The non-linearity in the 336 peak octahedral stress transition indicates an evolution of the shape of the 337 failure surface with both the mean stress and the Lode angle (Figure 6b). 338 Furthermore, the variation in the peak octahedral stress over the full range 330 of Lode angles, from 0° to 60° , is of comparable magnitude to the effect of 340 the mean stress for the range investigated in the present study (from 60 to 341 90 MPa). As for the residual stress, after peaking and softening, the values 342 depend on the mean stress and are rather independent of the Lode angle, 343 except for the tests at 0° angle where the residual stress is clearly above the 344



Figure 5: Octahedral stress (τ_{oct}) and volumetric strain (ϵ_{vol}) as a function of octahedral shear strain (γ_{oct}), analogue to τ_{oct} in the strain space. The curves are dashed in the post peak regime, indicating a loss of quasi-static conditions and apparatus displacement control regulation in all but tests at a Lode angle of 0° .

345 other values.

The evolution of global volumetric deformation, combining measurements 346 using DIC in the 1-3 plane and strain gauges in the out-of-plane direction 347 2, is also affected by the prescribed mean stress and Lode angle. In this 348 particular case, for selected loading paths at constant mean stresses, it can 349 be noted that the elastic part of the volumetric deformation is theoretically 350 vanishing. Therefore, the initial compactant behavior, represented in Figure 351 5c-d, suggests an inelastic deformation is occurring at the initiation of the de-352 viatoric loading phase. At the mean stress of 60 MPa, all samples displaying 353 an initially compactant behavior transition into a dilatant phase at approx-354 imately halfway through the pre-peak phase. At this lower mean stress, a 355 distinctly lower volumetric change is observed for the Lode angle of 0° . In 356 comparison, the samples tested at higher Lode angles display both a more 357 pronounced initial compactant and a subsequent well defined dilatant phase. 358



Figure 6: Evolution of the octahedral stress at dilatancy (τ_{oct}^{dilat}) and peak stress (τ_{oct}^{peak}) in (a). The same dataset is represented in the octahedral plane in (b).

At the mean stress of 90 MPa, the volumetric deformation, for the different 359 loading paths, follows two distinct evolutions during the pre-peak regime: at 360 the lower Lode angles of 0° and 15° , a monotonic volumetric deformation 361 sustains a moderately compactant behavior of the samples (however, a very 362 slight dilatation is observed at 15° towards the stress peak); whereas, at the 363 higher Lode angles, the response is similar to the behavior observed at the 364 lower mean stress, displaying a more pronounced compactancy followed by a 365 well defined dilatant phase. It is possible to identify the octahedral stress at 366 the octahedral strain where the inception of dilatancy occurs for each loading 367 path. In Figure 6, the decrease in the octahedral stress at dilatancy with de-368 creasing mean stress and increasing Lode angle is concordant with the trend 369 in the transition of the peak octahedral stress. In this Figure, the value at 370 $\sigma_m = 90$ MPa and $\theta = 0^\circ$ is omitted since the volumetric deformation is con-371 tinuously compactant for this loading path. At the higher mean stress and 372 intermediate values of the Lode angle, the difference between the octahedral 373 stress at dilatancy and at the peak decreases with decreasing Lode angle, 374 while it remains relatively constant for all Lode angles at the lower mean 375 stress. 376

In the post-peak regime, all samples tested at a mean stress of 90 MPa 377 have a compactant total volume strain past their respective peak octahedral 378 stress. However, since mature localization structures tend to emerge around 379 the peak stress, global measurements from average boundary displacements 380 become discontinuous in this phase of the mechanical response. The global 381 strain measurements are therefore less representative of the predominant de-382 formation mechanism occurring inside the sample. In addition to being the 383 dominant deformation mechanism at the sample scale during the post-peak 384 regime, localized deformations also play an important role on the mechan-385 ical response during the pre-peak regime. In the next section, incremental 386 full-field measurements are presented and compared for the different loading 387 paths, enabling to characterize the emergence of precursors and early de-388 formation structures during the pre-peak regime, and their relation to the 389 development of highly localized structures near and past the peak stress. 390

391 3.2. Localization patterns

A full-field representation of local deformation, obtained from DIC in 392 the 1-3, plane enables the identification of strain localization structures de-393 veloping during the deviatoric loading phase. In the multi-page Figure 7, 394 incremental 2D deviatoric and volumetric strain fields for each of the 10 ex-395 periments are depicted in consecutive series, from photograph $n \rightarrow n+1$. 396 Each increment in the series, associated with each experiment at different 397 loading paths, represents different characteristic phases of the mechanical 398 and kinematic behavior: an early quasi-linear phase (1-2), an intermediate 399 phase of volumetric compaction (2-3), the inception of dilatancy generally 400 associated with the inception of early deformation bands (3-4), the intensifi-401 cation of localized zones into well developed early deformation bands (4-5), 402 the development of mature localization structures organized into a single or 403 multiple parallel and conjugated bands (5-6), brittle faulting or propagation 404 of mature deformation band(s) (6-7). The series of photographs, from which 405 the represented incremental strain fields are produced, are labeled on the 406 associated individual stress-strain and volumetric curves. 407

In the initial volumetric compaction phase represented in increment 1-2, the deviatoric strain fields for all loading paths show relatively similar patterns of weakly defined regions of higher strain deformation. During this early loading phase, the deviatoric strain fields thus present some identifiable heterogeneities at the finer scale, where a spatial variation in the deformation is noticeable between neighboring correlation points forming small distributed clusters. Nonetheless, the represented strain fields do not, at this stage, exhibit any strong evidence of localization clustering or organization at the
sample scale.

In full-field images of subsequent increments, following photograph 2 in 417 respective experiments, two distinct types of deformation bands can be iden-418 tified to sequentially emerge into well defined localization structures. The 419 first type, referred to as *early deformation bands*, is observed to emerge well 420 before the peak stress and develop in series of parallel and conjugated linear 421 clusters of limited length, visible mostly in the central section of the ROI. 422 The localization structures which are well defined in increments 3-4 and 4-5, 423 can also be observed, if one looks closely, as weak precursors in increment 424 2-3. The second type, referred to as *mature deformation bands*, later develop 425 close to the peak stress and is characterized by one or multiple extended lo-426 calized regions traversing across the sample. Mature deformation bands can 427 be seen to initiate during increment 4-5 and 5-6, and to fully develop during 428 increments 5-6 and 6-7 in respective experiments. 429

The early deformation bands are seen to emerge from a progressive clus-430 tering of strain localization in specific areas of the visible surface of the 431 samples, forming preferentially orientated linear structures which are contin-432 uously evolving throughout the later pre-peak regime. During this phase, the 433 deviatoric strain inside early deformation bands gradually intensifies and fur-434 ther localizes in specific regions of the ROI. This evolutive behavior forming 435 localized regions is most noticeable for experiments following loading paths 436 at the higher mean stress of 90 MPa and higher Lode angles. It is also dur-437 ing increments 3-4 and 4-5, following the inception of the incremental global 438 dilatancy, that the volumetric strain fields start to show significant localized 439 dilatant zones, preferentially organized where localization structures are also, 440 and more noticeably, observed in the deviatoric strain fields. It is therefore 441 worth noting that, even for a relatively high porosity sandstone, the early 442 deformation bands are dilatant except for low Lode angles. 443

For all studied loading paths, the continuous evolution of strain localiza-444 tion towards the end of the pre-peak regime leads to the formation of mature 445 deformation bands, which develop concurrently to rapid stiffness weakening 446 effects and a well defined transition of the mechanical response from a pre-447 peak to a post-peak regime. The development of these mature bands tends 448 to occur in regions of the visible surface where early deformation bands have 449 been persistent during the late pre-peak regime. After the peak stress, during 450 increments 5-6 and 6-7 of Figure 7, most loading paths are seen to promote 451



Figure 7: (part 1) Evolution of deviatoric and volumetric strain fields over the 2D ROI, for selected consecutive loading increments. The stress state and 3D volumetric deformation corresponding to each photograph are identified on the macroscopic curves by red circles.



Figure 7: (part 2) Evolution of deviatoric and volumetric strain fields over the 2D ROI, for selected consecutive loading increments. The stress state and 3D volumetric deformation corresponding to each photograph are identified on the macroscopic curves by red circles.



Figure 7: (part 3) Evolution of deviatoric and volumetric strain fields over the 2D ROI, for selected consecutive loading increments. The stress state and 3D volumetric deformation corresponding to each photograph are identified on the macroscopic curves by red circles.



Figure 7: (part 4) Evolution of deviatoric and volumetric strain fields over the 2D ROI, for selected consecutive loading increments. The stress state and 3D volumetric deformation corresponding to each photograph are identified on the macroscopic curves by red circles.

a rapid concentration of strain localization into a unique linear structure propagating through the sample. Once such a well developed localized region starts to form, it tends to attract additional deformation. A notable exception to this deformation mode is identified for the loading path in Figure 7b (at $\sigma_m = 90$ MPa and $\theta = 0^\circ$), where mature deformation bands are continuously activated and seen to relocate during the post-peak regime.

For samples tested at a mean stress of 60 MPa and a Lode angle greater 458 than 0° , the development of mature deformation bands ultimately results 459 in a global mechanical instability just after the peak stress, which can be 460 explained by the relatively low stiffness of the apparatus compared to the 461 absolute value of the tangential stiffness of the samples during the post-peak 462 regime. Under these conditions, the deformation band propagates quasi-463 statically approximately halfway through the sample before quasi-static con-464 ditions are lost. At this instant, a complete propagation of the localized zone 465 occurs dynamically, as elastic strain energy accumulated in both the sample 466 and the apparatus, is suddenly released. For this type of failure mechanism, 467 the resulting deformation zone is mostly concentrated around a unique and 468 narrow band, with a normal of the band oriented at a moderately high angle 469 $(45^{\circ} \text{ to } 65^{\circ})$ with respect to the most compressive principal stress. 470

A71 At the higher mean stress of 90 MPa and Lode angles greater than 0°, 472 while mechanical instability can occur (see pressure regulation loops in Fig-473 ure 5), the softening response is generally better controlled. At this higher

mean stress level, a number of localized structures evolving from early de-474 formation bands are more prone to coalesce and form a complex localized 475 zone during the inception of a mature deformation band. The outcome of 476 this coalescence process is a higher variability in the band thickness and in-477 ternal orientation, which is not entirely captured by a single characteristic 478 length. In increment 6-7 of Figure 7, a combination of compactant and dila-479 tant zones is observed around the mature deformation band, corresponding 480 to alternating localization orientation along the deformation band. 481

A substantial difference in the manifestation of mature deformation bands 482 is observed, at both mean stresses, for a Lode angle of 0° . For these partic-483 ular ASC loading paths, it can be noted that the deformation bands are not 484 necessarily polarized in the 1-3 visible plane since the minor and intermedi-485 ate principal stresses are equal. In the presented strain fields, the mature 486 deformation bands evolve through the continuous intensification of extended 487 localized regions close to the peak stress and later in the softening regime. 488 This mode of localization occurs under a systematically compactant volu-489 metric strain of the mature deformation bands. Additionally, at the mean 490 stress of 90 MPa, localized deformation regions evolve with the activation 491 (and deactivation) of conjugated and parallel bands during the post-peak 492 regime, resulting in a continuous relocation of the localized regions. 493

It is noted that in the majority of cases, but not in all, the mature bands 494 pass through one of the corners of the sample. This corner attraction effect 495 is well known in axisymmetric tests on cylindrical samples. However, the 496 field measurements presented here clearly show that, probably thanks to the 497 quality of the lubrication and the flatness of the surfaces, the deformations 498 prior to the mature localization do not present any particular characteristics 499 linked to the edges or corners of the samples. These appear to have a negli-500 gible impact on the overall response of the sample but sufficient to influence 501 the position of the mature bands (not their orientation). 502

⁵⁰³ 3.3. Deformation band angles and dilatancy angle

The orientation of early deformation bands (β *) and mature deformation bands (β) in the visible plane is measured as the angle between the normal vector to the quasi-linear localized regions and the direction of the most compressive principal stress (σ_1). By characterising the deformation band angles during the loading phase from the incremental strain fields, the measure of the band angles reflects the intrinsic response of the material



Figure 8: Identification of early deformation band angles (β^*) from deviatoric strain field increments.



Figure 9: Evolution of the early and mature deformation band angles for the different loading paths in the octahedral plane(a), and dilatancy angle of mature deformation bands measured at their inception (b).

at the inception of the localized zones. Therefore, subsequent structural effects influencing the final band orientation, such as attraction to conjugated
bands or boundary imperfections during propagation, can be avoided. This
direct interpretation of the band angle at its inception is usually lost during
a post-mortem assessment of the failed material.

The predominant angle β^* characterizing early deformation bands is qual-

itatively assessed for the series of parallel and conjugated bands observed in
the central sub-region of the ROI represented in Figure 8. While a certain
variability in the early band angles in each sample can be observed, the angle of the red lines represents the general orientation of these bands as they
emerge in samples subjected to the different loading paths.

The measured angle of early and mature deformation bands is reported for 521 each experiment in Figure 9a. In both cases, the angle is seen to increase with 522 decreasing mean stress and increasing Lode angle. At both mean stresses, 523 the change in deformation band angle is generally more pronounced at lower 524 Lode angles and tends to become constant at the higher Lode angles. The 525 mature deformation bands are also systematically developing at a higher 526 angle than the preceding early deformation bands, regardless of the loading 527 path. 528

⁵²⁹ The dilatancy angle of mature deformation bands is defined as

$$\tan\phi = \frac{\Delta D^v}{\Delta D^s} , \qquad (3)$$

where ΔD^{v} and ΔD^{s} are respectively the volumetric and shear offsets across 530 the localized region [24]. With large measurement errors due to the speckle 531 quality degradation inside the highly deformed bands, the volume and shear 532 offsets are obtained from the averaged displacement on each side of the band 533 during increment 5-6. In Figure 9b the dilatancy angle, positive for a dilatant 534 band, is seen to increase with decreasing mean stress and increasing Lode an-535 gle, in a trend that is comparable to the evolution of the mature deformation 536 band angle. Therefore, experiments at a low Lode angle show a shear local-537 ization with compaction (compacting shear band) and at a high Lode angle, 538 a shear localization with dilation (dilatant shear band). Nevertheless, in this 539 simplified representation, the complexities observed in the mature deforma-540 tion bands are not captured and must be kept in mind. This is particularly 541 illustrated at the high mean stress of 90 MPa, where there are fluctuations 542 in local orientations that impart a kind of roughness to the mature bands, 543 as well as variability in volumetric strain along the band associated with this 544 roughness. 545

546 4. Discussion

547 Experimental results from this campaign on a high porosity sandstone 548 provide strong evidences that distinct loading paths, following deviatoric

stress increments in the octahedral plane, promote substantially different 549 mechanical and kinematic responses. The influence of the mean stress on the 550 stress-strain behavior and failure mechanism, widely recognized in the case of 551 axisymmetric (compression and extension) stress paths, is here also observed 552 at intermediate values of the Lode angles. The effect of the different loading 553 paths is also evidenced by the local strain evolution measured from full-field 554 DIC. The significance of localization precursors, their evolution leading to 555 different failure mechanism and the transition in the brittle to ductile regime 556 is here further discussed. 557

558 4.1. Localization Participation Ratio

To compare the rich information conveyed by the spatial distribution of local strain measurements across different experiments, and quantify its evolution during loading, the Localization Participation Ratio (LPR), first introduced to the field of geomechanics by [25], is calculated for each series of increments. This scalar index of localization provides an appreciation of the deviatoric strain concentration over the visible plane. It is mathematically defined as

$$LPR = \frac{1}{N_p} \frac{\left[\sum \epsilon_{dev}\right]^2}{\sum \left[\epsilon_{dev}^2\right]},\tag{4}$$

where ϵ_{dev} is the spatially distributed local deviatoric strain (as defined in 566 Appendix A), and N_p is the number of sampling points over the ROI. It is 567 calculated for each incremental field of deviatoric strain, quantifying a depar-568 ture from a homogeneous spatial distribution. Therefore, calculated values 560 of the LPR are independent from the size of the selected increment, consider-570 ing an equivalent homogeneous distribution of deviatoric deformation in this 571 increment is above the noise level resulting from the image acquisition and 572 treatment process. The upper limit, LPR = 1, corresponds to an homoge-573 neous distribution of the considered spatial variable; whereas the lower limit 574 depends on the number of measurements on the domain for which a strongly 575 localized state (e.g. a Dirac distribution) results in $LPR = \frac{1}{N_p}$. The ROI 576 over the considered two dimensional plane is a 600×300 area, excluding sub-577 regions on the fringe of the sample surface where the autocorrelation radius 578 or DIC residuals were showing larger uncertainties. 579

Figure 10 shows the evolution of the LPR for the incremental deviatoric strain fields reported in Figures 7. For all tested samples, the LPR indicates a weak variation in diffuse localization during the pre-peak regime until a



Figure 10: Localization Participation Ratio (LPR) evolution with octahedral strain for tests at (a) σ_m =60 MPa and (b) σ_m =90 MPa . The position of each point correspond to the end of the interval in which the LPR is measured. The sequence of increments are labeled in one of the curve as a reference.

strong decrease is initiated during the increment 4-5 (near the peak-stress), 583 characteristic of well-developed early deformation band and the inception 584 of a mature deformation band. At the mean stress of 60 MPa, the LPR 585 decreases rapidly at around 0.6% octahedral strain. At a mean stress of 586 90 MPa, for Lode angles of 0 and 15° the increase in the mean stress is 587 seen to induce a decrease in the LPR at around the same octahedral strain 588 of 0.6%. At higher Lode angles, the octahedral strain at which the LPR 589 starts to decreases is however noticeably higher and shows a more progressive 590 evolution towards the full development of mature deformation bands. Even if 591 the spatial organization of deviatoric strain is not captured in the LPR, this 592 observation is consistent with the progressive evolution in the coalescence 593 of localized deformation at higher mean stress and for Lode angles above 594 15°. This dissimilar kinematic response to an increase in the mean stress, 595 between Lode angles above and below 30°, suggests a strong influence of the 596 Lode angle on the deformation regime leading to failure. 597

598 4.2. From localization precursors to failure

⁵⁹⁹ During the early deviatoric loading phase, corresponding to increments ⁶⁰⁰ 1-2 and 2-3, the relatively large inelastic compaction observed at the sam-⁶⁰¹ ple scale for experiments conducted at higher Lode angles occurs in a rela-⁶⁰² tively diffuse deformation process, which is reflected by the initially stable or

slightly increasing LPR. Therefore, during this phase of loading, the sample 603 deforms mostly in the absence of identifiable structural localization patterns. 604 Nonetheless, samples experiencing a higher initial compaction at the sample 605 scale, are associated with a subsequent well defined transition into a dilatant 606 regime, during increment 3-4. Concurrently, these samples present a higher 607 deviatoric strain intensity and dilatant volumetric strains concentrated inside 608 early deformation bands. This relation between the initial compactant be-609 havior and the later localization behavior at different Lode angle emphasizes 610 the role of selected loading paths in a single octahedral plane in promoting 611 different diffuse deformation responses and transitions into the development 612 of localization structures. 613

The emergence of dilatant early deformation bands results from the pro-614 gressive clustering and densification of initially scattered localization precur-615 sors. Under monotonic deviatoric loading conditions in the octahedral plane, 616 the inception and intensification of these early bands appear to be driven by 617 shear deformation with a predominantly dilatant behavior. In this instance, 618 the dilatant volumetric strain, mostly apparent in localized zones at higher 619 Lode angles, is concurrent with a reversal from an incremental compactancy 620 to an incremental dilatancy in the global volumetric deformation measured 621 at the sample scale. This observation suggests that the presence of dilatant 622 early deformation bands constitute an important deformation mechanism 623 contributing to inelastic deformation and a concentration of weakening defor-624 mation in fewer regions of the porous rock during the later pre-peak regime. 625 The continued development of early deformation bands appears to be an im-626 portant phenomenon concomitant with the loss of linearity in the octahedral 627 stress-strain curve. It can therefore be inferred that, at least for the range of 628 mean stress investigated here, the lower octahedral stress attained at higher 629 Lode angles is related to the emergence and continuous organization of these 630 early structural deformation zones developing well before the peak-stress. 631

In samples where a well defined dilatant regime is observed, i.e. for load-632 ing paths where $\theta > 0^{\circ}$, strain localization tends to rapidly coalesce and 633 concentrate into fewer localized regions of higher intensity and increasing di-634 latancy as the peak stress is approached. Consequently, during this process, 635 previously localized regions tend to progressively become inactive. The peak 636 stress is reached when a dominant sublinear zone of high strain concentra-637 tion propagates through the sample and develops into a mature deformation 638 band by connecting early deformation bands of limited length into a contin-639 uous structure. During this transition, a dilatant region, comprising earlier 640

deformed regions, remains active ahead of the tip of the propagating ma-641 ture deformation band (identified in Figure 11b-c). Since early deformation 642 bands tend to initially form at a lower angle than the later mature deforma-643 tion bands, the localized zones become connected by sections of alternating 644 internal angles. Figure 11 illustrates the presence of echelon type patterns 645 connecting early deformation bands of higher activity along the length of 646 the mature localized region, with associated dilatant (high angle) and com-647 pactant (low angle) zones. The prevalence of this deformation mechanism 648 is corroborated by similar, although post mortem, observations in [7]. In a 640 series of experiments on Dunham dolomite in true triaxial loading conditions, 650 the author identifies the existence of secondary micro cracks, here identified 651 as early deformation bands, on the sample surface, as well as a variation in 652 the internal angles of mature deformation bands along its length. Conse-653 quently, the formation of early deformation bands, here identified at a lower 654 inclination, seems to plays a significant role on the roughness and thick-655 ness variation of mature deformation bands, which in turns can influence 656 the post-failure behavior of the material, during the quasi-stable permanent 657 regime. This suggests that the spatially inhomogeneous deformation and in-658 duced anisotropy from oriented early localized structures can influence the 659 later occurring failure mode in the material. 660



Figure 11: Correspondence between early localized regions (a) during the pre-peak and the mature deformation band angle variation (b) and volumetric strain (c) at the peak. The represented sub-regions are increments 3-4 (pre-peak) and 5-6 (peak) of Figure 7d.

While compactant sub-regions along propagating deformation bands are observed at higher Lode angles, a contrasting continuously compactant type of deformation bands is only observed in samples tested at a Lode angle of

0°. For these particular ASC loading paths, deformation mechanisms differ 664 significantly in terms of the development of localization structures during the 665 transition around the peak stress. In this case, strain localization appears 666 to be more distributed across the sample and develops simultaneously in 667 multiple and extended active regions. During the late pre-peak to post-668 peak transition, the distribution of compactant deformation bands over a 669 larger part of the sample suggests that, unlike dilating deformation bands, 670 compactant bands have a lesser tendency to concentrate strain localization 671 into a single linear mature deformation band, as previously suggested by 672 [18]. Instead, the stable deformation process inside compactant band result 673 in a network of evolving and highly connected internal sub-structures. This 674 phenomenon is most apparent at the higher mean stress of 90 MPa, where 675 multiple localized regions remain active during the post-peak regime and 676 progressively relocate to nearby lesser deformed regions of the sample. 677

678 4.3. Brittle-ductile transition

For the range of stress paths studied in this experimental campaign, the 679 variation in the mean stress and Lode angle between different loading paths 680 is shown to have a significant influence on the global mechanical response 681 and on the spatial evolution of localization phenomena. For the studied 682 Vosges sandstone, an increase in the mean stress or a decrease in the Lode 683 angle systematically induce a transition from a brittle to a ductile mode of 684 failure. This transition is apparent in the mechanical response by an increase 685 in the maximum octahedral stress, a progressive softening in the post peak 686 and a reduction in the incremental volumetric strain at the peak. In terms of 687 localized deformation modes, the brittle to ductile transition is seen through a 688 decrease in both the band angle of early and mature deformation bands and in 689 the dilatancy angle measured at the peak stress. Furthermore, concentrated 690 dilatant early and mature deformation bands are systematically observed in 691 samples showing a brittle failure mode, while a compactant behavior and 692 relocation of mature deformation bands is associated with a ductile failure 693 mode. 694

The transition in the brittle-ductile behavior in the deviatoric plane is further evidenced by the non-linear shift in the peak octahedral stress occurring in the low to intermediate interval of Lode angles (Figure 6). The similarity in the peak value between 0° and 15° at the mean stress of 90 MPa, reinforced by an additional point at 15° (Table 2), emphasizes the observation of a shorter transition range at higher mean stress. Past this transition, ⁷⁰¹ further increase of the Lode angles appears to have a diminishing effect on⁷⁰² the peak stress and mature deformation band angles.

In terms of strain localization patterns, a brittle-ductile transition can 703 generally be associated with the aforementioned change in the type of defor-704 mation bands formed during the post-peak regime. A shift in the deformation 705 patterns towards a ductile response is seen to occur with a decrease in the 706 Lode angles. In a study following similar loading paths at imposed mean 707 stress and Lode angle, Ingraham et al. [13] observed a similar trend, where 708 a decrease in the Lode angle results in a shift from well defined narrow de-700 formation bands to a more diffuse mode of failure, where individual bands 710 could not be identified in a post-mortem assessment. The authors also noted 711 that the shift towards a more ductile response occurs at higher mean stresses 712 for higher Lode angles. 713

Despite a general concordance between the mechanical and kinematic (i.e. 714 localization pattern) interpretation of the brittle-ductile transition, it can be 715 noted that, for samples tested at a mean stress of 90 MPa and Lode angles of 716 0° and 15° , while having a similar octahedral stress-strain response during the 717 pre-peak regime and a close peak octahedral stress, their mature localization 718 patterns is quit different. At the Lode angle of 0° , a ductile (continuously 719 relocating and compactant) deformation mode is observed, while at 15° the 720 deformation band can be seen as more brittle (propagating and compactant 721 with dilatant zones). Therefore, in this case the ductility in the deformation 722 mode is not uniquely related to the macroscopic stress-strain response, but 723 is specific to the loading path in the octahedral plane. 724

The range of the brittle-ductile transition is concurrent with a progres-725 sive shift in the intermediate principal strain (direction 2) with increasing 726 Lode angle and the increasing dilatant behavior observed in early deforma-727 tion bands. From these experimental observations, it appears that stress 728 paths promoting a shortening of the sample in the intermediate principal 729 direction 2 is contributing to localized dilatant effects in the visible plane 730 (1-3). The concentration of this effect in early deformation bands implies 731 that this mechanism probably exacerbates the alteration and weakening of 732 the rock fabric in localized zones. 733

In loading paths promoting a transition towards a ductile failure, the total octahedral strain in the sample at the inception of the softening regime is equivalent or lower than for loading paths leading to a more brittle failure. Therefore, the higher peak octahedral stress attained in those experiments seems to be attributed to the slower bending in the stress strain response, rather than a capacity of the samples to sustain higher global deformation,as the mechanical response transitions toward the ductile regime.

741 5. Concluding remarks

The presented experimental study, investigating the mechanical behavior 742 and full-field kinematics of a high porosity sandstone, contributes original 743 results obtained under unconventional and rarely studied true triaxial loading 744 paths in the octahedral plane. Using a unique experimental setup, strain 745 localization structures and their evolution during the loading phase were 746 assessed and compared for different deformation regimes. The use of optical 747 images, acquired at a high spatial and temporal resolution, and analysed 748 through digital image correlation (DIC), proved to be an effective method to 740 explore the role of micro-kinematics on the inception of localization structures 750 leading to different failure modes. 751

This study highlighted important transitions in the material response between the series of experiments performed at different purely deviatoric loading paths. Notably, it is demonstrated that an increase in the prescribed Lode angle results in a systematic increase in the angle of early (pre-peak) and mature (peak and post-peak) deformation bands, an increase in the dilatancy angle of mature deformation bands, as well as a decrease in the peak octahedral stress and an embrittlement of the sample response.

The evolution of kinematic structures identified at the surface of the sam-759 ple during the pre-peak regime clearly showed the emergence and continuous 760 development of early deformation bands. These bands are seen to organize 761 into parallel and conjugated sublinear strain localization regions of limited 762 length well before the peak stress. The ubiquitous presence of this inho-763 mogeneous mode of deformation seems to play an important role in the de-764 velopment of inelastic and dilatant effects at the sample scale. Also, the 765 observation of early strain localization is concordant with the continuous 766 weakening of the rock fabric integrity during the pre-peak regime. During 767 this loading phase, the progressive intensification and concentration of strain 768 in early deformation bands culminate into the formation of either dilatant 769 mature deformation bands propagating through the sample (fragile) or the 770 continuous deactivation/relocation of larger localized regions during the soft-771 ening regime (ductile). For the range of mean stresses investigated in this 772 study, the brittle-ductile transition, observed in both the strain localization 773

patterns and the mechanical behavior, occurs mostly in the lower to intermediate range of Lode angles, between $\theta = 0^{\circ}$ and 30° .

Finally, the angle of early deformation bands is found to be lower than the angle of mature deformation bands. Therefore, as early localized regions become connected, the alternating variation in internal angle of mature deformation bands influences their aspects (departure from flatness) and thus the material residual strength in the permanent regime.

These observations are important in taking into account the non-linear and complex response of porous rocks subjected to general true triaxial loading paths. Therefore, the relation between the mechanical response and development of strain localization, especially in the early stages of loading, should be considered to enrich existing constitutive models for high porosity sandstones, as well as other analog materials characterized by cohesivegranular micro-structures.

⁷⁸⁸ Appendix A. Strain decomposition

In the Software for Practical Analysis of Material, the deformation gradient tensor, **F**, is derived from the incremental displacement field obtained by 2D digital image correlation. In the large scale framework implemented in the strain calculation code, the change in length and angle is represented by the right stretch tensor:

$$\mathbf{U} = \sqrt{\mathbf{F}^T \cdot \mathbf{F}} = \sqrt{\mathbf{U}^T \cdot \mathbf{R}^T \cdot \mathbf{R} \cdot \mathbf{U}} = \sqrt{\mathbf{U}^T \cdot \mathbf{U}}$$
(A.1)

where **R** is the antisymmetric part of **F**, i.e. the rotation matrix, and " \cdot " denotes the inner product operator. This tensor is further decomposed into its isotropic and deviatoric multiplicative parts,

$$\mathbf{U} = \mathbf{U}_{iso} \cdot \mathbf{U}_{dev} \tag{A.2}$$

797 with

$$\mathbf{U}_{iso} = J^{1/2} \cdot \mathbf{I} \tag{A.3}$$

798 and

$$\mathbf{U}_{dev} = \frac{1}{J^{1/2}} \cdot \mathbf{U} \tag{A.4}$$

where J is the Jacobian, the determinant of **F**, giving the change in volume between the initial and final configurations. Therefore, the two scalar quantities representing the volumetric and deviatoric deformations are respectively,

$$\epsilon_{vol} = J - 1 \tag{A.5}$$

and the Euclidean norm of deviatoric part of the stretch tensor,

$$\epsilon_{dev} = \|\mathbf{U}_{dev}\| \tag{A.6}$$

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