



# Small-Scale Soft-Sediment Deformation Structures in the Cross-Bedded Coconino Sandstone (Permian; Arizona, United States); Possible Evidence for Seismic Influence

Leonard Brand\* and Sarah Maithel

Department of Earth and Biological Sciences, Loma Linda University, Loma Linda, CA, United States

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### \*Correspondence:

Leonard Brand  
lbrand@llu.edu

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The Permian Coconino Sandstone of northern Arizona contains numerous small-scale, soft-sediment deformation structures (SSDSs). These novel structures may be indicators of paleoenvironment or sedimentary processes. These SSDs are generally shallow and occur on the surfaces of cross-beds, in contrast to convoluted bedding up to tens of meters thick commonly observed in some other eolian sandstones. These differences in structures imply differences in the processes that formed the Coconino Sandstone, or differences in the underlying depositional conditions. These SSDs occur in outcrops at the Grand Canyon, and farther south in quarries near the towns of Seligman and Ash Fork. Size, orientation, structure, sedimentary context, clay content, and porosity of the structures are described. The SSDs occur as small folds and ridges on the paleo lee side of otherwise undisturbed cross-beds. Some are associated with small rotated sandstone blocks within the cross-beds. The structures are exposed on bedding plane surfaces and in cross-section on vertical quarry walls. A few SSDs up to a meter thick also occur in the Coconino Sandstone, but the others are only up to a few cm thick, 2–10 cm wide, and 20 cm to 10 m long. Evidence is presented that liquidization (as fluidization or liquefaction) may have been involved in producing these features, implying a high water content in scattered locations at time of deformation, but this process also requires some stressor to trigger the deformation. Seismic events may provide a triggering mechanism. The Coconino Sandstone SSDs represent unusual or previously overlooked small-scale features related to individual foreset surfaces.

**Keywords:** soft-sediment deformation, permian, cross-bedded sandstone, coconino sandstone, earthquake

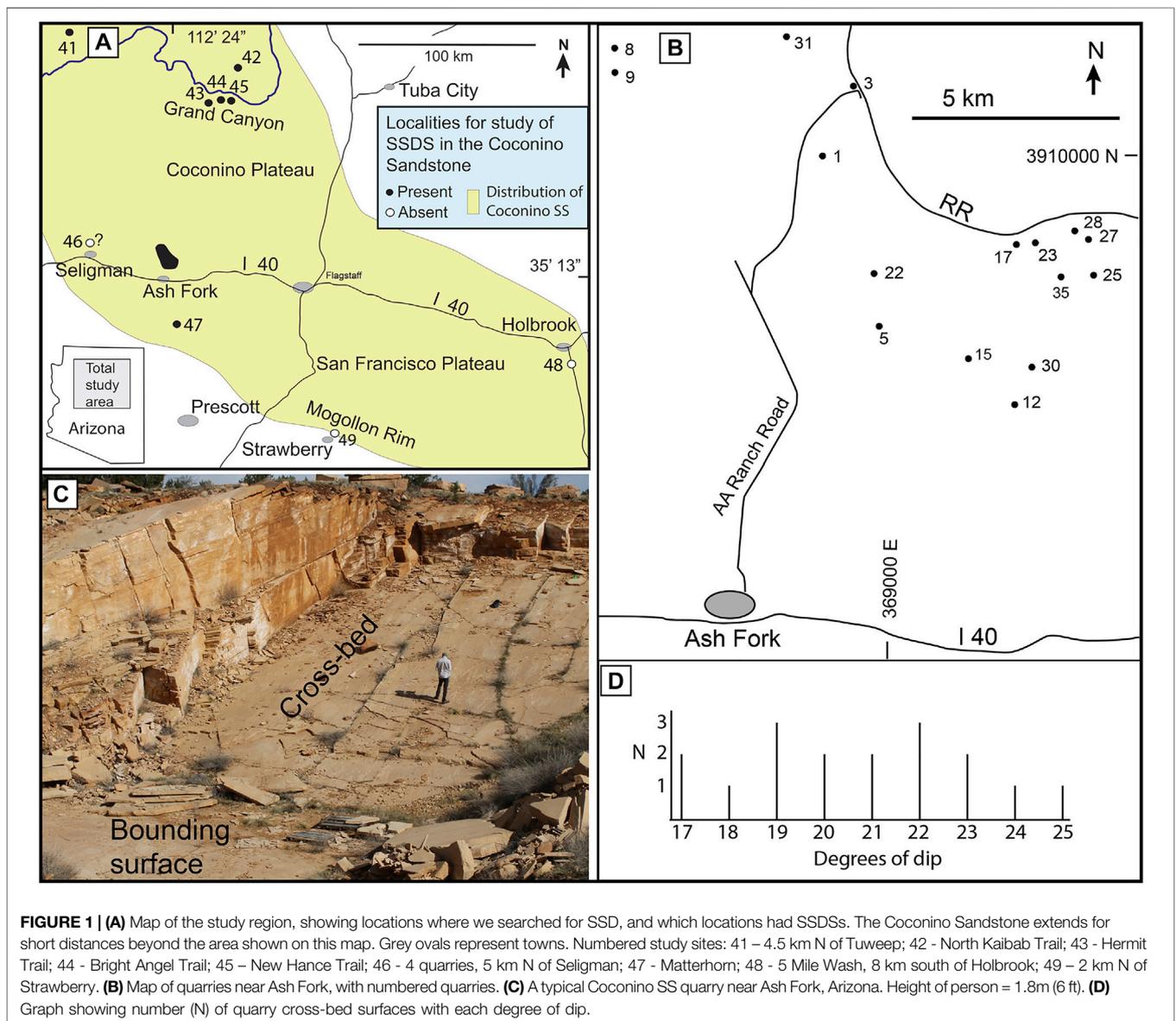
**Abbreviations:** SSD, soft-sediment deformation; SSDS, soft-sediment deformation structure; SSDs, soft-sediment deformation structures.

## INTRODUCTION

Rare examples of soft sediment deformation (SSD) have previously been reported in the Coconino Sandstone (Coconino SS), northern Arizona, United States, ranging from centimeter scale up to 4 m thick (McKee and Bigarella 1979; Whitmore et al., 2011). The current work documents numerous additional soft sediment deformation structures (SSDs) mostly on a centimeter scale, from this formation. These structures contrast strongly with much larger SSDs—up to tens of meters thick—that have been reported in other cross-bedded sandstones (Sanderson 1974; Bryant and Miall 2010). Such large-scale deformation examples have been interpreted to require a high water table (to liquefy the sand) or a high-moisture depositional environment (Doe and Dott 1980; Horowitz 1982; Alvarez et al., 1998; Netoff 2002; Chan et al., 2007; Rodríguez-López et al., 2008; Bryant and Miall 2010; Chan and Bruhn 2014; Bryant et al., 2016). The liquidization processes are thought to

facilitate the deformation of sediment before it is fully lithified (Allen 1977).

We hypothesize that the SSDs reported here in the Coconino SS also require liquidization, but involved smaller-scale triggers and some paleoenvironmental differences. A large global literature deals with soft-sediment deformation (SSD), which is defined as deformation in unconsolidated sediment (Mills 1983; van Loon 2009; Shanmugam 2017). Common types of soft-sediment deformation structures (SSDs) include folds, slumps, load structures, deformed cross-bedding, fluid-escape features and many others (Owen et al., 2011; Shanmugam 2017). These occur predominantly in coarse silt to fine sand (Mills 1983), and in both eolian and water-deposited facies (Cojan and Thiry 1992; Moretti 2000; Fernandes et al., 2007; Liesa et al., 2016). Deformation structures are commonly interpreted as products of liquidization (fluidization or liquefaction) triggered by seismic shaking. However, this is often impossible or very difficult to verify, so aseismic triggers



must be considered before settling on a seismic interpretation (Owen et al., 2011; Owen and Moretti 2011; Shanmugam 2017).

The middle Permian Coconino SS is fairly uniform in texture and structure throughout, and with few exceptions consists of vertically stacked, wedge planar or tabular planar cross-bed sets (McKee, 1974; Blakey and Knepp, 1989; Middleton et al., 2003). The sets of cross-beds vary from <1 m to over 20 m thick (measured from base of set). Cross-bed dips range from 13 to 27°. The grains in this strongly-cemented fine-grained sandstone are predominantly quartz (88–95%) with minor amounts of feldspar (Maitzel et al., 2019, 2021). The internal structure of the cross-beds was described by Middleton et al. (2003) as mostly thin laminae (<1 cm thick) that extend a considerable distance down dip within the set. As in other sandstones, the cross-beds are thought to represent preserved dune foresets, and Maitzel et al. (2021) suggested that grainflow and grainfall processes were responsible for most fine-scale sediment deposition.

The Coconino SS lacks substantial dateable material, but it has been stratigraphically defined as middle Permian (Middleton et al., 2003). The formation extends across northern Arizona (Figure 1) and is approximately 100 m thick at the Grand Canyon, thickening to the south as far as the Mogollon Rim. Near the town of Ash Fork, the lower contact is not exposed, but the unit is at least 160 m thick in that area.

On a larger scale, the Coconino SS is part of the Colorado Plateau, which covers northern Arizona and large parts of Utah, New Mexico and western Colorado. Its tectonic setting is defined by this plateau, which has been stable and only slightly deformed, particularly during the Paleozoic. The formation is surrounded on all sides by regions with much more faulting and deformation, beginning at least in the Mesozoic (Davis and Bump 2009).

McKee (1934) was the first to propose and develop an eolian depositional model for the Coconino SS. Subsequent studies followed this work (e.g., Reiche 1938; McKee 1945; Fisher 1961; Sorauf 1962; Lundy 1973; Elcock 1993; Sumner 1999; Maitzel et al., 2021), focused on stratigraphic relationships (Blakey and Middleton 1983; Blakey 1990), tetrapod trackways (Brand 1979, 1992; Brand and Tang 1991; Lockley and Hunt 1995; Brand and Kramer 1996; Millhouse 2009; Citton et al., 2012), or sedimentary properties (Maitzel et al., 2019, 2021). Similarly to McKee (1934), most authors interpret the formation as an eolian dune deposit (Reiche 1938; Baars 1961; McKee 1974; Blakey and Middleton 1983; Loope 1984; Blakey 1988; Middleton et al., 2003).

The small-scale SSD described in this paper are common in the Coconino SS, but have been almost entirely overlooked in previous studies. This research aimed to characterize these previously undocumented SSDs, and to interpret processes and triggers involved in their formation. Understanding fine-scale processes associated with these structures is significant because it may enable refinement of larger-scale paleoenvironmental models for cross-bedded eolian sandstones.

## MATERIALS AND METHODS

We examined Coconino SS outcrops across northern Arizona: along the North and South Rims of the Grand Canyon, near

Holbrook, at the Mogollon Rim, and in 25 flagstone quarries near the towns of Seligman ( $n = 4$ ) and Ash Fork ( $n = 21$ ; Figure 1). SSD was most readily studied in the flagstone quarries because of the well-exposed cross-bedding and bounding surfaces.

To determine the three dimensional distribution of the SSDs we photographed them on cross-bedding planes and in vertical quarry walls, and documented their locations and elevation with a handheld GPS (Garmin and a CHC Model X900). The orientation of each soft-sediment structure (SSDs) was determined with a Brunton compass and recorded with photographs. To characterize the surface features and internal structure of the SSDs we collected 53 samples from 21 quarries. From these samples, for this study and associated research, we produced 61 thin sections and 14 polished slabs for detailed study of the structures. At each quarry, we measured the strike and dip of the cross-beds with a Brunton compass ( $n = 21$ ). These data allowed the determination of any correlation between SSD and cross-bed dip. Regional dip of the Coconino SS in our study area was measured at Chino Wash, 5 km north of Seligman, using an Abney level.

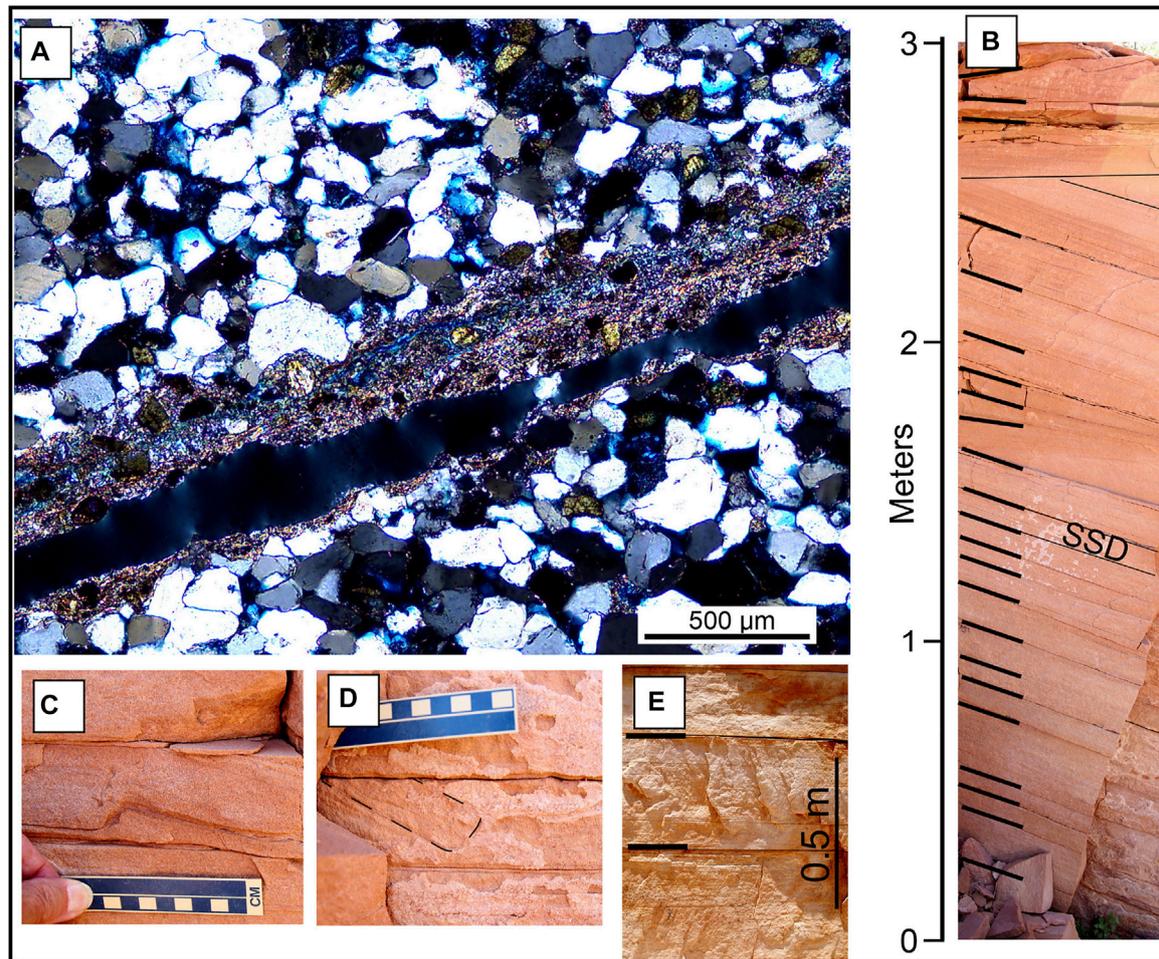
Quarry 25 at Ash Fork had numerous SSDs. We measured the length of each linear SSD ( $n = 25$ ) or linear segments of a complex SSD (separated by distinct breaks) ( $n = 39$ ), and determined its directional orientation with a Brunton compass. Thicknesses and distribution of SSDs were documented in vertical quarry walls, to evaluate the relationship between deformed and undeformed layers. Thirteen ridges and folds were described in cross-sectional view in the vertical quarry walls.

Clay mineral composition and distribution were documented to evaluate whether clays controlled the nature and occurrence of SSD. Clays were described in whole rock samples (Tescan/Vega/LSH scanning electron microscope; SEM) and in thin section (Olympus BX51 petrographic microscope). Thermo energy-dispersive spectrometry (EDS) and x-ray diffraction (Bruker D8) were also used to characterize clay mineralogy.

FIJI distribution of ImageJ software was used to quantify porosity from thin sections, as a percentage of the intergranular space in a sample (Schindelin et al., 2012; Schneider et al., 2012; Collins 2018). In this study limited porosity data were used; we collected porosity data from both deformed and undeformed portions of one sample, to explore the role of porosity as an indication of liquidization.

## RESULTS

All structures described in this study were observed in sets of cross-bedded sandstone, and texture from the Seligman and Ash Fork area was uniform. Grains averaged  $\sim 2.8$ – $2.9 \phi$  in size and were moderately sorted (excluding suspended fines, which were rinsed out in this study (Maitzel et al., 2021)). Seventeen out of the 21 Ash Fork quarries examined contain SSDs. In these 17 quarries, cross-bed dips range from 17 to 25° ( $n = 17$ ), with a mean of 20°. Most dips were toward the south. Regional dip of the Coconino SS (the upper first-order bounding surface) was measured at Seligman as 1.5° to the east. SSDs were also observed near Tuweep and along the North Kaibab, Hermit,



**FIGURE 2 | (A)** Thin section showing a clay drape lamina along a dipping ( $\sim 20^\circ$  dip) cross-bed surface, separating sandstone laminae below and above the clay drape. The black line shows where the bedding broke along the middle of the clay drape lamina. Up is toward the top of the photo. **(B)** A representative measured section on a vertical quarry surface. Thin lines outline laminae contacts; heavy lines are probable clay laminae, based on typical correlation between clay and cracks between laminae **(C,D)** SSDs in the middle laminae in **(B)**. **(E)** Thicker sandstone layers from another quarry. Thick lines are probable clay laminae.

Bright Angel, and New Hance trails in Grand Canyon National Park, and at a quarry 23 km (15 mi) SE of Ash Fork (**Figure 1A**).

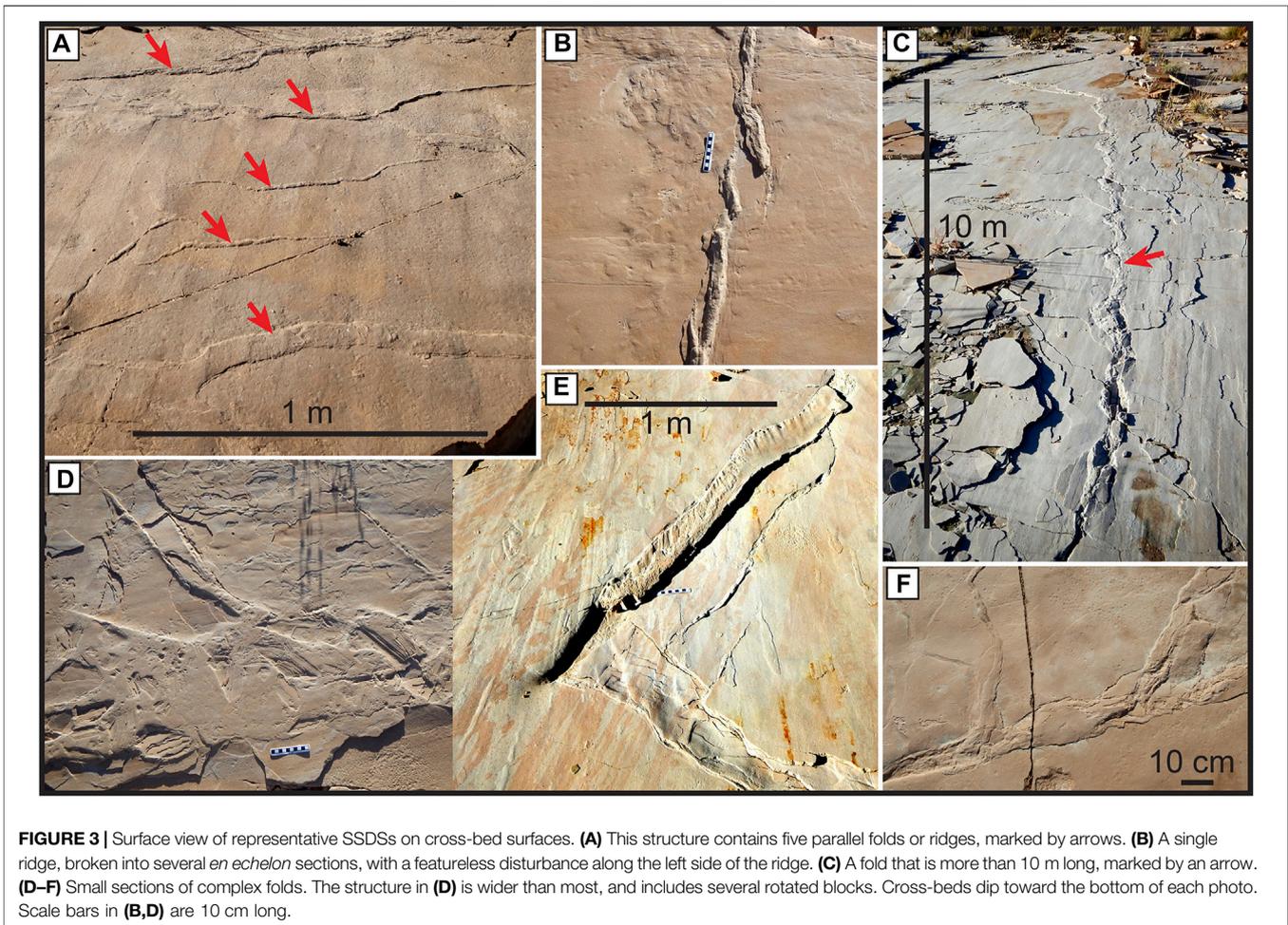
XRD data indicate a small percentage of kaolinite (estimated at  $< 1\%$ ; likely from feldspar dissolution), which was uniformly scattered throughout the thin-sectioned samples. No concentrations of kaolinite were seen in any of the samples. In contrast, concentrated clay drape laminae composed primarily of illite with a minor amount of kaolinite were observed, on the sloping surfaces of foreset beds, with an average slope of  $20^\circ$  (**Figure 2**). **Figure 2B** is a representative measured section on a vertical quarry surface. Thickness of sandstone layers between clay laminae ranged from 2.3 cm to over a meter. Analysis of clay was part of a separate study, and additional data on clay and its detailed distribution will be published elsewhere.

We found SSD on numerous cross-bedding planes, but did not see any on the 43 bounding surfaces that we examined, with two minor exceptions described later. As defined by Kocurek (1981) these were second-order bounding surfaces.

**TABLE 1 |** Number of each documented type of Coconino Sandstone SSD.

Feature	N	Figures
Quarries with SSD	17	
Individual folds or ridges	77	<b>Figures 3B,C,E, 4, 5</b>
Complex folds	32	<b>Figures 3A,D,F, 7A</b>
Groups of rotated blocks	18	<b>Figures 8, 9</b>
Monoclinical folds	2	<b>Figure 10</b>
Groups of pits or other fluid escape structures	14	<b>Figure 11</b>
Faults (to $\sim 4$ cm)	2	
SSDs in vertical quarry Walls	13	

The SSDs fall into several distinct categories. 1) Centimeter-scale folds and ridges on cross-bedding planes. In some cases these were associated with small rotated blocks of sandstone within the cross-beds. 2) Larger monoclinical folds. These are quite



different in structure, and occur on about a meter scale, rather than a centimeter scale. 3) Conical pits on the cross-bed surfaces. These are associated with other SSD features. 4) One case of convoluted bedding was found, which is different from the other structures. Evidence for liquidization in these structures was evaluated. The numbers of each type of SSDs are given in **Table 1**, and each will now be described individually.

### Folds and Ridges

Some SSDs consist of low-amplitude folds or sharp ridges on individual cross-beds whose surfaces are otherwise undeformed. SSDs of this type are common in the studied quarries and in some outcrops they are especially abundant. These all occur on the surface of dipping cross-beds (bedding planes).

The folds and ridges are 2–10 cm wide and range from 20 cm to 10 m long (**Figure 3**).

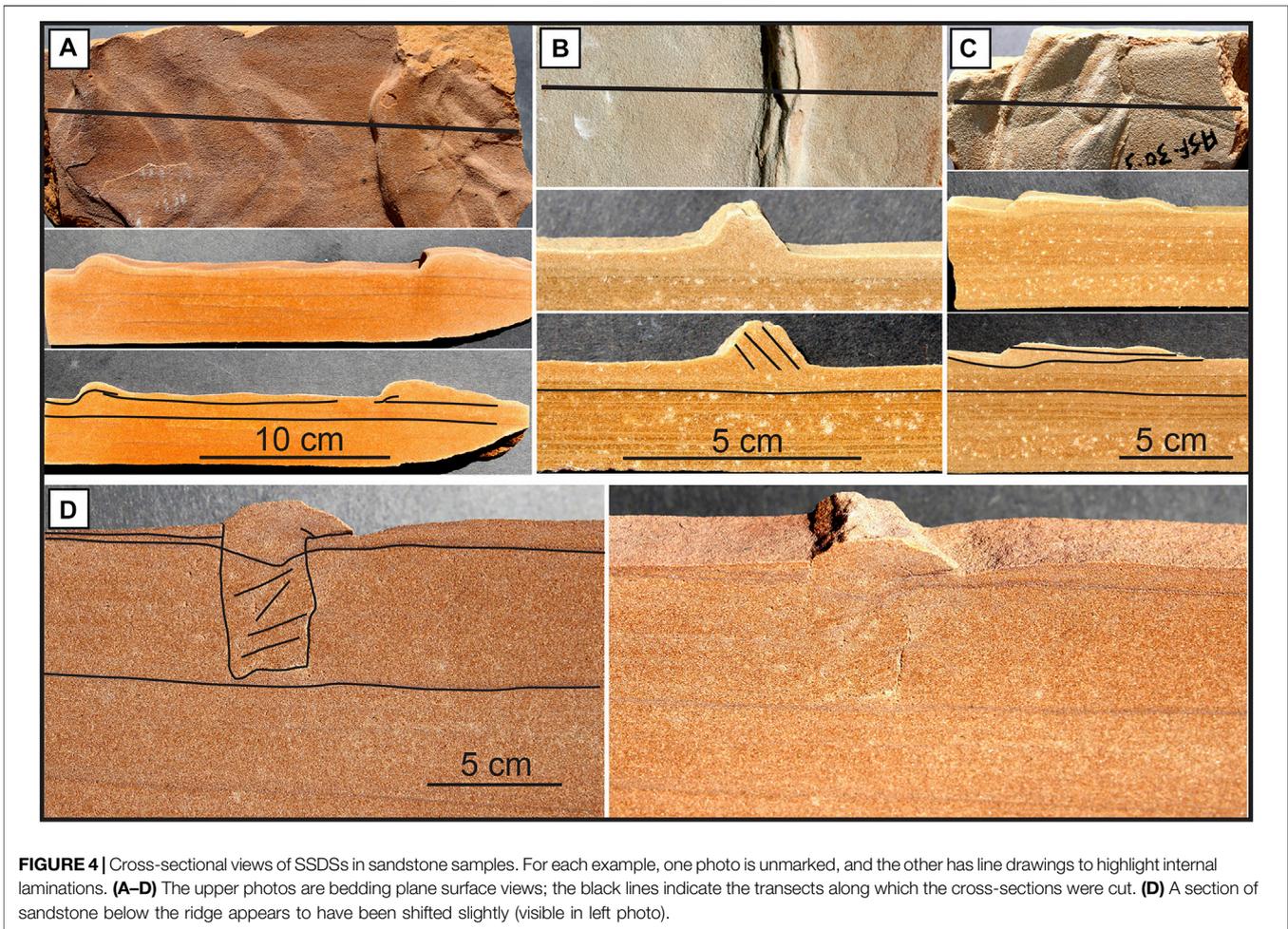
**Figure 4** shows cut and polished sections of sandstone samples, with cross-sectional views of the types of SSDs in **Figure 3**. The deformed sand forms either a sharp ridge (**Figure 3B**; **Figures 4B,D**; middle ridges in **Figure 3A**), or a wider, less elevated structure (lower feature in **Figure 3A**; **Figures 3D–F**). In cross sections through the ridges, laminations are tilted up sharply for a cm or more (**Figure 4B**; **Figures 5B1,B2**).

Deformed laminae in the upper first few cm below the surface follow the shapes of the surface features (**Figures 4, 5**). Undeformed laminae were observed in the underlying beds, usually 2 to 3 cm below each SSD, but in some cases, they first appear up to 8 cm below.

A ridge occurs along the top of the slab shown in **Figure 4D**, and a rectangular section of sandstone below that ridge appears to have shifted slightly, tilting to one side, while only producing a slight depression of the horizontal lamination below it. This tilting of a block below the ridge was not seen in any other section.

The SSDs in **Figure 5A** display another unique feature, in which sand extends over the top of the adjacent surface. Sediment appears to have moved in the direction shown by the arrows, and the subsurface structure is seen in cross section in **Figure 5B**; **Figures 5B1,B2** show cross sections along lines 1 and 2 in **Figure 5A**. At the forward end of the deformation, the sand appears to have flowed over the top of the original surface (**Figure 5B3**). Along the side of the deformation is a ridge, containing sand laminae tilted up sharply (**Figures 5B1,B2**).

Most of these SSDs are constrained to individual beds (**Figures 3–5**). Ridges and folds seen on vertical quarry walls were 3–8 cm thick, but some thicker examples were documented. In all cases the layers overlying and underlying these deformed



**FIGURE 4** | Cross-sectional views of SSDs in sandstone samples. For each example, one photo is unmarked, and the other has line drawings to highlight internal laminations. **(A–D)** The upper photos are bedding plane surface views; the black lines indicate the transects along which the cross-sections were cut. **(D)** A section of sandstone below the ridge appears to have been shifted slightly (visible in left photo).

layers were undeformed. **Figure 6** shows a fold about 10 cm thick that could be described as an overthrust over the adjacent sandstone layers (toward the left in the photograph). The top of the fold has been truncated by the overlying bed.

The shapes of these folds and ridges on bedding planes vary from approximately straight (**Figure 3C**) to complex in shape, with sharp changes in orientation at irregular intervals (**Figures 3D–F, 7A**).

The unusual cross-bed surface in quarry 25 curves sharply along strike, with relatively straight “arms” (008° and 080° dip directions) and an almost perpendicular angle between the two surfaces (**Figure 7C**). The surface with the 008° dip direction has many SSDs like those pictured in **Figures 3, 7A**, whereas the surface dipping at 080° exhibits none of these features.

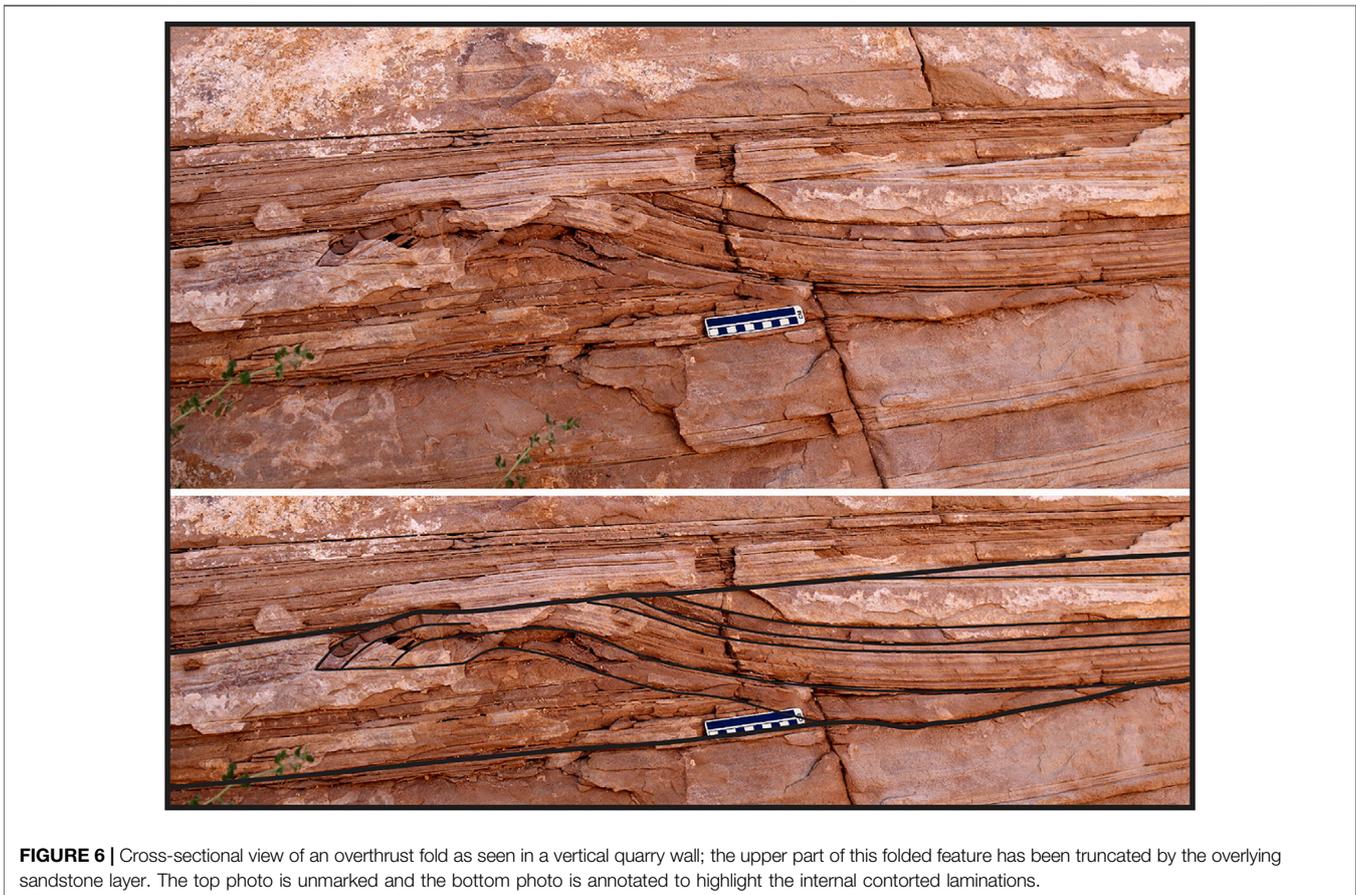
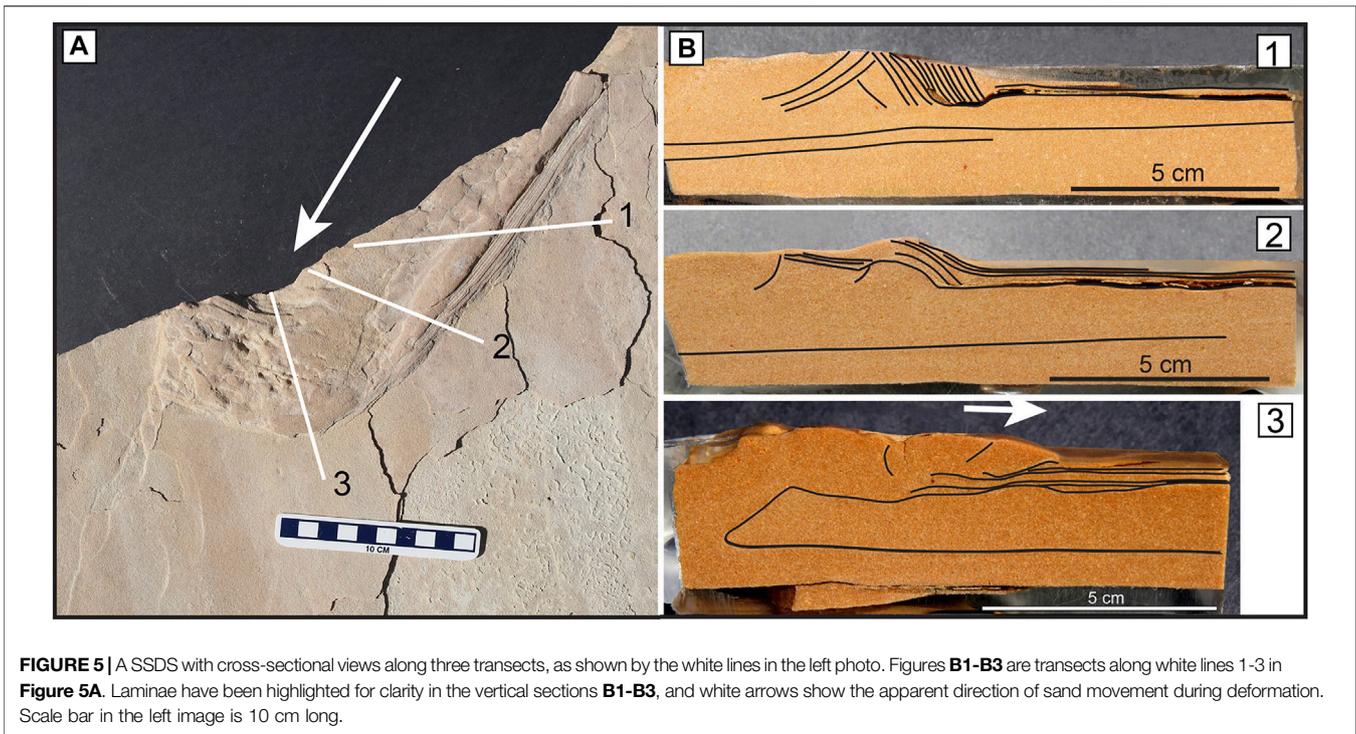
At this quarry the SSDs are sufficiently abundant to facilitate more detailed, quantitative comparisons of the folds. The orientation of straight folds or ridges, ( $n = 25$ ), or segments of complex folds ( $n = 39$ ) is shown in **Figure 7B**. Short folds or fold segments (less than 2.5 m in length) are oriented in diverse directions (**Figure 7B**), with very few along strike or dip, while the longer folds (3.5–10 m in length and mostly straight) are consistently oriented parallel to the dip of the cross-beds (approximately north-south; **Figure 7B**). In other quarries, the

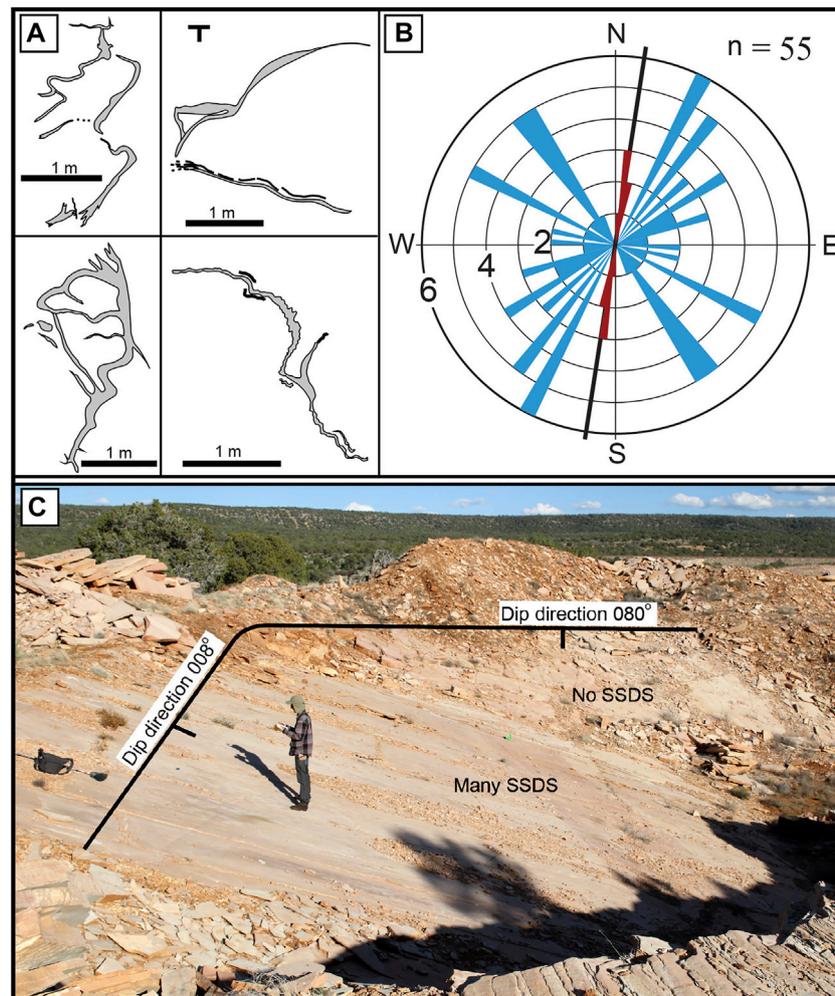
long folds or ridges ( $\geq 3.5$  m) are also oriented approximately along the cross-bed dip direction, toward the south.

### Rotated Blocks

Small, intraformational blocks of sandstone have rotated with respect to the undeformed cross-bedding surrounding them (**Figure 8**). Isolated examples occur, but clusters of these structures are common in some outcrops (18 clusters of these blocks were documented in various quarries). Where the upper edge of a tilted block meets the top of the bed, it is usually truncated at this level. The upper part of **Figure 8D** shows the typical appearance of the top surface of truncated blocks. In each case, the rotated blocks consist of fine-grained sandstone of the same texture as the surrounding bed. These blocks range from ~3–20 cm long in cross section, and on bedding planes they measure 5–15 cm wide (**Figure 8D**). The rotated blocks do not usually have sharp edges, but they have a definite, recognizable outline, and they generally maintain their laminated internal structure.

The rotated blocks do not tilt in a uniform vertical direction. While most blocks in **Figure 8D** have the same orientation, in **Figures 8A–C**, individual blocks tilt at different angles. Many more rotated blocks like those pictured here were observed, and





**FIGURE 7 | (A)** Examples of complex folds on Coconino Sandstone foreset beds, drawn in plan view. The structures in these drawings are raised folds or ridges (also shown in **Figure 3**). Cross-beds dip 18–25° toward the bottom of each image. **(B)** Fold-axis orientation of deformation structures from Ash Fork quarry 25 (also pictured in **Figure 8**). Blue: SSD ≤ 2.5 m long. Red: SSD 3.5–10 m long. The black line represents the cross-bed dip direction, toward the bottom of the diagram.  $n = 55$  simple folds or segments of 11 complex folds. **(C)** Sharply curved cross-bed surface at Ash Fork quarry 25. SSDs are abundant on the left side (8° dip direction; 196 sq m of surface), but absent on the right side (80° dip direction; 35 sq m of surface). Height of person = 1.8 m (6 ft).

they tilt at a wide range of angles, including almost vertical (perpendicular to the surrounding cross-bed; **Figure 8C**, in part). The orientations of rotated blocks vary widely, with most tilting upward to the north-north east, which is up dip with respect to the cross-beds (**Figure 9A**).

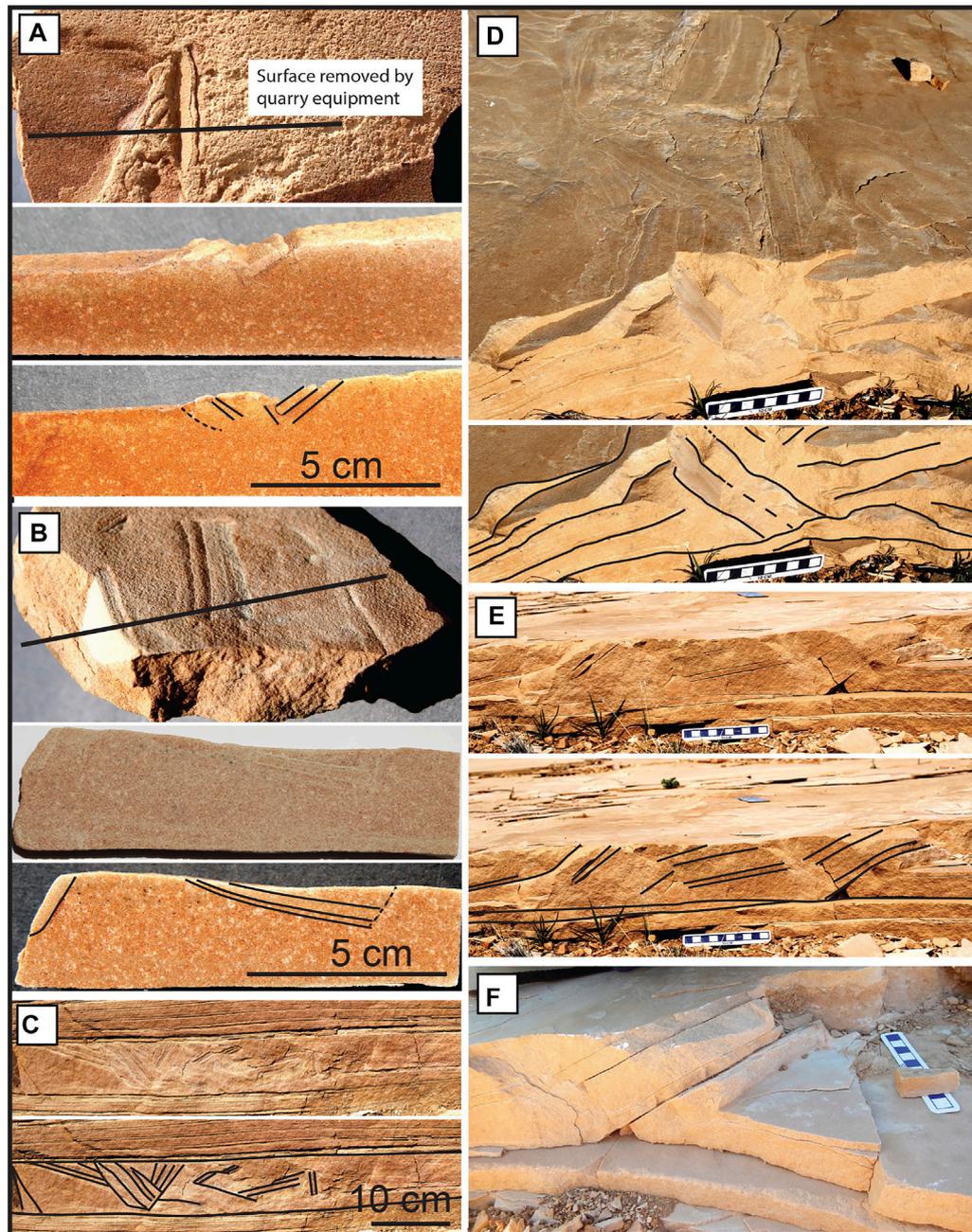
**Figure 9** shows an additional sample with rotated blocks (**Figure 9D**) and other deformation features including contorted bedding (**Figure 9C**). In this sample, the top surfaces of the rotated blocks and other deformations were not truncated along the top of the cross-bed, but exhibit up to 0.7 cm of relief above the upper surface of the bed.

### Larger Monoclinical Folds

Two larger SSDs occur in the form of simple monoclinical folds, which differ from the previously described folds and ridges in size and form. These are meter-scale features rather than

centimeter-scale, and are not just a localized deformation on an otherwise undeformed bedding surface; rather they each include a series of layers in a bed 0.5 to 1 m thick, that are folded into a monocline (**Figure 10**, lower part). They are unique among our findings, and are not part of a continuum of related structures. In one of these folds (**Figure 10A**), the deformation affects at least one vertical meter of sandstone, and it is folded 40 cm upward toward the right side of the photograph. This horizon is located stratigraphically near the top of the Coconino SS, at the top of the uppermost set of cross-beds in the section. Only 1 m of flat bedded sandstone occurs between this cross-bed set and the overlying Toroweap Formation. The axis of the fold is north west—south east, and the uplifted side is toward the north east.

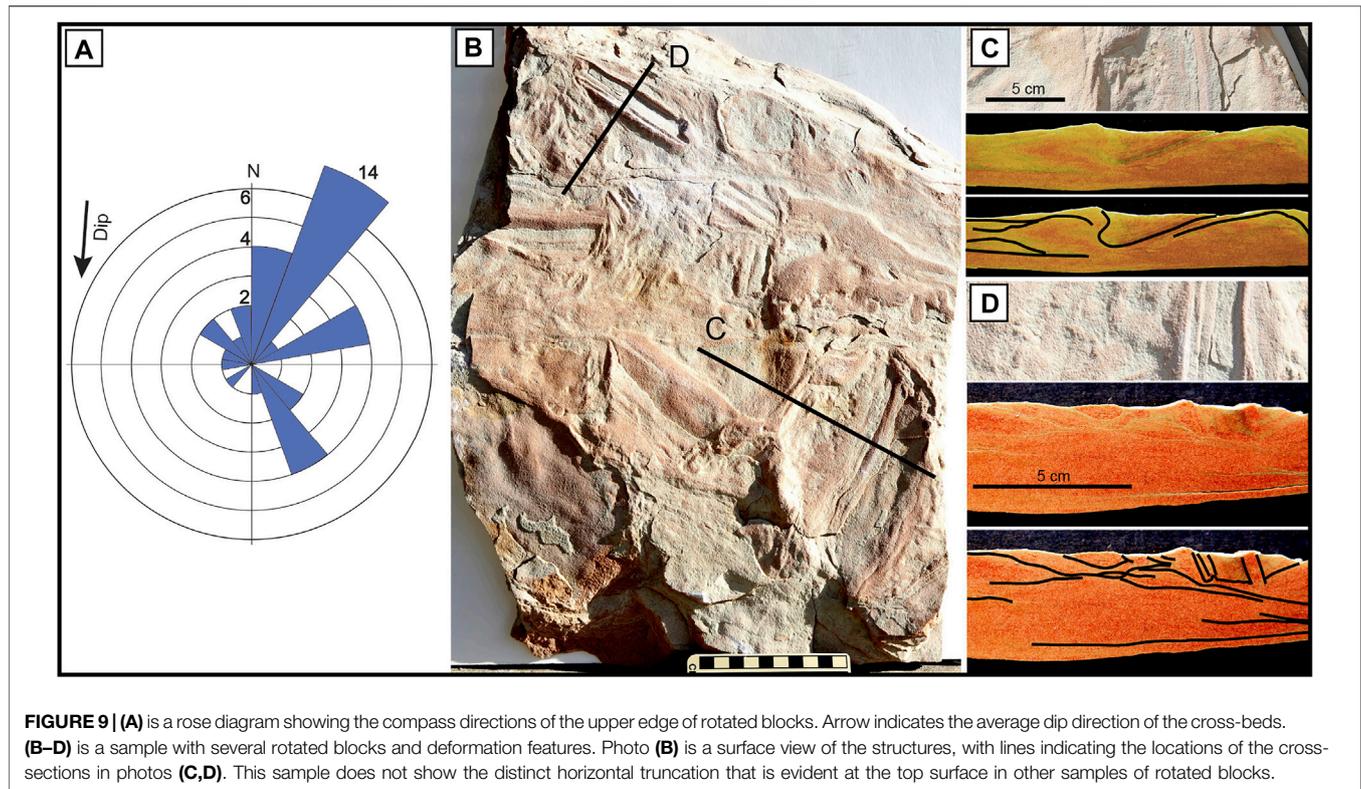
The second monoclinical fold (**Figure 10B**) is even larger and more complex. The folded unit spans a thickness of over 0.5 m, with all of these laminae exhibiting 23 cm of vertical relief, lifted



**FIGURE 8** | Cross-sectional views of four SSDSs, with rotated blocks. These are shown with and without lines annotating the rotated portions (**A–D**) Surface views of the structures, with heavy black lines in (**A,B**) indicating the transect orientations (**D–F**) Different views of a single SSDS. (**D**) shows the surface of the rotated blocks in (**E,F**), and (**F**) is a close-up of the right portion of (**E**). Scale bars in (**D–F**) are 10 cm long.

up toward the left in the photo (**Figure 10B**, bottom photo). The fold is not limited to just one stratigraphic level, but rises upward through at least 1.2 vertical meters of successive laminae, and is spread across ~3 m of horizontal distance (**Figure 10B**). The deformation likely extended much farther horizontally, but was removed by quarrying operations. This fold occurs about 44 m below the contact with the Toroweap Formation, in the

same quarry as the fold shown in **Figure 10A**. At least part of the fold (**Figure 10B**) may exhibit brittle deformation, in contrast to the fold in **Figure 10A**, which appears to exclusively represent ductile deformation. The axis of the fold in **Figure 10B** is approximately east–west, and the uplift is toward the north. The fold is stratigraphically higher at the east end, sloping down to the west.



### Conical Pits

Small, conical pits up to 3.5 cm in diameter were observed within 3–6 cm of some SSDs (14 total groups of pits in various quarries) (Figure 11). They usually occur in straight rows along one side of an SSD as seen in Figures 11C,D,F,G. Individual pits vary in width from 1 to 3.5 cm. The cross-bed shown in Figures 11F,G is 1.8 cm thick, and the pit extends vertically through at least the 1.8 cm bed (Figure 11G), and appears to continue below that.

Figure 11B shows a row of pits with a localized crack underneath; the crack extends vertically through the 3.5 cm-thick sample, up to the bottom of the pits. This crack does not appear to have formed from quarrying processes, but is closely associated with the pits and was likely an original feature.

Another slab has features that are similar to the pits, but are much larger: about 10 cm in diameter (Figure 11H). This loose sample was collected from a quarry at a location called the Matterhorn, 23 km (15 mi) southeast of Ash Fork.

### Convoluting Bedding

In an outcrop 4.5 km (2.8 mi) north of the Tuweep ranger station (north of the Grand Canyon), a zone of convoluted cross-bedding about 0.5 m thick occurs (Figure 12). Laminae appear intact, but are folded, and the deformation is constrained between the strata above (sharp contact) and below (gradual contact).

### Deformed Sediment

A cross-section through one of our Coconino SS slabs (float) exhibits distinctly visible laminations for most of its length, but toward one side, the laminae appear shifted, distorted, and lifted

upward (Figure 13). Porosity was measured as 8.74% in the deformed (left) side of this sample, compared to 12.85% on the right, which is a porosity difference of 32%.

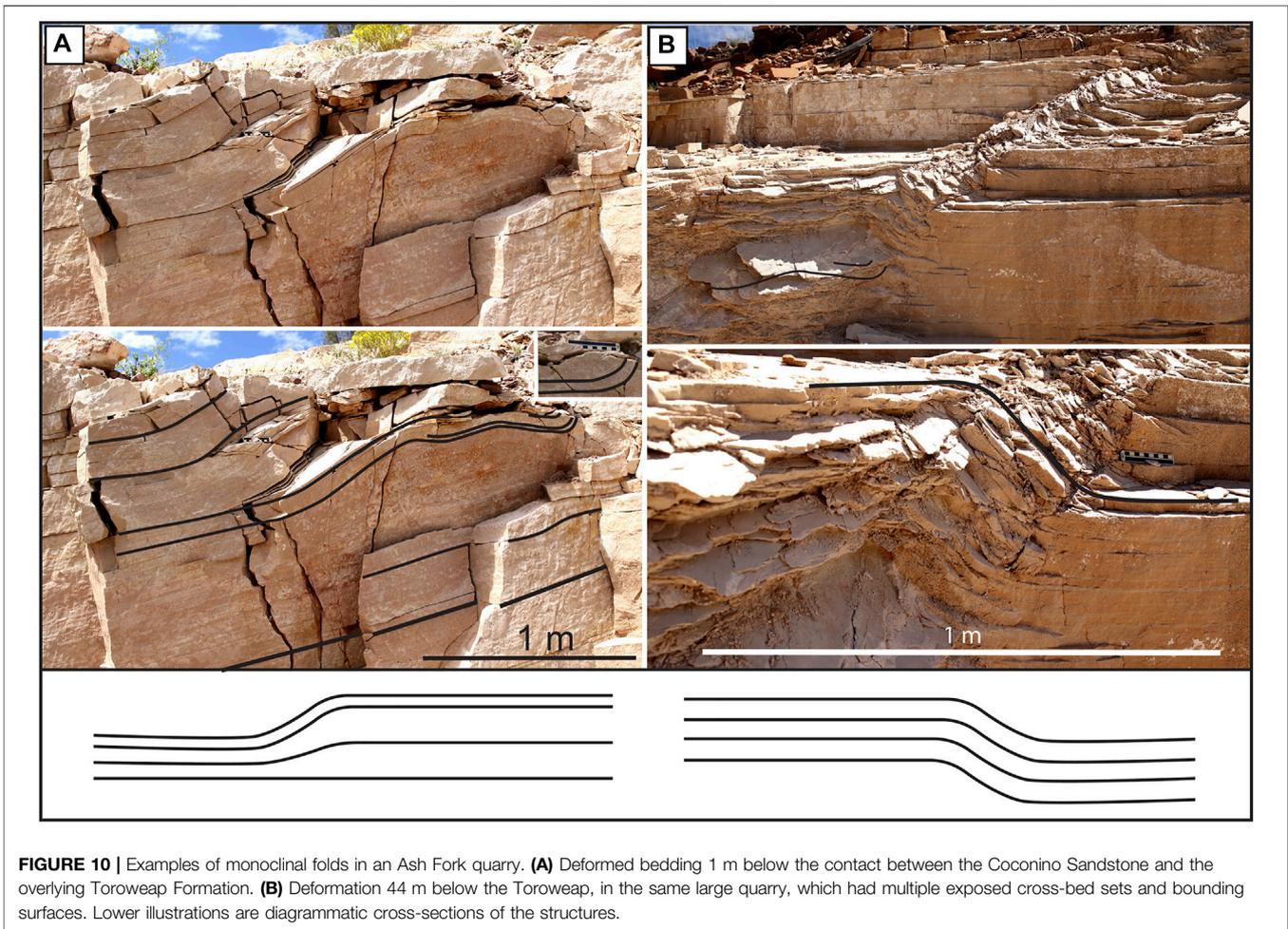
### Geographical and Stratigraphical Distribution of SSD

SSD is common in Coconino SS outcrops at the Grand Canyon and in quarries near Ash Fork. We did not find any of these features in the southern Coconino SS exposures along the Mogollon Rim, or farther east near Holbrook. We note that good outcrops in those areas are much less abundant (especially in the Mogollon Rim area), leaving some uncertainty about whether SSD occurs there.

On a more local scale, the quarries near Ash Fork cover over 43 square kilometers (16.6 sq. miles). SSDs are common over most of this area (Figure 1), observed in 17 of 21 quarries.

Vertical distribution of SSD within a single outcrop could only be assessed in the quarries near Ash Fork, where structures are widely distributed. The Ash Fork quarries expose sections from the upper Coconino SS contact to the lower portion of the formation. While the basal contact is not exposed in this area, at least 160 m of stratigraphic distance separates the upper and lowermost quarries. SSDs occur at irregular intervals throughout this vertical distance, which approximates their stratigraphical position (Figure 14A).

Local stratigraphic distribution of SSDs as seen in vertical walls exposed within a quarry (Figure 14B) varies widely. Vertical distance between deformed zones range from 10 cm



**FIGURE 10** | Examples of monoclinical folds in an Ash Fork quarry. **(A)** Deformed bedding 1 m below the contact between the Coconino Sandstone and the overlying Toroweap Formation. **(B)** Deformation 44 m below the Toroweap, in the same large quarry, which had multiple exposed cross-bed sets and bounding surfaces. Lower illustrations are diagrammatic cross-sections of the structures.

to 12 m (as measured in the three quarries in which these measurements could be taken). However, the measurements probably underestimate the stratigraphic frequency of SSD, since the deformation usually only covers a small part of the sloping upper surface of each bedding plane. Consequently, when cross-beds are exposed in a vertical section, it is likely that many SSDs present on some beds would not be visible in any given wall. Thus, the stratigraphic distances between beds with soft-sediment deformation structures are probably smaller than we were able to measure.

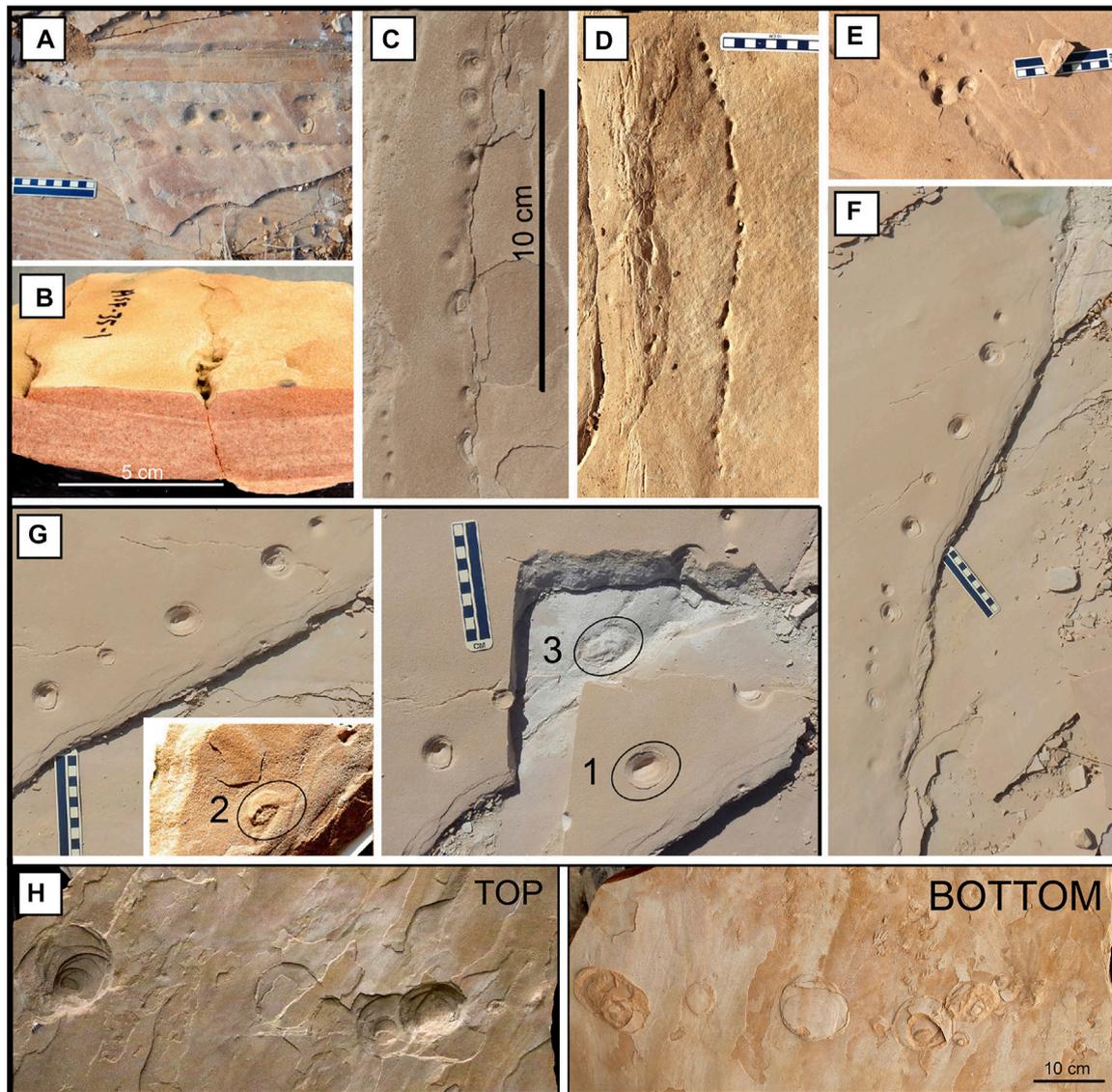
## DISCUSSION

Most of these SSDs, excluding the monoclinical folds and convoluted bedding, occur as shallow deformations in the otherwise extensive, undeformed cross-beds. In contrast, the majority of sandstone deformation literature describes much larger-scale structures than we observed (meters or tens of meters, versus centimeters in depth). The SSDs we observed also only occur on the surfaces of these cross-beds, and this has implications for the associated deformation processes. To interpret these Coconino SS soft-sediment deformation

structures, we will discuss potential, 1) deformation processes, and 2) triggers.

### Conditions for Deformation Conical Pits as Water Escape Structures

The conical pits appear to be the same features previously interpreted as ant lion pit traps by Elliott and Bartlett (2013), but we suggest—at least in the examples described here—that their origin was related to the soft-sediment deformation processes, since they always occur within or in close proximity to SSDs. They resemble, on a very small scale, pits made by sand volcanoes and related fluid escape (Lowe 1975; Lowe 1976; Owen 1995, 1996; Owen and Moretti 2011). In some cases (Figure 11), we see evidence of fluid escape that extends from beneath the pits—through several cm of sandstone and up to the bedding plane where the pits are exposed (Figures 11B,G)—suggesting that these are not surface features. Evidence of liquidization or slumping along these paths is not apparent. They seem to have involved saturated sand, but with enough cohesion to maintain their integrity when fluid escape occurred. The pits in Figure 11H also look like fluid escape structures, but on a larger scale. We suggest that all of these pits, including the structures in Figure 11H, were the result of water or air escape from recently deposited sand.



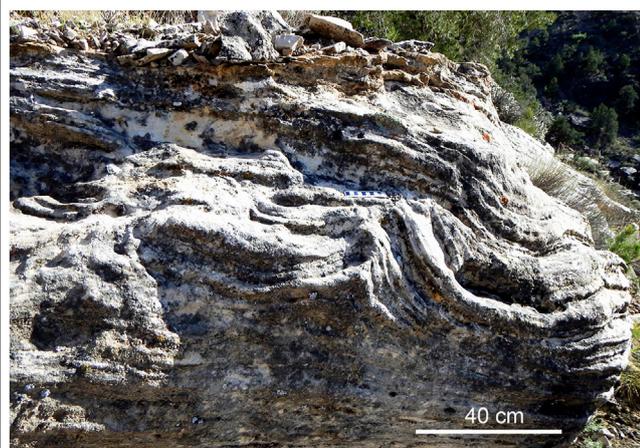
**FIGURE 11** | Conical pits associated with SSDs. **(A)** One of two groups of pits seen on a bounding surface. All others **(C–G)** occur within or near SSDs on cross-bedding planes. **(B)** A cross-section through a row of pits, with a localized crack leading vertically up to the pits. **(F, G)** These two photos are views of one group of pits, and show the successive surfaces which are part of the same structure. The plan view of one pit has been circled and annotated with a “1.” The same pit is visible on the bottom of a broken piece from that same bed, 2) and even continues into the underlying layer 3). **(H)** Structures similar to the above pits, but much larger. The right photograph has been reflected, horizontally, to facilitate comparison of the two sides of the slab, which is 5 cm thick. Cross-beds are dipping toward the bottom of the photos. Scale bars are in cm.

## Liquidization

The formation of SSD involves liquidization of sediment, as liquefaction or fluidization (Owen and Moretti 2011; Lowe 1976; Nichols 1995; Owen 1996). Rotated blocks and other SSDs in the Coconino SS appear to have required some type of liquidization to displace or deform the sediment. The reduced porosity associated with deformation in one slab (**Figure 13**) provides evidence for fluidization: bedding on the left side of that sample is elevated as might occur during this process (Lowe 1976). Portions of the sample in **Figures 6, 8, 9C, D** also appear to

be massive, structureless sandstone, which may suggest fluidization. However, this “massive” classification is not certain, since laminae are sometimes difficult to detect in the Coconino SS.

Evidence for liquidization is common in the SSD at many intervals in the Coconino SS, and the pits as probable water-escape structures indicate that a significant amount of water was present to liquefy the sand, at least at scattered intervals in time and space. If the structures were approximately syndimentary, the sand must have contained enough water at the time of



**FIGURE 12 |** Contorted bedding observed near the Tuweep ranger station. The deformation zone here is thicker than most of the others described in this paper.

deposition to account for these processes. In most cases, the episodes of liquidization were likely quite localized, as suggested by the infrequent, scattered evidence for their presence. Experimental study would be beneficial for further characterizing the nature of these processes, and to explain why the deformation is not more pervasive.

Liquidization might be expected to occur mainly in the troughs of large bedforms, where the water table is closer to the surface. However, the SSDs in the Coconino SS are not in troughs of large bedforms; rather they are spread across the sloping surfaces of foreset beds, with no evidence for a water table.

### The Influence of Clay

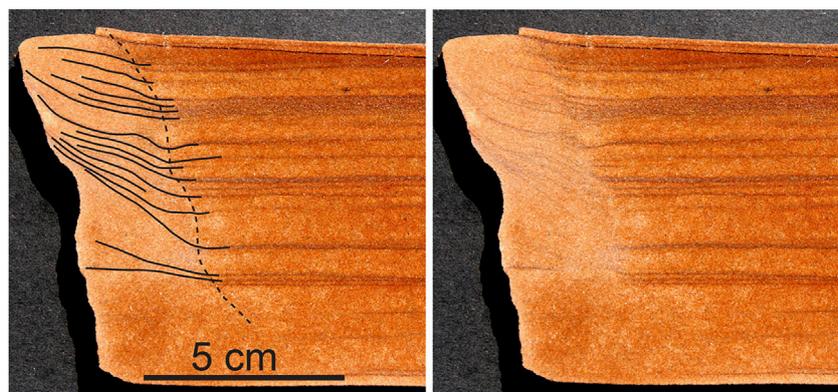
The illite laminae observed between some cross-beds (**Figure 1B**) allowed the sandstone to split cleanly into flat slabs, revealing the SSDs. Without this, it would have been difficult or impossible to find the SSDs in the well-cemented Coconino SS. It is possible that the lack of cohesion along clay laminae allowed movement in

cases of intrastratal SSD. In examples where SSD did not form intrastratally, the clay could have still been a factor, but the mechanism is not clear. Additional study is needed to explore these questions.

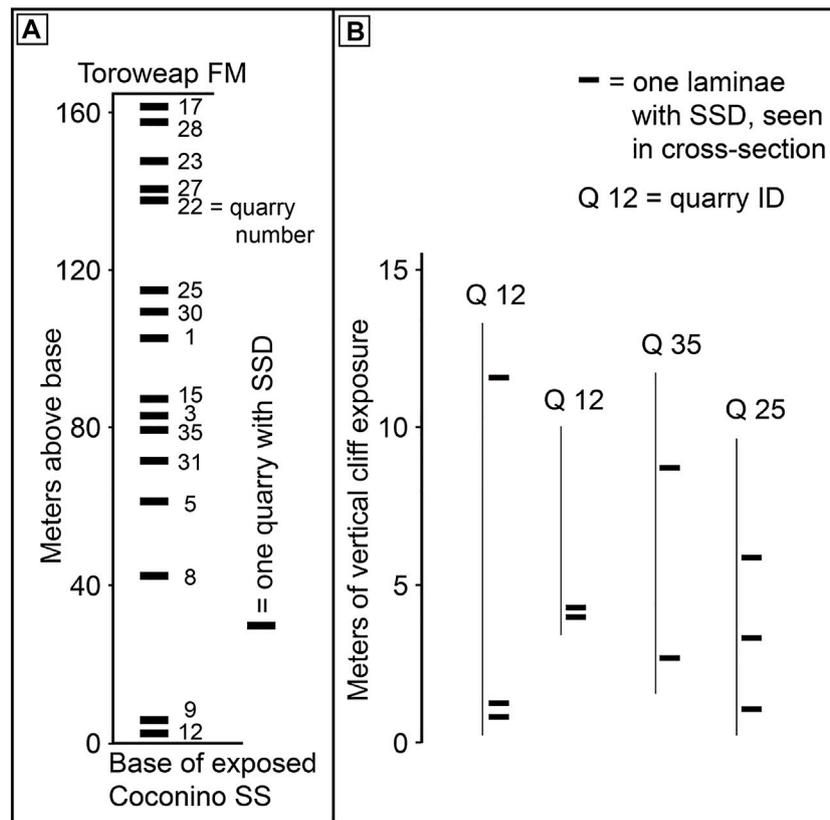
### Deformation Processes

Most of the raised folds, ridges, and rotated blocks were truncated by the processes that deposited the overlying cross-beds (**Figure 8**), suggesting that they were likely syndimentary. The surfaces of other SSDs were not truncated (**Figures 4, 5, 9B**), but the shapes of their surface features and the persistence of their shapes for several centimeters below the surface still indicate ductile deformation. While most of the SSDs are only a few cm deep, the monoclinical fold in **Figure 10A** implies that up to a meter or more of sand was unlithified at the time of deformation. The SSDs generally do not suggest evidence for extensive cementation before they formed, but in a few cases, deformation may have been preceded by minor cementation. The small folds in **Figure 8D**, the larger monoclinical fold in 10B, and some of the rotated block examples are features of this type. Some of the ridges contain distinct, upward-tilted laminae (**Figures 4B, 5B**). These features do not generally have sharp edges, as might be expected if they represented completely brittle deformations. However, they may have involved some early lithification, since the blocks remained intact while deformation processes were occurring. The implications of this depend on how rapidly early lithification could have occurred in this sandstone. Liquidization must have been involved in producing these structures, but the sand appears to have had sufficient cohesion to maintain laminae continuity.

Three other formations contain structures that may compare to our rotated blocks, raising the question of whether they formed by similar processes. Rotated blocks in the Late Cretaceous Rio Paraná Formation in Brazil have a preferred orientation along the cross-bed, and *Fernandes et al. (2007)* interpreted them as landslide deformational features or collapse breccias. Shallow, brecciated zones occur in the Navajo Sandstone, with clasts derived from underlying foreset beds (*Middleton and Blakey 1983*). These authors interpreted the clasts as having been ripped



**FIGURE 13 |** Deformed laminae on the left edge of a Coconino Sandstone float sample, with lower porosity in the deformed area. Deformed laminae are highlighted in left photo.



**FIGURE 14 | (A)** Stratigraphic distribution of quarries near Ash Fork containing ridges, folds, and/or rotated blocks, based on elevation. **(B)** Vertical distribution of SSD zones as seen in three quarries.

up and transported down the foreset by the avalanching of wet sand. In the gypsum sand dunes of White Sands National Monument, New Mexico, McKee and colleagues describe small blocks that moved downslope and rotated (McKee et al., 1971). The lower parts of these blocks are tilted upward, as might be expected in a slump feature. In all three of the above examples, the blocks—which are quite different from those in the Coconino SS (Figures 8, 9B,C)—were displaced by gravity-driven processes.

### Liquidization and Pore Water Pressure

The evidence for liquidization in the Coconino SS played an essential role in generating SSD (Owen et al., 2011; Owen and Moretti 2011). Another parameter associated with liquidization is the upward movement of trapped pore water producing excess pore pressure (Mills 1983; Owen 1995; Obermeier 1996). The presence of interpreted water-escape structures (pits) in association with the Coconino Sandstone SSDs is consistent with this process model. We suggest that the pore water pressure could have provided the shear stress necessary to deform the sand, if a trigger initiated shaking or vibration of the sediment.

For the small folds and ridges (Figures 3, 4, 7A) and small-scale overthrusting (Figures 4A, 5A, 6), lateral shearing from pore pressure may have pushed the sand into these raised ridges

or folds. We suggest that localized pore pressure also pushed pockets of sand upward to displace the rotated blocks (Figures 8, 9). The direction of this movement appears to have been inconsistent, even within a square meter on the bedding plane, which may suggest a lack of trigger directionality. However, the blocks were most commonly tilted up dip within the cross-beds (Figure 9A).

A paper by van Loon and Brodzikowski (1987) includes a photograph of raised ridges in Tunisia, apparently slightly lithified, which are very similar in appearance to those in the Coconino SS. Their proposed process is entirely different, however, as the horizontal Tunisia ridges are thought to have been upthrust at the contacts between salt plates in a sabkha. One possible similarity might involve internal stresses within the Coconino SS that exerted lateral forces to push up the ridges ahead of them, or to converge from two directions and push up the sediment between them.

The larger monoclinical folds likely required a stronger process of local uplift, perhaps from more significant pore-water pressure or from a direct seismic trigger. The complex fold in Figure 10B dips toward the west, and thus probably involved an uplifting force that was stronger toward the east. This folding would have occurred after sufficient burial to at least cover its upper edge, because the lateral continuity of the fold indicates that all of its

laminae were present when the folding occurred. Experimental study of these processes, as done by Moretti et al. (1999), would be instructive.

It appears that some of the SSDs involved intrastratal deformation. Our samples of raised folds and ridges (Figures 3–5), in contrast to most of the rotated blocks, do not show evidence of erosion along their upper surfaces. They were never observed in cross-sectional view except as seen in Figure 6, so it was usually not possible to evaluate their relationship to the overlying beds. However, it seems likely that exposed, unlithified structures like these ridges and folds would be at least reworked by subsequent sediment transport and deposition. Since the upper surfaces of these folds and ridges lack evidence of lithification, and yet were not eroded, they may have formed intrastratally.

The raised ridge in Figure 4D is unique among our samples. It appears that, after the raised ridge formed, pressure from above may have displaced a discrete block of sand directly below the ridge, to a depth of about 5 cm. This may indicate intrastratal deformation, and subsequent shifting from the weight of overlying sediment.

### Deformation on Cross-Bedding Planes

An important characteristic of these SSDs is that they occur on cross-bed surfaces. They were not observed as clusters buried in the sediment, but rather as long, linear or zigzag features on bedding planes (Figure 1C, 7). These folds and ridges commonly occur in groups on some cross-bed surfaces, but their distribution on layers above or below any given bed cannot usually be determined. The overlying sandstone was removed by erosion or quarrying processes, and the underlying beds are not accessible. The only way to evaluate these relationships is by studying cross-sections in vertical quarry walls, and as far as we could determine, the SSDs are not uniformly distributed stratigraphically.

In addition to the effects of gravity, the form of these SSDs was controlled by the sloping foreset surfaces (Figure 1B) and the extensive sloping laminae that underlie them. Some ridges extend up to 10 m along dip on a cross-bed that dips at  $\sim 18^\circ$  (for example Figure 3C). The Coconino SS in this area has almost no regional dip, so the  $18^\circ$  slope reflects depositional conditions. Because of their significant persistence and uniformity along the slope the processes and conditions that produced these ridges appear to have persisted for a substantial along-slope distance. The uniform characteristics of the original foreset surface may have controlled the movement of pore water and pressure involved in generating SSD. Clay laminae are typically quite thin, but may have influenced the movement of pore water and resulting pore pressure. This part of the deformation process, characteristic of at least some cross-bedded sandstones, requires more research to understand the dynamics of this system.

### Possible Triggers for the SSD

The wide variety of SSDs that occur in sedimentary rocks imply that multiple processes can trigger deformation. Papers on SSD commonly discuss the difficulties and uncertainty in determining deformation triggers (Rodríguez-Pascua et al., 2000; Owen et al., 2011; Owen and Moretti 2011; Shanmugam 2017). This uncertainty also applies to the Coconino SS, but some observations in this study may be helpful.

Coconino Sandstone SSDs appear to have been triggered by an external influence, not by the processes that deposited the cross-bedding. We suggest this interpretation because SSD orientation does not generally correlate with cross-bed dip direction.

The size of the deformations probably relates to the magnitude of the triggering force. In the Coconino SS, most of these SSDs are only several centimeters deep, with a few extending up to a meter deep. In contrast, some SSDs in other formations can be up to tens of meters thick, which seems to imply a difference in the magnitude of the trigger.

The SSDs in the Coconino SS are not only shallow, but are also localized; they are usually confined to individual cross-beds. Accordingly, the triggers must have had fairly localized influence to produce these shallow features. Soft-sediment deformation depends not only on the trigger, but also on the rheological properties of the sediment (Mills 1983; Owen 1987; Nichols 1995; Moretti and Ronchi 2011), which may explain the localized distribution of the structures. Liquidization was likely involved in forming these SSDs, but something must have triggered the liquidization and subsequent deformation. The following sections discuss possible triggers.

### Gravity Slumps

It could be suggested that the folds and ridges in Figure 3 are actually slumps. Slumps or slump-like structures are abundant in the Coconino SS, but they are broad features, with their long axes usually oriented along dip (as would be expected to result from a gravity-driven process). In contrast, our SSDs are rarely oriented along dip (Figures 3, 7B), except for the few long, narrow ridges (Figure 3C), which look very different from slumps. Many of the shorter ridges do not exhibit a preferred orientation, as they are components of larger, somewhat zigzag folds (Figures 3E, 7A,B). For this reason, gravitational slumping as a trigger is considered unlikely, at least for the elongate structures. As previously discussed, the rotated blocks also do not show evidence of being displaced by gravitational slumping.

### Climatic Cycles

In the Jurassic Navajo Sandstone, some outcrops exhibit cross-beds in which shallow SSDs—folds, faults, and slumped blocks of breccia (Loope et al., 2001)—occur, on a scale similar to many of those in the Coconino SS. These beds are relatively more resistant to weathering and repeat at regular intervals. Loope et al. (2001) attributed this deformation to wet periods in annual climatic cycles. The folds and rotated blocks in the Coconino SS do not exhibit a preferred orientation as is seen in the thrust-faulted, slumped sand masses in the Navajo Sandstone, nor are they arranged in any regular, repeating pattern that might imply climate cycles. We therefore suggest that processes which produced these structures did not result from climate-driven moisture changes.

### Miscellaneous Processes

Other possible triggers for SSD described in the literature include storms, tsunamis, landslides, glacial loading, volcanic activity, cyclonic waves, and tidal currents (Jones and Omoto 2000; Owen

et al., 2011; Owen and Moretti 2011; Shanmugam 2016; Shanmugam 2017). These processes are not likely to be relevant for the SSD in the Coconino SS cross-bedding, considering its continental depositional setting. Meteorite impacts are also an unlikely trigger, since no Permian meteorite strikes have been reported in northern Arizona.

### Seismic Events

Seismic events provide a candidate for triggering the SSD in the Coconino SS. Possible evidence for a seismic trigger can be observed in the quarry shown in **Figure 7C**. In this quarry, a curved cross-bed surface has many SSDs—like those in **Figures 3, 7A**—on one face and none on the other face of the same bed. It follows that the factors triggering the SSD must have affected these two surfaces quite differently. If the entire cross-bed was deposited simultaneously, this indicates a directional component to the triggering mechanism (at least for these features), and a seismic stimulus arriving from a specific direction could explain the directionality. However, if one face was deposited later (e.g., from a change in wind direction), the different times of origin of the two faces could explain the difference in SSDs occurrence.

Directionality is seen in this quarry at outcrop scale; however, the difference between these two cross-bed surfaces is the only evidence for directionality that we observed. The small-scale SSD (e.g., rotated blocks) do not exhibit consistent preferred orientation, even within an individual cross-bed, which suggests that they were probably not displaced by a unidirectional force. The individual folds and ridges also do not show a common directional orientation (**Figure 7B**), implying a similar lack of directionality for their trigger(s). Or even if the trigger had a directional component, it seems that the orientation of specific structures was determined more by other, local, influences.

It has been suggested that seismic triggers are more likely for SSDs that are constrained to a specific stratigraphic interval (Rosetti and Góes 2000; Owen et al., 2011). However, this criterion cannot be applied to the Coconino SS at an outcrop or regional scale: stratigraphic correlations within cross-bedded formations are difficult, since cross-beds cannot be traced past the bounding surfaces of each set. Therefore, we cannot reliably determine the lateral extent of horizons that contain deformation structures. In our study areas, SSDs exhibit a wide stratigraphic distribution, from low in the Coconino SS to near its upper contact.

However, other criteria may apply at the bedding scale. Some authors suggest that when a deformed bed is under- or overlain by undeformed sediment, and all beds have the same sedimentological features, this supports a seismic trigger for the deformation (Rosetti and Góes 2000; Fernandes et al., 2007; Moretti and Ronchi 2011; Owen et al., 2011). If this interpretation is correct, it could explain some of our SSDs (e.g., folds in **Figures 6, 8C, 10B**). Overlying beds were not present over our other samples (e.g., folds and ridges in **Figures 3, 4, 10A**), but we expect that these were similar, since the Coconino SS exhibits fairly uniform sedimentological characteristics within each cross-bed set. The 13 examples of folds and ridges seen in cross-section in vertical quarry walls, including **Figures 6, 8C**,

were always overlain and underlain by undeformed sediment. The significance of this must be qualified, since a given cross-bed could be undeformed on its exposed surface, but be deformed deeper along its length. Nevertheless, the consistency of this evidence suggests a seismic interpretation is worth considering.

Liquidization in sands can result from earthquakes of about magnitude 5 or higher (Obermeier 1996). Experimental study is needed to determine whether this applies to small SSDs—a few cm deep—such as those in the Coconino SS. If these SSDs were triggered by seismic events, their wide stratigraphic distribution and shallow nature may not be consistent with one or a few large earthquakes as the trigger(s). It remains possible that numerous, localized seismic events occurred, or that far-field effects from distant earthquakes played a role in deforming the sediment. In any case, an explanation is needed for how seismic events could produce such shallow, localized SSD features. Cementation is not likely to occur so rapidly as to leave only a surface layer of unlithified or semilithified sand. Further study is needed on the potential dynamics of this process.

Small-scale (cm scale to 1.5 m) faults occur in the Coconino SS, but physical evidence for seismic events, outside of the SSD, is uncommon. The source of these seismic stresses in the Coconino SS, if present, is therefore uncertain at this time. However, seismic shaking of the sediment may explain the SSD. A study of the geographic and stratigraphic distribution of these small faults in relation to the SSD could be instructive. In one case, correlation is possible: the monoclinical fold in **Figure 10A** is at the top of the Coconino SS, at approximately the same stratigraphic level as a fault with a vertical displacement of 1.5 m, along the Hermit Trail, Grand Canyon.

Understanding processes that could control the shallow, scattered nature of the Coconino Sandstone SSDs remains a challenge. Since deformation is restricted to certain foreset beds among hundreds, some characteristic of the individual beds (sedimentological parameters or depositional context) may explain this distribution. Even large seismic events will vary in their effect, based on the local rheology of the sediment and other parameters (Mills 1983; Owen 1987; Martin-Chivelet et al., 2011; Moretti and Ronchi 2011; Toro and Pratt 2015). These factors might determine whether seismic events produced shallow or relatively deep features, or none, and explain why they are stratigraphically scattered. A seismic trigger for the Coconino SS is plausible, but not demonstrated. However, for the reasons discussed above, the evidence is inconsistent with the other triggers listed—gravity slumping, climatic cycles, tsunamis, landslides, glacial loading, volcanic activity, meteorites, cyclonic waves, and tidal currents—for the Coconino SS. While uncertainty remains, we think seismic processes provide the most likely candidate at present.

### Paleoenvironmental Implications

The SSDs in the Coconino SS contrast with many of those in, for example, the Navajo Sandstone, not only in size but in the location of the deformations. Both involve water and liquidization, and both may be triggered by seismic events. In the Navajo Sandstone, the deformations are interpreted to have formed below the water table, and they may be of km-scale and involve multiple sets of cross-strata

(Bryant et al., 2016). In contrast, the Coconino SS SSDs are usually cm-scale and occur on individual cross-bed surfaces. Large, water table-associated SSDs have not been documented in the Coconino SS; rather, the deformation that we observed likely implies processes that were far more localized in time and space. More work must be done to understand the paleoenvironmental implications of water in so many localized intervals during Coconino SS deformation. The underlying Hermit Formation is thought to have been deposited in a moister environment (Blakey 2003), and provides a possible source of water.

The Navajo Sandstone is a quartz-dominated cross-bedded sandstone, as is the Coconino SS, and the grain size is fine sand in both units (Uygur and Picard 1980; Maitzel et al., 2021). One prominent difference is that the Coconino SS is much more strongly cemented than the Navajo Sandstone. The latter feature is not expected to affect the formation of SSD, but increases the likelihood of identifying SSDs in the Coconino SS. If a cross-bedded sandstone does not split into flagstone-like slabs, exposing the original foreset surfaces, it will be difficult to find small SSDs.

This research sheds light on long-debated details of the Coconino Sandstone's paleoenvironment. The formation is commonly interpreted as a dry, eolian environment, but the SSDs and the clay laminae described here have not been reported before, and these structures and the conditions necessary to produce them, imply that more water was present during Coconino SS deposition than previously recognized.

## Recommended Research

Cross-bedded Permian sandstones comparable to the Coconino SS occur in Scotland and in continental Europe (McKeever 1991; Maitzel et al., 2015), and fluidization and SSD have been reported in some of these formations (Glennie and Hurst 2007). These units should be further studied to explore potential similarity between their documented SSD and that observed in the Coconino SS. Also the extensive North Sea core datasets could be examined for SSD of this type. We recommend that future research address the relationship between SSD and clay abundance/distribution in cross-bedded sandstones. Do these other units split into flagstone slabs, and what is the relationship between such splitting and clay? Do we see a correlation between the clay laminae and the occurrence of SSD? It would also be beneficial to document the distribution of faults in the Coconino SS and their relationship to the deformation.

## CONCLUSION

The small-scale structures in the Coconino SS appear to represent a distinctive suite of SSD, in terms of their bedding-plane scale and their occurrence in scattered stratigraphic intervals. Liquidization, pore water pressure, and complex lateral shearing may have pushed the sand into ridges, folds, and wider elevated shapes, and rotated blocks of sediment. In some examples, deposition of the overlying cross-bed truncated the top of the deformed unit, but in others, the

deformation appears to have occurred intrastratally. Most of the deformation was likely syndepositional or happened shortly after deposition.

Even though these SSD occur over a broad region, from the Grand Canyon at least to the area of Ash Fork, Arizona (nearly 200 km), their geographic distribution was constrained; they were not found farther to the south or east. This implies that the trigger was somewhat localized.

The Coconino SS is widely thought to have been deposited in an eolian environment, but sufficient water must have been present, at least in scattered intervals, to fluidize the sediment and produce the SSD described here. While large deformations occur in other sandstones (like the Navajo Sandstone), our structures are much finer in scale and probably formed under very different conditions. Characterizing processes associated with these SSDs may refine paleoenvironmental models for Coconino SS deposition, and inform interpretations of similar structures if they are found in other sandstones.

Seismic activity provides a possible trigger for this deformation, but the presence of SSD is so far the primary documented evidence for these implied seismic events. Depositional processes and rheology of individual cross-strata may help explain why deformation was restricted to specific beds; more work should be done to explore these parameters.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

Both authors were fully involved in data collection and analysis. Manuscript written primarily by Brand, with input by SM.

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