Dynamic and static recrystallization-related microstructures in halite samples from the Kłodawa salt wall (central Poland) as revealed by gamma-irradiation

Zsolt Schléder, Stanisław Burliga, János L. Urai

Abstract

Microstructures of 33 rocksalt specimens from gallery walls from the highly strained part of the Kłodawa Salt Structure (Poland) were analyzed in gamma-irradiated and etched thin sections in reflected and transmitted light. Two types of microstructures could be distinguished i) dynamic recrystallization related ones caused by natural deformation and ii) static recrystallization related ones with uncertain origin, perhaps caused by subsequent mine-wall convergence.

Natural deformation-related microstructural features are the abundant subgrains and strain-free regions at grain boundaries together with elongated subgrains which imply dislocation climb controlled creep accompanied with fluid-assisted grain boundary migration as the deformation mechanism. Using subgrain size piezometry, differential stresses between 0.9 to 3.1 MPa were calculated.

All the samples contain a few percent (< 5 %) of euhedral statically recrystallized phase. In three samples the euhedral, statically recrystallized grains may comprise up to 85 % of the material. The microstructure suggests that the static recrystallization post-date the natural deformation-related features. The static recrystallization is thought to be due to mine-wall convergence. The pervasive crack system in the samples may also be explained by the stress concentration and subsequent minor mine-wall convergence. Detailed observations of the mutual relationship between the micro-cracks and the euhedral, statically recrystallized phase imply that as the new grains have grown, and
their grain boundaries have swept through the material, some of the pre-existing cracks have not
been consumed by the migrating boundary. This indicates that the material left behind by a
migrating grain boundary is not entirely crack-free but inherits some microstructures from the
consumed, old grains.
The presence of mining-induced static recrystallization warrants careful microstructure analysis
before rocksalt samples being analyzed from mine galleries.

Keywords: Naturally deformed rocksalt, salt mine, dynamic recrystallization, mine-wall
convergence, static recrystallization

**Introduction**

To date, studies of microscope-scale, deformation-related features in naturally deformed rocksalt
have provided important insights into deformation and recrystallization mechanisms of halite. URAI
et al. (1987) reported deformation mechanism of dislocation climb controlled creep accompanied
with recrystallization mechanism of fluid-assisted grain boundary migration (FAGBM) from
Zechstein salt (Asse salt mine). MIRALLES et al. (2000) systematically sampled and studied surface
outcrops of Eocene rocksalt of the southern Pyrenees and proposed that synkinematic, fluid-assisted
mechanisms (solution-precipitation creep and FAGBM) played the main role during the
decomposition of the salt diapir. SCHLÉDER and URAI (2005) focused on slightly deformed bedded
Röt salt from the Netherlands, and concluded that dislocation creep mechanisms combined with
solution-precipitation creep was the main deformation mechanism.

In this paper we present results of a study on highly strained rocksalt from a mine gallery of the
Klodawa Salt Structure. The study initially aimed to compare deformation mechanisms that operate
in nature in different salt layers in a wide range of settings. Altogether 33 samples were analyzed.
First inspection of the samples indicated that all the samples show comparable microstructures
except three samples which showed extensive static recrystallization. In this paper we focus on the
statically recrystallized samples. The importance of getting insights into the cause of static
recrystallization is stressed by the fact that such mine galleries are considered as suitable locations
for storing radioactive or dangerous waste. The widespread usage of caverns as hydrocarbon or gas
storage also implies the necessity of thorough knowledge of the micro-scale processes that operate
in the walls of openings in salt bodies.

The study was dominantly based on inspection of gamma irradiated rock salt samples. This
technique has proved to be one of the most effective methods in analyzing the internal structure of
halite (WILKINS et al. 1981; URAI et al. 1987) and some other minerals (WILKINS and BIRD 1980b;
WILKINS and BIRD 1980a). It reveals variations in defect and impurity content within crystals
allowing different generations of halite and different deformation mechanisms to be distinguished
(PRZIBRAM 1956; URAI et al. 1985; VAN OPBROEK and DEN HARTOG 1985; GARCIA CELMA and
DONKER 1996). Experimental work has shown that during irradiation a new, strain-free, euhedral
halite phase also grows at the expense of old, deformed ones during irradiation, which partly alters
the original structure (GARCIA CELMA and DONKER 1996). Thus, special attention was also paid to
those irradiation-induced structures when completing this work.

Geological setting

Klodawa Salt Structure is one of the most prominent salt ridges occurring in the Danish-Polish
Trough, extending over a distance of about 60 km and rising from a depth of about 6 km (Fig. 1). It
contains Zechstein salt series, which became intensely folded, faulted and boudinaged during the
complex structural evolution between the Triassic and Palaeogene. Geological observations carried
out in the mine in the Klodawa Salt Structure show that the eastern portion of the structure consists
of relatively weakly disturbed Zechstein sequences, while its inner and western portions consist of
strongly folded and distorted sequences (Figs. 2 and 3). The intensity of strain is related to
lithological variation of the Zechstein series: the most severe tectonic deformation is observed within rocksalt and potash complexes and the weakest within more competent rocks – anhydrites, dolomites, clays and clayey salts (BURLIGA 1996).

A microstructural study was performed in order to inspect the stress and deformation features within rocksalt samples. For this analysis, the most strongly deformed portion of the Klodawa Salt Structure was selected for sampling, i.e. its western side (Figs. 2 and 3).

33 spatially oriented samples were taken along a profile which cut perpendicularly numerous fold structures of different scale, built of the Na4 Youngest and Na3 Younger Halite rocksalts (Fig. 4). These rocksalts are folded together with clayey salts and anhydrites into sheath folds at various scales. The fold limbs and axial planes are very steep-to-vertical and strike concordantly with the salt structure extension (Fig. 5). Fold hinge zones are very narrow and commonly modified by minor shear folding. The axial planes of all generation sheath folds are mutually parallel. Because of gallery dimensions, the exact tectonic position of only a few samples could be assessed (see Fig. 4). Most of the samples were taken along a profile with the aim of sampling different halite units (Fig. 4). During sampling we have focussed on the pure halite layers as these horizons are thought to have experienced the most severe tectonic deformation.
Methods

From the oriented samples, 5 x 5 x 1 cm slabs were cut perpendicular to the bedding with a high-speed diamond saw using a small amount of water as cutting fluid to prevent micro-cracking. The slabs were gamma-irradiated in the research reactor of the Forschungszentrum Jülich with dose rates varying between 1 kGy/h to 3 kGy/h to a total dose of 3 MGy at a constant temperature of 100 °C. To check the effect of gamma-irradiation on microstructures, a few control samples were irradiated in the same conditions but to a total dose of 50 kGy (3 days of irradiation). After the gamma-irradiation, thin sections were prepared from the slabs, which were inspected with transmitted and reflected light petrographical microscope. The thin section preparation involved dry grinding of the slabs using grinding paper, which was followed by mounting to a glass plate using Körapox. The mounted slabs were cut with a diamond saw using small amount of water and the thin sections were grinded down to a thickness of about 10-20 μm and then etched using slightly undersaturated NaCl solution following the method of URAI et al. (1987). During every sample preparation step particular attention was paid to avoid introduction of any artificial microstructures, especially cracks. After the comparison of cracks in halite grains in the as-collected samples with those seen in thin section, we convinced ourselves that no additional cracks were introduced during sample preparation.

Microstructures

Most of the analyzed samples consist of pure halite with a few percent of anhydrite and/or polyhalite as main impurity phases. Two of the samples (nr. 3 and 15) also contained admixture of few percent of potash salts. The internal structure of rocksalts depicts a variation in grain structure, their mutual relations and individual characteristics. Despite various locations of the samples within rocksalt units, generally they show very similar set of microstructures therefore they are
characterized together. The exceptions are samples 8, 13 and 31 which contain abundant euhedral phase (see below).

The average grain size, measured by equal circular diameter method (ECD), varies between 3 to 25 mm. The aspect ratio is around one, but locally may attain up to two and in such cases the rocksalt possesses a distinct fabric due to shape-preferred orientation. In transmitted light most of the gamma-irradiated rocksalt samples appears dark blue. In all the samples a few percent (<5 %) of euhedral, pale blue phase is present, however in three samples the euhedral, pale blue coloured crystals with banding might account for up to 85 % of grain constituents (samples 8, 13 and 31). The contact between these euhedral and dark blue grains is colourless and occasionally it forms rims around the euhedral, pale blue grains. In some cases the colourless phase contains tiny (<10 μm) fluid and gas inclusions aligned into bands parallel to the grain boundary.

The grain boundaries are typically irregular although the euhedral grains have straight boundaries. They are invariably ornamented with fluid inclusions and secondary phases. It is worth noting that, in contrast to euhedral grains, fluid inclusions were rarely observed inside halite grains (Fig. 6a, b and c). In some grains Na-precipitate decorated slip lines were observed (Fig. 6c).

In most of the samples pervasive, grain-scale crack system is present with their orientation controlled presumably by crystallographic directions of the individual grains. The micro-crack system is marked by fluid inclusions and pale blue-to-colourless halos (Fig. 7a). The individual cracks may penetrate both the dark blue and pale blue phases as well as they can terminate at the boundary between the dark blue and pale blue grains (Fig. 7b, d). Less commonly the facets of pale blue grains are shifted across the micro-cracks or the growth bands have asymmetric thickness across the micro-cracks (Fig. 7b, d). Less frequently, along the cracks arrays of fine, <0.5 mm size,
pale blue grains occur (Fig 7a). Similar arrays were occasionally also observed along grain boundaries.

In reflected light most of the grains reveal well-developed equiaxial subgrains, however at grain boundaries they are occasionally elongated (Fig. 6d, e and f). Subgrain size ranges from 50 to 220 μm (Fig. 6d, e and f). The euhedral phases are commonly free of any substructure, although they occasionally contain elongated subgrains (Fig. 7).

Fig 7.

Discussion

The observed microstructures suggest that in the samples studied there are two classes of structures. One is due to natural deformation and associated dynamic recrystallization. Most of the samples show such microstructures. Another, less common set observed in three samples (nr. 8, 13 and 31) is interpreted as produced by static recrystallization (Fig. 8). Thus, in the following chapters these microstructures are referred as dynamic recrystallization and static recrystallization related and they are discussed separately.

Dynamic-recrystallization related microstructures

In this set of microstructures the ubiquitous subgrains indicate dislocation creep as a dominant deformation mechanism (Fig. 6). Although we did not find direct microstructural evidence for solution-precipitation creep, it may well be that this grain-size sensitive deformation mechanism also contributed to the total strain rate, especially in the fine-grained samples (c.f. SPIERS and CARTER 1998). The elongated subgrains at grain boundaries are interpreted to have formed by grain boundary migration recrystallization mechanism (see Fig. 8A). This interpretation is consistent with
earlier work on halite (SCHLÉDER and URAI 2005) and some other material (MEANS and REE 1988). The elongated subgrains occurring at both sides of a grain boundary (e.g. Fig. 6f) can be explained in two different ways. One is that the two grains simultaneously and completely replaced a highly deformed third one resulting in elongated subgrains on both sides. The other explanation is that by crack-seal mechanism (RAMSAY 1980), that is the two neighbour grains move away from each other with the gap opening between them is subsequently sealed with precipitates from the grain boundary fluid. In this case the microstructure points to grain boundary sliding as a supplementary deformation mechanism.

Subgrain size additionally was used for calculating paleo-stresses that prevailed during deformation. In 15 samples the equiaxial subgrains were analyzed following the method described by SCHLÉDER and URAI (2005). Applying the equation of $\sigma_1 - \sigma_3 = 107 D^{-0.87}$ (op. cit.), where the differential stress is expressed in MPa and the subgrain size in $\mu$m, the obtained differential stress values range on average between 0.9 and 3.1 MPa.

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This range of differential stress values is in a good agreement with earlier studies on naturally deformed salts (CARTER et al. 1993). While some of the highest differential stress values were calculated for two of the highly recrystallized samples (nr. 13 and 31) surprisingly the other statically recrystallized sample (nr. 8) shows the lowest differential stress value.

Elongation of subgrains at grain boundary regions together with the strongly localized occurrence of fluid inclusions at the grain boundaries imply that fluid-assisted grain boundary migration was the main recrystallization mechanism. The lack of any primary structures, such as primary (synsedimentary) fluid inclusions in grains, suggests that these were swept during grain boundary migration and the salt had completely recrystallized during its deformation. All the above listed features are consistent with so far published data on naturally and experimentally deformed rocksalt (CARTER et al. 1982; CARTER and HANSEN 1983; URAI et al. 1987; SENSENY et al. 1992; CARTER...

**Static recrystallization-related microstructures**

Euhedral overgrowth structures similar to those presented in this paper have been widely reported for gamma-irradiated rocksalt (PRZIBRAM 1956; GARCIA CELMA and DONKER 1996). So far, such structures have been interpreted as a result of gamma-irradiation, which induces defects within the crystal lattice. As the defect density increases in two neighbour grains, either the old grain boundary begins to migrate or a new grain nucleates at the grain boundary and it grows at the expense of the two old, deformed grains. Both processes result in a new, strain free, pale blue to colourless phase. Such a phase was also observed invariably in all irradiated specimens from the Klodawa Salt Structure. However, a contrasting content of pale blue faceted crystals within three specimens implies that the irradiation-induced recrystallization cannot exclusively be accounted for the origin of the pale blue and colourless phases. One must also exclude the irradiation dose as the possible cause for the observed extensive static recrystallization of the three samples as one control sample which was irradiated only for three days still depicts the same microstructures. Therefore the growth of euhedral phase is not related to the gamma-irradiation alone. Fluid and gas inclusions in the colourless phase may be the product of back-reaction of sodium colloids during grain boundary migration, thus indicating that this phase was grown during irradiation (Fig. 7c and e) (GARCIA CELMA 1993). In this process, as the grain boundary migrates and the grain boundary brine interacts with the colloidal Na, H\textsubscript{2} gas is released according to the equation of: 2Na+2H\textsubscript{2}O \rightarrow 2NaOH+H\textsubscript{2}.

This is additionally supported by detailed observations of mutual relations between pale blue and colourless phases, which show that where both the colourless phase and the pale blue phase are present, the colourless one occurs invariably as rims around the pale blue phase, and never as inclusions inside the pale blue phase (Fig. 7b, c and d). The new, pale blue phase commonly
nucleates at the old grain boundary region as evidenced by concentric growth bands. The nucleation of new strain-free grains is common in many materials, although the physics behind the nucleation process is poorly understood (URAI et al. 1986; PRIOR et al. 2004). The driving force for the static recrystallization arises from the internal strain energy which induces nucleation and subsequent grain boundary migration (HUMPHREYS and HATHERLY 1996). The increase of strain energy, which led to nucleation of new grains in the euhedral-grain-rich samples, is difficult to identify. Comparing to other naturally deformed salts (URAI et al. 1987; SCHLÉDER and URAI 2005), the microstructures and subgrain size are much alike, suggesting that natural process have not played a role in producing these new, recrystallized phases. A possible mechanism could be the mine wall convergence (see Fig. 8B-E), which may have increased the internal strain energy, which subsequently led to nucleation of new grains. It remains, however, temporarily unsolved why this phenomenon occurs only locally.

The parallel dark blue bands seen in the pale blue, euhedral phase are best interpreted as growth bands and are much alike as seen in fluorescence studies on artificial, doped halite crystals by MURATA and SMITH (1946). The difference in colour intensity between the bands is interpreted to be due to differences in impurity content (MURATA and SMITH 1946). The fact that the growth bands have asymmetric thickness across the micro-cracks and that the facets of the euhedral phase are shifted across the micro-cracks (Fig. 7b and c) implies that the cracks are older than the new pale blue, euhedral phase. Additionally, small, <0.5 mm sized pale blue coloured crystallites were also observed inside the cracks, which supports this assumption (Fig. 7a). If the cracks were younger than the euhedral phase then the euhedral crystals should be dark blue in transmitted light as a late cracking event would have introduced new dislocations and the gamma-irradiation is sensitive to the dislocation density.

Taken those findings together, this implies that as the new phase grows at the expense of the old deformed ones, some of the pre-existing micro-cracks are not erased from the material. Recently, some other authors arrived at somewhat similar conclusions by inspecting partly recrystallized,
experimentally deformed rocksalts. BESTMANN et al. (2005) noted that when grain boundary migration occurs between two substructured grains then the swept area inherited some microstructures from the consumed grain. In the same experiment the newly nucleated grains that swept faster over substructured old grains did not take over the microstructures of the consumed grains.

It is important to speculate on the origin of the pervasive crack system. From microstructural studies, it seems that the micro-cracks are rather uncommon features in naturally deformed rocksalts (URAI et al. 1987; MIRALLES et al. 2000; SCHLÉDER and URAI 2005), however recently SCHOENHERR et al. (2005) reported hydrocarbon impregnated micro-cracks from the vicinity of highly over pressured reservoirs and suggested that they aroused due to presence of fluids at lithostatic pressure. Although we cannot entirely rule out this mechanism provoking the pervasive crack system seen in the specimens studied, the fact that they occur only in 3 samples may suggest that this process did not play a role in generating the micro-cracks. Another possible candidate mechanism for the micro-cracking is that due to stress concentration around mine galleries. This process occurs in underground openings and is also a well-known phenomenon in some salt mines (slab-like slaking). The convergence process may well be responsible for the increase in strain energy, which in turn also controls the abundance of the new, euhedral statically recrystallized phase.

PEACH et al. (2001) systematically investigated the relation between the recrystallization and the confining pressure and noted that when the confining pressure is too low to prevent dilatancy (i.e. micro-cracks occur in the sample), and the intracrystalline brine escapes, the recrystallization is inhibited, and the rocksalt shows continuous work hardening. In this study, recrystallized, euhedral grains and micro-fractures co-exist, suggesting that some other mechanism was operative, which provided brine/air humidity to the grain boundaries, thus gave arise to recrystallization. It is perhaps the air humidity, which is conducted via capillary processes into the salt through the pervasive crack
system. This assumption, however, leaves the question unanswered why the static recrystallization occurs only locally even though the humidity level is assumed to be the same for the whole gallery.

Fig 8.

Conclusion

The inspection of rocksalt samples from the highly strained portion of the Kłodawa Salt Structure revealed that the rocksalt had recorded similar deformation processes and similar stress conditions throughout the analysed area. As evidenced from microstructures the main deformation mechanism was dislocation creep accompanied with fluid assisted grain boundary migration recrystallization. These features are in agreement with published data obtained from other salt bodies. However localized occurrence of some phenomena indicates that there are also additional factors which control the microstructural development of halite and rocksalt.

The pervasive micro-cracks seen in the specimens are interpreted to originate from the stress concentration around the mine gallery, i.e. they are not inherited due to natural deformation (Fig. 8). Similarly the presence of the new euhedral grains in some specimens implies that static recrystallization is also locally an important process and it evolves in a response to mine-wall convergence or other not deciphered mining works. Detailed observations on the mutual relationship between the cracks and the statically recrystallized phase indicate that the micro-cracks are not eliminated from the material by recrystallization process, e.g. by migrating grain boundaries. According to our observations on irradiated samples the pale blue, euhedral phase partly, if not entirely, records pre-irradiation recrystallization of halite within the rocksalt. This implies that the analysis of any irradiated naturally deformed rock salt sample should be more cautious, as not all pale phases and euhedral grains develop due to gamma irradiation. Further important consequence is that samples taken from salt mine galleries for microtectonic or crystal fabric studies may contain significant artefacts due to static recrystallization after mining. For example CPO measurements in
halite by neutron diffraction (KERN and RICHTER 1985; SKROTZKI 1994; SCHEFFZÜK 1998) may be misinterpreted if these new grains are not recognized. Static recrystallization of halite in walls of waste repositories is a previously unrecognized recovery process which removes damage from the deformed halite.

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References


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Figure and table captions

Fig. 1. Map showing the Zechstein basin (after LOCKHORST 1998). Insert: location of the Klodawa Salt Structure (modified after DADLEZ 2003).

Fig. 2. Simplified geological map of the sampled mine level (-600 m). The position of the cross-section (Fig. 3) and the sampled profile is also indicated (modified after BURLIGA et al. 2005).

Fig. 3. Cross-section throughout the central part of the Klodawa Salt Structure. The sampled profile at the level -600 m is indicated with a black rectangle (modified after BURLIGA et al. 2005). The legend is the same as in Fig. 2. No vertical exaggeration.

Fig. 4. Detailed stratigraphy of the sampled profile. The arrows with sample numbers indicate the sampled localities. Note that the PZ3 and PZ4 units shown on the Fig. 2 have been further divided into individual units. For legend see Fig. 2.

Fig. 5. Photo shows a near-vertical sheath fold. In the sampled profile such structures are the most common.

Fig. 6. Micrographs illustrate characteristic microstructures in the Klodawa salt. A) Two grains, one is without any substructure and one is locally rich in subgrains. The subgrains show up as white polygons. We interpret this micrograph as the substructure-free grain grows at the expense of the deformed neighbour. Transmitted light image of a gamma-irradiated thin section. B) Three grains separated by grain boundaries (g). All the grains are locally rich in subgrains. We interpret this image as the bottom left grain grows into the subgrain rich grain part of the other two grains. Transmitted light image of a gamma-irradiated thin section. C) Two grains separated by grain
boundary (show up as dark line). The upper grain contains numerous Na colloid decorated slip lines (E-W trending lines). This image is interpreted as the undeformed grain grows at the expense of the deformed one. The white grain in the deformed grain is polyhalite. Transmitted light image of a gamma-irradiated thin section. D) Two grains (bottom left and top right) consume the subgrain-rich grain in the middle. The black spots at the grain boundaries are fluid inclusions opened up during sample preparation. Note that the grain at top-right itself also contains subgrains. Reflected light image of etched thin section. E) Two grains separated by a grain boundary (N-S trending, wavy black line). The grain at the right hand side contains numerous equiaxial subgrains, the grain at the left contains elongated subgrains. We interpret that the left grain replaces the highly substructured on the right, and the grain boundary migration results in elongated “grown-in” subgrains. Reflected light image of etched thin section. F) Image shows two grains separated by a N-S trending grain boundary. Both grains are rich in subgrains and contain elongated subgrains at the grain boundary region. Such elongated subgrains can be interpreted as the grains completely consumed a former deformed old grain which was between the two grains, or, alternatively the microstructure evolved with crack-seal mechanism. Reflected light image of etched thin section.

Fig. 7. A micrograph illustrating relationships between cracks, pale blue and colourless phase. A) Cracks (c-c) cut through a grain and also penetrate into the neighbour grain. The grain boundary (g-g) between the two grains shows up as a dark line. In the NE-SW oriented crack a number of pale blue pale blue phases (show up as pale-gray) are observed. This relationship suggests that the cracks are older than the pale blue phase. B) Five grains separated by grain boundaries (g-g). Numerous cracks are also seen (c-c). The facets of the euhedral grain at the bottom right are shifted by one of the cracks. At the middle right of the image (see arrow) the grain boundary, which separates two pale blue grains, is also shifted across the crack. This interaction of facets, grain boundaries with the cracks implies that at least some of the cracks are older than the recrystallization. C) pale blue (pale-gray) euhedral grain rimmed by the colourless phase contains numerous tiny inclusions, which in
the image show up as dark spots. These inclusions are thought to consist of H$_2$ presumably produced by back-reaction of the colloidal sodium while the grain boundary migrated and the grain consumed its highly deformed neighbour. D) Four grains separated by grain boundaries (g-g). Similarly as in the image B, the cracks (c-c) shifting growth bands, as well as the grain boundary across the cracks can be observed (see arrows). The white rim is thought to be grown during gamma-irradiation. E) Image of etched thin section shows the colourless phase in reflected light. The og-og line marks the boundary between the pale blue and the colourless phase, the g-g marks the grain boundary between the colourless and the dark blue phase. The fine parallel lines between the og-og and g-g contain numerous tiny gas inclusions, which opened up during etching. The gas inclusions are the product of back-reaction during gamma-irradiation.

Fig. 8. Cartoon illustrates a likely evolution of microstructures in the Klodawa samples. A: Salt deforming under natural conditions (low strain rate, high confining pressure). The dislocation density in the individual grains is dependent on the relative orientation of stress field and grain's slip system. Grains with high dislocation density are replaced by their neighbour grains. The main deformation mechanism is a combination of dislocation creep and solution-precipitation creep and perhaps grain boundary sliding. The main recrystallization mechanism is fluid-assisted grain boundary migration. Note that the dislocations in the grains are arranged into subgrain walls. For the sake of simplicity, the subgrain boundaries and second phases have not been shown on the drawing. B: As the stress concentration around the mine gallery causes further deformation and as the mine walls converge, the dislocation density increases and cracks parallel to (100) develop. Contrary to the microstructures depicted in A, these new dislocations are not arranged into subgrain walls. Due to the increase in dislocation density some of the old grain boundaries start to migrate, and a few new grains nucleate at grain boundaries. These newly nucleated grains grow at the expense of the old, highly deformed ones. Note that the microstructure is not altered significantly compared to the image A. Most of the samples studied in this paper depict microstructures B. C: As
the mine wall convergence continues, the new phase progressively replaces the old grains and some new cracks are also introduced. As the new phase grows at the expense of the old ones, the old cracks are not erased by the migrating grain boundaries. D: In a very few extreme cases the new phase extensively replaces the old grains. This might be due to further mine-wall convergence and subsequent increase in dislocation density and/or due to presence of air humidity. E: During gamma-irradiation, minor amount of additional recrystallization occurs with the new phases further replacing the old ones. Note that neither the gamma irradiation nor the sample preparation do not alter the microstructures significantly. The image width for all the cartoons is about 3 cm.

Table 1. Table showing the measured grain, subgrain diameters and the calculated differential stress values for 15 samples. Note the high area percentage of the euhedral phase in samples 8, 13 and 31.
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Table 1. Table showing the measured grain, subgrain diameters and the calculated differential stress values for 15 samples. Note the high area percentage of the euhedral phase in samples 8, 13 and 31.