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TECHNOGENIC LAYERING IN IRON ORE PIT DUMPS: FORMATIONS, ORDERING, AND GEODYNAMIC INTERACTION WITH HOSTROCK

The purpose of the article is to illustrate and, where possible, explain the regularities of the internal structure of technogenic accumulations at the "Pivnichnyi" and "Pivdennyi" iron ore quarries located near Kryvyi Rih city. The research methodology consisted of the following stages: a) field measurements and data collection; b) laboratory data processing, which included: plotting structural data, statistical analysis, and calculating averaged values of azimuths and dip angles and the scatter of these values for planar structural elements of both bedrock blocks and technogenic accumulations, as well as calculating the rotation angles of the bedrock blocks and the Structuring Planes within the technogenic formations. Novelty of Research Results. A. The varying degree of structure in technogenic accumulations (screes, embankments, and filled artificial voids) of the quarry dumps has been established. The study identifies both unstructured and varying degrees of structured accumulations, specifically recording such structural elements as layering, mechanical foliation, and linearity within the latter. B. Two methods for calculating the rotation angles of bedrock blocks and the structuring planes of technogenic formations relative to the vertical and horizontal axes are proposed, which allowed for the quantitative assessment of their mutual displacement. C. It is established that the formation of newly formed planar structures within technogenic accumulations is a directed process, resulting from the inheritance of the host rock's structural anisotropy – initially shaped by regional strike-slip stress regimes – which leads to the creation of the accumulation's own, oriented technogenic stratification (layering). D. It is conceptually substantiated that the bedrock blocks and the technogenic accumulations develop and form as a single, mutually coordinated object, which is termed a "geological-technogenic system", functioning due to "geodynamic interaction." E) It is demonstrated that the transformation of technogenic accumulations (their self-structuring and "completion") is a constructive phenomenon that could serve as a natural laboratory for monitoring the processes of structural-textural element formation in loose media. The practical significance of this research lies in utilizing the classification of structural neoformations within technogenic accumulations as a criterion to assess their assimilation potential and suitability for economic development. This classification provides essential geomechanical parameters necessary for forecasting slope stability and minimizing collapse risks in open-pit mining.

Key words: ferruginous horizons, iron ore quarries, undisturbed blocks, technogenic accumulations, bedding elements, structuring.

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Introduction

The research was conducted on the territory of the Saksagan district of the city of Kryvyi Rih. Iron horizons of the Saksagan suite of the Kryvyi Rih series were discovered within the "Pivnichnyi" and "Pivdennyi" iron ore quarries. The studies were performed in connection with the issue of the lack of systematic monitoring information about the trends in the development of geodynamic processes and changes that occur within the technologically transformed areas of the subsoil and the earth's surface of Kryvbas. Therefore, the research of such areas is relevant and is aimed at their comprehensive and effective use, as well as prevention of the development of negative natural and technogenic processes [Report…, 2023].

The "Pivnichnyi" quarry began to function in 1953 as part of the "Dzerzhynskruda" trust. Currently, the quarry is being developed by "UKRAINIAN MINING COMPANY" LLC. The depth of the quarry reaches 350 m, the length is 4,000 m, and the width is 1,700 m [Report..., 2020]. The "Pivdennyi" quarry was put into operation in 1972; in 2001, it was transferred to the mine management for underground ore mining of KDGMK "Kryvorizhstal". The iron ore deposit was discovered to a depth of 1,100 m [Report..., 2018]. Currently, the "Pivdennyi" quarry is being developed by "RUDOMAIN" LLC. Achieved dimensions of the quarry: length – 1,050 m, width – 630 m, depth – 140 m. The quarry is extended submeridionally.

The fourth, fifth. and sixth iron and shale horizons of the Saksagan suite (Paleoproterozoic) of the eastern limb of the Saksagan syncline are spread directly within the development area of the “Pivnichnyi” and “Pivdennyi” quarries. On the western sides of the quarries, the upper tectonic scale, or part of the Saksagan anticline, is partially exposed, which is represented within the quarry by rocks from the arkose horizon of the Skelyuvat suite (Paleoproterozoic) and the talc horizon to the second iron horizon of the Saksagan suite [Report..., 2020*;* Report ..., 2023].

Both folded structures exhibit an almost isoclinal shape and have a submeridional strike with an azimuth 12-22°. The hinges pitch in the northern direction at angles between 9° to 22°. The dip of the axial surfaces is directed to the west, with angles ranging from 40° to 60° [Semenenko et al., 1981].

According to the geological survey results of “UKRAINIAN MINING COMPANY” LLC and “RUDOMAIN” LLC, it was established that the sections of the “Pivnichnyi” and “Pivdennyi” quarries were formed primarily due to technogenic factors related to the underground extraction of rich iron ores. This process caused the collapse of overlying rocks, leading to their mixing with iron martites and ferruginous quartzites. Additionally, it resulted in subsidence and slumping of the surrounding host rocks. As a conclusion, it was ascertained that the “Pivnichnyi” and “Pivdennyi” quarry sites belong to the technogenic genetic type of deposits [Report..., 2018; Report..., 2020*;* Report..., 2023].

Ninety-five anomalies were identified in the “Pivnichnyi” quarry, 140 anomalies were identified in the “Pivdennyi” quarry using the low-frequency ground-penetrating radar complex “Loza-2N” [Report..., 2021]. They were summarized into six groups: anomalies, which are vertical collapse zones filled with clay or soil; local anomalies such as voids; anomalies that form large conical structures and are filled with a mass of collapsed rocks or rock from dumps, clay or soil; structural anomalies reflecting the geological structure or individual structural elements; anomalies reflecting landslides or the development of landslide processes in the upper layers of sedimentary rocks; subsidence zones of the upper layers of soil and shale within landslides, subsidence funnels and collapses above stretches.

Over the decades, the depressions, sinkholes, and collapses formed were gradually filled with clay or soil, overburden, and substandard rocks. Thanks to this, multi-tiered dumps were formed, where subsidence and failure processes were renewed in some areas. Developed zones with a width of 150 to 800 m are interspersed with blocks composed of ferruginous quartzites and substandard hematite-martite ores (surviving block). The latter retain signs of belonging to primary stratigraphic horizons. As a result, the quarries canbe represented as a technogenic-geological formation, where relatively undisturbed blocks of crystalline rocks (surviving block) and blocks of technogenic accumulations alternate. The apparent thickness of both types of blocks ranges from a first tens to hundreds of meters.

The totality of the action of human industrial activity and natural processes generates processes that are layered on the created mining complex. This is a special group of processes and phenomena that G. I. Denisik and G. M. Zadorozhnya propose to be called derivatives. These researchers typify derivative processes and phenomena observed within the mining landscapes of Kryvyi Rih, according to several key indicators: genesis, speed, area, sequence of activation, age, relation to the Earth’s surface, nature of manifestation, and degree of regulation [Denisik & Zadorozhnya, 2013].

Research conducted in Kryvbas by V. P. Voloshchenko, G. M. Malakhov, I. D. Rivkin, and a number of their colleagues provided a clear understanding of the geomechanical processes occurring in the upper part of the Earth’s crust due to the underground development of iron ore deposits. In summary, the key aspects of the phenomenon can be be described as following [Malakhov, 1990]: a) the collapse of the ceiling of the void causes the advance of overlying rocks starting from the surface along the inclined side. As a result, sedimentary rocks from the surface fall into the void; b) the void is also filled with the rocks of the hanging side; c) on the surface, this process creates a trough of deflection, characterized by zones of collapse and landslide. The landslide zone develops at an angle between 80° to 42°.

In the works [Report…, 2023], technogenic accumulations, are distinguished by type according to the method of formation: bulk (dump), scree, shifted (landslide), collapsed (failed), and buried (formed as a result of underground mining). The primary characteristic of their technogenic type is the complete destruction of the stratigraphic arrangement of rock layers, resulting in a violation of the primary conditions of occurrence and the structure of the source rocks.

Recognition of the geological large-scale deposition in the Kryvyi Rih series of crystalline rocks raises the question of its modern structure due to technogenesis [Report..., 2023]. As shown above, the main focus has been on the shape of technogenic accumulations, the methods and conditions of their formation, and their material composition [Malakhov, 1990; Young-Suk Song et al., 2012; Report..., 2021; Report..., 2023]. Research into dump slopes [Gamma et al., 2017; Mu H., 2025] in open-pit mines indicates that the stability of such slopes is a critical issue in surface mining operations, frequently leading to slope failures (landslides). Studies on the stability of road embankments, slopes and coastal dams indicatethat several factors strongly influence the performance of these structures. These factors include: increase in strength with depth, degree of compaction [Graham J., 1979], uneven moisture content [Acharya et al., 2016; Zeidan et al., 2018], granulometric and material composition [Arif et al., 2023; Varsha et al., 2023], the presence of layering (which contributes to displacement) [Ronco et al., 2009; Lambert et al., 2014], direction of drainage and pore water pressure, anisotropy (according to various properties) of the soil base [Zdravković et al., 2002; Karstunenet al., 2005; Dar & Shah, 2020], as well as the presence of "existing tectonic disturbances" that contribute to "gravitational reactivation" [Agliardi et al., 2009]. Similar features are also considered when designing landscape reclamation following mineral extraction [Hancock & Willgoose, 2017]. Thus, the internal architecture of man-made accumulations is fundamental to their resistance to external influences. Unfortunately, this aspect of technogenic accumulations in quarries has not receined the attention it deserves. The patterns observed in the internal structure of these accumulations represent a significant, yet unresolved, issue. This work is dedicated to exploring that problem. The study of these patterns has shown that man-made accumulations are not static objects but are dynamic systems that evolve under the influence of man-made processes.

Methodology and Research Results

The general methodology for studying the transformation of the natural-technogenic geological environment of the "Pivnichnyi" and "Pivdennyi" quarries encompassed the following consecutive stages of work: 1) analysis of primary materials of predecessors and materials provided by the customer; 2) remote deciphering of technogenic morphostructures and components based on cosmo-topo materials; 3) conducting field observations in the quarry and adjacent territories on profiles and observation points with sampling for laboratory studies; 4) chamber processing of field and laboratory studies [Report …, 2023].

The research methodology directly conducted by the authors of this article consisted of the sequential execution of the following stages:

1. Field Measurements and Data Recording

A. Conducting field surveys and data collection. The study was carried out using the route survey method, ensuring systematic data collection. The authors recorded all structural elements available for measurement sequentially ("in a row", without targeted selection) within the observation areas. In doing so, two object categories were clearly delineated: massifs – relatively undisturbed blocks of ferruginous quartzites and schists (host rocks – and technogenic accumulations – the heaps and dumps formed from these rocks.

B. Measurement of occurrence elements. Direct measurements were taken for the occurrence elements (azimuths and dip angles) of planar structural and textural heterogeneities. Data concerning linear structural elements (azimuths and plunge angles) were also collected. These measurements were conducted both in the host rocks and in the technogenic accumulations.

C. Documentation. Detailed written records and photographic documentation were maintained for every measurement, and all observation points were plotted onto a topographic map for spatial referencing.

2. Laboratory Data Processing

A. Structural Data Plotting. The field measurements obtained for planar and linear elements were processed and visualized (plotted onto stereographic projections) using the specialized software StereoNett 2.46.

B. Statistical Analysis. Calculations were performed to determine the averaged values of azimuths and dip angles, as well as the statistical dispersion of these values, exclusively for the planar structural elements (massifs and technogenic accumulations), which were the subjects of comparison. Statistical analysis (calculation of averaged values and statistical dispersion) was not performed for the linear structural elements, due to the limited number of such elements observed by us in the technogenic bodies.

C. Key Calculations. The angles of rotation between the averaged planar structures of the massifs and the averaged structural planes of the technogenic formations were calculated to establish the empirical relationship (structural inheritance). This pioneering calculation methodology was developed specifically for this study, utilizing standard stereographic projection principles to quantify the relative displacement between the two structural elements.

3. Conclusion Formulation

Based on the comparison of statistical parameters between the two samples (host rocks and dumps), an empirical conclusion regarding the quantitative similarity of their orientation was formulated. This finding served as the basis for advancing the hypothesis of structural anisotropy inheritance.

Results of Work

The planar structural and textural heterogeneities (whose occurrence elements were measured) within the relatively undisturbed blocks of quartzites and schists (massifs, pillars) are expressed by banding (foliation), fold limbs, and schistosity. Banding is usually represented by alternating bands of quartzite**s.** Their thickness is measured in centimetres. They vary in color, mineral composition, and the sizes of mineral grains. Schistosity is expressed by uniformly oriented and closely aligned scaly minerals and their aggregates. Hinges of foldeds forms, elongated mineral aggregates, striation, and furrows represent linear structural elements.

Among technogenic formations, such as scree slopes, embankments, and filled artificial cavities, we identified at least two varieties based on the degree of structuring: unstructured and structured formations. In the unstructured type, we found no signs of structural and textural regularity. In contrast, the structured technogenic formations exhibited clear, signs of structural and textural organization. This organization is manifested through features such as layering, schistosity and linearity with the bedding elements present. The layering of technogenic accumulations consists of alternatiing layers, with thickness ranging from the first centimetersto several tens of *cm*. These layers differ in color and size of rock fragments. Such formations are emphasized by schistosity, which is expressed by uniformly oriented, flat mineral aggregates and fragments of crystalline rocks found along the layering planes (Fig. 1). Two linear structural elements were observed within the man-made formations: one in the form of hinges of bulk folds and the other along the long axes of host rock fragments. We also measured the azimuths and dip angles of the separation planes between the pillars, slumps, scree slopes, filled cavities, and other technogenic accumulations.

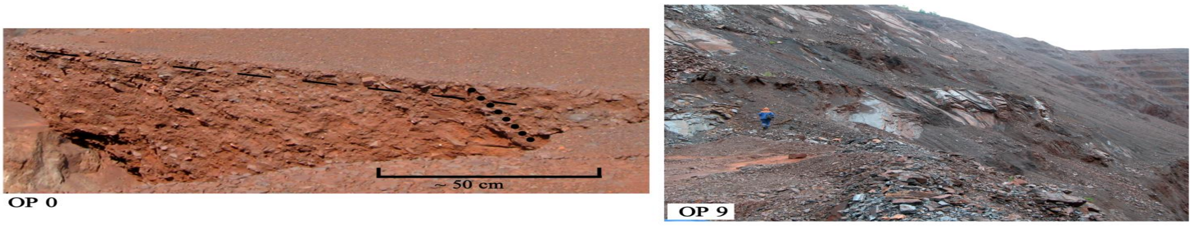

Fig. 1. Photo of structural elements of technogenic embankments (OP 0) and outcrops of pillars among unstructured scree in the eastern side (OP 9) of the “Pivnichnyi” quarry.

OP – observation point. In a man-made embankment, there are two generations of layering. The trace of the plane of one of them is highlighted with a dot-dashed line, the trace of another one is presented with a linear dashed line. Exposure of the outcrop is eastern.

All the above-mentioned measurements are shown in the tables (Tables 1–8) and processed using the program StereoNett 2.46 (Fig. 2).

In addition to the actual measurements, the averaged values of the azimuths and dip angles for the planar structural elements of the examined pillars and man-made accumulations are derived in the tables.

The averaged rotation was also calculated for the massifs and the planes of layering formation.

Table 1

Bedding elements of planar structural (banding, schistosity, and sides of folds), individual pillars of western border, and the northern part* of the “Pivnichnyi” quarry

No i/s	OP	dip azimuth, °	spread of values, °	angle, °	spread of values, °	average value: dip azimuth / angle,°	general direction and percentage of measurements from their total number
1	2	3	4	5	6	7	8
1	6	240	25	72	50	246.6 / 57.1	southwest 27.6
2		250		33			
3		240		83			
4	23	250		34			
5		235		40			
6	4*	238		62			
7	11*	260		68			
8		260		65			
9	6	290	90	35	53	296.3 / 40.3	northwest 55.2
10		271		51			
11	7	270		46			
12		280		56			
13		280		65			

Continuation of Table 1

1	2	3	4	5	6	7	8
14		360		40			
15		283		55			
16	12	310		15			
17		300		30			
18	23	280		27			
19		347		22			
20		290		23			
21		340		12			
22	19*	285		53			
23		280		53			
24	4*	275		61			
25	5	87	27	65	32	69.8 / 62	northeast 13.8
26		72		40			
27	11*	60		71			
28		60		72			
29	5	110	0	73	0	110 / 73	southeast 3.4

Generalization for the "Pivnichnyi" quarry. from the data presented in tables and Fig. 2 indicate the average dip azimuth of the layering in the south-western direction of technogenic accumulations differs from that of the planar structures in the pillars. Specifically, it varies by 14.4° from the structures in the same direction of the western border at 7.4° and by 21.4° from the eastern border. The average displacement of the planes in which layering occurres around the vertical axis is 11.6°, while the displacement of the planes of banding is 3° pillars. This shows that the dispersion of the planes in the man-made accumulations is nearly four times greater.

The dip angle of the layering in the south-western direction of technogenic accumulations differs from that of the planar structures in the same direction found in the pillars by 13.4°. The average displacement of the layering planes around the horizontal axis is identical to this displacement of the planes in the pillars. Additionally, this shift is even less pronounced than in the pillars of the eastern outcrop.

The average dip azimuth of the layering in the northwestern direction of technogenic accumulations differs by 15° from the dip of planar structures in the same direction within the pillars. Specifically, it differs by13.7° from the structures on the western bort and by 16.4° from those on the eastern edge of the quarry. The average displacement of the planes of layering around the vertical axis is 8.2°, while in the pillars, this displacement is measured at 5.5°, i.e., these indicators are comparable.

The dip angle of the layering in the northwestern direction of technogenic accumulations is identical to the average dip angle of planar structures in pillars, which is 43.9°. The average displacement of layer creation planes around the horizontal axis is 4.3°, while the average displacement of planes in pillars is 3.6°.

The average dip azimuth of the layering of the northeastern direction of technogenic accumulations differs by 7.1° from the dip of planar structures in the same direction within pillars. The average displacement of layer creation planes around the vertical axis is 7°, while in the pillars, this displacement is 5.9°, i.e., these indicators are comparable.

The dip angle of layering in the northeastern direction of technogenic accumulations is 59.6°, the average dip angle of banding in the pillars is 57.5°. The average displacement of layer creation planes around the horizontal axis is 5.5°. It is two times less than in the pillars, and is 10.5°.

The average dip azimuth of stratification in the southeastern direction of man-made accumulations differs by 25.4° from the dip of planar structures of the same direction in pillars. The average displacement of layer creation planes around the vertical axis is 8.3°, while in the pillars this displacement is 3.8°. The dip angle of layering in the southeastern direction of man-made accumulations is 49.1°, the average dip angle of banding in the pillars is 62.3°. The average displacement of the planes of creation of layering around the horizontal axis is 6.7°, and in the pillars, it is 9.3°.

If a range of 10° is considered an acceptable deviation, 68.75 % of the indicators studied within the technogenic accumulations correspond to identical indicators of native rocks (see Table 4, 8).

Table 2

Bedding elements of planar structural (banding and sides of folds), individual pillars of the eastern border of the "Pivnichnyi" quarry

No. i/s	OP	dip azimuth, °	spread of values, °	angle, °	spread of values, °	average value: dip azimuth / angle, °	general direction and percentage of measurements from their total number
1	3	265	15	40	38	260.6 / 58.2	southwest 20 %
2	9	260		55			
3	16	250		42			
4	20	265		76			
5	21	263		78			
6	2	290	85	35	60	293.6 / 47.4	northwest 64 %
7		290		40			
8		280		80			
9	3	280		38			
10	9	340		30			
11		290		43			
12		360		40			
13		280		40			
14		340		20			
15	17	280		50			
16		275		66			
17	20	275		49			
18		277		50			
19		290		68			
20	21	275		62			
21		275		48			
22	2	70	10	66	26	65 / 53	northeast 8 %
23	21	60		40			
24	2	110	15	70	37	102.5 / 51.5	southeast 8 %
25	9	95		33			

Table 3

Bedding elements of planar structural (layering, schistosity) technogenic accumulations of the "Pivnichnyi" quarry

No. i/s	OP	dip azimuth, °	spread of values, °	angle, °	spread of values, °	average value: dip azimuth / angle,°	general direction and percentage of measurements from their total number
1	2	3	4	5	6	7	8
1	1	235	70	35	42	239.2 / 44.3	southwest 16.7
2	4	240		38			
3	5	190		28			
4	6	260		30			
5		250		65			
6	13	260		70			
7	5	330	90	48	47	310 / 43.9	northwest 30.6
8		355		42			
9	13	280		65			
10		340		50			
11		310		45			
12		360		45			
13	14	270		40			
14		270		30			
15	18	280		50			
16	23	275		18			
17		340		50			
18	2	80	70	58	55	74.5 / 59.6	northeast 27.8

Continuation of Table 3

1	2	3	4	5	6	7	8
19		70		65			
20	4	70		60			
21		80		62			
22		90		25			
23		90		65			
24		65		55			
25	14	90		47			
26	15	20		80			
27		90		79			
28	1	110	75	60	60	131.7 / 49.1	southeast 25
29		140		50			
30		100		70			
31		160		20			
32	4	175		42			
33		120		40			
34		110		40			
35		110		40			
36	15	160		80			

Table 4

Summary of structural data for the “Pivnichnyi” quarry

Object	General direction and percentage of measurements from their total number							
	Southwest, 21.4 %		Northwest, 49.9 %		Northeast, 16.5 %		Southeast, 12.1 %	
	azimuth / angle, °	rotation, °*	azimuth / angle, °	rotation, °*	azimuth / angle, °	rotation, °*	azimuth / angle, °	rotation, °*
pillars of western bort and the northern part	246.6 / 57.1	3.1 / *6.3*	296.3/ 40.3	5.6 / *3.3*	69.8 / 62	6.8 / 8	110 / 73	*0 / 0*
pillars of the eastern bort	260.6 / 58.2	*3 /* **7.6**	293.6 / 47.4	*5.3 /* 3.8	65 / 53	*5 /* **13**	102.5 / 51.5	7.5 / **18.5**
technogenic accumulations	239.2 / 44.3	**11.6 /** 7	310 / 43.9	**8.2 / 4.3**	74.5 / 59.6	***7 /*** *5.5*	131.7 / 49.1	**8.3 /** 6.7
all studies pillars	253.6 / 57.7	*3 /* 7	295 / 43.9	5.5 / *3.6*	67.4 / 57.5	**5.9** / **10.5**	106.3 / 62.3	3.8 / 9.3
the difference (°) between the planes of man-made accumulations and pillars and the sign of displacement	–14.4/ –13.4	+8.6/ 0	+15 / 0	+2.7 / +0.7	+7.1 / +2.1	+1.1/ –5	+25.4/ –13.2	+4.5/ –2.6

**average calculated rotation (the ratio of the spread of angles to the number of measurements): for pillars, this is the spatial rotation of each of the blocks around the vertical/horizontal axes; for man-made layerings – displacement in space around the axes of the plane of creation of layering.*
The largest displacement values are highlighted in bold, and the smallest ones are in italics and smaller font.

Table 5

Bedding elements and relative displacements of individual pillars of the “Pivdennyi” quarry’s western side

No. i/s	OP	Dip of planar structures				Changing the spatial position of the block relative to the previous one (angle of relative rotation, °), by:		Angle of rotation, block relative to the statistical average, (°) by:	
		azimuth, °	average value	angle,°	average value	vertical axis	horizontal axis	vertical axis	horizontal axis
1	2	3	4	5	6	7	8	9	10
1	1	270	267.75	86	79.75	–	–	– 65.3	+ 30.9
2		273		68					
3		273		78					

Continuation of Table 5

1	2	3	4	5	6	7	8	9	10
4		255		87					
5	2	270	285	75	53.75	+ 17.25	– 26	– 48	+ 4.9
6		290		55					
7		270		35					
8		310		50					
9	6	255	264	45	52.8	– 21	– 0.95	– 69	+ 4
10		250		55					
11		280		44					
12		250		60					
13		285		60					
14	7	330	286.6	35	40.3	+ 22.6	– 12.5	– 46.4	– 8.5
15		290		30					
16		240		56					
17	8	285	306.6	53	51	+ 20	+ 11.3	– 26.6	+ 2.2
18		315		50					
19		320		50					
20	12	290	277	30	41,6	– 29.6	– 9.4	– 56	– 7.2
21		265		45					
22		290		33					
23		270		35					
24		270		65					
25	14	245	277.5	35	52	+ 0.5	+ 10.4	– 55.6	+ 3.2
26		280		55					
27		280		40					
28		270		58					
29		300		62					
30		290		62					
31	16	340	311.6	52	56	+ 34.1	+ 4	– 21.4	+ 7.2
32		300		61					
33		295		55					
34	17	325	335	25	25	+ 23.4	– 31	+ 2	– 23.8
35		345		25					
36	18	312	293,7	57	53	– 41.3	+ 28	– 39.3	+ 4.2
37		293		42					
38		320		45					
39		250		68					
40	19	290	300	30	29.7	+ 6.3	– 23.3	– 33	– 19.1
41		300		27					
42		310		32					
43	20	320	310	40	39	+ 10	+ 19.7	– 23	– 9.8
44		300		38					
45	25	20	16.7	35	35,3	+ 66.7	– 3.7	+ 43.7	– 13.5
46		10		35					
47		20		36					
48	26	320	317.5	45	49	– 59.2	+ 13.7	– 15.5	+ 0.2
49		315		53					
The average value for all the studied pillars on the west side			333	–	48.8	3.82	– 1.5	– 32. 4	– 1.8

Table 6

Bedding elements and relative displacements of individual pillars of the "Pivdennyi" quarry's eastern side

No. i/s	OP	Dip of planar structures				Changing the spatial position of the block relative to the previous one (angle of relative rotation, °), by:		Angle of rotation, block relative to the statistical average, (°) by:	
		azimuth,°	average value	angle,°	average value	vertical axis	horizontal axis	vertical axis	horizontal axis
1	2	3	4	5	6	7	8	9	10
1	9	265	286.7	30	28	–	–	– 6.6	– 3.9
2		300		27					

Continuation of Table 6

1	2	3	4	5	6	7	8	9	10
3		295		27					
4	10	285	298	33	38.2	+ 11.3	+ 10.2	+ 4.7	+ 6.3
5		320		40					
6		305		40					
7		305		38					
8		275		40					
9	11	275	275	40	40	– 23	+ 1.8	– 18.3	+ 8.1
10	21	290	295	47	42	+ 20	+ 2	+ 1.7	+ 10.1
11		300		37					
12	23	285	295	10	10	0	– 32	+ 1.7	– 21.9
13		305		10					
14	31	270	284.3	39	33	– 10.7	+ 23	– 8.7	+ 1.1
15		290		26					
16		293		34					
The average value for all studied pillars on the side			293.3	–	31.9	– 0.5	+ 1	– 4.3	– 0.03

Table 7

Bedding elements and relative displacements of heap, scree, and structuring planes and boundaries between technogenic accumulations and pillars of the "Pivdenniy" quarry

№ i/s	OP	Dip of planar structures				Changing the spatial position of the block planes relative to the previous one (angle of relative rotation, °), by:		Angle of rotation, block planes relative to the statistical average, (°) by:	
		azimuth, °	average value	angle,°	average value	vertical axis	horizontal axis	vertical axis	horizontal axis
1	3	295	327.5	30	42.5	–	–	– 22.5	– 17.1
2		0		55					
3	4	230	230	88	88	– 97.5	+ 45.5	– 120	+ 28.4
4	5	320	320	22	22	+ 90	– 66	– 30	– 37.6
5	7	70	70	75	75	+ 110	+ 53	+ 80	+ 15.4
6		70		75					
7	13	345	36.5	90	80	– 33.5	+ 5	+ 46.5	+20.4
8		88		70					
9	29	270	270	50	50	– 126.5	– 30	– 80	– 9.6
The average value for the studied technogenic accumulations			350	–	59.6	– 11.5	1.5	– 21	– 0.02

Table 8

Summary of structure data of the "Pivdennyi" quarry

Object	Average dip of planar structures		Blocks rotation, (°)	
			Sum statistical average	
	azimuth, °	angle, °	by the vertical axis	by the horizontal axis
pillars of the western side	333	48.8	– 201.8 – 14.3	– 22.4 – 1.7
pillars of the eastern side	293.3	31.9	– 14 – 1.9	2.4 0.5
technogenic formation	350	61.7	– 91.8 – 16.3	3.7 0.7
Average data for the quarry	325.4	47.5	– 102.5 – 10.8	– 5.4 – 0.5

Generalization for the "Pivdenniy" *quarry.*

The dip azimuths of quartzite bandingon the eastern side of the "Pivdenniy" quarry vary from 270 to 320°. Dip angles range from 10 to 47°. The average dip azimuth (on 16 measurements) of the quartzite banding is 293.3° on the eastern side of the quarry. The average dip angle (on 16 measurements) of the quartzite banding is 31.9° on the border. The average displacement of the pillars within the board, vertically and horizontally, is minimal – only a few degrees. However, we can only discussthe absolute displacement of the pillars in the quarry if we know the geological bedding elements of the rock before iron ore development began.

On the western side of the "Pivdennyi" quarry, the dip azimuths of the quartzite banding vary significantly, ranging from 240° to 20°. The dip angles range from 25° to 87°.

Based on 49 measurements, the average dip azimuth of the quartzite banding on the western side is 333°, and the average dip angle is 48.8°. In comparison, the average displacement of the blocks on the western side is significantly greater than that on the eastern side (see Table 5−8 and Fig. 2).

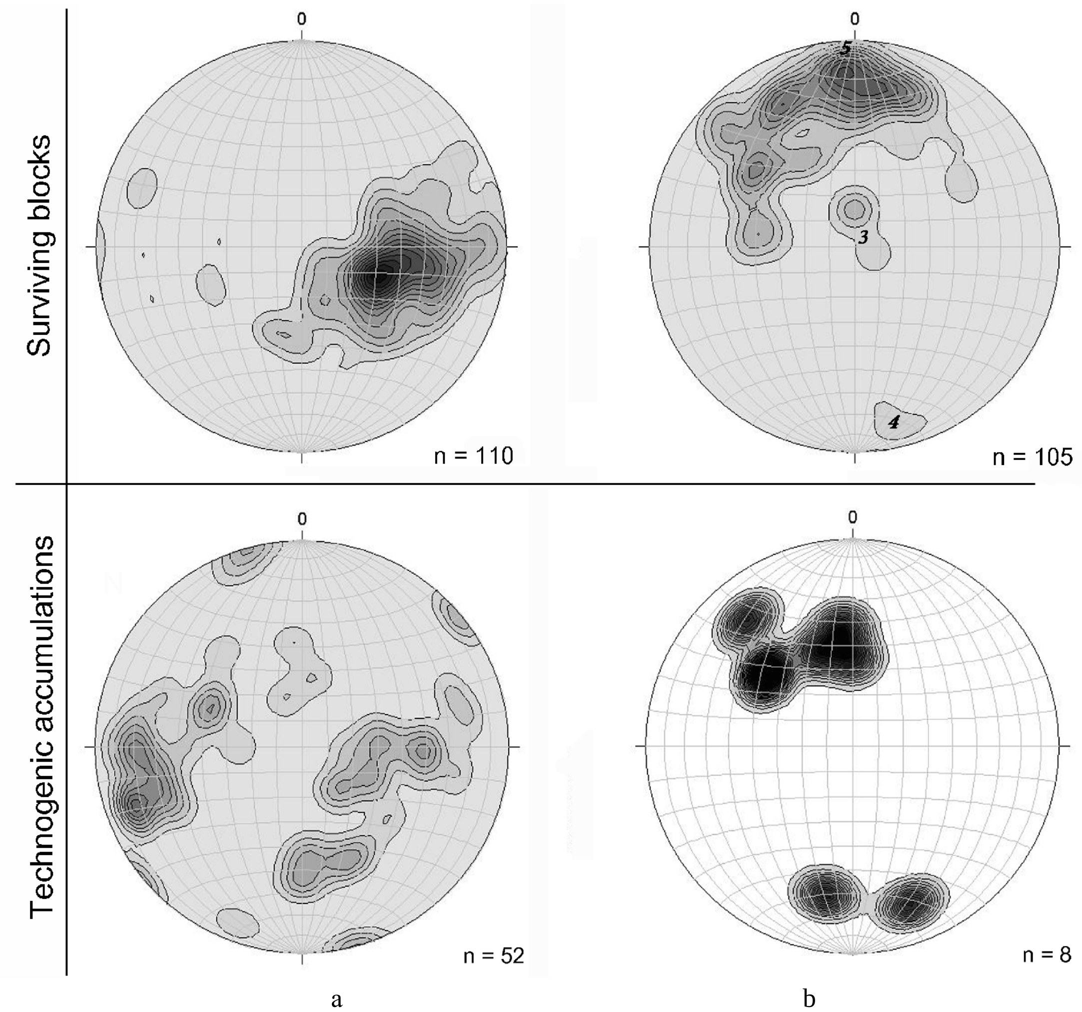

Fig. 2. Stereograms of the studied structures of the "Pivdennyi" and "Pivnichnyi" quarries: a – planar structures, b – linear structural. *Numbers correspond to generations structures. Projection to the lower hemisphere. Gradation of isolines: 1-2-3-4-5-6-7-8-9-10-11-12-13-14-15. n – number of pairs of measurements. StereoNett 2.46 program.*

The dip azimuths of technogenic textures formed in the "Pivdennyi" quarry vary between 230° and 88°, with dip angles ranging from 22° to 90°. The average dip azimuth (based on 9 measurements) for technogenic layers in the quarry is 350°, while the average dip angle (also based on 9 measurements) is 61.7°. The block displacement angles (observed in structured embankments and scree between the pillars) are comparable to similar indicators on the western side of the quarry, though they display opposite signs on the horizontal axis.

Therefore, the azimuths, dip angles, and the range of these values of the man-made layering are similar to those of the pillars. This suggests that the formation of structural and textural neoplasms within technogenic formations did not occur randomly in various planes and directions. Instead, the restoration of the integrity of the disturbed and completely eroded sections of the geological volume followed the pre-existing structural arrangement of the host rock.

Discussion

The layering we observed in the quarry dumps is a result of several factors: the technological processes involved in extraction and material placement, internal processes within the unconsolidated mass, and external influences from the geological environment. The influence of technological processes occurring in quarries on the creation of layering in tailings is expressed in the following:

1. *Technological Processes of Extraction and Dumping:*

· *Sequential Dumping:* The phased development of quarries and the separate handling of extracted materials (overburden, waste rock, or different ore grades) lead to layered deposition, where each batch forms a discernible stratum.

· *Material Variations***:** Lithological differences (e. g., quartzites, shales) and variations in grain size / composition within a single rock type (due to blasting or weathering) also contribute to the formation of distinct layers.

· *Dumping Method and Equipment:* The method of transport and discharge (dump trucks, conveyor belts) influences how the material settles, creating relatively horizontal "tiers" or inclined layers that build up at the material's angle of repose."*Bucket Memory*" *or Selection Mechanism:* Excavators and loaders can unintentionally promote a specific orientation of rock fragments, which may already carry the structural memory of the host rocks, subsequently influencing the dump's layering.

· *Operational Changes and Interruptions:* End-of-shift periods, equipment breakdowns, or changes in dumping locations can introduce subtle variations in the type or texture of dumped material, creating faint layer boundaries.

2. *Internal Processes within the Dumped Mass and Dynamic Influences:*

· *Gravitational Settling and Compaction:* Mechanical compaction occurs under the material's own weight and external influences. Anisotropic (platy) fragments (especially from ferruginous quartzites), under gravity, naturally tend to settle flat, orienting their longest dimension parallel to the dumping surface. This leads to gravitational differrentiation and fragment orientation.

· *Technogenic Vibration and Fragment Reorientation:* Vibrations from blasting, heavy machinery, and transportation continuously "shake" the dump material. These vibrations, propagating through the anisotropic host rocks, can act as a "resonating" or "orienting" force. This helps fragments "align" with the same orientation as the host rocks and enhances the compaction and alignment of the dump's layering. If the host rocks exhibit dominant systems of planar heterogeneities, these are actively replicated in the dumps.

· *Regional Anisotropy Control:* The existing structural anisotropy of the ferruginous quartzites in the Kryvyi Rih Basin, which is a key factor in the inheritance of orientation within the dumps, is a direct result of regional strike-slip stress regimes and the associated local structural elements [Pryvalov et al., 2020]. They formed the Precambrian structural framework of the Ukrainian Shield (UShch). Technogenic activity (quarry geometry, vibration) activates this primary, regionally conditioned symmetry. Thus, the local technogenic geodynamics is a response to the deep-seated structural plan of the UShch.

3. *Post-Depositional Processes and Evolution:*

· *Weathering and Erosion:* In older dumps, external factors (rain, wind, temperature fluctuations) cause differential weathering of various layers (e.g., oxidation of ferruginous layers, formation of clay minerals, dissolution). This visually enhances the contrast between layers, making the bedding more pronounced.

· *Processes Resembling Early Diagenesis:* Compaction, fluid redistribution, secondary precipitation of dissolved substances (e. g., iron oxides, silica, carbonates) within the dump's pores, and microbiological activity contribute to cementation and further consolidation of the material.

The mechanisms of layer formation and schistosity in natural conditions are substantiated in the works of O. I. Lukienko with co-authors [Lukienko et al., 2014]. In particular, in the conditions of the diagenetic subzone of the primary epizone, the optimal architecture of the accumulation environment is formed, which is in balance with the tectonic and P-T conditions at the time of the formation of layering and mechanical schistosity formation.

Therefore, a "geodynamic interaction" occurs between a man-made object (a quarry and its waste dumps) and the natural geological environment, which includes thehost rocks. It in this context refers to the active, dynamic influence and interrelationship between the technogenic object and the host rocks. Geodynamic interaction is evident through the transmission and modification of stresses and deformations, which directly influence the formation of new structures within the dumps. As the result, these dums often reflect the orientation and symmetry of the host rocks. This process creates an integrated system that blends both technogenic and natural elements that actively evolves in persuit of a new dynamic equilibrium.

Scientific Novelty of the Research Results

1. A range of structural organization has been identified in technogenic accumulations, such as scree, dumps, and filled artificial cavities resulting from quarry waste. This classification distinguishes between unstructured and variously structured accumulations. The latter displays structural features like layering, mechanical schistosity, and linearity.

2. Two methods are proposed for calculating the angles of rotation between the massifs and the structural planes of technogenic formations relative to the vertical and horizontal axes, which allow for the quantitative assessment of their mutual displacement.

3. The mechanism of structural inheritance has been established: Newly formed planar structures in technogenic accumulations arise due to the inheritance of structural anisotropy from the host rocks (massifs). This means that these structures develop in alignment with the regional symmetry of the Precambrian era, resulting in the creation of their own internal "architecture".

4. It is conceptually substantiated that the host rock massifs and the technogenic accumulations developed as a single, actively evolving technogenic-natural system, functioning due to "geodynamic interaction".

5. A constructive role has been identified: the transformation of technogenic accumulations – through self-structuring and remodelling – demonstrates constructive phenomena that can act as a natural laboratory for observing the formation processes of structural and textural elements in unconsolidated media. This transformation takes place against a background of long-term instability and reflects the systems efforts to establish a dynamic balance against destructive phenomena.

Practical Significance of the Research

1. Forecasting and Safety: The developed methodology for the quantitative calculation of rotation angles between massifs and technogenic planes (Novelty Point 2) provides a new tool for accurately predicting their mutual displacement and potential slope stability, as well as for optimizing dump geometry. This allows for the minimization of landslide risks and capital investments in engineering reinforcement.

2. Design and Infrastructure: The research findings on the factors influencing occurence and the "maturity" of technogenic structures, combined with the concept of structural anisotropy inheritance, can be used to accurately evaluate the bearing capacity of technogenic accumulations. This assessment is essential for planning future infrastructure projects, utilizing technogenic bodies for reclamation purposes, and designing effective drainage systems (especially for controlling contaminant migration).

3. Economic Development and Resources: Identifying and ranking structural elements within technogenic bodies, along with assessing their ability to self-structure, can provide a new criterion for evaluating their assimilation potential and suitability for economic development. This approach optimizes reprocessing these bodies for the extraction of residual valuable minerals and associated elements

4. Monitoring and Conceptualization: Introducing the concept of the "Geological-Technogenic System" and "geodynamic interaction' facilitates a shift towards holistic object monitoring. Furthermore, studying the self-structuring of technogenic accumulations as a "natural laboratory' opens opportunities for the long-term observation of the structural and textural element formation processes in unconsolidated media.

Conclusions

1. The bedrock block system of the "Pivdennyi" and "Pivnichnyi" quarries was formed under conditions involving rotation around both vertical and horizontal axes. The average calculated rotation of the block on the western side of the "Pivdennyi" quarry relative to the vertical axis is 14.3°, while the eastern side has a rotation of only 1.9°. The calculated average statistical rotation of the block of the western side relative to the horizontal axis reaches 1.7°, and the eastern side shows 0.5°. For the "Pivnichnyi" quarry, the difference between the eastern and western sides is minimal, based on the average measurements for planar structures.

2. Newly formed textures were found in 65 % of technogenic geological bodies (scree slopes, embankments, etc.) of the "Pivnichnyi" and "Pivdennyi" quarries, where iron horizons of the Saksagan suit are being re-developed. These textures include layering and schistosity, which are likely the result of successive filling and deposition, as well as gravitational compaction and granulation differentiation of the crushed rock mass during mining. Additionally, the rotation and reorientation of flat mineral aggregates and rock fragments contribute to these textures. In 68.75 % of the cases, the bedding elements of these newly formed textures in man-made bodies mimic the bedding elements of native rocks found in pillars.

3. The formation of newly established planar structures in technogenic accumulations (during rotational displacements) resulted from the inheritance of the host rock's structural features (which were formed under Precambrian regional strike-slip stress regimes), leading to the creation of the accumulation's own stratification. This indicates that the host rock massifs and technogenic accumulations developed in a geodynamically interacting and interconnected manner. Consequently, the studied technogenic-geological formation (quarries

where ferruginous quartzites are re-mined) represents a dynamic system: the "host rocks – technogenic accumulations", which has evolved over years and decades under surface conditions.

4. Traditionally, processes developing within technogenic landscape zones are viewed as destructtive. However, this study documents constructive phenomenon – structuring technogenic accumulations – which occurs against a background of prolonged instability and constitutes the system's attempt to find a new dynamic equilibrium. Thus, physical and chemical processes, similar to those found in natural environments, occur within technogenic accumulations. These processes are activated by human economic activity and are aimed at seeking a new equilibrium in the disturbed environment. The structures identified can be classified as derivative primary technogenic layering at the micro- and meso-levels, the formation process of which is unconsciously regulated by mining production factors.

5. The described phenomena are a unique natural laboratory for studying the formation of structural and textural elements in loose accumulations. Their long-term tracking in time would allow observing the processes of self-organization and evolution of modern technogenic and natural objects.

6. Identification and ranking according to certain features of the structural elements of technogenic bodies can be used as one of the criteria for assessing the assimilation potential (according to Dovgii et al., 2016) of the technogenically changed geological environment.

7. Research into structural neoformations within technogenic accumulations is promising for assessing their stability and suitability for further economic development. This is because the attitude elements and the degree of "'maturity" (development, consolidation) of these technogenic structures directly determine the stability level and the bearing capacity of the technogenic environment. At the same time, their spatial orientation is a critical geomechanical parameter for forecasting sliding planes and optimizing dump design.

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ТЕХНОГЕННА ШАРУВАТІСТЬ У ВІДВАЛАХ ЗАЛІЗОРУДНИХ КАР'ЄРІВ: ФОРМУВАННЯ, ВПОРЯДКУВАННЯ ТА ГЕОДИНАМІЧНА ВЗАЄМОДІЯ З КОРІННИМИ ПОРОДАМИ

Мета статті – відобразити й за можливості пояснити закономірності внутрішньої будови техногенних нагромаджень залізорудних кар'єрів "Північний" та "Південний" поруч м. Кривий Ріг. Методика досліджень така: а) польові виміри та фіксація даних; б) лабораторне опрацювання даних, що передбачало: проєктування структурних даних, статистичний аналіз та розрахунки усереднених значень азимутів, кутів падінь і розкид цих значень для площинних структурних елементів ціликів й техногенних нагромаджень, а також кутів обертань ціликів та площин структуризації техногенних утворень. Новизна результатів дослідження: а) встановлено різний ступінь структуризації техногенних нагромаджень (осипів, насипів та заповнених штучних порожнин) кар'єрних відвалів, де виділено як неструктуровані, так і різною мірою структуровані нагромадження, з фіксацією у межах останніх таких структурних елементів, як шаруватість, механічна сланцюватість та лінійність; б) запропоновано два способи визначення кутів обертань ціликів та площин структуризації техногенних утворень відносно вертикальної і горизонтальної осей, що дозволило кількісно оцінити їх взаємне зміщення; в) виявлено, що формування новоутворених площин у техногенних нагромадженнях є спрямованим процесом, який відбувається із успадкуванням структурної анізотропії корінних порід, сформованої під впливом регіональних зсувних напружень. Це призводить до утворення власної, орієнтованої техногенної стратифікації (шаруватості); г) концептуально обґрунтовано, що блочки ціликів і техногенні нагромадження розвиваються та формуються як цілісний, взаємоузгоджений об'єкт, який названо "геолого-техногенною системою", що функціонує завдяки "геодинамічній взаємодії"; д) показано, що перетворення техногенних нагромаджень (їх самоструктуризація та "добудова" є конструктивними явищами, які могли б слугувати природною лабораторією для моніторингу процесів формування структурно-текстурних елементів у сипких середовищах. Практичне значення досліджень: ранжування структурних новоутворень у техногенних нагромадженнях може бути застосовано як один із критеріїв оцінювання асиміляційного потенціалу цих нагромаджень та сприятливості для господарського освоєння. Зокрема, ці дані є необхідними геомеханічними параметрами для прогнозування стійкості схилів та мінімізації ризиків обвалів на кар'єрах.

Ключові слова: залізисті горизонти, залізорудні кар'єри, непорушені блочки, техногенні нагромадження, елементи залягання, структуризація.

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