

ELECTROCHEMICAL EXAMINATION OF THE OXIDATION PROCESSES OF SULPHIDE ORES

FROM THE ELECTROMOTIVE FORCE SERIES OF SULPHIDE ORES:

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INTRODUCTION, THE SO FAR OBTAINED RESULTS:

The hitherto performed examinations concerning the weathering of sulphide ores have shown^{1, 2} that the essence of the problem cannot be approached if the weathering of the sulphide ores is considered to be a purely chemical process, a simple chemical solution. All observed facts cannot be attributed to simple chemical changes (e. g. the change of the free sulphur content of the solutions circulating over various ore fragments and that of their total sulphate content, respectively, as well as the change of the pH of the solutions etc.). For instance that at the end of the experimental series the 0.05 N sulphuric acid circulating over a tetrahedrite fragment contained mainly ferrous and only to a small extent ferric iron, whereas under similar conditions in solutions circulating over other ores ferric iron dominates. It is also due to the above mentioned fact that in the solutions circulating over the tetrahedrite sample the separation of iron hydroxide could not be observed, although its free sulphuric acid content was lower and its pH higher than that of solutions circulating over other ores in which, on the other hand, iron hydroxide separated in ample amounts. The investigation of the interaction of systems with different redox potential consisting of metal ions (Cu, Fe, Mn) with different valences also affords a quantitative explanation of the problem as has also been pointed out² on the basis of qualitative examinations in the course of simple chemical tests.

In our papers mentioned above relating to the solution and oxidation of sulphide ore, more precisely that of some more important sulphide ores the decisive importance of the influence of the environment was already stressed. This is, of course, no new establishment as it has already been referred to by numerous authors, consequently not only the oxidation and solution of pure, or at least apparently pure ores were investigated, but also ore mixtures which can also actually be found in nature. These investigations, as well as those^{3, 4} aiming at the development of the electrochromatographic and the electrolytic structure etching methods pointed to the appropriateness of the electrochemical examination of ores, in the first place to that of their electromotive force series. However,

to be able to furnish not only qualitative data, but also a quantitative interpretation of the processes occurring during weathering on the systems occurring in nature electrochemical detailed investigations must be carried out taking the different active components into consideration.

Gottschalk and *Buehler*⁵ performed as far back as 1910—1912 also experiments concerning the establishment of the electromotive force series of ores who dealt with the oxidation of sulphide ores. They measured the potential of the different ores to metal copper in distilled water. On the basis of their measurements they established the following sequence:

Marcasite	0.37 V	Galena	0.15 V
Argentite	0.23	Chalcocite	0.14
Chalcopyrite	0.18—0.30	Niccolite	0.02
Enargite	0.18—0.23	Domeykite	0.01
Molibdenite	0.20	Metal copper	0.00
Covellite	0.20	Antimonite	-0.17 — -0.60
Pyrite	0.18	Sphalerite	-0.20 — -0.40
Bournonite	0.17		

Wells^{6, 7} performed similar examinations. According to him the potential of the various ores differs essentially if measured in acid or in alkaline medium. *Rosenkränzer*⁸ also refers to the significance of the electromotive force series and establishes that the extent of the solution of sphalerites is in proportion to the amount of iron and pyrrhotite they contain, the more they contain the greater the solution.

Recently *Rechenberg*⁹ dealt with the electromotive force series of ores. His results will be briefly mentioned here. He accomplished his more precise examinations with a valve-voltmeter the input resistance of which was 10^{12} Ohm reducing the current consumption of the apparatus and the occurring polarization phenomena to a minimum through the suitable construction of his apparatus. On the Multiflex MG 2 galvanometer which he used 1 scale division = 1 mm = 1 mV. The composition of the solution used by him corresponds to the composition of the mine inflow circulating over a certain lead-zinc deposit, containing 100 g NaCl, 22 g CaCl₂, 0.022 g FeCl₂, 0.74 g BaCl₂ per liter and SO₄²⁻ in traces. The pH of the solution was 4. The readings were taken 1/2 minute after the ore had been immersed into the solution. The results of his paper, only taking the data concerning the sulphide ores into consideration, are as follows:

I.		II.	
Pyrite	658 mV	Marcasite	646 mV
Marcasite	634	Pyrite	520
Chalcopyrite	558	Bornite	454
Sphalerite	459	Chalcopyrite	453
Covellite	448	Covellite	434
Bornite	416—448	Chalcocite	416

I.		I.	
Pyrrhotite	398,5	Molibdenite	411
Galena	395	Argentite	358
Argentite	276	Galena	328
Native copper	196	Native copper	199
Antimonite	120,5	Sphalerite	181
Chalcocite	111	Antimonite	96
Molibdenite	109,5	Hydrogen	0,000
Hydrogen	0,000		

The identical ores of the two sequels are of different origin. The sequel is the result of the measuring of the electrode potentials to a calomel electrode which were recalculated by Rechenberg for a normal hydrogen electrode in order to obtain an electromotive force series of ores which is analogous with that of the metals.

SULPHIDE ORES AS POLYELECTRODE SYSTEMS:

A heterogeneous polished ore surface can be considered to be a short-circuited polyelectrode galvanic cell on the surface of which numerous micro cathodes and micro anodes may occur. To put it more simply: both of the two sulphide ores if they come into contact with a given solution possess a certain electrode potential. Among the two phases of the system the one is more positive than the other. On direct contact, which usually occurs with polished sections and ore lodes in general, should the ohmic resistance be low in order to restore the electric equilibrium the intensity of the current between the two phases can assume relatively high values which in turn corresponds to a significant chemical alteration. In the phase playing the role of the negative pole of the different macro- or micro galvanic cells consisting of two different ores this electrochemical reaction results in the formation of cations i. e. in the solution of the phase. The ore with a more positive potential behaves as cathode, the less positive one as anode. As the extent of the solution of an anode depends among other factors also upon the size of the cathodic surface the smaller the cathode behaving as inclusion or impurity as compared to the anode, the smaller will be the extent of the solution of the anode due to electrochemical causes. The relatively great resistance of very pure ores to solution also supports this assumption.

For instance a 0.05 N sulphuric acid solution circulating over 300 g of selected really pure chalcopyrite fragment contained at the end of the experimental series an amount of copper corresponding to 0.0836 g chalcopyrite per liter, which corresponds to the dissolution of 0.418 g chalcopyrite assuming that 5 liter solution circulated over the fragment; i. e. 0.13 per cent of the pure chalcopyrite dissolved. On the other hand, under entirely similar conditions a solution circulating over 300 g pyrite fragment, containing as mechanical impurity 6,06 per cent chalcopyrite, thus altogether 18.18 gr, contained at the end of the experimental series



an amount of copper corresponding to 0.7969 g chalcopyrite per liter, hence again assuming the circulating solution to be 5 liter, of the chalcopyrite which was in direct contact with the pyrite a total amount of 3.98 g dissolved, i. e. 22.1 per cent of the chalcopyrite. Thus in the latter case, of the pyrite-chalcopyrite couple, the chalcopyrite played the role of the anode its solubility rising to 170 times that of the one observed in the case of the pure chalcopyrite. It should be mentioned that the grains of the pure chalcopyrite fragment were coarser and the ore itself more compact, than those of the chalcopyritic pyrite sample and that the chalcopyrite was distributed in very fine granules in the pyrite. All these factors definitely contributed to the extraordinary increase of the solubility of the chalcopyrite touching the pyrite mentioned above.

Bornite usually contains chalcopyrite which is a product of dismixture, furthermore the so-called chalcopyrite flames — products of decomposition — can also always be detected in it. *Ramdohr*¹⁰ established that dismixture bornites containing chalcopyrite are extraordinarily sensitive resulting in the decay of the bornite portion of the ore being far more rapid in the course of the oxidation-cementation processes than that of the chalcopyrite laminae. If the potentials of chalcopyrite and bornite are examined in any solution (s. Tables) the potential of chalcopyrite is always more positive than that of bornite, i. e. the chalcopyrite plays the part of the cathode in the ore and the bornite that of the anode, hence in the course of the oxidation processes the latter will be the first to dissolve providing an explanation for the empirical fact described above. However, weathering oxidation processes cannot only be brought about by macro- and micro-cells like the two examples mentioned above, but also by galvanic pairs in which case the dimensions of one of the electrodes may be below the limits of perceptibility as e. g. in the case of very finely distributed mechanical, or isomorphous impurities. *Rosenkränzer* has observed that the greater the iron content of a sphalerite the greater the extent of its solution. The sphalerites forming at high temperatures contain fairly large amounts of iron as the solubility of FeS in ZnS is of course in close relation with the temperature. In this case the sphalerite is anodic to the pyrrhotite of cathodic character its dissolution increases in proportion to the augmentation of its pyrrhotite content, i. e. the greater the amount of the component behaving as cathode the greater the solution.

In many polished sections prepared of apparently homogeneous ores it could be observed that the weathering and the oxidation begins and proceeds along the granule boundaries. The course of this process is visible during the electrolytic structure etching when the progress of the etching can be controlled under the microscope and photomicrographs can be made at the different stages.⁴ On the three attached photomicrographs it can be seen that in the apparently quite homogeneous chalcocite of the polished sections the grain boundaries appear (Fig. 1). Later the dissolution becomes still more marked along the grain boundaries thus the latter get more definite (Fig. 2) and finally the corrosion of the grain surface (Fig. 3) also takes place. Galvanic cells, can namely not only be composed by ores having a different chemical composition but owing to the differences in potential of the boundary surface and the

core of the same ore as has been undoubtedly proved¹¹ through the micro-potential measurements carried out on metals and alloys a difference in the grain structure of the same ore is sufficient to initiate decomposition along the grain boundaries. In the cases when the grain boundary is



Fig. 1. Chalcocite, 70 X



Fig. 2. Chalcocite, 90 X

anodic to the cathodic core the decomposition starts at the grain boundaries, whereas in the reverse case the decomposition begins at the center of the grain. The effect of this type of heterogeneity, however, is weaker from the point of view of the weathering than the electrochemical heterogeneity which can be found in the case of systems consisting of different ores. In a system composed of two components the conditions seem rela-

tively simple. However, they become far more complex in the case of a system consisting of three, or even more ores. For our future investigations of these systems the theory of Akimov¹² concerning the poly-electrode systems will afford a basis.

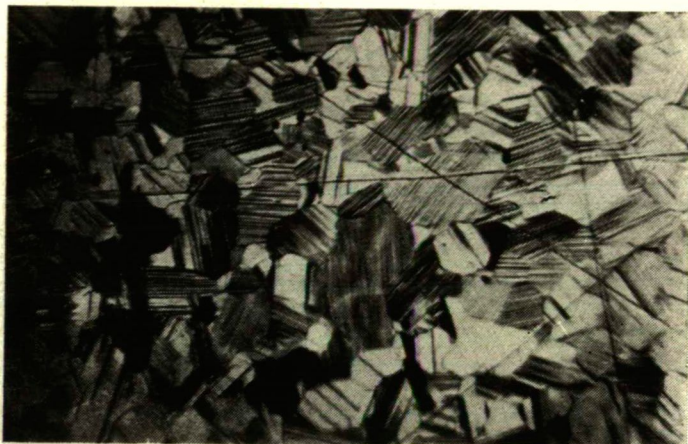


Fig. 3. Chalcocite, Oel imm. 400 X

THE INFLUENCE EFFECTED BY THE CHANGES IN CONCENTRATION OF SINGLE IONS AND THEIR SOLUTIONS, ON THE ELECTRODE POTENTIALS OF SOME SULPHIDE ORES:

As has already been indicated the authors dealing with this problem in relation to the weathering of the ores laid great stress upon the environment and to the place they occupied in the electromotive force series. The question arises whether it can be assumed that in the case of the ores there is also a constant electromotive force series of a standard value similar to that of the metals, furthermore if for the interpretation of the oxidation processes such a series is really necessary.

On the basis of present opinion that presumably there is also a given electromotive force series for ores, the purpose of the investigation was to elucidate how the different ions, in the first place Cu^{++} , Fe^{++} , Fe^{+++} , Mn^{++} , Zn^{++} and the solutions of their sulphates varying in concentration influence this assumed electromotive force series, as well as the sequence of the minerals, i. e. what is the effect of the change of the sulphuric acid concentration as in the weathering of sulphide ores primarily sulphuric acid, sulphated solutions are involved.

For the investigation the following possibly pure homogeneous polished sections were chosen:

pyrite, pyrrhotite, chalcopyrite, bornite, covellite, chalcocite, enargite, tetrahedrite, galena, arsenopyrite, loellingite, niccolite, ullmannite, smaltine, safflorite.

Before beginning each series of measurements the surfaces of the polished sections were polished with the finest polishing powder (mean grain size $< 20 \mu$) so that the quality of the surface of each ore should be identical

at all the measurements. A small glass bell into which an electrolyte was introduced was attached with bee wax to the surfaces of the ores after they had been polished and carefully cleaned. The end of the glass bell which was in contact with the ore was in every case identical in diameter (1 cm). Thus the same surfaces of the same size of all the ores came into contact with the electrolyte. As the perpendicular two opposite sides of the polished sections were polished parallel and fixed with a suitable forceps, a steady contact could be brought about. The measuring were carried out to a N calomel electrode having a compensator of 5 decade (10.000 Ohm resistance), as zero instrument - a galvanic meter with a sensitivity of $7,65 \times 10^{-7}$ V/scale div., 22 Ohm resistance served. At the measurements the values were recorded 1 minute after the contact had been established. At all measuring the same polished sections were used the surface being cleaned before each measuring series as mentioned above. The values in the Tables are recorded in the N calomel scale and not recalculated for N Hydrogen electrode.

The measurements were carried out in 0.005, 0.010 0.050, 0.100 N H_2SO_4 , 0.001, 0.010, 0.100 m $CuSO_4$, $FeSO_4$, $Fe_2(SO_4)_3$, $MnSO_4$, 0.1 m $ZnSO_4$ solutions and artificial mine inflow the composition of which was as follows: $CaSO_4 \cdot 2H_2O$: 0.68 g, $Fe_2(SO_4)_3$: 1.15 g, $CuSO_4 \cdot 5H_2O$: 4.47g, $MnSO_4 \cdot 4H_2O$: 0.16 g, $ZnSO_4 \cdot 7H_2O$: 0.23 g, $Na_2SO_4 \cdot 10H_2O$: 0.40 g, $MgSO_4 \cdot 7H_2O$: 1.47 g, H_2SO_4 : 2.98 g per liter. The different metal sulphate solutions corresponded to a solution of 0.05 N as defined in relation to sulphuric acid.

The results are summarised in the following Tables and Figures.

Table 1.

The changes of the electrode potentials depending upon the concentration of the sulphuric acid.

Ore	0,005 N	0.010 N	0.050 N	0.100 N
Pyrite	267 mV	273 mV	283 mV	287 mV
Tetrahedrite	219	218	219	219
Ullmannite	215	219	224	218
Covellite	211	206	203	194
Chalcopyrite	172	172	171	167
Enargite	161	159	161	161
Pyrrhotite	154	164	180	187
Bornite	138	135	124	121
Safflorite	126	126	133	133
Chalcocite	115	113	103	93
Arsenopyrite	63	66	85	95
Galena	56	46	36	24
Loellingite	43	45	53	65
Smaltite	6	5	5	4
Nicolite	-14	-14	-14	-14

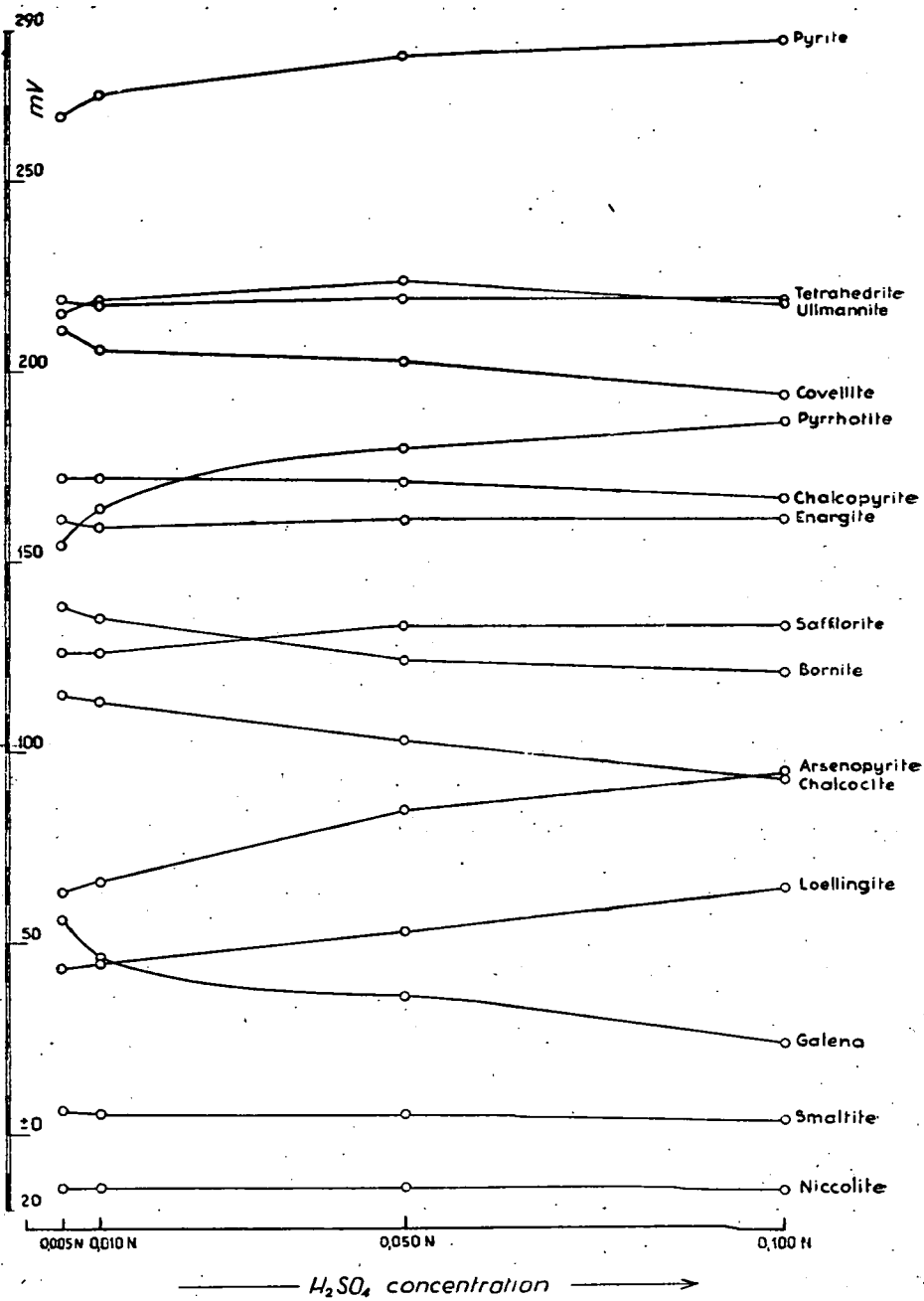


Fig. 4.

Concerning the above data it should be mentioned that some of the measurements represent mean values. As the the reproducibility for the values under -100 mV the deviation between the mean value and the single measurements is on the average ± 3 mV, in one case it is exceptionally ± 5 mV, for the higher values the deviation between the single measurements and the mean value is at the average ± 7 mV, not exceeding in any case ± 10 mV. Smaltine represents an exception considering that its potential changes very rapidly so that it could not be precisely measured by the described method, the reported value only corresponds to a very rough mean value though the order of magnitude and thus its place in the series can be safely stated.

Table 2.
Electrode potentials in a solution of 0.1 m
ZnSO₄

Pyrite	274 mV	Safflorite	111 mV
Tetrahedrite	234	Chalcocite	96
Covellite	185	Arsenopyrite	74
Ullmannite	176	Loellingite	56
Chalcopyrite	157	Galena	35
Bornite	123	Smaltite	9
Enargite	118	Niccolite	-29
Pyrrhotite	112		

Table 3.
Electrode potentials in artificial mine inflow.

Pyrite	429 mV	Safflorite	207 mV
Enargite	425	Bornite	187
Ullmannite	324	Arsenopyrite	183
Chalcopyrite	348	Loellingite	158
Pyrrhotite	326	Chalcocite	143
Tetrahedrite	294	Smaltite	82
Covellite	282	Niccolite	77
Galena	239		

Table 4.
The changes of the electrode potentials depending upon the FeSO₄
concentration.

Ore	0.001 m	0.010 m	0.100 m
Pyrite	258 mV	255 mV	232 mV
Ullmannite	204	230	221
Covellite	191	191	194
Tetrahedrite	174	182	189

Ore	0.001 m	0.010 m	0.100 m
Pyrrhotite	160	178	182
Chalcopyrite	139	145	170
Bornite	124	124	118
Safflorite	123	133	132
Enargite	122	139	161
Chalcocite	104	99	95
Arsenopyrite	76	85	83
Galena	69	69	73
Loellingite	58	59	58
Smaltite	34	24	14
Niccolite	-26	-26	-38

Table 5.

The changes of the electrode potentials depending upon the $\text{Fe}_2(\text{SO}_4)_3$ concentration.

Ore	0.001 m	0.010 m	0.100 m
Enargite	337 mV	409 mV	440 mV
Pyrite	330	417	467
Tetrahedrite	267	324	382
Ullmannite	262	343	399
Chalcopyrite	251	350	414
Pyrrhotite	238	319	387
Covellite	203	277	405
Safflorite	157	214	319
Galena	155	225	310
Bornite	143	168	213
Chalcocite	115	127	169
Arsenopyrite	109	169	270
Loellingite	97	153	262
Smaltite	48	98	255
Niccolite	10	36	49

Table 6.

The changes of the electrode potentials depending upon the MnSO_4 concentration.

Ore	0.001 m	0.010 m	0.100 m
Pyrite	267 mV	265 mV	268 mV
Pyrrhotite	250	199	196
Enargite	237	216	210

Ore	0.001 m	0.010 m	0.100 m
Chalcopyrite	225	212	201
Ullmannite	216	223	224
Tetrahedrite	210	213	214
Galena	193	177	166
Covellite	192	195	192
Safflorite	132	133	128
Bornite	127	122	116
Chalcocite	125	117	102
Arsenopyrite	98	100	92
Loellingite	42	56	62
Smaltite	20	21	22
Niccolite	-15	-22	-26

Table 7.

The changes of the electrode potentials depending upon the CuSO_4 concentration.

Ore	0.001 m	0.010 m	0.100 m
Pyrite	264 mV	272 mV	280 mV
Ullmannite	222	243	257
Tetrahedrite	215	229	243
Pyrrhotite	214	215	230
Covellite	192	202	221
Chalcopyrite	182	199	225
Enargite	177	187	209
Galena	164	178	204
Bornite	162	168	194
Safflorite	131	141	150
Chalcocite	114	124	151
Arsenopyrite	106	119	135
Loellingite	82	90	108
Smaltite	41	50	63
Niccolite	23	34	53

THE EVALUATION OF THE ELECTROMOTIVE FORCE SERIES OF THE ORES

On the basis of his investigations *Rechenberg*⁹ draws the following conclusions: the sequences of minerals is determined by the properties of their lattice structure, and influenced by their mechanical and/or isomorphous impurities. Furthermore, although the electrode potentials of the same minerals species originating from different deposits showed deviations of a centivolt in order of magnitude and the sequence also exhibited fluctuations, on the whole it was constant, i. e. the ore minerals

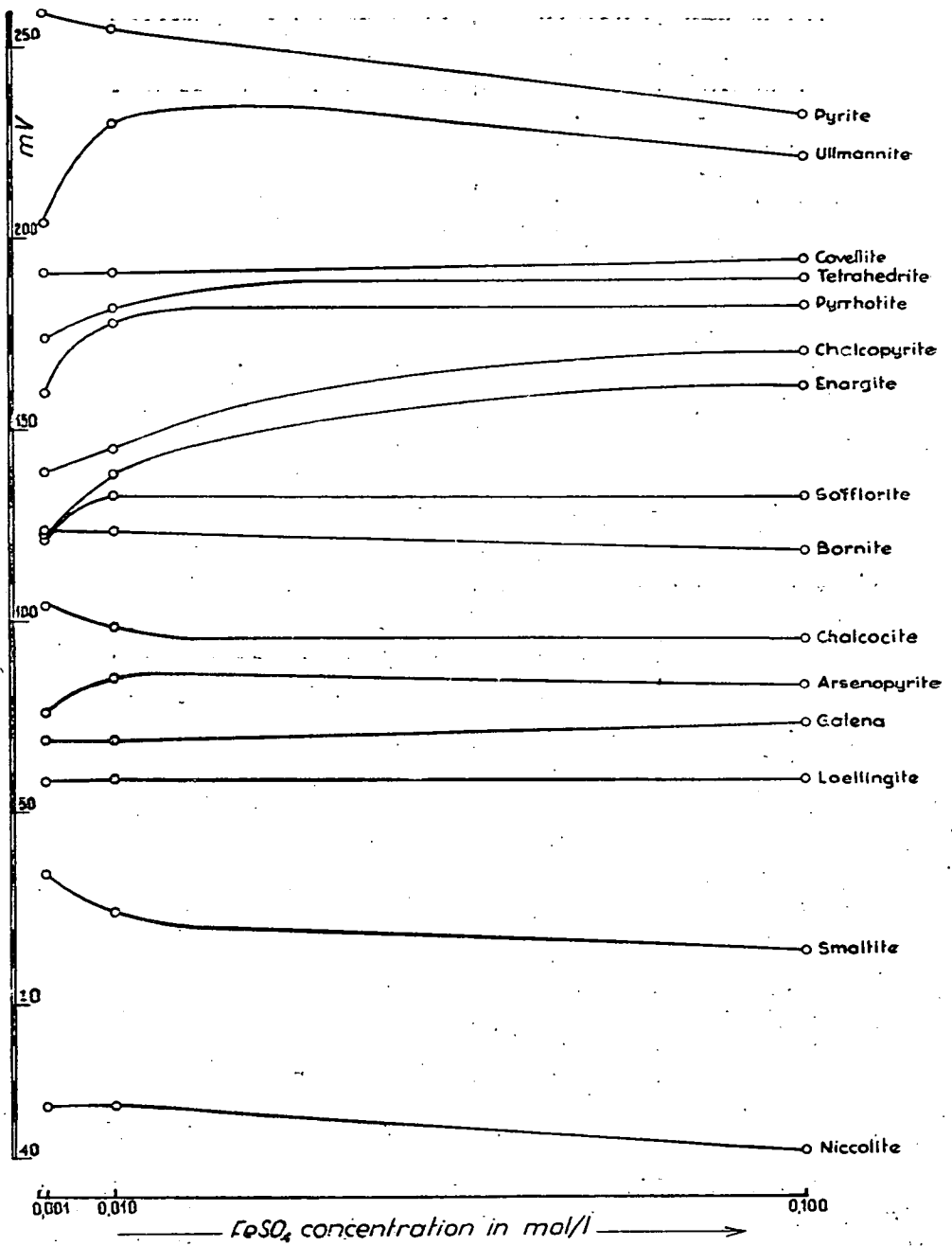


Fig. 5.

can be ranged into a certain electromotive force series. On discussing the examinations of the same author it was mentioned above that he recalculated his results for a N hydrogen electrode in order to obtain for the ores an analogous electromotive force series as that of the metals. As regards the above mentioned facts the following should be noted: in electrochemistry reversible electrode potentials correspond to the equilibrium potentials of a metal electrode and the ions of the same metal in a solution the concentration of which varies. Every reversible potential corresponds to a completely defined state of equilibrium which forms between the metal and its ions. If, therefore, the concentration of the metal own ions is increased at the electrode in the solution its electrode potential becomes more positive, if the solution is diluted it becomes more negative. The concentration of the metal ion in the solution corresponds to a definite electrode potential value. The potential which is derived to a N hydrogen electrode if the metal is immersed into a solution of a unite activity of its own ions at 1 atmospheric pressure and 25° C represents the N potential of the respective metal.

All these general establishments are only accentuated to show that if an electromotive force series of ores is mentioned and this is interpreted like that of the metals, i. e. an electromotive force series is regarded as the sequence formed from the N potentials, at the measuring of ores hitherto mentioned by various authors the sequences cannot be compared to the electromotive force series of the metals or still less considered to be analogous with them as the electrode potential values reported in the literature and in the present paper can by no means be identified with the N potentials of the ores. They cannot be considered to be the same, owing to the metal ions of the respective ore not participating in unit activity in the solution, but also because in the case of most ores the ore is usually immersed into a solution not containing its own ions, but in one containing foreign ions. Under such conditions the ore cannot be considered to be a reversible electrode and the potential is not either an equilibrium potential. Whereas, just the latter case approaches reality the most closely, i. e. the cases when the ore comes into contact with solutions containing not only its own, but also foreign ions, or often predominantly only the latter.

Hence in the case of ores there does not exist an electromotive force series analogous to that of the metals. It is true that signes of a certain constancy can be detected in the sequence a fact which has already been reported by Rechenberg and is also confirmed by the present investigation. To give only a few examples and only considering the present results: the potential of pyrite is in all solutions the greatest, the smaltine — niccolite sequence does not either change in various solutions except in that of $\text{Fe}_2(\text{SO}_4)_3$ of 0.1 mol when the electrode potential of smaltine increases to a great extent and that but for this one case the electrode potentials of both are at the end of the sequence; the of bornite-chalcocite or that of arsenopyrite-loellingite do not either change. In the copper ore series chalcopyrite and covellite had always more positive electrode potentials than bornite or chalcocite.

However, in the solutions of the different ions the concentration of which varied the sequence of the electrode potentials of ores showed a

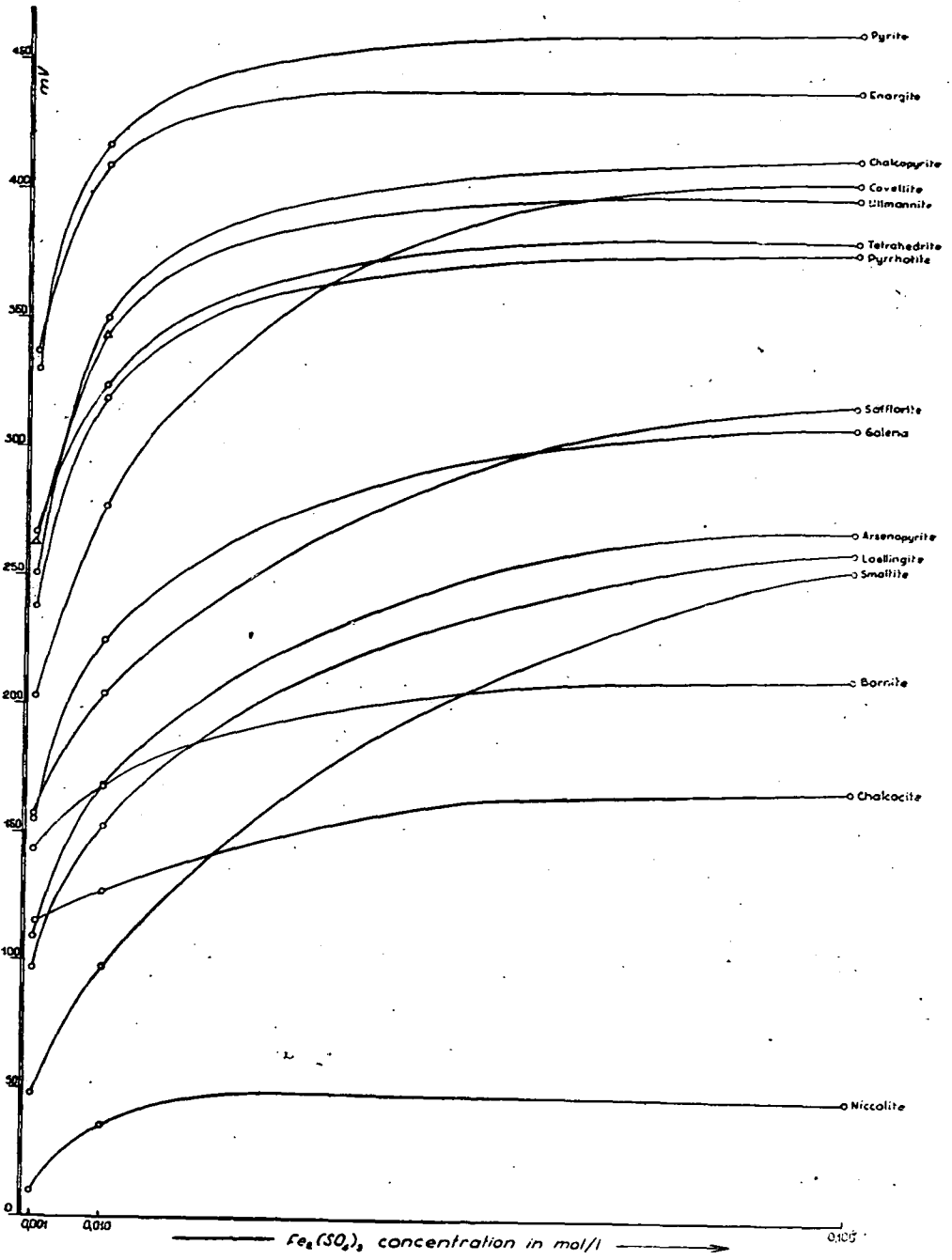


Fig. 6.

very marked change (s. Figs.) which seems to be in contrast with the assumption of the existence of a permanent sequence, although in our opinion this fact is not very essential. Whether or not there exists a constant sequence which is generally valid is all the less important considering that the electromotive force series is only a basis to deduce conclusions by virtue of the place of the ore in the series as to e. g. which of two ores will play the role of the cathode and which that of the anode, i. e. which will be oxidised on coming into contact with a certain electrolyte. As can be seen from the measurements when the composition of the solution changes not only the value of the different electrode potentials changes, but also the sequence itself, sometimes even to a great extent. Presumably in the case of ore lodes the conditions are considerably complex not only because they frequently represent polyelectroodic systems with many components, but also because in addition to the composition of the ore lodes being able to undergo changes from top to bottom, the composition of the electrolyte itself, that of the mine inflow, may change and indeed changes. Furthermore, even if the average composition of the ore body and that of the mine inflow remain the same there can still occur differences in the oxygen content of the mine inflow touching the upper zones and the deeper levels of the ore lode, which difference, in itself is enough to cause weathering, oxidising processes.

Hence as regards the weathering of the sulphide ores the establishment in the closer sense of the word of the electromotive force series based on that of the normal potentials is not an essential factor, the more so since hitherto such measuring results were not available. For instance on considering the electromotive force series of metals it is revealed that the normal potential of zinc is -0.762 , that of aluminum -1.67 , thus in the case of a galvanic couple consisting of the two metals by virtue of their place in the electromotive force series aluminum ought to dissolve, whereas in a solution of N sodium chloride just the contrary occurs, the potential of the zinc measured to a 0.1 N calomel electrode is -1 and that of aluminum -0.85 .¹¹ It may therefore be stated that also in the case of ores the normal electromotive force series is not essential, what is important is what potentials result for certain ores in a given electrolyte and what for a sequence will thus be created. This also supports the assumption which we have already suggested a few years ago that at the interpretation of the weathering and oxidation conditions of a mining district it should not be attempted establish the electromotive force series of the ores in general by determining their normal potentials, but that such investigations should deal with each respective mining district individually taking the mineral associations, the impurities contained in the minerals and the composition of the solutions influencing the mining districts — the active factors primarily influencing the electrode potentials of the ores — into considerations.

If the point of view stated above are actually realised we can still only interpret the mineral association of a mining district qualitatively concerning its oxidation conditions. To interpret also quantitatively the oxidation processes of polyelectroodic systems consisting of different ores even the most precise measurements of the electrode potentials of the given ores in a solution of a determined composition is not sufficient.

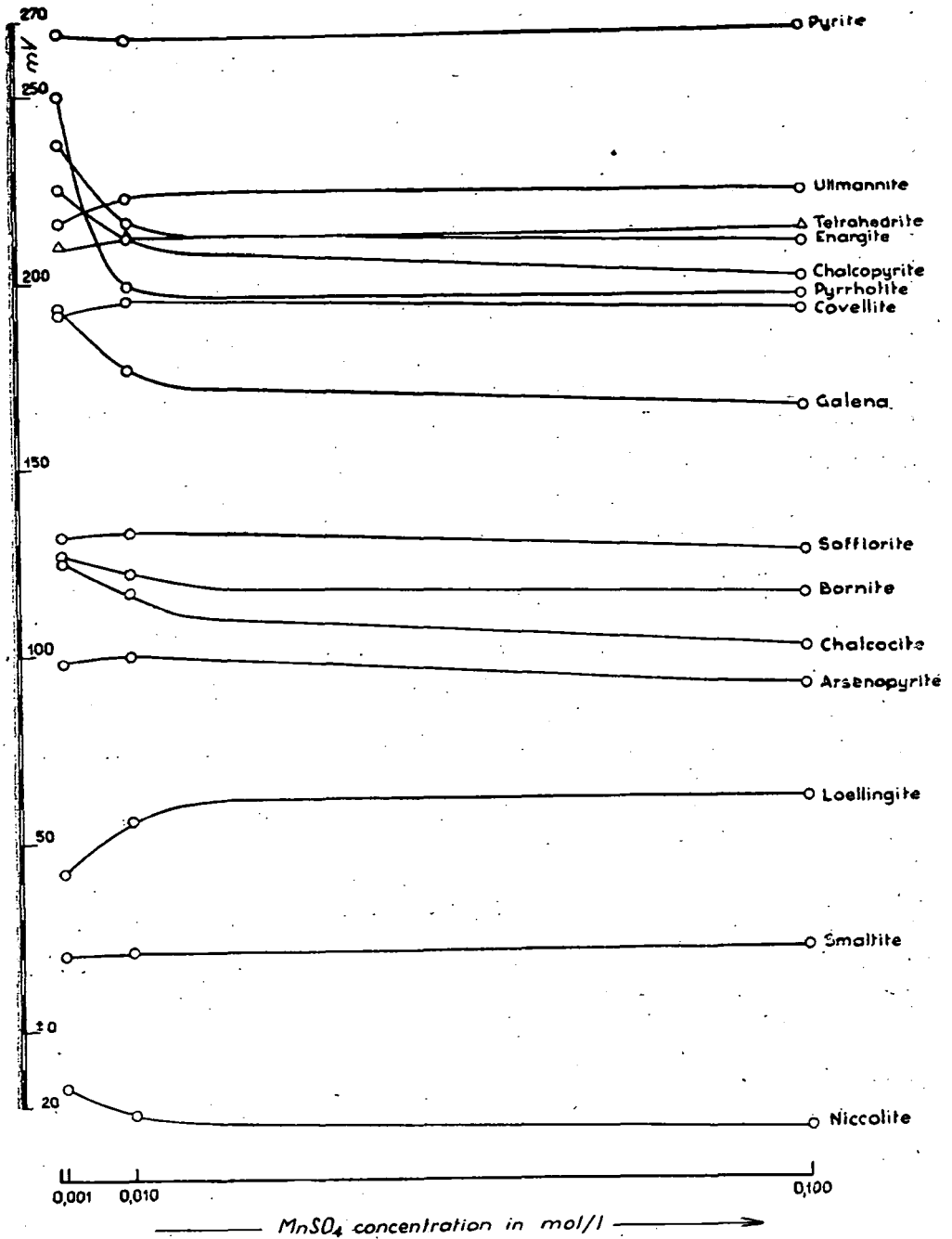


Fig. 7.

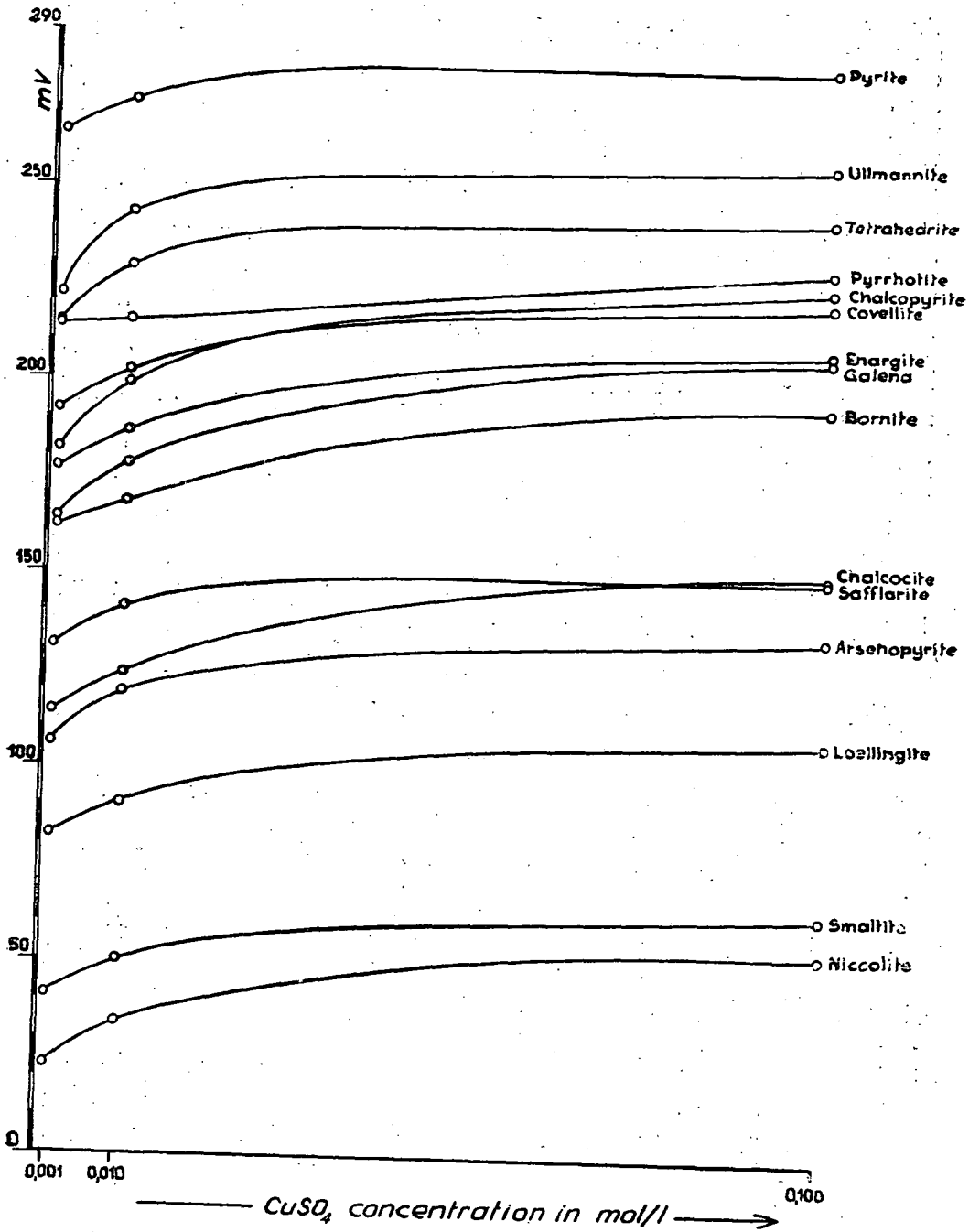


Fig. 8.

As even on the basis of the most precisely established electromotive force series the magnitude of the change and of the dissolution of the anodic ore, as well as the extent of its oxidation cannot be derived. It is true that the electromotive force series, particularly in the case of simple systems with two components, render it possible to ascertain that in a given solution which of the two ores will be the anode and which the cathode, as the potential difference between the two ores is a measure of the driving force tending to cause corrosion currents, but the magnitude of these currents is the only true measure of the velocity of the galvanic attacks. If two ores the electrode potentials of which are known compose a couple in a solution of given composition the electrode potential of the cathode and the anode, as well as the potential difference between the two only relates to the initial period of the functioning of the couple and these values soon change, thus as already mentioned, the rate of the weathering process is not in correlation with the initial potential difference of the two ores. Hence our investigations in progress deal with the changes of the electrode potentials of different ores related to time in a known solution, i. e. the cathodic and anodic polarizations and the change of the current magnitude related to time in systems with two or more components.

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