ORIGIN OF CERTAIN CANGAS OF THE "QUADRILÁTERO FERRÍFERO" OF MINAS GERAIS, BRAZIL*

by

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RESUMO

Êste trabalho oferece uma teoria de origem sub-superficial para umas cangas superficiais e sub-superficiais no Quadrilátero Ferrífero de Minas Gerais, Brasil. Propõe-se que a água de origem meteorítica percolando lateralmente e para baixo através de depósitos detríticos de itabirito, hematita compacta, filito decomposto e quartzo dissolve ferro, levando-o em solução até pontos onde as condições ambientes são propícias à sua precipitação. Aí o ferro é precipitado sob a forma de limonita que constitui o cimento entre os fragmentos detríticos formando a canga.

A teoria foi desenvolvida como resultado da observação da preservação de estrutura botryoidal nas superfícies da canga, isto é, em leitos de canga os quais estão parcialmente cobertos pelo solo. As melhores estruturas botryoidais preservadas ocorrem sob as margens de áreas cobertas de solo e ao longo das mesmas. A destruição das estruturas é mais completa à maior distância da camada de solo protetor de tal modo que a alguns metros abaixo desta cobertura as estruturas estão obliteradas.

Esta teoria está baseada no estudo da distribuição dos minerais e análises químicas de amostras da Fazenda da Alegria e Fecho do Funil, onde a canga foi exposta em recentes escavações. Determinações espetrográficas dos elementos traços de níquel, zircônio, cromo, escândio e molibdeno das mesmas amostras revelaram-se grandemente deficientes em suplementar as análises químicas, devido a baixa variação de teores e irregularidade de distribuição.

ABSTRACT

This paper advances a theory of subsurface origin for some surface and subsurface cangas in the Quadrilátero Ferrífero of Minas Gerais, Brazil. It is proposed that meteoric water moving laterally and downward through detrital accumulations of itabirite, compact hematite, decomposed phyllite, and quartz, takes iron into solution, and that where the chemical environment is favorable, the iron is subsequently precipitated from solution as a limonite cement between detrital fragments to form canga.

The theory has been developed as a result of the observed preservation of botryoidal structures on canga surfaces, that is, on canga sheets which are partially covered by

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soil. The best preserved botryoidal structures occur under and along the margins of soil covered areas. The destruction of the structures is more complete with increased distance from protective soil cover, so that a distance, usually of several meters, the structures are obliterated.

This theory is substantiated by mineral distributions and chemical analyses of samples from Fazenda da Alegria and Fecho do Funil where canga has been exposed in recent excavations. Trace-element spectrographic determinations of nickel zirconium, chromium scandium and molybdenum of the same samples proved largely ineffective in supplementing the chemical analyses because of the low magnitude of variation and irregularity of distribution.

INTRODUCTION

Canga, an iron-rich rock of combined mechanical and chemical origin, occurs throughout the Quadrilátero Ferrífero of Minas Gerais, Brazil (See Figure 1). The rock has long attracted attention both because of its physiographic prominence in covering many ridge crests, slopes, and some valley bottoms, and because of its economic value as an iron ore; its porous nature makes it more adaptable to some blast furnaces than some higher grade ores of other types. In addition to its use as a rock term, "canga" has for a long time been used in two Brazilian mining terms: "canga ore" and "canga rica", and had, in fact, its original geologic and mining usage as the former term. Canga of low hematite content, but high in limonite, such as was used in the Catalan forges is known as "canga ore." Where canga has a high content of compact hematite and a correspondingly high iron content it is called "canga rica."

Canga has several distinctive compositional characteristics, but by far the most important is the limonite* cement.

Limonite usually forms from 90 to 100 percent of the cementing material, and always exceeds the combined amount of other cementing materials. The cement content ranges from the minimum necessary to form coherent masses to the maximum permitted by inter-detrital spaces, an unmeasured range of perhaps 15 to 50 percent of the volume of the rock. The detrital fraction of canga is also distinctive, and in the majority of instances is composed of 80 percent or more itabirite fragments. However, compact hematite, phyllite, quartz, and quartzite are also common.

Besides the unusual compositional characteristics canga has other distinctive physical features. Its color ranges from light yellowish brown to very dark brownish black. The lighter colors are most commonly associated with the more recently exposed cangas and cangas of higher clay content. The grain size varies from silt and clay sized particles to large boulders, and sorting is poor to good. In general, as would be expected, diminution of size and increase in sorting are concurrent with the distance of transport. Though usually porous, canga is relatively impermeable and resistant to ero-

(*) The term "limonite" is used in this paper to refer to hydrous iron oxides whose specific identity is unknown. All of the hydrous iron oxides identified in the samples were determined by the X-ray diffractometer to be goethite.

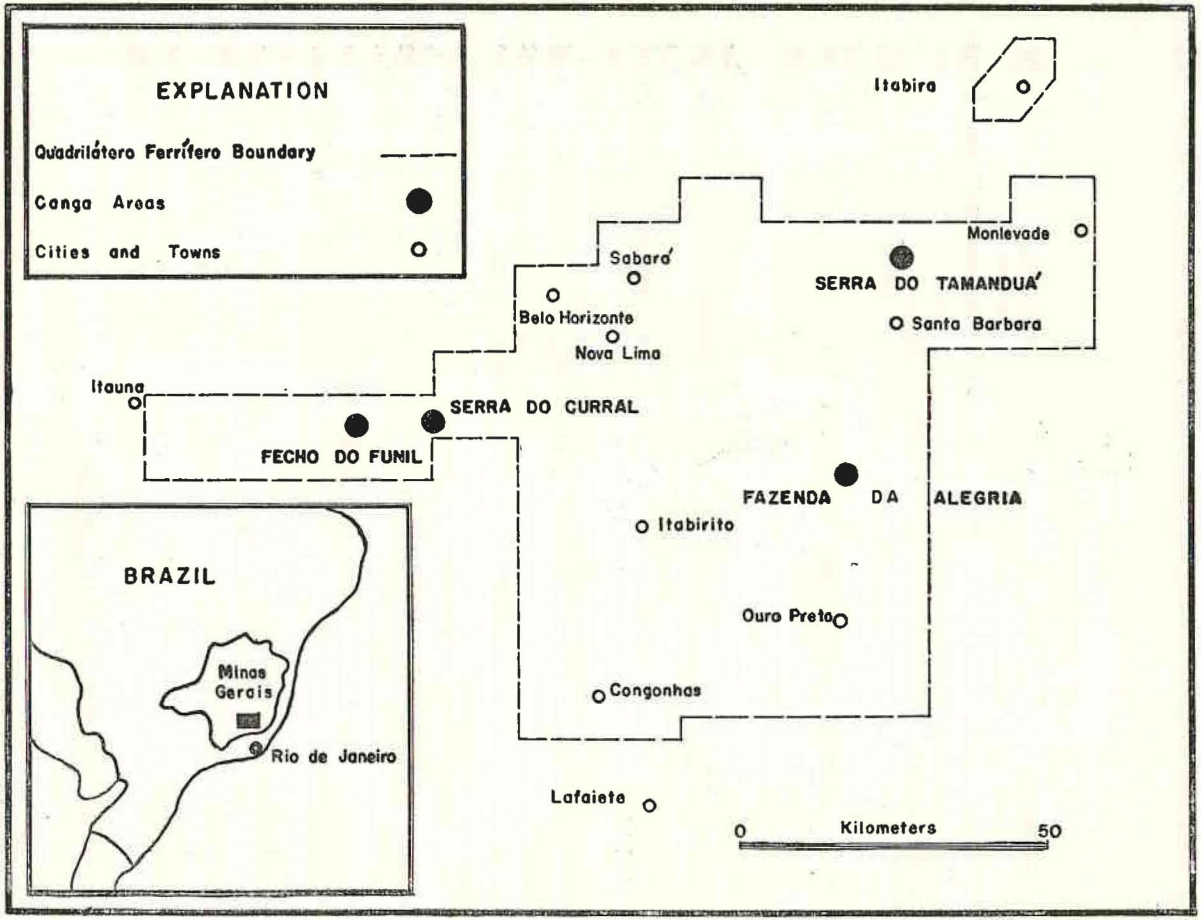

FIG. 1 — Index map showing location of canga areas of the Quadrilátero Ferrífero studied in this report

sion. The resistance to erosion can be seen in Figure 2, where erosion has taken place by the removal of underlying material and canga blocks calved off when the weight of the overhanging edge exceeded the tensile strength of the rock.

OCCURRENCE

Canga in the Quadrilátero Ferrífero is most commonly associated with the cauê itabirite, the older of the two formations in the Middle group of the Minas series*. The Cauê itabirite is a relatively resistant unit, and forms a prominent ridge to which most of the canga, both surface and subsurface, are spatially and genetically related. Canga is likewise found near outcrops of itabirite of the Gandarela formation and near pre-Minas iron formations, but canga beds related to the Cauê itabirite are more extensive and thicker than those related to other rock divisions. Canga occurs on and in unconsolidated sediments and directly on itabirite beds. Less commonly canga occurs directly on rocks other than itabirite.

Surface canga forms caps on many ridges which are underlain by itabirite beds, on slopes extending away from these ridges, and on flats of some valleys (See Figure 3). The largest areas covered by canga are those on topographic slopes which are inclined in the same direction as the dip of the itabirite beds. Canga blankets on these slopes are commonly one to there meters thick, but at one place in the Santa Rita Durão quadrangle near Fazenda da Alegria (See Figure 1) a thickness of 30 meters is reported (C. H. Maxwell, 1958, oral communication). Canga on inface slopes is not as extensive as that on dip direction slopes, though in some places as on the south side of the Serra do Curral such canga covers large areas.

Subsurface cangas also form blankets beneath slopes and valley flats, but have not been discovered near ridge crests. Due to their concealment less is known of the thickness and distribution of subsurface cangas. Numerous exposures on the south side of the Serra do Curral establish the continuity of the large surface and subsurface canga blankets in that area. Elsewhere, subsurface cangas have been encountered in road cuts and excavations near valley bottoms such as found at Fazenda da Alegria and near Fecho do Funil, und underlying the surficial material of alluvial fans such as found in the Serra do Tamanduá. In the Macacos quadrangle south of Belo Horizonte individual drill holes into unconsolidated sediments of either Tertiary or Quaternary ages or both, have encountered as many as four layers of canga. This indicates that conditions for forming canga have been in effect several times during the Cenozoic Era.

(*) The Minas series as now recognized was first divided into upper, middle, and lower groups by Dorr, Coelho, and Horen (1956, p. 286). Formal names were proposed for the groups the following year (Dorr, Gair, Pomerene, and Rynearson, 1957, p. 24-29), and the included formations were subsequently named and defined (Sociedade Brasileira de Geologia, 1958, p. 57-69).

ORIGINS PROPOSED FOR BRAZILIAN CANGA DEPOSITS

No controversy has been noted in the literature or reported in scientific meetings concerning the mechanically derived detrital part of canga. The fact that canga contains fragments of the same rocks that outcrop nearby, and the fact that the size of these fragments is diminished with distance from the outcrops point directly to the source of the detritus. There has been, however, considerable controversy concerning the manner of formation of the chemical fraction, the limonite cement, and it seems likely that it forms in several ways.

Dorr (1945, p. 53-4) described canga at two different elevations in the Morro do Urucum area of Mato Grosso. The high level canga is found in small areas in valleys on the mesas of Morro do Urucum and Serra da Santa Cruz. Dorr thought it possible that ground water moving through iron-rich beds enroute to the valley became saturated with iron, and that the iron was precipitated as hydroxide around alluvial fragments of hematite where the waters came to the surface and evaporated. The low level canga occurs in more extensive areas, especially near the base of Morro do Urucum mesa and along the road to Piraputangas and São Domingo. A similar origin was suggested by Dorr for the lower level cangas, but in the latter instance the linear distribution indicated that the iron bearing solutions might have risen along faults. Dorr (1958, written communication) has recently given additional information pointing out the differences between the two cangas. "The high level canga occurs on oxide-facies iron formation (itabirite) and contains detrital material from the iron formation. The low level canga occurs on granite, gneiss, and biotite schist, and contains very little detrital material." Another difference pointed out by Dorr is the distance in travel of the iron bearing solutions before limonite precipitation occurred. For the high level cangas the distance would probably be measured in meters, but for the low level deposits the nearest possible iron source is several kilometers away.

Guild (1957, p. 45-6, 59) recognized two origins for canga in the Congonhas district of Minas Gerais. In the first of these the canga is formed *in situ*, derived from the weathering of itabirite. During this weathering process quartz is leached by ground water, hematite is hydrated to limonite, and some limonite is precipitated from solution. Where the resulting product of this process maintains vestiges of the original bedding, Guild used the term "enriched itabirite," reserving the term "canga" por rock which does not show bedding. Guild suggested that iron-bearing waters percolating down slope provided another source for limonite cement in canga. In support of this idea he noted that canga deposits are more numerous on dip direction slopes than on inface slopes, and are thicker down-slope than up-slope

In the Itabira district J. Van N. Dorr and A. L. Barbosa (1958, written communication) have postulated that some canga is formed by the precipitation of limonite at the surface during dry season by evaporation when iron-bearing waters rise by capillary action to the surface. This theory is supported by J. E. Gair (1958, written communication) for canga in the Nova Lima and Rio Acima quadrangles of the Quadrilátero Ferrífero. Dorr (1958, p. 37) has favored this theory of origin for much of the canga in the Quadrilátero Ferrífero. And Putzer (1958, p. 38) has inferred that the canga ores of both the Morro do Urucum area of Mato Grosso and the Quadrilátero Ferrífero are formed by this process, "... products of an intermittent climate of the tropics, principally formed in distinct periodical dry times."

In the Rio das Pedras und Gandarela quadrangles of the Quadrilátero Ferrífero, J. E. O'Rourke (1948, written communication) described a process similar to that proposed by Guild, and observed that canga had formed in fractures of recently slumped blocks of itabirite. O'Rourke did not believe that capillary action could occount for the cementing of canga in the Quadrilátero Ferrífero because the water table in many canga areas is far below the canga level.

J. B. Pomerene (1958, written communication) believes that canga is formed only beneath a ferruginous soil cover ranging from a few centimeters to several meters thick, and that the overlying soil is the source of the iron which forms the limonite cement in canga. Pomerene adopted a classification which divided canga into three classes, all formed in the same manner: canga rica, ordinary canga, and chemical canga. Canga rica is characterized by high content of compact hematite. Pomerene's "ordinary canga" contains a much higher proportion of itabirite fragments to compact hematite fragments than does canga rica, and also has a higher content of limonite cement. Pomerene's "chemical canga" is composed of very fine ferruginous particles cemented by a large amount of limonite. Pomerene found that chemical canga had generally formed at a greater distance from the itabirite source beds than other types of canga, and noted that the detrital particles were of small size because of their great distance of transportation.

Pomerene cited places where chemical canga, recently denuded of its soil cover, exhibits botryoidal structure, and other places where chemical canga denuded of its soil cover shows a destruction of this structure. Pomerene inferred from this that botryoidal structure is characteristic of growing canga, removal of the soil precludes the deposition of more canga, and leads to the destruction of the botryoidal structure. This results in the formation of a rough surface, typical of canga exposures throughout the Quadrilátero Ferrífero.

In all of the above theories for the origin of canga it is concluded that the source of the iron which is precipitated to form the limonite cement is either hematite-rich sedimentary rocks or hematite-rich detritus derived from such rocks. These theories are in agreement that meteoric water is the agency by which iron is taken into solution. The theories differ principally over the cause of limonite precipitation: evaporation where water tables encounter the surface, evaporation in conjunction with capillary action, and precipitation where downward and laterally moving solutions encounter the proper chemical environment.

In studying the Serra do Curral, Serra do Tamanduá, Fazenda da Alegria, and Fecho do Funil cangas, the distribution and preservation of botryoidal structures are most nearly explained by the theory of Pomerene. At Fazenda da Alegria and Fecho do Funil where samples were taken for chemical analyses, the surface concentrations of resistates and the diminished removal of soluble components with depth in detritus above the canga, and the uniformity of composition of the detritus below the canga at Fecho do Funil seem explainable only by a theory involving downward and laterally moving meteoric waters.

THEORY OF ORIGIN

The theory of origin of canga proposed herein is based upon the study of canga at four localities. It is advocated in the theory that canga was formed by cementation of hematite-rich (largely in the form of itabirite) detritus principally through the action of laterally and downward moving meteoric water. Rain falling on the surface of these sediments dissolved organic material to form acid water, and dissolved iron as it circulated. Ultimately, the solutions reached a new environment where they became less acid because of dilution in the groundwater zone or became less acid or alkaline because of reaction with the materials through which they passed. Where this happened iron was precipitated as limonite around the detrital particles to form canga. As iron was dissolved, detritus of phyllitic origin in the sediments weathered to form clay minerals which were residually concentrated near the surface. Quartz, where finely divided, was removed by solution, but where in large grains or pebbles was concentrated near the surface with the clay minerals. At some place, erosion has removed the overburden of clay leaving exposed at the surface canga which was formed subaerially. Though here applied to only four deposits, the writer believes that the theory has widespread application which will become apparent as more detailed investigations of canga are made.

The conditions which bring about the formation of canga may also cause hydration, replacement, and laterization. These processes, though often associated with the formation of canga, are not necessary to its formation. Although most of the limonite cement is the result of precipitation from incoming solutions, some of the limonite is formed in place by the hydration of hematite. It is quite common to see in canga two pieces of itabirite in contact, welded together by the hydrated product (limonite) of the original constituents.

At many locations phyllite and schist fragments are found in canga. These fragments are commonly replaced by limonite. Though not necessary to the formation of canga, replacement has some economic importance in that it may raise the tenor of iron to ore grade. Of considerable geologic importance is the probability that the replacing limonite was deposited from the same solutions which removed the alumina and silica of the phyllite and schist.

Though the gradation between canga and laterite has been noted by Dorr (1958, p. 37) no attempt to separate the two by definition has been made. Both canga and laterite can form under the same weathering conditions, and the difference between the two is due to the difference in the materials weathered. Where there is gradation between the original materials then it seems only natural to expect a gradation in the end products of weathering. If a colluvial deposit is composed of both itabirite and soil of phyllitic or feldspathic origin, under the tropical weathering conditions in Minas Gerais canga will form in the part which is composed of itabirite detritus and laterite will form in the soil. Laterization is accomplished by the breaking down of the clay minerals and the leaching of silica with the result that the aluminum and iron sesquioxides are concentrated at or near the surface. In addition, iron is transported in solution from the upslope end of the colluvium, and is depositel with the indigenous sesquioxides down-slope. The resultant product can be differentiated only with great difficulty from fine grained canga which originaly contained numerous small pieces of itabirite.

Those attempting to separate canga from laterite by definition will be faced with some difficult problems. A separation based on the size, composition, or amount of detritus is contrary to the accepted usage of the term "canga." A separation on the basis of the origin of the iron would be extremely difficult as the iron can be deposited fron solutions which are local or have traveled long distances. If a separation is possible it will likely have to be made on the cause of precipitation of the limonite, whether it is due to fixation by clay minerals, replacement, or chemical precipitation. More work is needed before the definitions of canga and laterite can be further refined.

SERRA DO CURRAL CANGA LOCALITY

The Serra do Curral canga locality occupies several square kilometers on the south side of that range of mountains, southwest of Belo Horizonte (See Figure 1). It consists of erosional remnants of a once larger continuous sheet of canga which covered much of the south flank of the range. All of the exposures are in the Brumadinho N.º 1 and Ibirité quadrangles, and are accessible by company roads and tertiary (Jeep) roads which connect the town of Brumadinho with the village of Casa Branca and highway BR-3.

The canga at this locality occurs in and on unconsolidated sediments deposited on granite (now granite saprolite). Where the canga has not been eroded it preserves the approximate position of an old pediment surface which forms a distinctive topographic pattern (See Figure 4). The upper end of the canga sheet is exposed at the surface. The lower end is mostly covered by soil as much as several meters thick. Between the two extremes the canga is exposed wherever the soil has been removed, most commonly along streamlets, but also in many other places.

Along the margins of the soil covered areas the canga surface has botryoidal structures. Removal of soil over the canga also exposed the same structures. With distance away from the soil cover the botryoidal structure is progressively less distinct, and so the distance from soil cover is probably a direct correlative of the length of exposure. Figure 5 shows four canga samples from the Serra do Curral locality, taken at the margin of a soil covered area and at distances of one, two, and three meters from the soil. The samples show the increased breakdown of the botryoidal structure with distance from protective cover.

The presence of botryoidal structures under and at the margin of the soil, and the breakdown of the structures on exposure is interpreted as an indication that the structures were formed below the surface. The apparently low iron content of the overlying soil, and the inclination of the pediment indicate the likelihood that irom was dissolved from the overlyng material and was subsequently precipitated from downward and laterally moving solutions.

FAZENDA DA ALEGRIA CANGA LOCALITY

The Fazenda da Alegria canga locality is in the Santa Rita Durão quadrangle (See Figure 1), and is 5,430 meters south and 140 meters east of the quadrangle's northwest corner. The location can be reached by driving toward Fazenda da Alegria from the town of Santa Rita Durão, and is on the south side of the road within a few meters of the ford across the Piracicaba River, about 150 meters from the Fazenda house.

Recent widening of the road to Fazenda da Alegria near the Piracicaba River ford exposed a 105 centimeter thick section of hematite-rich alluvium and underlying canga. The alluvium deposited by the Piracicaba River, consists of poorly defined intercalated lenses. Some lenses contain concentrations of quartz, quartzite, and hematite pebbles, and others contain concentrations of finer particles and earthy material, mostly gibbsite. Almost all of the alluvium is derived from rocks of the Minas series.

Chemical weathering of the unconsolidated material is not in an advanced state, but some of the hematite pebbles have been partially hydrated to limonite, the hematite forming small cores insides shells of limonite. This hydration is most prominent near the surface, where some hematite fragments have altered completely to limonite, and diminishes with depth. The canga, like the overlying alluvium, contains poorly defined lenticular concentrations of coarser and finer clastic constituents. The surface of the canga has a botryoidal structure (See Figure 8). This structure is best developed under the protective cover and where the protective cover has been most recently removed. The destruction of the structure by recent weathering is greater with increasing distance from cover, and as at the other localities is probably related to the duration of exposure.

Here again, the distribution of the botryoidal structures is taken as evidence of its formation below the surface. The greater hydration of hematite toward the surface indicates that meteoric water passing through the sediments moved downward rather than upward. As the canga surface at this locality is only a meter or two above the level of the Piracicaba River it seems possible that its formation may have been governed by the presence of a water table.

Five samples were collected from the Fazenda da Alegria locality, four from the unconsolidated material and one from the canga. Of the four samples from the unconsolidated material, the uppermost was collected at the surface, the next two were collected within the unconsolidated material, and the fourth was collected immediately above the canga. The five samples were collected as nearly as possible in a vertical line, and each weighed approximately 0.3 kilograms. Care was taken to avoid the collection of large pebbles which would unduly bias samples of this small size. The samples were crushed, small fractions were removed for spectrographic and X-ray analyses, and the remainders were analyzed chemically. The results of the chemical and spectrographic analyses are presented in Table 1.

FECHO DO FUNIL CANGA LOCALITY

This canga locality is near the community of Fecho do Funil (See Figure 1). The site is in the Fecho do Funil n.º 2 quadrangle, 3,450 meters south and 3,600 meters east of the quadrangle's northwest corner. It can be reached by driving 300 meters southwest on the road from Fecho do Funil to the Saraiva mine. From this point the exposure can be seen about 50 meters southeast of the road.

Here, land leveling has opened a bank of alluvium in which a layer of canga is exposed. The alluvium is composed almost entirely of very fine grained to clay sized particles that before weathering were a homogenous mixture of detritus. The canga is overlain by 65 centimeters of sediment, and itself overlies 55 centimeters of exposed sediment. The material overlying the canga which consists mostly of kaolinite, is much more weathered than is the corresponding material at the Fazenda da Alegria locality. The canga is only five centimeters thick in the line of sampling, but is several times thicker along most of the outcrop. The upper surface of the canga has a botryoidal or mammillary structure, some of which has lobes that are considerably larger than that commonly seen in the Quadrilátero Ferrífero (See Figure 9). The material underlying the canga is dark brown, and contrasts with the light cream colored material above the canga (See Figure 10). It is composed largely of earthy material, and like the overlying canga contains sparse fragments of hematite and fine grained quartz.

As at the other three canga localities, the instability of the botryoidal structure to surface exposure is indicative of its fomation under a protective soil cover. At the Fecho do Funil locality where both top and bottom of the canga layer can be observed, only the upper surface has the botryoidal structure. It seems a logical deduction from this observation that the upper surface of the canga is the "growing" surface or the surface at which the limonite was being deposited. The weathered condition of the alluvium above the canga and the unweathered condition of that below, point to a dissolving and precipitation of iron by descending rather than ascending solutions. Also, if the botryoidal structure does indicate a "growing" surface, it would be difficult to explain how it could be formed by ascending solutions which would have to pass through a relatively impermeable canga layer.

Seven samples were collected from the Fecho do Funil locality: three from the unconsolidated sediments above the canga, one fron the canga, and three from the unconsolidated sediments below the canga (See Figure 10). Of the three samples collected above the canga the uppermost was taken near the surface, the second near the center of the material, and the third from immediately above the canga. Of the three samples collected below the canga the uppermost was taken immediately below the canga, the second near the center of the material, and the lowest from near the base of the exposure.

The samples were collected in a vertical line, and each weighed approximately 0.1 kilogram. The samples were prepared in the same manner as described for the Fazenda da Alegria samples, and the results of the chemical and spectrographic analyses are presented in Table 2.

EXPLANATION OF CHEMICAL ANALYSES

Because of variations in the original sediments forming the samples from the Fazenda da Alegria canga locality (See Table 1), and because weathering of these sediments is not in an advanced stage, the chemical analyses point out the differences in the sediments more than the effects of weathering. For example, Sample 2 (Table 1) is coarser grained and contained more compact hematite and itabirite than the other samples. Hence, its iron content is higher than the iron content of Samples 3 and 4, despite its having been subjected to more rigorous weathering than the latter two samples. The results of the weathering show best in Sample 1 where iron has been removed and in Sample 5 where it has been precipitated. Sample 5 comprises very fine grained sediments and unlike the four overlying samples contains few quartz, hematite, and itabirite pebbles, and probably was originally high in alumina. Now due to the precipitation of limonite to form canga, the iron content is much higher than in any of the other samples.

The chemical analyses from the Fecho do Funil locality (See Table 2) are more easily interpreted than those from Fazenda da Alegria because the original sediments were a homogeneous mixture. Weathering of the sediments above the canga is in an advanced stage. In the two upper samples (Samples 1 and 2) almost all soluble iron has been removed, and the small percentages which remain are probably fixed in the clay minerals, mostly kaolinite. The formation of clay seems complete, and hence the similarity in amounts of silicon and aluminum for the two samples. In the sample immediately above the canga (Sample 3) the iron has not been completely leached, and therefore has a higher value than Samples 1 and 2. Also, the

Table 1. — Results of analyses from Fazenda da Alegria canga locality

Sample N.º	Depth from surface in centimeters		Partial chemical analyses[1] in percent			Spectrographic analyses[2] trace elements in ppm				
	Top	Base	Fe	Si	Al	Ni	Zr	Cr	Sc	Mo
1	0	10	15.1	22.3	7.9	1.6	295.	155.	5.2	1.9
2	25	35	23.3	17.7	7.1	1.6	295.	155.	2.7	2.6
3	65	75	20.6	19.9	11.4	1.8	220.	155.	2.7	2.6
4	95	105	20.8	21.4	7.4	1.6	215.	240.	2.6	5.2
5 (canga)	105	115	37.3	4.3	10.8	.8	125.	340.	3.3	5.2

1 Analyzed by C. M. Pinto, chemist, Departamento Nacional da Produção Mineral.
2 Analyzed by C. V. Dutra, spectro chemist, Instituto de Tecnologia de Minas Gerais.

Table 2. — Results of analyses from Fecho do Funil canga locality.

Sample N.º	Depth from surface in centimeters		Partial chemical analyses[1] in percent			Spectrographic analyses[2] trace elements in ppm				
	Top	Base	Fe	Si	Al	Ni	Zr	Cr	Sc	Mo
1	0	20	3.5	20.8	18.7	4.7	75.	115.	4.9	0.0
2	35	45	3.2	20.8	18.5		(not analyzed)			
3	60	65	9.1	21.6	15.0	3.8	75.	115.	4.9	0.0
4 (canga)	65	70	43.1	10.5	3.4	6.3	110.	155.	5.1	0.0
5	70	75	32.5	16.6	6.1	5.1	120.	115.	5.2	0.0
6	90	100	36.2	15.6	4.7	5.5	155.	25.	8.5	2.6
7	115	125	38.4	14.6	4.6	2.7	50.	10.	5.5	2.2

1 Analyzed by C. M. Pinto, chemist, Departamento Nacional da Produção Mineral.
2 Analyzed by C. V. Dutra, spectro chemist, Instituto de Tecnologia de Minas Gerais.

aluminum value in Sample 3, as would be expected, is slightly lower than for Samples 1 and 2. The chemical values of the canga are normally proportioned, higher in iron and lower in both silicon and aluminum than the sediments above and below.

The difference in the silicon to aluminum ratios above and below the canga, about 5:4 and 3:1 respectively, is due to the solution and removal of quartz above the canga. This apparently was aided by the very fine grain size, and is contrary to what occurred at Fazenda da Alegria where the coarse grain sizes seem to have retarded solution.

Of special interest at the Fecho do Funil locality is the fact that weathering has begun in the sediments below the canga. It is not known whether the weathering below the canga commenced as a result of the opening of the exposure or to a lowering of the water table, or to some other cause. Nevertheless, the small variations of elements below the canga indicate the same process of downward migrating waters. The slight leaching of iron from the top of the sub-canga sediments corresponds to the slight concentration of aluminum and silicon (See Samples 5, 6, and 7, Table 2). It seems likely that another layer of canga is now forming at some level below the exposure.

INTERPRETATION OF SPECTROGRAPHIC DATA

Quantitative work was completed for nickel, zirconium, chromium, scandium, and molybdenum. Nickel and scandium had such little variation in magnitude that they were deemed useless as indicators of the direction of movement of meteoric waters. Molybdenum, when subjected to chemical weathering, dissolves readily, is carried away in solution, and is precipitated only under unusual conditions. Molybdenum at the Fazenda da Alegria and Fecho do Funil localities conforms with the theory of downward moving solutions, the sediments at both localities being devoid or lowest in this element in their upper parts. It was thought that zirconium would be concentrated in the sediments most leached, both as restates and precipitates absorbed by the clay minerals. This condition seems substantiated at Fazenda da Alegria, but the irregular zirconium distribution at Fecho do Funil is difficult to explain by any solution movement. It was thought that the chromium distribution would be the same as the expected zirconium distribution. Instead, at Fazenda da Alegria the chromium has an inverse relation to zirconium. At Fecho do Funil the chromium has an irregular distribution somewhat like that of zirconium, and likewise difficult to explain by any solution movement.

Although the evidence for any theory of canga formation given by the trace element work is inconclusive, the trace element data have been included in the tables for what interest it might have for other students of this problem, and because of a general dearth of published information of this type.

CONCLUSIONS

1. The canga deposits studied at Serra do Curral, Serra do Tamanduá, Fazenda da Alegria, and Fecho do Funil were formed by lateral and downward moving waters which permeated through hematite-rich sediments, taking iron into solution, and subsequently precipitating it as limonite around detrital particles to form canga.

2. Botryoidal structures on canga are developed in the subsurface, and are indicative of "growing" surfaces. As canga is relatively impermeable, the presence of these structures on the upper surfaces of the cangas at the four studied localities points to their formation by the deposition of limonite from downward moving solutions, not upward moving solutions.

3. The distribution of minerals and their chemical analyses at Fazenda da Alegria and Fecho do Funil shows the greater intensity of weathering toward the surface, and also points to downward rather than upward moving solutions as being responsible for the formation of canga.

4. The results of the trace elements work are not well understood. These results neither prove or detract from the theory of origin here presented.

ACKNOWLEDGEMENTS

For the past 12 years the United States Geological Survey, in conjunction with the Departamento Nacional da Produção Mineral do Brasil, and presently under the auspices of the International Cooperation Administration of the United States Department of State, has been making a detailed study of the geology and ore deposits of the Quadrilátero Ferrífero of Minas Gerais, Brazil. This paper is an outgrowth of that study.

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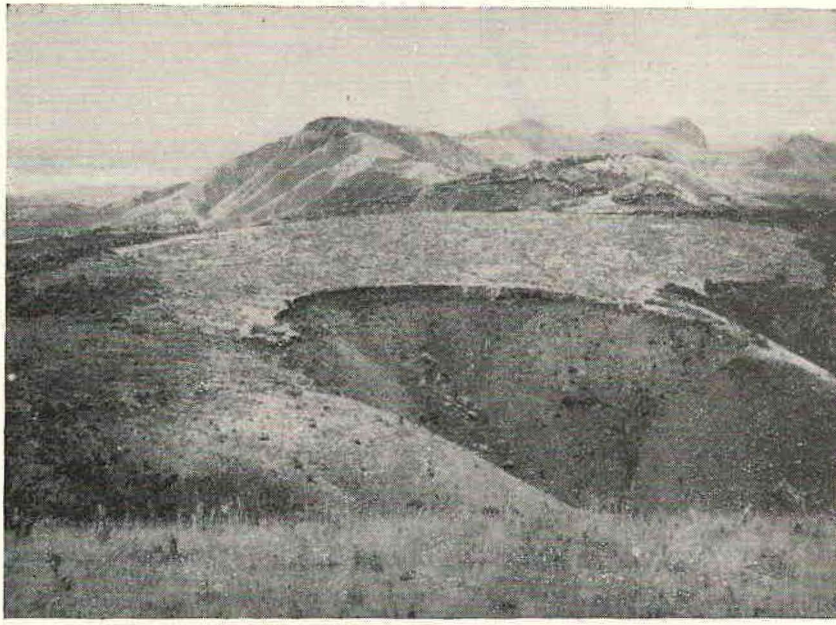


a — General view.

b — Detailed view.

FIGURE 2 — Erosion of canga by undercutting; near the crest of the Serra Curral

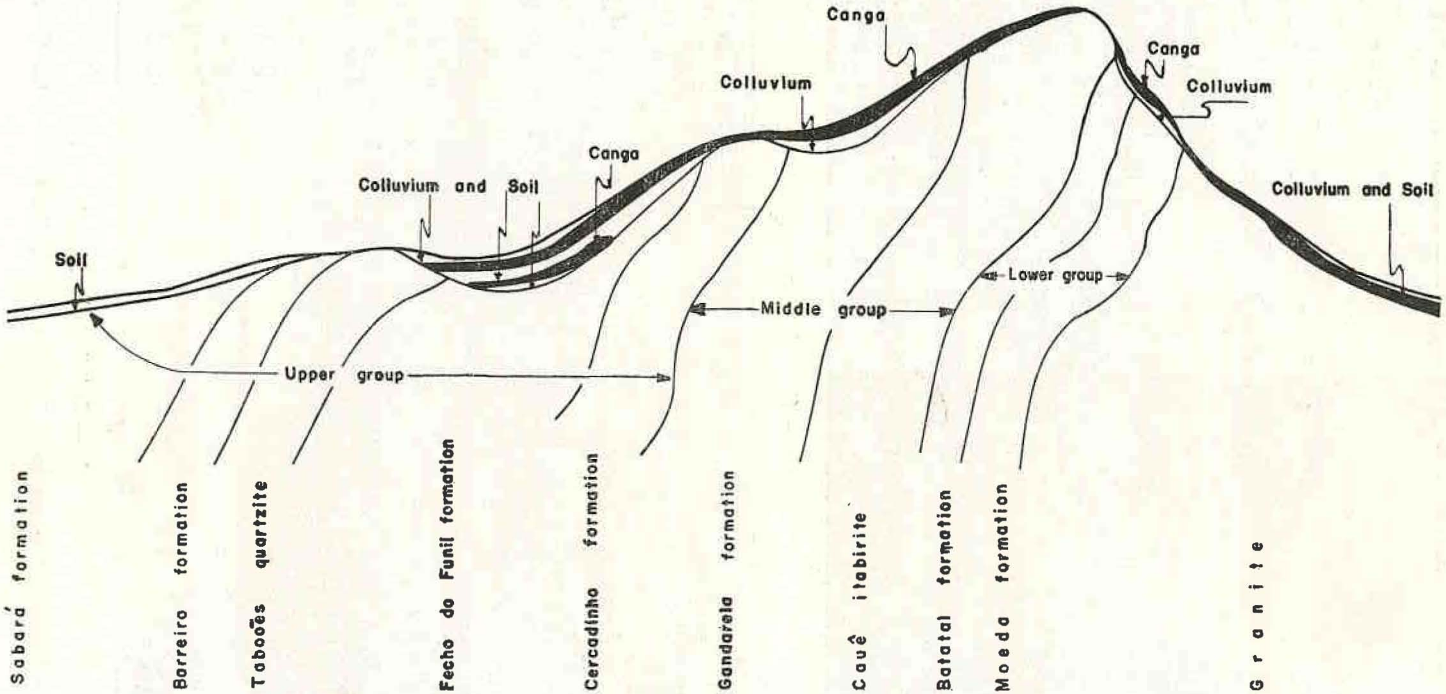
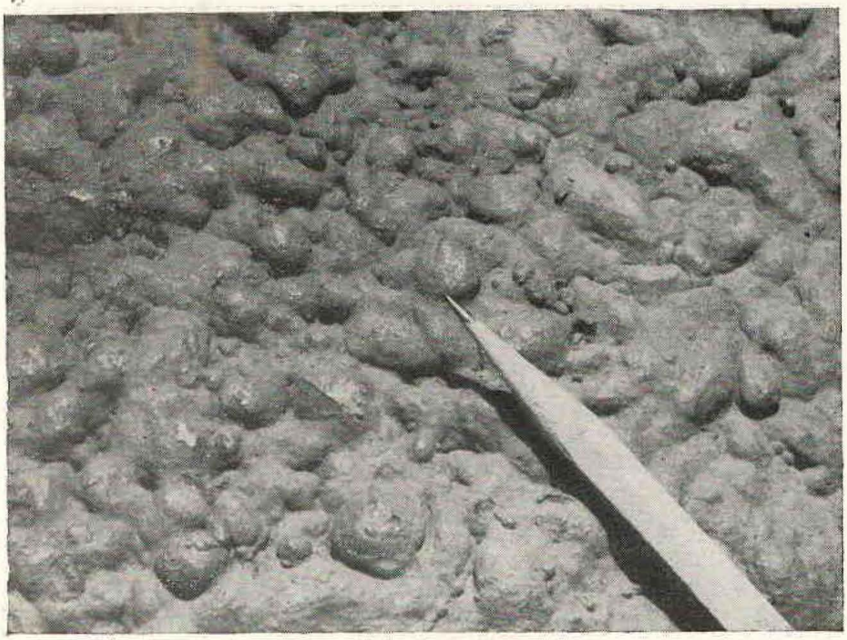


FIG. 3 — Diagrammatic cross section showing some common occurrences of cangas.

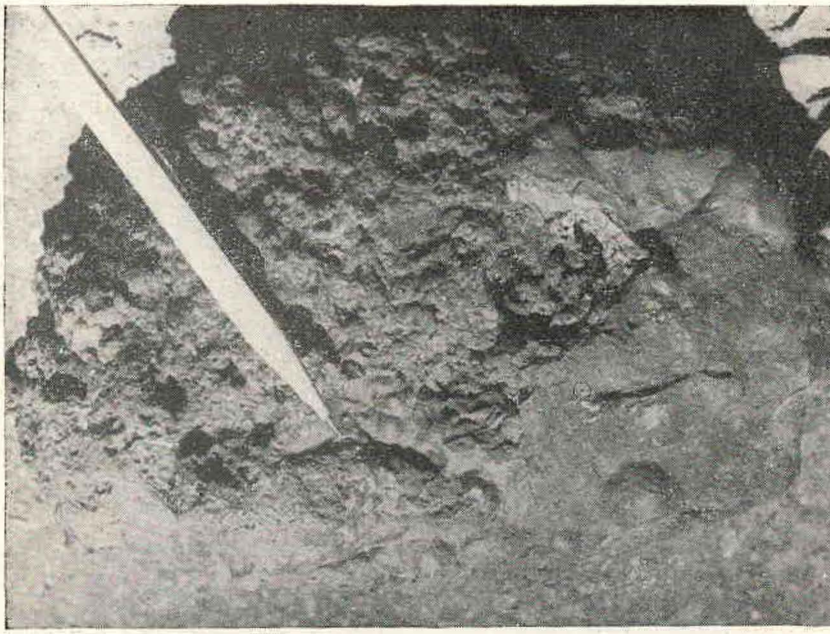
FIG. 4 — Distinctive topography of old pediment maintained by canga (light colored) at Serra do Curral canga locality. Scale 1:20,000



a — Freshly uncovered.

b — One meter from soil cover.

FIGURE 5 — Breakdown of botryoidal structure at the Serra do Curral canga locality.



c — Two meters from soil cover.

d — Three meters from soil cover.

FIG. 5 — (Cont.) — Breakdown of bothroydal structure of the Serra do Curral Canga locality.

FIGURE 6 — Serra do Tamanduá canga locality. Alluvial fan overlies quartzite (exposed at right).

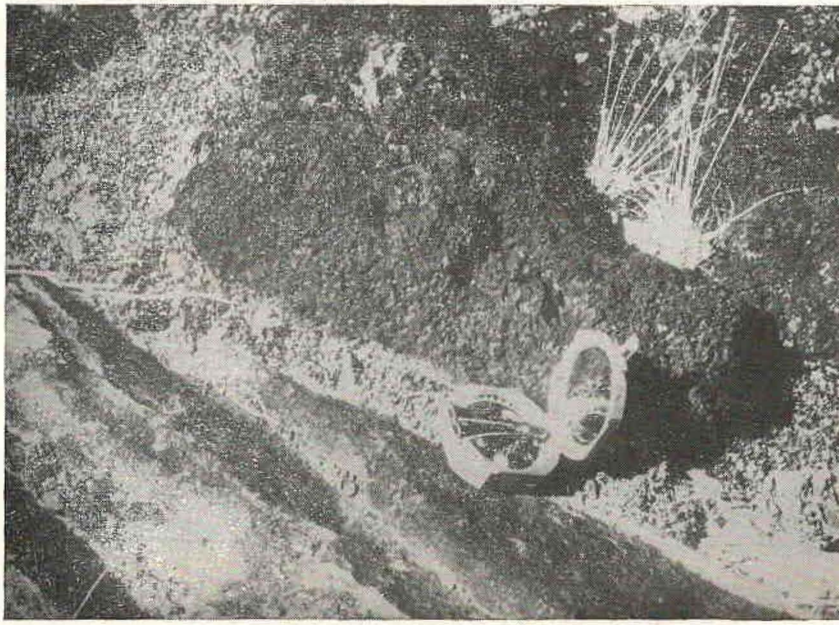


FIGURE 7 — Canga (top) overlying quartzite (bottom) at the Serra do Tamanduá canga locality.

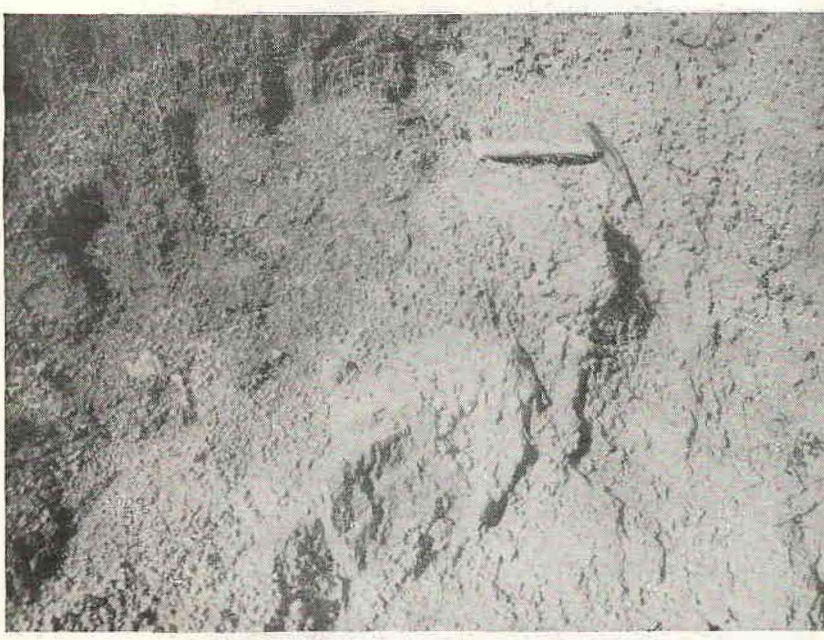


FIGURE 8 — Freshly exposed canga surface near Fazenda da Alegria, showing botryoidal structure.

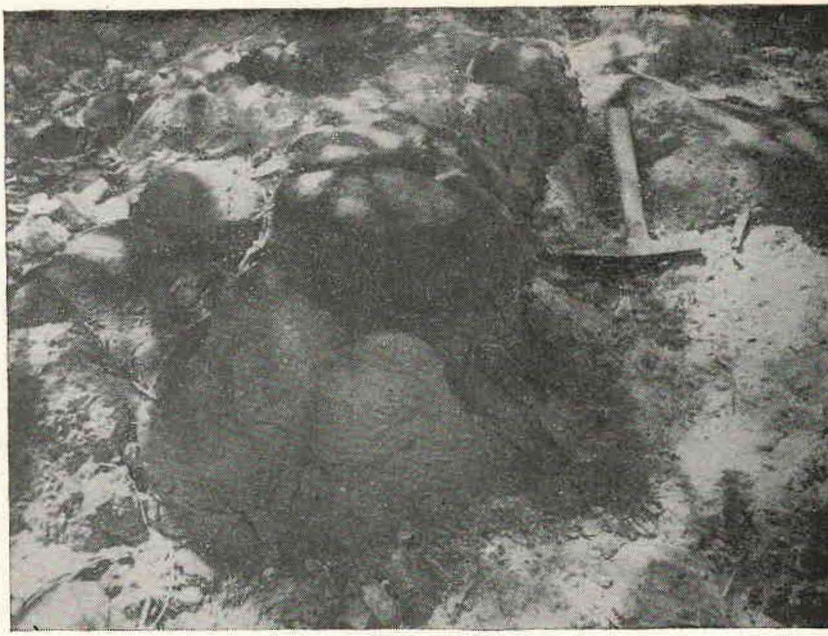


FIGURE 9 — Recently exposed canga surface near Fecho do Funil, showing bothryoidal structure.

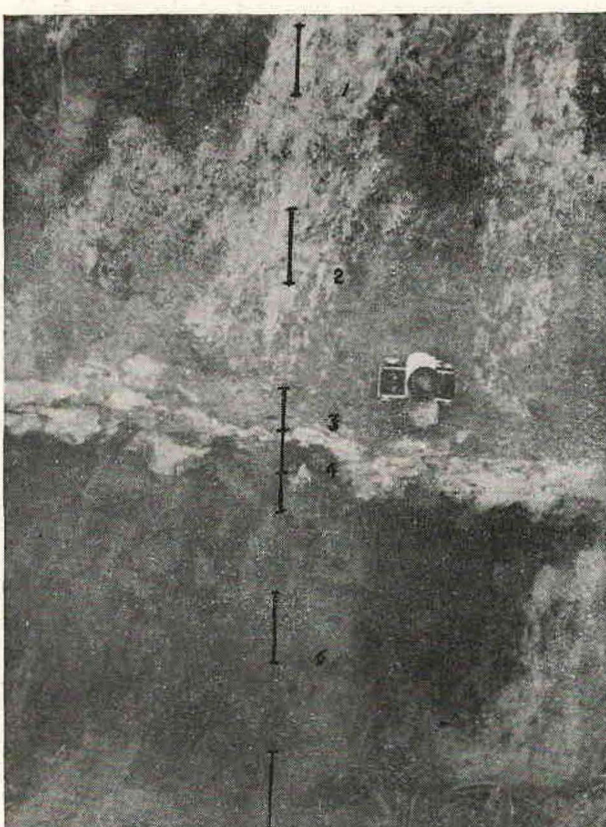


FIGURE 10 — Canga exposure at Fecho do Funil showing contrast in color above and below canga and location of samples.

BIBLIOGRAPHY

DORR, J. VAN N. II, 1945, *Manganese and iron deposits of Morro Urucum, Mato Grosso, Brazil*: U. S. Geol. Survey, Bull. 946-A, p. 1-47.

————, 1958, *Ocorrências minerais*, Guia Geológico e Roteiro das Excursões para o XII Congresso Anual da Sociedade Brasileira de Geologia, p. 34-40.

———— and BARBOSA, A. L., *Geology and ore deposits of the Itabira district*, Minas Gerais, Brasil — U. S. Geol. Survey, Prof. Paper in preparation.

————, COELHO, I. S., and HOREN, ARTHUR, 1956, *The manganese deposits of Minas Gerais Brasil*: Symposium sobre yacimientos de manganeso, tomo 3, 20 th Internat. Geol., Cong., Mexico.

GAIR, J. E., *Geology and ore deposits of the Nova Lima and Rio Acima quadrangles, Minas Gerais, Brazil*: U. S. Geol. Survey, Prof. Paper, in preparation.

GUILD, P. W., 1957, *Geology and mineral resources of the Congonhas district, Minas Gerais, Brazil*: U. S. Geol. Survey, Prof. Paper 290, 90 p.

O'ROURKE, J. E., *Geology and ore deposits of Rio das Pedras and Gandarela quadrangles, central Minas Gerais, Brazil*: U. S. Geol. Survey, Prof. Paper in preparation.

POMERENE, J. B., *Geology and ore deposits of the Belo Horizonte, Ibirité, and Macacos quadrangles, Minas Gerais, Brazil*: U. S. Geol. Survey, Prof. Paper, in preparation.

PUTZER, HANNFRITT, 1958, *Quatäre Krusten-Bildungen im tropischen Süd-Amerika*: Geol. Jb., Band 76, s. 37-52, Hannover.

REICHE, PARRY, 1945, *A survey of weathering processes and products*: Univ. of New Mexico Publications in geology, N.º 1, 87 p.

SOCIEDADE BRASILEIRA de GEOLOGIA, 1958, *Symposium of the stratigraphy of the Minas series in the Quadrilátero Ferrífero, Minas Gerais, Brazil*: Bol. Soc. Bras. Geol., Vol. 7, N.º 2, p. 57-69.