COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN No. 20

GEOLOGY OF THE BROKEN HILL ORE DEPOSIT, BROKEN HILL, N.S.W.

by

J. K. GUSTAFSON, H. C. BURRELL
and
M. D. GARRETTY

Issued under the authority of Senator the Hon. W. H. Spooner,
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Minister: SENATOR THE HON. W. H. SPOONER

Secretary: H. G. RAGGATT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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ABSTRACT

The lead-silver-zinc ore deposit of Broken Hill, New South Wales, is among the great ore deposits of the world because of its size, richness, and continuity. To the end of 1946, approximately £50,000,000 in dividends had been won from recoverable metals worth £210,500,000 gross contained in 63,800,000 tons of ore. The deposit is a hypothermal deposit of Pre-Cambrian age resulting from the selective replacement of two closely adjacent, tightly and complexly folded stratigraphic rock layers.

The original sedimentary rocks of the area now consist of tightly folded sillimanite-garnet gneisses with subordinate thin quartzite beds. These contain numerous folded sills of augen gneiss (granite), amphibolite (gabbro), and pegmatite. Post-folding peridotite, granite and pegmatite occur. Probably after considerable uplift and erosion, thin dykes of diabase (dolerite) were intruded, then pegmatite dykes and silicifying solutions, and finally ore-bearing solutions.

The folds of the region are tight, steeply inclined, and extremely complex structures resulting from plastic deformation. Individual minor folds were studied in great detail by a method of axial-plane and axial-line analysis. An angular relationship exists between minor and major folds due to strain under torsional stresses. The regional pitch is flatly south. However, sudden reversals of pitch and divergences of pitch in adjacent folds are common. "Second-order" folds or folded folds exist. Cutting and offsetting the folds are "buckles" with vertical axes and crush zones of schisted rocks resulting from post-folding but pre-ore faulting movements.

The lode occurs in a "belt of attenuation" between a wide arch on the west and a wide basin on the east. It consists of massive lead-zinc-sulphide replacement orebodies forming (before erosion) a long continuous, irregular, flat, curving pencil of ore, 2,000 to 3,000 feet high and 300 feet thick. In longitudinal section it describes a flat arc pitching downward at each end.

The "lead lodes" resulted from the selective replacement of two closely adjacent, highly folded, favourable beds. Each lode is distinguishable by its gangue mineralogy and metal ratios. No. 3 Lens (the lower) has fluoritic-rhodonitic gangue and comparatively high Zn:Pb and Ag:Pb ratios. No. 2 Lens, the upper, has calcitic gangue and comparatively low Zn:Pb and Ag:Pb ratios. At least three "zinc lodes," with similar mineralogy, occur at higher stratigraphic horizons at the south end of the field.

There is little observable zoning. Ore solutions are believed to have migrated up the regional pitch from the south. Intra-mineralization fracturing helped to localize ore shoots within favourable formations.

INTRODUCTION

SCOPE

The lead-silver-zinc ore deposit of Broken Hill, N.S.W., ranks among the great ore deposits of the world because of its richness, size and continuity. To the end of 1946, approximatuly £50,000,000 in dividends had been won from recoverable metals worth £210,500,000 gross contained in 63,800,000 tons of ore. The primary ore before erosion must have comprised at least 80,000,000 tons of practically continuously stopable ore within a narrow belt developed over a length of 3½ miles above a vertical depth of 3,000 ft. Additional ore of average dimensions and average value is now being developed and mined from both ends of this 3½-mile belt.

This deposit is also noteworthy because of its unusual mineralogy and complex geological environment.

Although the district has been previously studied ably in a reconnaissance way and the ore deposit has been frequently mentioned in geological literature, the Broken Hill orebodies were mapped and studied in comprehensive detail for the first time during 1936-1939 by the Central Geological Survey. Some of the results of the Survey's work are confidential, but many scientifically noteworthy results can be discussed. This bulletin presents the general geology of Broken Hill as worked out by the Central Geological Survey with special emphasis on stratigraphy and structure and their control of ore deposition.

CENTRAL GEOLOGICAL SURVEY

The Central Geological Survey (1) was organized jointly by North Broken Hill Limited, Broken Hill South Limited and Zinc Corporation Limited primarily to appraise the possibilities of major extensions and repetitions of ore. Its work began in June 1936 and was completed in April 1939. All accessible underground workings at Broken Hill were mapped at least once, and the majority two or three times, on scales of 30, 40, or 60 feet to the inch. All available drill core was logged. The surface outcrops were mapped with a plane table on a scale of 100 feet to the inch using mine-triangulation systems and other mine-survey controls. Numerous old plans, ledgers, scrap-books, newspaper files, and other records were searched for information about old inaccessible workings and virtually forgotten drill holes. Mapping and other data were assembled and interpreted on 100-scale and 400-scale plans and sections. The 100-scale plans of the mines area were on the average at approximately 50-foot vertical intervals; the cross-sections averaged about 60 feet apart. Many longitudinal sections and special plans brought the number of finally accepted geological tracings to more than 500.

From the countless observations and interpretations recorded on these plans and sections, a three-dimensional picture of one of the most contorted portions of the earth's crust was painstakingly pieced together, and the fascinating and eventful life history of a great ore deposit was read from it. Extensive exploratory diamond drilling was recommended to test various possibilities of major extensions and repetitions of ore. This exploration, retarded during the war, is not yet completed.

PREVIOUS GEOLOGICAL WORK

Excluding private reports to the mining companies, the geological literature contains at least 19 important papers on Broken Hill. These, as well as other more general papers on Broken Hill, are included among the 39 items of the Broken Hill bibliography listed at the end of this bulletin. Reports on five previous investigations warrant special attention:

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(1) Chief geologist: J. K. Gustafson; geologists: H. C. Burrell and M. D. Garretty; draftsmen: R. Miller-Randle, R. Wallace. J. R. Adam, of the North Mine staff, was geological assistant for a brief period at the start of the investigation.

(1) An able Government survey and report by Jacquet in 1894.

(2) The investigation and report by the Geological Sub-Committee of the Broken Hill Scientific Society in 1910.

(3) A regional consideration of age relationships and petrology of the district by Sir Douglas Mawson (1912)—the first general study of the broader aspects of the field.

(4) The investigation by E. C. Andrews and his associates from 1919 to 1922 (Andrews *et al.*, 1922) which produced the first regional geological maps as well as greatly expanded detail maps of the neighborhood of the lodes and several outlying areas. The report is a comprehensive treatise on the district, with appendices on regional petrology by W. R. Browne, petrology near and in the lode by F. L. Stillwell, analyses of rocks and minerals by the mine staffs, and mineralogy by George Smith.

(5) The investigations of the mineralogy of the lodes in 1926-1927 by F. L. Stillwell, with the first microscopic study of the ore minerals.

E. C. Andrews (1922) briefly summarized most of the findings up to 1922. A paper by E. J. Kenny (1932) contains a brief summary of earlier structural concepts and a discussion of his own findings and interpretation. This paper gives a clear general picture of the lode structure and forecasts much of the general spirit of more recent findings.

SUBSEQUENT GEOLOGICAL WORK

After completion of the Survey's work, Burrell (1942) with financial assistance from the three companies, made an exhaustive mathematical statistical analysis of metal ratios obtained from assay data and a microscopic study of Broken Hill ores. After completion of the Survey's work, Garretty remained in Broken Hill as chief geologist of North Broken Hill Limited and later as consulting geologist for that company and for Broken Hill South Limited. He also made an independent mineralogical study of the ores and a statistical study of assay data (Garretty, 1943). Gustafson returned to Broken Hill as consultant to Zinc Corporation Limited for 5 months in 1947 and, during that time reviewed the new developments in geological knowledge and thought since his departure in 1939.

Since 1939, considerable new geological information has been made available as a result of mine developments in the North Broken Hill Limited, Broken Hill South Limited, Zinc Corporation Limited, and New Broken Hill Consolidated Limited properties. These companies, particularly the two last under the direction of Haddon F. King, are also actively extending the area of close geological and geophysical investigation. Several structures postulated by the Survey and projected by it for distances of half a mile have since been drilled. Others projected for lesser distances in the mines have since been opened by drives and cross-cuts. In general the results have confirmed the Survey's interpretation. Numerous small quantitative changes in mine maps and cross-sections have, of course, resulted. Where these changes would affect the correctness of the reader's understanding, the illustrations included in this bulletin have been correspondingly changed. Minor changes have not been made in the other illustrations from Gustafson's report of 1939.

ACKNOWLEDGMENTS

We are indebted to our associates Mr. J. R. Adam, the late Mr. R. G. Miller-Randle, and Mr. R. Wallace for their excellent assistance during the Central Geological Survey study, to the general managers and mine staffs for their co-operation and help throughout the investigation, to Mr. W. S. Robinson and the

late Sir Colin Fraser, who personally sponsored and encouraged the work, and to their colleagues on the boards of directors of the mining companies. The Geological Society of America financed the drafting of illustrations preparatory to printing this work in their publication "Bulletin of the Geological Society of America" (Volume 61, Number 12, Part 1, December 1950). The Society then made available to the Commonwealth of Australia blocks for use in printing the illustrations for this Commonwealth bulletin, which is the Australian edition of the paper. Copies of Plate 1 included in this bulletin were made in America for the Commonwealth.

The splendid pioneering work of E. C. Andrews and his associates (1922) gave us a quick familiarity with the regional geology and provided many clues which led us to a surer understanding of the structure. Largely through them we benefited from the work of earlier investigators. References in the text are limited, because ours was a comprehensive and detailed study which examined the evidence anew. The countless points of agreement and disagreement between us and our predecessors are not discussed although most of the major points at issue are indicated.

A preliminary magnetic survey of the White Lead and Zinc Corporation areas under the direction of J. M. Rayner in 1939 and a later more comprehensive magnetic and gravimetric survey under the direction of Oscar Weiss in 1947 were of considerable value in interpreting that region of sparse outcrops.

Figure 1—Map of Australia.

AUTHORSHIP

This bulletin is based on the Central Geological Survey report of 1939 (Gustafson, 1939), and at least 50 per cent. of the text is taken from Vol. II of that report. Gustafson wrote all the bulletin except the production data, which Garretty prepared. He, however, had access to Burrell's report (1942), to parts of Garretty's thesis (1943), and to written comment by Garretty. The illustrations are all based on the 1939 Gustafson report but were revised as necessary in 1947 by Gustafson for the Zinc Corporation and New Broken Hill Consolidated properties and by Garretty for the North Mine and South Mine.

BROKEN HILL DISTRICT

GENERAL DESCRIPTION

Location and Physiography.—Broken Hill, New South Wales, is a town of about 27,000 inhabitants, is at latitude 31° 58' 23", longitude 141° 28' 10", and is

699 miles by rail west of Sydney and 320 miles by rail north-east of Adelaide. It is in the West Darling district in the Barrier Ranges, an elongated plateau dissected into low hills rising above an extensive arid plain.

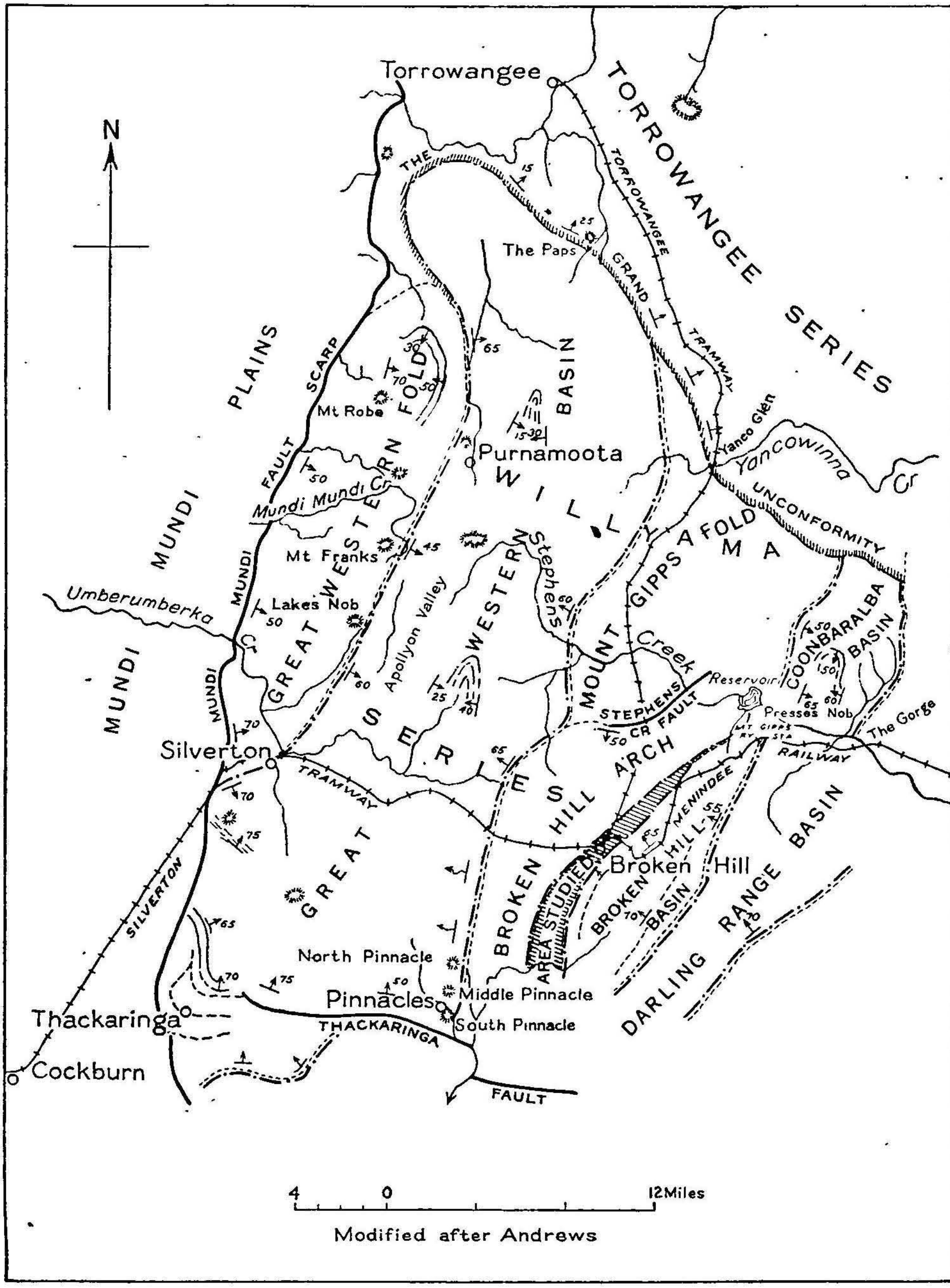

Figure 2—Key Map to the Principal Geological Structure of the District.

The lode outcrop at Broken Hill is 1,000 to 1,100 feet and the surrounding plain about 800 feet above sea level. The drainage is south-easterly toward the Darling River. The topography is one of late maturity.

The mines, which are contiguous, are strung along a north-south ridge rising a few tens of feet above the town of Broken Hill (Pl. 2, fig. 1).

Climate.—The climate is dry, hot in summer, and cool in winter. To the end of 1947, the average annual rainfall was 9.20 inches with a maximum of 17.61 and a minimum of 2.24. The rate of evaporation is high. During the same period the lowest temperature recorded was 27.0°F. (June) and the highest was 115.9°F. (February). The mean minimum yearly temperature was 53.1°F. and the mean maximum temperature 75.8°F. (Rainfall and temperature data from Commonwealth Meteorological Office). High winds and dust storms are fairly common.

Vegetation.—Various stunted forms of acacia—especially mulga—and salt bush and blue bush are characteristic, together with eucalyptus trees in the larger ephemeral creek beds. The natural scarcity of vegetation is aggravated by over-grazing by sheep and rabbits, and by the cutting of wood for fuel and small mine timbers in the early days of mining.

Water.—Water for the town and mines is obtained from a reservoir at Stephen's Creek 10 miles north, and another at Umberumberka 19 miles west. During the severe drought of 1945 water was carried in by railroad cars. A pipeline now under construction will bring water 70 miles from the Darling River at Menindie.

HISTORY

The early history of Broken Hill (Bridges, 1920; Woodward, 1940) is a fascinating record of geological misinterpretation of a large leached ferruginous gossan which forms a prominent landmark.

The first white man to see the Broken Hill outcrop was Captain Charles Sturt who led his ill-fated expedition across the desert in a vain search for an inland sea. In 1844 Sturt sat on the Broken Hill lode outcrop to make a pencil sketch of the surrounding country. His description of "hepatic iron ore" along the spine of an isolated hill probably refers to the barren ferruginous gossan of the Broken Hill ore deposit. During a gold rush to the Barrier Ranges in 1858-1861, when many died of thirst and privation, prospectors looking for quartz veins again passed by this great deposit. By 1866 the Mount Gipps sheep station had been established at Stephen's Creek 9 miles north, and the name "Broken Hill" had been given to a 50,000-acre paddock embracing the lode outcrop.

Rich horn silver was discovered and mined from veins at Thackaringa and Umberumberka 20 miles south-west during 1876-1880. By 1885, small but rich silver deposits had been found at Silverton, Purnamoota and the Apollyon Valley, and Silverton for a brief time was a boom town of 3,000. Broken Hill was derisively referred to as the "hill of mullock" (waste rock) and was avoided by "smart" prospectors.

On 5th September 1883, Charles Rasp, a boundary rider for the Mount Gipps sheep station, lacking both knowledge and prejudice but equipped with a prospector's handbook, staked out a claim on the iron lode outcrop because it seemed to fit the description of black oxide of tin. With visions of a new Mount Bischoff tin deposit, Rasp and six associates, including McCulloch, manager of the station, staked out the whole outcrop and formed a syndicate. Early test pits encountered some lead and a little silver, but were generally discouraging. Some of the original seven sold one-fourteenth interest shares for as low as £100, shares which would have been worth millions later. The syndicate was reorganized into the Broken Hill Mining Company in 1884. Horn silver was found in a shaft in 1885. In the same year the Broken Hill Proprietary Company Limited was organized with a capital of £320,000, and shares were offered to the public. The riches of the ore deposit beneath its barren outcrop were rapidly discovered and exploited. The original company was enlarged, and new companies were formed to finance the development of other blocks of ground along the outcrop.

From 1885 to 1898, the rich oxidized silver ores were mined chiefly by open-cut and were mostly smelted locally. In 1898 the smelter was transferred to Port Pirie, S.A. From 1898 to 1915, up-to-date mining concentrating practice in the exploitation of large lead-zinc-silver sulphide orebodies was developed and adopted. During this period lead and zinc concentrates were treated overseas. The creation in 1915 of the Broken Hill Associated Smelters Proprietary Limited and the Electrolytic Zinc Company of Australasia Proprietary Limited enabled the entire lead concentrate production and most of the zinc concentrate production to be treated in Australia.

By 1940, the central part of the lode had been fairly well worked out, and the old B.H.P. mine was idle. Present production comes from the north and south ends of the lode—from the properties of North Broken Hill Limited, Broken Hill South Limited, The Zinc Corporation Limited, and New Broken Hill Consolidated Limited.

PRODUCTION

Entirely accurate production data are difficult to compile. Approximate figures since the commencement of operations are:

Tons of crude ore mined to 31/12/1946	63,795,241
Tons of lead recovered from 1886 to 31/12/1946	8,580,226
Tons of zinc recovered from 1889 to 31/12/1946	5,194,125
Ounces of silver from 1885 to 31/12/1946	538,040,847
Ounces of gold recovered from 1893 to 31/12/1946	164,658
Total value of production to 31/12/1946	£A210,500,000
Total dividends and bonuses paid to shareholders to 31/12/1946	£A50,000,000
Average number of tons of ore raised per annum per man employed at present time (excluding staff)	255

RECENT PRODUCTION FIGURES

Company	North Broken Hill Ltd.	Broken Hill South Ltd.	Zinc Corpn. Ltd.	New B.H. Cons. Ltd.	Totals
Year Ended	July 30, 1947	July 30, 1947	Dec. 31, 1946	Dec. 31, 1946	
Tons of ore milled	347,443	277,980	448,037	41,723	1,115,183
Av. Mill Head					
Grade—Pb%	14.1	12.8	14.1	7.6	
Ag. ozs. per ton.	7.6	6.9	3.2	1.6	
Zn%	11.6	11.7	11.1	11.3	
Tons of Lead Conc. produced	65,881	45,650	79,313	3,851	194,695
Grade of Lead Conc. % ..	72.5	74.7	76.9	76.7	
Tons of Zinc Conc. produced	69,215	55,431	84,631	8,221	217.498
Grade of Zinc Conc. % ..	50.9	51.9	52.3	52 2	
Mill Recoveries					
Pb in Pb Conc. %	97.0	95.9	96.8	93.6	
Ag. in Pb Conc. %	91.8	90.1	92.7	84.6	
Zn in Zn Conc. %	86.9	88.2	88.6	91.3	

Lead concentrate averages 0.435 lb. of cadmium per ton of lead content.

Zinc concentrate averages 0.42 lb. of cadmium per ton of zinc content.

REGIONAL GEOLOGY

ROCKS—SUMMARY OF EVENTS

The rocks of the immediate district, all Pre-Cambrian—probably Archaean—in age, belong to the Willyama Series, a highly metamorphosed folded aggregate of sedimentary rocks intruded by several kinds of igneous rock both before and after folding (Table 1).

The sediments originally constituted a huge thickness of monotonously similar alternating beds of clays, sandy clays, and sands. These were intruded by thick granitic sills, thinner sills of gabbro, and finally by sheets of pegmatite varying

TABLE 1.—SEQUENCE OF MAJOR GEOLOGICAL EVENTS

	12. Uplift and erosion.
	11. Deposition of Palaeozoic, Mesozoic, and Cainozoic sediments.
Upper Proterozoic	10. Deposition of Torrowangee series.
	9. Uplift and erosion.
Either Lower Proterozoic or Archaean	8. (*c*) Emplacement of lodes. Rhodonite* and "garnet sandstone"* (accompanied by silicification on margins of lodes) early; then quartz, calcite, fluorite, and sulphides. A little shearing and fracturing intervened between early and late minerals. (*b*) Post-folding shearing repeated or continued on old shears. (*a*) Intrusion of late pegmatite (including green felspar "lode" pegmatite).
	7. Intrusion of dolerite, in east-west cracks.
	6. Strong period of shearing began. Major development of crush zones, the De Bavay and British Faults, puckering of the north-south folds and development of local mild east-west folds.
	5. Uplift and erosion.
Probably Archaean	4. (*c*) Intrusion of granite, aplite, pegmatite in large quantity. (*b*) Intrusion of peridotite (now serpentine). (*a*) Some development of shears both north-south and east-west along which granite later intruded.
	3. Period of main folding on north-south axes; regional metamorphism, possibly accompanying approach of batholith in depth.
	2. Intrusion of granite, gabbro, and pegmatite sills (in order named)—now augen and "platy" gneiss, amphibolite, and folded pegmatite.
	1. Deposition of Willyama sediments—now mainly sillimanite gneisses.

* Probability according to Gustafson and Garretty. Burrell considers these to be products of dynamic metamorphism formed during (3) with recrystallization and rearrangement during lode emplacement. Neither view is held with strong conviction.

from very thin to very thick, all predominantly along bedding planes (2). There followed a period of strong folding with a north-south trend. It is impossible to say whether folding began before the appearance of the igneous rocks. It is certain that they experienced the major squeezing during which the sediments were converted to sillimanite gneisses—many garnetiferous—containing thin beds of quartzite; the granitic rocks became augen and "platy" gneisses; the gabbros became amphibolites and hornblende schists.

After the main period of folding, the surrounding country was invaded by irregular small intrusive masses of peridotite (now serpentine) and by bosses, dykes, and sills of granite. The granite was accompanied by some pegmatite and aplite. Neither granite nor serpentine, however, crops out within a few miles of the line of lode. Small dykes of dolerite (diabase), then dykes of pegmatite and silicifying solutions entered still later, closely followed by the ore solution.

Without doubt considerable uplift and erosion succeeded the folding (and probably the intrusion of granite) and preceded the introduction of the thin fine-grained dolerite dykes, an apparently shallow intrusive type. Both the character of the post-dolerite rock deformation and the lode mineralogy indicate much shallower depths than the plastic deformation obtaining during folding.

Important shearing movements began sometime after folding and continued or were repeated until the period of ore deposition. Some granite, pegmatite, and aplite dykes, for example, probably followed early shears which cut across the north-south folds; yet the dykes themselves are sheared. Long narrow crush zones and faults were formed. These crush zones appear in some measure to have guided the entrance of late pegmatite and hydrothermal quartz. In a few cases, however, the pegmatite and quartz are strongly sheared by continuation or repetition of fault movements. East-west folds or "buckles" developed very locally across the dominant north-south grain of the country, probably during faulting.

Whether all these post-folding disturbances are different manifestations of the same stresses is not yet determined. Possibly the small movements that took place after the introduction of early gangue minerals, but before the appearance of sulphides, were their last feeble expression.

Post-lode fractures in the mines cause bad ground but do not affect the understanding of the structure.

The country was uplifted after ore deposition; and some erosion ensued. The Willyama complex was covered by the glacial and fresh-water sediments of the Torrowangee (Upper Proterozoic) Series, and by later Palaeozoic, Mesozoic, and Cainozoic formations, all relatively undisturbed (3). Erosion finally laid bare the Willyama Series with its rich orebodies.

STRUCTURE

Andrews (Andrews *et al.*, 1922) portrays the structure between the Mundi Mundi Plains on the west and the alluvial flat beginning at Redan on the east as shallow structural basins separated by relatively narrow arched zones of dislocation and contortion (Fig. 2). The broad basins are shown as embroidered with countless minor folds—little more than corrugations in the regional sense.

Our observations of the large Broken Hill Basin and smaller Hanging Wall

(2) Possibly some of the pegmatite stringers are easily liquefied portions of the gneiss "sweated" out of the rock during folding in the manner advocated by Eskola (1933).

(3) The lower beds of the Torrowangee Series are somewhat deformed (Andrews *et al.*, 1922). They contain boulders of the quartz-magnetite "lode" cropping out at "The Sisters." The garnet-magnetite-hematite "lodes" and quartz-magnetite "lodes" of the district, generally considered to be the same age as the lead-silver-zinc lodes, more likely are not lodes at all but original clayey iron beds converted to their present condition by regional metamorphism. Hence the relative ages of lode formation and Torrowangee sedimentation may be less definite than here assumed. No granite or pegmatite intrusives cut the Torrowangee beds (Andrews *et al.*, 1922, p. 63) although quartz veins are present in them.

Basin suggest steeply-inclined structures rather than the shallow structures hypothecated by Andrews. We investigated too small an area, however, to judge whether the other structures portrayed as shallow basins may also be tightly folded.

Folding occurred under such extreme conditions of temperature and pressure that the rocks in general yielded plastically. Beds are greatly thickened on the noses of folds, greatly thinned on the limbs. Even during the later period of shearing and faulting which produced the "crush zones," the yielding action of the sediments was predominantly one of rock flowage, although the more brittle igneous rocks and the Footwall Gneiss were commonly offset by rupture.

The Broken Hill line of lode is in a dominantly anticlinal portion of the zone of dislocation and tight folding between the wide Broken Hill Arch on the west and the wide Broken Hill Basin on the east. Attention is here confined almost entirely to this narrow zone of complicated structure.

Careful mapping of countless small minor folds and drag folds, and the plotting of such details as mineral elongation, have been an important part of the underground study. Such features give the clues to the larger structures that govern the distribution of orebodies. In the mine area gneissosity is consistently parallel to bedding even in the noses of folds; linear elongation of light and dark mineral aggregates is conspicuous and is almost invariably parallel to axial lines (except for felted sillimanite). Elsewhere in the district where schists of a lower-grade metamorphism occur, axial-plane cleavage is highly developed.

METAMORPHISM

Dynamic Metamorphism.—High-grade regional metamorphism characterizes the district. Sediments originally clayey were converted to garnet-biotite-cordierite-sillimanite gneiss. Calcareous sands (?) were transformed into quartz-plagioclase-garnet gneiss (Footwall Gneiss). Gabbros were converted to amphibolites, commonly garnetiferous. Granites were recrystallized into augen and platy gneisses without much mineralogical change other than local development of garnet. Some originally sandy ferruginous beds are now quartz-garnet-magnetite rocks. The characteristic coarse grain and gneissic texture indicate complete recrystallization.

The almost complete plasticity obtained during folding, even of thick gabbro and granite sills, probably could be achieved only through profound recrystallization. Accordingly we ascribe the regional metamorphism to the period of folding and consider that the folding took place at great depth under heavy load.

Abundant contorted lenticular quartz-felspar pegmatite stringers half an inch to several inches thick occur in many rocks, and notably in the Footwall Gneiss. These stringers obviously have been subjected to much, if not all, of the squeezing experienced by the host rocks. They may be segregations within the rock, developed during metamorphism.

Ten miles or more from Broken Hill, staurolite and andalusite schists, chloritoid schists, and similar lower-grade metamorphic rocks prevail (Andrews *et al.*, 1922). We do not accept Andrews' theory of a genetic as well as spatial relationship between intensity of metamorphism and intensity of ore mineralization, because we believe metamorphism occurred during folding at great depth whereas ore mineralization occurred much later at shallower depth after uplift and erosion. The localization of the higher grade of metamorphism at Broken Hill may have been caused by the presence in depth here of a buried batholith which locally contributed heat and possibly mineralizers to the rocks during metamorphism.

Contact Metamorphism.—Some of the gneisses bordering the augen gneiss (Hanging Wall Granite sill) and locally comprising some of the "banded gneiss" (Andrews *et al.*, 1922) look like granitized sediments that have been dynamically metamorphosed. Little or no contact metamorphism accompanied the intrusion of the other igneous rocks, although very locally some of the gneiss adjacent to amphibolite may have been silicified and impregnated to a minor degree with dark minerals at the time of amphibolite (gabbro) intrusion.

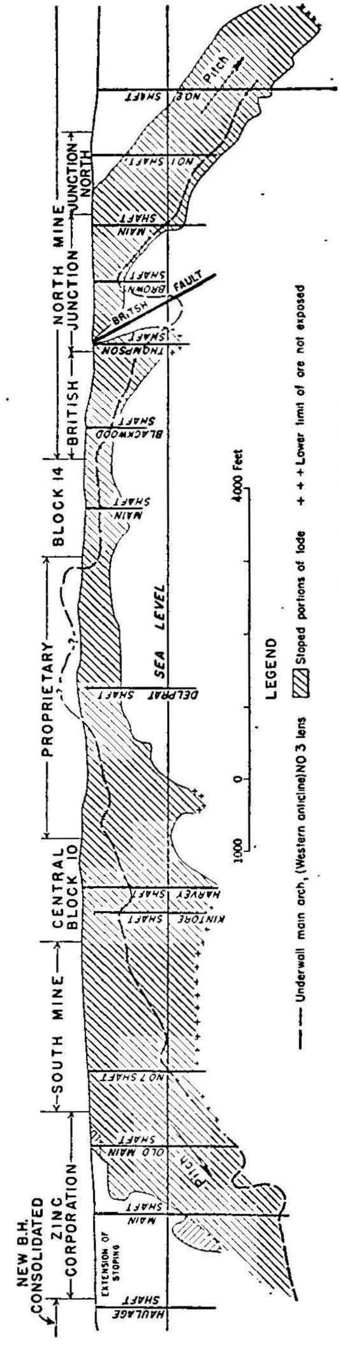

Figure 3—Longitudinal Projection of Broken Hill Lodes.

LODE MINERALOGY AND WALLROCK ALTERATION

GENERAL CHARACTER OF LODES

The Broken Hill lodes are massive lead-zinc sulphide replacement orebodies forming (before erosion) a long continuous, irregular flat, curving pencil of ore roughly 2,000-3,000 feet high and 300 feet thick.

In longitudinal section (Fig. 3), the deposit describes a broad arc, flat in its middle (highest) portion, and pitching downward at each end. This arc is continuously mineralized for a horizontal distance of more than 3 miles and, except for one fault interruption between the British and Junction Mines, consists of continuously stopable ore. In plan the deposit also has the appearance of an arc, though flatter than that appearing in longitudinal section. Cross-sections through the lode display ore outlines representing tight folds.

One of the most significant features of the ore is that its boundaries are almost invariably parallel to bedding planes in the ancient metamorphosed sedimentary strata enclosing it; the sedimentary layers characteristically wrap around irregular projections and undulations in the outline of the ore. Looking closely at the ore in the back of a stope, one sees both small and large areas of ore in which bedding planes, usually contorted, have survived the obliterating process of mineralization. There is evidence that the ore has been introduced into an old, already folded, rock and has replaced certain favourable layers of that rock, particle by particle, with large tonnages of garnet, rhodonite, fluorite, marmatite (and wurtzite), galena, and the other minerals that constitute the orebodies.[4] The possibility that rhodonite and garnet *may* be metamorphic rather than hydrothermal is discussed under "Favourable Rocks and Selective Replacement."

The orebodies occur only where the favourable rock is intersected by a steep tabular belt of intense plastic deformation known as the "belt of attenuation."

The ores are high-grade. The average mill-head grade for the three large producing companies during the period 1934-1939, (Woodward, 1940, p. 261) was 15.0 per cent. Pb, 6.34 oz. Ag, and 11.32 per cent. Zn. Massive sulphide ores constitute perhaps a third of the total millfeed. Because of their composition or appearance some ores are also described as rhodonitic, fluoritic, calcitic, siliceous, zincy, steely, and/or orbicular.

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(4) One type of lead-silver deposit in the district is very different from the main Broken Hill lodes and from most of the lesser outlying lodes. This type has a gangue of iron carbonate. The more important representatives of this type are the Purnamoota, Maybell, Lubra, Day Dream, Apollyon Valley, Silverton, and Thackaringa groups with which may be classed the Consols group in M. Ls. 234, 97, and 98 east of the North Broken Hill Limited property (Andrews *et al.*, 1922, p. 169). They are all characterized by haloids of silver in a quartz ironstone gangue in the oxidized zone. The Consols Mine also contained small quantities of smaltite, cobaltite, chalcopyrite, pyrrhotite, arsenopyrite, pyrite, native antimony, molybdenite, and a few less common minerals, (George Smith, Andrews *et al.*, 1922, Appendix IV). Although the Thackaringa lodes appear to be replacements of folded beds (Jacquet, 1894, p. 112), the Consols lodes, and probably many of the others, are veins which occupy faults. The main Consols lode occupies a fault, striking N 86.5° W and dipping 30°-35° S, which cuts across and displaces amphibolite and gneiss. The great difference in both mode of occurrence and in mineralogy suggests that these lodes, although possibly not genetically unrelated to the main Broken Hill lodes, may represent a separate period of mineralization under different conditions of temperature and pressure and of chemical composition of ore solutions. The siderite veins are mesothermal, the main Broken Hill lodes hypothermal. Andrews *et al.* (1922, p. 190) consider the siderite veins younger on evidence outside the area studied by us. Small platinoid lodes with cobalt, nickel, and copper associated with serpentine and small tin-wolfram deposits in the late pegmatites also occur but not in the area covered by this bulletin. (Andrews *et al.*, 1922).

LODE MINERALOGY

PRIMARY MINERALS.—The metallic and gangue minerals that compose the primary lodes as observed by us are [5]:

1. Abundant and Conspicuous minerals:

Metallic	*Gangue*
sphalerite (marmatite)	quartz
galena	rhodonite
	garnet
	calcite
	bustamite
	hedenbergite
	fluorite
	microcline*

2. Metallic minerals that are widespread but generally visible only under the microscope, and gangue minerals that are locally abundant but inconspicuous, difficult to identify, or secondary:

Metallic	*Gangue*
wurtzite	pyroxmangite
pyrrhotite	johannsenite (?)
chalcopyrite	wollastonite (?)
marcasite	manganocalcite
tetrahedrite	rhodochrosite †
cubanite	
dyscrasite	
pyrargyrite	
gold	

3. Metallic minerals of local occurrence that generally can be seen only under the microscope, and rare and accessory gangue minerals that, in most cases, can be seen only under the microscope:

Metallic	*Gangue*
löllingite	graphite
arsenopyrite	apatite
X-mineral	titanite
pyrite	olivine (?)
bournonite	iddingsite (?) †
magnetite	micas
niccolite	basaltic hornblende (?)
molybdenite	sturtite †
gahnite	kaolin †
wolframite	tourmaline
scheelite	
cobaltite	
meneghinite	
goethite †	
covellite †	

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(5) Stillwell (1926, 1927) also reports argentite, berthierite, bornite, chalcocite, chalcostibite, cuproplumbite, enargite, meneghinite, jalpaite, stromeyerite, and willyamite.

* Green felspar of "lode pegmatites."

† May be entirely supergene.

Burrell's microscopic study suggested the following order of deposition of metallic minerals, with considerable overlapping: löllingite, arsenopyrite, pyrite, pyrrhotite, sphalerite, tetrahedrite, chalcopyrite, bournonite, galena, pyrargyrite, wurtzite, and marcasite, with the last three possibly supergene. Garretty concluded that the major sequence of mineral precipitation, with considerable overlapping, was: magnetite, pyrite, löllingite, arsenopyrite, molybdenite, wolframite, scheelite, cobaltite, pyrrhotite, chalcopyrite, marmatite, tetrahedrite (*i*), bournonite, dyscrasite and galena, tetrahedrite (*ii*), pyrargyrite, and gold.

Our difference of opinion and doubt as to the probable origin and sequence of deposition of some of the gangue minerals is discussed under "Favourable Rocks and Selective Replacement."

Table 2 summarizes the diagnostic mineral criteria for each major ore horizon and its ore type.

SECONDARY MINERALS.—The near-surface oxidized ores have long since been mined out, and consequently were not studied by us. The extensive assemblage of secondary minerals in the oxidized zone has for the most part been abundantly described by others [Smith (Andrews *et al.*, 1922); the Geological Sub-Committee (1910); E. C. Andrews (Andrews *et al.*, 1922); and F. L. Stillwell (1927)]. There was great silver enrichment and zinc impoverishment near the surface, with a local thin zone of secondary chalcocite just above the primary sulphides. Oxidation and secondary enrichment are particularly well described by the Geological Sub-Committee (1910).

Open solution cavities, cellular "boxworks," and other signs of local oxidation occur in the mines on the deepest levels more than 2,600 feet below the pre-mine water level. The occurrence of a soft grey zinc-rich material, covellite, and limonite in microscopic cracks in the ores and the presence of pyrargyrite, marcasite, and wurtzite are microscopic evidence of deep supergene activity. It is difficult or impossible always to distinguish between deep natural oxidation and post-mine oxidation resulting from artificial lowering of the water table. Gustafson is inclined to agree with Garretty and Blanchard (1942) that virtually all the deep oxidation is post-mine. Burrell thinks most of it may be natural oxidation during a former arid period of low water table. Andrews *et al.* (1922, p. 29) hint at other evidence for such a period.

Metal-ratio studies led Burrell and Garretty to different conclusions regarding the depth of secondary enrichment of silver. Burrell concluded that deep local supergene enrichment of silver is well demonstrated by variation of the silver-lead ratio in the B.H.P. Mine. Garretty, on the other hand, believes that variation of the silver-lead ratio in the "main shear" syncline of the B.H.P. Mine is directly related to structure; that in the North Mine there is no significant variation in the silver-lead ratio with depth; but that the silver-lead ratio is systematically somewhat higher in synclines and lower in anticlines, because fracturing late in the paragenetic sequence when silver minerals were being deposited was more prevalent in synclines. Garretty regards the absence of demonstrable supergene rearrangement of metals in the northern orebody of the North Mine, which has been notably affected by deep oxidation, as evidence that deep supergene enrichment is unlikely in the B.H.P. Mine. Gustafson believes that the statistical and mineralogical evidence does not conclusively show that either secondary silver enrichment or a structural control of hypogene silver distribution is solely responsible for the distribution of silver-lead ratios.

TABLE 2.—SUMMARY OF DIAGNOSTIC CRITERIA FOR EACH MAJOR ORE HORIZON AND ITS ORE TYPE *

Modified after Burrell (1942)

Mineral	No. 2 Lens	No. 3 Lens
CALCITE	common to abundant STRONGLY INDICATIVE	rare
FLUORITE	sporadic to rare	common INDICATIVE
GARNET with index of refraction less than 1.794	common typical possibly highly diagnostic	present not diagnostic*
GARNET with index of refraction between 1.794 and 1.7945	present not diagnostic*	present not diagnostic*
GARNET with index of refraction greater than 1.795	absent†	present TYPICAL part of index range
RHODONITE with beta index of refraction less than 1.730	common HIGHLY DIAGNOSTIC	absent
RHODONITE with beta index of refraction greater than 1.74	absent	common to abundant HIGHLY DIAGNOSTIC
PYROXMANGITE with beta index of refraction greater than 1.74	absent	local HIGHLY DIAGNOSTIC
PYROXMANGITE with beta index of refraction between 1.738 and 1.74	not identified but possible*	not identified but possible*
PYROXMANGITE with beta index of refraction less than 1.738	not identified but possible†	not identified but unlikely to be found
BUSTAMITE	common HIGHLY DIAGNOSTIC	absent
WOLLASTONITE	rare except south end HIGHLY DIAGNOSTIC	absent
JOHANNSENITE	probably present	absent
HEDENBERGITE with beta index of refraction less than 1.740	sporadic HIGHLY DIAGNOSTIC	absent (?)
HEDENBERGITE with beta index of refraction greater than 1.740	possible*	possible*

* Further field work and laboratory tests might clarify whether this mineral might be highly diagnostic in any portion of the indicated range in refractive index.
† Further field work and laboratory tests should check this point.

WALLROCK ALTERATION

In general, wallrock alteration is neither intense nor extensive. It is not uncommon to find ore enclosed by but slightly altered gneiss. The most widespread wallrock alteration is silicification; where intense, it converts all gneisses to fine-grained "quartzite." Garnetization occurs also rather abundantly but seldom reaches very far beyond the lodes. Many of the "quartzites," especially where metallized, are impregnated with very fine-grained garnet and are noted as lavender or brown "garnet quartzite." Often seen in stopes is an alteration-product termed "garnet-sandstone," consisting almost entirely of small garnet grains poorly cemented by quartz. There are all gradations between "garnet sandstone" and "garnet quartzite" and between "garnet quartzite" and relatively unaltered sillimanite gneiss.

Slightly altered gneiss in the walls of the lode is generally bleached, the biotite and sillimanite having been changed to sericite. Large garnet porphyroblasts have also been destroyed in the gneiss near ore (Andrews *et al.*, 1922, p. 390).

By far the most extensive hydrothermal alteration in the district is in and close to the zinc lodes above No. 2 Lens Formation in the Zinc Corporation and New Broken Hill Consolidated Mines where fine-grained silicification and garnetization occur on a comparatively large scale accompanied by rather dispersed sulphide mineralization.

METAL RATIOS

During 1936-1938 the Zinc Corporation systematically sampled its stopes, and Burrell, then mine geologist, mapped ore types. Burrell and C. P. Boundy made a statistical study of assay data to determine the metal ratios and their possible meaning in terms of zoning, recognizable ore horizons, secondary enrichment, and related problems.

Before, analysis assays had been cut by arbitrary mine conventions to 10 per cent. Pb, 10 oz. Ag, 15 per cent. Zn. Many hundreds of samples were plotted on a pair of "scatter diagrams,". one with Pb on the abscissa and Ag on the ordinate. The resulting cloud of points was obviously crudely clustered about two axes on each diagram. Most of the points clustered about one axis were derived from fluoritic ore, whereas most of the points clustered about the other axis were derived from calcitic ore.

Next, "class mean graphs" were constructed to obtain clearer definition of the axes mentioned above. Treating the two ore types separately, all samples were classified into 2 per cent. Pb classes—0 to 2 to 4 per cent., etc. The average Pb, Ag, and Zn content of each class was calculated, and the resulting points for each ore type plotted and joined. (Figs. 4 and 5).

Gustafson, mapping in the South Mine, had decided on structural grounds that the ore was divisible into two, or possibly three, folded stratigraphic horizons.

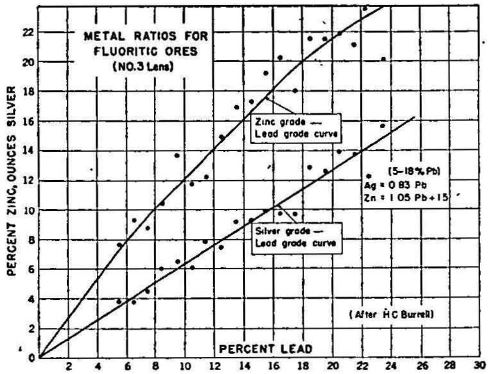

Figure 4—Metal Ratios for Fluoritic Ores (No. 3 Lens)

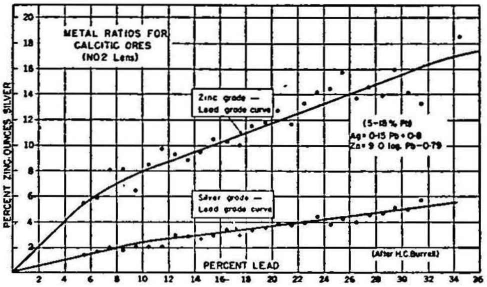

Figure 5—Metal Ratios for Calcitic Ores (No. 2 Lens)

With minor adjustments in the interpretation it was possible to show that the fluoritic type of ore with its characteristic metal ratios corresponded to one ore horizon, and the calcitic type of ore corresponded to another (or, as then thought, to two others). The distinction between high-lead calcitic ore and high-zinc "silicate gangue" ore—but not the stratigraphic significance of these ore types—was early recognized by the Geological Sub-Committee (1910).

Eventually the metal ratios so obtained were found to be essentially valid for the entire line of lode; they were successfully used to distinguish ore types and to work out structure in old worked-out inaccessible portions of the mines.

Burrell and, to a lesser degree, Garretty carried out further comprehensive statistical studies of the Broken Hill assay data, the results of which will be published later.

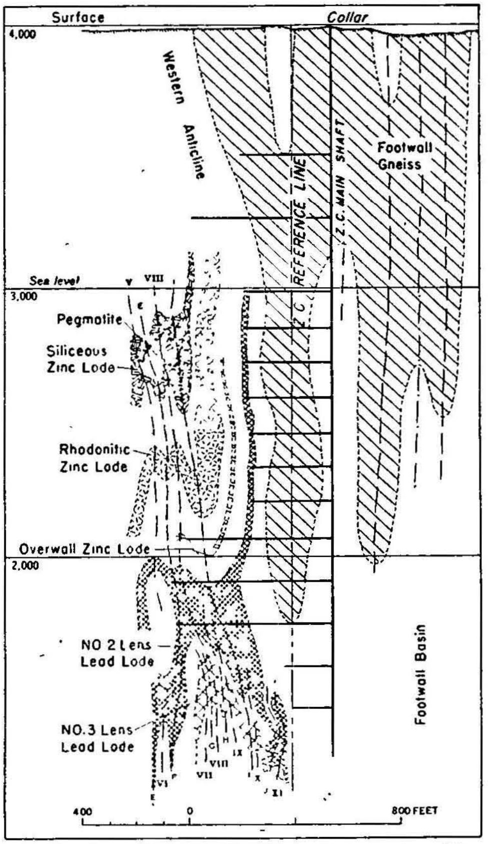

Figure 6—Cross-Section 30. Zinc Corporation Mine.

FOLDED ORE HORIZONS

GENERAL.—The first fact of major importance in understanding Broken Hill orebodies is that they were formed by the selective replacement of closely adjacent favourable stratigraphic rock layers which have been closely folded.

All the steep tabular ore replacing the shear zone known as the "main shear" was at first called "shear ore," but most of it was later identified as replacing favourable rock formations where they are involved in the shear. There remains very little such "shear ore" which cannot be identified as belonging to recognized favourable rock formations; such ore occurs chiefly above the "broad lodes" in the Zinc Corporation and South Mine. "Shear ore" will be used here to distinguish the steep, narrow, tabular ore above or below the "broad lodes" even though it has been recognized as an attenuated fold (or limb of a fold) of a favourable rock formation and has been so designated on the plans and sections.

Stratigraphic position is but one of several requirements for an orebody. Others will be dealt with in the discussion of structure.

The two favourable beds that have contributed virtually all of Broken Hill's ore are known as the No. 2 Lens ore formation (upper) and No. 3 Lens ore formation (lower) (Fig. 6). The No. 2 Lens and No. 3 Lens orebodies are usually readily distinguishable. Each possesses its own characteristic assortment of gangue minerals and its own distinguishing metal ratios.

The Central Geological Survey recognized a third formation, the No. 1 Lens formation overlying No. 2 Lens formation in the Zinc Corporation Mine. A new structural analysis of Zinc Corporation data in 1947 by Gustafson and King proved that there are only two lead ore horizons, a situation suspected by Burrell 1942, (p. 21, 231, 435) as a result of mineralogical and statistical study.

There are also in the district other rock layers stratigraphically above these which have been mineralized but which have never yielded much ore. They are discussed under "Zinc Lodes."

The relative positions of the lodes are shown in Figure 6.

NO. 3 LENS ORE FORMATION.—This lowest ore horizon has produced approximately 50 per cent. of the ore and the richest ore in Broken Hill. It is continuously mineralized from where it is exposed in the Zinc Corporation Mine northward to the British Fault. This same folded formation gave the Junction, Junction North, and North Mines their southern or lower orebody on the other side of the British Fault. In most of the mines the No. 3 Lens orebodies are bigger than the No. 2 Lens orebodies. In the South Mine near the Zinc Corporation boundary, however, the No. 2 Lens orebodies are considerably larger. Where the No. 3 Lens ore is being developed in the Zinc Corporation, moreover, it appears that this increase in size of the No. 2 Lens orebodies is accompanied by a marked diminution in size of the No. 3 Lens orebodies.

The primary metallic minerals [6] are: sphalerite slightly in excess of galena; extremely subordinate pyrite, löllingite, and (locally massive) pyrrhotite; and rare chalcopyrite. Large stope areas consist of massive sulphides with a small percentage of gangue. The gangue minerals are: occasionally conspicuous fluorite, usually disseminated but also in patches; fine- to medium-grained "rhodonite"; sugary quartz; garnet; and very rare calcite. [7] Large masses of almost pure rhodonite occupy more than 50 per cent. of the cross-sectional area of No. 3 Lens

(6) Unless otherwise noted, only those minerals are considered which can ordinarily be seen with the naked eye. See Andrews *et al.*, (1922), Stillwell (1926) for a fuller discussion of mineralogy. "Rhodonite" henceforth refers to any of the pink minerals of the rhodonite group (rhodonite, pyroxmangite, bustamite). "Hedenbergite" refers to the green minerals (hedenbergite and johannsenite) of the same group, and "wollastonite" to white varieties, all possibly bustamite.

(7) Patches of calcitic ore in No. 3 Lens ore formation are apt to have No. 2 Lens metal ratios.

in portions of the Block 14 and British Mines, although in the other mines it more often occurs disseminated through the sulphides or as small partly replaced patches in the sulphides.

"Garnet sandstone" is commonly developed on the margins of the lode, especially on the underwall side. Poorer portions of the orebody may consist of scattered sulphides or small seams of sulphides in highly silicified rock ('quartzite'). Green felspar is sometimes seen in "lode pegmatite."

Metal ratios are shown in Figure 4. Typical medium- to high-grade ore assays 18 per cent. Pb, 11.5 oz. Ag, 20 per cent. Zn. In the ore-bearing folds probably 80 per cent. of this formation was replaced by ore over a strike (pitch) length of 3½ miles.

No. 2 Lens Ore Formation.—This middle horizon is responsible for about half of Broken Hill's ore. It has furnished important ore in the Zinc Corporation, South Mine, British Mine, North Mine, and in the Broken Hill Proprietary open-cut. A few stopes exist in it in the south end of the Central Mine. Most of it has been eroded in Block 14 and the Junction Mine. Except at the south end of the line of lode, mineralization is generally more erratic and less intense than in No. 3 Lens. Nevertheless probably 80 per cent. of the formation in the ore-bearing folds was replaced by minable ore for a distance of 3½ miles.

The metallic minerals are: galena, somewhat predominant over sphalerite; very subordinate chalcopyrite; pyrrhotite; pyrite (especially on the overwall side in Zinc Corporation). Sulphides seldom constitute more than 50 per cent. of many large stope areas. The gangue minerals are abundant calcite and/or quartz; local small patches of coarse-grained massive "rhodonite"; occasional "hedenbergite"; rare fluorite (usually green or white, seldom red or brown); and garnet. "Garnet sandstone" is usually less abundantly developed on the margins than is the case with No. 3 Lens. Lean ore as in No. 3 Lens usually consists of poorly mineralized "quartzite." Green microcline pegmatite occurs in some stopes. Metal ratios are shown in Figure 5.

This description applies to the No. 2 Lens occurrences north of the Zinc Corporation Mine and in the Zinc Corporation Mine above the 12 level. The lower levels of that mine, however, reveal a change in the mineralogy of No. 2 Lens. "Rhodonite" exceeds calcite over large stope areas, and very low-grade portions of the orebody, tens of feet wide, are composed almost entirely of "rhodonite," although the "rhodonite" retains the Ca-Mn-Fe ratio diagnostic of No. 2 Lens. "Hedenbergite" ("green rhodonite") is also prominently developed in many of these areas, especially along the east margin of the orebody and along the underwall. "White rhodonite" or "wollastonite" (possibly all bustamite), rarely seen heretofore, is the chief constituent of some low-grade areas of No. 2 Lens ore on the 18 level of the New Broken Hill Consolidated Mine in the nose of the Western Anticline. Except for conspicuous amounts of calcite and general higher galena-sphalerite ratios for such sulphide mineralization as exists, these low-grade or barren rhodonite areas closely resemble the rhodonite areas in No. 3 Lens in the old British Mine. Another change is the local occurrence of conspicuous pink fluorite crystals encased in calcite in No. 2 Lens ore.

There is some suggestion in low-grade portions of the orebody of a greater prevalence of high zinc and low silver assay values. These resemble No. 3 Lens or zinc lode ratios for lead and zinc but are typical of No. 2 Lens ratios for lead and silver.

Zinc Lodes.—Since completion of the Central Geological Survey work in 1939, developments in the Zinc Corporation and New Broken Hill Consolidated Mines have provided much additional information about the zinc lodes. Haddon F. King in early 1947 arrived at a tentative structural interpretation which was essentially confirmed and extended by Gustafson and King a few months later. The King-Gustafson interpretation given here is considerably different from the tentative one proposed by the Central Geological Survey in 1939. No microscopic work has been done on the new exposures.

In the south end of the Zinc Corporation Mine and in the New Broken Hill Consolidated Mine two prominent ore horizons and a few lesser mineralized beds exist stratigraphically above No. 2 Lens formation. These horizons are eroded where they would be in the ore-bearing folds in the central part of the field. They are insignificant at the north end of the field. Consequently the south end is discussed.

Rhodonitic Zinc Lode: The lower zincy ore bed, known as the "Rhodonitic Zinc Lode," occurs about 125 feet, measured perpendicular to bedding, above No. 2 Lens. Where strongly mineralized on the limb of a fold but near its nose, the bed may be 40 feet thick. Where weakly mineralized, it may be unrecognizable or may consist of two narrow strands of feebly mineralized "garnet quartzite."

Better-grade ore consists of massive sulphides, chiefly sphalerite in marked preponderance over galena, some pyrrhotite with lesser amounts of pyrite and chalcopyrite along the margins, and a gangue of abundant "rhodonite," "hedenbergite," quartz, "garnet quartzite," rare green fluorite, and occasionally "garnet sandstone" and unreplaced pegmatite containing green microcline. Rarely a little calcite occurs in this lode. Such ore may contain 7 per cent. Pb, 1 oz. Ag, and 15 per cent. Zn.

Some high-lead ore shoots with typical No. 2 Lens ratios occur in the lode. Low-grade portions may be massive "rhodonite" and "hedenbergite" (8) and/or "garnet quartzite" with sparse sulphides. All signs of "rhodonite" and "hedenbergite" may disappear along strike, and the only sign of the lode may be poorly metallized "garnet quartzite." Löllingite has been noted in drill core. In general, the favourable bed is much more erratically and incompletely metallized than No. 2 Lens formation or No. 3 Lens formation. Less than 50 per cent. of the formation is ore-bearing in most mine cross-sections.

Siliceous Zinc Lode: The upper important zincy ore bed known as the "Siliceous Zinc Lode," occurs about 30 to 60 feet measured perpendicular to bedding, above the "Rhodonitic Zinc Lode." It appears to be about 10 to 40 feet thick where not thickened or considerably thinned by folding. Ore-bearing portions appear to be somewhat more continuous than in the Rhodonitic Zinc Lode. High-grade ore, similar in assay value to high-grade ore in the Rhodonitic Zinc Lode, consists principally of sphalerite preponderant over galena, small amounts of pyrrhotite, pyrite and chalcopyrite, fine-grained quartz, and fine-grained garnet, with small residual remnants of unreplaced pegmatite and "garnet quartzite." Subordinate ore shoots have typical No. 2 Lens metal ratios. Calcite in small quantity is rarely seen in the ore. Lower-grade portions are merely poorly mineralized "garnet quartzite" and pegmatite. "Hedenbergite" has been seen only rarely and "rhodonite" has not been recognized.

Overwall Zinc Lode: Another zinc lode, a 5- to 10-foot lode known as the "Overwall Zinc Lode," occurs only about 40 feet above No. 2 Lens formation, between it and the Rhodonitic Zinc Lode. This lode contains some "hedenbergite," and locally it contains conspicuous pink fluorite. It has some minable ore shoots. Metal ratios are typically those of the other zinc lodes but occasionally are like No. 2 Lens ratios.

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(8) Since this paper was written, specimens of "hedenbergite" from this formation were found by W. T. Schaller to have beta indices corresponding to hedenbergite, pyroxene, (1.71 $\pm$), and hornblende (1.65 $\pm$).

Other Zinc Lodes: Other smaller, less important, less well known, and probably discontinuous, siliceous zinc lodes occur above the Siliceous Zinc Lode. Their oxidized outcrops contain conspicuous gahnite.

FAVOURABLE ROCKS AND SELECTIVE REPLACEMENT.—The authors are not sure why some beds were favourable to replacement, others not. Certainly the favourable beds so nearly resemble the rest of the rock as to be virtually indistinguishable where neither ore-bearing nor highly altered. However for economic reasons they are seldom exposed by either underground workings or by drill holes beyond the limits of metallization or of intense hydrothermal alteration. Thus their study is difficult.

Original Chemical Differences: The fact that the No. 3 Lens orebody is characterized by rhodonite having distinctive Ca-Mn-Fe ratio, conspicuous pink fluorite and a distinguishing Pb-Ag-Zn ratio, whereas the No. 2 Lens orebody is characterized by a calcite gangue with subordinate rhodonite having different Ca-Mn-Fe ratio and generally little or no fluorite, as well as by a different Pb-Ag-Zn ratio, strongly suggests that the beds originally differed in chemical composition. It suggests, moreover, that differences in chemical composition may have been a deciding factor in selective replacement.

Gustafson (1939, p. 17) considered the possibility (*a*) that the high-manganese content of No. 3 Lens and high-lime content of No. 2 Lens were due to differences in sedimentation of the two formations, and (*b*) that these components were merely greatly rearranged (recrystallized and transported) by the ore solutions rather than introduced by them as previously concluded by Andrews (Andrews *et al.*, 1922) and Stillwell (1926). He concluded, nevertheless, that "if chemical composition was an important factor in determining the favourableness of certain beds, the part it played was neither simple nor obvious," and that the calcite, rhodonite, and garnet in the ore had probably been hydrothermally introduced.

Burrell (1942) now favours the hypothesis that the favourable formations were originally calcitic, siliceous, ferruginous, manganese carbonate (or oxide) beds intermixed with clays and sands; that the calcite, apatite and quartz of the lodes were in large measure sedimentary constituents; that the rhodonite and garnet were preponderantly formed during regional metamorphism; and that these "early complex" minerals gave the beds a brittleness and a distinctive chemical character that accounts for their favourableness during the later introduction of lode pegmatite, fluorite, and sulphides and for the selective control exerted by them on sulphide deposition which resulted in the characteristic metal ratios of the ores. Among the arguments for this hypothesis are:

(1) Metamorphosed siliceous, calcareous, and manganiferous sediments in India and Brazil produced mineral assemblages not unlike the gangues of the Broken Hill lodes.

(2) Differences in characteristic lime-iron-manganese ratios of stratigraphically neighboring ore beds noted in manganiferous sediments throughout the world resemble the differences in lime-iron-manganese ratios of rhodonite in the Broken Hill lodes.

(3) The persistence and regularity of such differences is readily explained by selective sedimentation, and a similar process may have produced the original differences in the mineral assemblages of the various ore beds at Broken Hill.

(4) The influence of such original differences upon replacement activity might explain the development of characteristic metal ratios in each ore bed.

This theory does explain how rhodonite and calcite became selectively distributed, if not how millions of tons of sphalerite, galena, pegmatite, and fluorite were introduced into the ore beds so that each bed has its own diagnostic metal ratios and gangue characteristics. It is hard to escape the belief that some selective catalytic action by calcite, rhodonite, and garnet (if not by less obvious constituents of the replaced strata) affected the precipitation of sulphides and fluorite.

Probably the strongest arguments against the sedimentary-metamorphic hypothesis and for the hydrothermal hypothesis are:

(1) The ore beds wherever traced for even a few feet on strike or down dip beyond the limits of commercial mineralization do not contain conspicuous rhodonite or calcite, but are made up of thin beds of garnet "quartzite" and altered gneiss. Elimination of the beds through attenuation on the limbs of folds during folding does not appear to explain the absence of calcite or rhodonite in many instances. For example, there are no limy beds of No. 2 Lens formation above the No. 3 Lens ore in some parts of the small eastern folds in the South and Central Mines where calcitic ore is missing. Yet here beds are bunched in the nose of a fold, not attenuated. Another example can be found in the Rhodonitic Zinc Lode. Generally, where sulphide mineralization is strongest, there is abundant brown and pink rhodonite; where sulphide mineralization is weaker there is hedenbergite and "garnet sandstone" with subordinate rhodonite; where sulphide mineralization fades out, there is lavender garnet "quartzite" spotted or veined with occasional growths of hedenbergite and rarer rhodonite. Yet the widths of the formation may be constant. Consequently, if the "sedimentary hypothesis" is valid, one must assume that (*a*) No. 2 Lens, No. 3 Lens, and the favourable beds occupied by the Rhodonitic Zinc Lode all possessed the high manganese or high lime content in an extremely elongated channel of sedimentation which later became the crest of the Western Anticline, and that (*b*) these beds became, except for the minor exceptions of large rhodonitic areas in No. 3 Lens and in the Rhodonitic Zinc Lode, practically 100 per cent. replaced by ore wherever they were so composed.

(2) In addition to the intimate spatial relationship of rhodonite, garnet, "garnet sandstone," and calcite with sulphides and fluorite, the textures of these mineral aggregates and their cross-cutting relationship to bedding planes clearly indicate that they were in many cases transported by and crystallized from hydrothermal solutions during the ore-forming period. Every gradation can be observed underground between hydrothermally relatively unaltered banded sillimanite gneiss, through banded silicified gneiss with alternating bands of "garnet quartzite," to pure lavender "garnet quartzite," and between "garnet quartzite" and "garnet sandstone." There are also good cases of coarse hedenbergite veining "garnet sandstone," and of "garnet sandstone" veining blue hydrothermal quartz.

All observers agree that most of the rhodonite, lode garnet, and calcite are earlier than the sulphides, but Burrell (1942), contrary to Andrews (Andrews *et al*, 1922) and Stillwell (1926), thinks that these silicates also antedate the lode pegmatite. Gustafson and Garretty are unsure as to the conflicting evidence on this point but question its significance. Much of the coarse-grained silicates and calcite seen in stopes was either dissolved, transported and precipitated by ore solutions or was introduced by ore solutions. These gangue minerals could be earlier than lode pegmatite and still be hydrothermal.

Original Physical Differences: The close dependence of mineralization on structure indicates that relatively high permeability distinguished the favourable beds from others. The shapes into which they were crumpled indicate a high degree of plasticity during folding differing little, if at all, from that of adjacent unfavourable beds. It is thus difficult to see how crushing during folding could have induced such selective permeability.

Nevertheless, meagre evidence in the case of the zinc lodes at least suggests that favourable beds consisted of alternating thin layers of quartzite and shale (before metamorphism to gneiss), whereas some unfavourable beds at least were more homogeneous. Excessive slipping on well-defined bedding planes separating materials of different competency may have induced greater permeability.

Although all rocks may have behaved more or less alike under the extreme conditions of folding, they did not necessarily behave alike under the wholly different temperature-pressure conditions accompanying post-folding movements. Possibly during the adjustment of the folded pattern to later movements most of the "take up" occurred in the favourable beds as well as on the stretched limbs of folds. If so, any initial inequality of permeability must have been accentuated. (It will be demonstrated later that post-folding movements developed shears on stretched limbs.)

Other Factors: The cross-sections show extreme thinning of ore on the limbs of the Western Anticline. Most, but not all, of this thinning is due to stretching of the favourable beds during folding (with compensating thickening in the crests of folds). Intensity of mineralization and amount of ore decrease with distance from the anticlinal arch. Where in some cases drives have followed the strike of a mineralized bed beyond the limits of sulphides, sulphides give way to highly garnetized and silicified rock which in turn grades into less altered rock, not because favourable beds are eliminated but because they are merely not mineralized. A few rock laminae within the favourable bed continue to be mineralized much beyond the others—evidence of selectivity *within* the favourable formation where mineralization is less intense. Moreover, in one cross-section of the Western Anticline, No. 3 Lens may appear as a considerable thickness of lode material, whereas in another cross-section it may appear as a narrow band of sulphides in the arch of the fold. It may be safely assumed that more rock laminae belonging to the No. 3 Lens formation have been replaced in the first instance. The evidence is even more compelling in the case of the zinc lodes.

Thus, favourable formations sometimes appear to be less definite things than favourable surfaces such as rock contacts, and the thickness of ore at any place in a "favourable formation" appears in some measure to represent the width of rock replaced on one or both sides of the favourable bedding plane along which ore solutions entered. The width may have been determined partly by the extent of crushing of adjacent rock layers, partly by the intensity of mineralizing agencies.

Merging of Orebodies on Favourable Horizons: Orebodies on the two favourable rock horizons sometimes merge or are separated by a very thin partition of unreplaced rock. There are several reasons:

(1) Thin barren rock partitions are stoped along with ore if they are too small to be left as pillars. Where the structural interpretation has been carried through old inaccessible stopes, no record of thin partitions remains. We frequently had to divide the ore of a stope into two horizons merely on the basis of projected structure without evidence of intervening rock even where it may have existed.

(2) Replacement in some places has progressed from formation to formation along small subsidiary shears.

(3) Intervening rock in some cases was probably either squeezed out during folding or, more probably, so crushed that ore solutions replaced it along with the normally more favourable rock.

STRATIGRAPHY

STRATIGRAPHIC SUCCESSION

The chief rock types have been mapped and described by Andrews and his associates (Andrews *et al.*, 1922). The Central Geological Survey attempted to subdivide the rock assemblage into stratigraphic units (Table 3), determine the order of sequence of these units, and solve the structures they portray. The newer interpretation differs from the older chiefly in that: (1) Rock formations are now correlated on the two sides of the main lode (notably the Footwall Gneiss with the Potosi Gneiss, the Alma Augen Gneiss with the Hanging Wall Granite, and amphibolites of the Hanging Wall Basin with certain ones to the east). Andrews' cross-section reveals a somewhat similar tentative correlation although he does not stress it in the text. (2) Great thicknesses of sillimanite gneiss are split up into smaller rock formations. (3) The new structural picture differs radically from the older one in detail, although it harmonizes with the larger structures previously recognized.

DESCRIPTION OF FORMATIONS (9)

General Outline.—The absence of persistent "key" "horizons" everywhere distinguishable from all other rock layers and the inability to recognize top and bottom of beds were the greatest obstacles to the complete solving of either rock succession or folded structures. The gradation from fine garnets to coarse garnets in a sillimanite gneiss near a sharp quartzite contact is apparently evidence of approach toward the top of a clay bed overlain by a sand bed. It is very rare, however, to find exposures where the technique is applicable.

The old granite sills or the amphibolites are easily separated from other rocks, but many layers of each cannot be told apart. The Potosi Gneiss and Footwall Gneiss (here correlated) also can ordinarily be distinguished from the other rocks. Among the sedimentary rocks generally, however, each formation contains sillimanite gneiss beds of coarse and fine grain, quartzite beds, and often pegmatite layers. Beds containing coarse garnets are fairly reliable markers, for short distances at any rate, but there are too many of these and they all look alike. Formations must therefore, with few exceptions, be distinguished by their varying proportions of component rock types common to all, and by their stratigraphic position in known structures. Where the walls of cross-cuts are dirty or the rocks are highly altered close to lodes, recognition of formations is commonly impossible. Rocks also have been rendered indistinguishable in places by shearing and schisting.

Table 3 and the illustrations of this bulletin are the final interpretation of countless factual data shown on plans and work sheets supplied to each mine and on file in Broken Hill (Gustafson 1939) but too bulky to present in this bulletin.

Most of the descriptive terms used are self-evident. Quartzite means true sedimentary quartzite as distinct from "quartzite" a product of hydrothermal silicification.(10) Coarse-grained garnet means garnet at least one-half an inch in diameter. The various amphibolites are all very similar and are the metamorphosed gabbro sills (Table 1, item 2). There may be errors in the correlation of these, because individuals may transgress other formations, lens out, or bifurcate. However, they are remarkably persistent in lateral extent and in stratigraphic position. They are all obviously highly folded. The granite gneiss is the older folded granite (Table 1, item 2). Numerous post-folding pegmatite dykes occupying fractures in the older rocks and late uralite dolerite dykes are omitted from this discussion and from the plans and sections.

I Formation.—The oldest rock formation considered is exposed in deep drill holes in the Broken Hill Proprietary Company property and Block 14 and possibly on the surface in the Eastern Anticline. It consists predominantly of fairly coarse-grained sillimanite gneiss containing fairly abundant coarse-grained garnets, and contains numerous but very subordinate thin quartzite beds (1 inch to 1 foot thick).

(9) The Andrews monograph (Andrews *et al.*, 1922) gives petrographic descriptions, photographs, and chemical analyses of the various rock types. It should be noted that the two petrographers (Browne and Stillwell) disagree as to the origin of the "quartzites," "Footwall Gneiss," "Potosi Gneiss," and amphibolite.

(10) The field evidence tends to confirm Stillwell's conclusions that the "quartzites" are sedimentary, and not intrusive as Browne concluded (Andrews *et al.*, 1922, Appendices 1 and 11).

TABLE 3.—STRATIGRAPHIC SUCCESSION

GROUP	FORMATION No.	FORMATION NAME	Thick-ness* (Feet)	DESCRIPTION
OVERWALL GROUP	XVII	Hanging Wall Granite	2,000	Pre-folding intrusive sill of porphyritic granite, now granite gneiss with augen or platy texture containing one narrow layer of gneissic aplite.
	XVI	XVI Formation	800	Sillimanite gneiss with considerable coarse - grained garnet: subordinate quartzite beds.
	XV	Town Amphibolites	200	Pre-folding intrusive sills of gabbro, 1-4 in number, now amphibolite.
	XIV	XIV Formation	150	Sillimanite gneiss with thin beds of quartzite and fine-grained granular gneiss. One diagnostic, thin, well-bedded garnet-magnetite bed at bottom locally. Occasional small quartz-gahnite lodes.
	XIII	Bonanza Amphibolites	10	Local thin amphibolite sill(s).
	XII	Potosi-Footwall Gneiss	200-500	Granular gneiss, lacking sillimanite; contains round garnets and numerous highly-folded pegmatite stringers; probably sedimentary.
LESSER ZINC LODE GROUP	XI	XI Formation	500	Where unaltered, sillimanite gneiss bands alternating with 2 bands containing chiefly quartzite beds; local garnet-magnetite bed near top. At Zinc Corporation, South Mine, and elsewhere, contains zinc sulphides and gahnite-bearing lodes and much "garnet quartzite."
	X	Consols Amphibolites	200	1-2 (or more?) local amphibolite sills.
	IX	IX Formation†	200	Where unaltered, sillimanite gneiss containing at least 2 wide coarse garnet bands. A few local zincy and quartz-gahnite lodes.
MAIN ZINC LODE GROUP	VIIIb	Siliceous Zinc Lode formation†	25	Lode or "garnet quartzite." Not identified where unreplaced.
	VIIIa	VIIIa Formation†	45	Alternating layers thinly bedded gneiss and quartzite (or "quartzite").
	VIII	Rhodonitic Zinc Lode formation†	25	Lode or "garnet quartzite." Not identified where unreplaced.
	VII	VII Formation†	125	Alternating layers thinly bedded gneiss and quartzite (or "quartzite") containing at least one zinc lode of importance ('Overwall zinc lode").
MAIN LEAD LODE GROUP	VI	No. 2 Lens ore formation	50	Lode or "garnet quartzite." Not identified where unreplaced.
	V	V Formation	70	Coarse - grained sillimanite gneiss.
	IV	No. 3 Lens ore formation	50	Lode, "garnet sandstone" or "garnet quartzite." Not identified where unreplaced.
UNDERWALL GROUP	III	III Formation	500	Coarse - grained sillimanite gneiss with subordinate beds of fine-grained granular gneiss, both generally with abundant coarse garnets; subordinate thin beds of quartzite.
	II	Underwall Amphibolites	50	1 or 2 amphibolite sills; probably local.
	I	I Formation	400 (exposed)	Like III formation.
		Total 4,900 (+) — 5,500 (+)		

* Thickness given is a rough guess as to average thickness, allowing for packing and duplication in the noses of folds and for attenuation on the limbs of folds. The figures give only relative orders of magnitude.

† Where the zinc lodes are not mineralized we are unable to distinguish Formations VII-IX, inclusive, satisfactorily.

The formation is indistinguishable from III Formation. The two form a sedimentary unit split by sills of the Underwall Amphibolites. Minimum of 400 feet exposed.

A deep drill hole put down in 1890 by the Broken Hill Block Silver Mining Company (Brisbane Blocks drill hole No. 3) intersected "garnet sandstone" beneath amphibolite on the west limb of the Western Anticline. This possible "No. 4 Lens" ore horizon in I Formation was the objective of a drilling campaign in the B.H.P. Company Mine, which failed to find ore.

UNDERWALL AMPHIBOLITES (II FORMATION).— Amphibolite sills of this formation are exposed for certain only in deep drill holes in the Central Mine, B.H.P. Company Mine, and Block 14. It is not certain that all the scattered drill-hole intersections in both the Western Anticline and Eastern Anticline belong to one continuous sill, but they are so interpreted on the large-scale cross-sections. The thickness as revealed by drill core is variable. If but one sill is duplicated by folding, the thickness is perhaps 50 feet.

III FORMATION.—The rock resembles I Formation. It immediately underlies the No. 3 Lens orebodies and on the structural interpretation presented here is believed to crop out as the core of the Eastern Anticline east of the line of lode from Block 12 northward (Pl. 3, fig. 1). Thickness: probably 500 feet. The coarse garnets were generally destroyed by hydrothermal alteration within 50 feet of the lodes, though in some places they are found against the lode. In the Zinc Corporation Mine the rock near the lodes locally appears slaty and well bedded. In Block 14, the South Mine, and elsewhere, a thin lode a short distance under the main orebody may be a locally mineralized bed in this formation.

NO. 3 LENS ORE FORMATION (IV FORMATION).—Already described under "Folded Ore Horizons." Thickness: extremely variable, averaging perhaps 50 feet. This formation is more persistent as a recognizable unit beyond the limits of ore than are the other lode horizons. On the west limb of the Eastern Anticline, this (?) horizon can be traced north of the east side of Imperial Ridge and Round Hill to where it meets the Globe-Vauxhall crush. Here it occurs in the main as a hard, silicified, fine-grained, manganese-stained rock approaching a "garnet quartzite" in appearance. It is finely bedded, and its bedding planes are generally highly drag-folded. This type of rock grades into true "garnet quartzite" which is locally mineralized.

Where No. 2 Lens ore formation and No. 3 Lens ore formation are both ore-bearing and crop out close to one another along the main line of lode, No. 3 Lens generally contains more "garnet sandstone," whereas No. 2 Lens is harder, more siliceous, and contains more "garnet quartzite." Both are manganese-stained.

Ordinarily both ore horizons are difficult to trace, even underground, beyond the limits of ore. Neither is recognized on the surface with certainty on the east limb of the Eastern Anticline or on either limb of the Alma Anticline.

V FORMATION.—Where not too highly altered, this rock is a coarse-grained "mottled" (11) gneiss with very subordinate thin quartzite beds. Bedding is seldom very conspicuous. Fine-grained garnets are occasionally in evidence, but garnets are almost never large or conspicuous, although the formation is beginning to carry coarse garnets on the deep levels of the Zinc Corporation and New Broken Hill Consolidated Mines. Thickness: extremely variable, averaging about 50 feet.

NO. 2 LENS ORE FORMATION (VI FORMATION).—Already described under "Folded Ore Horizons." Thickness: extremely variable, averaging perhaps 50 feet. The northern continuation of No. 2 Lens in the west limb of the Eastern Anticline

(11) Mottling produced by fairly distinctive elongate white felspar-quartz patches. All coarse-grained gneisses are more or less "mottled."

is less certain. Here the first quartz-gahnite lode above No. 3 Lens has been tentatively considered to be No. 2 Lens ore formation.

VII Formation.—Where observed the rock is generally composed of alternating layers of thinly bedded gneiss and "garnet quartzite" in varying ratios of abundance depending on the amount of alteration. In Zinc Corporation and New Broken Hill Consolidated property, it contains the narrow "Overwall zinc lode" already described. Thickness: about 125 feet.

Rhodonitic Zinc Lode (VIII Formation).—Already described under "Folded Ore Horizons." Thickness: averages about 10 to 40 feet. This formation occurs as an ore horizon only in the Zinc Corporation and New Broken Hill Consolidated Mines. North of here it probably exists as a feebly mineralized "garnet quartzite," but it has not been identified with certainty. Where this and the upper zinc lodes are "missing," IX Formation is shown on plans and sections as immediately overlying No. 2 Lens ore formation.

VIIIa Formation.—Recognized as a separate formation only where the underlying and overlying zinc lodes (VIII Formation and VIIIb Formation) are mineralized, it generally consists of "quartzite" whose texture, where not too highly silicified, suggests derivation from thinly bedded sillimanite gneiss and quartzite. Thickness: 30 to 60 feet.

Siliceous Zinc Lode (VIIIb Formation).—Already described under "Folded Ore Horizons." Thickness about 10 to 40 feet. Ore-bearing only in the Zinc Corporation and New Broken Hill Consolidated Mines. Not identified with certainty farther north.

IX Formation.—Well exposed on the surface of Block 14 west of the lodes, where it consists of two wide bands of sillimanite gneiss alternating with two somewhat narrower bands of sillimanite gneiss with conspicuous coarse-grained garnets. It can be recognized with fair certainty in a similar position in Block 10. According to our structural interpretation, the rocks immediately east of the Main Shear in the South Mine and (on upper levels) in the Central Mine belong to this formation. Here there is a lower narrow band of gneiss (5-50 feet thick) containing abundant coarse-grained garnets overlain by alternating thin beds of quartzite and gneiss which in turn are overlain by a considerable thickness of alternating thin beds of coarse-grained gneiss and fine-grained granular gneiss, both with medium- to coarse-grained garnets.

The formation is difficult or impossible to separate from XI Formation in many places. The rocks are considerably altered in the Zinc Corporation in the nose of the Western Anticline. Thickness: believed to be about 100 to 200 feet. Where the zinc lodes are absent, rock properly belonging to VIII, VIIIa, VIIIb, and X Formations has possibly been included in this formation.

Consols Amphibolites (X Formation).—The Consols Amphibolites comprise one or two (?) amphibolite sills. They are well exposed on the east side of the Footwall Basin and wrap around the northern rim of this structure. Owing to their lenticularity, the correlation of individual sills on two sides of a fold may be in doubt as, for example, on the two sides of the Footwall Basin, even though the amphibolites on the two sides clearly belong to the same formation. The amphibolites lens out on the west side of this Footwall Basin going south before the South Mine property is reached. They are everywhere missing west of the line of lode south of the De Bavay Fault.

Owing to the difficulty in distinguishing IX Formation from XI Formation, it is by no means certain that these amphibolites occur at the exact stratigraphic position recognized as the contact between these two formations in places where the amphibolites are missing. They probably merely approximate this position. The variable distance between Consols Amphibolites and the Potosi-Footwall Gneiss in the Footwall Basin suggests that the amphibolite cuts across bedding planes at an acute angle. In fact there is independent clear evidence that the amphibolite sills cut across the other formations at an acute angle. The northernmost outcrops of the amphibolites in the Footwall Basin may occupy as low a stratigraphic position as IV-VI Formations. On the other hand, in M.Ls. 55 and 79 the same (?) sills are very close to XII Formation.

The interpretation of the structure north of the Imperial Dam Fault is admittedly weak. Some of the lower amphibolites here may be Consols Amphibolites rather than Town Amphibolites. (See also later discussion of structure between the De Bavay Fault and Round Hill.) Thickness: probably averages 200 feet.

XI FORMATION.—The lowermost bed in this formation is regarded as the lowermost strong "quartzite" (or quartzite ?) above the upper band of coarse garnets in IX Formation. The upper limit of the formation is regarded as the Potosi-Footwall Gneiss.

On the west flank of the Western Anticline in Block 14 and Block 10 the formation consists of two strong bands containing chiefly quartzite ("quartzite?") separated and overlain by sillimanite gneiss with very subordinate thin quartzite beds. In the Central Mine, South Mine, and Zinc Corporation it contains numerous siliceous zincy lodes containing gahnite. Lodes of this kind also occur in this formation in the North Mine, in M.L. 3, and elsewhere, although there are fewer of them. Most gahnite lodes cropping out from White Lead to Rising Sun North also probably belong to XI Formation. In contact with the Potosi Gneiss in the Zinc Corporation and South Mine, also north of the De Bavay Fault in M.L. 3, and at White Lead and Rising Sun, is an altered gneiss containing abundant round fine-grained to medium-grained garnets. This rock is somewhat doubtfully assigned to XI Formation; it may be sheared altered Potosi (Footwall) Gneiss. Below this rock in turn in M.L. 3 is a gneiss containing coarse garnets. Two bands of coarse garnets which probably belong to this formation were mapped in a similar stratigraphic position under the Potosi-Footwall Gneiss in the Footwall Basin just east of the De Bavay Fault.

The quartz-gahnite lodes beneath the Footwall Gneiss on both sides of the Footwall Basin are assigned to XI Formation, but XI Formation and IX Formation are difficult to separate east of the line of lode. The rocks between the Consols Amphibolites and the Footwall Gneiss generally contain fewer quartzite beds than does XI Formation in the Western Anticline and fewer coarse garnets than is typical of IX Formation in the structure. Just east of Kintore Shaft in the Central Mine, coarse garnets occur next to the Potosi Gneiss. Either they belong to XI Formation, or XI Formation has been eliminated by shearing during folding.

Near the top of XI Formation not more than 20 feet or so below the Footwall Gneiss there occurs locally a narrow layer (zero to 10 feet thick) of very distinctive rock termed a "garnet-magnetite lode" by Andrews (Pl. 3, fig. 2) and marked on our 100-scale surface plans furnished to the mines as BIF (banded iron formation). The rock is fine-grained, remarkably well- and thinly-bedded, and consists principally of garnet and magnetite, with subordinate quartz and apatite. The bedding planes are commonly wrinkled into small minor folds. In our opinion this bed and the very similar bed overlying the Footwall Gneiss are sedimentary layers which, when present, are everywhere in the same stratigraphic positions [12].

(12) This "lode" is shown on Andrews' maps locally as cutting the Footwall Gneiss and elsewhere as cutting sillimanite gneiss remote from the Footwall Gneiss. Our mapping revealed very few instances where the bed is bordered on both sides by Footwall Gneiss (probably infolded) and no instance where the bed is remote from the Footwall Gneiss or Potosi Gneiss. Where Andrews (Andrews *et al.*, 1922) shows the bed in sillimanite gneiss, we recognize on one side of it a band of Footwall Gneiss not mapped by Andrews (the eastern limb of the Alma Anticline). Whether or not the garnet and magnetite were introduced hydrothermally or are the metamorphic products of an iron-rich sediment is somewhat in doubt. In a few places at least the bed contains a few per cent. of lead. In a few others, we were tempted to correlate with it a "garnet quartzite." The garnet, moreover, is a manganese-rich garnet like the lode

Continued on next page

The bed crops out abundantly on both limbs of the Alma Anticline and in the nose of the Broken Hill Basin, occurs in a number of the structures on the east side of Rising Sun and White Lead, and it, or the almost identical bed overlying the Footwall Gneiss, has been observed but not mapped on the east limb of the Broken Hill Basin. The bed, however, has not been found on either limb of the Eastern Anticline or Western Anticline except south of the Zinc Corporation. Thickness of XI Formation: about 500 feet.

POTOSI-FOOTWALL GNEISS (XII FORMATION).—Andrews and his associates called the fine-grained phase of this formation the Potosi Gneiss ("granulite") and the coarse-grained phase the Footwall Gneiss. Andrews (Andrews *et al.*, 1922, p. 86) and Browne (1922) regarded both as intrusives; Stillwell (1922) offered the minority opinion that they are sedimentary [13]. They look more like sediments than intrusives. What appear to be highly folded bedding planes can be seen locally. The most conspicuous banding in the rock is, however, due to its gneissic texture or to the parallelism of pegmatite veins (Pl. 4).

The Footwall Gneiss, as defined by Andrews, is a moderately coarse-grained grey gneiss forming bold outcrops on the east side of the line of lode. It is distinctly granular and is composed chiefly of felspar (orthoclase and plagioclase), quartz, biotite, and garnet. Sillimanite is conspicuously absent. The rock generally contains numerous fairly round garnets an eighth of an inch to half an inch in diameter. Generally it contains numerous small highly convoluted pegmatite stringers. The Potosi Gneiss, very similar but finer-grained, generally occurs on the western side of the line of lode but was recognized by Andrews on the east side in the Central Mine. Portions of the Footwall Gneiss as mapped by Andrews are fine-grained and could, we believe, be classed as Potosi Gneiss with equal justice. In our structural interpretation, the two types are regarded as different phases of a single formation, probably sedimentary but in any case occupying a single stratigraphic position.

The formation occurs on the east side of the mines in the Footwall Basin and in the west limb of the Broken Hill Basin (east limb of Alma Anticline) [14]. Underground we have found it only in the Zinc Corporation and North Mine. West of the mines the formation occurs locally on both limbs of the Hanging Wall

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garnet. On the other hand, wherever the bed crops out, over a distance of many miles, it is always the same in appearance with no visible change in composition. If a lode (i.e., a replaced bed), it is unique in its uniformity. Even detached pods of this bed in the De Bavay Fault are no different from other exposures, a fact which suggests that the garnet and magnetite formed before the period of main faulting and therefore before the period of mineralization. The evidence favours the view that the bed is a metamorphosed iron-rich sediment into which, as into most of the other rocks in the district, a little galena found its way very locally during the main period of mineralization. It was noticed during the magnetic survey of the Zinc Corporation's southern leases that abnormal quantities of magnetite had been developed locally in the gneiss at amphibolite contacts. Elsewhere (especially at Imperial Ridge) the gneiss next to amphibolite has been profoundly altered by what may be contact metamorphism. Possibly the magnetite and garnet of the garnet-magnetite and quartz-magnetite "lodes" of the district were introduced hydrothermally into favourable beds by "ore solutions" emanating from the reservoir of gabbro magma from which the amphibolite sills were also ejected. If so these "lodes" have been subjected to dynamic metamorphism and folding.

(13) Chief arguments given for an intrusive origin are:

(1) The rock masses are lenticular. They do not, however, appear to be necessarily more lenticular than other sedimentary gneiss types. Excessive thinning on the limbs of folds and packing in the noses will probably explain their lens-like character even if sedimentary lenticularity is not used as an argument. The biggest "lenses" are structural basins.

(2) There is said to be contact alteration next to them. The alleged "contact alteration" is apparently the local development of staurolite and probably andalusite in adjoining gneisses. But these minerals are widespread through the district and can be accounted for as products of the regional metamorphism. In our mapping we found no evidence of peculiar alteration at the contacts not found in the gneisses elsewhere.

(3) Their chemical composition suggests igneous rocks. Yet Stillwell thought the chemical analyses favour a sedimentary origin! At best the chemical evidence is inconclusive.

(4) They contain numerous small highly folded stringers of pegmatite, but so do locally the sillimanite gneisses. It is perhaps noteworthy that the old amphibolite sills generally do not. Perhaps bedding planes afforded easiest access to the old pegmatites.

(14) Shown as sillimanite gneiss on Andrews' maps except for one isolated outcrop east of Round Hill which is marked Potosi Gneiss.

Basin. It also appears in the Zinc Corporation and South Mine in what appears to be a small syncline in the west limb of the Western Anticline. It is missing over a portion of the field in the east limb of this structure and where present it is very narrow, probably as a result of attenuation during folding. (The formation is obviously highly folded and greatly thickened in the trough of the Footwall Basin.) Thickness: extremely difficult to determine; probably averages between 200 and 500 feet.

BONANZA AMPHIBOLITES (XIII FORMATION).—Immediately overlying the Footwall Gneiss in the Footwall Basin near the Bonanza Shaft in M.L. 222 is a small lenticular amphibolite. The formation is not recognized with certainty elsewhere. Doubtfully correlated with it west of the mines is the easternmost amphibolite in Block 10, Block 14, and British Mines, although this may belong to the Town Amphibolites (XV Formation). The formation is apparently missing on the east limb of the Alma Anticline. It might be better to regard all the amphibolites above the Potosi-Footwall Gneiss as belonging to one formation and all the sillimanite gneiss between the Potosi-Footwall Gneiss and the Hanging Wall Granite as belonging to another.

XIV FORMATION.—The rocks overlying the Potosi-Footwall Gneiss are for the most part a fairly featureless assortment of sillimanite gneiss beds alternating with thin layers of quartzite and fine-grained granular gneiss. Garnets are nowhere conspicuous. Locally a poor quartz-gahnite lode occurs near the bottom of the formation. In places on both limbs of the Alma Anticline immediately overlying the Potosi-Footwall Gneiss or separated from it by a few feet of coarse sillimanite gneiss is a thin garnet-magnetite bed normally indistinguishable from the one in XI Formation. This upper one appears to be somewhat more persistent, and we suspect that it contains more magnetite. In places on the east limb of the Alma Anticline the magnetic bed has apparently been duplicated by minor folding (or there is locally more than one bed.)

The Silver Hill, Potosi, Silver Peak, Globe, Star, and Carbonate Ridge Mines, all of which have produced a little ore, appear to be in XIV Formation on the west limb of the Hanging Wall Basin, but were not studied. Thickness of the formation: probably 150 feet.

TOWN AMPHIBOLITES (XV FORMATION).—This formation comprises a group of amphibolite sills that crop out abundantly on the edge of the town of Broken Hill on both sides of the Hanging Wall Basin (Pl. 5, fig. 1). In many places only one amphibolite is present; in others there appear to be as many as four, although the amount of duplication by minor folding is not known. Also assigned to this formation are amphibolites in the same approximate stratigraphic position on the east limb of the Alma Anticline. Thickness: estimated at 200 feet.

XVI FORMATION.—This formation, between the Town Amphibolites and the Hanging Wall Granite, is composed chiefly of sillimanite gneiss of both coarse and fine grain with subordinate thin quartzite beds. A fair percentage of the coarse gneiss contains abundant and conspicuous coarse garnets. Thickness: seen only on (thinned) limbs of folds; probably 800 feet.

HANGING WALL GRANITE (XVII FORMATION).—This uppermost formation dealt with is essentially a sill of gneissic porphyritic granite (Table 1, item 2) although locally some of the rock of which it is composed appears to be metamorphosed granitized sedimentary rock. It crops out prominently in the Hanging Wall Basin at Lord's Hill, Billy Goat Hill, and the Abattoir Ridge (Hanging Wall Gneiss of Andrews). It also forms bold outcrops on the east limb of the Alma Anticline in the town of Alma in Hebbard Street, along Turpin's Ridge, and for some miles north and south (Alma Augen Gneiss belt of Andrews). Where more foliated than elsewhere, it has been referred to by Andrews as "platy gneiss." The most prominent minerals are quartz, orthoclase (and subordinate plagioclase), biotite, and garnet (Pl. 5, fig. 2).

A band of aplite up to 200 feet wide is commonly in the granite mass. This appears to have been a separate intrusive slightly later than the main granite mass. In some places it is near the centre of the granite sill (Turpin's Ridge); in others at or near the top (Alma Township); in still others near the bottom (Lord's Hill). In the De Bavay quarry at Lord's Hill, sillimanite gneiss locally intervenes between granite and aplite.

Although not indicated as a separate formation, a much thinner granite sill locally underlies the main body and is separated from it by 50 to 200 feet, as for example at the north end of the Billy Goat Hill exposures and along the west side of Turpin's Ridge. Thickness: probably at least 1,000 feet.

STRUCTURE

GENERAL

Geological problems of economic importance in Broken Hill are primarily structural. The Central Geological Survey's energies therefore were chiefly spent in a detailed and comprehensive analysis of the structure. Because the structures are very complex, and because some of our major conclusions are based on what may at first appear to be small structural details, a complete understanding of the problem demands thorough and critical study of many plans and sections, only a few of which can be reproduced in this bulletin. The following discussion summarizes our views and appraises the validity of our conclusions where based on incomplete or unsure evidence.

Two principal types of structures are discussed: (1) folds, the products of tremendous southeast-northwest shortening in the earth's crust which plastically deformed every cubic inch of rock in the district, and (2) faults and "buckles," the products of later stresses of smaller magnitude that were relieved very locally at places of weakness. Faults and buckles offset and deformed the already existing folds.

The folded structure between Barrier South Shaft and the De Bavay Fault is much better understood than it is either south or north of these limits. Therefore discussion, insofar as it is concerned with folds between the Hanging Wall Basin and the Footwall Basin, is confined to the central portion of the field. Understanding of the structural interpretation here makes possible extension of the interpretation north and south.

In projecting complex structures to unexplored depths of a mile below the surface and to eroded heights of a mile above the surface, as has been done on the cross-sections, very considerable inaccuracies are inevitable. Nevertheless, these cross-sections are not merely uncontrolled "sketches" of what might be. All observations of pitch and dip made on the surface and underground were utilized in their construction. Axial lines for the underwall and overwall of most of the recognizable rock formations in each recognizable fold—more than 50 axial lines in all—drawn in longitudinal projection in such a way as to satisfy all our scattered information, were used to guide the drawing of the cross-sections. Thus each cross-section is consistent with all our pitch-dip-position data for the whole line of lode.

MAJOR FOLDS

General.—From east to west the major folds [15] in this district are: (1) the Broken Hill Basin, (2) the Alma Anticline, (3) the Footwall Basin, (4) the Eastern Anticline, (5) the Eastern Syncline, (6) the Western Anticline, (7) the Hanging Wall Basin, and (8) the Broken Hill Arch (Pl. 1). The main ore-bearing structures are minor folds which embroider the Eastern Anticline (west limb), the Eastern

(15) Items (1), (7), and (8) were named by Andrews and his associates (Andrews *et al.*, 1922) who also recognized the existence of (5) and (6).

Syncline and Western Anticline. All folds, with the possible exception of the Broken Hill Arch, are tight, isoclinal, complex folds with nearly vertical limbs.

BROKEN HILL BASIN.—This large structure, clearly shown on Andrews' maps, is 20 miles long and 4 miles wide. Only a portion of the western rim was mapped by the Central Geological Survey, although a large part of it was examined.

BROKEN HILL ARCH.—West of Beryl Street in Broken Hill, large quartzite beds make their appearance, whereas the amphibolites and granite gneisses found to the east are missing. The latter have been eroded from the broad Broken Hill Arch which embraces the town and extends for some miles westward (Andrews *et al.*, 1922). This structure was not mapped by the Central Geological Survey, nor are its rocks described in this bulletin.

HANGING WALL BASIN.—East of the Broken Hill Arch is a narrow basin whose axial plane lies parallel to and between Argent and Crystal Streets. Its maximum width is about 4,000 feet. Because of lack of outcrops, little is known about this structure south of the municipal boundary. Its undulatory pitch is revealed by outcrops of the Hanging Wall Granite. A major crest in the pitch line occurs opposite the B.H.P. Mine, and a major trough in the pitch line occurs in the vicinity of the De Bavay Fault.

The syncline is cut by the strong Globe-Vauxhall crush zone which runs roughly parallel to its axial plane and along its western rim just inside the Potosi-Footwall Gneiss formation. Movement on the fault appears to have been west side northward, the western rim of the basin (as defined by the Potosi-Footwall Gneiss) having been carried about 2½ miles north of the eastern rim (as defined by the No. 3 Lens ore formation) [16] at the northern extremity of the basin where the two rims (as defined by the same formation) would ordinarily meet. The Consolidated Mine is situated where the No. 3 Lens ore formation at the eastern rim meets the fault, about 4 miles north of Broken Hill. Only a portion of the eastern rim of the Hanging Wall Basin was mapped by the Central Geological Survey.

FOOTWALL BASIN.—Not mentioned by Andrews, but comparable in size to the Hanging Wall Basin, is the Footwall Basin, clearly marked by the Potosi-Footwall Gneiss outcrops east of the line of lode. The nature of its southern continuation south of the Zinc Corporation Mine is in doubt because of lack of outcrops. Its pitch line is roughly parallel to that of the Hanging Wall Basin with a crest opposite the B.H.P. Mine and a trough in the region of the De Bavay Fault. Small minor folds with flattish west dips in Dunstan's Quarry (M.L. 285) indicate strong (but local?) overturning to the east. Most of this basin was mapped in the critical area.

ALMA ANTICLINE.—An anticline between the Footwall Basin and the Broken Hill Basin is a structural necessity. Our mapping suggests that this anticline is an extremely tightly sheared one in which rock formations are greatly attenuated, some being eliminated completely for considerable distances. The structure is about 800 feet wide. The Consols Amphibolites give eloquent testimony to the tight folding, although many details are obscure. Single limbs are not everywhere distinguishable from double limbs. The behaviour of pitch lines could not be satisfactorily determined. The gneisses and quartzites in Eyre and Piper Streets in Alma (South Broken Hill) west of Foulke's Ridge have not been assigned formation names with any confidence. No. 3 Lens ore formation should probably either crop out here, or approach fairly close to the surface, but it has not been recognized. Some small "garnet quartzite" outcrops are the only signs of mineralization. A large portion of the Alma Anticline was mapped in the critical area.

WESTERN ANTICLINE, EASTERN SYNCLINE, AND EASTERN ANTICLINE.—The dominantly anticlinal region between the Hanging Wall Basin and the Footwall Basin,

(16) The Potosi-Footwall formation has not been recognized where it would form the eastern rim in this vicinity. Assuming a position for it on the basis of stratigraphy, the apparent horizontal component of fault movement at this place is about 3 miles, although the actual movement may be considerably less. The vertical component of movement is not known, but is believed to be very small in comparison with the horizontal component.

about 1,200 feet wide, is extremely complex. Its major structural elements—the Western Anticline, Eastern Syncline, and Eastern Anticline—are each made up of many smaller folds (17) which are important because they contain the main Broken Hill orebodies. It is not, however, the number of minor folds so much as the differences in their shape and attitude from place to place that make their study so difficult.

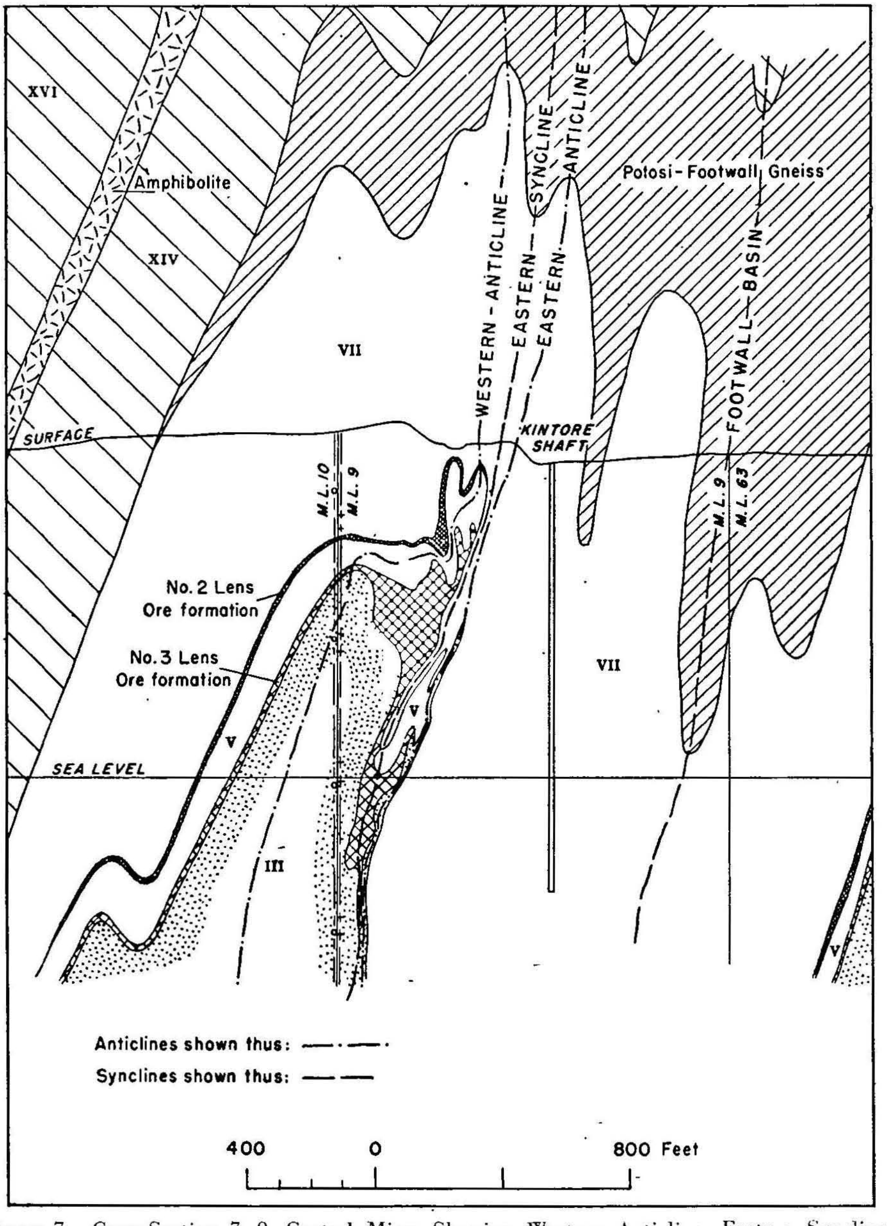

Figure 7.—Cross-Section 7 - 8, Central Mine, Showing Western Anticline, Eastern Syncline, and Eastern Anticline.

(17) In turn made up of still smaller folds, and so on down to wrinkles of microscopic dimensions. The other major folds already discussed are similar in this respect but have not been analysed in such detail.

Figures 7 to 12 inclusive, a series of cross-sections at intervals from south to north, illustrate the relationship of the three major structural elements under discussion. Figure 7, a cross-section through the Central Mine, shows the Western Anticline to be considerably elevated with respect to the Eastern Anticline and the Eastern Syncline to be greatly depressed with respect to either anticline.

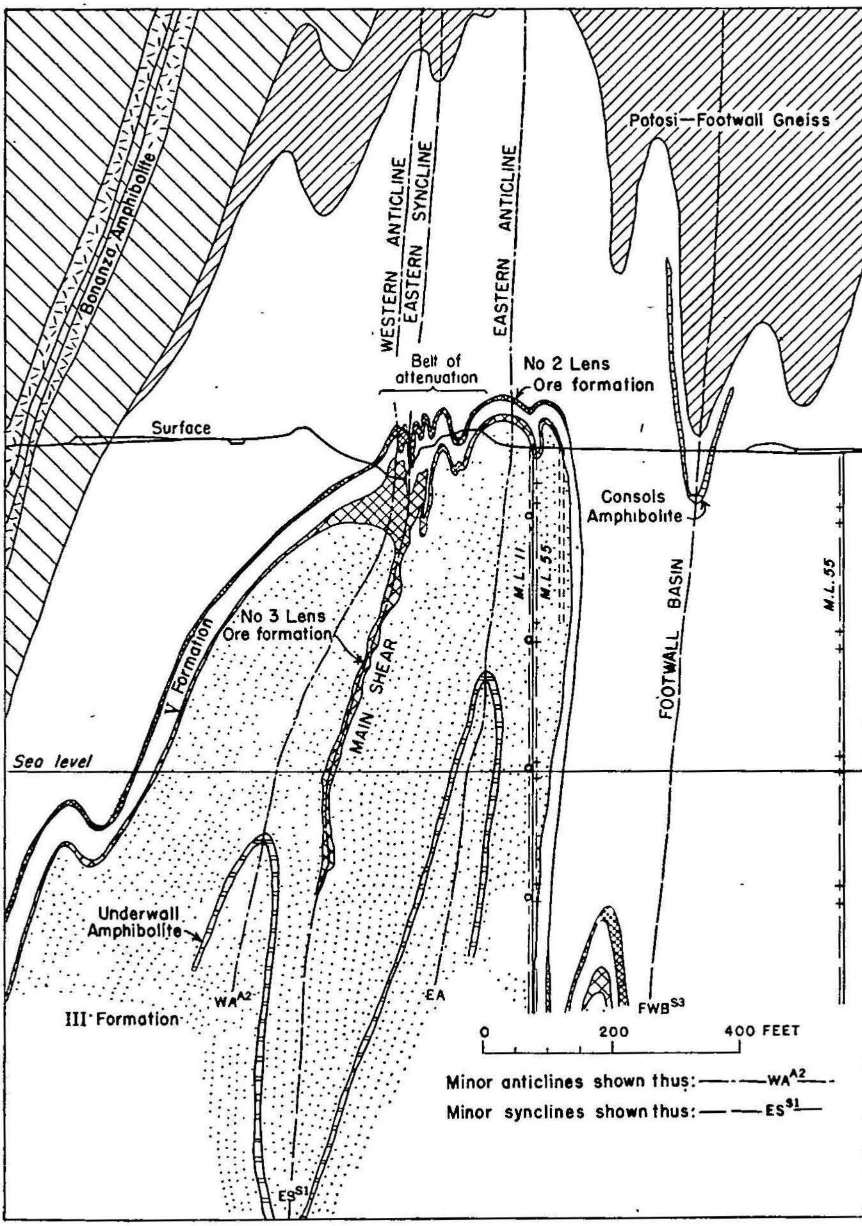

Figure 8.—Cross-Section, B.H.P. Mine (3,520), Showing Western Anticline, Eastern Syncline, and Eastern Anticline.

Figure 8, a cross-section through the B.H.P. Mine, reveals a gradual change in the relative positions and shapes of these structures. The Eastern Anticline has moved up with respect to the Western Anticline, and some of the more easterly minor folds of the Eastern Anticline (presumably too deep to show in Figure 7) have rolled up into the nose of that structure and made it broader. The Eastern Syncline is still in part a deep elongated fold.

In Figure 9, a cross-section through the Block 14 Mine, the long attenuated portion of the Eastern Syncline has disappeared; the Eastern Anticline, as defined

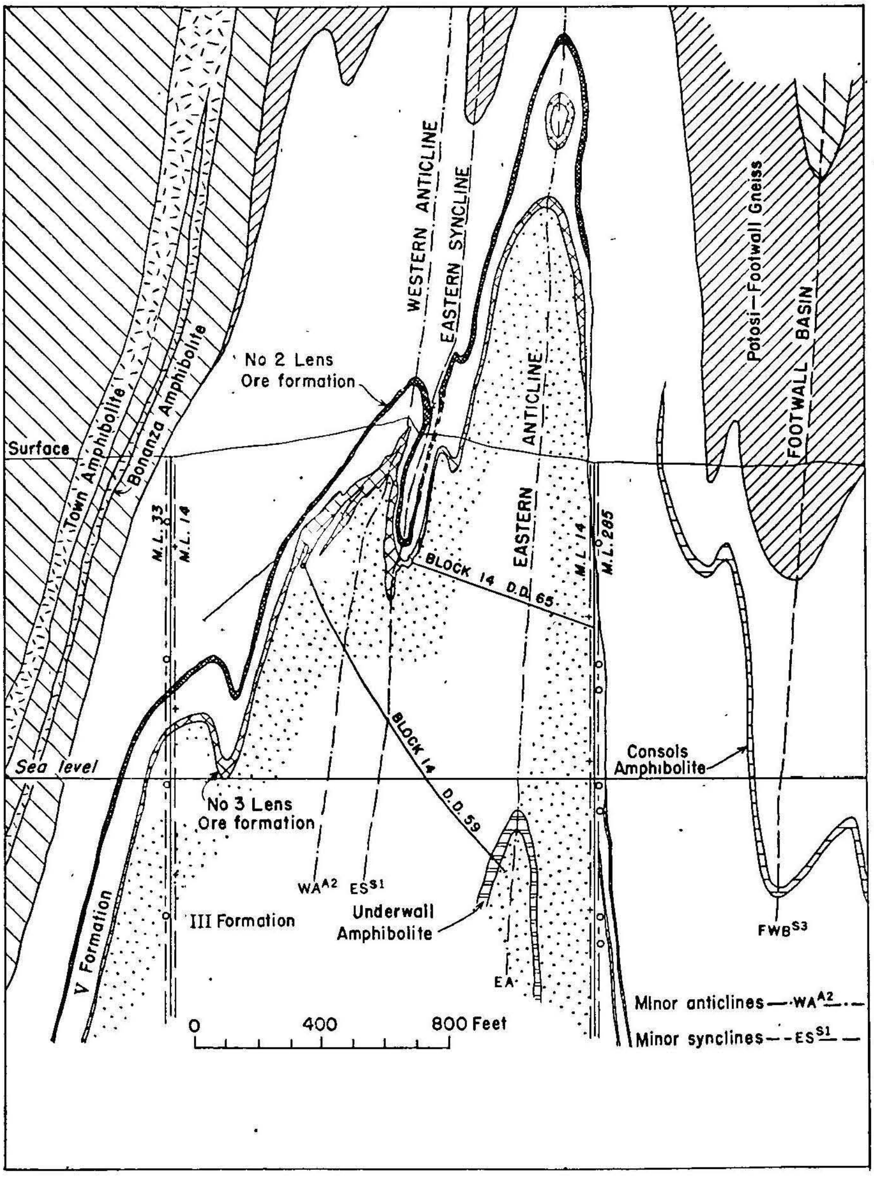

Figure 9.—Cross-Section 7 - 8, Block 14 Mine, Showing Western Anticline, Eastern Syncline, and Eastern Anticline.

by the ore formations, is now considerably higher than the Western Anticline and has been eroded.

Figure 10, a cross-section through the southern part of the British Mine shows the Eastern Syncline moved up with respect to both the Western Anticline and the first prominent synclinal component of the Eastern Anticline. Eastern portions of the Eastern Anticline, however, have continued to roll up and are now well above the Western Anticline.

Figure 11, a cross-section through the northern part of the British Mine, reveals conditions much the same, with the main arch of the Eastern Anticline cut off by the British Fault. The Western Anticline has virtually disappeared as an ore-bearing structure.

Figure 12 is a cross-section through the Junction and North Mine. Precise correlations of small structures across the British Fault are impossible. The Junction, Junction North, and North Mine ore-bearing folds are, however, believed to be the same minor folds that carry ore in the Thompson section of the British Mine. According to this interpretation, the Eastern Anticline has been elevated so far above the other structures and has become such a large fold that the Western Anticline and Eastern Syncline are now no more than small minor folds on its western leg. According to a second possible interpretation—that the ore-bearing structures are more easterly minor folds on the west leg of the Eastern Anticline than any appearing in the British Mine—the Western Anticline, Eastern Syncline (and other mineralized folds there) have either died out or exist in depth down the east leg of the Eastern Anticline as minor folds of that structure. In the discussion of the British Fault, reasons are advanced against this interpretation.

Figure 13 illustrates in a highly simplified way the kind of changes just described. (In this sketch each structure is assumed to have a constant pitch. Actually this is not true.)

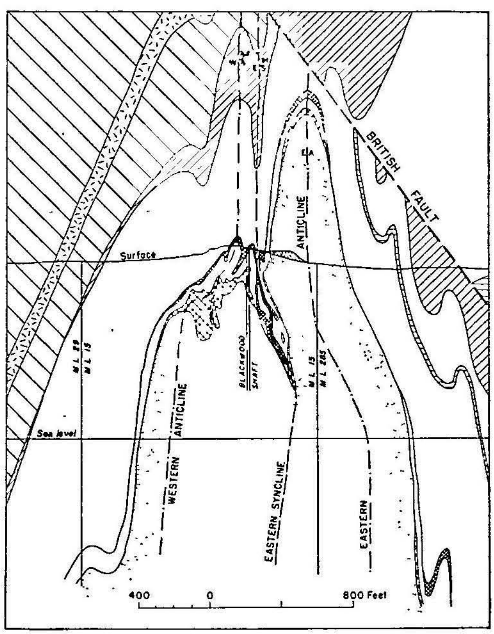

Figure 10.—Cross-Section, Southern Part of British Mine (British 430 N), showing Western Anticline, Eastern Syncline, and Eastern Anticline.

The chief evidence of the validity of this generalized interpretation is as follows:

1. The Western Anticline and Eastern Syncline are proved from the Zinc Corporation to the British Fault by abundant structural and stratigraphic data.

2. No. 2 Lens ore formation where it forms the eastern limb of the Eastern Syncline can be seen on the South Mine 1,630-foot level to turn over eastward into an anticline and to dive underfoot. This interpretation is the only one that appears at all rational in this mine, the Zinc Corporation, the Central Mine, and the southern part of the B.H.P. Mine. The low-grade ore cropping out east of Wigg Shaft in the vicinity of Section 37 of the B.H.P. Mine can be accommodated satisfactorily only by this interpretation.

3. The old North Central Extended Shaft in M.L. 55 near the M.L. 11 boundary was sunk 700 feet before 1901. Old reports describe iron- and manganese-stained lode material containing specks of silver chloride and silver bromide, but no payable lode. Another old shaft near the west boundary of M.L. 79 is shown on Jacquet's map (Jacquet, 1894). A third, near the south-west corner of M.L. 80 put down in 1889 by the Broken Hill Central Blocks Company, is reported to have struck "highly mineralized country." (These shafts are now covered by mine dumps). Probably they encountered poorly mineralized No. 3 Lens ore formation where it forms the eastern limb of the Eastern Anticline.

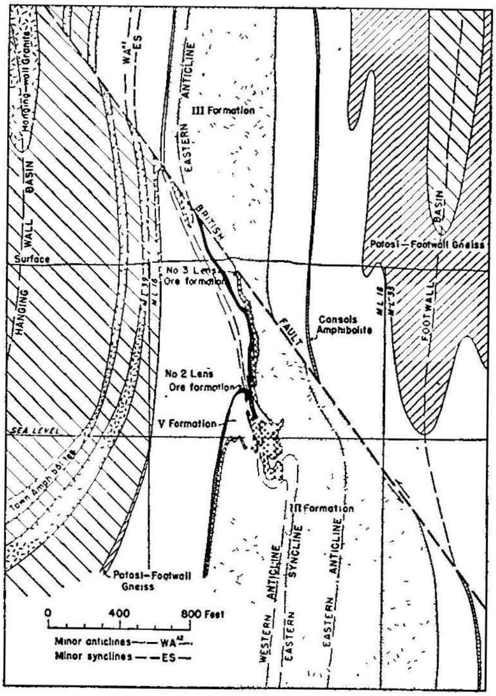

Figure 11.—Cross-Section, Northern Part of British Mine (British 1700 N), Showing Western Anticline, Eastern Syncline, and Eastern Anticline.

4. Just as, in the southern part of the line of lode it is very difficult to interpret the ore horizons as extending upward after they emerge from the Eastern Syncline, so is it difficult to interpret them as doing anything else in the British, Junction, Junction North, and North Mines. Minor folds in both walls of the orebodies in these mines suggest an anticline to the east; and in the British Mine two strands of ore corresponding to No. 2 and No. 3 Lens ore formations extend upward.

5. The coarse garnet gneiss between the lodes and the Potosi-Footwall Gneiss east of the North Mine resembles the coarse garnet gneiss seen underground below No. 3 Lens ore formation.

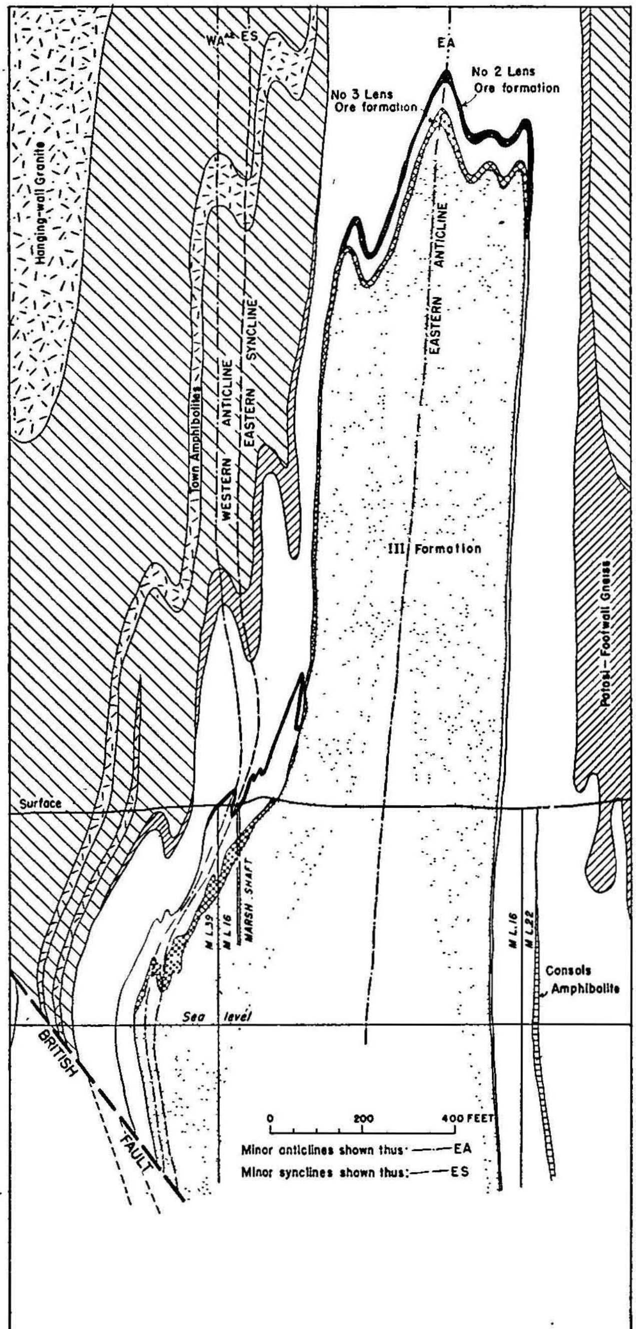

Figure 12.—Cross Section, Junction Mine (British 3100 N), Showing Western Anticline, Eastern Syncline, and Eastern Anticline.

6. The correlation of the Footwall Gneiss with the Potosi Gneiss as a single stratigraphic horizon (see "Stratigraphy") has much to recommend it. The lode horizons definitely underlie the Potosi Gneiss in the Western Anticline at the North Mine, and they also underlie the Footwall Gneiss in the Footwall Basin at the South Mine.

7. On the surface, the Potosi-Footwall Gneiss in the Footwall Basin is 1,100 feet east of the North Mine orebodies, 900 feet east of the Block 14 orebodies, 250 feet east of the Central Mine orebodies, and almost touches the Zinc Corporation orebodies. This steady convergence southward alone strongly suggests that the intervening Eastern Anticline is pitching south (relative to the orebodies) and that it is probably becoming a progressively smaller feature on the east leg of the Western Anticline the farther south it extends.

8. The Hanging Wall Granite in the Hanging Wall Basin, on the contrary, converges on the lode northward, a fact suggesting that the Western Anticline, a prominent structure at the south end, is pitching north (relative to both the Hanging Wall Basin and Eastern Anticline) and is becoming a progressively smaller feature on the west limb of the Eastern Anticline the farther north it extends.

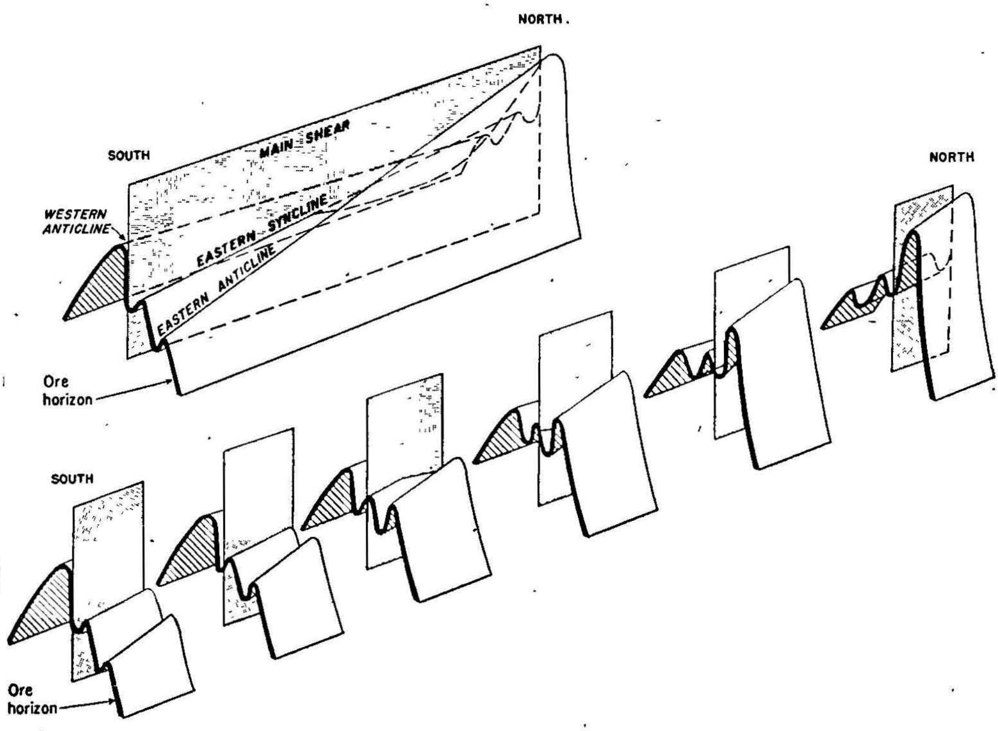

Figure 13.—Simplified Illustration of Western Anticline, Eastern Syncline, Eastern Anticline, and Main Shear Relationship.

9. The transition from dominant Western Anticline with subordinate Eastern Anticline to dominant Eastern Anticline with subordinate Western Anticline is indicated to be gradual and relatively harmonious by the detailed behaviour of minor folds. (See discussion of "Ore-bearing Folds"; and various longitudinal sections showing pitch lines.)

Composite Behaviour of Major Folds.—The composite behaviour of major folds is summarized on Plate 1.

BELT OF ATTENUATION AND MAIN SHEAR.—The central portion of the field between the Hanging Wall Basin and Footwall Basin is a complex anticline with dominant but not continuous south pitch. When attention is focussed on the ore-bearing formations, the Eastern Syncline appears as a deep crease dividing this complex anticline into the Western Anticline and the Eastern Anticline, but a crease that starts at the north end of the field on the west side of the large anticline and ends up at the south end of the field on the east side of the large anticline, crossing the larger structure at a very acute angle (Fig. 13).

The tightest folding and greatest stretching of the ore-bearing formations anywhere within the complex anticlinal region is obviously confined to a narrow belt about 150 feet wide which coincides in a general way with the crease that is the Eastern Syncline. Actually the belt extends chiefly along the east side of the Western Anticline and frequently, but not invariably, includes the Eastern Syncline. At the north end of the field, where the Eastern Syncline has lost its significance, the belt occupies the west limb of the Eastern Anticline. The belt has no clearly defined limits but almost any cross-section of the lodes reveals that the westernmost minor folds are fairly open whereas the minor folds near the footwall of the lodes are tight and often greatly elongated. This belt of most intense plastic deformation is of supreme importance. The Broken Hill orebodies were localized where this structure intersected the favourable beds of No. 2 Lens and No. 3 Lens ore formations. Whatever minor folds happen to be involved in this belt are greatly attenuated although the same minor folds elsewhere may be very open.

The "main shear" occurs within the belt of attenuation. The narrow, steep, tabular ore above the "broad lodes" in the Zinc Corporation and South Mines, which is termed the "narrow lode," is structurally a smeared-out anticline of No. 2 Lens ore formation. This structure, the long, downward-projecting, and greatly attenuated syncline of No. 3 Lens ore ("L" syncline) in the Central Mine below the "broad lodes," and the stretched ore-bearing eastern limb which connects the Western Anticline with the Eastern Syncline in the South Mine are all manifestations of the main shear. Where later faulting along the structure has not schisted the rock, the main shear would be very difficult to recognize had mineralization not made it conspicuous. Along the footwall side of the North Mine orebodies, and extending above them to the surface, is a similar plastic shear along which very considerable rock movements must have occurred; yet here the shear is not conspicuously marked by mineralization, and it is not so easily identified.

The main shear is not, however, one continuous plane throughout the line of lode. By "main shear" is meant merely the most conspicuous (plastic) shear plane at any place within the belt of attenuation, whether or not it has been accentuated by later shearing during the period of faulting and buckling. Actually the main shear occupies at least three planes offset *en echelon* between the Zinc Corporation and the British Fault. The main shear thus coincides first with one part of the folded structure and then with another. For example, from about McBryde Shaft in the B.H.P. Company property to some unknown distance into the South Mine, No. 3 Lens ore formation is stretched downward into a very tight syncline ("L" syncline). A short distance north of McBryde Shaft, however, "L" syncline rapidly recedes upwards, and "M" syncline suddenly becomes the dominating structure. "M" syncline assumes prominence because a new shear plane (the "East Vein"), offset *en echelon* to the east and north and coinciding with "M" syncline, takes up the burden of most intense movement at the place where the old main shear coinciding with "L" syncline ceases to be the locus of such movement. The new main shear continues as "M" syncline, but with no such extreme elongation on it as heretofore until the British Mine is reached. In the vicinity of Howell Shaft the main shear takes another abrupt jump to the east and continues northward as the British Mine "East Vein." "M" syncline is abandoned, the new main shear coinciding now with "P" syncline. So far the discussion has been confined to the relationship existing between the main shear and minor folds involving the underwall of No. 3 Lens ore formation. The cross-sections show that the main shear does not continue up the axial plane of any minor fold and so occupy the same structural position at say the overwall of No. 3 Lens ore formation or the underwall of No. 2 Lens ore formation. Instead it cuts through various minor folds to which it is inclined at an acute angle. The transgression of structures by the main shear is much more abrupt vertically than it is along the strike.

The continuation of the belt of attenuation southward is in doubt, probably chiefly because of a lack of outcrops. The faulted segment of the belt north of the De Bavay Fault has not been recognized with certainty because of the very complex geology in this region. Over what distance north and south the twisting movement between Western Anticline and Eastern Anticline was effective in producing the belt of attenuation cannot be determined. This particular strain must have been very local in a regional sense. Other similar belts of attenuation which may (or may not) have served as feeder channels through which ore solutions were conducted to favourable formations undoubtedly exist, but their recognition from surface outcrops is a different matter.

Several places have been suggested to the mining companies as possible new belts of attenuation which may intersect No. 2 Lens and No. 3 Lens ore formations.

ORE-BEARING FOLDS

METHOD OF ANALYSIS [18] AND DEFINITION OF TERMS.—The ore-bearing folds, which are minor folds making up the Eastern Syncline and portions of both the Western Anticline and Eastern Anticline, have been analyzed in great detail. (1) All exposures were mapped for structural features, rock types, and ore mineralogy, and all drill core was logged for the same features. (Mapping was done on a scale of 30 feet, 40 feet, or 60 feet to the inch.) (2) These data, together with pertinent assay data, were plotted on 100 scale cross-sections and plans, the formations were coloured with distinctive colours, and structural outlines where data permitted. (3) Lines were drawn on plans and cross-sections to show the traces of the axial planes of the separate folds, and these were adjusted on plans and cross-sections to give agreement. The earlier structural picture was revised as required. (4) Plotted in longitudinal projection were all known "axial line points"—the points on plans and sections where the axial planes cut the underwall and overwall of ore-bearing formations. By connecting these points, longitudinal projections of axial lines were obtained. Plans and cross-sections were again revised where necessary and permissible to obtain agreement with the requirements of the longitudinal projection. (5) The axial lines were then plotted in plan projection in much the same manner as described for the longitudinal projection. (6) Using chiefly the longitudinal and plan projections of axial lines, the structures were projected beyond present mine workings where the need arose. (7) Each axial plane and axial line was given a temporary number. (8) Finally structures were correlated according to the best evidence and a consistent numbering system was adopted for axial planes on axial lines.

The term "first-order-fold" describes an ordinary fold, however complex, whose axial plane has not been notably deformed by a continuation of the folding movements, though it may be deformed by post-folding buckles or faults. "Second-order-fold" describes a fold whose axial plane has been folded by a continuation of the same rock movements that produced the first-order fold. A second-order fold is thus a folded fold. It is not always possible to distinguish between the two;

(18) This procedure was not followed in the orderly manner here suggested. Most places were re-mapped at least once (some as many as three times), and the structural interpretation was constantly revised as knowledge and technique improved. In a final review the method of steps (3) to (8) was re-applied to the whole line of lode.

they ordinarily have approximately the same pitch. Post-folding buckles, on the other hand, normally have very steep pitch and can usually be distinguished from folds except where the latter also have steep pitch.

Tabulation of Minor Folds.—Minor ore-bearing folds were tabulated and correlated with major folds on two charts. The system of notation used is as follows:

(1) Axial planes of anticlines are numbered from west to east with Arabic numerals north of the British Fault and with Roman numerals elsewhere, and are portrayed on plans and cross-sections thus — · — · — · —

(2) Axial planes of synclines are lettered from west to east with small letters north of the British Fault and with capital letters elsewhere, and are shown on plans and cross-sections thus - - - - - -

(3) Points on axial lines are designated by the letter or number of the axial plane to which they belong, by an "O" or a "U" according to whether they are overwall or underwall points, and by a "2," or a "3," depending on whether they are referred to No. 2 Lens ore formation or No. 3 Lens ore formation. Thus IXU3 is a point on the underwall of No. 3 Lens ore formation in No. IX anticline.

The discussion accompanying each album of 100 scale plans supplied to the companies called attention to the more conspicuous uncertainties in the interpretation.

Plate 6, a longitudinal projection of some of the axial lines in the South Mine, illustrates the character of the axial-line study of pitch.

OTHER FOLDS

Numerous minor folds which make up the major folds are portrayed on the various plans and cross-sections. For example, the Footwall Basin is composed of at least the following minor synclines and anticlines: FWB^{s1}, FWB^{a1}, FWB^{s2}, FWB^{a2}, FWB^{s3}. FWB^{a3}, FEB^{s4}.

Locally a minor fold becomes so big as to be in reality a new major fold—the Imperial Ridge Syncline, for example, at Imperial Ridge. This structure farther south is merely a small minor fold on the west flank of the Eastern Anticline. Similarly, the minor fold FWB^{a3} is believed to grow progressively larger south of the Zinc Corporation New Main (Freeman) Shaft until it becomes a major structure and is recognized as the Alma Anticline, whereas the fold comprising the Alma Anticline farther north, AA^{a1}, has apparently grown smaller and become merely a minor fold on the flank of the Alma Anticline.

MECHANICS OF FOLDING

Plastic Folds and Plastic Shears.—Projections and geological interpretations of the intricate ore-bearing folds will be made with greater confidence and more accuracy if the nature of the folds and their method of formation is understood. The shapes of the folds reveal that the rocks of the district acted under compression like soft plastic materials. Rock was squeezed away from the places of greatest pressure such as the limbs of folds and flowed into places of least pressure such as the crests and troughs of folds. Such rock flowage can be accomplished in rocks like granites and gabbros only with the aid of extensive recrystallization. The metamorphic minerals of the gneisses are minerals stable at high temperatures and great pressures characteristic of great depth in the earth's crust. It is not unlikely that these rocks were overlain by from 10 to 20 miles of rock at the time of folding.

Places like the belt of attenuation where the greatest escape of material took place can be regarded as "shear zones" provided that *plastic* shear rather than granulation is understood. The rock in plastic shear zones need not look any more broken or schisted than elsewhere. Frequently it does, but only because of later fault movements in these old zones of weakness.

Main Shear and Belt of Attenuation.—The development of the belt of attenuation between the Eastern and Western Anticlines can be readily explained if the relationship between these two folds is clearly understood (see discussion under "Major Folds"). Figure 13 and Plate 1 clearly indicate the strong twisting movement that must have occurred during folding to produce these two divergent anticlines. This movement was in large measure confined to the steep narrow belt, between the two structures, that is now recognized as the belt of attenuation.

The axis of rotation (Pl. 1) occupies the region between Weatherly Shaft in M.L. 11 and Wilson Shaft in M.L. 13 of the B.H.P. Mine. No satisfactory correlation can be made between the prominence of the main shear as an ore-bearing structure and its position relative to the axis of twisting. At Weatherly Shaft the main shear and belt of attenuation are well developed. Just north of the axis of rotation, however, between Dickinson Shaft and the British Mine where the displacement was small, the belt of attenuation and main shear are least well developed. In the Zinc Corporation at the south end of the field, on the other hand, where one direction of maximum movement (with east side down) existed, the belt of attenuation and the main shear find their best development. Likewise in the North Mine at the north end of the field where the other direction of maximum movement (with west side down) existed, the belt of attenuation is also well developed and a main shear —though virtually unmineralized—is clearly in evidence.

An outstanding characteristic of the footwall of the main shear at the southern end of the field is the rather frequent occurrence of nearly vertical, somewhat rounded, hollows and ridges in the contact between ore and wallrock. They vary in size but are characteristically 2 to 5 feet from hollow to hollow and 20 feet or more long. Some of these are almost certainly "buckles" due to post-folding movements and are described as such. It may well be, however, that many of these ridges and hollows constitute mullion structure produced by the essentially vertical movement on the main shear during folding as a result of the twisting motion which here depressed the Eastern Anticline and elevated the Western Anticline.

The main shear in the southern part of the field appears to have been essentially vertical in cross-section (as were the axial planes of folds) until a very late stage

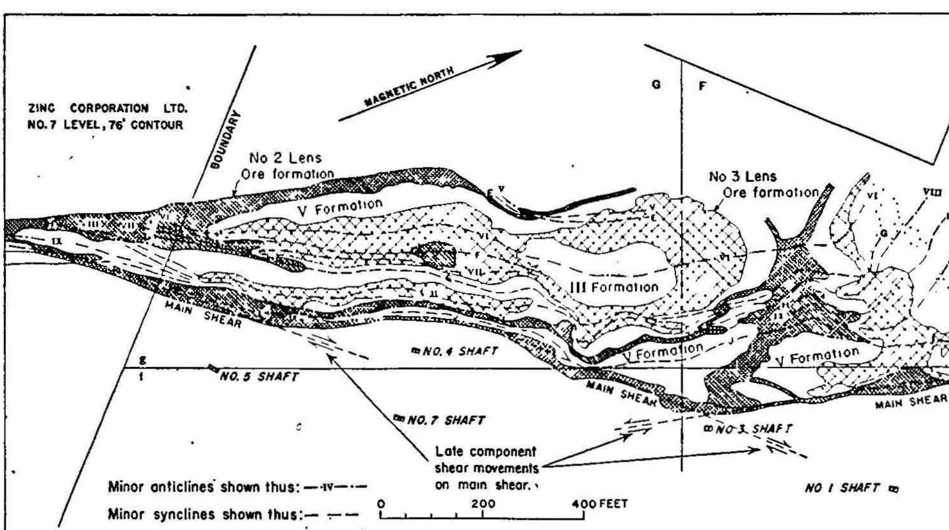

Figure 14.—South Mine 1070 Level and Portion of Zinc Corporation No. 7 Level 76 Ft. Contour.

in the folding. Locally, however, during the final compression, two sets of shear planes appear to have developed at an acute angle to the old direction, and overthrusting movements on these occurred. Some second-order folds were doubtless developed at the same time by the same movements (Figs. 14, 29). The perfect plasticity that characterized the rocks during the major part of the folding period (during which the relief was vertical and no true shear planes were developed) was apparently lessened in the latter stages. Further attempts to elongate vertically could no longer be accomplished wholly by plastic flow but were assisted by movement along two sets of shear planes as already described. Possibly belonging to the east-dipping shear direction are the "East Vein" shears of the B.H.P. Company and British Mines (Figs. 15, 16.) Each structure was obviously the locus of plastic shearing (and probably also of faulting) after the main folding pattern was already established.

RELATION OF MINOR FOLDS TO MAJOR FOLDS AND TO BELT OF ATTENUATION. —Casual inspection of successive cross-sections of the orebodies from the Zinc Corporation to the British Mine reveals a rough constancy of fold pattern wherein the Western Anticline and Eastern Syncline are ever present although changing in shape from place to place. Detailed analysis of the small minor folds that make up the Western Anticline has, however, revealed a relationship between minor folds and major folds which, to our knowledge, has never been described in geological literature.

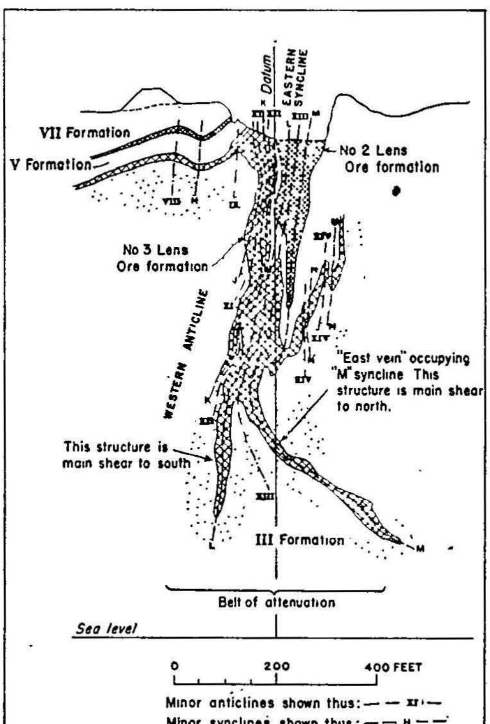

Figure 15.—B.P.H. Section No. 35, Showing 'East Vein."

Consider Figures 17 to 22 inclusive in their numerical order, i.e. from north to south in the direction of predominant pitch. Watch first axial line points VIIIU3 and VIIIO3. These at first occupy a small wrinkle out on the western limb of the Western Anticline. Southward, these points progressively cross over the crest of the Western Anticline and migrate down the eastern side of the main arch until they come within the influence of the belt of attenuation. Suddenly the anticline changes from a mere wrinkle to a long attenuated structure. Now watch points GU3, JU3, XIIO3, and others. The same spiralling form of migration up, over, and down from west to east is shown by each minor fold as it progresses southward; and each in turn may apparently begin as a small wrinkle which assumes sudden prominence as it enters the belt of attenuation. In the case of Anticline XII, there is a strong suggestion that it passed through the main shear and emerged as a diminished structure on the eastern side, although exploration has not yet gone deep enough to permit a decisive statement. Careful search will reveal similar, if not so striking, examples of migration of minor folds in the cross-sections of the other mines.

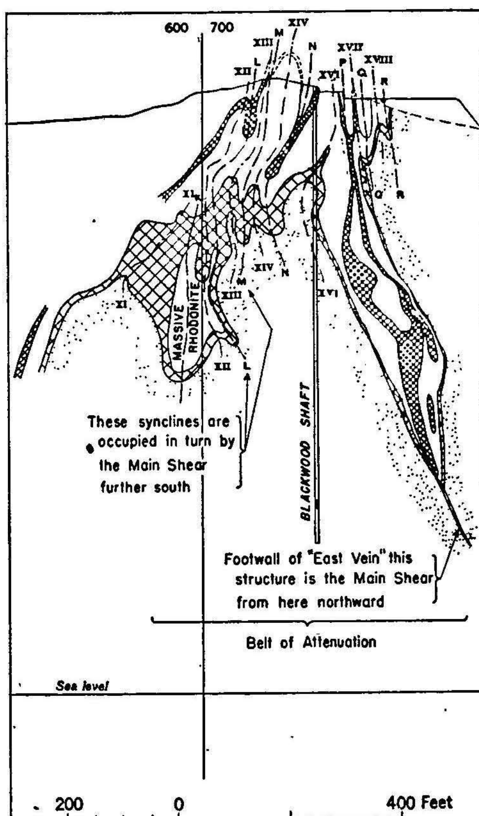

Figure 16.—British Mine Section 430, Showing "East Vein."

Two large charts which correlate major and minor folds and show diagrammatically the angular relationship between minor and major folds existing at the underwall of No. 3 Lens ore formation and at the overwall of No. 2 Lens ore formation for the whole line of lode—included in the report by Gustafson (1939) but not in this bulletin—indicate the considerable extent to which the transgression of minor structures by the belt of attenuation is accomplished by sudden jumps rather than by progressive angular encroachment. They also reveal that although more and more easterly minor anticlines occupy the highest place in the Western Anticline as one goes north, there are numerous small setbacks during this change. To some extent second-order folding is responsible for these setbacks.

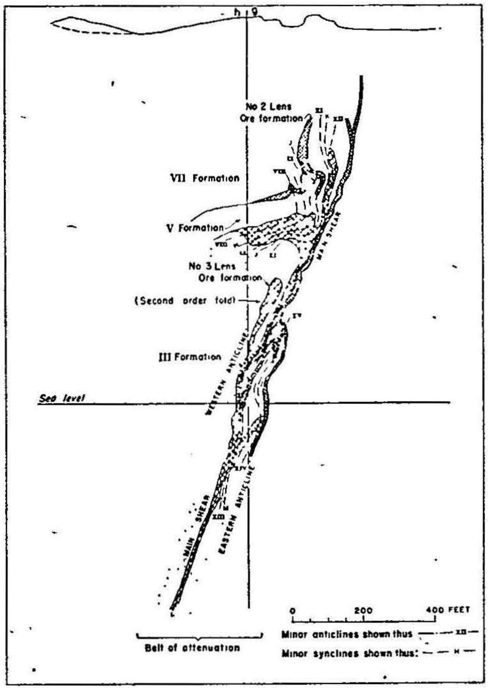

Figure 17.—South Mine, Section B2B3.

This migratory character of "minor folds" in relation to "major folds" is also possessed by the "major folds" in relation to folds of the next higher degree of magnitude, as indicated by the relative behaviour of the Western Anticline, Eastern Syncline and Eastern Anticline discussed under "Major Folds" (Figs. 13, 23). One explanation of this angular relationship is: (a) the Eastern Syncline developed as an indentation at the top of a large anticline very early in folding; (b) as squeezing continued, because of torsional stress, the eastern half of the anticline (Eastern Anticline) rolled up into a large fold at the northern end of the field whereas the western half (Western Anticline) developed into the major structure to the south; (c) thus the early syncline indentation maintained its identity throughout folding, serving as a locus of rotational plastic shear and now being identified as the belt of attenuation.

Second-order Folds.—The distribution and orientation of local stresses within the Western Anticline and Eastern Syncline (including the belt of attenuation) must have been not only a very complex but a constantly changing system. Certain elements can, however, be analyzed.

In the discussion of "The Main Shear and Belt of Attenuation," it was postulated that, at a late stage in folding, vertical relief was accomplished with the aid of two sets of plastic shear planes. Outside the belt of attenuation, the rock movement during this late stage was one of broader warping or second-order folding rather than of plastic shearing confined to any single plane. Nevertheless, two directions of movement comparable and probably related to the two plastic shear directions are indicated by the second-order folds (Figs. 24-28). The commonest and largest second-order folds are those indicating "west side up"; those less common and generally smaller indicate "east side up."

Not all second-order folds, however, can be quite satisfactorily related to the very late stage of folding during which the two plastic shear planes operated. For example, the important second-order fold in "L" syncline (of No. 3 Lens) in Fig. 26 with its nearly vertical dip may belong to the earlier stage of folding when plastic movement on the main shear occurred, but before that structure was deformed by the younger shears.

CHANGES OF PITCH.—The pitch line of the orebodies in a general way describes a flat arc plunging southward at the Zinc Corporation, northward at the North Mine. Local wobbles and sudden reversals of pitch are frequent. Reference to the various longitudinal sections will show very marked divergence in the pitch lines of both minor folds and major folds.

Changes of pitch of either a single minor fold or of a whole group of folds are fairly common and are extremely important when projecting orebodies. Both the North Mine and the Zinc Corporation are today paying dividends from ground that was obtained at low cost because former holders, through lack of understanding of pitch, were pessimistic about its value.

Pitch changes in the orebodies have been brought about by several influences—

(1) "Normal" changes of pitch unaccompanied by any marked deviations in the axial planes of the folds. The reason for the position of a high place in the

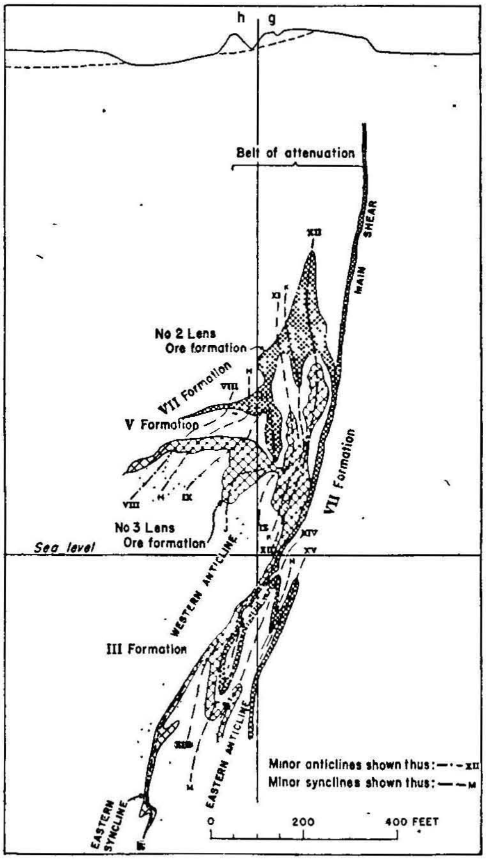

Figure 18.—South Mine, Section D3D4

axial lines due to pitch reversals of this kind is as obscure as the reason for the location of an anticline. No essential differences detected in the shapes of the folds could be regarded as typical of axial line peaks rather than of axial line troughs or of intermediate axial line slopes, nor was any mechanism other than longitudinal

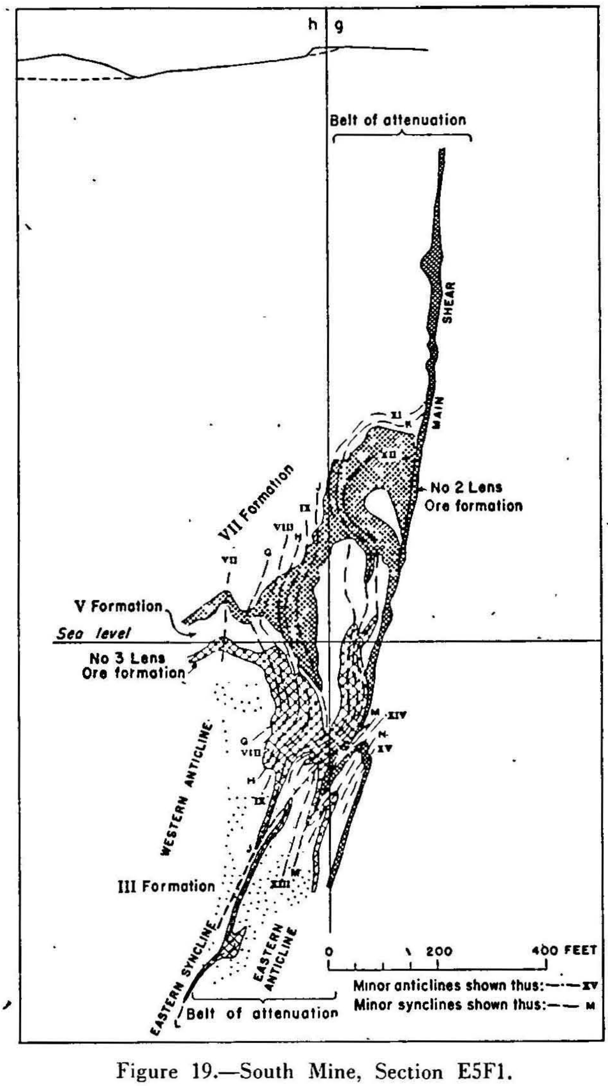

Figure 19.—South Mine, Section E5F1.

bending of the folds suggested for pitch changes of this type. The sudden pitch change at the B.H.P. Company–Block 14 boundary is of this type. So also in part at least are the major pitch changes in the South Mine. Here, however, other influences—buckles and second order folds—complicate the issue.

(2) Pitch changes due to strong local development of second-order folds. The pitch changes in the Central Mine opposite the main shaft are chiefly due to this cause (Fig. 27), although a steep buckle here may be a contributory factor.

(3) Pitch changes due to post-folding deformation. The buckling of the rocks at the South Mine-Zinc Corporation boundary is probably at least partly responsible for the local vertical pitch at this place. Another prominent buckle in the South Mine (at G1 on the 1370 level) appears to have caused the pitch of the more easterly ore-bearing folds to steepen. In the Central Mine opposite the Kintore Shaft and in the British Mine near Howell Shaft, buckles accompany pitch changes. Whether buckling produced these pitch changes or whether buckling was most easily accomplished at places of sudden pitch change is still in doubt.

The most abrupt pitch change along the line of lode, and one of considerable magnitude, is that caused by drag on the British Fault. Figure 29 illustrates a local severe pitch change in the Zinc Corporation Mine.

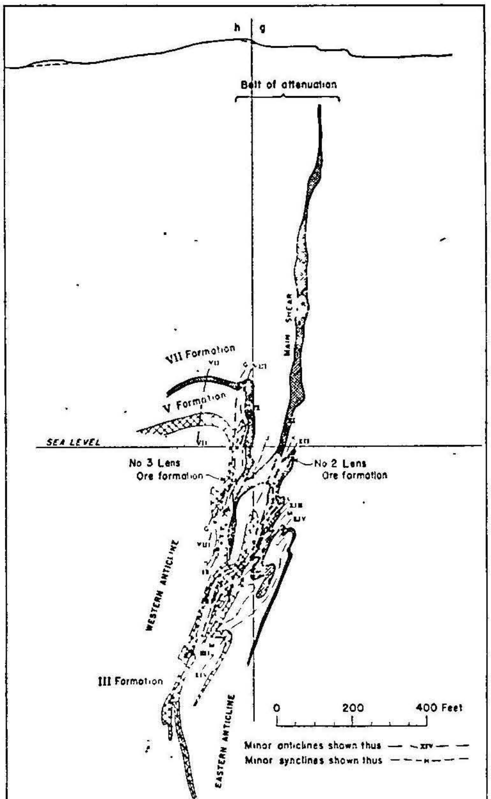

Figure 20.—South Mine, Section G1G2.

Variable Shapes of Different Rocks in the Same Folds.—A striking characteristic of the fold pattern is that different rock layers have totally different shapes in the same folds (Figs. 19-25). What is a very prominent fold in the underwall of No. 3 Lens ore formation may be a smaller fold in the overwall of this same formation. Again, a predominant fold in the underwall of No. 3 Lens ore formation may be a smaller fold in the overwall of No. 2 Lens ore formation. Again, the minor fold that constitutes the main underwall of the Western Anticline as outlined by No. 3 Lens ore formation frequently does not constitute the main underwall of the Western Anticline as outlined by No. 2 Lens ore formation in the same cross-section.

Even more striking is the lack of concordance between the folds as outlined by the zinc lodes and as outlined by the lead lodes in the Zinc Corporation Mine. Consider the long upward-extending limb of zinc lodes (Fig. 29) in relation to the narrow lead lode ("main shear"). It seems fairly certain that the "main shear" here is a tightly smashed anticline of No. 2 Lens ore formation which was replaced by ore to form the "narrow lead lode," yet both the eastern limb and the nose of this anticline are missing in the stratigraphically higher horizons comprising the zinc lodes. On the other hand, No. 3 Lens ore formation does not appear to be involved in this structure at all.

Cross-sections reveal that in general the zinc lode formations were more competent than the lead lode formations; at least they were less complexly crumpled.

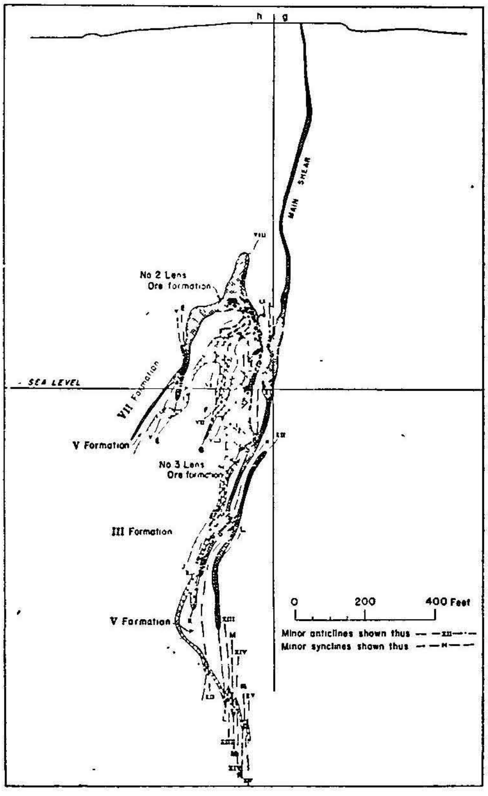

Figure 21.—South Mine, Section H.H2.

Differences in strength of competency do not, however, explain all differences in shape between rock formations, because what appears to be the competent rock in one place appears to be the incompetent rock in another. A partial explanation lies in the angular relationship existing between minor folds and the belt of attenuation which permits the portion of a fold occupied by No. 3 Lens ore formation to be drawn out in the belt of attenuation, whereas the portion of the fold occupied by No. 2 Lens ore formation remains outside the belt of attenuation. In general, however, it appears that local stress differences were relieved locally and immediately by the very nearly perfect plastic flow of whatever rock was nearest.

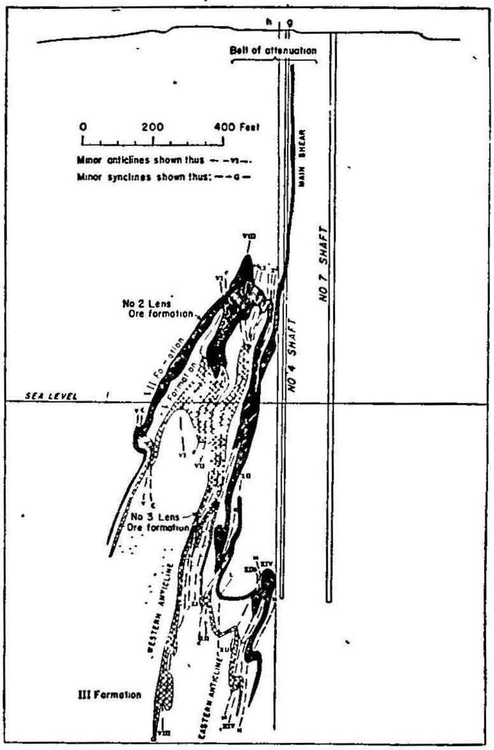

Figure 22.—South Mine Section I_1I_2.

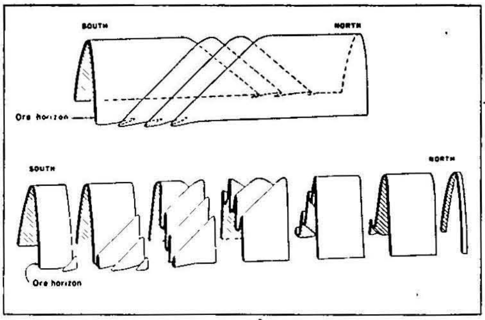

Figure 23.—Simplified Portrayal of Angular Relationships Between Minor and Major Folds in South Mine.

Some structures, for instance that portrayed by Figure 30, with a long attenuated downward-projecting syncline, are difficult to understand mechanically if those rock formations portrayed are alone considered. Very likely, however, the overlying thick and comparatively strong layers of Hanging Wall Granite and

Town Amphibolites determined the shapes of the larger folds, and the softer, more plastic sediments shown in the illustration were forced to accommodate themselves as best they could to the conditions imposed by their more competent neighbors.

Variable Shapes of the Same Rocks in Different Folds.—The extreme variation in amount of packing in the noses of folds makes it impossible to estimate accurately the vertical distance separating any two stratigraphic horizons. The fact that the Potosi-Footwall Gneiss is approximately 1,000 feet above the No. 3 Lens ore formation in the Western Anticline at the North Mine and is nearer 2,000 feet above at the Zinc Corporation illustrates how unreliable such figures are for estimating the distance between two formations at different places in the same structure. They are still more unreliable for estimating the distance in some other structure, as for example the Footwall Basin.

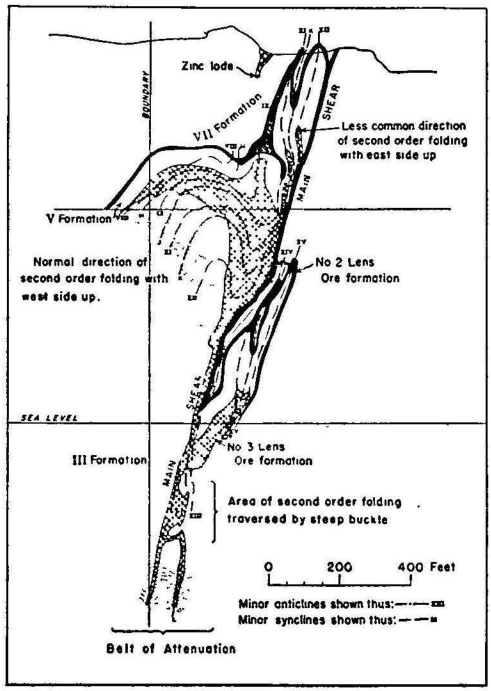

Figure 24.—Central Mine, Section 5-6, Showing Second-Order Folding.

MAJOR FAULTS

General.—The larger faults in the district and the numerous small but important buckles that warp the ore-bearing folds belong to a second main period of rock deformation that is chronologically intermediate between folding and ore deposition. During the folding period, strains permeated the entire body of the rock, and deformation was largely plastic flow through micro-faulting and recrystallization. Gneisses, not schists, were formed. The stresses of the second period found relief very locally and produced well-defined narrow belts of schisted or sharply flexed rock (Pl. 7, fig. 1). Yielding took place more by means of rupture and mechanical shear, although some rock flowage took place in the crush zones once they were established by fracture.

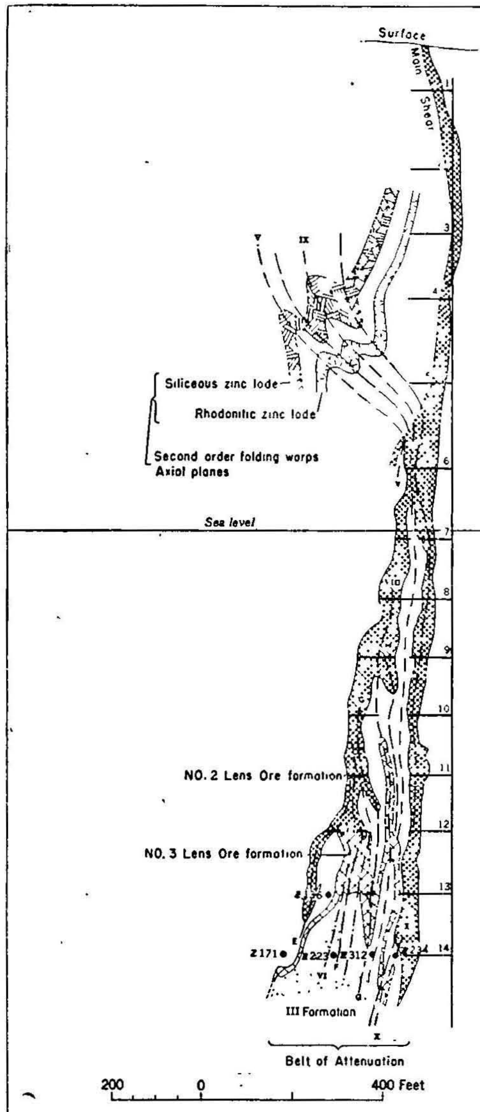

Figure 25.—Zinc Corporation, Section 10, Showing Second-Order Folding.

The pre-ore age of the major faults is established by the following evidence [19]. (1) Although they are jointed and locally traversed by small post-ore faults, the bodies of massive sulphides, lenses of garnet sandstone, and large masses of rhodonite are neither crushed nor conspicuously sheared even where they occupy strong buckles and zones of warp adjacent to the British Fault. (2) The steep bulges of ore on the main shear are the result of ore replacing

(19) Andrews (Andrews *et al.*, 1922, p. 131) regards the faults as older than the lodes, but Kenny (1927, p. 545) believes the De Bavay Fault, at least, to be younger than the lodes. Mr. Kenny in conversation stated that he, like Andrews, considered the garnet-magnetite beds to be lodes, and, because they are clearly older than the fault, presumably the lead lodes are also. Evidence is given elsewhere in this bulletin that these garnet-magnetite beds are not genetically related to the lead lodes.

previously-buckled rock, not the result of ore deformed into these shapes. Yet the buckles were probably the result of the same stresses that caused the faults. (3) Lenses of undeformed sulphides in the Globe-Vauxhall crush zone clearly replace the mica schists. Had these sulphides been present during the development of this strong fault, they would have been greatly deformed. (4) The flat south-pitching buckles or drag folds common north of the British Fault may conceivably be related to the faulting period. In any case they are unquestionably replaced by the ore.

There are two main fault groups and a third subordinate one in the immediate district:

(1) Faults with strike approximating N50°E to N70°E (+); dip 80° south-east. Examples: Globe-Vauxhall crush zone, Morgan's Fault; to the extent that it has participated in the second period of deformation, the main shear may also be classed as a fault of this group. Characteristics: essentially parallel to the strikes (and axial planes) of rock formations; marked by belts of mica schist containing occasional pegmatite lenses. Some strong first-group faults terminate faults of the second group but are nevertheless flexed by them; other smaller ones are offset by faults of the second group. Movement: North-west side has moved north-east; vertical component not known but probably smaller than horizontal component; apparent horizontal offset on Globe-Vauxhall crush zone probably about 3 miles (see footnote in discussion of Hanging Wall Basin.)

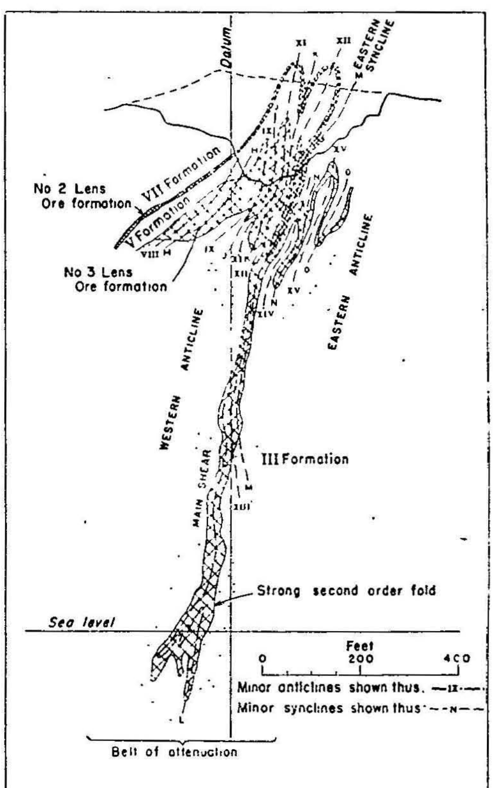

Figure 26.—Broken Hill Proprietary Section 49, Showing Second-Order Folding.

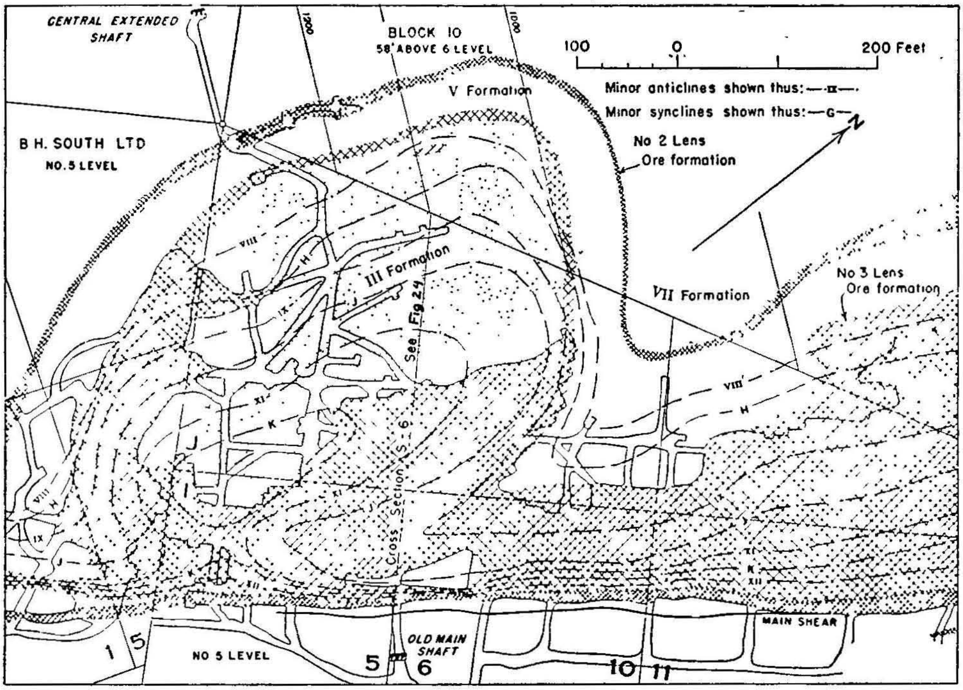

Figure 27.—Portion of Central Mine No. 5 Level, Showing Second-Order Folding.

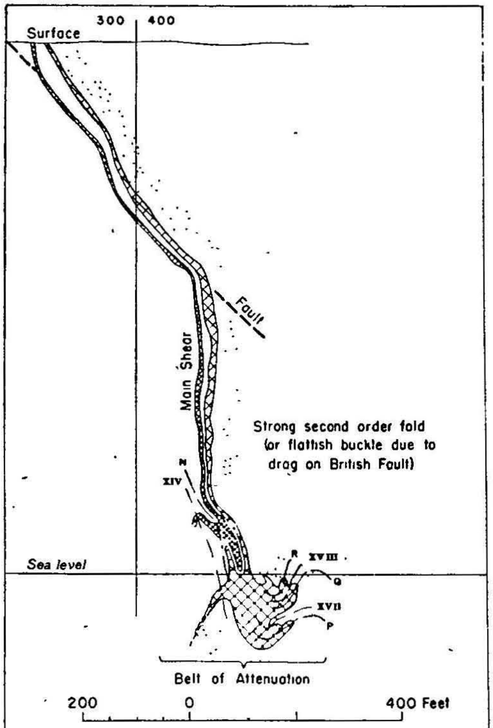

Figure 28.—British Mine, Section 18, Showing Second-Order Folding (Or Flattish Buckle Due to Drag on British Fault.)

(2) Faults with strike approximating N15°W to N-S; dip, steep to east. Examples: De Bavay Fault, British Fault. Characteristics: cut transversely across rock formations warping or off-setting them; marked by belts of mica schist

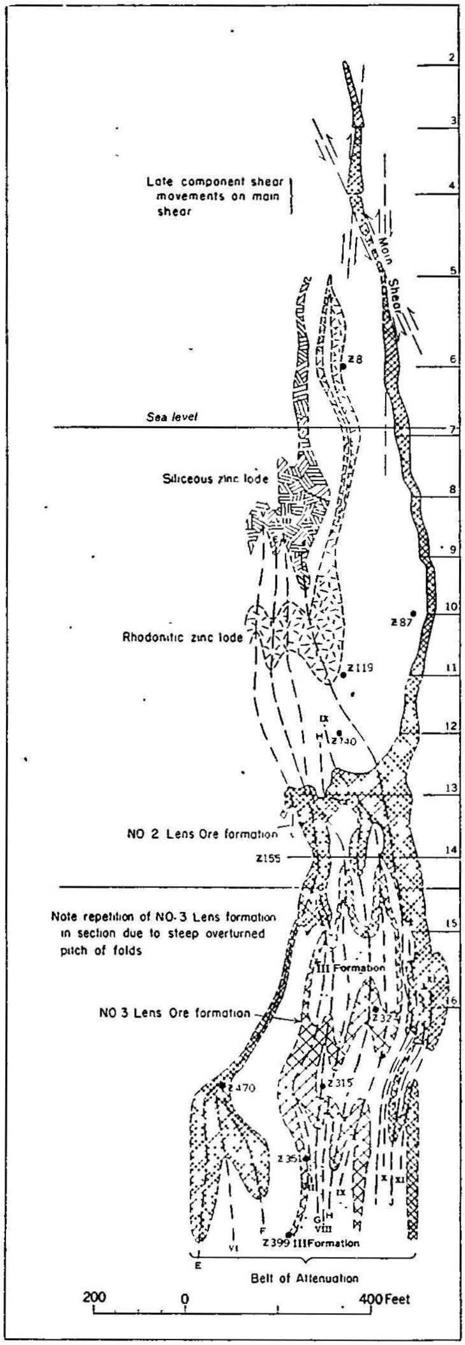

Figure 29.—Zinc Corporation, Section 24 Showing Local Severe Change in Pitch.

containing numerous lenses of pegmatite. Faults may end where they meet and merge with strong faults of the first group warping them slightly, or they may offset smaller faults of the first group. Movement: east side has moved north and up; horizontal offset on De Bavay Fault approximately half a mile.

(3) Faults with strike approximately N25°W to N45°W; dip, north-east at 55°. Examples: numerous small un-named faults cutting across the Potosi-Footwall Gneiss of the Footwall Basin. Characteristics: sharp fractures or zones of shear 1 inch to 10 feet wide, frequently containing pegmatite dykes. The uralite dolerite dykes have a similar strike and may occupy faults of this group. These dykes appear to have been offset by small faults of the first group. Movement: east side has moved north; vertical component not known but probably in most instances east side is the downthrow side. Maximum horizontal offset mapped is about 300 feet.

There are other miscellaneous small faults less easily classified. The Consols vein, for example, occupies a fault of small offset striking NW and dipping flatly SW.

The British Fault and De Bavay Fault, which alone have an important bearing on the immediate problems, are discussed in detail.

BRITISH FAULT.—The British Fault causes a major interruption in the continuity of orebodies between the Thompson Shaft section of the British Mine and the Junction Mine. Where the southern part of the fault crosses the Hanging Wall Granite and Town Amphibolites on the rim of the Broken Hill Basin, where it crosses the Consols Amphibolites in the Alma Anticline, and to a less certain degree where it crosses the Potosi-Footwall Gneiss in the Footwall Basin, the rocks appear to be sharply ruptured and offset by a narrow well-defined fault plane. North and west of here, however, in the region of the lodes, the rocks have been dragged and sheared into their new position across a zone of warp extending several

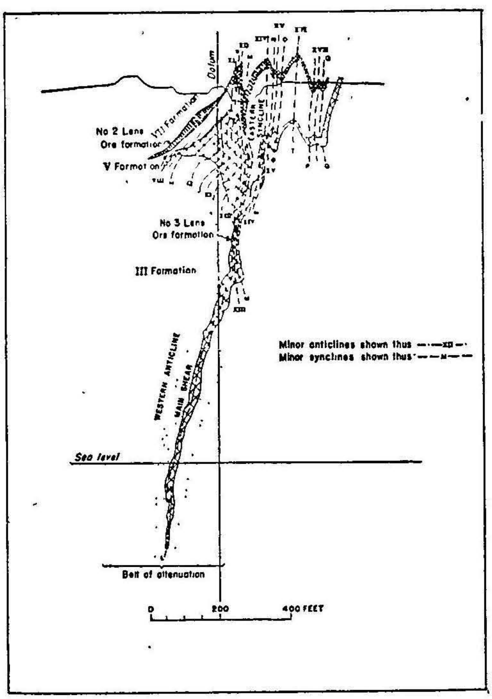

Figure 30.—B.H.P. Section 41, Showing the Main Shear Syncline.

hundred feet on either side of the fault plane. The amount of movement in this warped zone is very important in determining whether the ore-bearing folds in the British Mine are the same as the ore-bearing folds in the Junction Mine. The orebodies of both mines unquestionably belong to the No. 2 and No. 3 Lens ore formations.

The direction of movement is obvious. The Junction side has been thrown north (west on mine co-ordinates) with respect to the British side. The Junction side has also moved up with respect to the British side (a condition revealed by the repetition of the underwall of the Potosi-Footwall Gneiss in the Footwall Basin.) The magnitude of the fault movement cannot be measured directly and must be estimated from circumstantial evidence. That evidence is in the form of facts suggesting that the Junction (Junction North-North Mine) ore-bearing folds are the same as the ore-bearing folds in the Thompson section of the British Mine. Obviously, if the ore-bearing folds in the Junction Mine are *not* the same as those in the British Mine, the Junction folds must be a more easterly group. The evidence that the ore-bearing folds on both sides of the fault are the same is chiefly as follows:

(1) The amount and direction of fault movement necessary to explain the offset in the orebodies is consistent with observed horizontal components of fault offset and also with fault striations which were observed to pitch 67° south-east in the plane of the fault on the surface in M.L. 285. On the other hand, according to the hypothesis that the Junction orebodies occupy more easterly folds, the British Fault can have no appreciable vertical component of movement as is required by the striations noted above. The reappearance of the underwall of the Potosi-Footwall Gneiss at the surface in the Footwall Basin is further evidence of a substantial vertical component of fault movement.

(2) The fault movement required for offsetting the ore-bearing folds also is suitable to explain the dragging of No. 3 Lens synclines "P," "Q," and "R" into anticlinal shapes that has occurred in the British Mine just south of the fault (Fig. 28). (This dragging may, however, be due to second-order folding).

(3) The lack of any outcrops of south-pitching folds south of the British Fault corresponding to the more easterly folds hypothecated for the Junction orebodies supports the contention that the orebodies on the two sides of the fault occupy the same folds.

(4) If the belt of attenuation has jumped from one set of folds to another set at the British Fault, it might be reasoned that the belt of attenuation and the British Fault were both superimposed on the earlier folds at the same time in response to the same stresses; but all other evidence suggests that the belt of attenuation was developed during folding (by plastic deformation) and that the British Fault was developed much later. The crossing of the line of lode by the British Fault at the exact place where the belt of attenuation jumps from one set of folds to another must be pure coincidence then, unless there are two belts of attenuation—one strong south of the fault, the other strong north of the fault. Neither explanation is as satisfactory as our explanation that the orebodies occupy the same belt of attenuation in the same folds on both sides of the fault.

(5) Occupation of the same folds by the ore on two sides of the fault requires a simpler, more easily understood picture of a single governing ore structure.

(6) Small drag folds and minor folds in the British and Junction Mines near the fault tend to substantiate the structure required by the hypothesis of a single group of ore-bearing folds offset by the fault.

(7) Folds in XII Formation corresponding to the ore-bearing folds are evident in the North Mine. There is no evidence of an additional more westerly set of folds in XII Formation such as would be expected if the British ore-bearing folds are more westerly than those of the North Mine.

Correlations of structures across the fault were made according to their shape and proximity to the upward extending plastically sheared east limb of ore. The fault movement obtained by comparing correlated axial line points on both sides of the fault by descriptive geometry gave values as follows (assumed dip 65° 46'):

FAULT PROPERTIES MEASURED	AXIAL LINE POINTS				
	WAO3	ESO3	WAU3	ESU3	RO3 & ro3
Vertical displacement	2032'	1936'	1158'	1019'	2118'
Horizontal displacement	985'	980'	1085'	1149'	1085'
Slip (movement in plane of fault)	2260'	2170'	1598'	1537'	2380'
Offset in 400 scale longitudinal projection	325'S	301'S	320'N	420'	338'
Horizontal offset measured along strike of fault	820'	827'	1190'	1250'	1065-900'
Plunge (true vertical angle)	64½°	63°	47½°	42°	62¾°
Azimuth of plunge	S69°E	S67°E	S33°E	S27°E	S67°E
Pitch (angle in plane of fault)	79°	77½°	52°	46½°	78°
Ratio: $\frac{\text{vertical displacement}}{\text{horizontal displacement}}$	2.48	2.34	0.98	0.82	1.95

There is a fairly wide range of values obtainable depending not so much upon the correlation of structure as upon the assumptions made in projecting structures to the fault plane through the warped zones immediately adjacent to the fault.

Other important properties of the fault are: Strike: average N4°W (magnetic); Dip: variable to the east; averages about 65° 46' according to a contour study of underground information available for about 800 feet below the surface; measured at 81° on the surface in M.L. 285.

De Bavay Fault.—The De Bavay Fault is approximately parallel to the British Fault in strike and probably also in dip. The direction of horizontal offset is the same for both faults, but the magnitude of offset differs considerably. Whereas the horizontal component of movement on the British Fault is between 500 and 1,250 feet, it appears to be about 2,000 feet on the De Bavay Fault. It is safe to infer that the vertical component of movement is the same in direction but greater in magnitude on the De Bavay Fault. The British Fault is marked either by a very narrow schisted zone or by a broader zone of warp. The De Bavay Fault is marked by a crush zone of mica schist 200 feet wide.

The orebodies of the North Mine unquestionably terminate where they meet the De Bavay Fault. Vital geological problems are consequently (a) the "behaviour" of the orebodies between present workings and the fault, and (b) the possibility of ore repetitions beyond the fault. The first problem is not considered in this bulletin. The second problem, involving interpretation of the very complex rock structures beyond the fault and estimation of the fault movement, is investigated in some detail under "Geology from De Bavay Fault to Round Hill." Only the conclusions are stated here. The structure is too complex and the evidence too meagre to permit a definite quantitative conclusion.

The strike of the De Bavay Fault is N15°W (magnetic.) The dip is steep to the east, probably about 60°. The steeper dip agrees with most surface measurements, but many surface measurements of the dip of the British Fault gave readings of about 80°, whereas contouring of more accurate underground data suggested an average dip of about 66°.

The amount of fault movement is conjectural, only the horizontal component being known with any precision. However, a vertical component of movement about 2,300 to 2,500 feet appears to fit in best with our structural data and interpretations. Such a movement gives a ratio of vertical displacement to horizontal displacement comparable to that measured for the British Fault. Such a movement also obviously would lift up the ore-bearing North Mine folds on the far side of the fault.

BUCKLES

GENERAL.—The term "buckles" is used in this bulletin to distinguish certain steeply pitching contortions clearly younger than the folds which they deform. They apparently belong to the second main period of deformation to which the major faults also belong.

The main shear has already been described as a plastic shear or stretch zone. Only locally does this structure look like a shear. We believe that it resembles a shear only where it has served as a locus of appreciable movement during faulting.[20] Other lesser shears have a similar origin. Numerous small drag folds in the main shear pitch very steeply north or south (see "Mechanics of Folding"). They indicate movement on the shear in response to an essentially horizontal stress couple, whereas the essentially flat-pitching "folds" are referable to a nearly vertical stress couple. Almost invariably the drag folds on the shears indicate that the west side has moved north with respect to the east side (a direction of movement that is the same as that of the Globe-Vauxhall crush zone which is roughly parallel to the main shear.)

Furthermore, ore shoots within the main shear lode itself generally have nearly vertical axes in contrast to the flatter pitch of ore occupying folded rock layers. Figures 31, 32, and 33 illustrate this condition in the southern part of the field. Widths of workings in "shear ore" were plotted in longitudinal section and the widths contoured. Bulges on the main shear are seen to pitch steeply. The bulges are believed to have been formed by drag-folding of the shear itself. The deep ore won by the Central Mine is a notable example. Figure 34 illustrates the probable mechanism of drag-folding.

Steeply dipping transverse belts in which folds change their pitch have already been mentioned in the section on "Mechanics of Folding." One of the best illustrations of reversal of pitch occurs in the Central Mine vertically above the deep ore described above. The reversal is attended by a marked warping of the axial plane of the Western Anticline but, because of a strong second-order fold, it is difficult to determine how much of the warping of the axial lines (and changing of pitch) can be attributed to buckling and how much to folding.

In numerous other places there appears to be puckering of the folds west of the shear with comparatively little modification of the shear zone and virtually no modification of the rocks east of the main shear. Possibly, movements resulting from bending of the hangingwall rocks were dissipated on the shear. Certainly the footwall rocks seem to be very little affected.

A transverse buckle of major importance occurs in the vicinity of Howell Shaft on the British Mine where no shear comparable to the main shear exists. Its axial plane is steep. The buckle is responsible for a change of pitch in the folds here. Its proximity to the British Fault strongly suggests a genetic relationship, although the resolution of stresses is by no means clear. The structure is further

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(20) Schisted zones in this district all appear to have been formed by faulting, not by the plastic "shearing" or stretching of folding. Some local movement on the main shear may also be post-lode in age.

complicated here because movement, presumably on the British Fault, has drag-folded the minor folds north of where they emerge from the buckle. The double folds resulting in this case so closely resemble second-order folds produced during the folding period that their origin is somewhat doubtful.

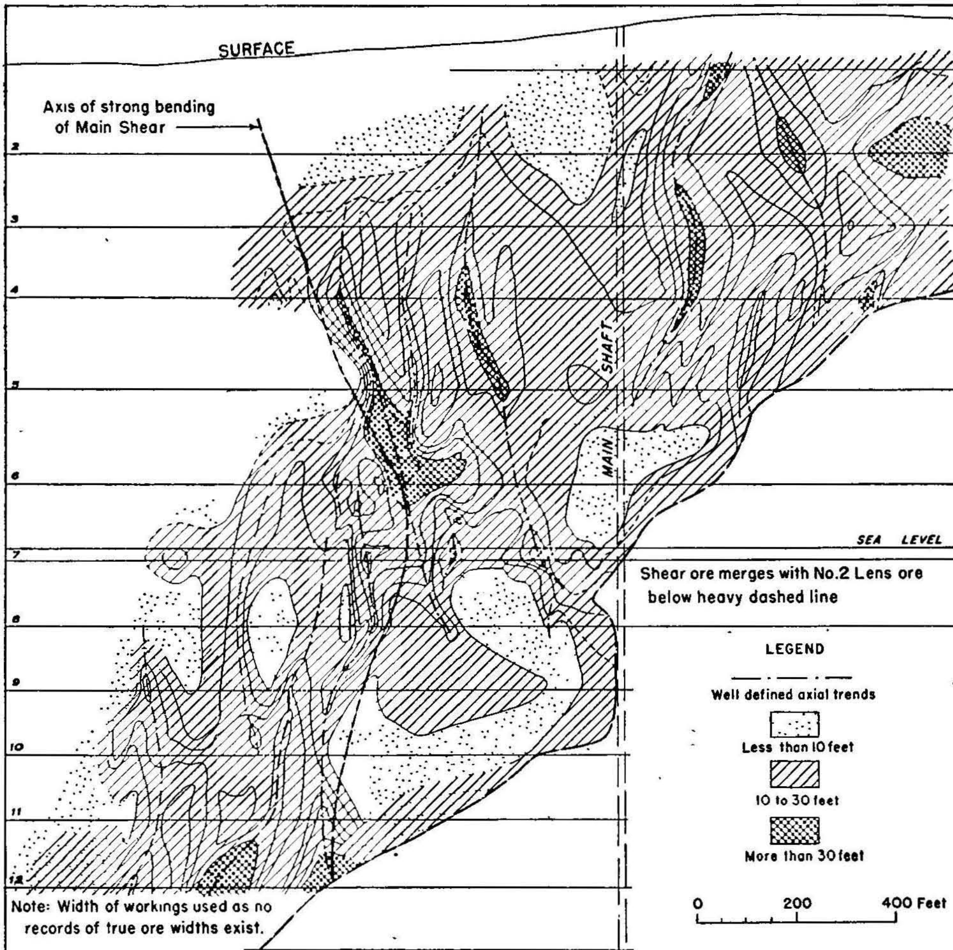

Figure 31.—Longitudinal Projection of Main Shear Ore, Zinc Corporation.

All the buckles are not referable to the Globe-Vauxhall direction of shearing. The rocks (and orebodies) in the North Mine encounter a steep north-pitching buckle in about Section 27 that was clearly caused by drag in sympathy with the De Bavay shear movement. It is the first of a series of such buckles between here and the De Bavay Fault.

In the South Mine there appears to be some correlation between a steeply inclined belt of north-pitching structures, steep axes of bulge ore on the main shear, and marked bends in the shear itself. Here the buckles appear to be the "hinges" on which the main shear changes its strike. However, the relationship is general rather than exact.

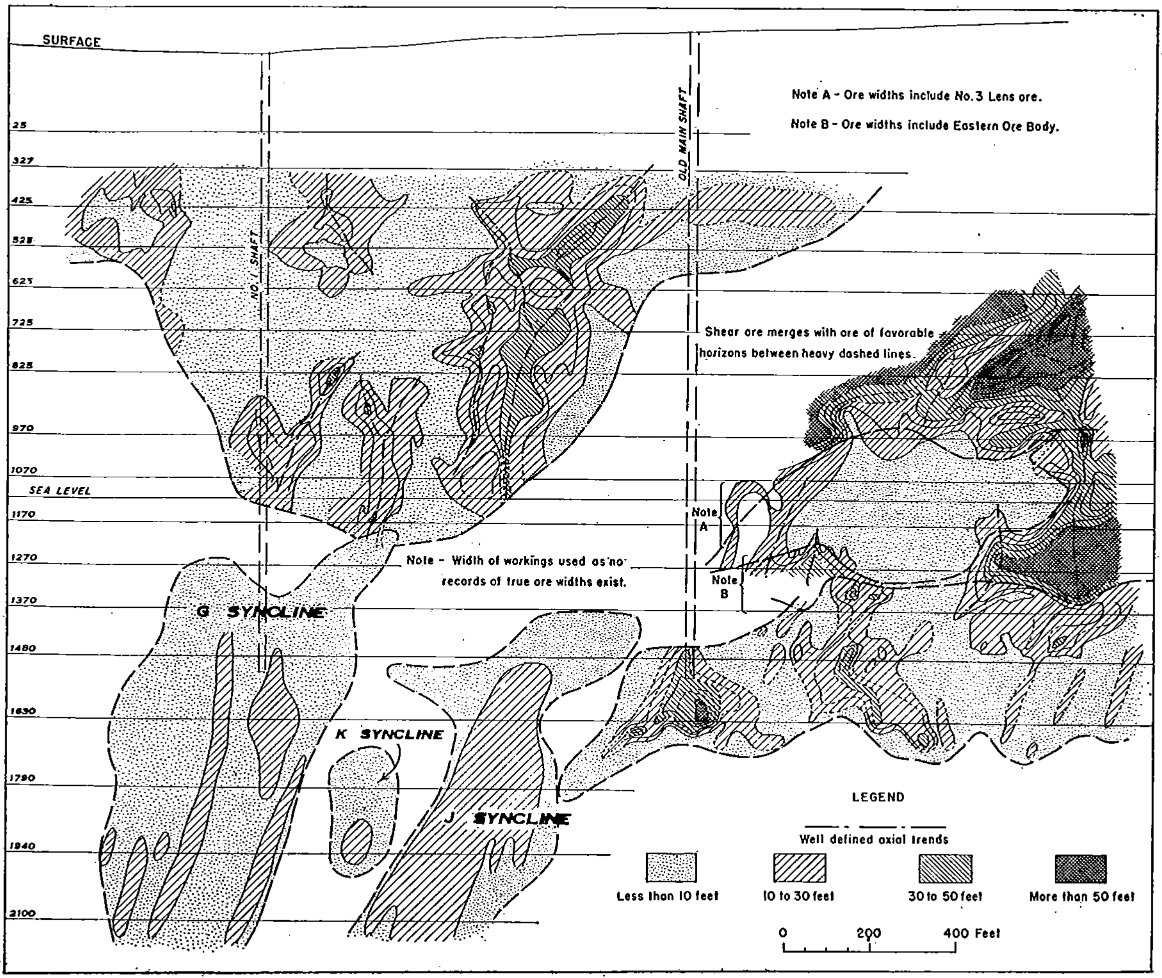

Figure 32.—Longitudinal Projection of Main Shear Ore, South Mine.

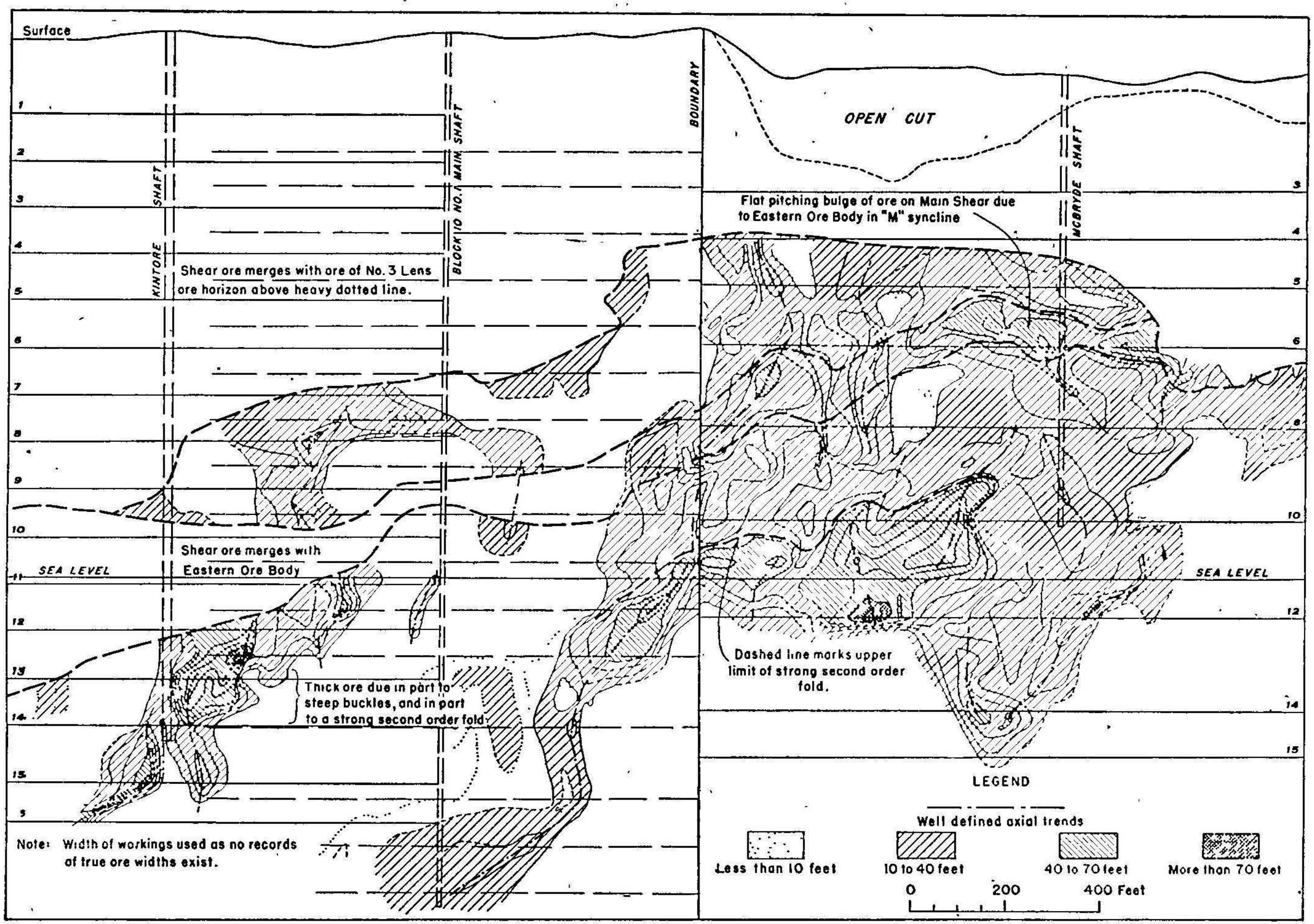

Figure 33.—Longitudinal Projection of Main Shear Ore, Block 10 and B.H.P. Mines.

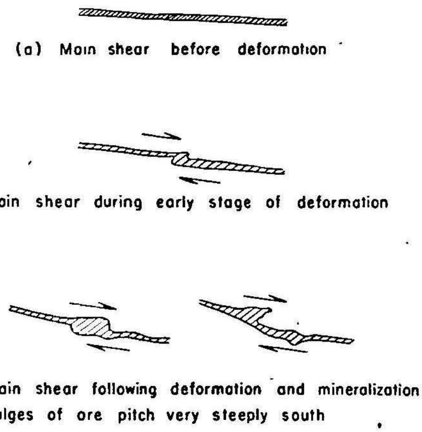

Figure 34.—Deformation of the Main Shear by Post-Folding Movements.

The main shear on the Zinc Corporation as visualized in a three-dimensional model has the curvature of a simple much flattened propeller blade. The northern and southern halves appear to be "twisted" about a nearly vertical axis (Fig. 35). It is significant that No. 2 Lens horizon where it forms the arch of the Western Anticline pitches southward toward this axis at about 45°, meets the axis and follows it down vertically for 300 feet, then leaves it to pursue a more normal course of about 35° (Fig. 31). No. 3 Lens ore formation is but little affected.

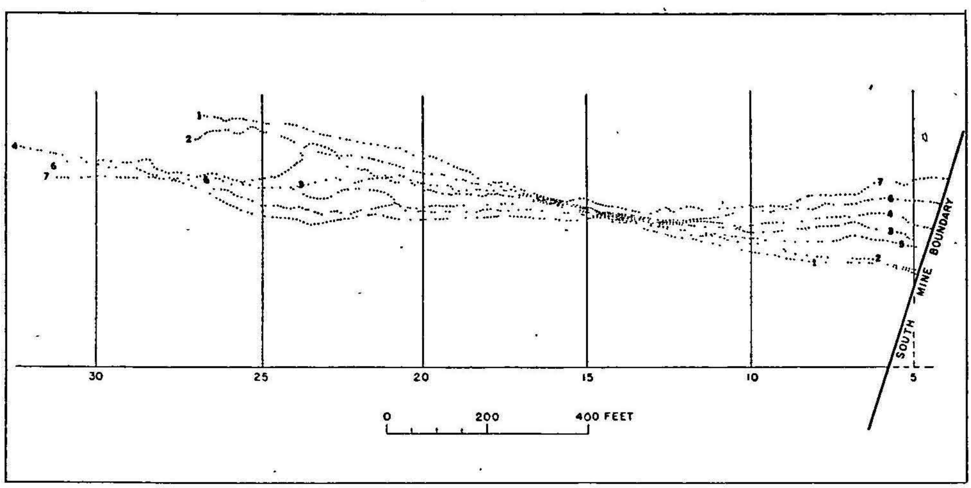

Figure 35.—Composite Plan of Main Shear on Selected Levels, Zinc Corporation. See also Figure 31.

Economic Significance.—The chief economic significance of the buckles is that they control in large measure the ore shoots in the steep tabular portions of the lode (Figs. 31, 32, and 33). In the south drives of the Zinc Corporation where the lode becomes very narrow it is sometimes difficult to tell whether the end of payable ore has been reached or whether more southerly bulges can be expected. Similar difficulties are being encountered on the lower levels of the South Mine.

Recognition of buckles is also important when making projections of ore structures to (newer) deeper levels.

SMALL FAULTS AFFECTING LODES

FAULTING BEFORE AND DURING MINERALIZATION.—Numerous small faults of different ages have affected the ore-bearing folds. Fault movements of small magnitude on the main shear and on other similar shears have already been mentioned. The Geological Sub-Committee (1910) also presented a case for pre-lode movements on the "intersecting fault" (no longer accessible for inspection.) There is also evidence that some shearing took place after the emplacement of "lode pegmatite," rhodonite, "garnet sandstone," and "quartzite," but before the appearance of sulphides. Occasional small lens-shaped bodies of rhodonite, "garnet sandstone," or "quartzite" occur with bedding planes of enclosing (sheared) gneiss wrapping around them. Some of these lenses were once connected as a continuous rock layer, first stiffened and made brittle by replacement (or by metamorphism—see earlier discussion of lode mineralogy) and then pulled apart by shearing stresses. The lenses are sometimes veined by later quartz and sulphides and by small quartz-biotite intergrowths. Large masses of rhodonite in No. 3 Lens ore formation were also fractured before the appearance of later minerals, as is evident in the Block 14 and British Mines.

The main shear, moreover, frequently bends at both the overwall and underwall of the "broad lodes" as if the favourable formations either before or after lode formation acted as a fulcrum; for example, the "propeller blade" shape of the main shear in the Zinc Corporation. The sulphides are not deformed. Possibly the bending occurred after the early gangue minerals formed but before the sulphides appeared, although either late folding movements or pre-lode faulting might be responsible for such bending.

POST-ORE FAULTING.—Countless post-ore faults and joints—both flat and steep—cut the orebodies. The displacement on these is negligible. Some of the larger ones are large open cavities several feet across where encountered in stopes. The walls of the cavities are lined with secondary minerals. Other faults are tight cracks containing only thin films of secondary minerals. Still others contain pug seams up to one foot wide.[21] Because these faults had no bearing on the immediate problems of the Central Geological Survey they were not studied. Nevertheless, they are responsible for most of the bad ground along the line of lode, which causes the heavy falls of ground and resulting loss of life and loss of dividends.

Many of the post-ore faults originated prior to ore emplacement but were re-opened later. One prominent fault of this kind in the North Mine inhibited mineralization, strong ore stopping against silicified selvedge on both sides of the fault.

DRAG FOLDS WITH FLAT SOUTH PITCH

Small drag folds with flat southerly pitch—characteristically about 36°—are abundant in the Junction, Junction North, and North Mines (i.e. north of the British Fault) although major folds and orebodies pitch north. They were very misleading until it was recognized that they constitute a new structural "texture," superimposed upon and but very slightly modifying the original folded pattern, and that they represent a post-folding period of movement as yet not fully understood but manifestly pre-ore in age. This type can often be distinguished from drag folds of the main folding period in the following manner:

(1) Regardless of the strike and dip of bedding planes, practically 90 per cent. (or more) of the crinkles show that the east side has moved up with respect to the west side.

(2) Often the crinkles appear to be aligned along a fracture.

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(21) There is some evidence that pre-ore faults of the main faulting period converted the rock to schist, whereas post-ore faults, probably formed under lighter load, converted the rock to fault gouge or pug.

(3) Crinkles of this type characteristically fail to show appreciable thickening of beds on the crests and troughs with consequent thinning on the limbs as do drag folds of the main folding period.

MECHANICAL INTERPRETATION OF FAULTING AND BUCKLING

Materials tested under compression in the laboratory commonly fail along two well-defined shear directions with or without the development of a third direction of tension. The two major fault directions (Globe-Vauxhall and De Bavay) may possibly be regarded as these two shear directions. The buckles and small drag folds on the main shear then appear as manifestations of the Globe-Vauxhall direction of shearing where a dragging movement embracing a wider belt of rock has partly or completely taken the place of movement on two sides of a clean break. Thus the buckle in the British Mine does not show drag in the right direction to satisfy the British Fault movement because it is an expression of the complementary (Globe-Vauxhall) shear direction.

The subsidiary third group of small N25°W to N45°W pre-ore faults previously discussed, possibly including the fractures occupied by the small dolerite dykes and occasional pegmatites, may be expressions of the tension direction. Continued movement on the British and De Bavay Faults would probably induce such movement on any tension cracks already formed. Movement of this kind on tension breaks with accompanying drag may explain the buckles affecting the North Mine orebodies between present workings and the De Bavay Fault.

Figure 36 illustrates the pattern of stress and strain relationship in terms of the strain ellipsoid.

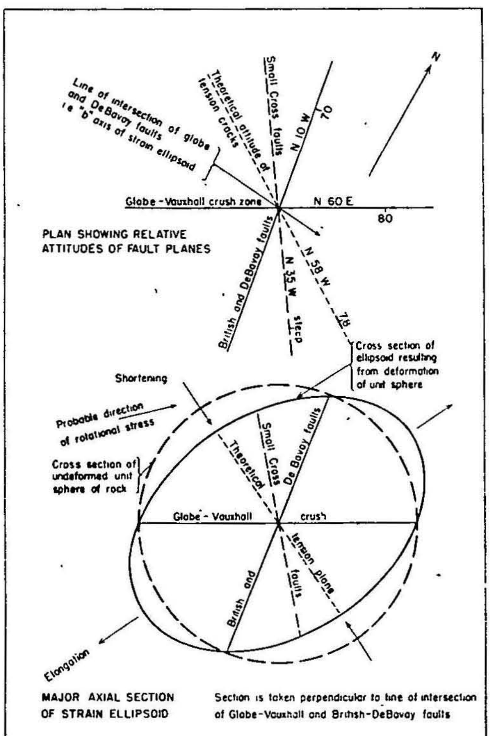

Figure 36.—Diagram Showing Probable Orientation of Strain Ellipsoid in Relation to Prominent Shear Directions.

SPECIAL STRUCTURAL STUDIES

Several attempts were made to find a quantitative expression for various structural relationships that we knew only in a qualitative way. The results were not significant enough to warrant more than mention here.

STRUCTURE CONTOURS OF MAIN SHEAR.—The main shear, where recognized as a structural element in the Zinc Corporation, South Mine, Central Mine and B.H.P. Mine, was analyzed in a three-dimensional way by the method of structure contours, based on the technique developed by Connolly (1936). A theoretical plane whose strike and dip were the average strike and dip of the main shear was first determined. The horizontal distances separating this plane from the main shear were measured and the figures representing these distances were plotted in longitudinal section and then contoured. The resulting plan shows the "topography" of the footwall of the main shear. The longitudinal section, when compared with longitudinal sections showing such features as pitch of orebodies, widths of main shear ore (i.e. buckles) and grade-width distribution, revealed poor relationships, but none warranted further analysis. Garretty subsequently applied the method successfully to predict pitch changes in the North Mine.

STATISTICAL STRIKE–DIP–PLUNGE [22] RELATIONSHIPS.—A highly important characteristic of the line of lode is that changes of pitch in the orebodies are accompanied by changes of strike. Just as the lode describes a broad arc in longitudinal section with north pitch at the north end and south pitch at the south end, so does it describe an arc in plan. Even small wobbles in the pitch lines are almost invariably accompanied by wobbles in the strike. A quantitative expression for this relationship would be valuable in exploration of northern or southern extensions of the line of lode, since strikes can be determined fairly reliably in overlying rock but it is impossible to obtain continuous accurate pitch data.

The main shear, the only measurable structural element available, was analyzed for strike and dip [23]. Axial line points were taken on immediately adjacent folds and the plunge calculated in each case. A common reference strike line was determined and all strike measurements were converted into positive or negative departures from this reference strike. The horizontal was taken as the reference for the dip and plunge. Corrected strike, dip and plunge values for 150 places were written on separate cards, and the data were then analyzed according to standard statistical practice for correlation. Constants derived were:

QUANTITIES CORRELATED IN PAIRS	STATISTICAL INDICES					
	(r)	(P.E.r)	η	$(\eta^2 - r^2)$	(σ)	3
Strike-Dip	0.0898	—	0.241	—	—	—
Strike-Plunge	0.4730	0.0428	0.607	0.1441	0.062	0.186
Plunge-Dip	0.420	—	0.384	—	—	—

r = Correlation coefficient
P.E.r = Probable error of the correlation coefficient
η = Correlation ratio
σ = Standard deviation

(22) Plunge is the true vertical angle between two points on the same structure, whereas pitch is the angle measured in the plane of the structure. (In the case of folds, pitch is measured in the axial plane.)

(23) This work was done before the strikes of axial planes were determined. But the strikes of axial planes are inferred and therefore cannot yield accurate measurements.

There was a fair correlation between strike and plunge and a negligible correlation between strike and dip and between plunge and dip. There is, moreover, no valid evidence of non-linearity in the relationship between strike and plunge.

A formula was developed by the method of least squares expressing the linear relationship between strike, dip, and plunge:

Plunge = 0.858 strike + 0.305 hade — 2, where south pitch is taken as positive and north pitch as negative; where strike is given as positive (clockwise) and negative (anti-clockwise) from a datum whose bearing is 55°44' magnetic and whose dip is expressed as the positive (west) and negative (east) hade of the shear.

The formula, however, does not accurately express the relationship in any individual case and is therefore of very limited practical use.

(As might be expected in cases of plastic folding, the relationships between dip, strike, and pitch are wholly unlike the theoretical relationships that should obtain if the rocks were simply bent.)

REGION FROM DE BAVAY FAULT TO ROUND HILL

GENERAL.—Such structural features as the Footwall Basin, Alma Anticline, and eastern leg of the Hanging Wall Basin can be recognized without difficulty in their offset positions beyond the De Bavay Fault (Pl. 1). Determining the precise faulted position of the North Mine ore-bearing folds is not so simple, as it involves interpreting a region of great structural complexity with too scanty evidence. Several alternative interpretations are possible.

STRATIGRAPHY EAST [24] OF DE BAVAY FAULT.—The coarse garnet gneiss forming the core of the Eastern Anticline is the same on both sides of the fault and consists almost certainly of I and III Formations. The lowermost lode horizon lying above the coarse garnet gneiss—and traceable from the De Bavay Fault along the east (south) side of Imperial Ridge and Round Hill to the Globe-Vauxhall crush zone—is very probably No. 3 Lens ore formation. The Hanging Wall Granite can also be recognized with certainty wherever mapped, and there is no doubt concerning the presence of the Potosi-Footwall Gneiss in M.L. 3 (although a small portion of the quartzite shown as underlying the Potosi-Footwall Gneiss closely resembles that formation also.)

There is greater doubt as to the exact stratigraphic position of other rocks. "Difficulties" inherent in any interpretation are that (a) the Potosi-Footwall Gneiss formation is missing between the No. 3 Lens ore formation and the Hanging Wall Granite, and in fact crops out only in M.L.3 [25]. This formation is, however, also missing in the west limb of the Western Anticline for considerable distances along the line of lode. Also, whereas only two thin amphibolites intervene between the No. 3 Lens ore formation and the Hanging Wall Granite in M.L.44, at least four amphibolites, including one very thick one, intervene between these two formations in the Imperial Ridge Syncline. (The big amphibolite mass at Round Hill possibly marks a centre of intrusion.) Thickening in the troughs and thinning on the limbs —in evidence everywhere—may account for the apparent discrepancy even if original lenticularity is not considered to be a contributing factor.

STRUCTURES EAST OF DE BAVAY FAULT.—Several prominent structures require explanation and correlation.

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(24) For east read north if thinking in terms of North Mine co-ordinates.

(25) Between the uppermost and next lower amphibolite in the Imperial Ridge Syncline is a coarse granular rock which closely resembles Footwall Gneiss in some cases, but in others it appears to grade into amphibolite. We believe that it is sedimentary material that was subjected to contact metamorphism at the time of amphibolite intrusion.

The double anticline of Potosi-Footwall Gneiss in M.L. 3 looks like a fold rather than a buckle because of the great thickening and thinning of material in different parts of the structure, the profuse development of minor folds, and its flat pitch. The drag folds suggest, but do not prove, that the fold is a first-order rather than a second-order fold. The syncline of Hanging Wall Granite in the corner of M.L. 44 resembles a buckle rather than a true synclinal fold, with angular drag folds without noticeably thickened noses, with nearly vertical pitch, and with incipient schisting of the rock. Compare the amphibolites here with the Consols Amphibolites wrapping around the north-east end of the Footwall Basin. The Imperial Ridge Syncline is a tightly folded syncline with predominant flattish south pitch except at its southern end where the reversal of pitch is extremely abrupt and was apparently assisted by faulting. The Round Hill Syncline is a similar, though smaller, structure. The Imperial Anticline is a very tight attenuated structure. The amphibolites of the Imperial Ridge Syncline should underlie the Hanging Wall Granite in the Hanging Wall Basin, but they are missing along the west limb of the Imperial Anticline. Their elimination probably occurred during folding, although there may have been some later faulting here.

Various faults other than the De Bavay Fault occur; the most important is the Imperial Dam Fault whose exact strike, dip, and movement are not known.

ALTERNATIVE STRUCTURAL INTERPRETATIONS.—Continuity of these structures is broken at both the De Bavay and Imperial Dam Faults. The three following structural interpretations indicate the range of uncertainty in correlating the various folds across these two faults. Minor modifications of these interpretations are also possible.

Interpretation No. 1: This interpretation which is portrayed on the surface plan and cross-sections, is preferred (Fig. 37.) The essential point to note is that the westernmost of the two anticlines in M.L. 3 and one minor anticline belonging to the Imperial Ridge Anticline are both considered to be the Western Anticline which contains the North Mine orebodies. On this hypothesis, exploration for the No. 2 Lens and No. 3 Lens ore formations within these structures east of the fault *might* find ore [26]. Even if these structures are not the same as the North Mine ore-bearing fold, they are very similar structures worth exploring.

According to this interpretation, the "syncline" of Hanging Wall Granite and Town Amphibolites in the north-east corner of M.L. 44 is regarded as a buckle, as the field evidence suggests, rather than a normal fold.

The Imperial Ridge Syncline, Round Hill Anticline, and Round Hill Syncline must be regarded as folds—on the west flank of the Eastern Anticline—which die out southward. By a combination of pitch changes and fault movements, the Imperial Ridge Syncline must be sufficiently high above the surface south-west of the De Bavay Fault to prevent the occurrence of outcrops of No. 3 Lens ore formation on that side of the fault. An abrupt pitch change and considerable vertical throw on the Imperial Dam Fault are necessary postulates. The great thickness of Town Amphibolites in the structures suggests that the sills were possibly originally abnormally thick at this place before folding.

Interpretation No. 2: This interpretation (Fig. 37) (a) supposes rather drastic changes in the fold in a short distance (wherein fold No. 3 takes the place of fold No. 1 as the main structure of the Hanging Wall Basin in a very short distance), and (b) requires apparently inconsistent offsets on the Imperial Dam Fault. The possibilities of ore repetitions remain essentially as they were under interpretation No. 1.

(26) Even if this correlation is absolutely correct, there is no guarantee that the favourable beds would be ore-bearing in these structures. The faulting occurred before mineralization, and the ore solutions may have had sufficient access to the structures on only one side of the fault. There was also a tendency for ore deposition to be poor immediately north of strong transverse structures—e.g. just north of the strong buckle in the Central Mine, north of the British Fault in the Junction Mine, and north of the buckle in Section 27 in the North Mine.

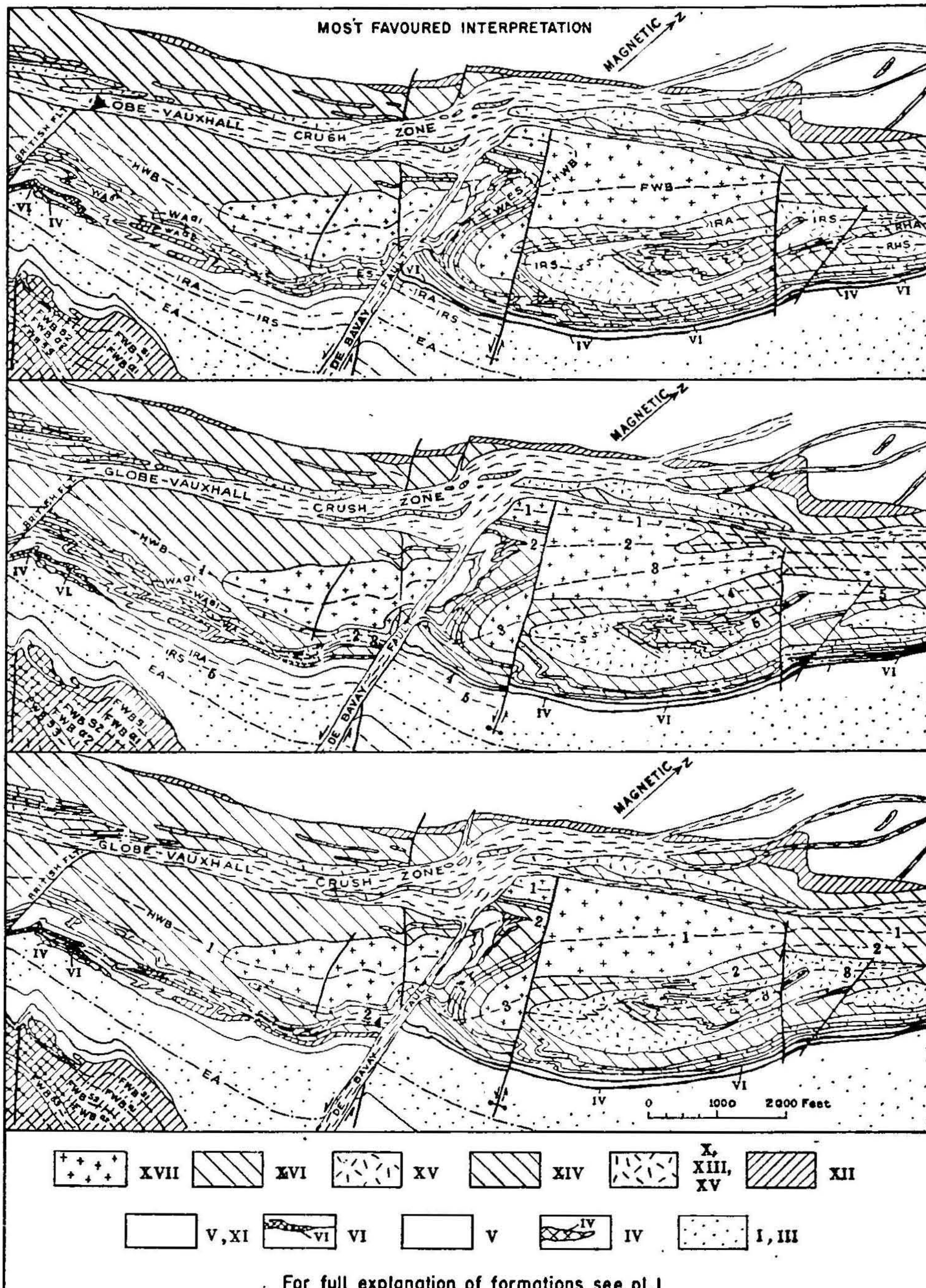

Figure 37.—Sketch Plans Indicating Three Possible Interpretations of Geology from the De Bavay Fault to Round Hill.

Interpretation No. 3: The same objections can be raised against this interpretation (Fig. 37) as against interpretation No. 2. The exploratory objectives, however, remain virtually unaltered.

REGION FROM ZINC CORPORATION TO WHITE LEAD

GENERAL DESCRIPTION.—The region between the Hanging Wall Basin and the Broken Hill Basin was mapped for 3½ miles south of the Zinc Corporation boundary. Outcrops are sparse, and the geology was difficult to interpret, although in many places magnetic surveys determined the position of the garnet-magnetite bed that occurs just below the Potosi-Footwall Gneiss. Subsequent correlation of the geophysical and geological data has resulted in the geological interpretation worked out jointly by King and Gustafson in 1947, modifying the Central Geological Survey interpretation (Gustafson, 1939).

The interpretation is probably substantially correct in its broad outlines but, being built on scanty data, it is inevitably inaccurate in detail. The garnet-magnetite bed is lenticular; and in some places where this bed and mappable contacts are missing, the geology had to be projected for long distances. As an example of the kind of uncertainty that exists, the Rising Sun Anticline is unquestionably the equivalent of the Western Anticline as indicated on the map, but it is uncertain whether WA^{a1} or WA^{a2} is the dominant minor anticline in this major structure. Also, the southern continuation of WA^{s1} is considerably in doubt. The pitch of most structures had to be inferred indirectly from other evidence.

On the positive side, the finding of a garnet-magnetite bed at the Potosi-Footwall Gneiss contact in the east limb of the Rising Sun Anticline (Western Anticline) goes far to strengthen the correlation of Potosi Gneiss with Footwall Gneiss upon which the structural interpretations in this bulletin are based.

MAJOR STRUCTURES.—The major structures recognized in this area are, from west to east: the Hanging Wall Basin, Rising Sun Anticline (equivalent of Western Anticline), Footwall Basin, Alma Anticline, and Broken Hill Basin. Many minor folds have been detected but fewer than farther north where data are more numerous.

The way in which the Western Anticline grew large as the Eastern Syncline grew small southwards, in the central part of the field, continues in a striking manner approximately as far south as the old White Lead prospect. The Eastern Anticline, if it exists at all in this region, is a small drag fold no longer recognizable, but the relative behaviour of the Western Anticline (Rising Sun Anticline) and the Alma Anticline expresses this change of emphasis from eastern to western structures going south. The Western Anticline is clearly the dominant anticline between the Hanging Wall Basin and the Broken Hill Basin in the vicinity of Rising Sun whereas, around the Zinc Corporation New Main (Freeman) Shaft, the Alma Anticline reaches higher than the Western Anticline. Note, for example (Pl. 1) how the Alma Anticline as defined by the Potosi-Footwall Gneiss formation plunges beneath the surface about 9,500 feet south of the Zinc Corporation New Main Shaft, whereas the Western Anticline (Rising Sun Anticline) as defined by the same formation continues above the surface for 7,000 feet south.

Somewhere near the old White Lead prospect, however, the Alma Anticline again begins to play a dominant role, as revealed by the outlines of the Town Amphibolite and the Hanging Wall Granite in these two structures. The Western Anticline (Rising Sun Anticline) as outlined by these formations plunges beneath the surface well ahead of the Alma Anticline (Pl. 1). Thus about 3,000 feet south of White Lead there exists the same kind of "axis of twisting" between anticlines (between Rising Sun Anticline and Alma Anticline) as occurs in the vicinity of Delprat Shaft (between Western Anticline and Eastern Anticline).

(As here interpreted the fold AA^{a1}—which constitutes the Alma Anticline farther north—actually becomes a very small fold south of the air shaft, whereas the minor fold FWB^{a3} grows large and southward takes its place as a major structure. There is thus a choice as to whether this major anticline should still be called the Alma Anticline or given a new name.)

PROBLEM OF PITCH AND ORE POSSIBILITIES.—Even if the New Broken Hill Consolidated orebodies continue indefinitely southward, they are valuable only as long as they remain at a minable depth. Plunging below this depth, however, they might reappear farther south within the minable zone if crests in the pitch line of the Western Anticline exist.

Pitch data here are meagre and relatively uncertain. Readings on drag folds could be made in only about ten scattered places. Generally pitch had to be inferred from the distance separating two limbs of a fold and from the size and position of magnetic anomalies defining the garnet-magnetite beds. Such evidence is circumstantial and, although probably fairly conclusive for major trends, it is not wholly reliable for details.

On present evidence, pitch trends south of the Zinc Corporation New Main Shaft are on the average flatly south to beyond the old White Lead prospect. Possibly, pitch crests occur in which the favourable beds are closer to the surface than elsewhere.

Outcrops of XI Formation in the Western Anticline contain numerous gahnite-bearing siliceous lodes a few of which have contained small lenses of minable sulphides at White Lead, Rising Sun, and Rising Sun North. Of little or no commercial interest, they testify to the passage of ore solutions through them and, therefore, possibly also through the more favourable formations that lie below. Details of structure could not be successfully worked out from the attitude of these lodes.

VERTICAL INTERVAL BETWEEN FORMATIONS.—The vertical interval between two formations in the nose of a fold is a limiting factor in drawing pitch lines in longitudinal projection and in constructing cross-sections from projected data. Although such intervals vary considerably over great distances and in different structures, they are not believed to fluctuate rapidly in the same fold. For example, in the construction of the cross-sections, it was found necessary to have a true interval (i.e. measured perpendicular to pitch) of 1,630 feet between the underwall of XII Formation and the overwall of No. 2 Lens ore formation in the Western Anticline at the Zinc Corporation and an interval of only 800 feet between the same formations in the same structure at the North Mine. Whatever the reason for this discrepancy—either a difference in packing during folding, or sedimentary lenticularity (the zinc lodes are absent at the north end)—we arbitrarily decided during the construction of cross-sections south of the Zinc Corporation to keep the interval between XII Formation and No. 2 Lens ore formation approximately constant at the interval found suitable at the Zinc Corporation. Similarly, the interval between XV Formation and XII Formation was assumed to remain approximately constant. Nevertheless, the total interval between No. 2 Lens ore formation and XII Formation is controlled within narrow limits by surface outcrops.

The fact that XV Formation amphibolites do not crop out until some distance south of White Lead is in itself evidence of very flat net pitch between the Zinc Corporation boundary and White Lead.

SUMMARY OF MAJOR FOLDS FROM WHITE LEAD TO ROUND HILL

The major folds of the northern, central and southern portions of the district are listed and correlated in Table 4.

Viewing the district as a whole (Pl. 1), the major structures have a very predominant flat south pitch. The north pitch of the North Mine orebodies is a very local feature.

ORE GENESIS AND STRUCTURAL AND STRATIGRAPHIC CONTROL OF ORE DEPOSITION

ORE SOLUTIONS

Broken Hill orebodies are the kind generally associated with ore solutions emanating from granitic magmas (Buddington, 1933). If the ore solutions were thin, moderately dilute, hot liquids whose chief component was water, vast quantities of solution had to flow through the rock to form the ore deposit. The average cross-section (corrected for pitch) of the Broken Hill ore deposit reveals something like 5,200 tons per linear foot of ore containing (where unoxidized) roughly 14 per cent. Pb. and 14 per cent. Zn.

Assuming that the ore solutions contained 2 per cent. Pb. and 2 per cent. Zn., 121,000 tons of ore solution would have to deposit all its metal content to produce 1 linear foot of the main Broken Hill lode. To form the orebody $2\frac{1}{2}$ miles long would require 2,240,000,000 tons of ore solution. Further, assuming the solubility of water in a granite melt to be 4 per cent., an underlying granite batholith containing 5 cubic miles of granite would be required to have yielded this amount of ore solution. The widespread mineralization of the district suggests that the granite mass is much larger.

TABLE 4.—MAJOR FOLDS

	AT RISING SUN (SOUTH END)	AT B.H.P. MINE (MIDDLE)	AT ROUND HILL (NORTH END)
West	Hanging Wall Basin	Hanging Wall Basin	Hanging Wall Basin
	Rising Sun Anticline Small minor folds	Western Anticline Eastern Syncline Small minor folds Small minor folds Eastern Anticline	Imperial Anticline Imperial Syncline Round Hill Anticline Round Hill Syncline Eastern Anticline
	Footwall Basin	Footwall Basin	Footwall Basin
	Alma Anticline	Alma Anticline	Alma Anticline
East	Broken Hill Basin	Broken Hill Basin	Broken Hill Basin

FEEDER CHANNELS

The ore solutions obviously moved predominantly in the permeable favourable beds up the pitch [27]. The upward extending fin of the main shear above the "broad lodes" may have been locally the avenue of escape for the ore solutions that had completed their mineralization. It is an empirical fact that no known ore along the line of lode occurs more than a few hundred feet east or west of the main shear. Consequently, the belt of attenuation may somewhere be a vertical link between the source of the ore solution and the favourable rock formations, although the latter may indeed have been in direct contact with the source.

(27) In the South Mine, Central Mine, and B.H.P. Company Mine, where the pitch of the folds is predominantly south, the Western Anticline goes through a sudden reversal of pitch. In each of these the main arch and western limb of No. 3 Lens ore formation ceases to be ore-bearing (although it is feebly mineralized) where the pitch is to the north and just as abruptly takes up its ore-bearing role again where the pitch reverts to the south. In the North Mine, however, the ore occurs in north-pitching folds.

The obvious shear zones of the district are not the plastic shears developed during folding but the strong post-folding faults (Globe-Vauxhall, British, and De Bavay). The field evidence is that the favourable beds are apt to be barren where cut by these faults. The only important break in the continuity of the main line of lode, in the warped zone of the British Fault, is due as much to feebler mineralization as to the thinness of favourable beds.

The intersection of No. 3 Lens ore formation (?) (several miles north-east of Broken Hill in M.L. 216) with the Globe-Vauxhall crush-zone does not contain an orebody; what little ore there was in No. 3 Lens appears to have terminated before the fault was reached. Consequently exploration cannot be directed to the intersections of faults with favourable rocks in the hope of finding favourable ore loci. Plastic shears and belts of attenuation involving favourable rocks must be sought.

The size of the igneous mass that contributed the ore solutions suggests that almost any zone of shearing, if deep enough, would tap the source of ore. Such masses, however, have irregular surfaces with upward projecting knobs or cupolas in which ore solutions probably gather as the magma cools. It may thus require (1) a feeder channel that will connect such a cupola with (2) a favourable rock in (3) a favourable temperature-pressure environment to produce any orebody. For a large orebody to be produced, the feeder channel must tap (or consist of) the favourable beds where (4) they have been bunched up into thick folded masses.

FAVOURABLE BEDS

This survey has shown that with small exception all of the ore along the main line of lode occurs in a few closely adjacent sedimentary beds, of which the lower two—No. 3 Lens ore formation and No. 2 Lens ore formation—are overwhelmingly important. Other higher horizons were mineralized, and contained orebodies locally, but only No. 2 Lens and No. 3 Lens ore formations have been mined under average cost-grade relationships. The zinc lodes at the south end of the field, profitably stoped during high metal prices, promise to be of greater economic importance in the future.

FAVOURABLE STRUCTURES

A great variety of structures influence the shape and size of the orebodies. However, except for the belt of attenuation, the British Fault and the De Bavay Fault, no structural feature appears to have been important in determining the existence of an orebody. *The orebodies occur in the favourable beds where those beds are intersected by the belt of attenuation, except where the intersection has been strongly disturbed by pre-ore faulting and warping.* This statement summarizes the main facts of ore occurrence but does not account for variations in the size or quality of the lode from place to place.

The Broken Hill lodes are remarkable in that they continue for more than 3 miles as uninterrupted stopable ore, except for the small gap occasioned by the British Fault. Along these 3 miles, the lodes vary greatly in metal content (Pl. 8.) Had mineralization been less intense—or if we could consider the base of this graph moved up so that zero tons per linear foot were where 5,000 tons per linear foot is now—the Broken Hill orebodies would be repetitive and "erratic" instead of continuous and persistent. It follows that any new system of orebodies may be of the repeating kind. The orebodies of the main line of lode may, as they die out, become repetitive also.

Cross structures to account for variations in the metal distribution along the line of lode would, it was hoped, define narrow east-west belts within which deep or lateral exploration should be confined. The attempts to find such structures have so far been unsuccessful for practical purposes. Peaks in the metal distribution curve cannot, we believe, be explained by any one simple structural relationship but are the composite effect of many. Buckles, second-order folds, changes of pitch; coincidence of the main shear with certain strong minor folds, variable strength of the main shear, and *en echelon* offsetting of the main shear all appear to have played their part. The presence in some places of large low-grade rhodonitic masses and the localization of ore shoots within the zinc lodes indicate that the variable amount of fracturing from place to place of early gangue minerals during mineralization was important in providing channel-ways for later sulphides. This more than any other single influence—unless it was sedimentary differences from place to place in the favourable beds—probably accounted for variations in the metal content of the lodes.

LOCALIZATION OF ORE BY INTRA-MINERALIZATION FRACTURES

The lodes display abundant evidence that fracturing of the favourable beds during mineralization was a continuing or repeated occurrence. Within No. 3 Lens formation, for example, "garnet quartzite" and "garnet sandstone" masses were invariably fractured, and the fractures were filled with younger lode minerals. All gradations are seen from "garnet sandstone"—traversed by a network of tiny sulphide and quartz veinlets—to massive sulphide ore containing residual remnants of "garnet sandstone." Again, in the British and Block 14 sections, large unreplaced rhodonite masses display similar characteristics. Sulphide ore occurs as shoots controlled by fracturing within these masses which themselves, on a larger scale, are islands in the ore of No. 3 Lens ore formation.

Within No. 2 Lens ore formation in the Zinc Corporation and New Broken Hill Consolidated Mines, the same type of thing is seen in low-grade portions of the lode rich in hedenbergite, rhodonite, and wollastonite. Definite streaks of low-grade ore traverse the lodes in a manner clearly controlled by fracturing rather than by the hospitability or inhospitability of any favourable bed.

In the lead lodes generally, the distribution of fracturing during mineralization appears to explain why some sections of the lodes are better, but mineralization was so intense that there was virtually continuous ore even in the poorer places. Localization of ore shoots by fracturing is best illustrated by the zinc lodes in the Zinc Corporation and New Broken Hill Consolidated Mines. Here ore amounts to only one-third to one-half of the lode formations, and steep ore shoots occur within flatly-pitching folds. For example, in the Rhodonitic Zinc Lode, where fracturing was early and feeble, only the most favourable thin beds were converted to feebly-metallized "garnet quartzite." Where fracturing was stronger and persisted longer, massive rhodonite and hedenbergite with thin residual layers of "garnet quartzite," both traversed by seams of sulphides, occupy the lode formation. Where intense, continuous, or repeated fracturing occurred, the entire formation consists of massive ore containing residual patches of rhodonite. An early to intermediate stage is reflected by large masses of "garnet sandstone" veined by hedenbergite.

The Siliceous Zinc Lode is similar except that large, barren or very low-grade areas of "pegmatite" (hydrothermal replacement quartz and felspar) exist in place of rhodonite-hedenbergite. Good ore shoots occur on one flank of a fold or as a tabular mass traversing the formation where it is thickened in syncline "I." High lead shoots in the zinc lodes were possibly governed by very late fracturing, since deposition of galena apparently continued after deposition of sphalerite.

ZONING

There is little recognizable zoning within the Broken Hill ore deposit. The profound mineral differences within the deposit are due to other causes related to the sedimentary strata replaced by ore. No. 2 Lens ore is consistently calcitic and has characteristic Pb-Zn and Pb-Ag ratios from top to bottom and throughout the length and breadth of the lode. No. 3 Lens ore likewise is consistent in its different and characteristic mineralogy and distinctive metal ratios. Each of the two main zinc lodes also is composed of diagnostic mineral assemblages different from those of other lodes. Since the ore beds are closely and intimately folded, No. 3 Lens ore often extends far above No. 2 Lens ore. Also, because of pitch, there is both No. 2 Lens ore and No. 3 Lens ore higher than zinc lode ore. The ore types were clearly dictated by the character of the replaced sedimentary strata regardless of their position with respect to each other or to the source, or sources, of ore solution.

Some of the progressive changes within the lodes may also be due to variations in the sedimentation of the ore beds rather than to zoning. At the north end of the field the No. 3 Lens orebody is much bigger and more important than the No. 2 Lens orebody, and the zinc lodes are practically non-existent. In the centre of the field, all but No. 3 Lens orebody have been eroded. In the south end of the South Mine and in the Zinc Corporation Mine, however, No. 3 Lens orebody has dwindled to very small size. With the diminution of No. 3 Lens orebody, No. 2 Lens orebody has become much larger and the zinc lodes have assumed increasing importance.

From the No. 8 level of the Zinc Corporation to No. 18 level of the New Broken Hill Consolidated, a vertical distance of 1,420 feet and linear distance along pitch of about 3,000 feet, the zinc lodes improve. They contain more ore and more high-lead streaks. Because of the high-silver character of No. 3 Lens ore, these changes result in much more high-silver ore at the north end of the lodes than at the south end. Because of the zinc lodes, there is much more high-zinc, low-silver ore as well as more high-lead, low-silver ore, at the south end. It is more likely that this condition reflects a progressive sedimentary change in the favourable beds rather than a zonal control of ore deposition, although the No. 3 Lens type of ore could have been deposited more profusely at the north end and the No. 2 Lens ore type and the zinc lode ore types at the south end because of temperature and/or other zoning controls. Even less certain is the reason for No. 2 Lens ore apparently becoming increasingly "rhodonitic" and "wollastonitic" (?) in depth.

One mineralogical change that does seem due to zoning is the increase in the amount of pyrrhotite, especially along the margins and in poorer portions of the ore at the south end of the field. This seems to indicate higher temperature conditions to the south. An increase in the amount of arsenopyrite, also a "high-temperature" mineral, at the south end of the field is suspected (Stillwell, 1926, p. 103.)

Metal ratios within any one ore type are amazingly constant throughout the field. Gustafson's impression, shared by Zinc Corporation and New Broken Hill Consolidated personnel (George Fisher, Struan Anderson, R. Hooper, verbal communication), is that there are larger and more numerous zincy spots in the lead orebodies on the deeper levels of the Zinc Corporation and New Broken Hill Consolidated properties. Like the similar impression that the zinc lodes are becoming more "leady," this is not backed by statistical evidence and could be in error, or correct for a local condition only.

Meagre evidence of zoning, coupled with the predominant south pitch of the district, strongly suggests that the ore solutions moved up the pitch of the folds within favourable strata from some unknown hot magma source to the south.

CLASSIFICATION OF ORE DEPOSITS AS TO TEMPERATURE AND DEPTH OF ORE FORMATION

There is a considerable range of published opinion regarding the classification of the Broken Hill ore deposit according to its temperature and depth of formation. Andrews (1922, 1926) took the extreme view that the lodes as well as the igneous rocks of the district were injected under conditions of great temperature, great pressure, and deep burial as "pressure lenses" in "pressure slacks." Lindgren (1933) classed the deposit as hypothermal.

We are unanimous in our belief that folding occurred at great depths characteristic of plastic deformation, perhaps as deep as 12 to 20 miles, whereas ore deposition occurred long after folding, following an interval of uplift and erosion, at much shallower depths (following emplacement of dolerite dykes), and further that the lodes owe their shapes to the replacement of folded rocks. We are however, divided as to the emphasis that we place on such evidence as:

1. The first conspicuous stage of ore deposition was the introduction of large amounts of "lode pegmatite" characterized by green microcline and quartz, accompanied by silicification and garnetization of the gneiss. Much, if not all, of the quartz and felspar of this stage replaced the rock rather than intruded it in igneous fashion, as irregular patches in "garnet quartzite" testify. In this early stage occurred the introduction (or recrystallization) of large quantities of rhodonite, johannsenite, pyroxmangite, bustamite, hedenbergite, and garnet—all relatively "high-temperature" minerals. Fibres of tremolite, 2 inches long and intergrown with quartz and sphalerite, have been found in the Siliceous Zinc Lode. Occasional quartz-biotite veinlets cut garnet sandstone. Considerable amounts of pyrrhotite, arsenopyrite, and löllingite occur in the ore, often closely associated with hedenbergite. These mineral associations betoken relatively high temperatures of ore deposition.

2. The large size of the ore deposit, the general absence of zoning, and the limited extent of wallrock alteration are characteristic of hypothermal deposits as defined by Lindgren (1933) and Graton (1933).

3. The introduction of tremendous quantities of sphalerite and galena, microscopic tetrahedrite, and some chalcopyrite and other sulphides was accompanied by the introduction of fluorite, calcite, and quartz, and the replacement and continued recrystallization of rhodonite and garnet. This mineral assemblage need not be hypothermal, and in fact is frequently mesothermal [Lindgren (1933), Graton (1933)].

4. The presence in the ore of such minerals as pyrargyrite, wurtzite, and marcasite suggests distinctly shallow conditions of ore deposition, if indeed these minerals are not supergene.

Burrell (1942) holds that most of the manganese silicates and calcite are of metamorphic origin, although they were recrystallized by the ore solutions. He believes that the evidence of the lode pegmatites and limited wallrock alteration nevertheless places the deposit in the hypothermal group, but that cooling was sufficiently rapid to permit conditions during the latter part of the ore-forming activity to approach mesothermal conditions. He considers the pyrargyrite, wurtzite, and marcasite to be probably supergene.

Garretty (1943) considers the manganese silicates and also the pyrargyrite to be truly hydrothermal. Gustafson considers the manganese silicates to be hydrothermal and the pyrargyrite to be probably supergene. Both consider the deposit to be hypothermal.

There is little direct evidence as to the temperature of ore formation. Wright and Mawson (Mawson, 1912, p. 310) showed blue lode quartz from Broken Hill to be the "low" type and concluded that ore deposition occurred below 575° Centigrade. Schwartz (1927) considers that ore deposits containing cubanite-chalcopyrite intergrowths were formed above 400-450° Centigrade. Stillwell (1926) describes similar chalcopyrite-pyrite-cubanite intergrowths from Broken Hill.

The effects of great pressures on such points on the "geological thermometer" is imperfectly known. According to Graton (personal communication) such points established at low pressure should be raised somewhat where applied to reactions at depths. On the other hand, during the long period of ore deposition, the thermal gradient was steepened by the flow of hot ore solution. Assuming the ores were formed in the 450-500° Centigrade range and extrapolating from the present thermal gradient of the mines, these figures correspond to maximum depths of 54,000 to 60,000 feet. With the steeper gradient obtaining during ore deposition the same temperature range must have obtained at considerably shallower depths.

Melbourne,
14th March, 1952.

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EXPLANATION OF PHOTOGRAPHIC PLATES

PLATE 2

Fig. 1.—Aerial view of Broken Hill, looking north: Zinc Corporation Mine in foreground.

Fig. 2.—Narrow gossan, Main Lode, outcrop of 'Shear Ore"; Broken Hill Proprietary Company Limited Mine.

PLATE 3

Fig. 1.—Coarse sillimanite-garnet gneiss of I or III Formation in nose of Eastern Anticline north-east of North Mine. Photograph shows 45° southerly pitch.

Fig. 2.—Banded iron formation (garnet-magnetite rock) of XI Formation in Alma Anticline south of North Mine.

PLATE 4

Figs. 1 and 2.—Potosi-Footwall Gneiss in Footwall Basin south of North Mine. Note contorted pegmatite and round garnet porphyroblasts.

PLATE 5

Fig. 1.—Town Amphibolites in Alma Anticline south of Zinc Corporation Mine.

Fig. 2.—Hanging Wall Granite (augen gneiss) in Hanging Wall Basin near North Mine. Note coarse ragged garnets.

PLATE 7

Fig. 1.—Mica schist in De Bavay Fault.

Fig. 2.—Small steeply dipping pegmatites perpendicular to gneissosity, west of lode outcrop M.L.15. These pegmatites are post-folding and are either the same age as the lodes or somewhat older.

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GEOLOGY OF THE BROKEN HILL MINES AREA

1000 0 5000 10000 Feet

½ 0 1 2 Miles

LATE 2

'Fig. 1

Fig. 2

PLATE 3

Fig. 1

Fig. 2

PLATE 4

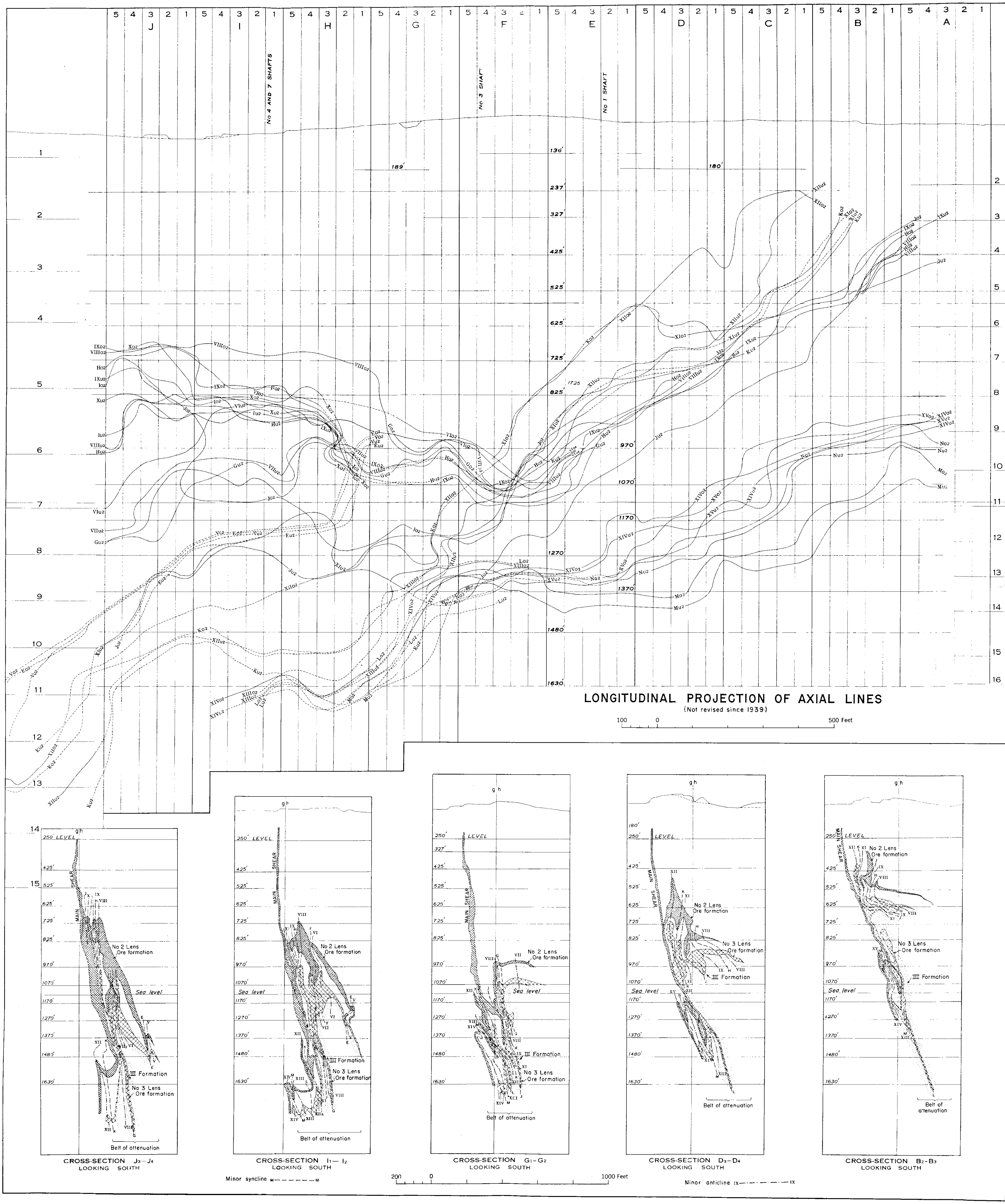
Fig. 1

Fig. 2

PLATE 5

Fig. 1

Fig. 2



LONGITUDINAL PROJECTION OF AXIAL LINES WITH EXPLANATORY CROSS-SECTIONS, BROKEN HILL SOUTH LIMITED

PLATE 7

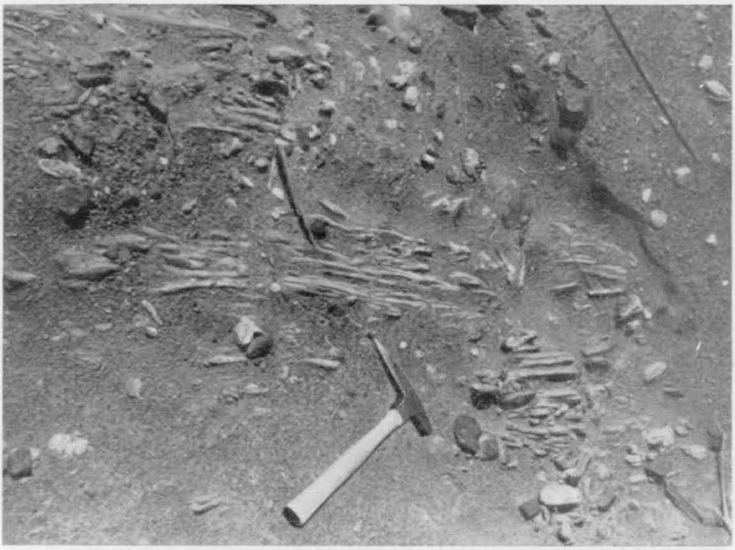
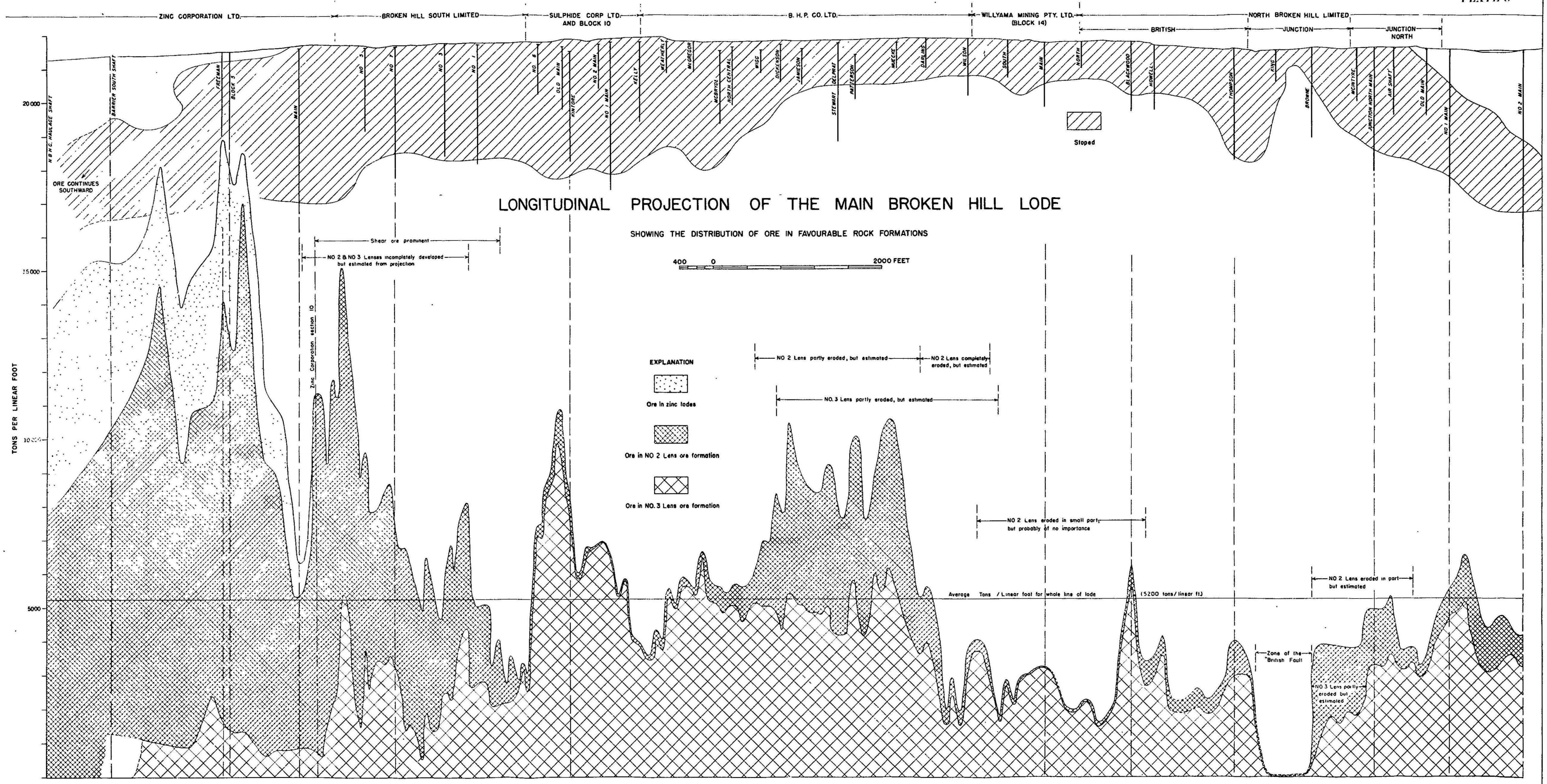


Fig. 1

Fig. 2

PLATE 8



ORE TONNAGE DISTRIBUTION IN THE BROKEN HILL LODES.