15 LEDGE ORE DISCOVERY, HOMESTAKE MINE, LEAD, SOUTH DAKOTA

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ABSTRACT

Economic gold mineralization in 15 Ledge is localized in siderite-dominant phyllite of the Homestake Formation. Orebodies are composed of pyrrhotite, arsenopyrite, native gold, chlorite, quartz and siderite with subordinate garnet, grunerite, and pyrite. The 15 Ledge structure is a large, well developed, double synform with varied fold plunge ranging from steep northeast to moderate southeast. This structure lies on the eastern margin of a major, 1000 meter wide, ductile shear zone and within the upper greenschist - lower amphibolite facies metamorphic transition zone which contains the majority of orebodies within the mine.

15 Ledge is the first new ore ledge (mineralized plunging fold structure) to be discovered in the Homestake mine since 1969. The 15 Ledge ore discovery resulted from the projection of favorable structure and stratigraphy, and from the recognition of the significance of existing anomalous gold mineralization in the upper 15 Ledge fold structure. The resulting target zone was 700 meters in height, 500 meters wide, 1300 meters in length, and was located between the 5300 and 7400 levels. A systematic drilling program was implemented to test the targeted area.

Drilling commenced on the 6950 mine level in January, 1985 with a program designed to test the entire 1300 meter strike length on widespread drill hole centers. Drilling results disclosed ore grade gold intercepts ($\geq$ 4.7 g Au/t) in 15 Ledge at the 6950 level. Further drilling identified ore grade gold intercepts on the 5600 and 5900 levels. These ore grade intercepts were characterized by internal grade discontinuity. In March, 1987 after the completion of 36 core holes, discovery drill hole #37 intersected 7 meters of economic mineralization near the 6200 level which contained abundant pyrrhotite, arsenopyrite, and native gold. The intercept assayed 24.4 g Au/t and contained internal grade continuity. Development drifting in 1987-1988 and close spaced development drilling in 1988-1990 on the 6200 level verified the presence of economic gold mineralization, within which initial mining activities have commenced.

INTRODUCTION

The Homestake gold mine is located in the northern Black Hills of South Dakota (fig. 1). It is the largest iron-formation-hosted gold deposit known, and has produced over 1,120 metric tons of gold from more than 128 million metric tons of ore milled since discovery in 1876. Ore is currently mined to depths of 2.4 kilometers. The mine is accessed by two large surface shafts, the Yates and the Ross. Gold is the principal commodity produced with silver as a by-product. The gold/silver ratio averages about 5:1. Base metals are negligible.

GEOLOGIC SETTING

The Black Hills are a Laramide uplift or dome (fig. 1) consisting of a core of Early Proterozoic metasediments, metavolcanics, and granitic plutons (Darton and Paige, 1925). Phanerozoic rocks unconformably overly the Early Proterozoic core. The whole package is intruded by numerous, Tertiary, calc-alkalic and alkalic dikes, sills, and small stocks in a northwest-trending belt across the northern Black Hills (DeWitt et al, 1986). The Homestake gold mine is centered in the Whitewood mining district under the city of Lead, on the northern end of the dome.

The Homestake gold deposit is hosted within quartz veined, chloritic, sulfide-rich segments of an Early Proterozoic carbonate-facies iron-formation called the Homestake Formation (Caddey et al., 1990). It is enclosed in a sequence of originally calcareous, pelitic, semi-pelitic, and

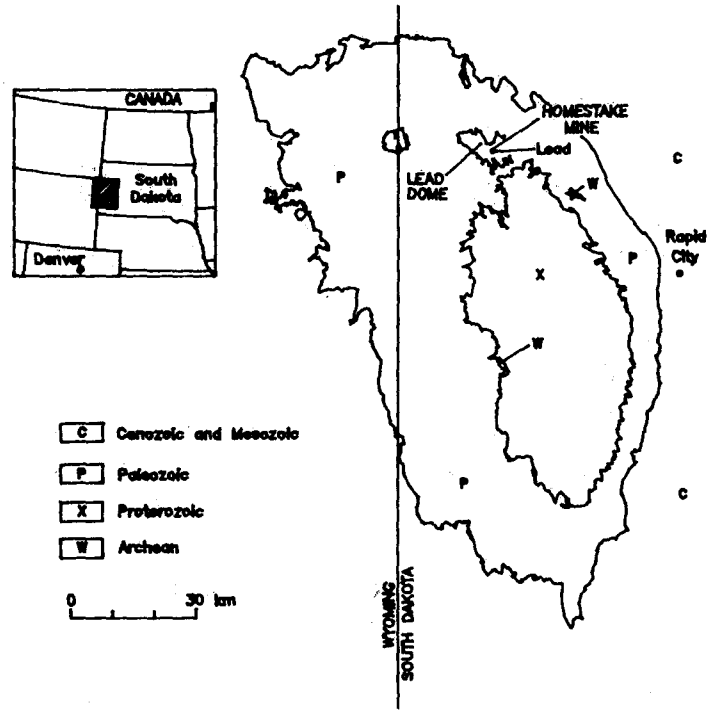

Fig. 1. Generalized geology of the Black Hills uplift. Modified from Dewitt et al. (1986).

quartzose rocks (fig. 2). Mine area rocks have been metamorphosed to upper greenschist and lower amphibolite facies (Noble et al., 1949). The garnet isograd (fig. 2) crosses through the Homestake mine area. The major Precambrian structures, outlined by the folded Homestake Formation, include the Lead anticline and Poorman anticline. The foliation dips steeply northeast (fig. 3) and the folds plunge 30° to 60° southeast and northeast.

Three major Early Proterozoic formations in the mine (Noble and Harder, 1948) are from oldest to youngest the Poorman, Homestake, and Ellison Formations. The lower Poorman Formation is a voluminous hornblende-plagioclase schist, and is interpreted as a thick succession of tholeiitic sea floor basalts. The upper Poorman Formation consists of a thin bedded, well layered sequence consisting of sericite and biotite, carbonate-bearing phyllite and graphitic phyllite. Its protolith was a calcareous and carbonaceous siltstone and mudstone sequence. The Homestake Formation consists of massive grunerite-garnet schist in the eastern mine at higher metamorphic grades, mixed siderite/grunerite in the productive central mine, and thin-bedded siderite phyllite in the western mine at lower metamorphic grades. It is interpreted as an iron-formation with local thin chert interbeds. In the ore producing areas, the iron-formation is commonly chloritic (mineral alteration product). Its protolith was an iron-silica-carbonate-rich sediment. The Ellison Formation consists of well banded to massive sericite and biotite phyllite or schist, with interbedded impure quartzite. Its protolith may have been clastic sediments in a shallow water delta complex. The Homestake Formation is the main host rock for the gold orebodies but ore does extend locally into the Ellison and Poorman Formations.

The stratigraphic package at Homestake has been extensively folded and sheared synchronous with Early Proterozoic metamorphism (figs. 2 and 3). The structural deformation sequence is very complex, consists of at least four events the first of which, D_1, was most intense and largely responsible for producing the large scale structural pattern as shown on figure 2 (Caddey et al., 1990). Gold mineralization occurred late in the deformation during a ductile-brittle shear event. It post dates prograde and retrograde metamorphism, and a majority of the large scale folding and shearing.

Within the Homestake mine, plunging fold structures are referred to as ledges and those containing ore bodies are ore ledges. Nine ore ledges have produced gold in the Homestake mine. From east to west (fig. 3) they are: Caledonia, Main, 7, 9, 11, 13, 17, 19, and 21 Ledges. Ore ledges are generally synformal fold forms composed of a series of subordinate anticlines and synclines. Interconnecting antiformal fold forms (even numbered ledges) are less complex structurally, contain locally anomalous gold, but are generally barren. Each ore ledge contains a varied number of orebodies. Overall, orebodies comprise less than 3 percent by volume of Homestake Formation in the mine area.

HISTORICAL IN-MINE EXPLORATION

Historical Ore Ledge Discoveries

Caledonia and Main Ledges were discovered in surface outcrops in 1876 by prospectors following placer gold occurrences upstream along Deadwood Creek. Economic zones of the other seven producing ore ledges are blind at the surface and were all discovered by in-mine

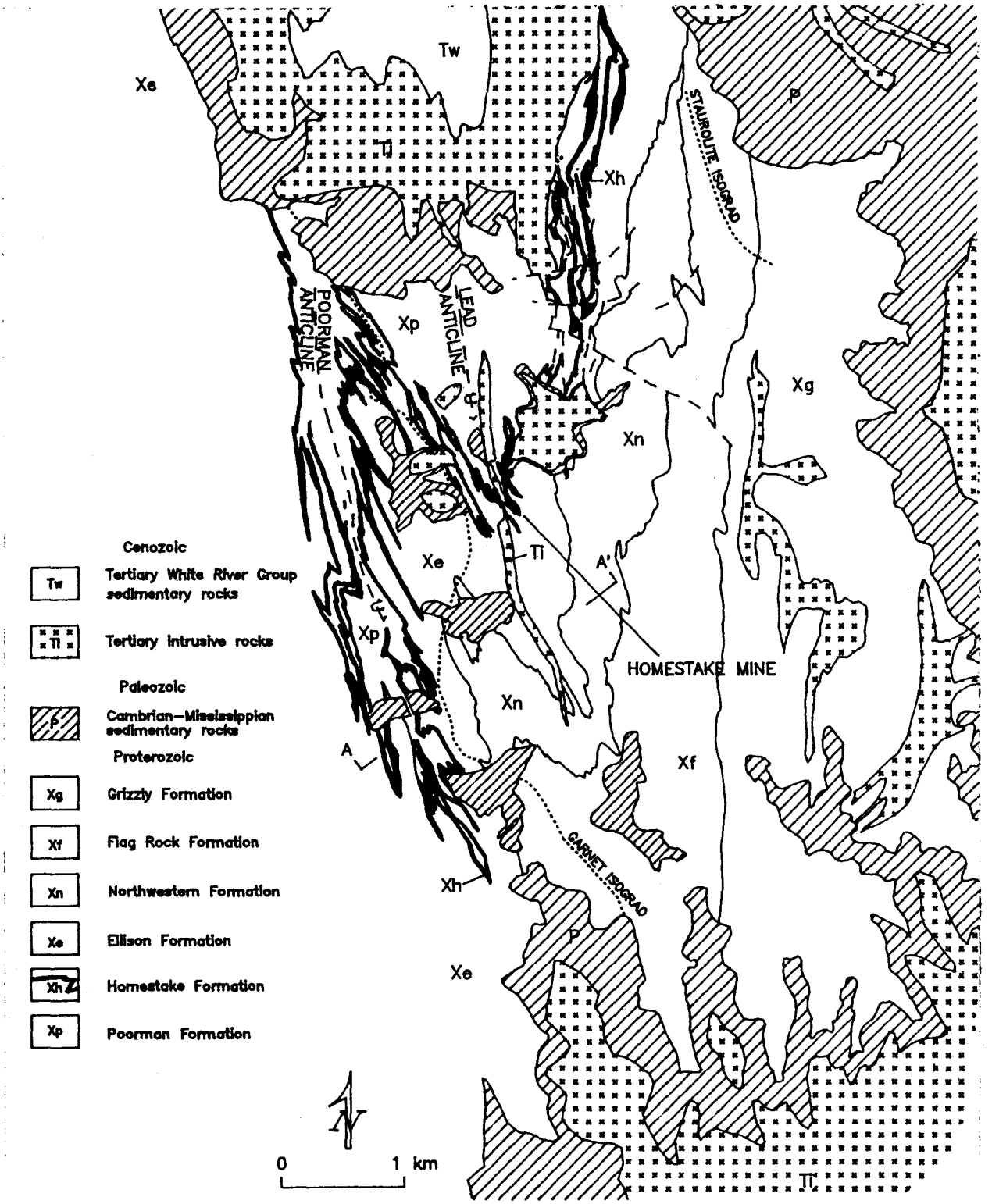

Fig. 2. Generalized geologic map of the eastern portion of the Lead dome of the Black Hills uplift, South Dakota. Modified from Noble et al. (1949).

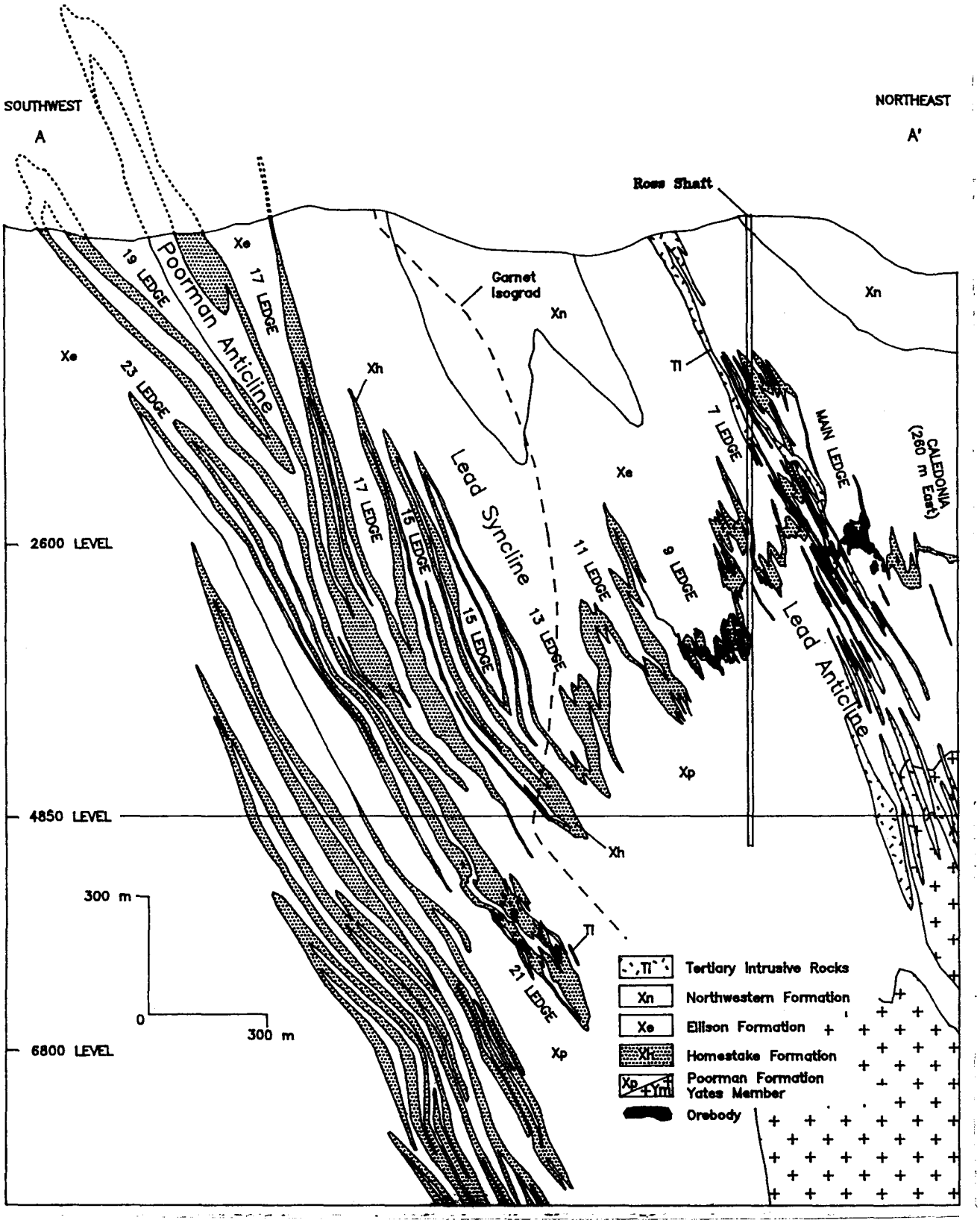

Fig. 3. Generalized geologic cross-section through 33 Stope - Main Ledge Reference Line, Homestake mine, Lead, SD. See fig. 2 for location. Modified from Caddey et al. (1990).

crosscutting, drifting, and drilling. The Ross shaft was sunk in the mid-1930's to connect with the crosscut/drift development headings. Level development initially discovered ore in both 9 and then 7 Ledges during this period. The ore ledges, cumulative production plus reserves, method and year of discovery are illustrated on figure 4.

In-mine exploration over the next 35 years consisted of progressive and extensive crosscutting, drifting, and drilling on systematically deeper levels. Horizontal core holes, each from a separate drill chamber, were drilled east and west on the new mine levels routinely and systematically on 165 meter centers through the folded iron-formation. Intercepts of ore grade gold were followed up with drilling on tighter centers. The process was time intensive, expensive, and tested Homestake Formation with multiple drill holes in systematic fashion, conducted one level at a time. Newly discovered ore ledges were found in synformal fold structures progressively deeper and to the west. It was believed for several decades that the ore trend in the mine approximated a northeast bearing and raked downward to the southwest.

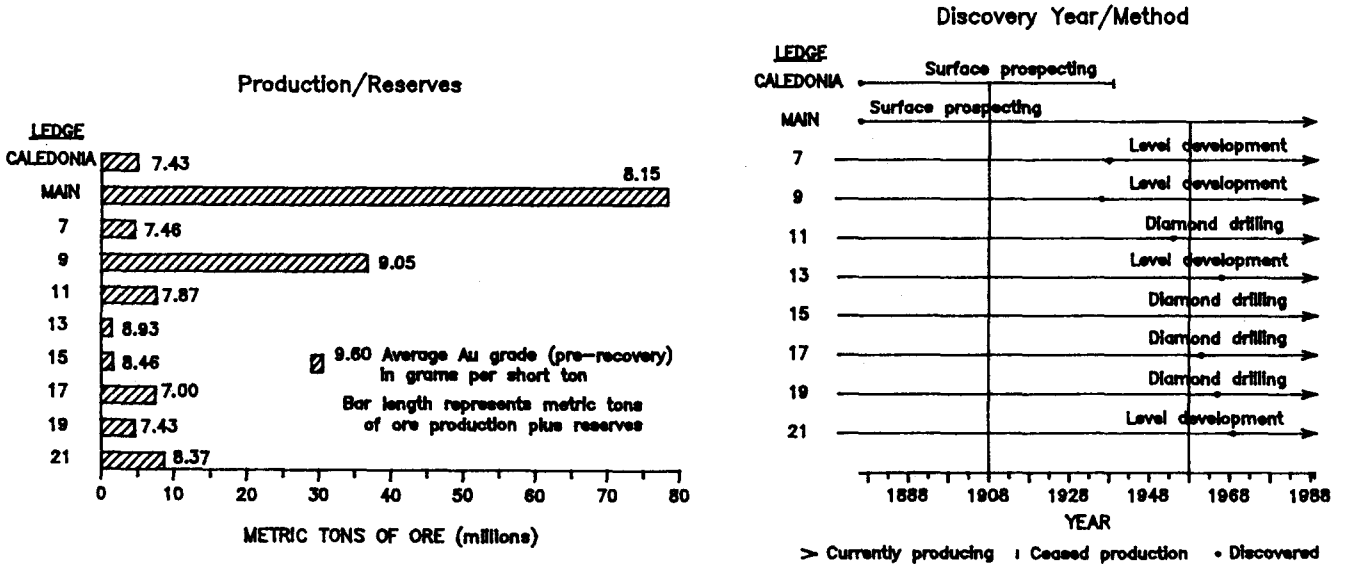

Fig. 4. Cumulative ore production plus reserves are 150.8 million metric tons averaging 8.36 g Au/t shown through 1989 by ore ledge along with method and year of ore ledge discovery, Homestake mine, Lead, SD. Modified from Caddey et al. (1990).

Ore Ledge Sizes

Ore ledge sizes (fig. 4) in the mine range from over 75 million metric tons (Main Ledge) to less than 2 million metric tons (13 Ledge) of ore produced. Most ore ledges are in the 5 to 10 million metric ton range. In general, the larger ore ledges (Main and 9) are found in the largest and most complex synforms dominated by the most intense ductile-brittle shearing (Caddey et al., 1990). Average gold grades as a result of mining show small variations among the ore ledges ranging from 7.00 g Au/t (17 Ledge) to 9.05 g Au/t (9 Ledge), a 1.95 g Au/t variance overall.

15 LEDGE EXPLORATION SEQUENCE

Introduction

The 15 Ledge structure is located between two gold producers, 13 and 17 Ledges (fig. 5). It is a large double synform with fold plunge ranging from steep northeast to moderate southeast. It is located along the eastern margin of a major, 1000 meter wide ductile shear zone, the Homestake Deformation Zone (HDZ; Bachman and Caddey, 1990). Much of the 15 Ledge fold structure lies within a metamorphic transition zone from upper greenschist to lower amphibolite facies where the majority of orebodies in the mine occur. Ore grade Homestake Formation consists of pyrrhotite, lessor arsenopyrite, and native gold. Gangue minerals include predominantly quartz, chlorite and siderite, and subordinate grunerite, garnet, and pyrite. Quartz veins are abundantly developed in mineralized segments.

The 15 Ledge ore discovery resulted from the projection of favorable structure and stratigraphy and from the recognition of the significance of existing anomalous gold occurrences in the upper 15 Ledge fold structure. The target zone as originally conceived was 700 meters in height, 500 meters wide, and 1300 meters long (strike length) between the 5300 and 7400 levels. This led to the implementation of a systematic core drilling program to test the targeted area. The drilling process was often difficult because of 1) unpredictable and unfavorable drill hole deflection that caused targeting problems, and 2) availability and access to suitable drilling platforms. Drill hole coverage encompassed the entire fold structure.

Historical Status, Pre-1983

Prior to 1983, there were eighty-three existing core holes in 15 Ledge between the 2600 and 6800 levels. Most of the drilling was focused between the 2600 and 4850 levels. Much of this drilling was non-systematic and widely spaced. Eleven holes contained narrow intervals (typically 1.6m) of scattered pyrrhotite and arsenopyrite, some with ore grade gold. The mineralized zones were discontinuous, low grade, and concentrated between the 4850 and 5300 levels. Of five holes drilled on the 5300 level, all were barren but one which assayed 49.7 g Au/t over 1.6 meters (best intercept in the eighty-three pre-1983 holes). There were seven holes drilled on the 5900 level and thirteen on the 6800 level, and they were barren. Of twenty-five holes drilled on or below the 5300 level, one penetrated the favored fold hinge of 15 Ledge and it was barren. Of eighty-three holes drilled, twenty-four penetrated into or through only the west limb and terminated short of the main target. Roughly 70% of the core drilling was completed above the 5300 level. The structure was viewed as small with no orebodies detected.

Planning/Research Period, 1983 - 1985

In 1983, an exploration program was implemented to discover new ore ledges in the mine and district and 15 Ledge was soon recognized as a priority drilling target for the following reasons: insufficiently known geology below the 5300 level, existing drill hole distribution was inadequate to detect orebodies in the structure, 15 Ledge was the only uneconomic synform known in the mine, and it was bordered on either side by two gold producers. The presence of pyrrhotite-arsenopyrite $\pm$ visible gold in some drill hole intercepts, combined with chloritically

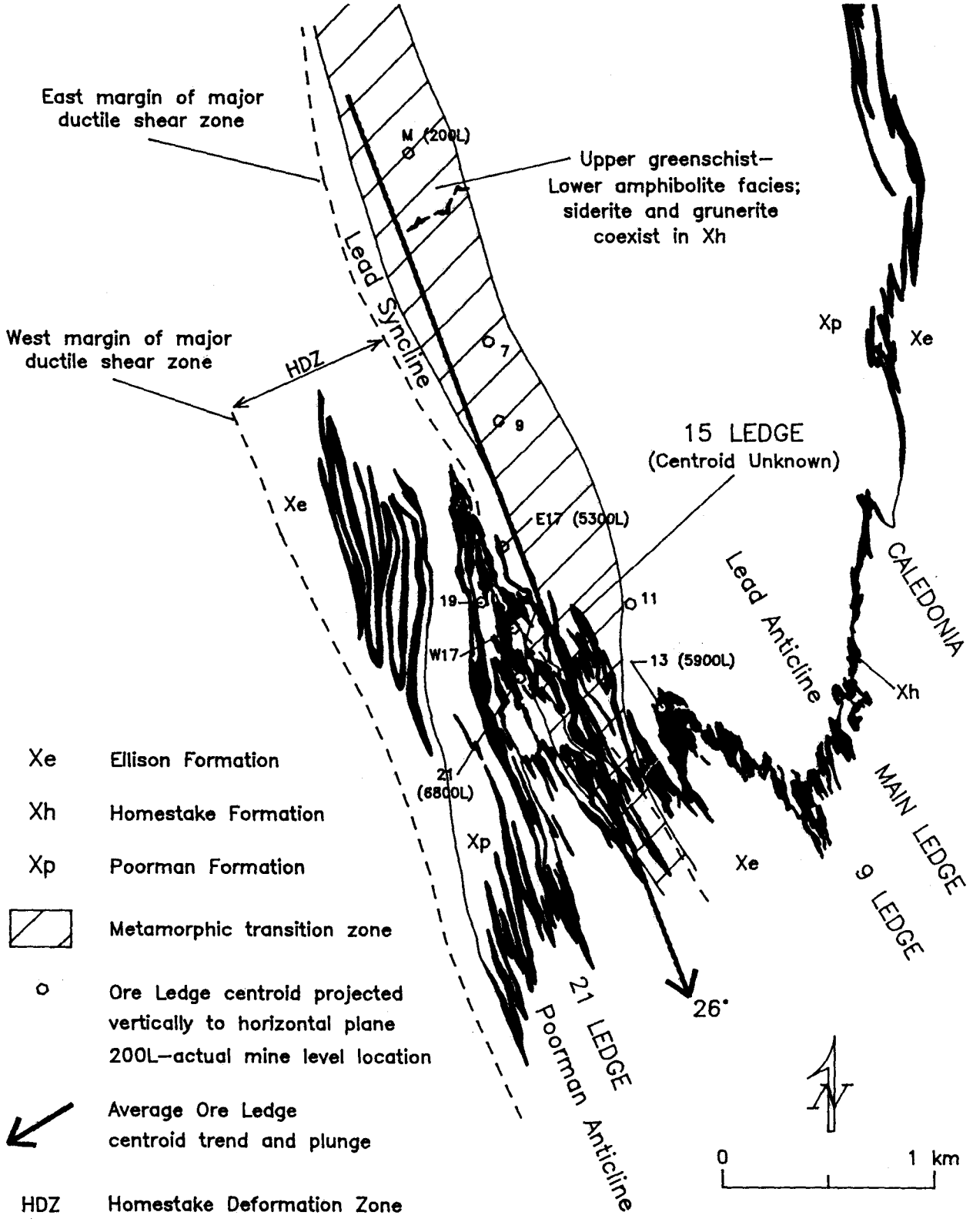

Fig. 5. Geology of the 5900 level showing the projected ore centroid trend, major ductile shear zone (HDZ), metamorphic transition zone, and location of 15 Ledge, Homestake mine, Lead, SD.

altered Homestake Formation and associated quartz veins was recognized as important. Existing gold grades ranging from 0.31 to a high of 49.7 g Au/t, even though representing short ($\leq$ 1.6 meters) intervals, suggested that a mineralizing system may be present in 15 Ledge.

Ore ledges are composed of numerous, disconnected, discrete orebodies. Orebodies are tabular to pipe-shapped segregations of quartz veins, chlorite, coarse-grained siderite, sulfides, and minor native gold. Over 50 percent of the contained gold in an ore ledge is concentrated in the core area. Ore ledges are defined by three geometric elements, core, upper tail, and lower tail areas, and the core area (fold hinges) contains the largest and most continuous ore bodies. The mine level within a core area containing the largest cross-sectional ore area is termed the ore ledge centroid. Each ore ledge has a defined ore centroid level. The number and size of ore bodies decrease away from the centroid level, both up and down plunge. Distal ends of each ore ledge are longitudinally asymmetric, divided into upper (up plunge) and lower (down plunge) tail areas. Lower tail areas are twice the length of upper tail areas. Beyond tail the areas, economically mineralized Homestake grades into barren Homestake Formation.

Known pyrrhotite-arsenopyrite $\pm$ visible gold in 15 Ledge was regarded as indicative of an upper tail position of a small ore ledge, similar to 13 to 19 ore ledges. Furthermore, existing drilling data indicated an increased number of gold occurrences from the 2600 to the 5300 levels, suggesting an overall increase in gold abundance below the 5300 level.

The minimum number of drill holes required to statistically obtain at least one ore grade intercept within an orebody with a given systematic drill hole spacing was determined for various segments in the ore ledges throughout the mine. An optimum drill hole spacing was selected for 15 Ledge (67 to 83 meter intervals), modeled after 13 Ledge. As in previous mine drilling, the structure was drilled roughly 90° to foliation to optimize the chance of an orebody penetration. Different from previous mine drilling, drill hole arrays consisting of multiple long range holes were drilled from a single drill chamber. Azimuth and inclination determined for each drill hole, were dependent on foliation attitudes and anticipated drill hole deflections. Each drill hole was designed to cross through (western limb to eastern limb) the entire 15 Ledge synformal structure and averaged 650 meters in length (longer holes reached 1000 meters in length). Drill hole position in the pattern array was periodically surveyed using fiber optics or "light-log" equipment developed for use in magnetic rock environments. Drill hole progress was graphically plotted and monitored on a continuous basis in plan view, cross section, and longitudinal projection along with mapped drill core geology and liberal projections of the targeted 15 Ledge fold structure. We recognized that if 15 Ledge was indeed small, the orebodies would probably also be small and infrequent. The number and quality of gold occurrences were compared incrementally from one level to another and vectors toward maximum gold concentration were estimated.

Ore ledge centroids in the mine form a trend on average N20W overall and plunge 26° SE (fig. 5). The eastern ore ledge centroids (Caledonia to 13 Ledges) form a trend NW and plunge shallowly to the SE. Conversely, the western ore ledge centroids (17 to 21 Ledges) form a trend near N-S and plunge steeply south, changing to steeply north on the deeper levels. The 15 Ledge structure was targeted for initial drilling on a mine level thought to contain its projected centroid, although its position was unknown. It was uncertain whether 15 Ledge resembled the

eastern or western ore ledge systems. The projected centroid location of 15 Ledge was based on a combination of projecting the eastern centroid trend down to the 7400 level, and western centroid trend up to the 5300 level, the mine levels where both trends intersected the 15 Ledge synformal structure. We chose an average mid-point between the two level projections to arrive at the 6950 level for targeting initial drilling. This level also contained suitable accessibility for a drill platform.

Exploration Drilling Commenced, 1985

The 15 Ledge exploration core drilling program commenced on the 6950 level in January with a program designed to systematically drill the synform limits on 67 to 83 meter intervals (fig. 6). The first encouraging results were obtained in February (a 1.6 meter wide sample assayed 4.7 g Au/t). The first ore grade intercept was obtained in April (5 meters assayed 5.0 g Au/t). Drilling continued for the entire year on the 6950 mine level from which nineteen holes were completed. The 15 Ledge structure was fully tested with the designed drilling pattern which revealed a much larger synform than expected. There were numerous low grade gold intercepts (0.31 - 4.6 g Au/t) and three were marginally ore grade (5 meters averaging 4.7 g Au/t). The structural symmetry and attenuation of 15 Ledge resembled the western ore ledge system and a decision was made to drill similar patterns between the 6950 and 5300 levels. The 5900 level was selected as the next step.

Drilling Progressed, 1986

Three core holes were drilled in January-February on the 5900 level (fig. 6). Two of those holes contained abundant occurrences of low grade gold ($\geq$ 1.6 meters averaging 0.31 - 4.6 g Au/t), and one hole was ore grade. Four core holes were drilled in March-May on the 5300 level, resulting in low grade results (fig. 6). Four additional core holes were drilled in June-September on the 5600 level (fig. 6). Several intercepts of low grade gold ($\geq$ 1.6 meters averaging 0.31 - 4.6 g Au/t) were encountered along with an ore grade intercept (DDH#30). The intercept was 9.3 meters averaging 9.9 g Au/t but was characterized by internal grade discontinuity. The highest component assay was 34.2 g Au/t over 1.6 meters indicating potential for system strength. Drilling below the 5300 level disclosed an increase in structural size of 15 Ledge and development of a double synform on the 6950 level which was viewed as a positive indication.

The best drilling results were obtained on the 6950 and 5600 levels. Splitting the difference between the two, drilling commenced on the 6500 level in October. The holes were deflected upwards, across and into the foliation, and traversed through 15 Ledge between the 6200 and 6500 levels, centered on the 6350 level (not shown). Four holes were completed by late January, 1987.

Discovery Year, 1987

Results from the four holes drilled in 15 Ledge across the 6350 level were mixed. There were several intercepts of low grade gold ($\geq$ 1.6 meters averaging 0.31 - 4.6 g Au/t) and one 1.5 meter sample assayed 14.3 g Au/t. The synformal structure was poorly covered by the

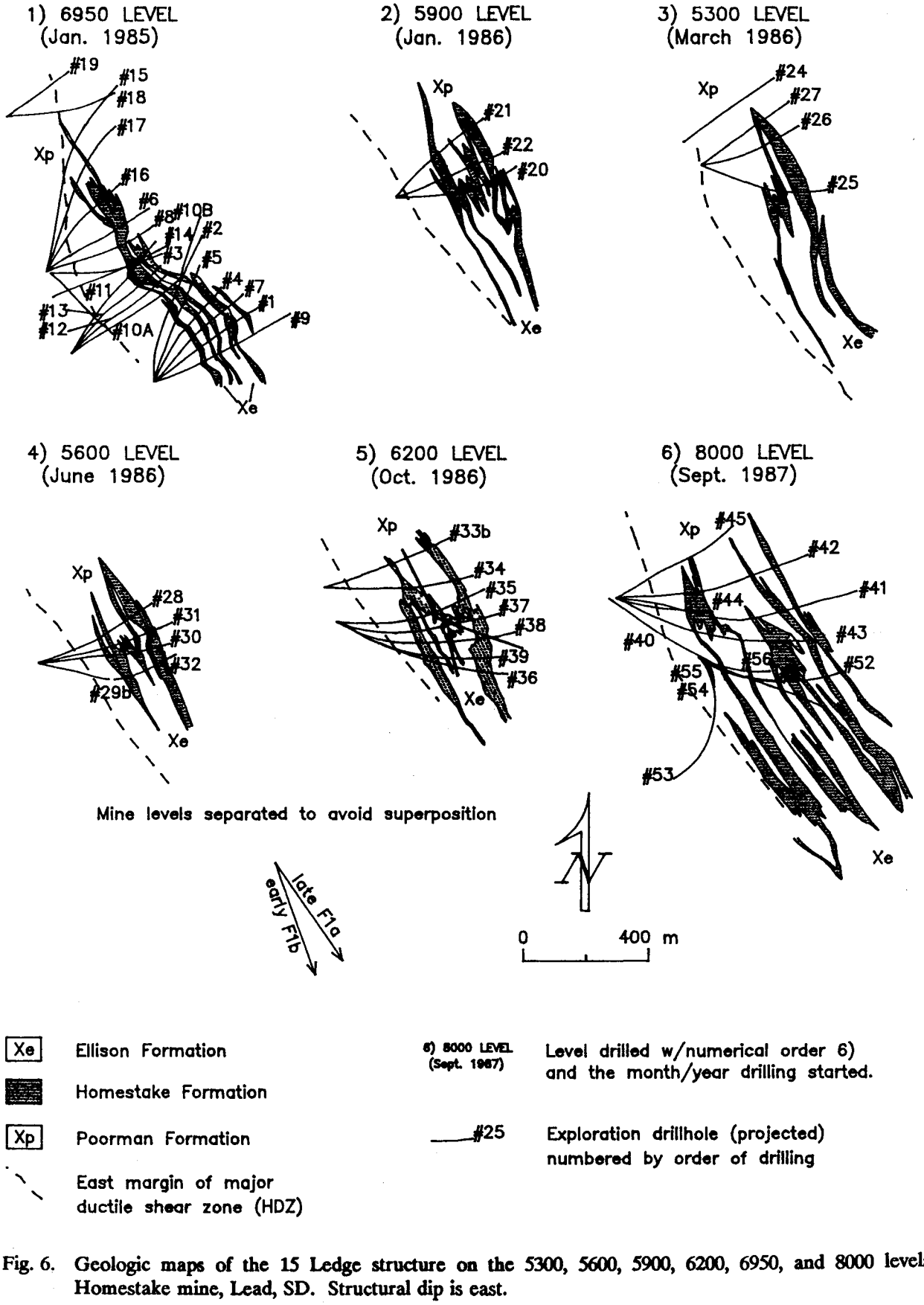

Fig. 6. Geologic maps of the 15 Ledge structure on the 5300, 5600, 5900, 6200, 6950, and 8000 levels, Homestake mine, Lead, SD. Structural dip is east.

drilling array in that the fold closures were bracketed by the drill holes but not penetrated. Thirty-six drill holes had now been completed in 15 Ledge (fig. 6) on five mine levels in nearly two years. Significant occurrences of gold and associated sulfides/gangue minerals were encountered below the 5300 level, but a conclusive discovery ore hole ($\geq$ 5 meters averaging $>$ 4.7 g Au/t with internal grade continuity) was still lacking. The drilling program was halted in 15 Ledge in late January.

The 15 Ledge drilling data were compiled and examined on mine level plans, cross sections, and in longitudinal projection over the next three months. The distribution of exploration drill holes (1985 to present), mine levels, the composite synformal hinge of 15 Ledge along plunge, and proven ore reserves are illustrated in longitudinal projection on figure 7. An apparent fold plunge reversal was observed to exist from the 6200 to the 6950 levels, a common local feature present in the productive western ore ledges. It was attributed to the affect of D1a ductile shearing that changed orientation of conical fold development patterns. The drill hole distribution (fig. 7) containing ore grade intercepts indicated an increase in gold content from the 5600 to below the 6950 levels.

Evaluation of the 15 Ledge data compared with similar data for 13, 17, and 19 Ledges indicated that additional drilling was warranted. We were uncomfortable with leaving the fold closures of 15 Ledge untested on the 6350 level. The drill was moved back to the 6500 level in May and another hole (DDH#37) was drilled. It penetrated one of the targeted fold closures in 15 Ledge just below the 6200 level and encountered an ore intercept containing 44 specks of visible gold in a pyrrhotite-rich orebody with excellent internal grade continuity (figs. 7, 8 and 9). Seven meters of strongly mineralized rock averaged 24.4 g Au/t. A diagonal was subsequently driven from the 13 Ledge header into 15 Ledge on the 6200 level. Two drifts were driven along 15 Ledge to provide access for development drilling. Of seven drill holes completed on the exploration array (67 to 83 meter intervals) across the 6350 level, only one encountered an orebody as shown on the 6200 level in figure 9.

During the next two years, 17 more drill holes were completed on the 7400 (not shown) and 8000 levels in 15 Ledge (figs. 6 and 7). Combined data from four levels (fig. 6) were utilized to construct an isometric view shown on figure 10.

Development Drilling, 1988 - 1990

Development core drilling (not shown) commenced in 15 Ledge on the 6200 level (fig. 9) in August, 1988 and was completed early in 1990 by the Homestake mine Geology Department. The 15 Ledge structure was drilled systematically and completely on close spaced 16 and 33 meter centers. Development drill holes were oriented roughly east and west, and drilled above, on, and below the 6200 level. Several orebodies were identified (fig. 11). There were numerous ore intercepts most with internal grade continuity (fig. 12). To date, over 100 development core holes have been completed on the 6200 level in 15 Ledge.

Initial stope development and sill mining commenced on the 6200 level in October, 1989. Initial ore reserves were calculated in December, 1989. 15 Ledge although not fully explored is the second smallest ore ledge in the mine (fig. 4) comparable in size to 13 Ledge.

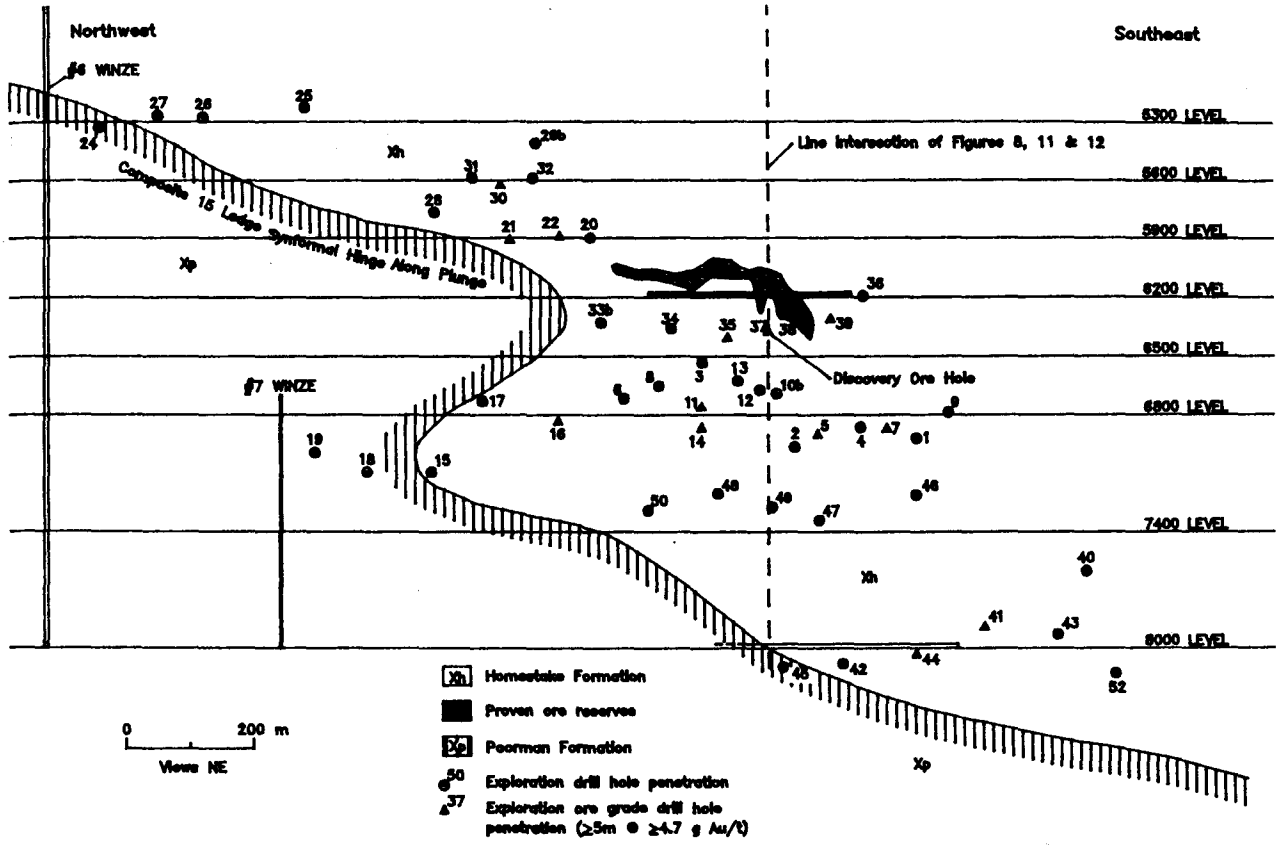

Fig. 7. Longitudinal projection along strike and dip of the 15 Ledge structure showing structural plunge, drill hole penetrations, ore holes, and proven ore reserves. See fig. 9 for location.

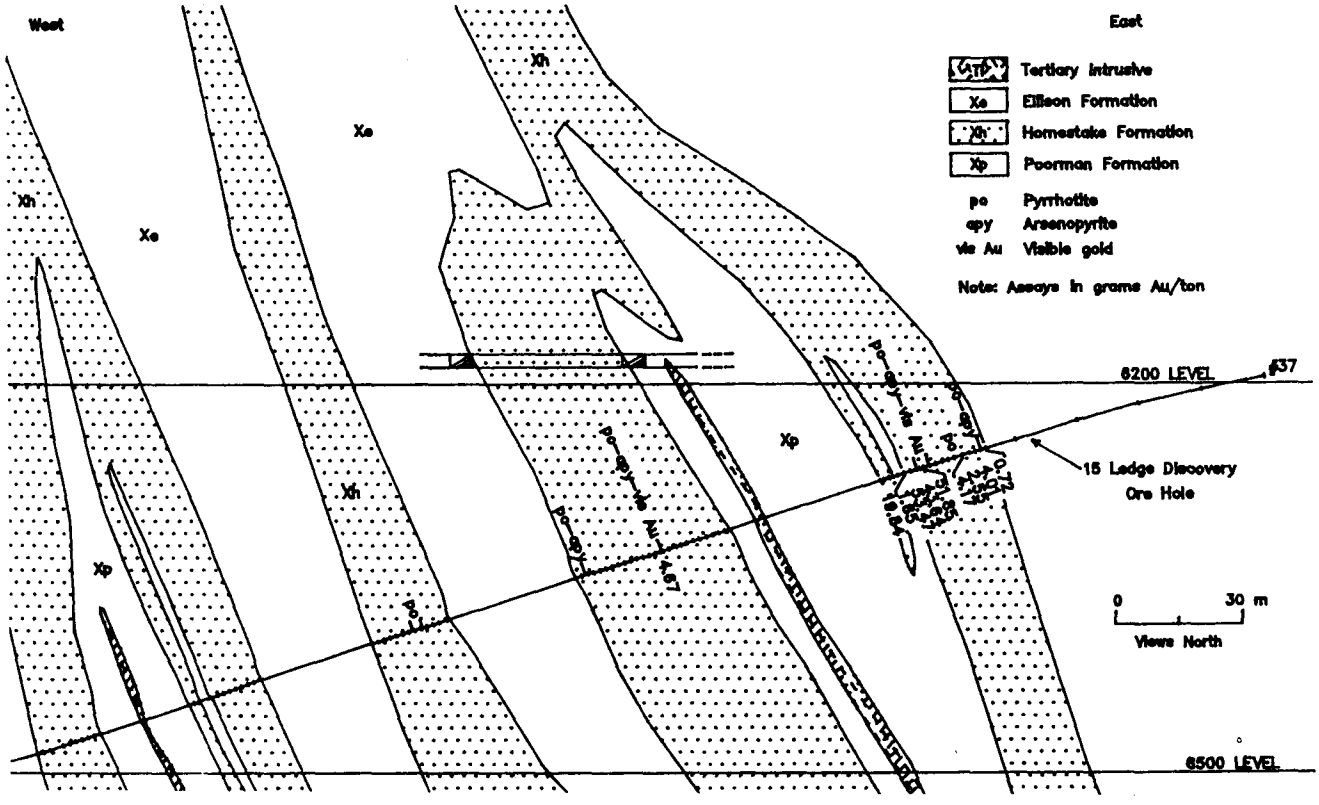

Fig. 8. Geologic cross-section along a portion of diamond drillhole #37, 15 Ledge, Homestake mine, Lead, SD. Cross-section is based on pre-mining geology. See fig. 9 for location.

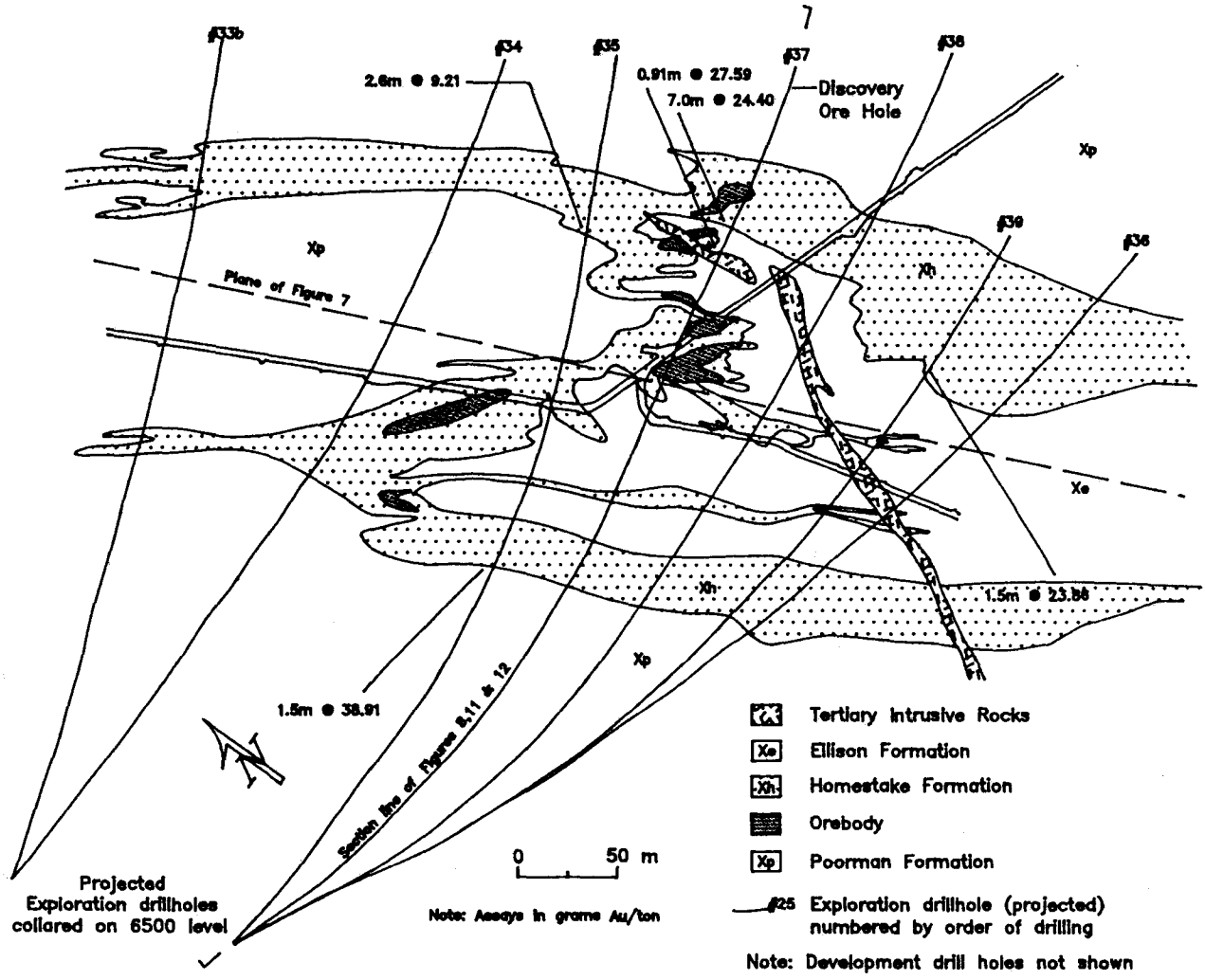

Fig. 9. Geologic map of the 15 Ledge structure on the 6200 level, Homestake mine, Lead, SD.

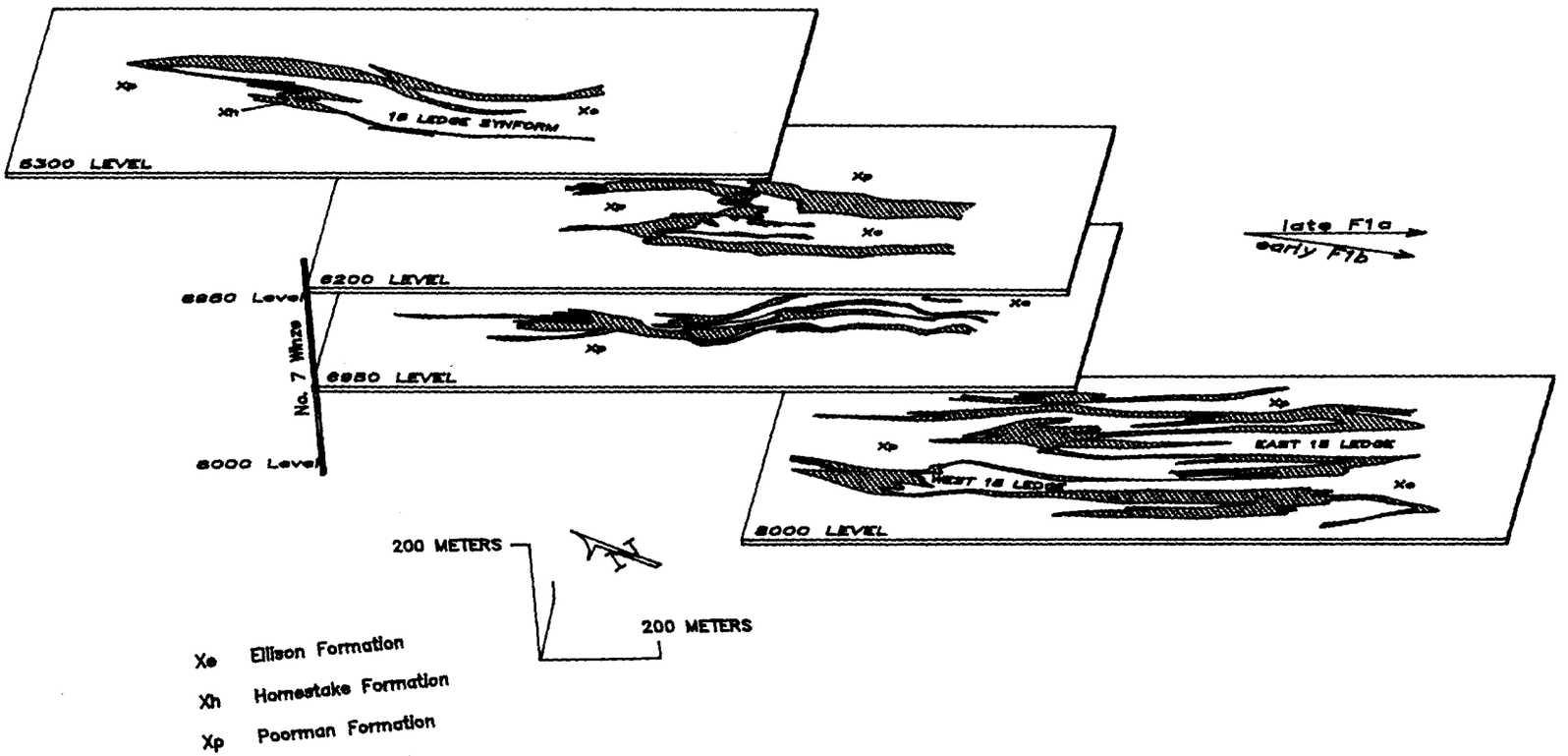

Fig. 10. Isometric view of 15 Ledge geology on 5300, 6200, 6950, and 8000 levels, Homestake mine, Lead, SD.

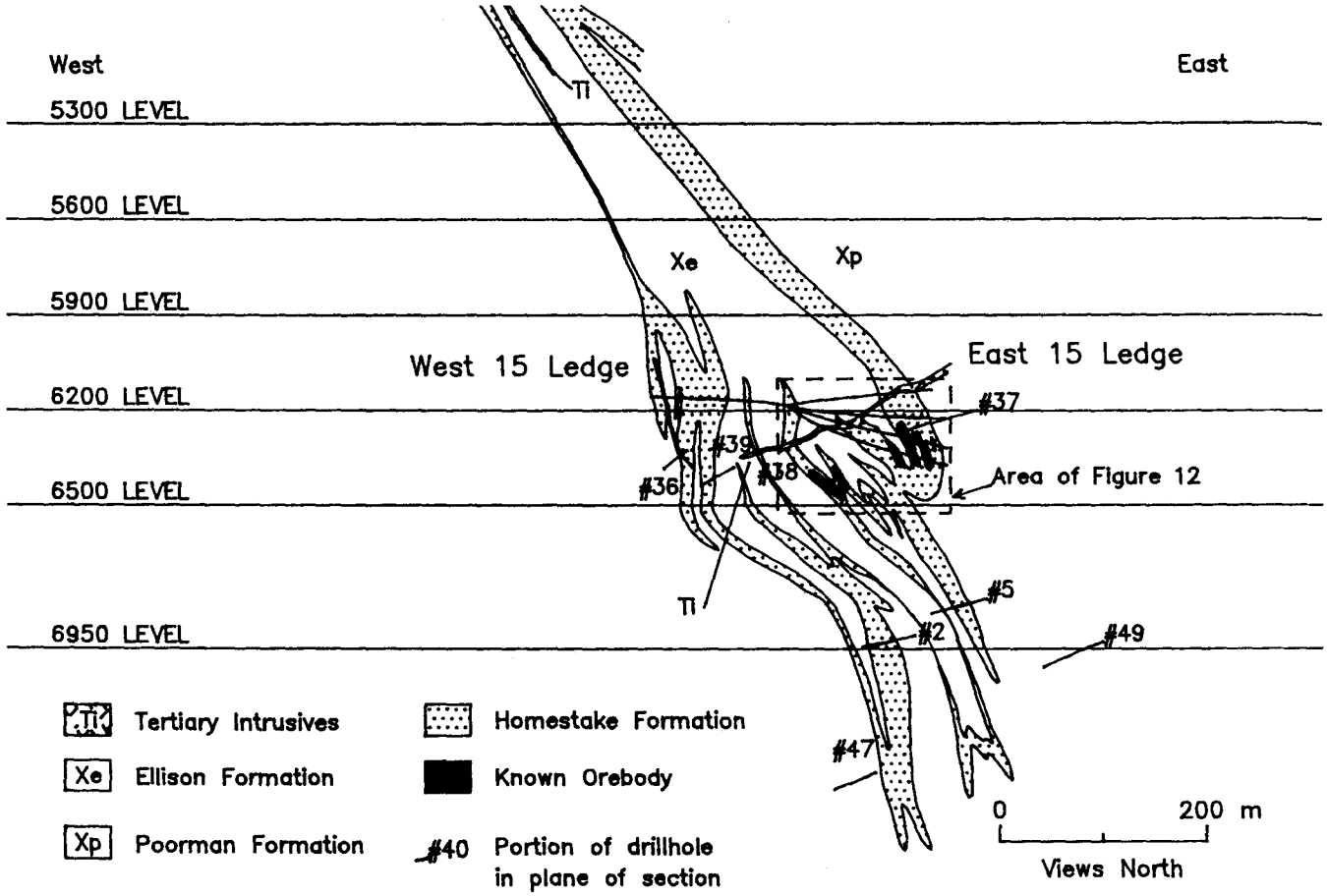

Fig. 11. Geologic cross-section through 13 Stope, 15 Ledge, Homestake mine, Lead, SD. See fig. 9 for location.

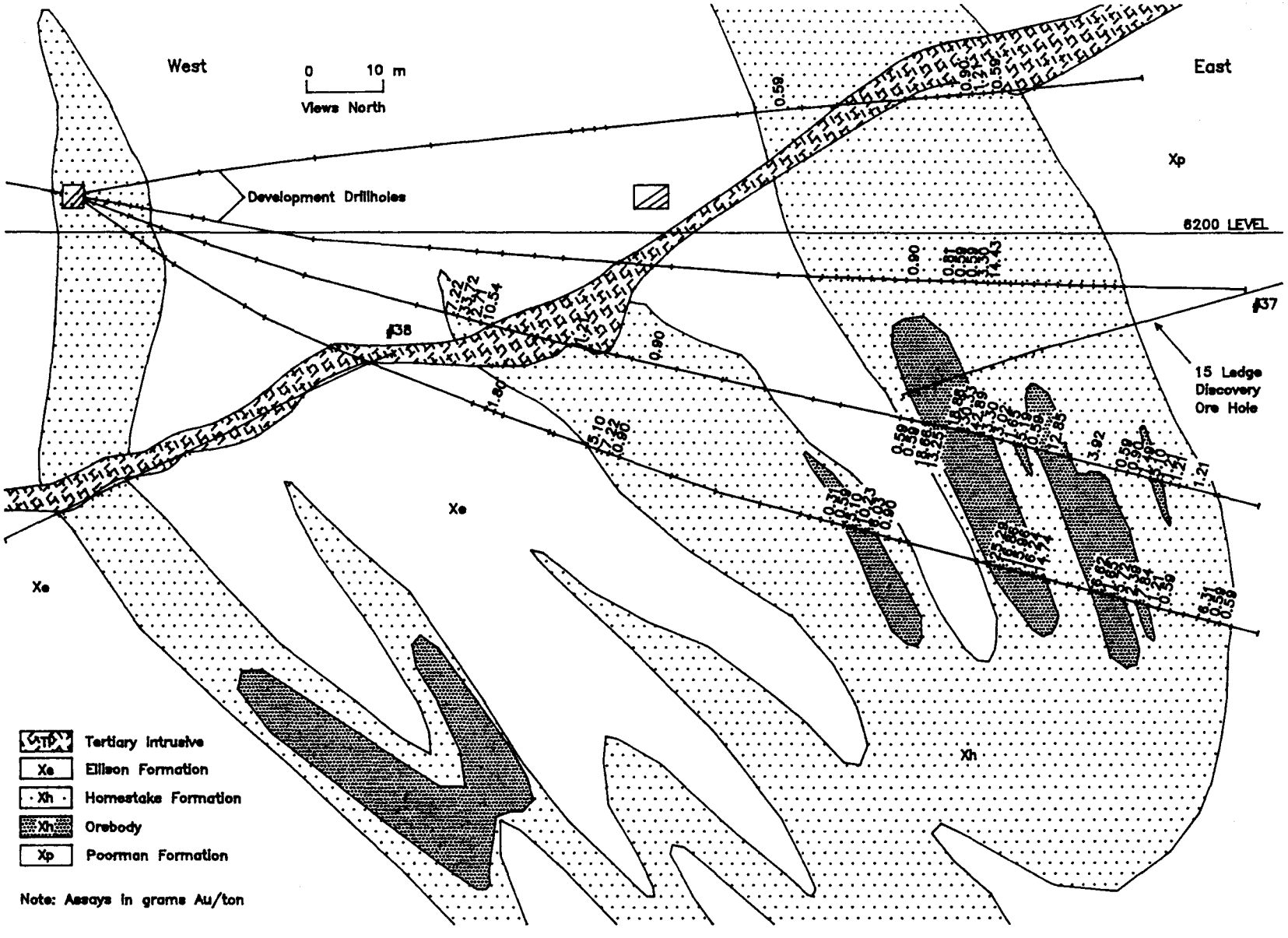

Fig. 12. Detailed geologic cross-section through 13 Stope, East 15 Ledge, Homestake mine, Lead, SD. See fig. 11 for location.

Furthermore, the centroid of 15 Ledge may lie near the 6200 level but its true location remains uncertain. The 15 Ledge ore discovery events are summarized on Table 1.

BLE 1.

SUMMARY SEQUENCE OF 15 LEDGE
ORE DISCOVERY EVENTS

Event	Date
Eighty-three core holes completed between the 2600 and 6800 levels, no orebodies were detected.	Pre-1983
Systematic exploration drilling commenced, focused below the 5300 level	Jan. 1985
First encouraging drilling results (1.6m ≥ 4.7 g Au/t), on the 6950 level	Feb. 1985
First ore grade intercept (≥5m≥4.7 g Au/t), on the 6950 level	Apr. 1985
Discovery ore hole #37, encountered near the 6200 level	June 1987
Development drifting commenced on the 6200 level	Oct. 1987
Development drilling commenced on the 6200 level	Aug. 1988
Preliminary orebodies delineated on, above and below the 6200 level	June 1989
Stope development and sill mining commenced on the 6200 level	Oct. 1989
Initial ore reserves defined	Dec. 1989

Geologic Summary

Variations in fold style along plunge observed in 15 Ledge are characteristic of all ore ledges in the mine (fig. 10). The attenuated nature of the fold profiles on mine level plans is characteristic of the western ore ledge system localized along the eastern margin of the Homestake Deformation Zone (HDZ, fig. 5). The 15 Ledge structure evolves into a well developed double synform with attenuated fold forms and sheath folds from the 5300 to the 8000 levels (figs. 10 and 11). The orebodies are localized within middle D1b shears (not shown). Most orebodies occur near or along rheologic boundaries between Homestake Formation and adjacent phyllites or quartzites of the Poorman or Ellison Formations respectively as shown simplified on figure 12 (Caddey et al, 1990).

CONCLUSIONS

The exploration success of 15 Ledge can be attributed to several factors. The importance of subtle low grade gold occurrences was recognized and properly interpreted as representing an upper tail position in a small ore ledge. The 15 Ledge centroid level was a projection of the

known centroid trends of the eastern and western ore ledge systems. It was targeted to lie well below the 5300 level. Systematic drilling in a predetermined array and spacing was patterned after historical drilling results in the known ore ledges. Multiple mine levels were drilled to optimize the statistical chance of penetrating an orebody. The successful outcome required persistence, patience, and determination in addition to management support to complete the drilling program as originally designed. The drill hole array and drilling process was innovative, technologically advanced, and markedly effective by drawing on past experiences, successes, and shortcomings. Consequently, it was possible to discover a new ore ledge over a shorter time interval and at lower cost relative to historical exploration practices.

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