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STRUCTURAL EVALUATION OF THE ANVIL DISTRICT, YUKON TERRITORY

PART 2: STRUCTURAL ANALYSIS

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INTRODUCTION

Ten days were spent in the Anvil district evaluating the structural setting of the Anvil sulphide deposits and assessing the exploration programme of Curragh Resources. Particular attention was focussed upon the structural evolution of the orebodies and their host rocks and upon the collection of structural data during the mapping and exploration programmes.

The following recommendations are made regarding the geological programme in the Anvil District -

RECOMMENDATIONS

1. The overall structural database for the Anvil District is sound and of good quality. However more attention could be focussed upon the following features -

a) Recognition of D_2 extensional faults within the metasedimentary sequence - they will be found not only at the margins of the Anvil Batholith but also within the cover sequence. Kinematic indicators such as rotated porphyroblasts, shear bands and crystallographic textures need to be analysed in order to determine the shear sense. Identification of these D_2 extensional faults in drill core will be extremely important in drawing correct cross-sections.

b) More linear data need to be collected to define structural domains and plunges of structures. This should then be incorporated in the drill hole analysis to reorient structural features in the core.

c) Great care needs to be taken in distinguishing between S_0, S_1, and S_2 planar fabrics. In some cases (e.g. NW Faro area) the flat lying, gently SW dipping schistosity is probably S_1 and not S_2 as it is generally assumed to be. This needs to be taken into account as it cannot automatically be assumed that S_1 was everywhere steeply dipping prior to the D_2 deformation.

d) Down plunge projection techniques should be used for section construction. The structural data base should be established in conjunction with a computer programme such as TRIPOD (H. Charlesworth, University of Alberta). The dip-isogon technique for fold profile reconstruction should be used on down plunge projections in order to reconstruct reasonable cross-sections on a detailed scale.

2. The structural history, as outlined in the main body of the report, places significant geometric constraints upon exploration strategy in the Anvil District. These are -

a) The linear distribution of orebodies within the Anvil District is either a reflection of a primary, near-linear syndepositional fault control on sulphide body location, or the result of structural alignment during D_1 deformation (probably the hinge region of a large recumbent F_1 fold), or the result of a combination of both of the above processes. If the first is true then one might expect other primary fault/growth trends to be mineralised but now buried at depth under the large F_1 fold that dominates the district. If the second hypothesis is true then orebodies will be located in the F_1 hinge regions only and largely constrained to linear trend already well defined. If the third hypothesis is true then the early linear structure controlled the inversion of the orebody trend such that the F_1 hinge and the syndepositional feature now coincide. In the last two cases, F_1 hinges would be the most favourable exploration targets.

b) Major D_2 extensional faults disrupt the F_1 fold such that on flat or shallowly dipping limbs, prospective stratigraphy is extended and separation occurs. For steep, to overturned F_1 fold limbs the strata are repeated in a horizontal plane such that a widening of the zone of favourable strata occurs.

c) F_3 folds are relatively minor with significant folds having only been identified in the Faro pit area. These produce hinge thickening in the ore zone and are locally important for grade control within the pit.

3. Detailed mapping of the Faro open pit is essential and should be continued not only to establish close grade controls but also to improve the structural data base for exploration and use in the subsequent open pit operations. In particular the Vangorda pit should be mapped from its inception. A fully qualified structural geologist with at least MSc level structural geology training should be employed to undertake this work. Such a programme should be married to the establishment of a structural database and projection computer programme (e.g. TRIPOD) in order to effectively handle the data generated and to be able to incorporate them in section and map construction.

4. A research project should be established to undertake detailed analysis of the structure and genesis of the Vangorda deposit as it comes into production. As the Vangorda mine life is expected to be relatively short, it is important that this project be initiated as soon as possible. Such a research project would complement the production geology and provide important data for local grade control as well as data for exploration.

5. It is recommended that the use of the UTEM EM system be investigated in order to locate conductive horizons at depths of 1Km or greater. Trial experiments should be carried out over the Vangorda, Grum and DY deposits to see if graphitic schists and sulphides can be distinguished at depth. The EM may also help to delineate the effects of large D_2 extensional faults at depth.

STRUCTURAL ANALYSIS

The Anvil District, central Yukon (Fig. 1) lies just north of the Cretaceous-Tertiary Tintina dextral strike-slip fault system. Most of the district is underlain by strata with affinities to ancestral North America whilst the southern flank contains suspect or allocthonous terranes (Jennings and Jilson, 1987).

The Anvil District is underlain by up to 5 km of poly-deformed, greenschist to amphibolite facies, metasediments and volcanics that range in age from Late Precambrian (Hadrynian) through Mississippian-Permian. These have been intruded by a Cretaceous plutonic suite (the Anvil Batholith). The stratigraphic column for the Anvil area is summarised in Fig. 2 (from Jennings and Jilson, 1987).

Five ductile deformations have been documented (Jennings and Jilson, 1987) in the region. The first two deformations, D_1 and D_2 produced penetrative foliations (S_1 and S_2 respectively), folding and ductile faulting. D_3 to D_5 produced minor folding and steeply dipping crenulation foliations that deform S_1 and S_2.

The dominant structure of the region is a broad doubly plunging antiform, the Anvil Arch (Fig. 3) which is attributed to emplacement of the Batholith, uplift and associated ductile extensional faulting (Fig. 3).

The observations and analysis which form this report generally confirm the broad structural patterns as defined by Jennings and Jilson (1987). Differences in interpretation, however, have been found and the implications for various tectonic models are discussed. Table 1 summarises the deformation features as found by Jennings and Jilson (1987) and in this study.

D_1 DEFORMATION

D_1 deformation is documented by sparse outcrops of F_1 folds and their associated S_1 foliation (cleavage) in the southern Vangorda Plateau area in the vicinity of Blind Creek and the DY deposit. Here they appear to be protected from later D_2 deformation by nearby intrusives. Where observed in outcrop the F_1 folds are upright, close to isoclinal with an upright S_1 foliation (Fig. 5). The vergence of these F_1 folds appears to be consistently to the NE (Fig. 6). Where observed the S_1 foliation is crenulated by a flat lying to SW dipping S_2 foliation (Figs. 5 - 7). The poor outcrop hinders the recognition of larger D_1 structures but possible large F_1 fold closures may occur in the Grum deposit (Jennings and Jilson 1987). The overall structure of the first deformation appears to be that of a large, penetratively deformed thrust sheet or thrust nappe. As such the basal detachment cannot as yet be clearly identified on the SW side of the Anvil Arch - not surprisingly as here it would essentially be parallel to the dominant foliation, where S_1 and S_0 are essentially parallel.

D2 DEFORMATION

D_2 Deformation is characterised by a penetrative SW dipping foliation S_2 and minor to meso scale SW verging folds. D_2 folds typically have S_1 preserved in their hinge regions (Fig. 8) whereas on their limbs S_1 is transposed parallel to S_2 (Figs. 9 & 10). This form of transposition is accompanied by severe thinning on the limbs of F_2 folds (probably achieved by pressure solution) and the development of microlithons (Figs. 9-11). On the limbs of F_2 folds it is almost impossible to distinguish between S_1 and S_2 foliations in the hand specimen or in outcrop.

On the Vangorda Plateau S_2 is the dominant foliation with S_1 only being observed in the hinges of F_2 folds (Figs. 8 & 9). In the Faro

Northwest area the dominant foliation appears in some outcrops to be rotated S_1 shown by the relationships around F_2 folds (Fig. 12).

In drill core from the Grum and Vangorda deposits, S_1 and S_2 are the dominant foliations (Figs. 13 & 14) with S_2 being a pressure solution foliation that concentrates the sulphides (Fig. 13). In some cores S_0, S_1 and S_2 can all be found (Fig. 14) but determining their true orientations is extremely difficult.

D_2 Extensional Faulting

This study found that D_2 ductile extensional faulting around the margins of the Anvil Batholith was more pervasive than hitherto thought. One such ductile fault (extensional shear zone) runs parallel to stratigraphy on the SW side of Mt. Mye (Fig. 15) and links into the Tie Fault. Such faults are recognised by a narrow zone of intense shearing (Fig. 16) with the development of cataclasites and ultra-cataclasites (Figs. 17 - 19). These rocks are commonly fragmented, very fine-grained to ultra-fine-grained, black in colour and largely consist of highly comminuted Mt. Mye schists. In places a characteristic S-C band structure is developed and where observed these always indicate top to the SW on the SW side of the Anvil Batholith - i.e. extensional tectonics. In cross-section the hangingwall Mt. Mye schists dip at a lower angle than the extensional shear zone. The granite close to this detachment is also foliated and displays classic S-C band relationships indicating down dip extensional movement parallel to the granite - country rock contact (Fig. 15). The calc-silicates and marbles in the country rock Mt. Mye schists develop ductile shear fabrics with classic porphyroclast rotational structures (Fig. 20).

In drill holes - e.g. DDH A98 (Fig. 21), the granite/country rock contact also exhibits ductile to brittle extensional fault fabrics with a transition from highly sheared and S-C banded granite through a brittle 'chloritic breccia' to highly foliated fault gouge within the country rock schists (Fig. 21). Elsewhere, similar foliated fault gouges with extensional S-C bands are found - particularly in the footwall to the DY orebody. These data together with reinterpretation of surface data indicate that pervasive ductile to brittle extensional faulting occurred probably late in the D_2 deformation. The fabric relationships indicate that S_2 foliation was developed sympathetically with these extensional faults.

These structures and lithologies are characteristic of metamorphic core complexes - here they are associated with the emplacement and uplift/unroofing of the batholith. The transport on the unroofing faults is probably only of the order of 1 - 3 km maximum - sufficient to develop a narrow penetrative shear zone capped by an upper brittle detachment.

D_3 - D_5 DEFORMATION

These deformations are most commonly observed as crenulation lineations on S_2 surfaces. Mesoscale F_3 folds are found in the vicinity of the Faro orebody (Jennings and Jilson 1987) possibly due to the anisotropy and ductility contrasts provided by the massive sulphides. Great care needs to be exercised in assigning any particular fold/crenulation to D_3 through D_5 as orientation alone cannot be used as a discriminator.

Table 1 below summarises the main elements of the deformation history of the Anvil area. D_3 to D_5 from Jennings and Jilson (1987) have been retained for consistency but will require careful justification in future research.

TABLE 1 SUMMARY OF DEFORMATION HISTORY

EVENT	STRUCTURE	VERGENCE	FABRIC ELEMENTS
D_1	Thrusting Thrusts? Anvil Nappe?	NE	S_1 and F_1 Folds
D_2	Shearing Extensional Faulting	SW	S_2 and F_2 Folds Transposition of S_1 to S_2
D_3	Folding Crenulations	NE	S_3 and F_3 Folds
D_4	Crenulations	NE	Weak S_4
D_5	Weak Folding	?	Weak S_5

Adapted from Jennings and Jilson (1987).

DISCUSSION

Within the Anvil District there are a number of distinct features that are directly relevant to exploration and to models for the development of the Anvil Orebodies.

1. S_2 is penetratively developed, SW dipping and with a SW vergence.
2. S_1 is mainly observed in the hinges of F_2 folds..
3. In many outcrops S_1 and S_2 are parallel - generated by transposition of S_1 to the S_2 orientation.
4. D_1 and D_2 deformations are essentially coaxial but with opposite vergences.
5. Deformations D_{3-5} are essentially minor - of importance in mining and for definition of the orebodies but probably not in their effects in controlling exploration targets.
6. The extreme linear distribution of the Anvil orebodies (Fig. 3) points to a fundamental tectonic control.

Depositional Model for the Anvil Massive Sulphide Orebodies

The extreme linear distribution of the Anvil deposits attests to a fundamental tectonic/structural control. By analogy with previous research on other stratiform sulphide orebodies it is likely that syndepositional extensional faulting played an important role in the localisation of the sulphide deposits. Such a model invokes a terraced platformal area (i.e. relatively shallow water) which is cut by a system of linked extensional faults that lead into a deeper water half-graben basin system (Fig. 22). Such a system would have a linear or near linear trend and in cross-section would appear as in Figure 23.

Deformation Models

Early deformation of such an extensional fault system would involve inversion of the half graben with partial reactivation of the graben faults into thrust faults (Fig. 24). Such a system places a primary control on the disposition of the thrust faults which persists even when the contractional deformation becomes penetrative and extreme. Thus it is believed that such a system of faults as schematically outlined in Figure 22 would exert a fundamental control on the later contractional structures - folding and faulting.

The following structural scenario for D_1 and D_2 deformations is postulated (Fig. 25)-

D_1 SW to NE directed thrust faulting, development of an Anvil Nappe with penetrative S_1 foliation sub-parallel to S_0.

D_2 NE to SW directed shearing and extensional faulting - perhaps in part associated with 'orogen collapse' and in part associated with emplacement and unroofing of the Anvil Batholith.

Figure 25 is a schematic summary of this model. D_2 deformation is a variation on a metamorphic 'core complex' model in which younger rocks are emplaced by ductile to brittle extensional faulting against higher grade, older rocks.

The kinematics for such a model have important implications for the fabric relationships that one might expect in outcrop or in drill core. These are -

1. S_1 shows the relationships in Figure 26 with respect to an 'Anvil Nappe'.

2. Refolding by SW directed shearing produces
   - Type 3 interference folds - on the upper limb S on Z asymmetry, in the F_1 hinge S on M asymmetry whereas on the overturned F_1 limb the D_2 deformation simply enhanced/amplifies the folding (S on S).
   - S_1 is upright in the hinges of F_2 folds.
   - S_1 is folded about F_2 folds but with different axial surfaces.
   - On the limbs of F_2 folds S_2 and S_1 will be virtually indistinguishable (except in thin section).

These relationships are highlighted in Figures 27 and 28. The

implications for small scale structural observations are important.
-Classification of structures based simply upon orientation of fabric elements is not possible - close observation of overprinting relationships is essential and in many cases may only be resolved by petrofabric analysis using thin sections cut from oriented hand specimens.

FUTURE RESEARCH

Future analysis of the Anvil area will need to address the following-

1. The nature and the geometries of the D_1 deformation - are there more thrusts in the sequence?
2. The relationships of S_1 and S_2 fabric elements and the implications for the kinematics of D_2 deformation.
3. The geometries of interference folds and their positions on F1 fold limbs.
4. Definition of vergence zones in order to map out F_1 folds and F_2 structures.
5. Close analysis of events D_3 to D_5 in order to constrain these both geometrically and kinematically.

REFERENCE

Jennings, D.S. and Jilson, G.A. 1987. Geology and sulphide deposits of Anvil Range, Yukon. in Morin, J.A. (ed.) Mineral Deposits of the Northern Cordillera. CIM Special Volume 37, 319 - 361.

APPENDIX SUMMARY OF ACTIVITY

DAY 1 Structural geology of the Faro pit and review of the geology of the Faro orebody.

DAY 2 Geology of the DY and Blind Creek areas. Grum pit and Grum drill cores.

DAY 3 Southern end of Vangorda Creek and the Tie Fault Zone.

DAY 4 Anvil Batholith and Mount Mye sequence.

DAY 5 Faro NW and the calc-silicate succession.

DAY 6 Review of Anvil District geology, maps and sections.

DAY 7 Faro pit and core examination.

DAY 8 Core logging and analysis, Grum camp.

DAY 9 Core logging and analysis, Grum camp.

DAY 10 Report compilation.

DAY 11 Report compilation.

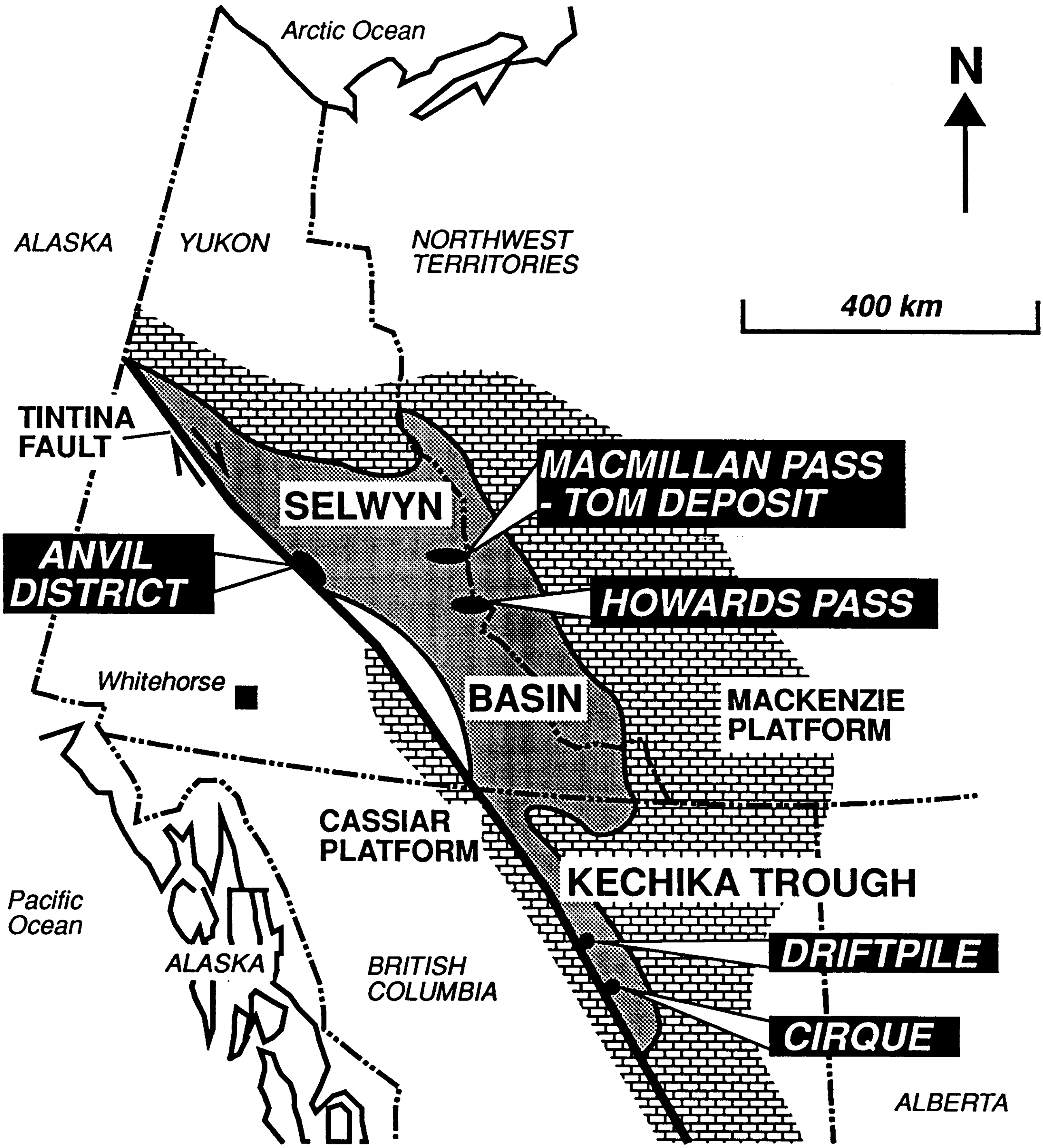
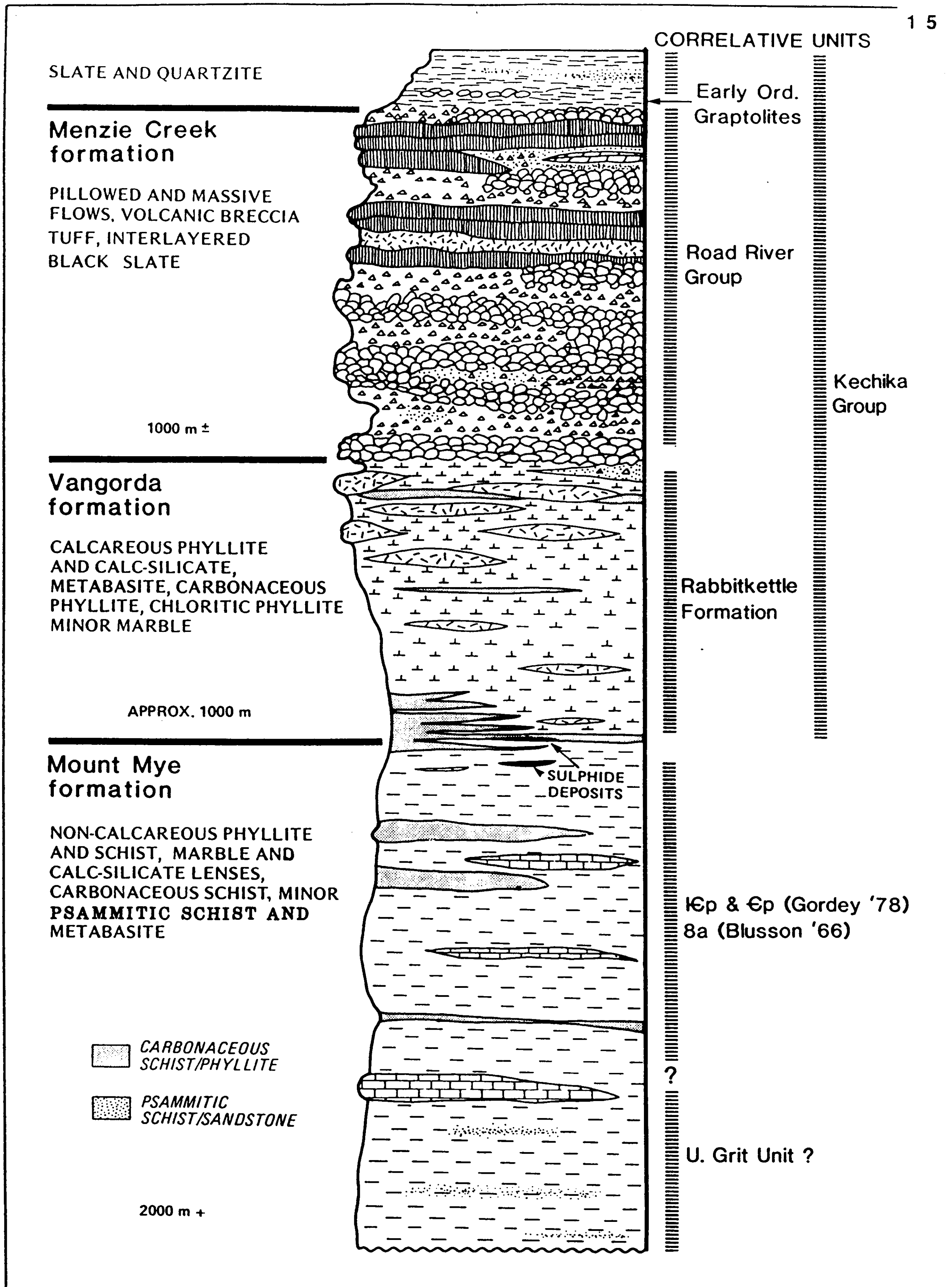


FIGURE 1 Location of the Anvil District, Yukon.



A schematic column of the older portion of the stratigraphy of the Anvil District. The sulphide deposits consist of several horizons in the upper Mt. Mye and lower Vangorda formations. The thickening of carbonaceous phyllite near the ore deposits is represented as if viewed looking northwest. The over-all section is rich in mafic volcanic and subvolcanic material but most is younger than the ore deposits.

FIGURE 2. Schematic stratigraphic column of the Anvil District (from Jennings and Jilson, 1987).

ANVIL LEAD-ZINC DISTRICT, YUKON TERRITORY

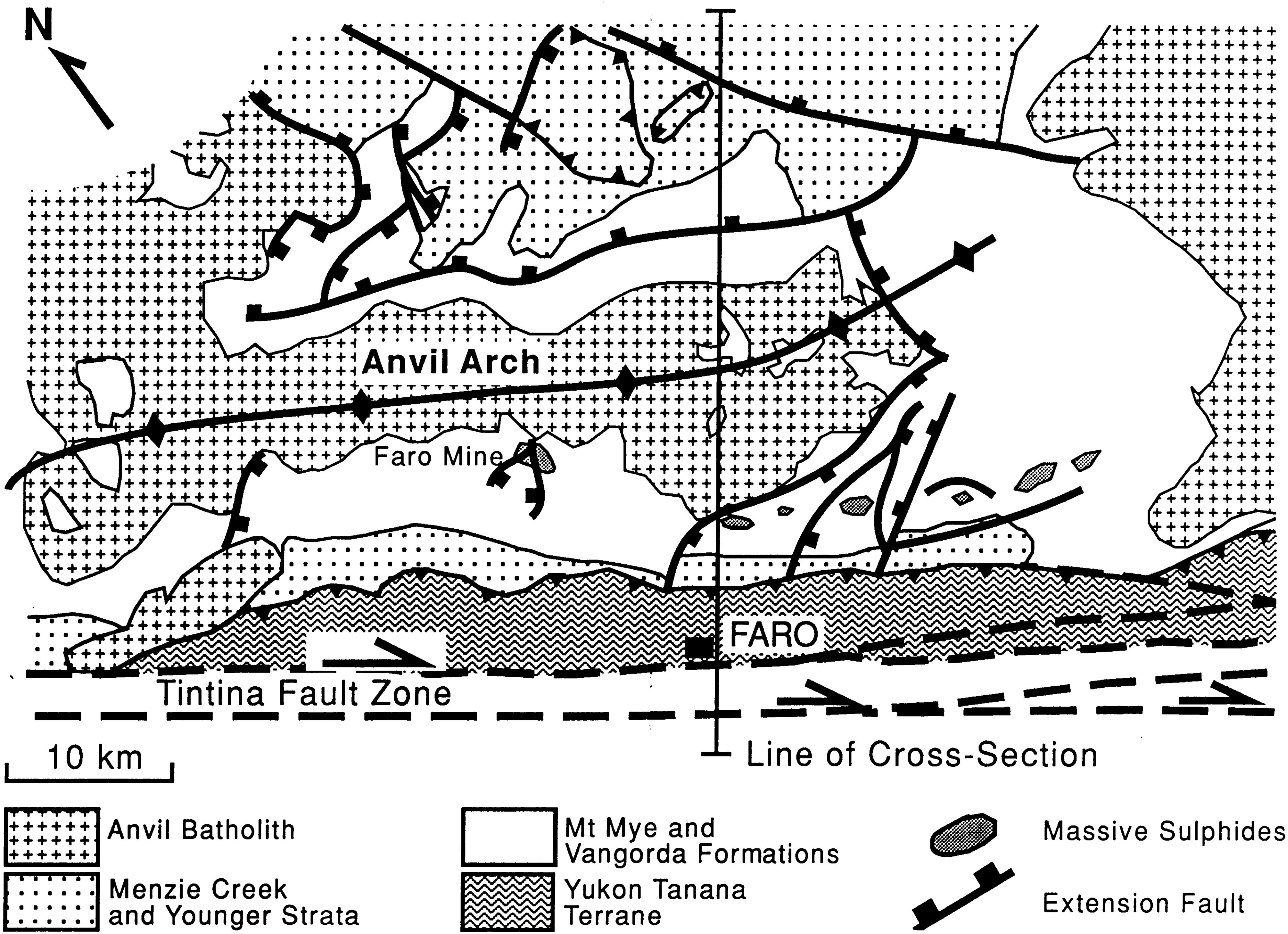


FIGURE 3. Summary map of the Anvil District emphasising the D_2 extensional faults.

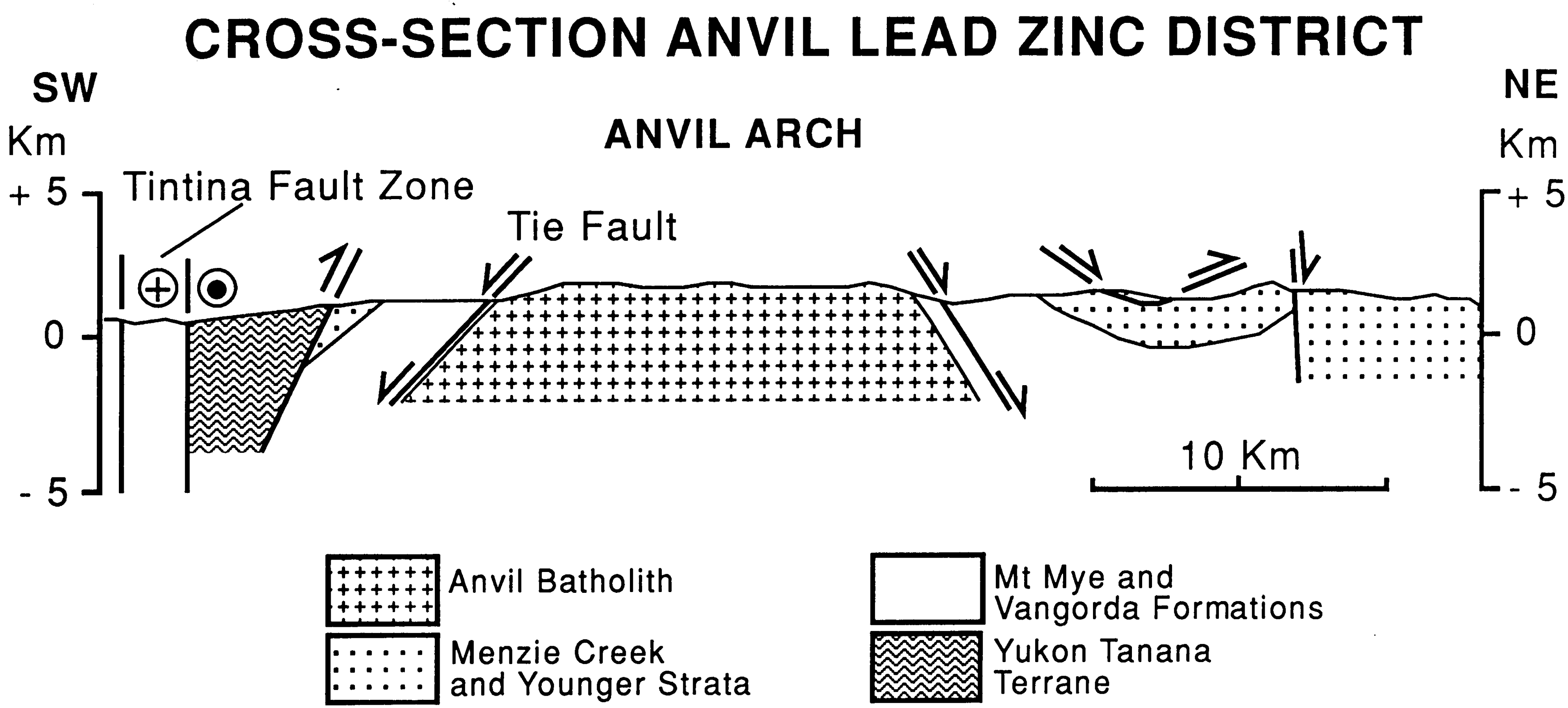


FIGURE 4. Cross-Section through the Anvil District.

FIGURE 5. Photograph of an upright F_1 Fold, Blind Creek area, Vangorda Plateau.

FIGURE 6. NE verging F1 Fold cross cut by shallowly dipping S_2 foliation.

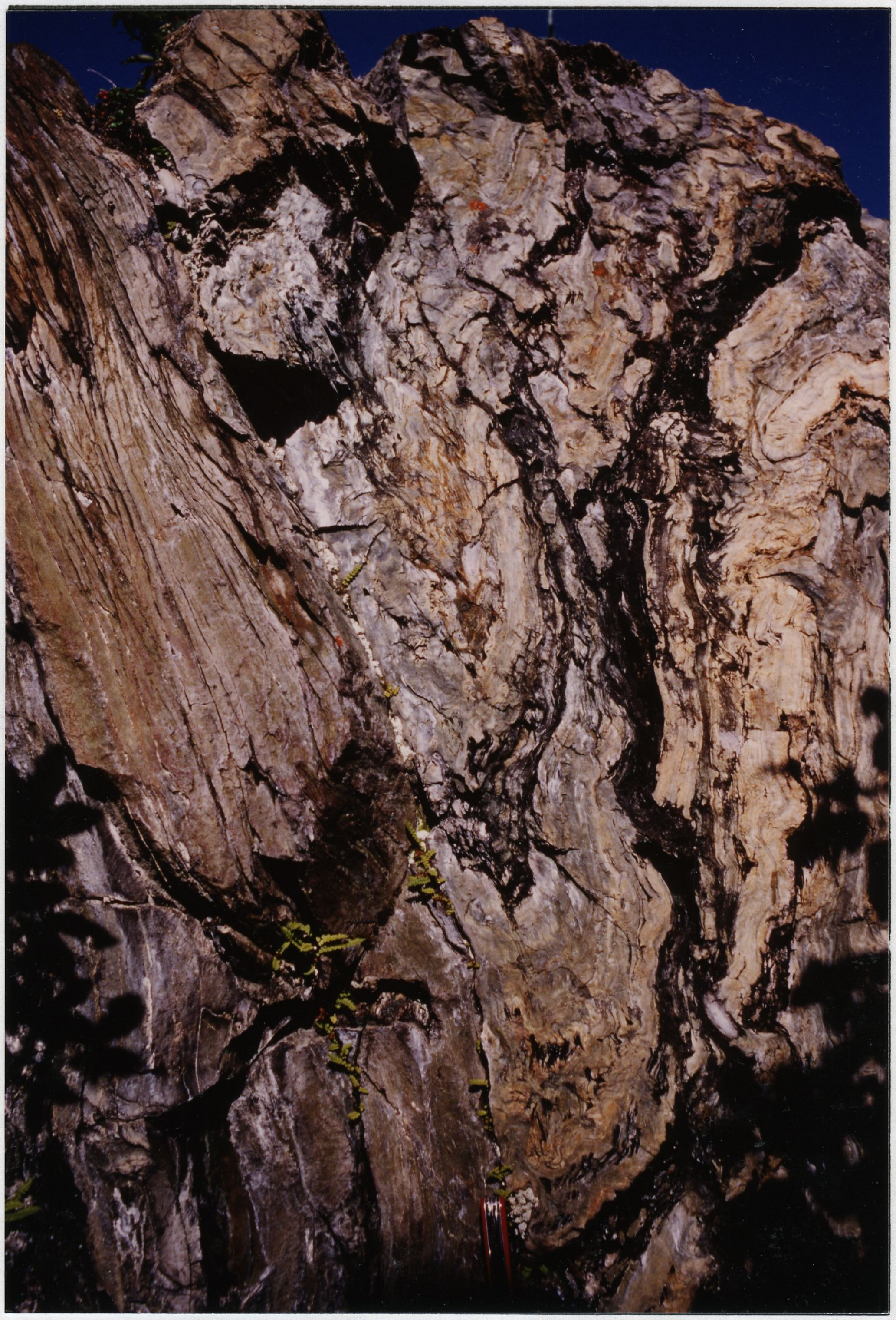


FIGURE 7. Upright F_1 Fold cut by a foliated dyke. Blind Creek area, Vangorda Plateau.

FIGURE 8. F_2 Fold with folded S_1 in the hinge zone. Vangorda Creek.

FIGURE 9. F2 Folds with S_1 in hinge zones. Blind Creek Road.

FIGURE 10. S_2 microlithons formed by the hinge zones of F_2 Folds.

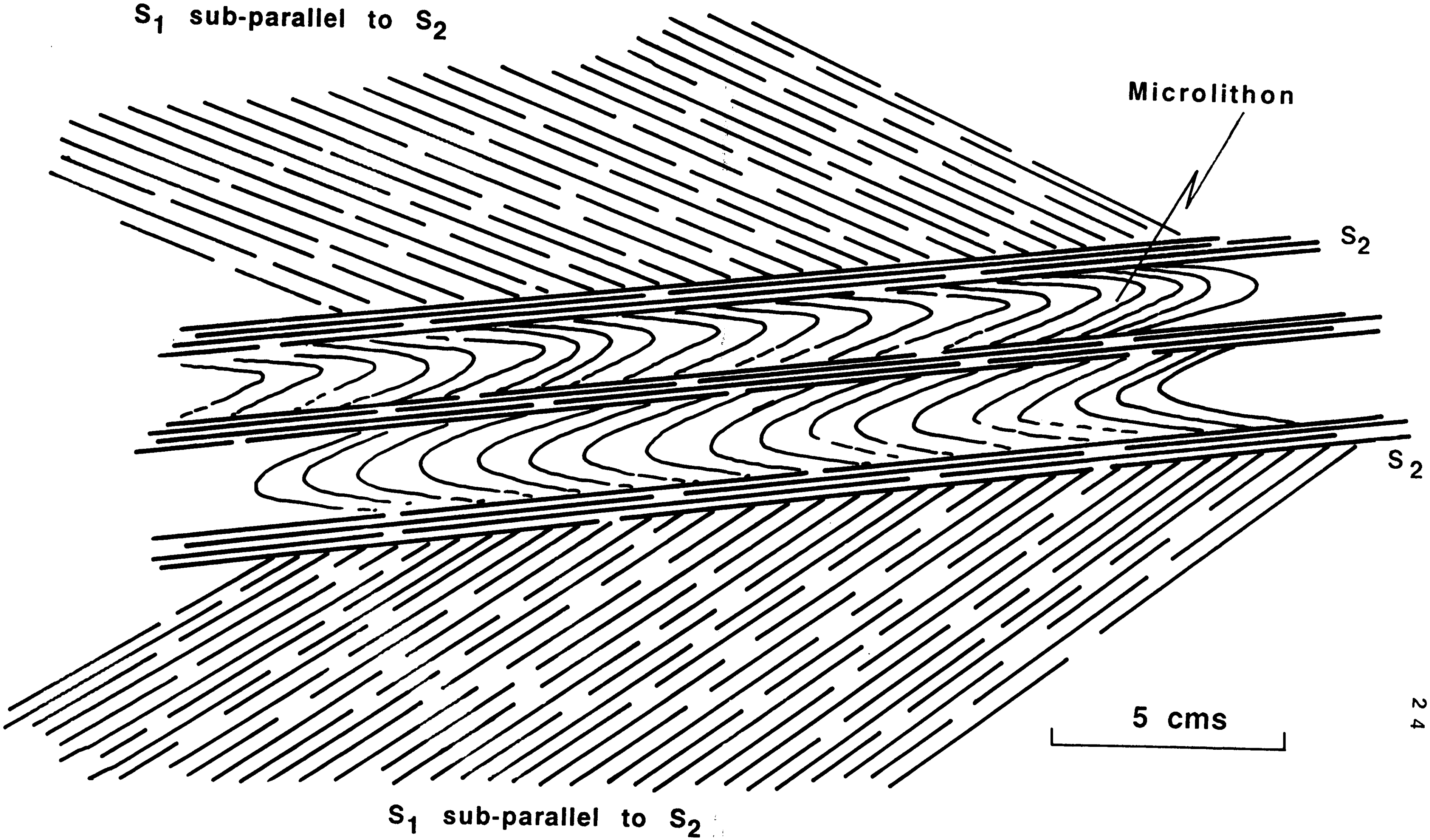


FIGURE 11. Sketch of microlithons in hinge region of F_2 folds.

FIGURE 12. F_2 fold deforming the F_1 foliation and exhibiting a weak S_2 foliation. Faro NW area.

FIGURE 13. Photograph of drill core from the Grum deposit showing typical development of S_2 foliation with pressure solution concentration of sphalerite in the foliation.

FIGURE 14. Photograph of drill core from the Grum deposit showing S_0, S_1, and S_2 in fine-grained graphitic schists.

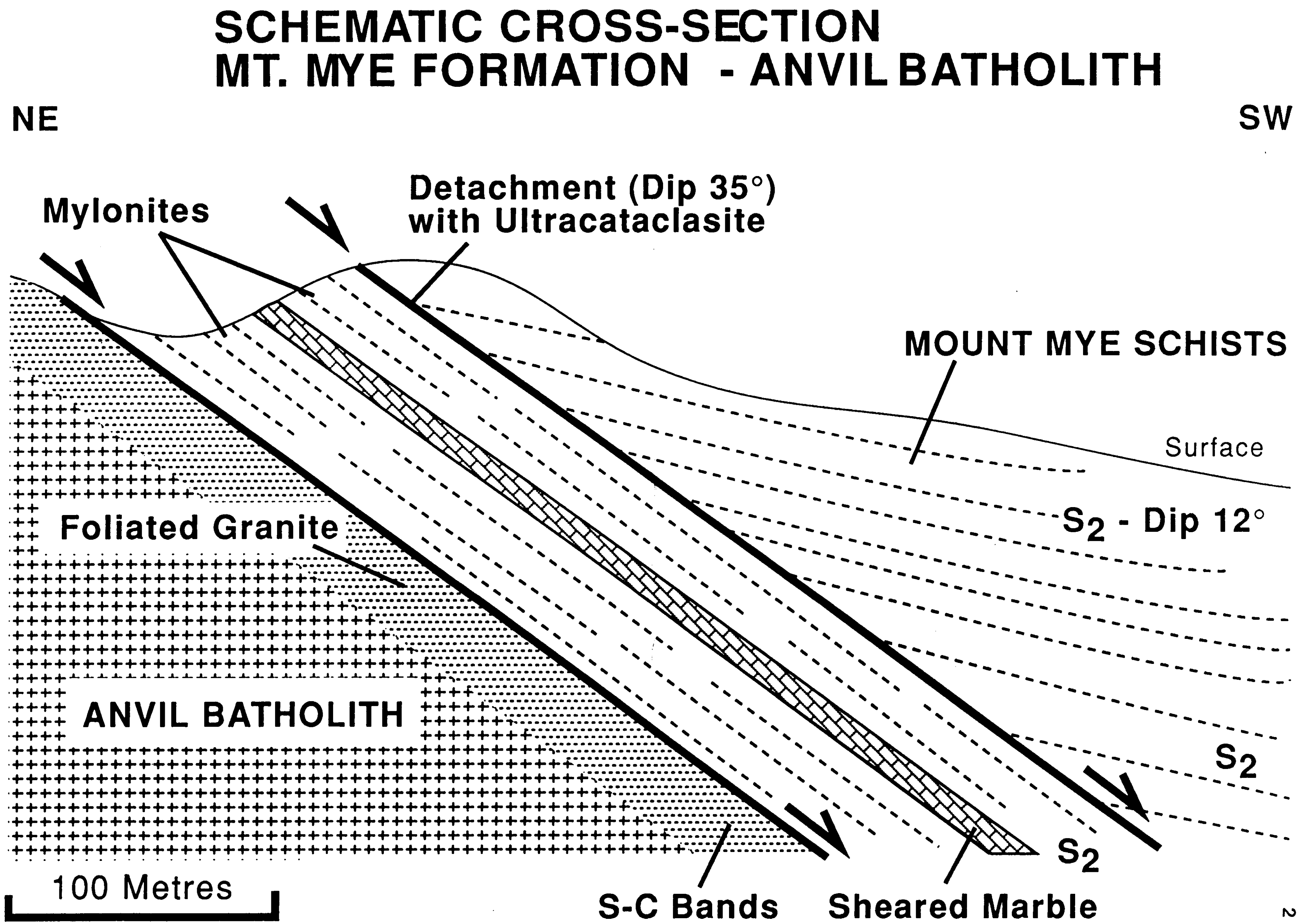


FIGURE 15. Schematic cross-section through the southern flank of Mt. Mye.

FIGURE 16. Cataclasite developed at the upper detachment of the Mt. Mye fault zone.

FIGURE 17. Cataclasite bands and ultracataclasite in the upper part of the Mt. Mye detachment, flank of Mt. Mye.

FIGURE 18. Black ultracataclasite (crush rock) in the Mt. Mye fault zone. Note offsets in the black bands by small faults.

FIGURE 19. Foliated cataclasite from the Mt. Mye fault zone showing well developed S-C bands that show extension to the left in this hand specimen.

FIGURE 20. Highly foliated marble within the Mt. Mye detachment system (Fig. 15) showing rotated calc-silicate porphyroblasts which indicate a down dip movement direction, i.e. extensional.

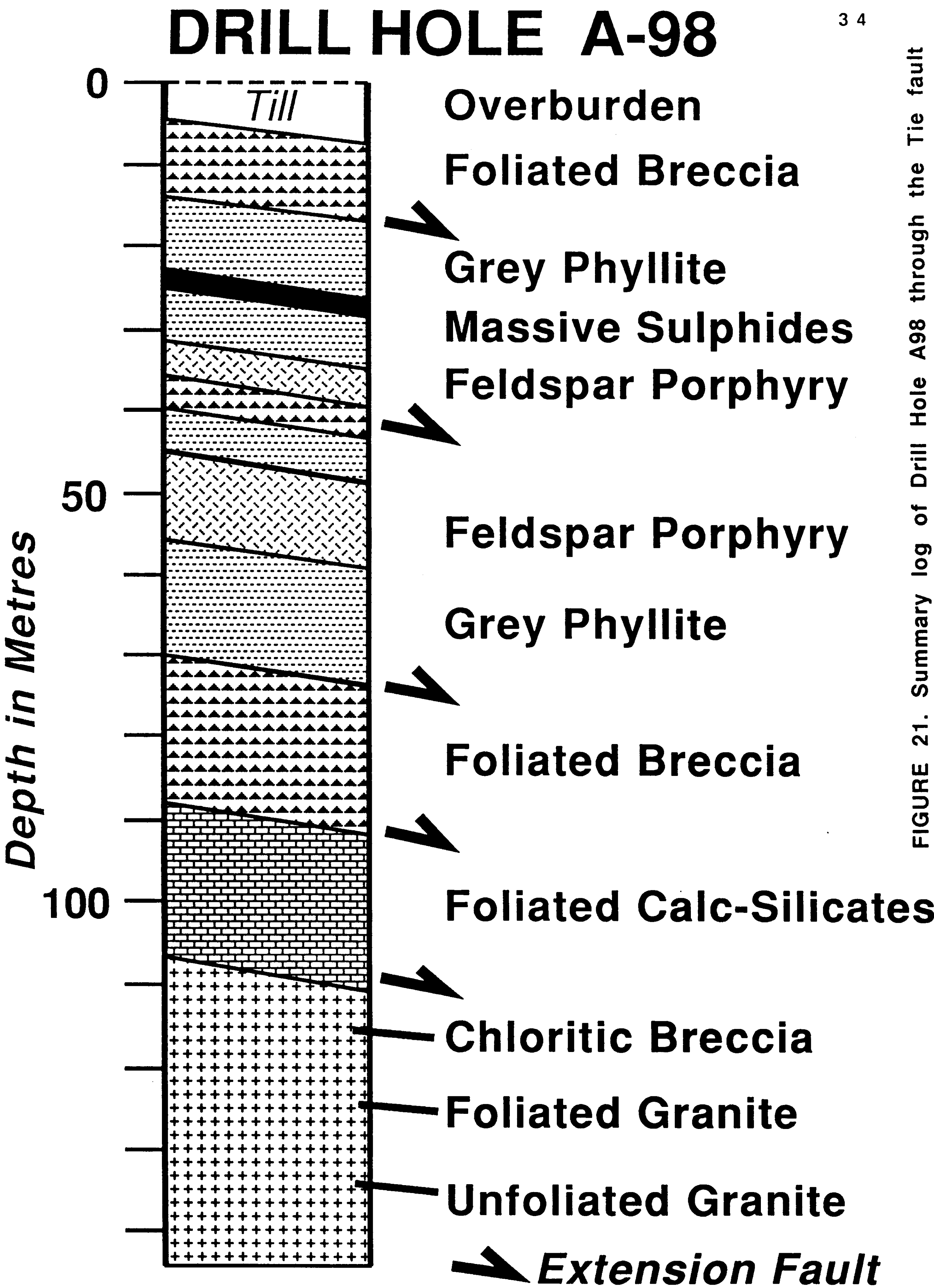


FIGURE 21. Summary log of Drill Hole A98 through the Tie fault zone. Note the development of foliated breccias and chloritic breccias adjacent to and within the granite.

DEPOSITIONAL MODEL FOR THE ANVIL MASSIVE SUPLHIDE DEPOSITS

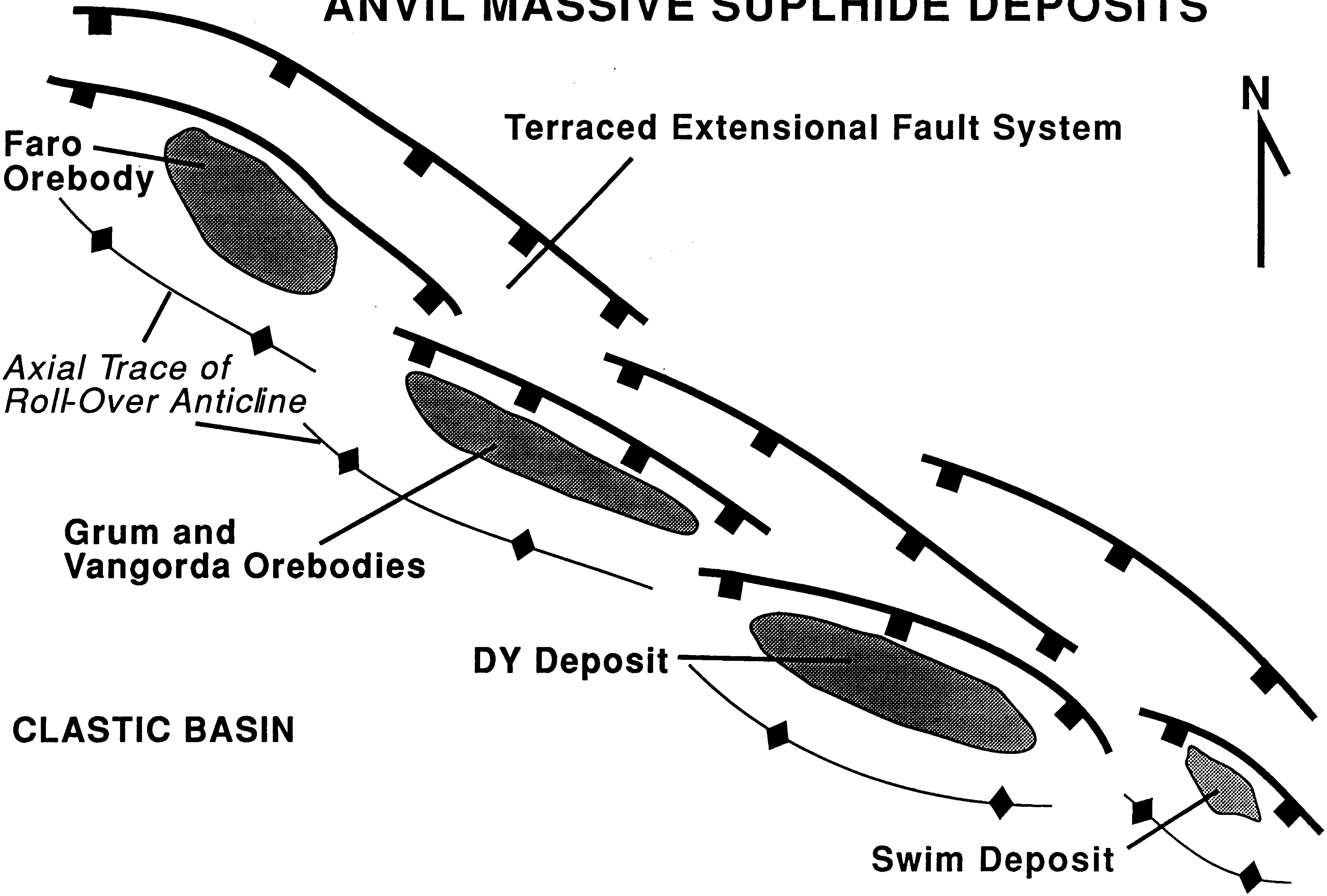


FIGURE 22. Schematic depositional model for the distribution of the Anvil massive sulphide deposits.

DEPOSITIONAL MODEL FOR ANVIL MASSIVE SULPHIDE DEPOSITS

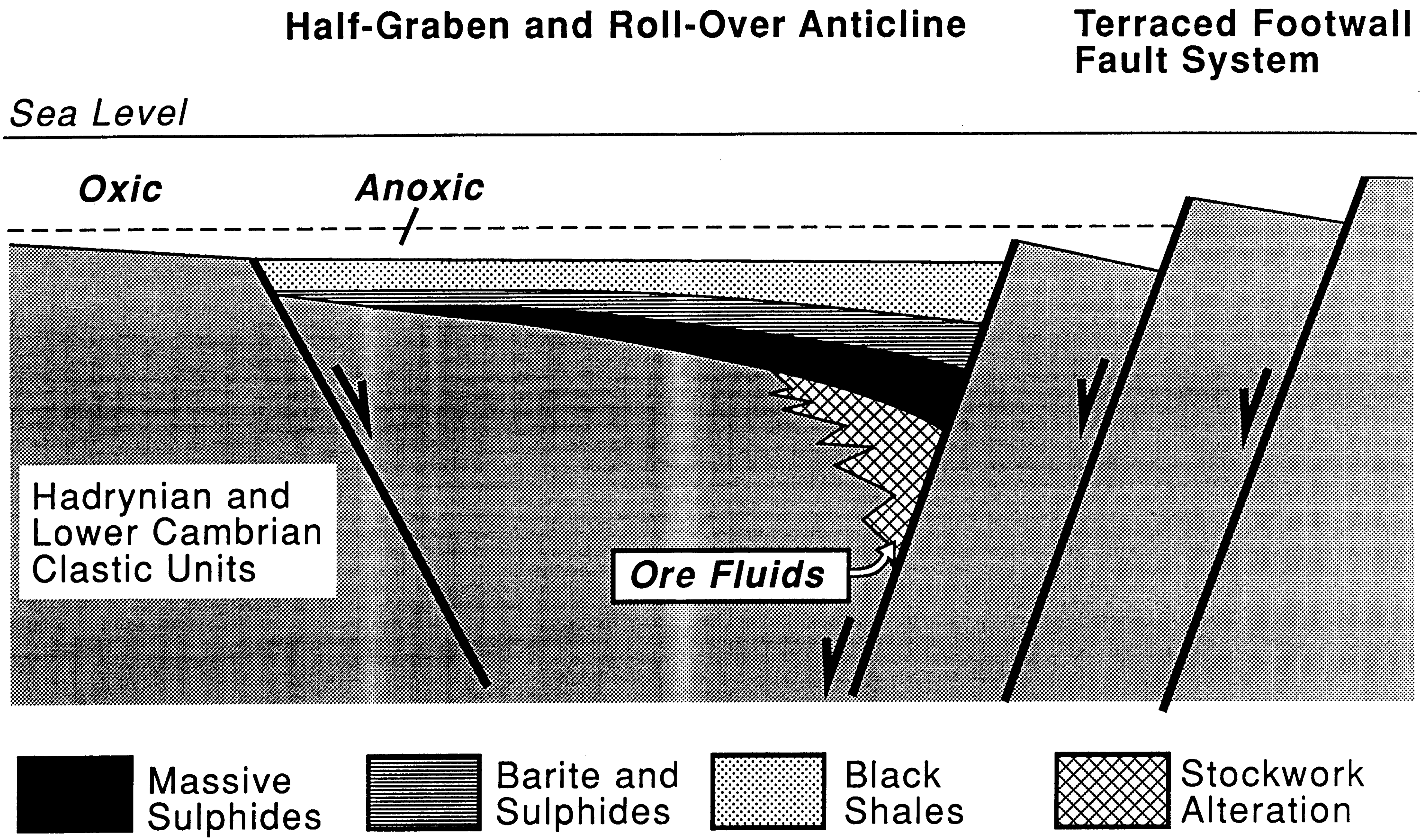


FIGURE 23. Schematic cross-section through an Anvil-type massive sulphide-barite deposit.

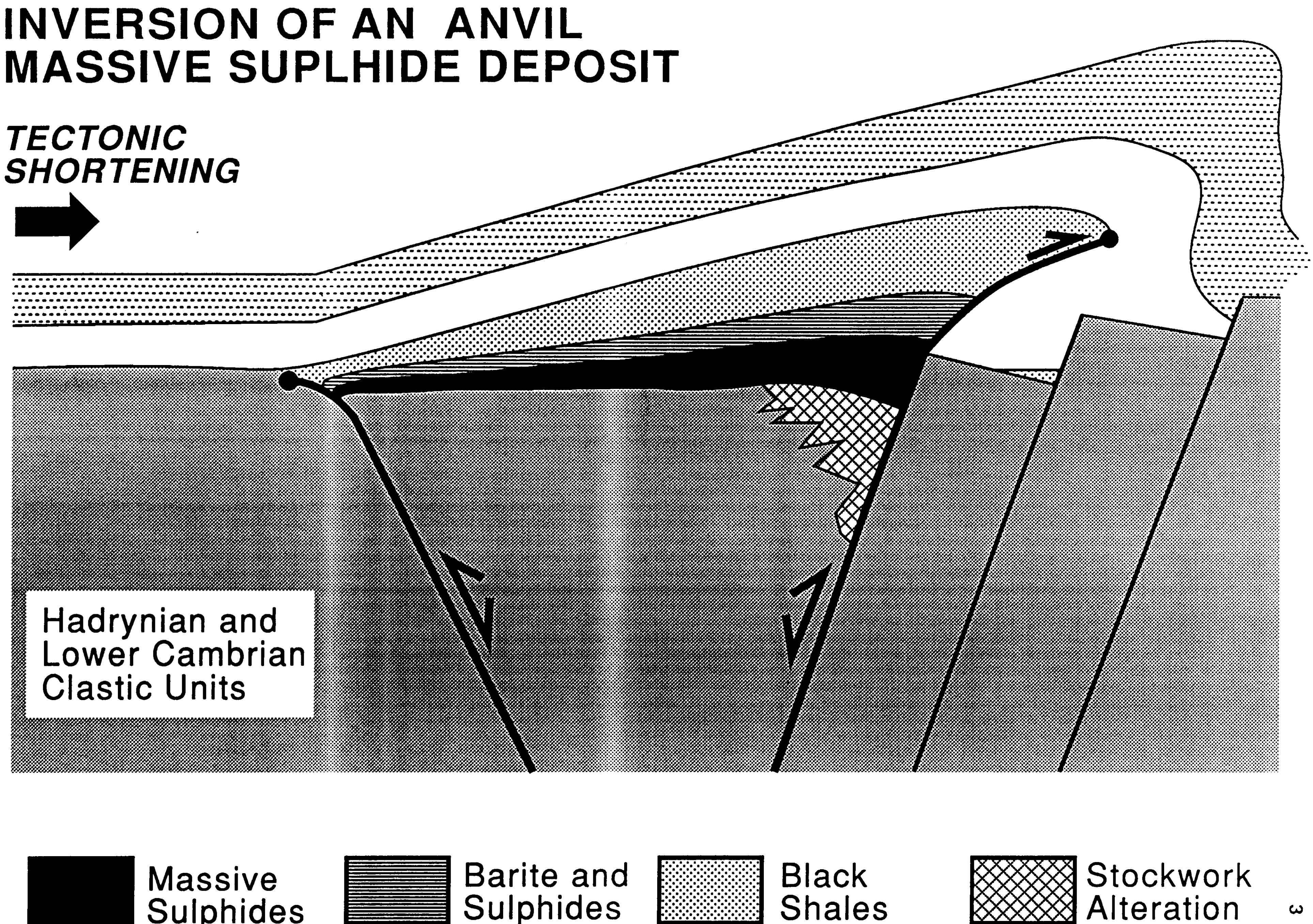


FIGURE 24. Schematic model for the partial inversion of an Anvil type massive sulphide deposit.

D_1 - D_2 DEFORMATION ANVIL RANGE

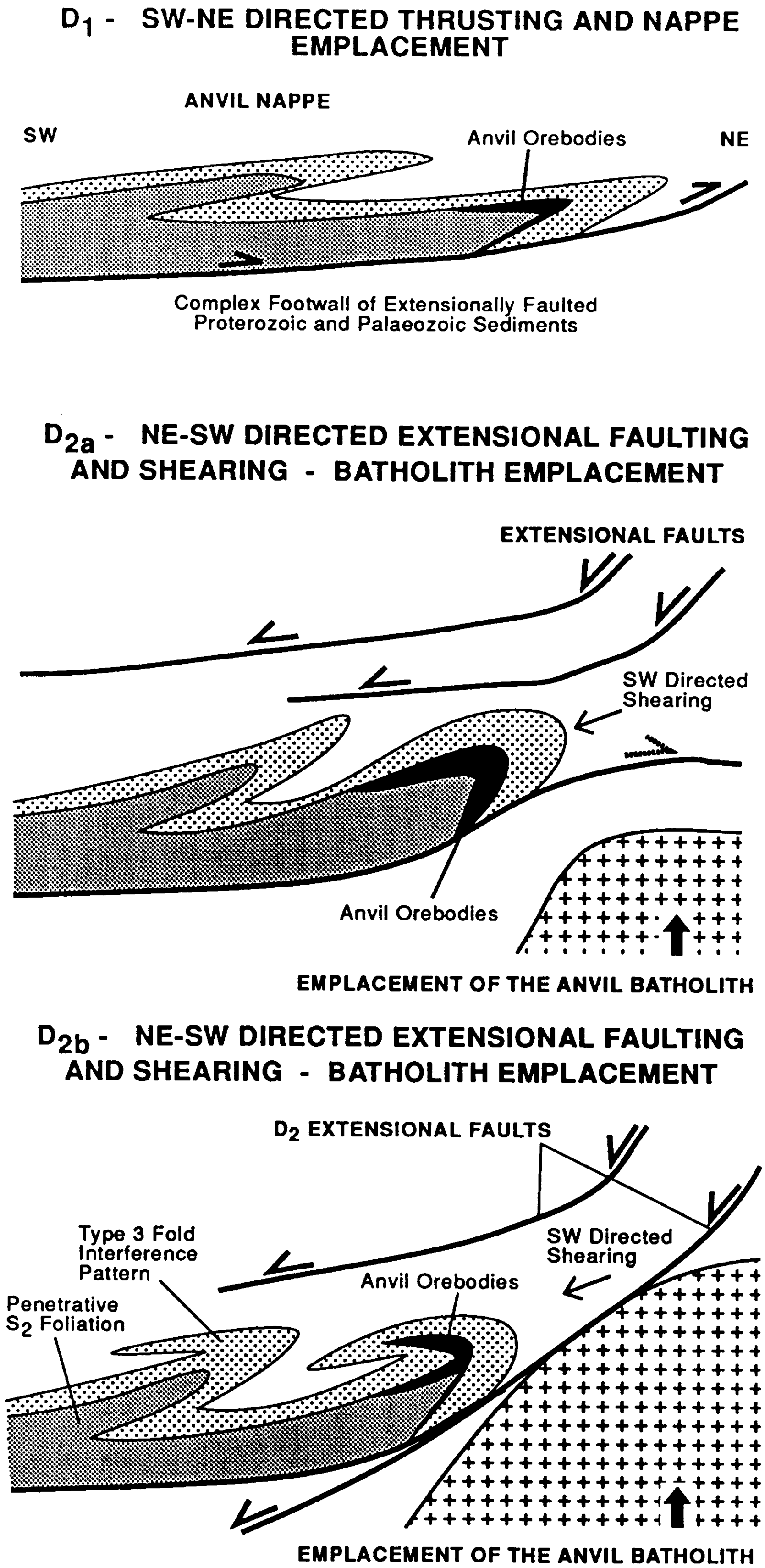


FIGURE 25. Schematic model for D_1 to D_2 deformation.

D_1 DEFORMATION - NE NAPPE EMPLACEMENT?

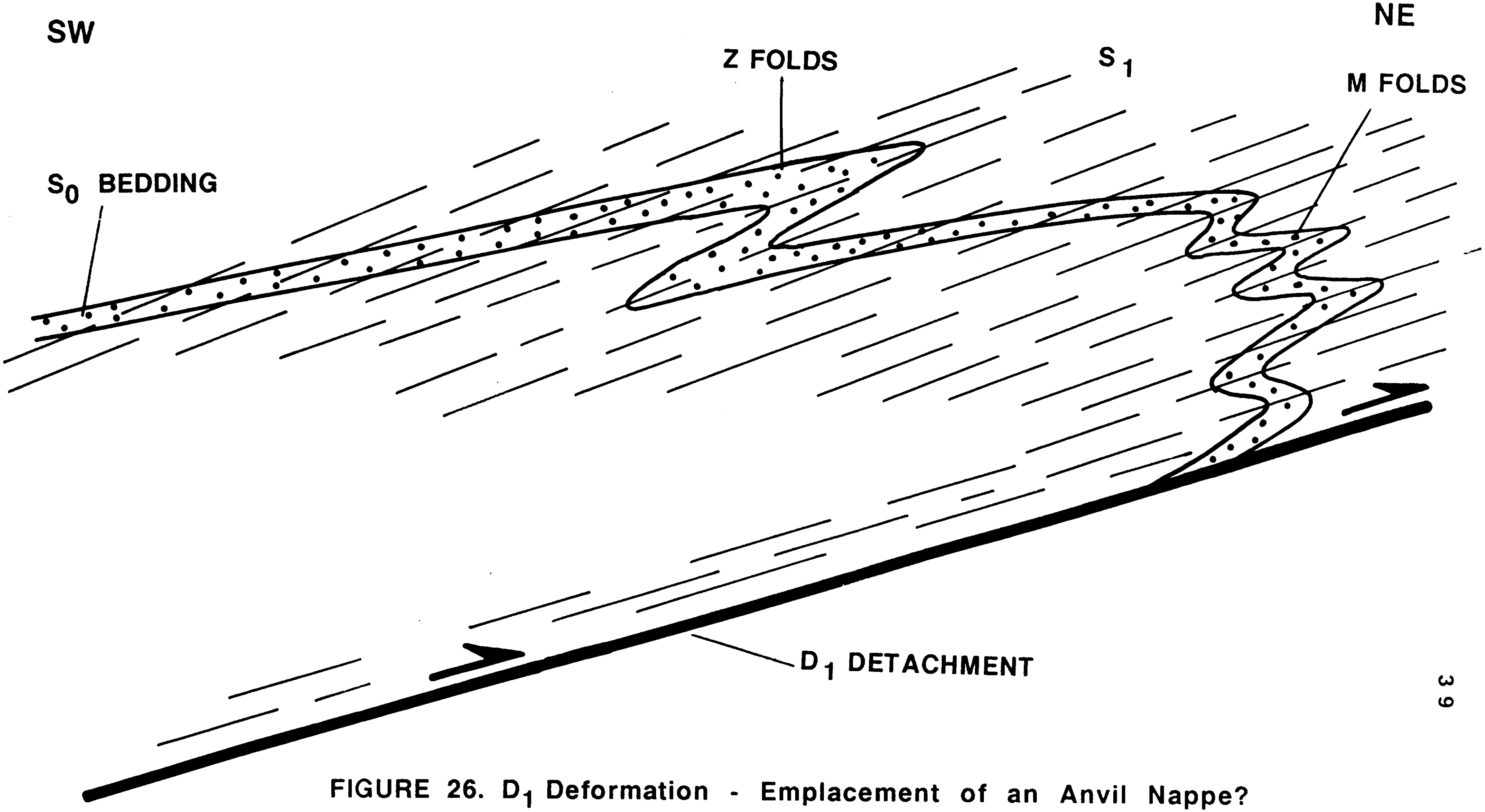


FIGURE 26. D_1 Deformation - Emplacement of an Anvil Nappe?

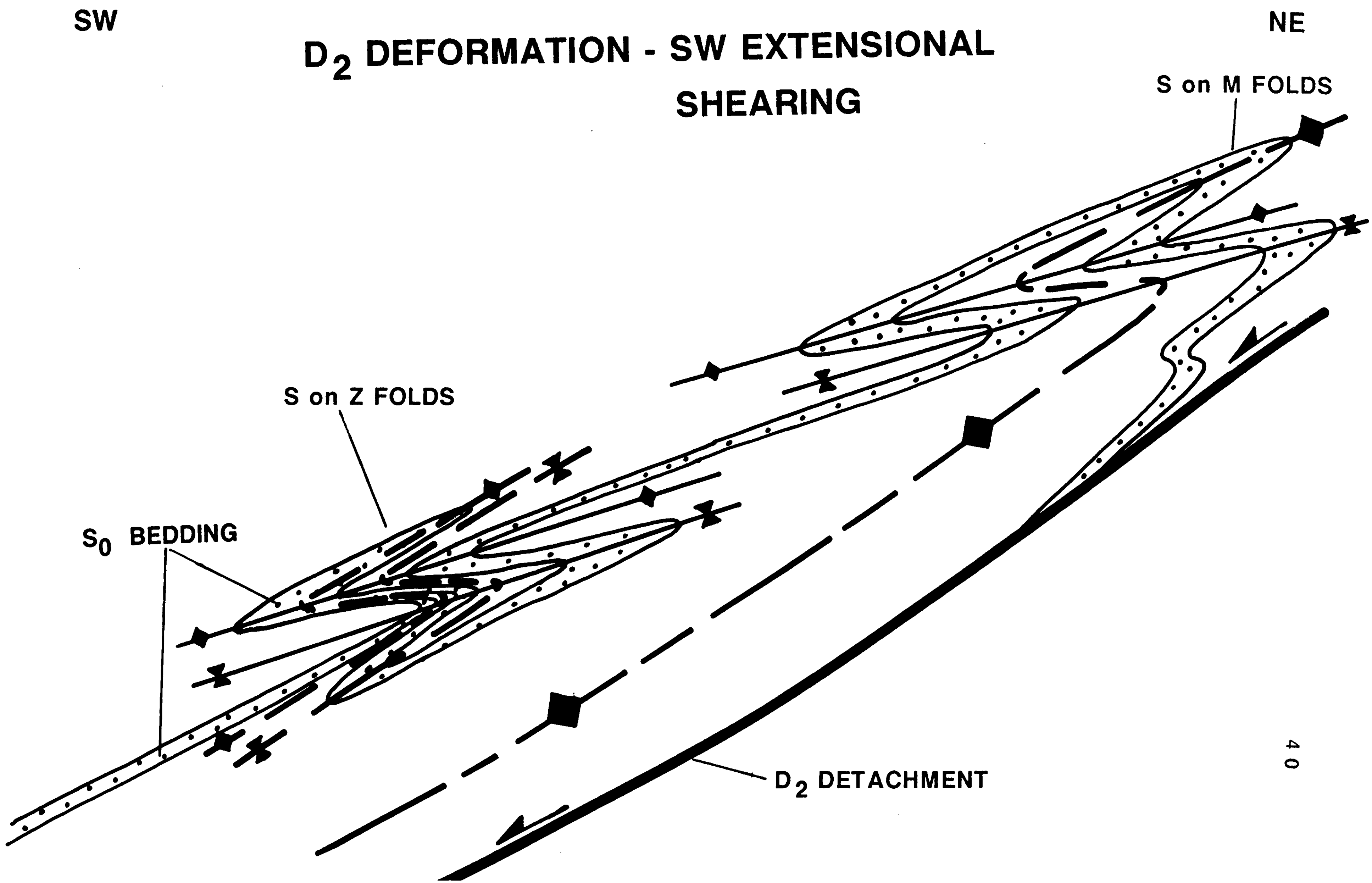


FIGURE 27. D_2 Deformation - SW directed shearing, extensional faulting and refolding of D_1 structures.

D_2 DEFORMATION - SW EXTENSIONAL SHEARING

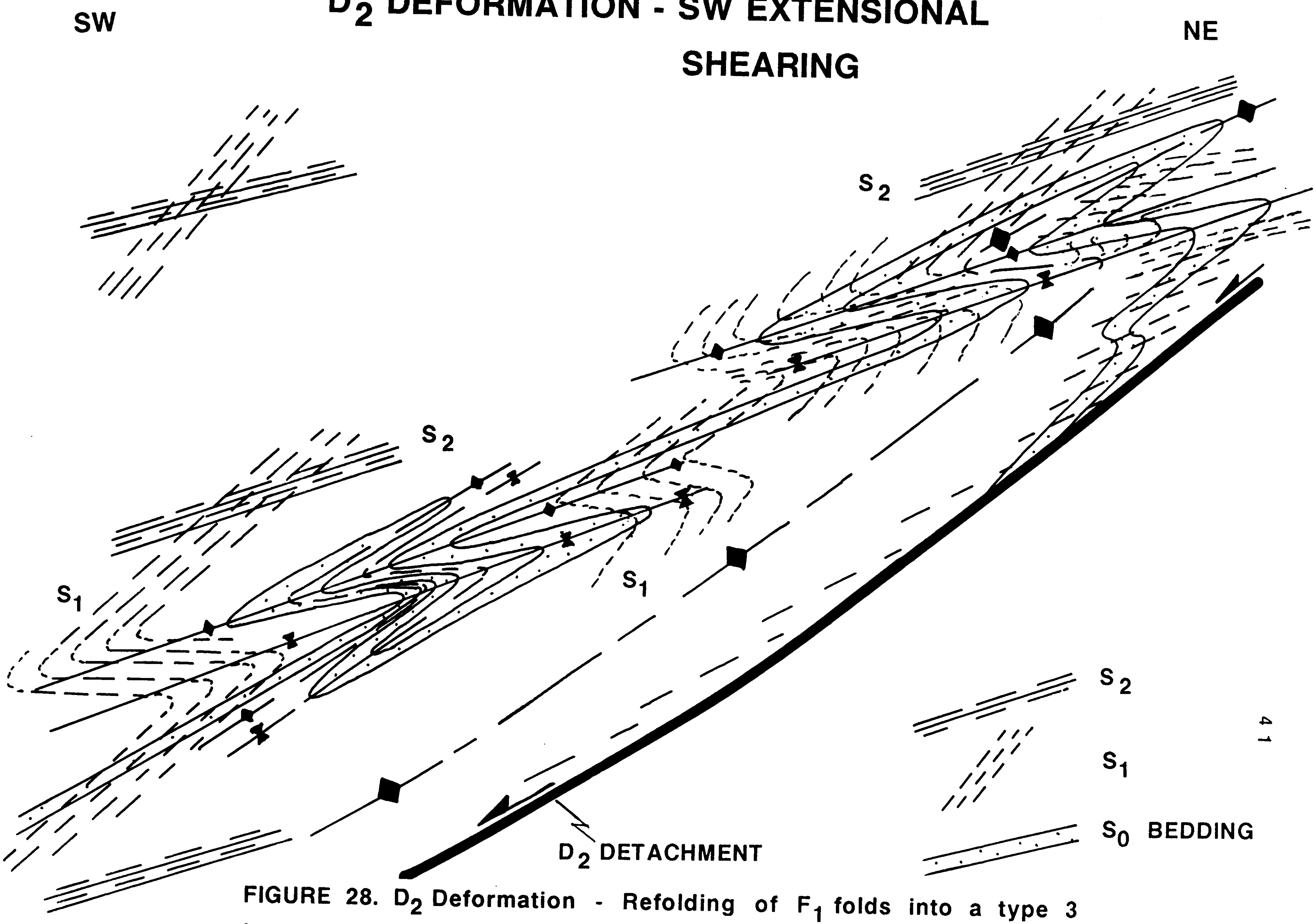


FIGURE 28. D_2 Deformation - Refolding of F_1 folds into a type 3 interference pattern. Note the folding of the S_1 cleavage.