# Preliminary Observations on the Structural Setting of the J-M Reef, East Boulder Mine, Stillwater Mining Company, Sweet Grass County, Montana

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The East Boulder mine has been under development since 1998, and production of 1,000 tons per day is expected during the third quarter of 2002. The ore occurs in the J-M Reef within the mafic-ultramafic Stillwater Complex of Montana. Now that production stopes are being mined, structural observations have been possible in three dimensions in the J-M Reef and adjacent rocks. The general pattern that has emerged consists of four main sets of faults as follows: West-northwest strike (WNW Set) subparallel to the reef with dips of 40 to 70 degrees to the north and subsidiary dips of 40 to 70 degrees to the south; North-south to north-northeast strike(NNE Set) with dips between 70 degrees east and 70 degrees west; Northeast-southwest strike (NE Set) with generally steep dips to the southeast; and Northwest-southeast (NW Set) with variable dip, generally steep to the southwest. This suggested pattern is preliminary and our interpretation continues to develop as mining continues. Magmatic layering strikes west-northwest and generally dips 50 to 60 degrees to the north. Although locally complex, the general level of structural complexity at the East Boulder mine appears to be less than at the Stillwater mine to the east where a series of thrust ramp and thrust faults with accompanying strong alteration extends through the mine area.

The structural history of the Stillwater Complex includes: probable syn-magmatic deformation; possible reactivation of earlier Precambrian strike-slip faults; Proterozoic faulting, development of penetrative foliation, and dike emplacement; pre-Middle Cambrian tilting and erosion; thrust faulting during the Laramide orogeny; and normal faulting during Tertiary Basin and Range extension (Jones and others, 1960; Page, 1977; Page and Zientek, 1985). It is likely that the complex structures observed in the East Boulder mine are the result of some combination of all these periods of deformation. The WNW fault set has strands that dip northeast subparallel to the dip of the magmatic layering and others that dip south. It is likely that these faults are expressions of the major west-northwest striking reverse and thrust faults mapped through the area by Jones and others (1960) and by Page (1977). Jones and others (1960) recognized four categories of faults in the Stillwater Complex including: NW striking, northeast dipping ramp and thrust faults; west striking, south dipping reverse faults or flat thrusts; east-west striking vertical faults; and steep transverse faults that strike between N30E and N30W. The steep transverse faults cut both the northeast dipping ramp faults and the south dipping thrusts (Page and Nockleberg, 1974).

Mafic dikes occur along the NE, NW, and NS striking fault sets. The wall rocks adjacent to the dikes are altered to epidote, calcite, quartz, and tremolite (all mineralogy based on hand specimen identification only). The dike contacts are commonly sheared and brecciated, suggesting that the dikes followed zones of structural weakness that were later reactivated. Offset across some of the larger dikes is on the order of 50 to 100 meters. Mafic dikes as thin as 0.2M can be traced from level to level in the mine. Some of the apparent offset along the dikes is probably due to emplacement in dilatent zones. This is supported by the general lack of internal deformation within the dikes. However, finite relative displacement of the dike walls is indicated for most dikes by the strong evidence of shearing along the dike contacts and by recognizable offset of magmatic stratigraphy in the host rock of the Stillwater Complex. Where the amount of apparent offset across a dike can be demonstrated, it is commonly greater than the width of the dike. The fault set that is most persistent from level to level is the NNE set, especially where these are followed by mafic dikes.

Felsic dikes as thin as 0.1M can also be followed from level to level in the mine. The felsic dikes are typically 1.0 cm to 1.0 meter thick. They are medium grained, white in color and consist of feldspar, quartz, and biotite. Biotite rarely makes up more than 5% of the rock and commonly is oriented approximately perpendicular to the dike contacts. Many felsic dikes occur in fault zones and appear to bracket the age of deformation.

Some faults appear to form grade boundaries, suggesting that precursor structures may have been present when the mineralizing event occurred. Early development of some of the faults is also suggested by the presence of coarse grained, mineralized pegmatoidal zones, pods, or clasts in the host cumulates along them. The sulfide mineralization in the reef generally appears to have formed late in the paragenetic sequence. Sulfides occupy intercumulate sites, probably as a result of crystallization from an immiscible sulfide melt. If the sulfide is late, and growth faults formed while the cumulate layers were still at elevated temperatures, then these structures could have acted to impede or channel sulfides during mineralization of the reef.

Alteration along other faults, such as the WNW set, locally appears to have decreased grades in the J-M Reef. It is possible that these faults have remobilized the primary magmatic sulfides, as suggested by Polovina and Hudson (2002, in press, this volume). Juxtaposition of variably mineralized reef sections cannot yet be ruled out as the cause of these variations in grade based on the limited data presently available at the East Boulder mine.

Syndepositional faults characterized by slump folds, attenuation of layers, and related features have been described on the East Boulder Plateau by Foose (1985, p.). Foose also noted that these early faults have probably been reactivated later. Carr and others (1994) recognized similar early faults in the Bushveld Complex and proposed that these structures were a response to magmatic loading of the Transvaal basin. Ductile thinning of magmatic units similar to that described by Carr and others (1994) and Foose (1985) is thought to occur at the East Boulder mine although evidence collected to date is open to alternative interpretations. Reef lithologies and the contained mineralization thin and thicken markedly along strike. These changes are thought to have resulted in part from ductile disruption of the partially consolidated reef to produce incipient boudinage. Anorthosite appears to have moved into the thinned zones.

Closely spaced fractures in the anorthosite of the hanging-wall are common in some parts of the mine. This fabric appears to be spatially associated with the NNE Set of faults but is cut by strands of this fault set. This incipient fracture cleavage probably represents the earliest structure recognized to date. Probable recrystallization of feldspar within bleached selvages along these fractures suggests that they formed at relatively high temperatures. Where well developed, the fracture cleavage and associated alteration selvages obliterate the original cumulate textures of the host rocks. Segerstrom and Carlson (1982) mapped a series of faults and mafic dikes extending southeast from the Frog Pond Adit south of the East Boulder mine. These faults are parallel in strike to the NNE Set in the mine and do not appear to extend into the upper part of the Stillwater complex, nor into the overlying Paleozoic section. The dikes along the faults have radiometric ages of 1200-1500my for unmetamorphosed varieties and 2562+-126my for metamorphosed varieties (Mueller, 1971). Page (1977) proposed a fault with 600-1,200 meters of offset extending along the east side of the East Boulder River in the same general area. These faults and dikes are probable surface expressions of the NNE faults and dikes recognized in the East Boulder mine.

Some of the NE and NW faults probably form a conjugate set defining horsts and grabens in the reef. These faults, in particular, make mining difficult since they require a sharp turn to the left or right and then a sharp turn to the opposite side some meters ahead.

Where well developed, the WNW Set has strong alteration associated with it. This alteration includes serpentine, carbonate, chlorite, and epidote derived from magmatic silicates such as olivine, pyroxene and plagioclase. These zones commonly have lower PGE values than adjacent unaltered portions of the reef and can therefore cause production problems. Fortunately, most of these zones extend for only a few meters along the reef and then give way to less altered material.

The reef between 70,250 west and 70,450 west is deflected to the south in a broad synformal bend (sag). Alteration in this interval is moderate to strong, grades fall off, and the normally continuous olivine-rich lithologies of the J-M Reef become less continuous. This bend is bounded at each end by well-developed northeast striking fault zones with moderate to steep easterly dips and apparent left lateral offset. The spatial relationship between these faults, the “sag”, and associated changes in stratigraphy and grade in the reef may indicate that they started as growth faults.

It is commonly difficult to correlate the smaller faults from one stope level to the next (vertical distance 43 feet). This observation, combined with the common occurrence of calcite-filled cross-over structures connecting en echelon fault strands at the scale of a mining face, suggest that some of the faults in the East Boulder mine are arranged en echelon. An alternative interpretation is that these faults are listric, but the relative paucity of low-angle faults up- and down-dip suggests that an en echelon arrangement is more likely.

Where faults, especially the NNE Set, can be correlated between levels, it is not uncommon for the apparent sense of displacement on the same structure to be opposite on different levels. This is interpreted to indicate rotational movement on at least some of these structures. Jones and others (1960, p. 321) proposed similar rotational movement on transverse faults in the area of the Gish mine approximately 8 km southwest of the East Boulder mine and in the Benbow mine area at the eastern end of the Stillwater Complex.

The pattern of faults in the East Boulder mine is interpreted as consisting of a conjugate set striking NE and NW, with an extensional set oriented NNE. This pattern is complicated by movement along a set of WNW faults that is approximately layer-parallel; and by probable reactivation of some or all of the fault sets throughout a long history, possibly starting with syn-magmatic structures. However, our understanding of the fault pattern is still preliminary.

The remarkable continuity of the J-M Reef at the scale of the 40km strike length of the Stillwater Complex is reflected in the East Boulder mine. However, at the scale of a stope, a better understanding of the generally minor (1M to 10M) offsets along the structures described in this paper will be important in mining the reef efficiently.

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