Kinematic Analysis of Fault-Slip Data in the Central Range of Papua, Indonesia

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Manuscript received: Juny 30, 2015; revised: July 22, 2015;
approved: November 23, 2015; available online: January 18, 2016

Abstract - Most of the Cenozoic tectonic evolution in New Guinea is a result of obliquely convergent motion that led to an arc-continent collision between the Australian and Pacific Plates. The Gunung Bijih (Ertsberg) Mining District (GBMD) is located in the Central Range of Papua, in the western half of the island of New Guinea. This study presents the results of detailed structural mapping concentrated on analyzing fault-slip data along a 15-km traverse of the Heavy Equipment Access Trail (HEAT) and the Grasberg mine access road, providing new information concerning the deformation in the GBMD and the Cenozoic structural evolution of the Central Range. Structural analysis indicates that two distinct stages of deformation have occurred since ~12 Ma. The first stage generated a series of en-echelon NW-trending (π-fold axis = 300°) folds and a few reverse faults. The second stage resulted in a significant left-lateral strike-slip faulting sub-parallel to the regional strike of upturned bedding. Kinematic analysis reveals that the areas between the major strike-slip faults form structural domains that are remarkably uniform in character. The change in deformation styles from contractional to a strike-slip offset is explained as a result from a change in the relative plate motion between the Pacific and Australian Plates at ~4 Ma. From ~4 - 2 Ma, transform motion along an ~ 270° trend caused a left-lateral strike-slip offset, and reactivated portions of pre-existing reverse faults. This action had a profound effect on magma emplacement and hydrothermal activity.

Keywords: Central Range Papua, Erstberg Mining District, fault-slip, kinematic analysis

INTRODUCTION

The study area is located in the Gunung Bijih Mining District (GBMD), which is part of the Central Range of Papua formerly known as Irian Jaya (Figure 1). Most of the deformation in the Central Range is a result of an oblique convergent motion that led to an arc-continent collision between the Australian and Pacific Plates (Sapiie, 1998; Cloos *et al.*, 2005). The results of detailed structural mapping at the GBMD along a 15-km traverse of the Heavy Equipment Access Trail (HEAT) and the Grasberg mine access road have provided new information concerning the Late Cenozoic structural evolution of the Central Range of Papua (Sapiie, 1998; Sapiie and Cloos, 2004; and Cloos *et al.*, 2005). The main purpose of this paper is to present the results of a detailed kinematic analysis using fault-slip data (fault plane and striation/slickensides) in the ramification deformation and tectonic evolution of the study area.

Regional Geology and Tectonic Setting

Geographically, the island of New Guinea has been divided into the Bird's Head, Neck,

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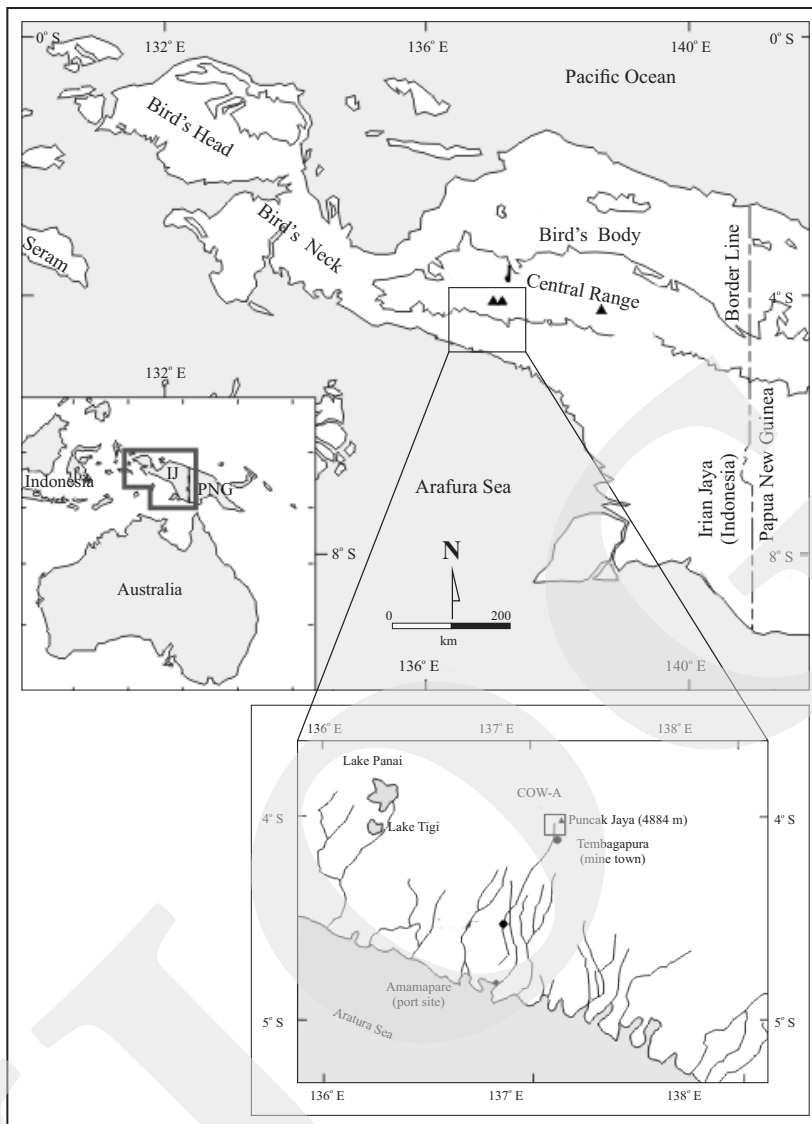
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Figure 1. Locality map of study area showing the Gunung Bijih (Ertsberg) Mining District Contract of Work. The study area is part of Irian Jaya (now is Papua) Province located in the western half of the island of New Guinea (modified from Sapiie, 1998).

Body and Tail regions (Figure 2). The central portion of New Guinea (the Bird's Body) can be divided into four lithotectonic provinces: the New Guinea Foreland, the Central Range fold-and-thrust belt, a metamorphic and ophiolite belt, and a collided Melanesian arc island arc complex (Sapiie, 1998).

The Arafura Platform is underlain by marine and nonmarine Pliocene and Holocene siliciclastic sedimentary rocks which are underlain by the Cenozoic carbonate and Mesozoic siliciclastic strata deposited on the northern passive margin of Australia (Dow and Sukamto, 1984a,b). The

Central Range is an orogenic belt that stretches 1300 km from West Papua to the Papuan Peninsula. The Ruffaer Metamorphic Belt (RMB) is a 1000 km long and 50 km wide zone of highly-deformed, generally low-temperature (<300°) metamorphic rocks which are bounded on the north by the Papua Ophiolite belt (IOB) and on the south by deformed, but unmetamorphosed, passive margin strata (Dow *et al*., 1988; Cloos *et al*., 2005). The most northern orogenic belt in Papua is a poorly exposed, complex zone involving oceanic rocks from a collided Melanesian island arc built into the Pacific Plate. The
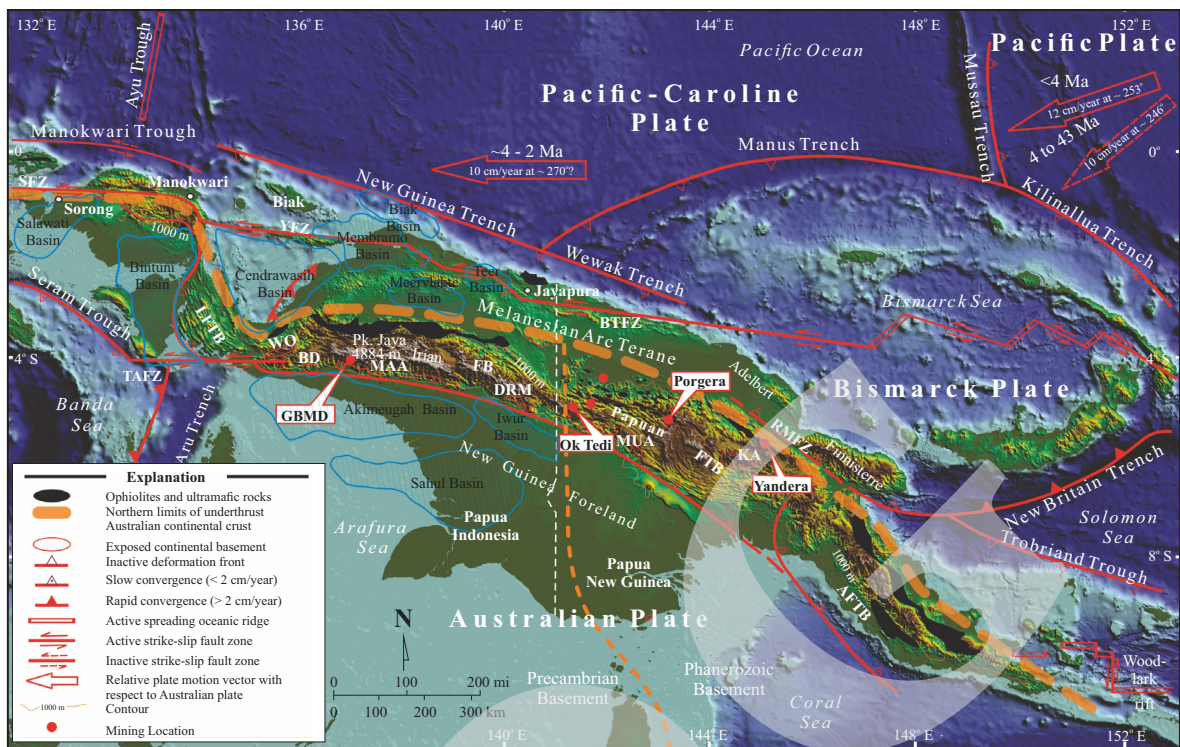
Figure 2. Tectonic Map of New Guinea with outcrops of Australian continental basement and ophiolite delineating the collisional suture between the Pacific and Australian Plates, and the location of major mineral districts (Ok Tedi, Porgera, Yandera). From west to east the island consists of the following tectonostratigraphic provinces: the Lengguru Fold-and-Thrust Belt (LFTB), Weyland Overthrust (WO), Irian Fold Belt (FB) and Papuan Fold and-Thrust-Belt (FTB), GBMD = Gunung Bijih (Ertsberg) Mining District. Other tectonic features include: AFTB = Aure Fold-and-Thrust, BD = Baupo Dome, BTFZ = Bewani-Torricelli Fault Zone, DRM = Digul Range Monocline, KA = Kubor Anticline, MAA = Mapenduma Anticline, MUA = Muller Anticline, MFTB = Mamberamo Fold-and-Thrust Belt, RMFZ = Ramu-Markham Fault zone, SFZ = Sorong Fault Zone, TAFZ = Tarera- Aiduna Fault Zone, YFZ = Yapen Fault Zone (Simplified from Hamilton, 1979; Cooper and Taylor, 1987; and Dow et al., 1986; and modified from Sapiie, 1998).

Mamberamo Thrust-and-Fold Belt (MTFB) is a 200-km wide, NW-trending zone of convergent deformation, largely within the Melanesian arc terrane, that began in the Pliocene and it is still active (Dow and Sukamto, 1984a, b; Dow et al., 1988).

The Cenozoic tectonic evolutions in New Guinea are the subject of debate as several kinematic models have been proposed. The subduction polarity reversal known as arc re-versal model which entails movement of the Australian continental crust into a northward dipping subduction zone, followed by collision and initiation of present-day southward sub-duction of the Pacific Plate at the New Guinea Trench (Hamilton, 1979; Johnson and Jaques, 1980; Milsom, 1985). Other model proposed to explain relationships in eastern New Guinea

requires that the island is underlain by a doubly-subducted slab of oceanic lithosphere ("zip-pering" model), which would be probably the westward continuation of the Solomon Sea Plate (Ripper and McCue, 1983; Cooper and Taylor, 1987). The third model, which is similar to the one involving northward-dipping subduction of the Australian Plate, but subduction rever-sal, does not occur. In this model, the formerly north-dipping subducted Australian lithosphere is thought to be dipping vertically (Dow et al. 1988). However, all authors agree that most of the present-day New Guinea was the passive northern margin of the Australian continent from Early Mesozoic to Late Cenozoic, when one or more volcanic arcs collided with it. Based on the change from carbonate sedimentation to clastic sedimentation derived from orogenic uplifts, the

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collision, known as the Melanesian Orogeny, began in the Late Miocene (Dow and Sukamto, 1984a; Dow *et al*., 1988). However, based on the metamorphic age of rocks in Papua New Guinea and the island arc sequence, some workers conclude that the collision began in Early Oligocene (Pigram *et al*., 1989; Davies, 1990). Quarles van Ufford (1996) proposed that the island is the site of two orogenic events that are spatially and temporally distinct. The Eocene-Oligocene event, the "Peninsular orogeny," was restricted to easternmost New Guinea. The "Central Range orogeny" on the other hand, was an island wide event that began in the Middle Miocene. In addition, Quarles van Ufford (1996) divided the Central Range orogeny into pre-collisional and collisional stages. The precollisional stage is related to the "bulldozing" of passive margin sediments into a northward-dipping subduction zone. The collisional stage occurs when buoyant Australian lithosphere actually jams the subduction zone. Collisional delamination is proposed as the tectonic process that occurred within the subducting Australian lithosphere between 7 to 3 Ma (Cloos *et al*., 2005). This process causes late-stage igneous activity and vertical mountain uplift.

Fault Pattern and Style In The GBMD

Geologically, the study area (GBMD) consists of Jurassic-Cretaceous Kembelangan Group, Tertiary New Guinea Limestone Group, and Quaternary Alluvium (Figure 3). Numerous fault-slip data such as fault plane and striations/slickensides were collected along the roads (*i.e.* presented in Figure 4). Previous work by Sapiie (1998) in the GBMD resulted in the mapping of five major left-lateral strike-slip fault zones trending ~299º. These fault zones bound the structural domains (D1-D5) of numerous minor faults that form networks of R and R' Riedel shears (terminology used from the clay-cake experiment by Tchalenko, 1970). The fault patterns (types and orientations) in the study area from both the Grasberg and HEAT road traverses are summarized in Table 1.

METHODS

In addition to conventional structural analysis, fault-slip data were analyzed using the graphical kinematic method described by Marrett and Allmendinger (1990). The purpose of this analysis was to test the homogeneity of the data sets and to determine the geometric relationships that are represented by kinematic axes. Fault-slip data were processed using the computer software Faultkin 1990, Kinematic analysis of fault-slip data (Marrett and Allmendinger, 1990).

The Marrett and Allmendinger method generates the shortening (P) and extension (T) axes for a given population of coeval faults of equal displacement. The actual calculation of kinematic axes is based on an infinitesimal strain approach. The kinematic axes, P and T, are constructed by bisecting the orthogonal nodal planes of a best-fit fault plane solution (Figure 5a). Each pair of axes lies in the movement plane (M) containing the slip vector and the normal vector to the fault plane (a). The axes form an angle of 45° with respect to each of the vectors (Figure 5b).

Analytically, the P- and T-axes are equivalent to eigenvectors of the symmetrical part of a displacement gradient tensor for the deformation, and the eigenvalues define their magnitudes (Marrett and Allmendinger, 1990). Shortening (P) and extension (T) axes are contoured using the method from Kamb (1959) to obtain the distribution and orientation of the maxima. Linked Bingham distributions provide objective directional maxima of the shortening and extension axes of the fault array. This procedure is the same as the moment tensor summation from Molnar (1983) but with uniform weighting of the slip data. The linked Bingham distribution analysis of fault-slip data in the study area is best represented as a pseudo-fault-plane solution.

The Marrett and Allmendinger "kinematic" method differs from the so-called "dynamic" methods commonly used to infer the orientation of a stress field from fault-slip data via numerical (Angelier, 1984; Gephart and Forsyth, 1984; Reches, 1987; Huang, 1988) or graphical
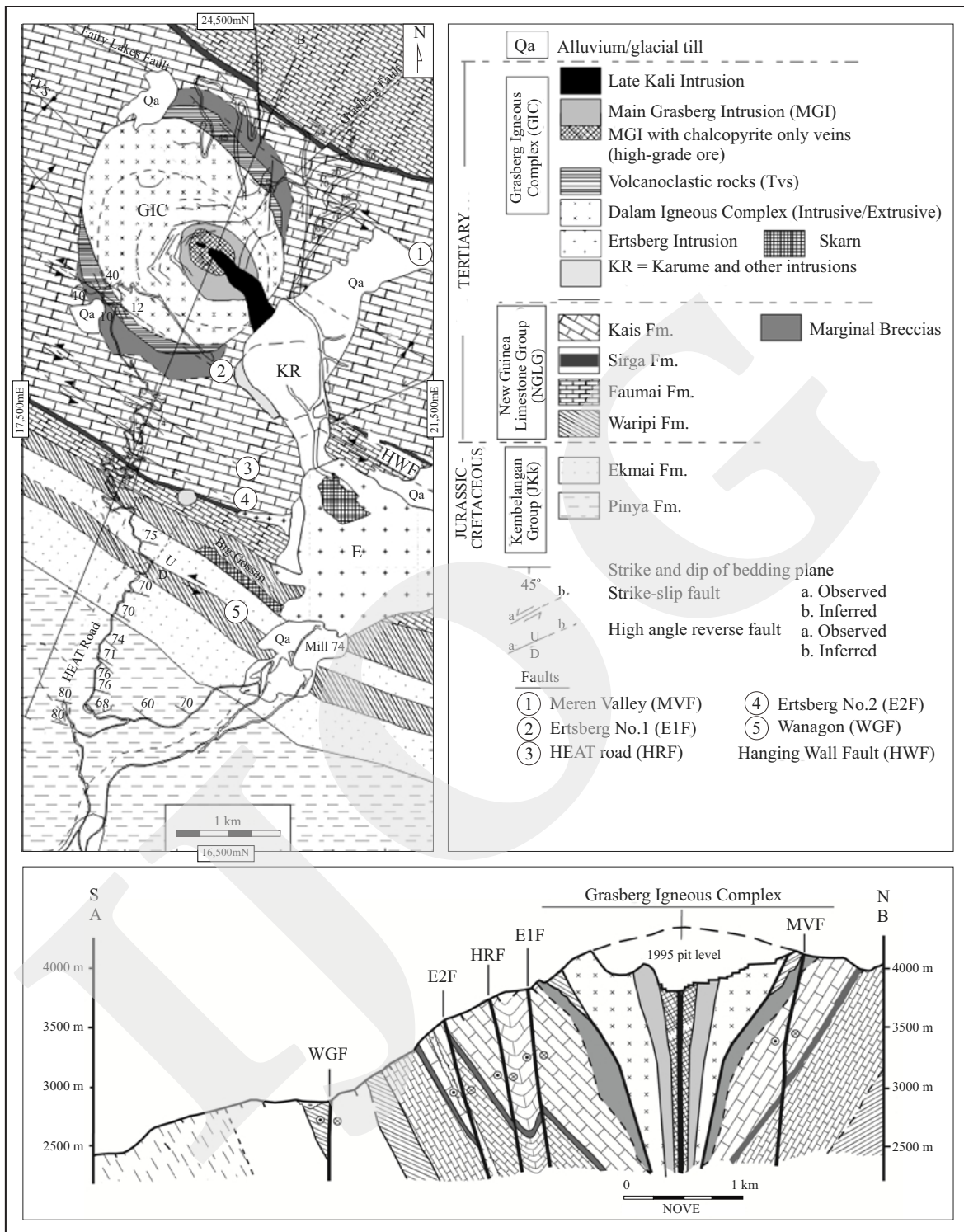
Figure 3. Geologic map and A-B cross-section of HEAT and Grasberg roads shows relationship between major structures and sedimentary formations in the GBMD (modified from Sapiie, 1998).

techniques (Reches 1983; Lisle, 1987; Angelier, 1994). Assumptions in the dynamic methods are that the fault-slip is in the direction of maximum resolved shear stress on the fault plane. This re-quires that the stress field is homogeneous, faults are coeval and faults do not interact mechanically, all of which are untenable assumptions (Marrett and Allmendinger, 1990). Dynamic analysis can

Figure 4. Field example of outcrop-scale fault-slip surface showing horizontal slicken-sides (photograph by Mark Cloos).

become very misleading wherever the local pattern of faulting is strongly controlled by anisotropy (*e.g.*, Hancock *et al.*, 1987).

RESULTS AND ANALYSIS

Application to Heat and Grasberg Road Data

In an attempt to quantify the deformation, it is necessary to estimate finite strain. Theoretically, the finite strain can be calculated using fault slip data as a moment tensor summation (Molnar, 1983; Allmendinger, 1989; Peacock and Sanderson, 1993; Little, 1995, 1996). However, this method requires information on displacement magnitudes to calculate the weighting factors for the fault-slip (Marrett and Allmendinger, 1990). One approach is to use the width of the fault gouge to estimate the offset, but this method only works if the fault gouge width is scale-invariant (Marrett and Allmendinger, 1990). In the absence of

indicators of slip magnitude, any estimate of the fault-related finite strain can only be a crude one.

The scarcity of distinctive offset markers in the study area severely limits quantitative analysis. Assuming all faults in each domain have a similar offset and that they crop out proportionally to the true number and orientation of all minor faults in an area, the P- and T-axes can be used as the basis for calculating an "unweight" moment tensor summation by using Bingham statistics in which the P- and T-axes are linked to one another (Allmendinger, 1989; Marrett and Allmendinger, 1990).

The fault-related strain was estimated by assuming a negligible offset along each fault (*i.e.*, infinitesimal strain), and assuming faulting is scale-invariant (Allmendinger, 1989; Marrett and Allmendinger, 1990).

Analysis indicates remarkably homogeneous kinematic axes as defined by the near-horizontal NE-SW shortening and near-horizontal NW-SE extension (Figure 6 and Figure 7). This result is in excellent agreement with the regional pattern of extension indicated by veining (Sapiie and Cloos, 2004). The finite strain axes (el, e2, e3) were evaluated using a Flinn diagram to show the variability of the strain field (Table 2). The calculated strain ellipsoids from the HEAT road domains have a prolate shape, whereas those from the Grasberg road transect have an oblate shape (Figure 8). A prolate strain ellipsoid is expected in a divergent strike-slip system, whereas an oblate strain ellipsoid is expected in a convergent strike-slip system (Sanderson and Marchini, 1984; Ratschbacher *et al.*, 1993; Little, 1996).

Table 1. Average Fault Orientations recognized from Stereographic Analysis of Structural Domains along the HEAT and Grasberg Roads.

Fault Type	D1	D2	D3	D4	D5	Clay Cake Model
Dextral	001°/85°	005°/69°	184°/81°	003°/72°	011°/80°	R`
Sinistral	057°/80°	053°/78°	054°/74°	082°/80°	075°/79°	R
Sinistral	-	-	-	102°/79° ?	-	P
Dip-slip a	101°/70°	109°/66°	098°/63°	298°/81°	317°/80°	N/T
Dip-slip b	205°/85°	203°/80°	-	-	-	N/T

(*) Fracture sets are interpreted by comparison to physical model results of clay cake experiments by Riedel (1929) and Tchalenko (1970). R = Riedel shear fractures, R' = conjugate Riedel shear fractures, P = P-shear, N = normal and T = thrust (Sapiie, 1998).
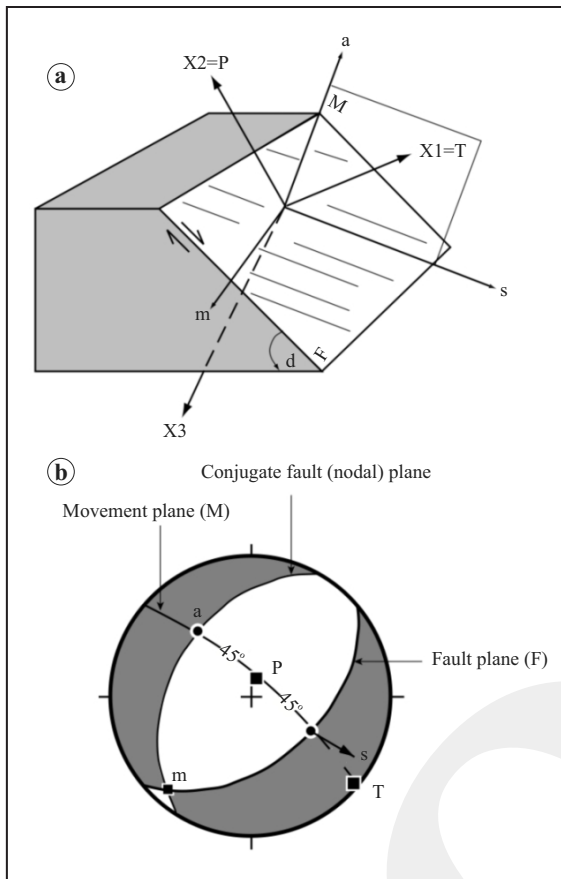
Figure 5. a) Geometry and coordinate system of fault-slip kinematics showing relationship between kinematic axes (X1, X2, X3), fault plane (F), slip direction (S) and movement plane (M) where a = pole to fault, m = pole to movement plane, d = fault dip. b) Lower hemisphere equal area projection illustrates graphical representation of P and T axes where P and T are infinitesimal principal shortening and extension directions (modified from Marrett and Allmendinger, 1990).

Deformation Analysis

The local deformation pattern can be explained in the context of the regional plate tectonic history. The island of New Guinea has been subjected to oblique convergent motion since Early Cenozoic. The relative plate motion between the Australian and Pacific Plates changed from 246° to 253° at ~4 Ma (Quarles van Ufford, 1996). Any tectonic model of the Central Range must account for this relative motion change as well as consider the probable short-lived existence of a distinct kinematic entity, the Caroline Plate, a prong temporally broken off the Pacific Plate (Cloos, 1992). Regional structures in the Central Range are dominated by en echelon km-scale folds with
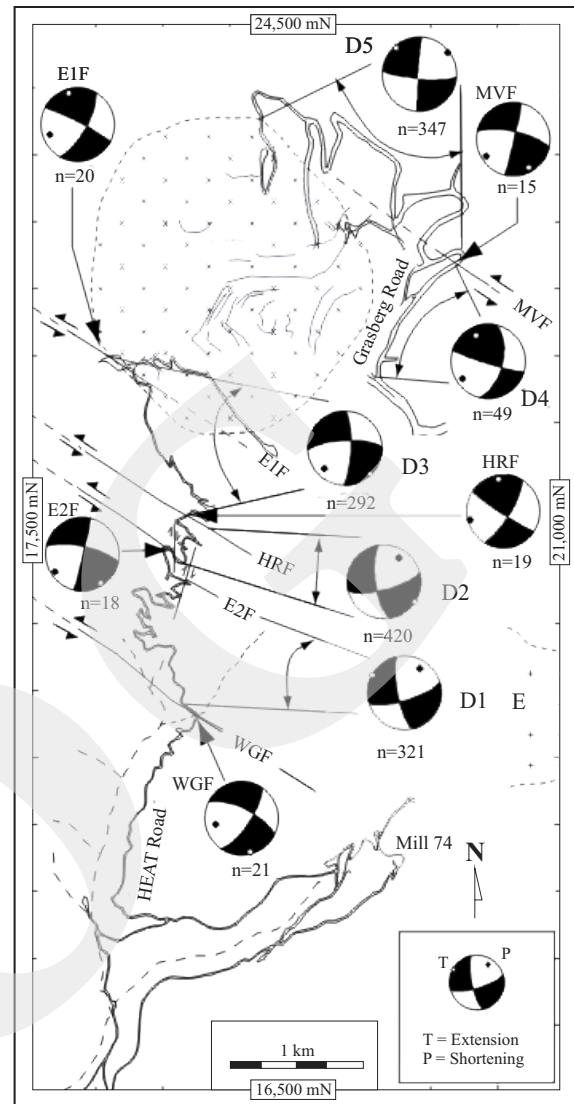

Figure 6. The results of kinematic analysis fault-slip data (n=total data) applying the method of Marrett and Allmendinger (1990). Each structural domain and major fault zone shown separately.

subsidiary high-angle reverse faults that are the product of tens of kilometers of shortening related to subduction and collisional orogenesis. The strike-slip faulting documented in this paper reflects hundreds of meters to at most a few kilometers of offset. Strike-slip offsets are of relatively minor significance tectonically, but of profound significance for magma intrusion and mineralization.

Before magmatic activity began at ~4 Ma, the GBMD area was dominated by km-scale folding trending NW-SE (π-fold axis of 300°, 3°). Symmetrical upright chevron folds with steep to verti-
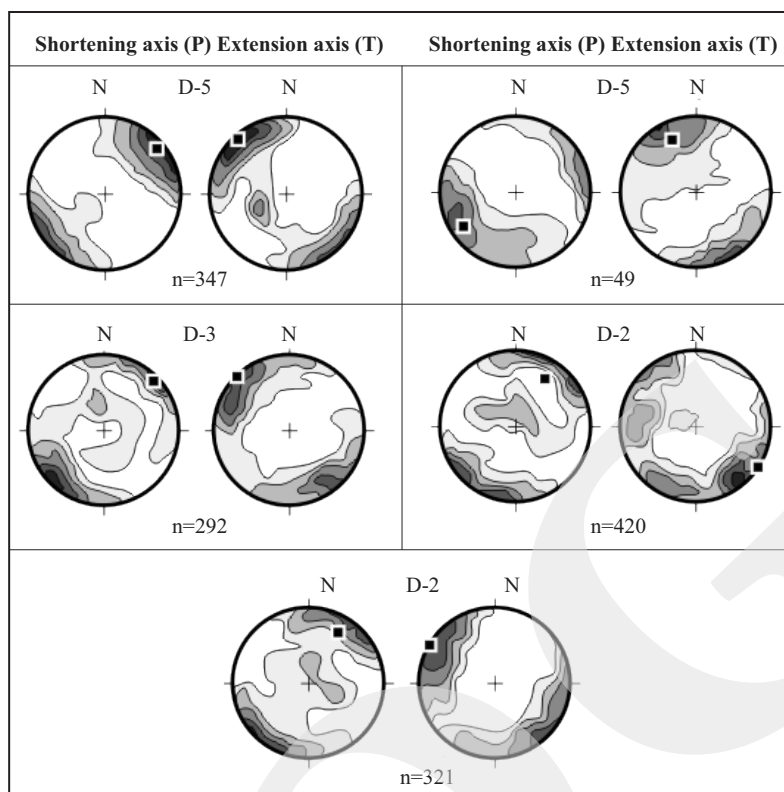
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Figure 7. Analysis of fault-slip data (n=total data) from each of the five domains along the HEAT and Grasberg roads. Data sets are separated for different kinematic axes in each domain and are contoured. Kamb (1959) contour interval = 2 sigma. Solid boxes represent linked Bingham distribution maxima of T- and P-axes respectively (Marrett and Allmendinger, 1990). Fault-slip data from across the district show a similar direction of NW-SE extension and NE-SW shortening.

Table 2. Calculated Shortening (P) and Extension (T) Axes for all Fault-slip Data from all Domains in the study area (see text for explanation).

Structural domain (D)	Shortening P-axis (pl, tr)	Extension T-axis (pl, tr)	e1	e2	e3
1	23°, 031°	1°, 300°	0.1801	-0.0672	-0.1129
2	26°, 033°	1°, 124°	0.1228	-.00237	-0.0990
3	9°, 046°	0°, 316°	0.1574	-0.0553	-0.1022
4	18°, 236°	26°, 335°	0.1605	-0.0046	-0.2427
5	9°, 049°	5°, 319°	0.2298	-0.0125	-0.2423

(*) The Faultkin method also calculates the relative magnitude of the strain ellipsoid axes (e1,e2,e3) for each dataset. Faulting-related finite strain axes are illustrated in a Flinn diagram (see Figure 6). pl = plunge, tr = trend.

cal axial-planes indicate a sub-horizontal NE-SW (210°) direction of shortening. Across the 10-km wide section in the GBMD, the shortening was ~5 km (Quarles van Ufford, 1996).

Evidence from the GBMD shows that the km-scale folds are crosscut by numerous strike-slip faults with a minor offset. Major strike-slip faults are oriented sub-parallel to the upturned sedimentary bedding in the GBMD, but it is

clear that they postdate folding (Sapiie, 1998). The overall regime is one of slightly convergent transform motions. Because reverse faults are less abundant than normal faults in the domains between the major faults on the HEAT road, the local structural pattern in this part of the district from ~4 Ma is interpreted to be one of extensions parallel to the strike-slip fault zone exceeding perpendicular shortening (Figure 9).
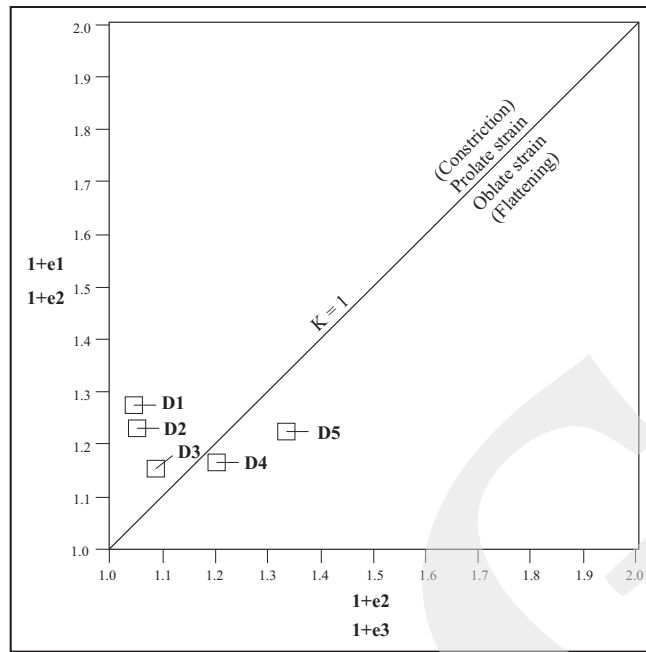
Figure 8. Flinn diagram showing the shape of a three-dimensional strain ellipsoid determined from fault-slip data collected from each domain (1 to 5) along HEAT and Grasberg roads. Strain ellipsoid axes (e1, e2, e3) were calculated from fault-slip data. The calculations show that the data sets fall into two groups: HEAT road domains (D1 to D3) have prolate strain ellipsoids whereas Grasberg road (D4 and D5) have oblate strain ellipsoids. Domain (D) 4 is a realm of plane strain. K= strain axis ratio with K = 1 for plane strain.
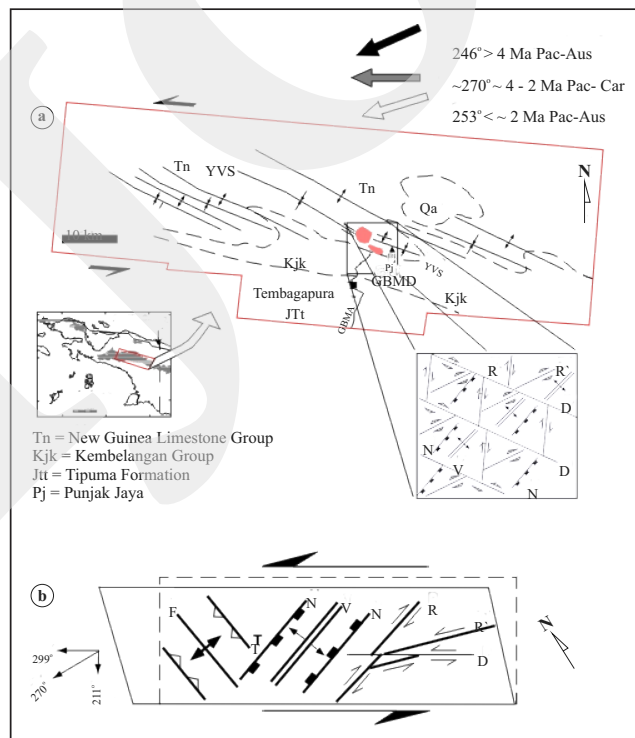

Figure 9. a) Structural patterns in the GBMD and their relationship to regional deformation patterns of the Central Range of Irian Jaya (modifed from Quarles van Ufford (1996) interpretation of mosaic SPOT acquired 1987). b) Lower diagram is an ideal model of the strain pattern in a strike-slip deformation with extension parallel to strike exceeding shortening perpendicular to strike. The overall regime is one of highly oblique, slightly convergent (ß = 19°) transform motion. R = Riedel shear, R' = conjugate Riedel shear, D = D-shear, N = normal fault, T = reverse fault, F = fold, V = vein (extension fracture).

Stereographic analysis of extension fractures are represented by calcite and pyrite veins with mean trends of 040°, indicating a uniform sub-horizontal NW-SE extension (Figure 10). The kinematic analysis of the fault-slip data yield a result consistent with the left-lateral strike-slip faulting with a principal shortening direction trending NE-SW, a principal extension direction trending NW-SE, and an intermediate principal strain that is sub-vertical (Sapiie and Cloos, 2004).

DISCUSSIONS

Relationship to Regional Tectonics

Two distinct deformation events are clearly recognized in the GBMD: tens of km of short-ening accompanied by km-scale folding and minor reverse faulting, followed by hundreds of meters to perhaps a few km of left-lateral strike-slip faulting. Based on local biostratigra-phy and regional stratigraphic correlation, the pattern of sedimentation in the region changed dramatically at ~12 Ma (Quarles van Ufford, 1996). This event is interpreted as being the widespread emergence and erosion of uplifts due to the bulldozing of the Australian passive margin strata (Quarles van Ufford, 1996). The fission track analysis of Weiland and Cloos (1996) led to the conclusion that the uplift of basement rock at the mountain belt began at ~7 Ma with the formation of the Mapenduma Anticline. Based on crosscutting relationships, the history of the GBMD is divided into two stages: Stage 1 (~12 - 4 Ma) and Stage 2 (~ 4 - 2 Ma) (Figure 11).
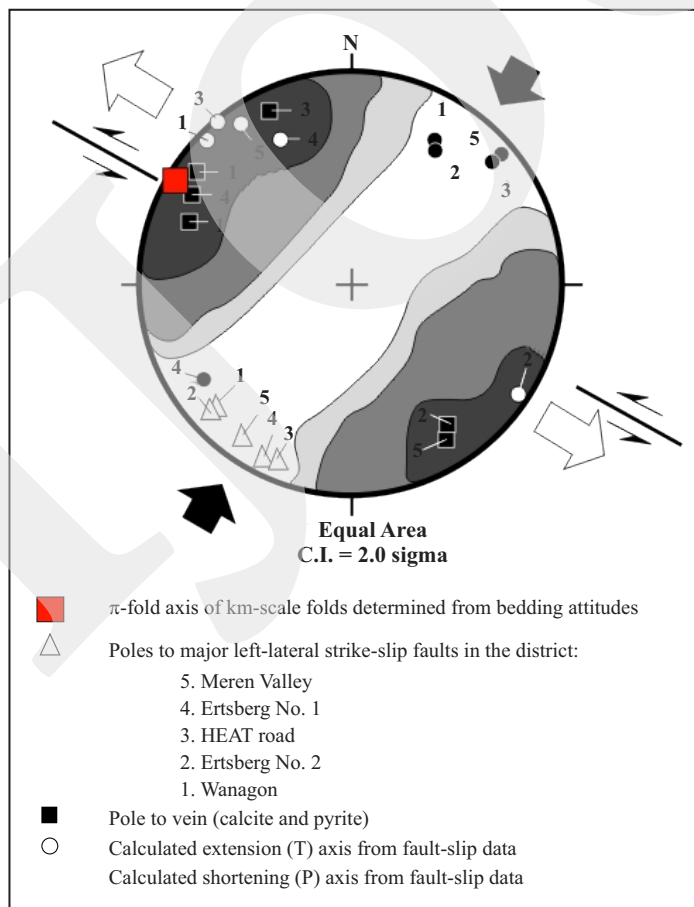

Figure 10. Lower hemisphere equal-area stereogram summarizing relationships among structural data types. Kamb (1959) contour interval = 2 sigma for extension axis (T-axis) calculated from fault kinematic analysis using method of Marrett and Allmendinger (1990). Dark arrows represent the principal axis of early shortening inferred from km-scale folding. White arrows represent the direction of extension as inferred from veins.
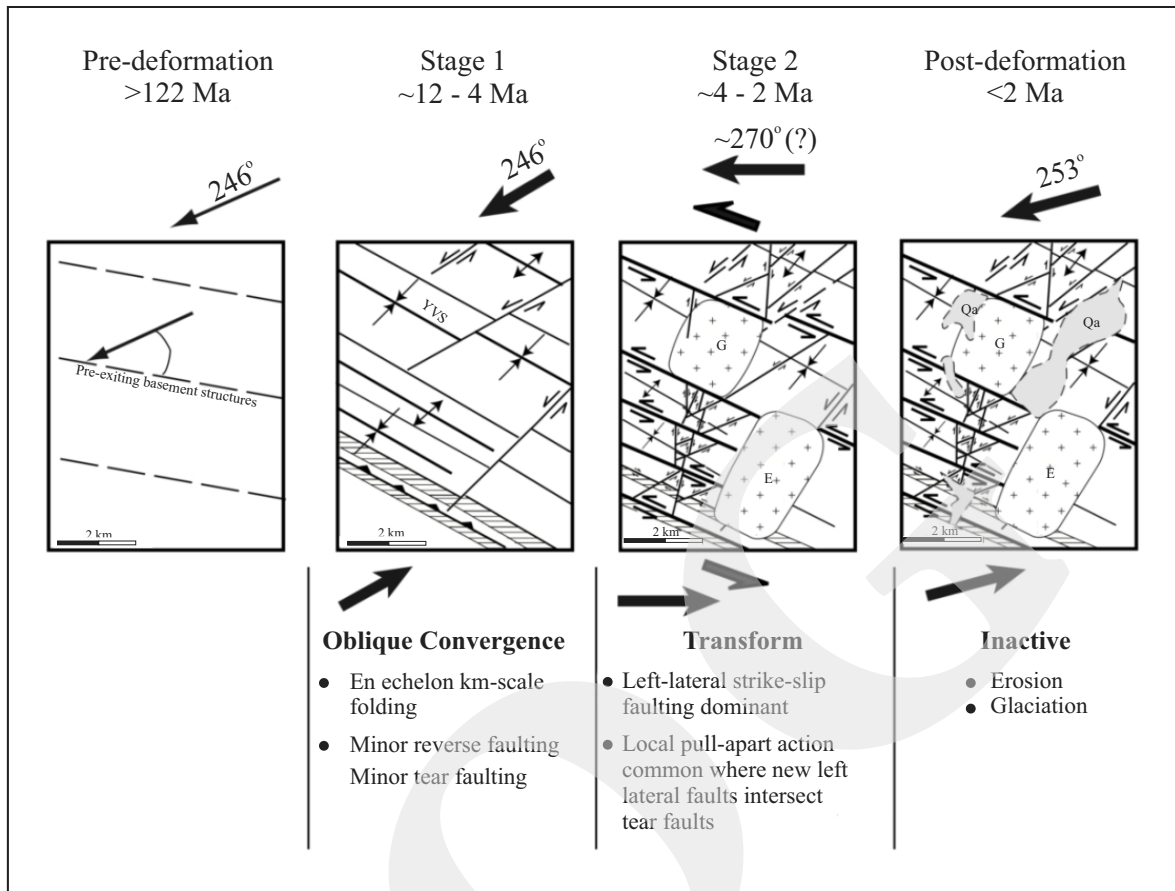
Figure 11. Proposed model for the deformation history of the Gunung Bijih Mining District (GBMD) showing two distinct stages of deformation. The pre-deformation stage shows pre-existing basement structures (280°/100°) prior to ~12 Ma (Quarles van Ufford, 1996). Stage 1 shows en echelon folding that develops as a result of ~EW oblique convergence where β, the obliquity of major pre-existing weaknesses to the direction of regional shortening is 30°-40°. Stage 2 shows the relative motion between the Australian and Pacific Plates changes at ~4 Ma from 246° to ~280°, with formation of the kinematically distinct Caroline Plate (Cloos, 1995). This small change created a sinistral strike-slip faulting along bedding and the local reactivation of pre-existing (oriented ~299°) high angle reverse faults (*e.g.*, part of the WGF and MVF). Cross-cutting strike-slip faults (~065° and ~299°) generate local pull-aparts at left steps which were important not only for magma ascent in the district, but also for hydrothermal fluid escape. The post-deformation stage, since ~2 Ma, the region is inactive and the study area undergoes erosional, unroofing, and more recently glacial erosion and deposition.

Pre-Deformation (>12 Ma)

Prior to ~12 Ma, the study area was a stable passive margin with a shallow marine sedimentation blanketing the Australian continental basement. The beginning of the Central Range Orogeny is characterized by the deposition of the siliciclastic strata of the Buru Formation at ~12 Ma (Quarles van Ufford, 1996). It is believed that pre-existing structures generated by Mesozoic rifting and oriented ~280°/100° (Figure 10) played a major role in the structural development of New Guinea Island during collisional orogenesis, *e.g.* western PNG; Central Range (Granath

and Argakoesoemah, 1989) and Western Papua (Quarles van Ufford, 1996).

Stage 1 (~12 - 4 Ma)

The first stage of collisional deformation generated km-scale en echelon folds between ~12 and 4 Ma (Quarles van Ufford, 1996; Weiland and Cloos, 1996). These folds formed as a result of the southwest verging shortening (~246°). Subsidiary high-angle reverse faults developed toward the later stage of the symmetrical upright chevron folding (*e.g.*, WGF and MVF). The ~065°-trending left-lateral strike-slip

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faults in the northeast part of the GBMD are tear faults that formed synchronous with the folding (Figure 3).

Stage 2 (~4 - 2 Ma)

The second stage of deformation involved hundreds of meters to a few kilometers of a left-lateral strike-slip offset oriented sub-parallel to the regional grain of the upturned bedding. Field evidence indicates that two of the major strike-slip faults (WGF and MVF) were segments of older high-angle reverse faults (Figure 3). There-fore, the ~299°-trending strike-slip faults are oriented sub parallel to the regional grain gener-ated by the folding, which in turn was probably controlled by pre-existing zones of weakness in the basement (Figure 11). The structural analysis of slickensides within the fault zones indicates that the movement is dominated by a left-lateral strike-slip offset.

Pervasive minor strike-slip faults with orien-tations similar to those generated in the classic Riedel (1929) shear experiments developed in the domains between the major faults (Figure 11). R- and R'-shears are numerous in the region. The relative abundance of minor normal faults along the HEAT road indicates that the exten-sion parallel to the strike-slip offset exceeded the shortening perpendicular to the strike (Sapiie and Cloos, 2004).

In areas where crosscut structures such as the NE-trending tear faults generated during fold-ing are present, left-stepping bends locally were opened in the sinistral strike-slip fault system. At least three of the major strike-slip fault zones (WGF, E2F and ElF) have breccias, igneous dikes, and mineralization, indicating the strike-slip faulting was a significant factor in creating openings for intrusion and permeability for the flow of hydrothermal fluid (Sapiie and Cloos, 2004).

The profound change in deformation style from the contractional folding to the strike-slip offset is interpreted to be a manifestation of the change in the relative plate motion between the Australian and Pacific Plates at ~4 Ma and the

temporary formation of a distinct kinematic entity, the Caroline Plate north of New Guinea. Abers and McCaffrey (1988), Dow *et al*. (1988) and Quarles van Ufford (1996) believe that defor-mation in the Central Range of Papua was solely the result of a continuous oblique convergence between the Australian and Pacific Plates. How-ever, structural analysis along the HEAT road suggests that the geology at the time of intrusion and mineralization in the district was predomi-nantly a strike-slip offset. Strike-slip deformation in the district cannot be directly related to the oblique convergence between Australian and Pacific Plates. Instead, it is proposed here that the strike-slip regime was the product of the dominant transform movement between the Australian Plate and a short-lived Caroline Plate between ~4 and 2 Ma. Such interaction would create a transform offset, if the relative plate motion occurred along a trend slightly oblique to 299°.

The concept of the existence of the Caroline Plate north of New Guinea is a subject of con-troversy, however others proposed it long before this investigation. The age of the sea floor north of New Guinea is Oligocene, which is much younger than the rest of the western Pacific sea floor, which is Jurassic. This region of anomalous age has been termed the Caroline Block by Cloos (1992). The idea that this Oligocene sea floor was once kinematically distinct from the motion of the Pacific and Indo-Australian Plates is based upon evidence of a young spreading center at the Ayu Trough and convergence at the Mussau Trench. This evidence led to the proposed existence of a Caroline Plate by Weissel and Anderson (1978). Cloos (1992) proposed that prior to ~4 Ma and since ~2 Ma the Oligocene crust of the Caroline Block has moved as a part of Pacific Plate. Only from ~4 to ~2 Ma, the time of magmatism and mineralization in the GBMD, did the Caroline Plate act as a distinct kinematic plate tectonic entity.

The reason for this change in plate tectonic configuration according to Cloos *et al*. (2005) is that at ~4 Ma the motion of the entire Pacific Plate with respect to the Australian Plate changed

from SW (~246°) to WSW (~253°). As a result, a prong of the Pacific Plate wedged between the Philippine and Australian Plates broke off. To account for the strike-slip deformation in the GBMD, the movement of the broken prong, the Caroline Plate with respect to the Australian Plate, would have been approximately parallel to the major structural grain in the region (as recognized from the km-scale folds). Relative motion along an ~270° trend would account for the observed strike-slip-dominant deformation in the GBMD. When this occurred, two pre-existing structures, the Wanagon and Meren Valley Faults, which were originally sites of high angle reverse offset, became reactivated as left-lateral strike-slip fault zones.

The magnitude of left-lateral strike-slip faulting was probably only a few hundred meters to a few kilometers at most. This is adequate to account for the space needed for the Grasberg emplacement and other intrusions in the district.

Post-deformation (< 2 Ma)

The GBMD is presently not a site of active faulting based upon regional seismicity. In addition, glacial deposits are observed in many places and exposed by mining. No faulted glacial deposit has been observed indicating the district has not been the site of faulting for at least hundreds, if not thousands, of years.

When the GBMD became inactive is uncertain. In northern New Guinea, the change to major strike-slip faulting occurred before 2 Ma with the establishment of the Bewani-Torricelli and Yapen-Sorong fault zones as connections to the spreading center in the Bismarck Sea (Taylor, 1979). The concept proposed by Cloos *et al*. (2005) is that the strike-slip transform motion was distributed across the Central Range between ~4 Ma and ~2 Ma (Warren, 1995). Since ~2 Ma, the relative motion of Australian-Pacific Plates has been mostly located along the northern margin of the island.

Although strike-slip action at the longitude of the GBMD is now inactive, some strike-slip offsets continue at a similar latitude to the west

and east. In the Bird's neck area, a strike-slip related deformation is presently active along the Tarera-Aiduna fault zone. Earthquake focal mechanisms show that the seismic activity over the period 1976 - 1997 within the Central Range was dominated by a strike-slip offset in this area as well as near the border region in Papua New Guinea. These regions are connected to the Yapen Fault Zone (YFZ) by a convergent motion at the Mamberamo-Thrust-and-Fold-Belt and by an extension at the Waipona Trough (Sapiie *et al*., 1999).

In summary, a short-lived tectonic event (~4 - 2 Ma) is considered to have played a significant role in the structural development of the Central Range of Papua. In the GBMD, the period of the Caroline Plate's origin is recorded by the change from an obliquely convergent to a dominantly transform strike-slip fault offset (Figure 11). This tectonic activity generated conduits for magma ascension and the concentration of hydrothermal fluid flow, which generated the world-class Cu-Au ore deposits of the GBMD.

Conclusions

The results of the mesostructural analysis along an ~15 km transect of the HEAT and Grasberg roads in the GBMD reveal several new conclusions concerning the internal deformation of the Central Range of Papua as follows:

1. Structural analysis indicates two distinct stages of deformation since ~12 Ma. The first stage generated a series of en-echelon NW-trending (π-fold axis = 300°) folds and a few reverse faults. The second stage resulted in a significant left-lateral strike-slip faulting sub-parallel to the regional strike of the upturned bedding.

2. The pattern of minor strike-slip faulting in the domains between the major fault zones mimics the minor fault patterns found in the classic experiments. Faults trending 040° - 070° have left-lateral slickensides (rakes of 5° - 15°) plunging to the NE and are in-

terpreted as R (synthetic Riedel fractures). Faults trending 355° - 015° have right-lateral slickensides (rakes of 10° - 20°) plunging to the N and are interpreted as R' (antithetic Riedel fractures). Faults trending 280° - 300° have left-lateral slickensides (rakes of 10° - 30°) plunging to the NW and are interpreted as D-shears parallel to the primary displacement zone (PDZ) in the basement. Kinematic analysis reveals the areas between the major strike-slip faults form structural domains that are remarkably uniform in character.

3. The change in deformation styles from contractional to strike-slip offset is explained as being the result of a change in the relative plate motion between the Pacific and Australian Plates at ~4 Ma. From ~4 - 2 Ma, transform motion along an ~270° trend caused a left-lateral strike-slip offset and reactivated portions of pre-existing reverse faults. This action had a profound effect on magma emplacement and hydrothermal activity.

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