

## SCIENTIFIC COMMUNICATIONS

### GRADE DISTRIBUTION OF THE GIANT OK TEDI Cu-Au DEPOSIT, PAPUA NEW GUINEA

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#### Abstract

The Ok Tedi porphyry Cu-Au deposit in Papua New Guinea is a world-class mineral deposit. In its pre-mining stage, it contained 5.5 Mt Cu and 18.1 Moz Au; skarn accounts for ~80% of the current 1.9 Mt Cu and 7.7 Moz Au in total resources. Two composite felsic stocks intruded a tectonostratigraphic sequence of clastic and carbonate rocks at  $\sim 1.16 \pm 0.10$  Ma, in a postcollisional tectonic setting. Ensuing magmatic-hydrothermal mineralization occurred within a geologically short time span of ~200 k.y. On the mine scale, heterogeneous metal grades (0–2.5% Cu) reflect contrasting styles of mineralization, conforming to classic skarn- and porphyry-type mineralization. A three-dimensional geologic model, alteration distribution, mineralization styles, and grade distribution indicate that fluids, exsolved from a deeper magma chamber, used shallow stocks as their preferred permeable pathway upward. Where limestone was present at depth, high-grade skarn formed, with the permeable stock having very low (<0.1% Cu) grade. In contrast, where the intrusions were encapsulated solely by impermeable silicified siltstone, economic grade (avg 0.6% Cu) developed within the intrusion, showing concentric patterns interpreted to represent individual magmatic pulses within the stock. The rare opportunity to visualize this in three dimensions and interact with the model is provided in the interactive electronic supplementary material.

#### Introduction

Porphyry copper-gold deposits and skarn copper-gold deposits are both associated with fluids exsolved from hydrous oxidized magmas at upper crustal levels but are frequently treated separately in the literature, mainly because the deposit types are defined by different mineralogical associations and contrasting mineralization styles (Einaudi et al., 1981; Cooke et al., 2005; Meinert et al., 2005). The fundamental differences among host rocks to porphyry intrusions affected by mineralizing fluids were emphasized for various porphyry copper deposits in Arizona by Titley (1971). Also, the common association of skarn deposits with many porphyry copper deposits (Meinert et al., 2005), including the world's largest at Grasberg, Irian Jaya (Meinert et al., 1997), and Bingham, Utah (Atkinson and Einaudi, 1978), has long been known. However, there is a notable lack of published material on accompanying Cu- and Au-grade variations in such systems. Often, only average tonnage and grade (e.g., Cooke et al., 2005) are documented, which fail to represent spatial variability in grade. Furthermore, they are established using a cutoff grade at the time of reporting, and therefore biased by the economics of mining. In this study, we investigate the intrinsic spatial variability of magmatic-hydrothermal mineralization due to geologic factors.

We present a case study of the Ok Tedi Cu-Au deposit (Papua New Guinea) that highlights the relationships between host rock, mineralization style, and grade distribution, and that is a clear example of the close temporal and geometric association between skarn and porphyry-style deposits.

Three-dimensional models constrained by company logs of more than 960 diamond drill holes, blast-hole assays, and field work show that two types of alteration and mineralization correlate directly with variations in grade distribution. We interpret this to be a result of variable permeability and reactivity of the wall rocks. This interpretation is not rigorously demonstrated, however, but is consistent with classical models for the origin of such deposits. Ok Tedi is considered one of the world's largest Au-rich porphyry copper-gold systems (Cooke et al., 2005). It contained 5.5 Mt Cu and 18.1 Moz Au in its pre-mining stage (electronic supplementary material). Skarn accounts for ~80% of the current 1.9 Mt Cu and 7.7 Moz Au in total resources. Ok Tedi's size and geologic relationships warrant a more detailed deposit description than recent research papers on chemistry and geochronology have provided (Van Dongen, 2010a, b). Here, we combine well-established general concepts of magmatic-hydrothermal mineralization with geologic observations from the mine site and drill core to arrive at a model for the formation of Ok Tedi and explain the grade distribution. This is visualized using three-dimensional models and sections of geology and metal grades.

#### Regional Geology

The Ok Tedi deposit is located in the southern extension of the Papua New Guinean fold belt (Hill et al., 2002), near the border with Irian Jaya (Fig. 1). Paleozoic metamorphic and granite rocks of the West Papuan platform (Bamford, 1972) comprise the basement of the fold belt. Regionally extensive sedimentary rocks that also host the mineralized intrusions overlie the basement. This basement cover consists of the Ieru siltstone, a Late Cretaceous formation with a total thickness of 1,350 to 1,500 m, composed of mudstone-shale with sandstone and siltstone units, the massive late Oligocene

<sup>†</sup>Interactive electronic supplementary material for this paper is available at <http://economicgeology.org/> and at <http://econgeol.geoscienceworld.org/>.

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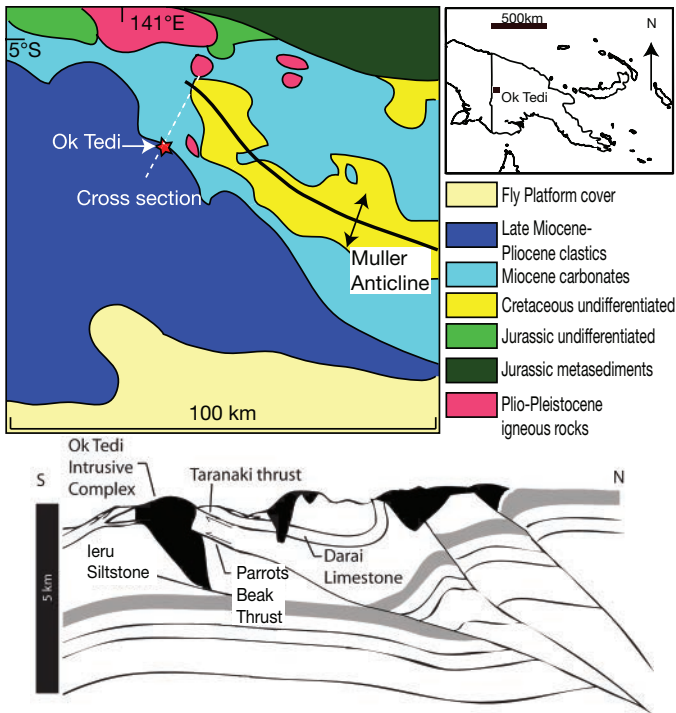


FIG. 1. Simplified regional geology of the Ok Tedi deposit in Papua New Guinea, modified from Hill et al. (2002), with schematic north-south cross section (modified from Mason, 1997). Intrusions in cross section are in solid black, gray unit is top of Toro sandstone, a marker unit in regional cross section constructions.

Darai limestone, up to 1,000 m thick, unconformably overlying the Ieru siltstone, and the mid-Miocene Pnyang Formation, conformably overlying the Darai limestone, up to 1,200 m in thickness and consisting of calcareous sedimentary rocks. South-directed folding and thrusting occurred in the late Miocene, during and after which a series of calc-alkaline felsic plutons intruded the fold-and-thrust belt along a NNE-trending lineament during the Pliocene (Arnold et al., 1979; Mason, 1994). The 2.9 to 1.1 Ma (Page and McDougall, 1972; Page, 1975) Ok Tedi Intrusive Complex is part of this intrusive event.

### Structural Setting

The Ok Tedi stocks and their deposits are within the regional scale NW-SE-trending Ok Tedi anticline and are closely associated with two N-dipping faults, which caused repetition of parts of the stratigraphy by producing a thrust wedge (Figs. 1, 2) that dies out away from the intrusive complex (Mason, 1994). The thrusts are known as the Parrots Beak thrust and the Taranaki thrust.

The lower Parrots Beak thrust (Fig. 3D, E) is cut by the Ok Tedi stocks (Figs. 2, 3) and crops out in the west of the open pit and also outside the mine area (Mason, 1994). The thrust caused partial repetition of a sequence comprising Ieru siltstone and Darai limestone, giving rise to an upper and a lower layer of Ieru siltstone and Darai limestone layers (i.e., UDL and LDL, Fig. 3B) surrounding the stocks. In contrast, the Taranaki thrust has not caused repetition of the stratigraphy and occurs as a dome-shaped plane immediately above the Ok

Tedi stocks (Fig. 2, section A-A'). Since erosion has removed the higher parts of the system, it is unknown whether the Taranaki thrust ever cut the stocks.

These two thrusts were active before magma emplacement, as evidenced by intrusion of the thrust stack by the stocks. Deformation continued after emplacement and mineralization, including movement on the Parrots Beak thrust, as evidenced by (1) intense and kinematically complex faulting of the stocks and host rocks exposed in the mine walls, (2) fractures in monzodiorite, which is partly replaced by endoskarn, and a 3-m intense zone of faulting defined by a fault gouge oriented parallel to the Parrots Beak thrust, and (3) tectonic breccias containing magnetite skarn blocks.

### Ok Tedi Intrusions and Alteration

The Ok Tedi Cu-Au deposit is centered on two neighboring vertical and roughly cylindrical stocks known as the Fubilan monzonite porphyry, to the north, and the Sydney monzodiorite stock to the south (Figs. 2, 3). The Sydney stock is linked to a larger U-shaped body known as the Ok Tedi Intrusive Complex, which extends over an area of  $\sim 2 \times 3$  km and consists of a number of intrusions of mostly equigranular monzodiorite. The Sydney stock consists of an equigranular to subporphyritic monzodiorite, which is intruded in the north by the 900-m-wide, semicircular porphyritic monzonite Fubilan stock containing a quartz stockwork core in its center (Bamford, 1972).

The igneous rocks comprising the Fubilan stock and the northern part of the Sydney stock contain miarolitic cavities and have been altered to K-feldspar- and biotite-bearing assemblages (Bamford, 1972; Arnold et al., 1979; Katchan, 1982), typical of hydrothermal alteration in the cores of porphyry copper systems (Sillitoe, 1973). Rocks of the Fubilan stock are more intensely altered than those of the Sydney stock, and this is reflected in the Fubilan by a marked increase in the modal abundance of K-feldspar, sericite, biotite, pyrite, and chalcopyrite (Van Dongen et al., 2010a), and an accompanying increase in alkali, silica, copper, and gold content. Both stocks also contain intensely K-feldspar-biotite altered porphyritic xenoliths, suggesting that they incorporated blocks of earlier intrusive pulses that were also hydrothermally altered.

The Fubilan monzonite represents a more altered variety of a rock essentially identical to the Sydney monzodiorite, as inferred by removing alteration effects on original rock compositions using immobile element trends (Doucette, 2000; Van Dongen, 2010a). This means that the Fubilan monzonite would be more accurately referred to as "Fubilan monzodiorite" but, because of historic reasons and the lack of unaltered Fubilan rock, we have opted to retain the original name. Toward the contact with the country rocks, the stocks contain breccias and veins with sericite-quartz-pyrite assemblages (Bamford, 1972). Alteration of the host rock surrounding the Fubilan stock is characterized by local silicification of the Ieru siltstone with dispersed pyrite grains and subvertical 1- to 10-cm-thick veins of massive pyrite spaced at  $\sim 1$ -m intervals. In the brecciated zone between the Fubilan and Sydney stocks, mineralized clasts, epidotized clasts, and quartz-veined siltstone clasts are found, indicating multiple brecciation and alteration events.

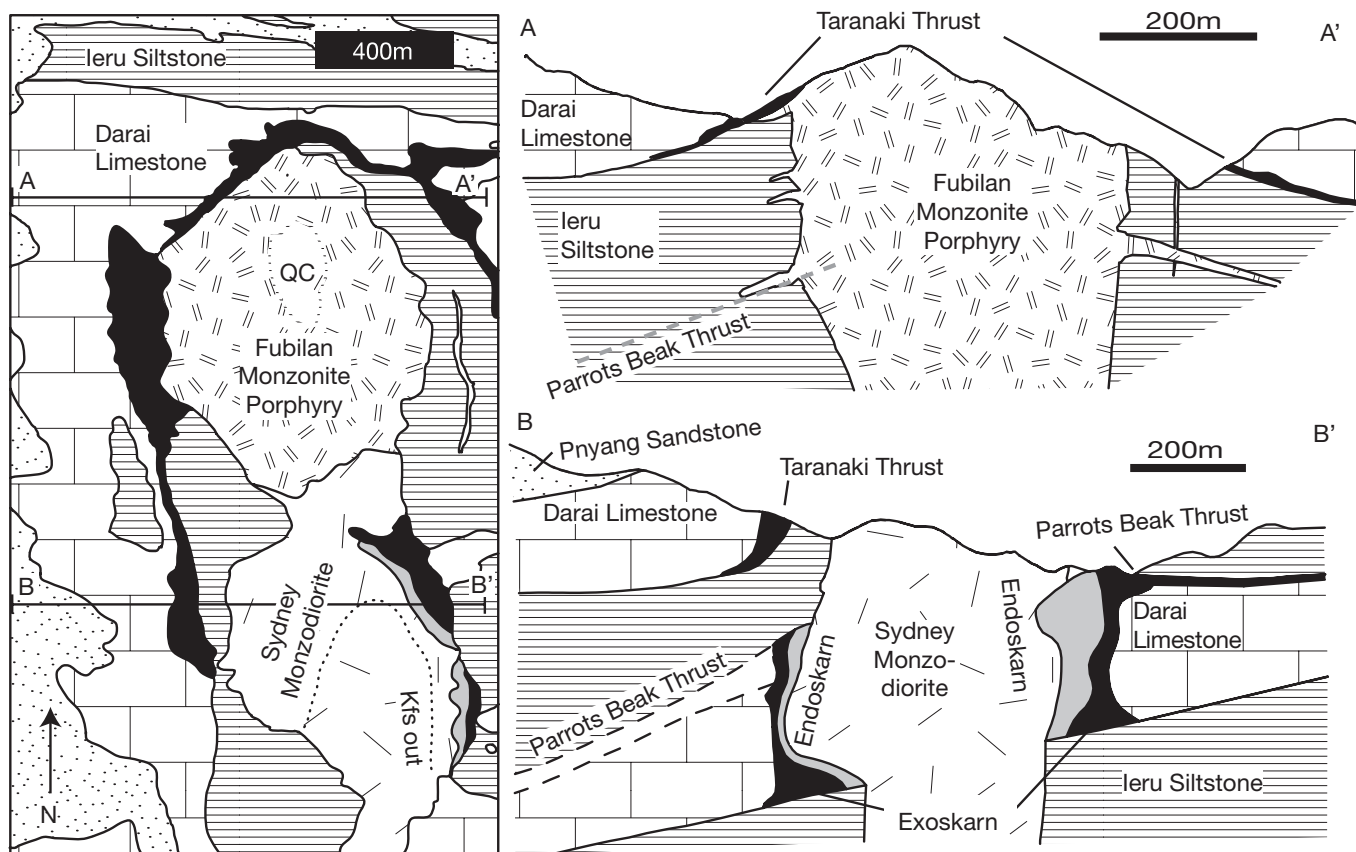


FIG. 2. Pre-mining surface geologic map and west-east cross sections in the northern and southern parts of the Ok Tedi mine (A-A' and B-B', respectively). On the map, the spotted line ("Kfs out") within Sydney monzodiorite indicates the southern limit of potassic alteration, as inferred from drill core study throughout the intrusions; QC denotes the location of the quartz stockwork core. Cross sections show the Taranaki deposit (skarn, in black) is exposed at the surface in the west, whereas the Center Pit deposit (endo- and exoskarn, in gray and black) only occurs in B-B', surrounding the Sydney monzodiorite at depth in the west and at the surface in the east. In A-A' the Parrots Beak thrust is inferred, marked by the thick gray dashed line, and separates two structurally repeated sequences of Ieru siltstone. In contrast, in B-B' the Parrots Beak thrust (dashed) is a well-developed deformation zone in the structurally lower layer of Darai limestone. For sense of movement on thrusts, refer to Figure 1.

A crucial difference between the Fubilan and Sydney stocks is the geometry of country rocks encasing them. The southern Sydney stock cuts the structurally lower wedge of Darai limestone that is sandwiched between structurally repeated Ieru siltstone layers. This wedge reaches a thickness of up to 250 m in the south, but gradually narrows and dies out northward close to the contact between the two stocks (Fig. 2, section B-B'). The wedge hosts mineralized skarn and resulted from the geometry of the Parrots Beak thrust. Because limestone wedges out northward, the Fubilan stock was emplaced almost entirely within Ieru siltstone (Figs. 2, section A-A', 3). The upper Darai limestone layer, domed above the Taranaki thrust, would have capped both stocks, but has been eroded away. Unique, interactive three-dimensional visualization of the deposit is available in electronic supplementary material Figures A1 and A2.

### Mineralization

Two distinct mineralization styles have been identified at Ok Tedi (Rush and Seegers, 1990). Typical porphyry copper-style mineralization comprises the bulk of the mined portion of the

Fubilan stock encased by Ieru siltstone (avg ~0.6% Cu and <0.5 g/t Au). Replacement-style mineralization is restricted to the structurally lower Darai limestone layer and associated skarn encapsulating the Sydney stock (Figs. 3, 4), and to the structurally higher limestone layer capping the Fubilan stock. The typical porphyry copper-style ore in the Fubilan stock is characterized by disseminated mineralization and quartz veins containing pyrite, chalcopyrite, secondary chalcocite, and molybdenite found within the K-feldspar and biotite alteration zone (Fig. 4). Similarly intense alteration is also found in the northern part of the Sydney stock, but grades tend to be below 0.01% Cu.

The replacement deposits can be subdivided into two types based on differences in volume, extent, and composition (Table 1): Center Pit type and Taranaki type. The Taranaki-type deposit closely follows the gently domed Taranaki thrust at the base of the structurally higher layer of Darai limestone. It is typically thin, but laterally extensive, and has a magnetite-pyrite-dominated mineral assemblage. Although extending well beyond the mine, the Taranaki thrust contains chalcopyrite in the vicinity of the Fubilan stock. In contrast, the Center

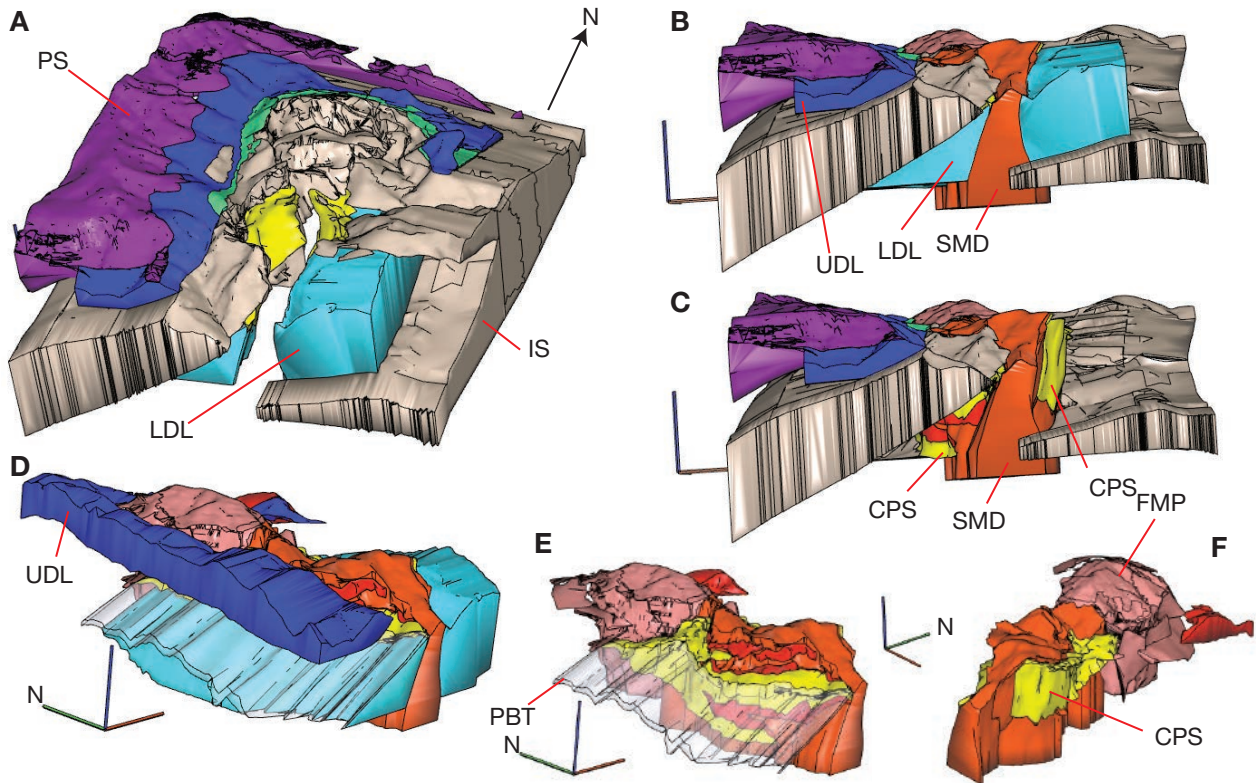


FIG. 3. Three-dimensional geologic model (in shaded relief), constructed from company drill core logs. A. Overview of the host-rock geology of the Ok Tedi mine area and surroundings, with stocks taken out to emphasize the “layer-cake” stratigraphy, with the Pnyang siltstone (PS, in purple) being the youngest sedimentary unit. B. View from the south, showing the Sydney monzodiorite (SMD, in orange) stock intruding subvertically into this layered stratigraphy, including the wedge of lower Darai limestone (LDL, in light blue). C. Same view as B, but with Darai limestone left out, to show how the skarns (CPS, in yellow) form at the limestone-intrusion contact. D. View from southwest, showing the upper Darai limestone (UDL, in dark blue) not in contact with the intrusions and showing the wedge shape of the lower Darai limestone (in light blue). E. Same view as D, but with both limestone layers left out, showing the Parrots Beak thrust (PBT, in transparent white) and how skarns (CPS, endoskarn in yellow and exoskarn in red) wrap around the limestone-intrusion contact. F. View from southeast, showing extent of skarn development along the limestone-intrusion contact. Note the absence of significant skarn in the north around the Fubilan monzonite porphyry (FMP, in pink), which is completely encapsulated by Ieru siltstone (IS, in beige in 3A-C).

Pit-type deposits wrap around the southern Sydney stock, following the enveloping Darai limestone, which is brecciated in its upper part by the Parrots Beak thrust (Figs. 2, section B-B',

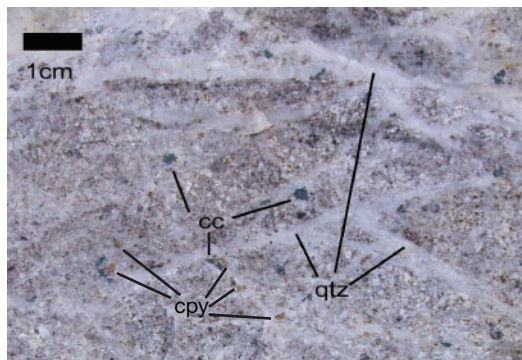


FIG. 4. Stockwork quartz (qtz) veining with disseminated chalcopyrite (cpy), in many cases reacted to form chalcoite (cc), and as selvages to quartz veins in a sample of Fubilan monzonite porphyry (FMP). This is typical of the porphyry copper-style mineralization within the formation. Sample taken from exposure along the northern pit wall.

3). Thus, its horizontal width away from the stock is limited to 50 to 100 m on average, and its vertical extent is limited by the thickness of the Darai limestone (Figs. 2, 3). Similar to the Taranaki-type deposit, the Center Pit-type deposits are characterized by magnetite, pyrite, chalcopyrite, and tremolite-actinolite and are spatially associated with magmatic rocks that are intensely altered, forming an endoskarn (Fig. 2; cf. Einaudi et al., 1981) characterized by a garnet-, epidote-, and diopside-bearing assemblage (Table 1). Massive magnetite skarn bodies replaced limestone and mudstone (Fig. 5). Magnetite skarn is also found as blocks in tectonic breccias. Magnetite deposition was followed by deposition of sulfides that commonly fill fracture planes in massive magnetite rock and form the matrix of magnetite breccias (Fig. 5A). Massive Cu-bearing sulfide skarns of <2-m width are widespread, but are located at irregular intervals, and were most probably the result of a combination of passive replacement (cf. Fig. 5B vs. 5C and 5D vs. 5E) and active fracture-controlled sulfide deposition.

Endo- and exoskarn development within and around the Sydney monzodiorite strongly suggests that the Center Pit deposit formed as a result of the Sydney magmatic-hydrothermal

TABLE 1. Contrasting Styles of Mineralization at Ok Tedi Mine

	Porphyry style	Replacement style	
		Center Pit	Taranaki
Cu and Au grade	Low (< 0.5 wt % Cu, 0.5 g/t Au)	High (2 wt % Cu, 1 g/t Au)	Generally low
Mineralization location relative to pluton	As irregularly shaped bodies within Fubilan monzonite porphyry; highest grades of Au mostly above, and Cu below, oxidation depth	Adjacent to Sydney monzodiorite in contact with limestone breccia	Dome-shaped on top of Fubilan monzonite porphyry and extending along the Taranaki thrust
Host rock of pluton	Dominantly Ieru siltstone	Mostly Darai limestone breccia at depth	Darai limestone cap on top of intrusion
Alteration	Potassic and phyllic	Outward from Sydney monzodiorite <sup>1</sup> : 1. Potassic 2. Calcic/endoskarn 3. Exoskarn	Magnetite-dominated exoskarn

Notes: Potassic: K-feldspar + biotite; phyllic: quartz + sericite; calcic/endoskarn: garnet + pyroxene + epidote; exoskarn: from massive magnetite to magnetite + pyrite + chalcocopyrite

<sup>1</sup> (Katchan, 1982)

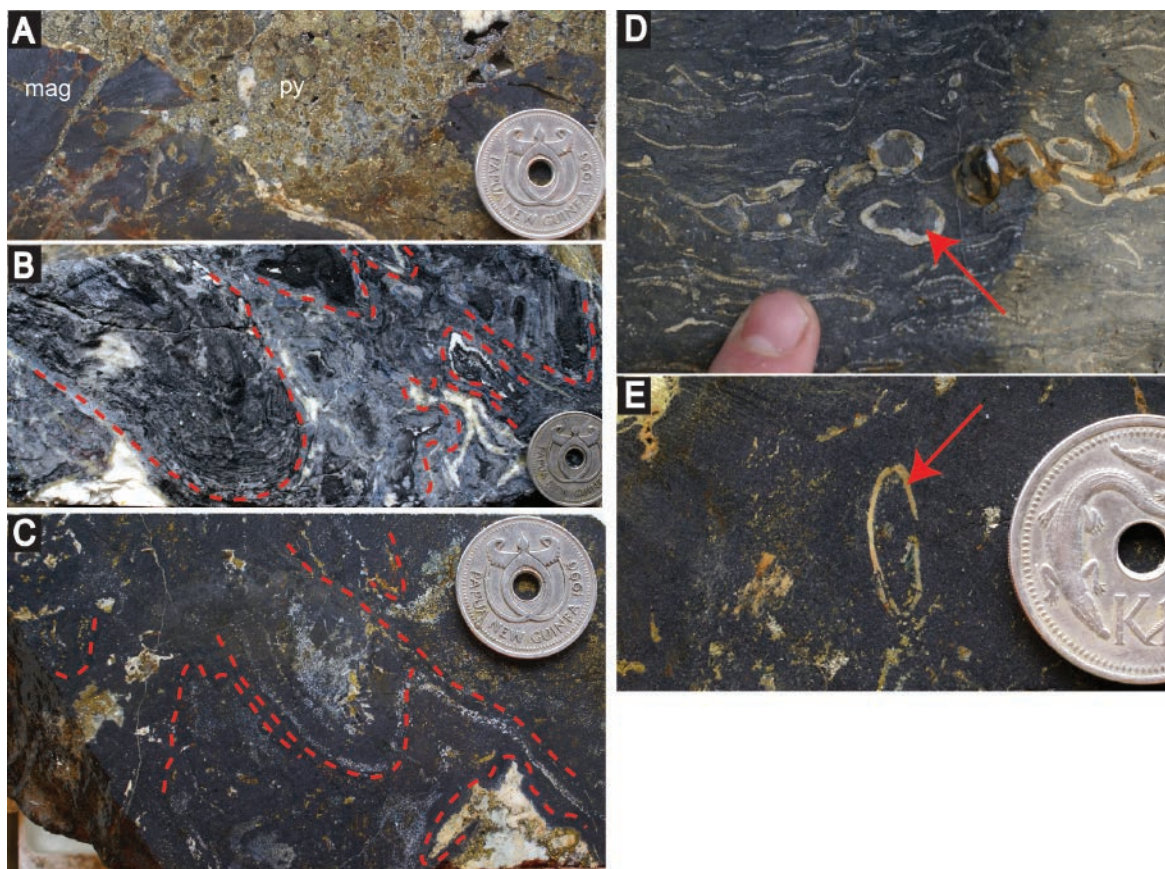


FIG. 5. A. Magnetite-skarn breccia with pyrite-chalcocopyrite matrix and vein filling, suggesting fracturing and sulfide deposition by hydrothermal fluids after magnetite formation. Sample from Center Pit deposit, east of Sydney monzodiorite, DDH 894, ~100-m depth. B. Slump textures (indicated by dashed red line) in an unaltered mudstone bed of Ieru formation, ~400 m west of the mineralized Fubilan monzonite porphyry. The white mineral infill is zeolite, based on hand lens identification. C. Slump textures (indicated by dashed red line) in magnetite-sulfide skarn suggesting passive replacement of mudstone by metal-bearing fluids originating from the stock. Sample location adjacent to the western side of the Sydney monzodiorite (DDH 947, ~70-m depth). D. Bivalves (red arrow) in unaltered Darai limestone formation. Sample from exposure along the western pit wall road, ~200 m west of the mineralized Fubilan monzonite porphyry. E. Bivalve (red arrow) bearing magnetite-sulfide skarn, suggesting passive replacement of Darai limestone by magnetite. Samples from DDH 947, ~183-m depth, adjacent to the western side of the Sydney monzodiorite.

event. Zircon SHRIMP U-Pb ages (Van Dongen et al., 2010b) for both stocks cluster around  $1.16 \pm 0.10$  Ma and are within analytical error of each other. The ages of the intrusive rocks plus hydrothermal alteration within them are bracketed between 1.26 ( $1.16 + 0.10$  Ma, maximum zircon age) and 1.06 Ma ( $1.11 - 0.05$  Ma, minimum K-Ar age from Page and McDougall, 1972; Page, 1975), with the latter representing the final cooling age. Therefore, the hydrothermal event associated with emplacement of the Fubilan monzonite porphyry and Sydney monzodiorite occurred in a geologically short time span of 200 k.y. We do not have cooling ages from minerals in the skarn bodies to constrain the duration of the event. It is possible that skarn formation lasted longer than the alteration events within the Fubilan monzonite porphyry, but for the purpose of conceptualizing the magmatic-hydrothermal system, we regard the porphyry and skarn mineralization as contemporaneous on a geologic time scale and possibly forming from the same hydrothermal system.

### Grade Distribution

Inspection of blast hole Cu and Au grades shows lateral and vertical heterogeneity (Figs. 6, 7), both on the deposit scale and within individual orebodies. The average (bulk) Cu grade in the skarns is more than 1% (Fig. 6) and commonly up to 2.5%, making them the highest-grade Cu bodies of the deposit. The Fubilan monzonite porphyry has an average (bulk) grade of ~0.6% Cu, with grades varying between 0.01 and 0.9% Cu (Fig. 6), whereas the intensely K-feldspar-altered parts of the Sydney monzodiorite have an average grade below 0.1% Cu. The Au distribution mimics that of Cu, with the highest Au grades in the skarns, followed by the Fubilan monzonite porphyry, whereas the Sydney monzodiorite is nearly barren. In contrast to relatively high and homogeneous grade in the skarns, there are concentric patterns of grade distribution (Fig. 6) that form rings of high grade within the intrusions that have otherwise low grades.

Vertical heterogeneity (Fig. 7) also corresponds to the differing rock units, but is complicated by the additional effects of supergene processes. There are four significant high-grade Au zones ( $>0.5$  g/t, indicated by numbers 1–4 in Fig. 7A) and they occur as bodies of apparent steep northward dip. Two bodies (1 and 2) are hosted within the Fubilan monzonite porphyry, directly surrounding the unmineralized quartz core (Fig. 2). The one on top of (former) Mount Fubilan (no. 2) corresponds to Ok Tedi's historical residual gold cap, the resource that allowed for mine construction. A third body (no. 3) corresponds to the Center Pit skarns, and the fourth body (no. 4) occurs within the Sydney monzodiorite. Comparison with Figure 6 suggests that bodies 3 and 4 are part of the concentric high-grade bodies (see concentric high inside Sydney monzodiorite in Fig. 6B, D, and F). Quite in contrast to the gold distribution, the high-grade Cu zones (Fig. 7B) are at or below the base of supergene enrichment (at depth) but are highest where they coincide with the high-grade Au zones.

### Controls on Grade Distribution

We identified three main controls on grade variations:

1. Reactivity of the host rock: Where limestone bordered the intrusions, skarn developed and these skarns have higher

bulk grades than the intrusions. This suggests that pH buffering by limestone was an important control in skarn formation (cf. Williams-Jones et al., 2010). It is beyond the scope of this paper to assess in similar detail the relative importance of all factors (i.e., changes in pH, P, T,  $f_{O_2}$ ,  $a_{Cl^-}$ ,  $a_{H_2S}$ ) that could have controlled sulfide deposition in both porphyry and wall rock. However, we could identify sulfidation, in which silicates and magnetite provided Fe, as being the key reaction mechanism, since we observed that disseminated sulfides in the porphyry were associated with former mafic minerals, whereas in the skarns, they were associated with abundant magnetite.

2. Permeability structure: On the deposit scale, the intense internal alteration of the Fubilan and Sydney stocks, combined with low-intensity alteration of their country rocks, suggest that fluids flowed predominantly through them, and were unable to enter the relatively impermeable and chemically inert Ieru siltstone. However, they were able to escape through the brecciated contact with the limestone wedge surrounding the Sydney stock at depth. Ultimately, the fluids that flowed through the Fubilan monzonite, lacking a reactive limestone wall rock, most likely escaped through the cupola region at the top, primarily along the Taranaki thrust, reacting with and mineralizing the overlying thin bed of limestone, thus forming the Taranaki skarn.

3. Permeability creation: The contrasting hand sample-scale features of porphyry vs. skarn mineralization (cf. Figs. 4, 5) attest to differences in permeability creation. In the stock, increased permeability was achieved through fracturing (i.e., vein networks), whereas in the skarns, volume loss due to chemical reactions typical of skarns (e.g., Zhang et al., 2000) increased their permeability to the extent that failure of the rock was apparently inhibited. The resultant differences in grade suggest that at Ok Tedi, pervasive fluid flow through a reactive host rock was more favorable to produce high-grade mineralization than vein-controlled fluid flow through a less-reactive host rock.

A salient feature of the blast hole images (Fig. 6) is the rings of high-grade mineralization within the intrusions. The rings could have formed through radial cooling of individual plugs, they could represent fluid pathways along intrusive margins, or they could be the results of grade dilution by late-stage plugs. Our (limited) drill core study of this phenomenon confirms that the stock is composed of multiple intrusive phases. The mine logs on which the three-dimensional model is based, however, did not distinguish between these pulses because of their similar mineralogy. The explanation therefore remains somewhat speculative, as there is currently no suitable data available to test relationships between grade and magmatic pulses.

The porphyry copper-style mineralization within the Fubilan monzonite porphyry is similar to that of a number of other porphyry copper deposits worldwide (Sillitoe, 1997; Cooke et al., 2005). The replacement-style Center Pit deposit with its massive magnetite-sulfide alteration is comparable to other porphyry-related skarn and carbonate-hosted metal deposits worldwide, e.g., Grasberg-Ertsberg in Irian Jaya (Katchan, 1982; Meinert et al., 1997, 2003) and Bingham, Bisbee, and Leadville in the Western U.S. cordillera (Titley, 1996). In those systems, the grade relationships between the two deposit

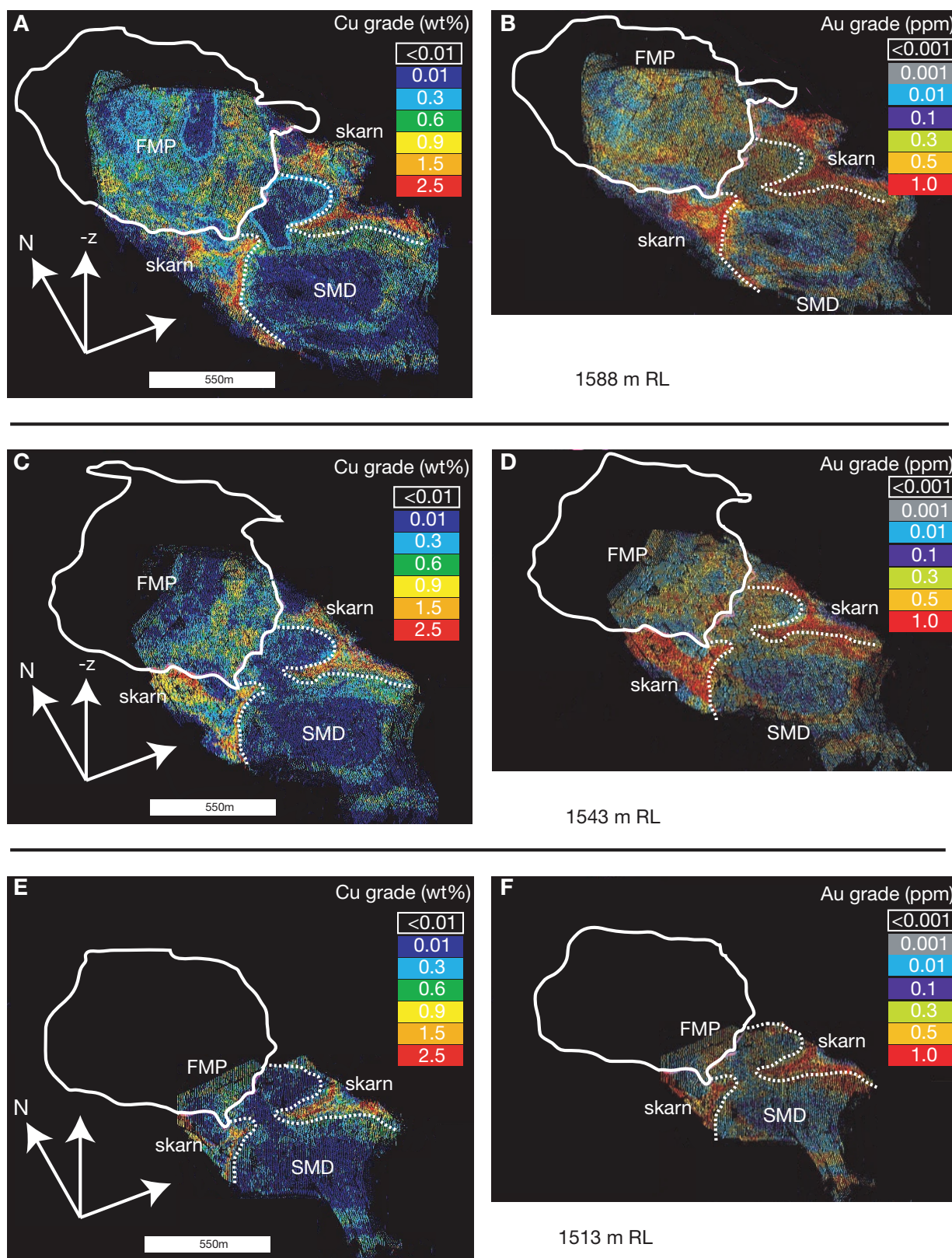


FIG. 6. Blast hole grades of Cu (left) and Au (right) at elevations of 1588 m (top row), 1543 m (middle row) and 1513 m (bottom row). The modeled outlines of the different rock types intersecting the respective mine level (RL) are shown in white. Cu grade is high inside the Fubilan monzonite porphyry, which was emplaced into siltstone. By contrast, Cu grade is low inside the Sydney monzodiorite but high in the Center Pit deposit (exoskarn, Fig. 2 A-A'). Notice the concentric grade distribution patterns.

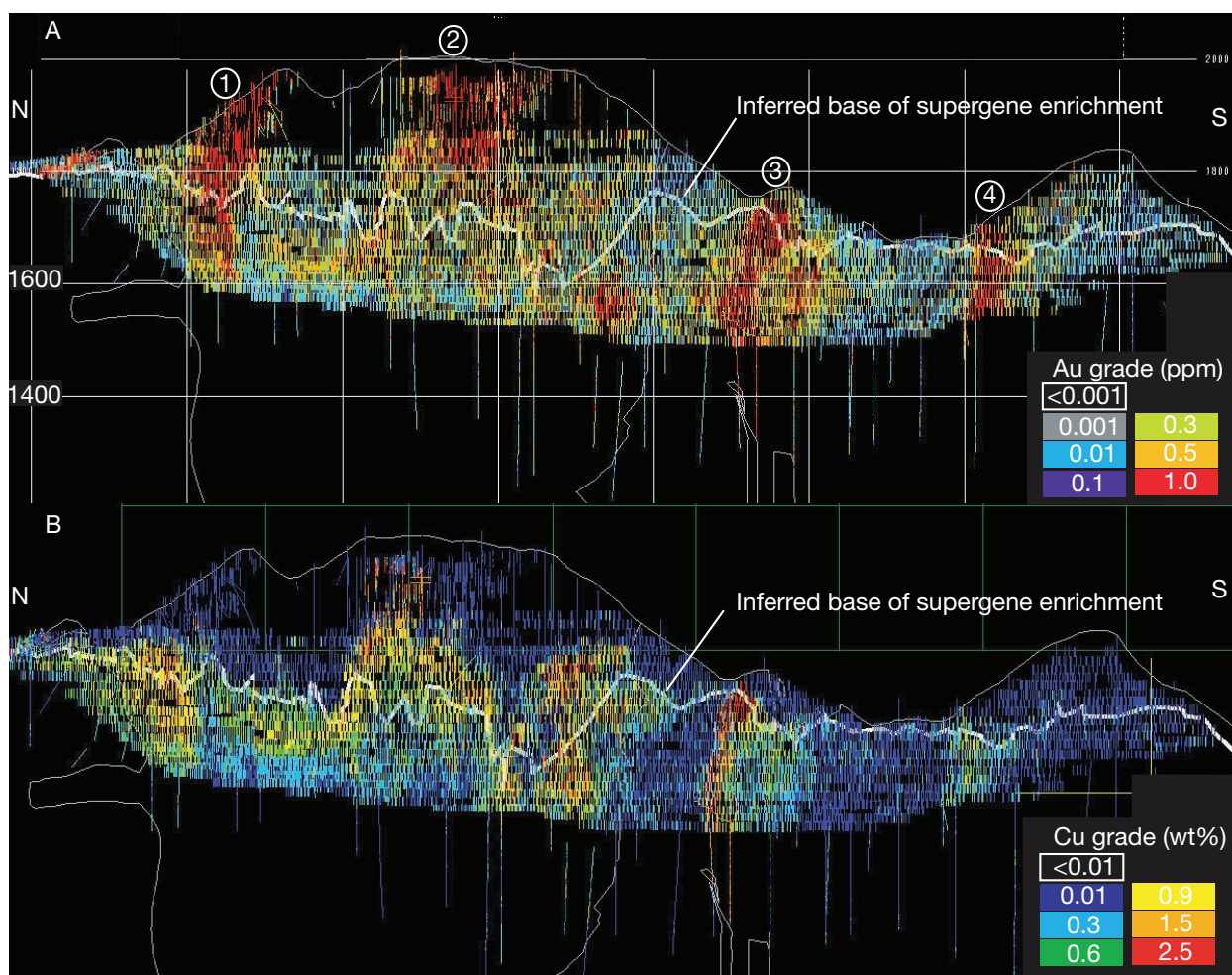


FIG. 7. Blast hole grades of Au (A) and Cu (B) along a section that follows the long axis of the deposit, roughly north-south. The inferred base of supergene enrichment is indicated, constructed from documented occurrences of chalcocite by mine geologists. High-grade zones are indicated by circled numbers in A, and the mine level (RL) is indicated on the vertical axis, for comparison with Figure 6. See text for description of important features.

types are poorly documented, and the control of rock types on the style and grade of mineralization can be obscured by distance, geometry, and unclear age relationships. Researchers who have studied those deposits have concluded that rock type controls skarn formation and permeability controls fluid flow and ore deposition, and Ok Tedi demonstrates this interplay very well.

### Conclusions

The Ok Tedi deposit conforms to a deposit model in which a deep large magma chamber exsolves fluids that deposit Cu and Au along permeable pathways, dictated by the three-dimensional distribution of lithology and faults. The Fubilan and Sydney stocks are statistically indistinguishable in crystallization age (both 1.1 Ma) and the simplest interpretation is that both the skarn and the porphyry mineralization occurred contemporaneously from the same fluid exsolution event. The Fubilan and Sydney stocks acted as the main pathways for the ore fluid from the magma chamber at depth, probably in a more complex way than described in this paper, whereas the local host rock type determined

whether the metals were deposited in the style of skarn or porphyry. The deposit was subsequently weathered and supergene mineralization modified the three-dimensional grade distribution.

The Ok Tedi resource, averaged out over the entire deposit, is typical of a large tonnage-low grade Cu-Au deposit. However, the strongly heterogeneous distribution of metal grades documented in this study indicates that accurate assessment of the resource potential of similar magmatic-hydrothermal Cu-Au deposits relies heavily on dense drill hole spacing. Furthermore, when low-grade intersections are encountered within a strongly altered porphyry during early exploration stages, this may be indicative of skarn mineralization away from the stock (e.g., within the surrounding wall rock and/or at depth) or that a postmineralization pulse within a larger, mineralized stock has been drilled. The first option can be assessed by understanding the three-dimensional geology and subsequent modeling using the simple permeability-reactivity concepts discussed in this paper. The second option requires a more comprehensive resource assessment—for example, by more closely spaced drilling.



### Acknowledgments

Karl Smith, Roland Kaegi, Luke Jackson, and Ok Tedi Mining Limited are thanked for logistical support, access to the mine site, and use of exploration and production data. The Australasian Institute of Mining and Metallurgy Gold '88 award is acknowledged for travel support. MvD's PhD study was financed by scholarships from Monash University and the predictive mineral discovery Cooperative Research Centre. Reviewers S. Rowins and I. Kavalieris, and Editors L. Meinert and A. Williams-Jones are thanked for providing feedback and suggestions that have much improved this manuscript.

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