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Stability assessment and ground support design for drifting through a cemented paste filled stope at the Big Gossan mine, Indonesia

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Abstract

This paper focuses on the process of developing a safe and stable drift through cemented paste fill (CPF) at PT Freeport Indonesia's Big Gossan mine which allows access to the Kucing Liar mine. The access drift was designed with dimensions of 5.5 m width and 6.5 m height with a length of 20 m through a CPF stope.

A risk assessment to develop a drift through a cemented paste filled stope indicated that a specific process of development and support sequence together with a stability analysis must be performed to ensure long-term stability. The analysis included in situ sampling and laboratory testing to determine the geomechanical material strength properties of the CPF. Stability analyses were conducted to determine the required thickness of in-cycle fibre reinforced shotcrete and mesh, pinned by friction bolts, as the main ground support system. The development operational stage was closely monitored through inspections and scanning to determine the effectiveness of the excavation process and ground support.

In conclusion, this study successfully evaluated the feasibility of developing a drift through CPF, with effective ground support systems, to access the Kucing Liar mine safely. The risk assessment, development, and ground support sequence prior and after execution provided a robust foundation for design and safety considerations. This study serves as a valuable reference for engineers and mining professionals seeking to implement similar solutions in underground mining operations.

Keywords: *Big Gossan, Kucing Liar, cemented paste fill, fibre reinforced shotcrete, risk register*

1 Introduction

Big Gossan (BG) mine, owned by PT Freeport Indonesia (PTFI), is located in the Sudirman mountain range of Papua in the Ertsberg minerals district (Figure 1) and is one of the world's largest stoping mines.

The mining method implemented at BG is open stoping with a cemented paste backfill. Ore is transported via ore passes, then trucked to a crusher and hoisted onto the existing conveyor system and out to the mill stockpiles. The paste plant is underground and located at the top of the orebody. The mill provides a tailings feed for the paste plant. A spiral ramp connects all the levels for personnel and material handling, and a shaft is used for production hoisting. The BG mine is producing approximately 7,000 tpd (Casten et al. 2020).

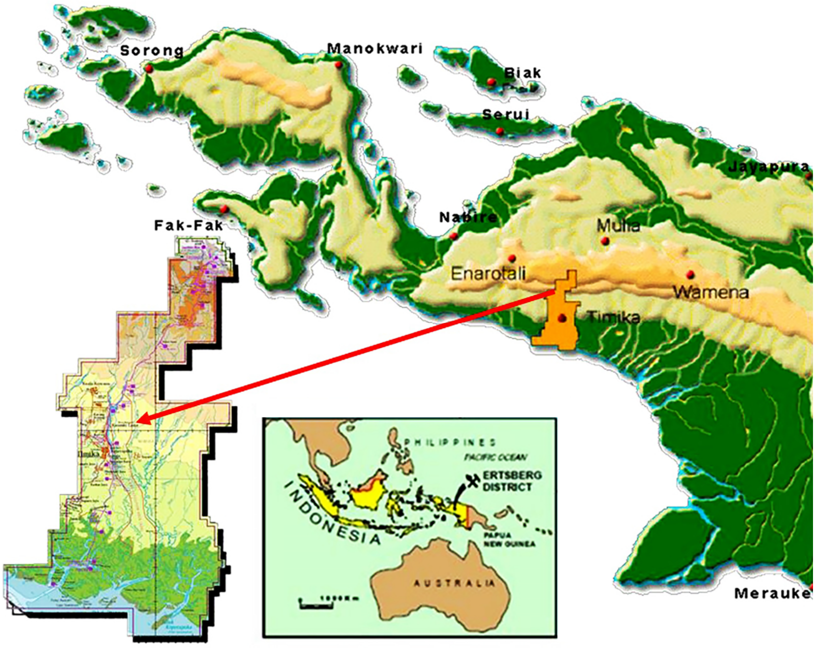


Figure 1 Location of PT Freeport Indonesia mines in Papua, Indonesia

Within proximity to the BG mine, development for the Kucing Liar (KL) underground block caving mine is underway. It was decided to access the KL fixed facilities infrastructure through a filled BG cemented paste fill (CPF) stope to reduce development meters and cycle times. An access drift was designed with dimensions of 5.5 m in width and 6.5 m in height, with a development length of 20 m through the CPF stope and with serviceability of a minimum of two years. As illustrated in Figure 2, the CPF barricade will require blasting to be removed to expose the CPF, which is located 15 m to the brow of the stope. Surrounding stopes to the design drift are back filled, including the bottom level stope and both adjacent crosscut stopes.

In order to determine the design and ground support needs within the CPF, the material was studied by drilling through the CPF and collecting samples for field and laboratory testing and stability analysis. Monitoring systems were also implemented, during and after the excavation, to proactively mitigate any potential hazards.

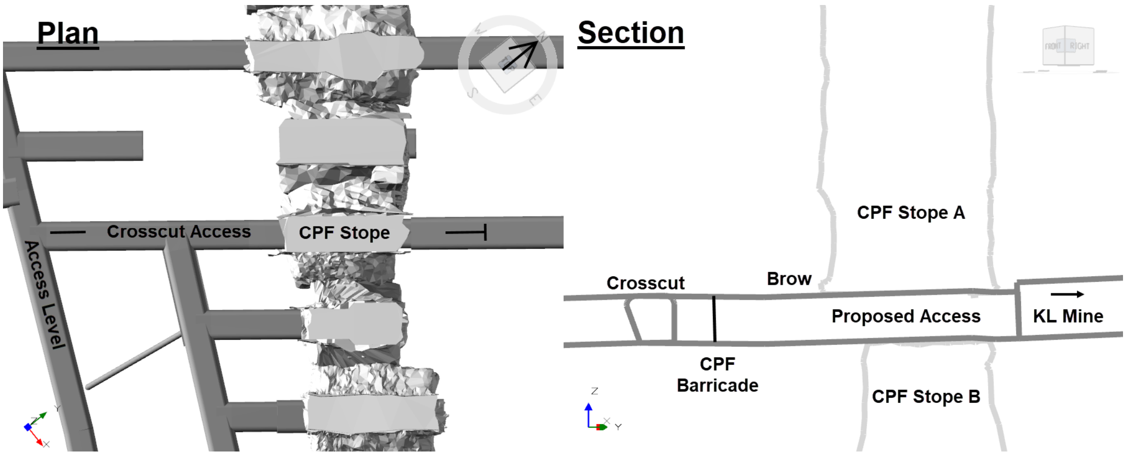


Figure 2 Plan and section view of the proposed design cemented paste fill (CPF) drift

2 Preliminary assessment

Investigation of the existing CPF fill conditions and historical data were assessed prior to the planned drilling. In order to assess the stability of the placed fill material, the existing strength properties and homogeneity data was collected and evaluated.

Cold joints or air gaps formed by filling practises (Pakalnis et al. 2005), such as a change to binder content, sequencing, or incremental filling caused primarily by downtime, could result in varying curing times. This is a major factor in assessing the stability of the fill material. Based on the stope's fill pour data, there were two instances of downtime which may have formed cold joints. The location of the potential cold joints from the sill elevation was back calculated from the total CPF volume filled over time and will require further investigation through drilling to confirm its existence.

The material's strength was determined by performing laboratory uniaxial compressive strength (UCS) tests over a selected number of curing days to determine curing rates. Fill material strength increase with curing age for the stope within the drift limits (Stope A), as well as the underlying stope (Stope B), are summarised in Table 1. The underlying stope must also be reviewed due to bearing strength requirements, i.e. the weight of equipment and personnel traveling on it. Stope B has higher strengths due to a higher cement content. Further investigation of the strength would be planned through a drillhole, and it is expected that the CPF strength will increase due to a longer curing period after placement. Stope A will have been filled for four years and Stope B for eight years.

Table 1 Stope A and Stope B cemented paste fill strength summary

Curing days	Stope A UCS (kPa) Cement content: 4.5%	Stope B UCS (kPa) Cement content: 6.0%
7	120	–
14	160	470
28	200	540
56	300	640
84	200	750
150	660	–

3 In situ drilling analysis

Drilling of the in situ fill material was conducted at the top crosscut of Stope A. The ground conditions were inspected in the field, and minimal rehabilitation was required prior to the drill rig setup. Given that the filled Stope A dimensions are 40 m high, 15 m wide and 49 m long, a 90° downhole (NX with 75 mm diameter) intersecting Stope A and B was planned in the centre of the stope. The core was visually inspected (Figure 3) and logged to identify any layering (e.g. cold joints). Samples with a minimum length of 20 cm at approximately 2 m intervals were collected. Field test data (penetrometer) and laboratory data (UCS, triaxial compressive strength [TCS] and density) were collected. Laboratory testing was conducted at a laboratory on site, as well as at two third-party laboratory facilities with a total sample size of 51.

Figure 3 Cemented paste fill core samples

Penetrometer testing, performed over the total length of hole, indicated the majority of the results to be >1,300 kPa. UCS and density testing also showed consistent results, as indicated in Table 2. Based on the number of samples tested, a representative and average UCS of 1,200 kPa was adopted for design purposes.

Table 2 Uniaxial compressive strength (UCS) laboratory results

	Stope A Density (kg/m^3)	Stope A UCS (kPa)	Stope B Density (kg/m^3)	Stope B UCS (kPa)
Maximum	2,118	1,581	2,013	4,770
Average	2,019	1,214	1,980	3,827
Minimum	2,118	752	1,934	3,157
Standard deviation	62	217	21	483
-1 standard deviation	1,977	997	1,913	3,343
Design UCS	2,020	1,200	1,980	3,800

Equations 1 and 2 explain TCS results using p-q plots to derive the cohesion, friction angle, and UCS as shown in Figure 4 and Table 3. The p-q method was implemented for simplifying the analysis for TCS results along with the UCS data, given the characteristics of the fill material. The Mohr–Coulomb method was also used for comparison. For design purposes, a p-q combined plot that includes the UCS laboratory test data was used for the assessment. Cold joints were not observed in the core are there were no natural breaks or air gaps found, and homogeneity may be assumed within the proposed drift area.

$$p = \frac{1}{2}\sigma_1 + \frac{1}{2}\sigma_3 \quad (1)$$

$$q = \frac{1}{2}\sigma_1 - \frac{1}{2}\sigma_3 \quad (2)$$

where:

σ_1 = failure pressure.

σ_3 = confining pressure.

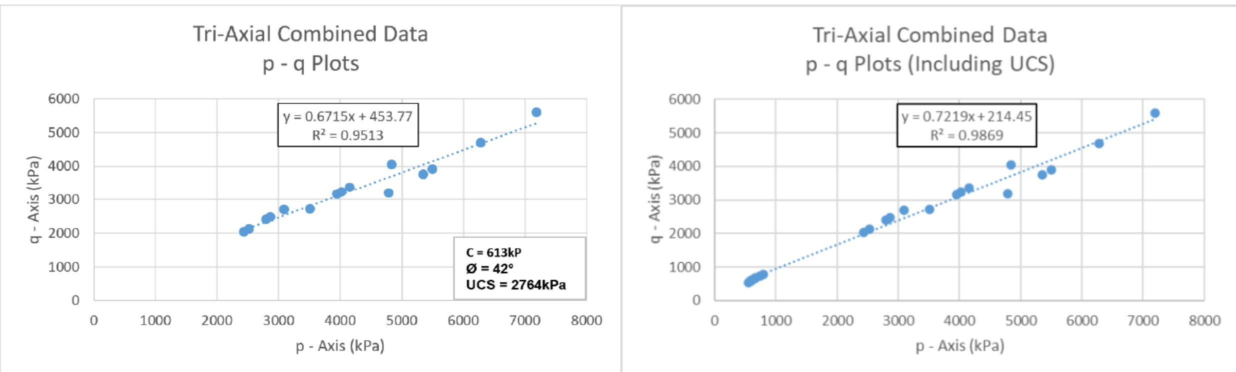


Figure 4 Laboratory triaxial compressive strength and uniaxial compressive strength (UCS) data p-q plots summary

Table 3 Triaxial compressive strength laboratory and p-q plots summary

Method	Cohesion (kPa)	Friction (°)	UCS (kPa)
Mohr–Coulomb	974	36	3,752
p-q	613	42	2,764
p-q (with UCS)	289	47	1,449

4 Design

The design approach and recommendations on CPF stability was studied in two areas. First was the undercut sill exposure, or the stability of the roof of the drift. The other was the walls or vertical exposure of the fill material. Failure mechanisms for both areas were studied with a drift entry Factor of Safety of 1.5.

Based on a conservative two-dimensional approach method described by Mitchell (1991) in Figure 5, stability and strength of the undercut sill was determined by assessing the failure mechanisms which include caving, shear, flexural, rotational and/or crushing. Based on the in situ drilling data and laboratory strength test results, each failure mechanism was calculated as shown in Table 4. Several iterations were compared to understand the sensitivity of the analyses and to mitigate potential risks during excavation. Although observation from drilling indicated that no cold joints were present, a 5 m sill mat thickness was assumed with a drift width of 8 m (overbreak) as a worst-case scenario (i.e. cold joint hypothetically situated 5 m above the roof elevation of the proposed design drift with overbreak or damage due to hypothetical sequencing techniques). Results of the caving failure mechanism indicated stable conditions based on a UCS to tensile strength ratio of 8. Flexural failure would be critical if the sill plug thickness was less than the span of the excavation and would play a major role if there was a cold joint resulting in thin beams, which is very unlikely. Due to the inclination of the proposed drift dimension, rotational failure would be an unlikely scenario. Finally, shear failure is the most common large failure type in underhand stoping; the results indicate low strength requirements due to the small span opening of the drift in comparison to the stope dimensions. Overall, the design of the fill material for the undercut sill exposure passes the acceptance criteria for each failure mechanism when compared to the lower end and average strengths of the in situ fill material.

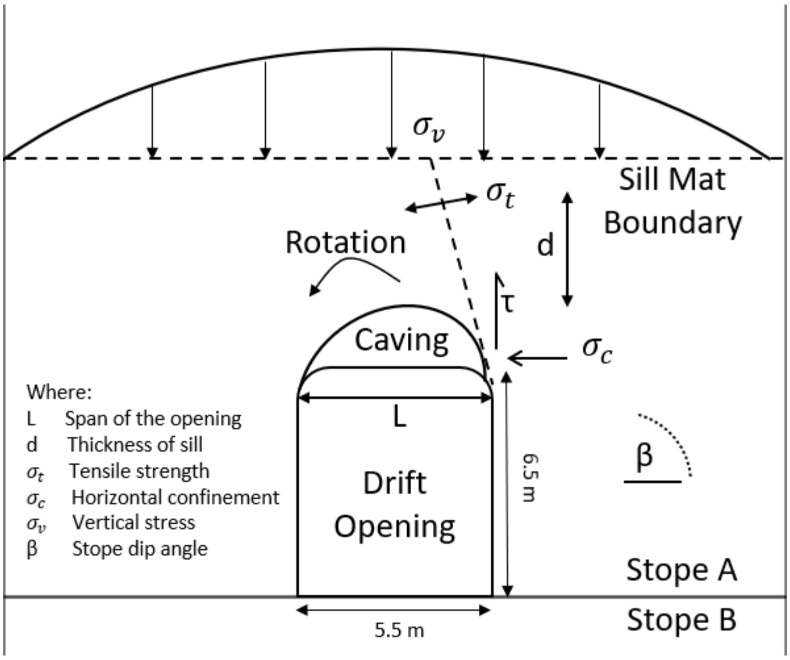


Figure 5 Typical failure mechanisms (after Mitchell 1991)

Table 4 Underhand sill plug failure mechanism design results

Failure mechanism	Compressive strength (kPa)
Caving	600
Shear	100
Flexural	–
Rotational	300

The drift was designed to be exposed on two 20 m transverse length faces, assuming fill in the end walls. In this instance, a design approach on assessing the vertical wall CPF exposure was needed.

Given a Factor of Safety of 1.5, the required strength of the CPF, or required UCS, may be calculated utilising different methods. Some of these include calculating wedge failure, Terzaghi's sloughing due to fill weight without arching, and Terzaghi's method with arching (Baldwin & Grice 2000). Results in Table 5 indicate that the strength for vertical wall exposure of the fill material is lower than the paste strength as presented in Table 2.

Table 5 Vertical wall exposure design results

Method	Self-weight strength (kPa)
Terzaghi fill weight	100
Terzaghi with arching	120
Limit equilibrium wedge	80

The design analyses and results from the in situ sample parameters identified that the caving failure mechanism was the critical mechanism and required a strength of 600 kPa. The laboratory and field test results along with field observations indicate the material strengths meet the acceptance criteria, and a stable drift can be developed.

5 Risk assessment

Prior to implementation of the design, a risk assessment was conducted to identify potential hazards and to establish mitigation measures. Table 6 outlines the risk assessment conducted for the potential hazards during development:

Table 6 Risk assessment for drift development

Hazard	Likelihood	Consequence	Unmitigated risk	Mitigation measures	Mitigated risk
Drift collapse at working face	Possible	Moderate	Moderate	Minimise advance to 3 m Mechanical development Control blasting Support up to the face No entry for personnel in unsupported areas	Low
Drift collapse at entrance or middle	Possible	Catastrophic	Significant	Support as per recommendation Conduct daily QA/QC on fibre reinforced shotcrete Conduct CPF UCS tests Determine sill plug thickness through drill holes in back Monitor visually daily/continuously for cracks Monitor scan before next 3 m advance Limit access to personnel	Moderate

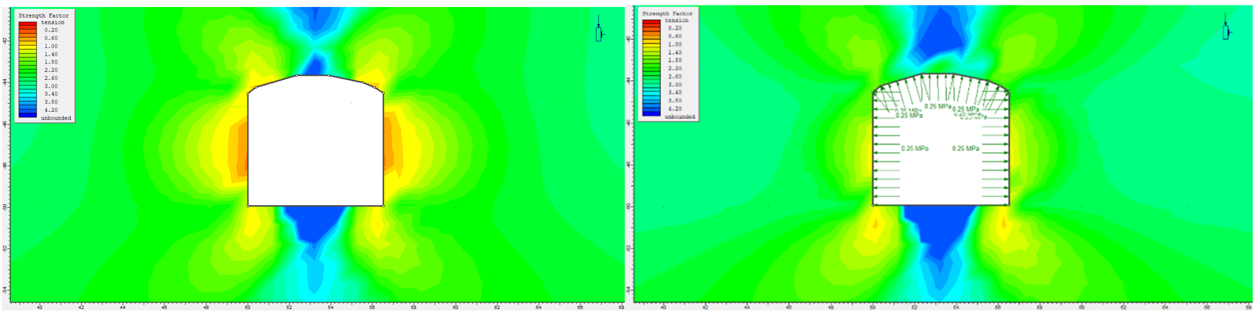
After completing the development, the CPF contact was demarcated within the drift, as illustrated in Figure 6. This will provide awareness to operations and personnel. In addition, the signage is used as a reference point to inspect the support conditions (brow to brow) and to ensure no heavy loads are suspended from the roof in the CPF drift.

Figure 6 Cemented paste fill drift condition looking south after development and with signage

6 Extraction development and sequencing

Drift sequencing and recommendations for the ground support were developed based on industry experience from a case study. A similar approach was outlined at Cannington Mine (Li et al. 2011) and considered according to BG fill conditions and drift design constraints.

TCS data was used to run a basic modelling program Rocscience (2001) Phase 2D/Examine 2D to determine the effect of the ground support (Figure 7). Results with the recommended ground support indicate the strength factor to be greater than 1.0. A support pressure of 250 kPa on the CPF was applied based on the surface support and friction bolts installed. The support and sequence are further explained in detail.



(a) (b)

Figure 7 (a) Strength factor of the cemented paste fill without support; (b) Strength factor with the recommended support

The development and support sequencing recommended for the CPF material is summarised in the following steps:

1. Restrict drift development advances to 3 m.
    a. Minimise damage through mechanical excavation. If required, use controlled blasting or light charges.

2. Apply a first layer of 50 mm fibre reinforced shotcrete (FRS) as soon as possible after each 3 m advance up to the face.
3. Determine re-entry time based on FRS strength.
   a. FRS curing test results indicated that six hours was sufficient to achieve 1,000 kPa which will allow ground support drilling without damaging the FRS. This period of six hours will be used as a minimum re-entry time.
4. Followed with a layer of 8.0 mm mesh pinned by 3.0 m long (47 mm diameter) friction bolts on a 1.0 m × 1.0 m pattern.
   a. The support hole was only drilled to <1 m and the friction bolt pushed into the CPF.
5. Apply a second layer of 50 mm FRS before advancing the next 3 m. A re-entry time of 12 hours is set based on the strength of 5,000 kPa of the first layer of FRS.

This methodology was applied in an arched back tunnel shape to minimise the tensile zone. Although areas of overbreak or damage were not encountered during the excavation process, shotcrete arches were recommended and designed for mitigating those unstable conditions. Over-mucking was controlled to ensure the drift dimensions were not increased.

7 QA/QC and monitoring

During development, various QA/QC tests were conducted with different monitoring tools to ensure safe mining through the CPF.

Penetrometer tests was completed on the CPF soon after each 3 m advance and the first layer of FRS to confirm the strength of the CPF. QA/QC tests were done to determine the strength of the FRS after six hours to confirm that the re-entry times of six hours were met. No significant issues were reported on the re-entry time and protocols.

Moreover, FRS thicknesses were measured through drillholes and ground penetrating radar (GPR) scanning. This was to ensure minimum thickness recommendations were met as provided by the GPR reflection patterns and hole data. The GPR used a CBD antenna with 800 MHz frequency and minimum vertical resolution of 5 cm. The data collected confirmed the FRS in all areas was greater than the recommended first layer of 50 mm and combined thickness of 100 mm. The holes that were drilled to determine the FRS thickness, also allowed any water contained in the CPF to drain out. This which was observed temporarily to be dripping near the brow contact. This allowed proper curing of the FRS and aid on dewatering during and after the excavation process.

Pull-out tests were performed on installed split sets to determine the frictional properties of the installed friction bolts. All the friction bolts indicated a pull-out load of +90 kN (30 kN/m). No tests failed, which provided confidence on the support installation.

Three-dimensional laser scanning of the drift during and after development was conducted to monitor surface movement. The example in Figure 8 compares the initial scan to the final drift profile. Results in this case indicate the major variances (red) are due to the recent excavation activity, and cumulative movement of +100 mm (red) indicate the thickness of the applied FRS.

Monitoring of the drift is done on a monthly basis to identify any movement to ensure the stability of the area for a serviceability period of two years.

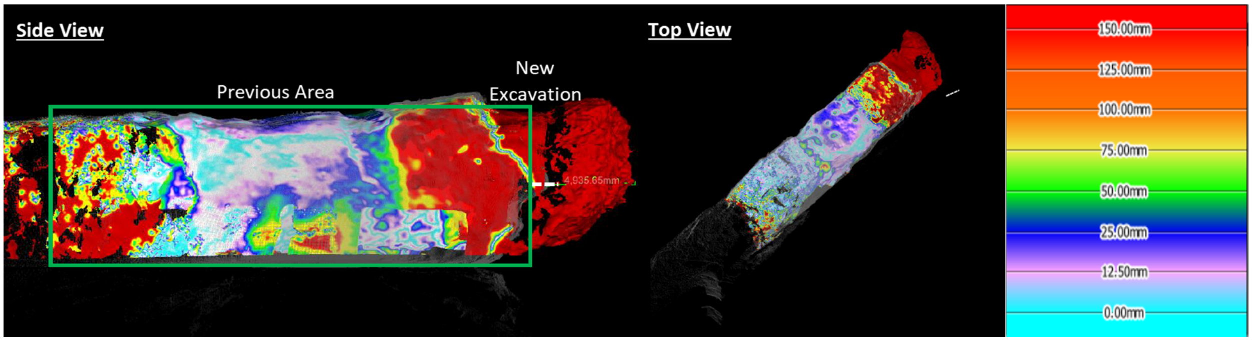


Figure 8 Monitoring scan results during excavation measuring cumulative surface displacement

8 Conclusion

The access drift through the BG mine's CPF stope was developed by first conducting a thorough assessment of CPF material stability through research in the field and laboratory testing, analysis of material strengths and behaviours, and simulation of failure mechanisms prior to excavation.

The investigation concluded that the CPF material met acceptable parameters for strength and stability within the planned drift area. Detailed design approaches, including ground support sequencing and development strategies, were implemented based on an industry case study and modelling.

Continuous monitoring and QA/QC throughout the development phase assured adherence to design parameters and mitigated potential risks. Laser scanning and post-development inspections confirmed stability and indicated continuous safe access to the drift.

Overall, the investigation and design, implementation strategies, and ongoing monitoring and risk management enabled the development of a stable access drift.

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