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The successful integration of 3D seismic into the mining process: Practical examples from Bowen Basin underground coal mines

This paper discusses how mine staff from a number of Bowen Basin coal mines have effectively and efficiently integrated 3D seismic information into their work practices. Comprehensive reconciliation procedures have evolved over the years to help understand how the 3D seismic data responds to particular geological conditions. High-resolution seismic imaging of fault structures has helped target borehole drilling for fault evaluation and grout pattern design. High density seam-roof elevation data extracted from seismic have been merged with borehole seam picks to assist with both in-seam gas drainage programs and the design of cutting profiles for production mining.

Stratigraphic interpretation of the 3D seismic data has contributed to the overall geological understanding of the mine area, and has contributed to predicting roof and floor conditions that impact mining operations. The full potential of the 3D seismic data has only been realised through the constant interaction of mine-planning staff and the seismic interpreters. Successful integration of 3D seismic data into the mine planning process requires the 3D seismic volume to be treated as a live commodity that is constantly evolving through the life of the mine.

INTRODUCTION

Acquisition of 3D seismic data has become a vital exploration tool for underground coal-mining operations. This is highlighted by the fact that a total of 45 3D seismic surveys designed to provide coal-mining staff with high resolution subsurface images and detailed fault delineation have been acquired in the Bowen and Sydney Basins since 1997. With this growth of 3D seismic comes the new challenge of effectively integrating large volumes of seismic data (and their derivatives) into mine planning and development. Little has been published on this subject, and to date individual coal-mine sites have endeavoured to determine their own methodologies to facilitate the successful integration of seismic data.

Drawing on the experiences of a number of mines in the Bowen Basin, this paper provides a summary of some of the more effective approaches for integrating seismic data with traditional mine planning and development information. Experience has shown that successful data integration is largely dependent on all mine staff having a strong understanding of the inherent advantages and limitations of the seismic method. Further, such information needs to be consistently included in all mine planning and development documents and discussions. When a mine makes the effort to effectively integrate seismic data into their mine planning and development, the mine is rewarded with significant technical and cost benefits.

3D SEISMIC

Seismic exploration is a geophysical method that involves imaging the sub-surface using artificially generated sound waves. Surface receiving devices, or geophones, are used to detect the seismic energy that originates from a seismic source (e.g. small dynamite explosion), travels down into the earth, and gets partially reflected back to the surface at geological boundaries. A 3D seismic survey involves using a grid of surface receivers to detect the reflected seismic energy generated by each seismic source in an exploration area, rather than using a single line of receivers (2D seismic). Figure 1 illustrates a typical source and receiver layout for a 3D seismic survey in the Bowen Basin.

The resultant volume of seismic data is a 3D representation of all geological boundaries in the survey area as a function of two-way reflection time. Seismic interpretation is the process of tracking significant geological boundaries (e.g. target coal seams) and producing two-way time (TWT) horizon surfaces. These TWT surfaces, together with the seismic volume itself, can be used to derive a number of secondary seismic attributes (TWT gradient, seismic amplitude, instantaneous frequency) to yield high-definition structural maps, locate stratigraphic anomalies and provide detailed fault information.

Such attribute maps, together with interpreted lineaments and other features can be imported into mine planning software packages. This is discussed in greater detail below. More complex seismic interpretation procedures, that involve full seismic waveform analysis and geological inversion, can also provide information on physical properties such as coal quality and rock type.

Note that, because a 3D seismic volume and the horizon picks that track any significant geological boundaries in the survey area are referenced to two-way reflection time, it is often difficult for mine geologists to integrate the actual seismic structural surfaces into mine planning packages. Provided sufficient geological control exists (e.g. borehole data), reliable time-to-depth conversion can be performed. The accuracy and dependence of seismic depth conversion

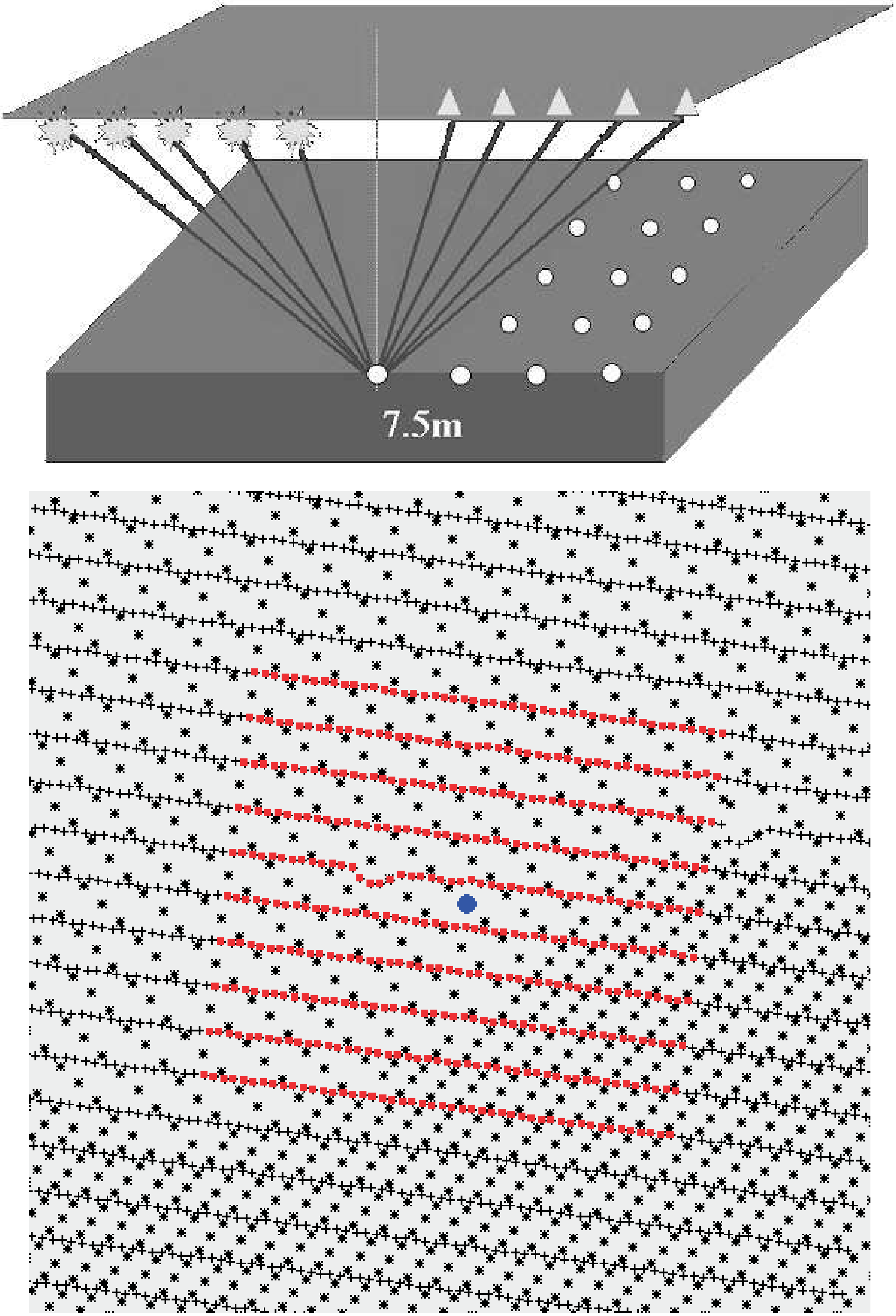

Figure 1: Typical 3D acquisition source and receiver layout. Top is the acquisition in section view and Bottom is in plan view Shots= *, Receivers= +

on geological control and mathematical gridding algorithms is examined in detail by Zhou & others (2004). Following the seismic depth conversion, there are a number of approaches resulting in the effective use of the elevation surfaces as discussed below.

Overall, interpretation of a 3D seismic volume results in vast quantities of spatial data (typically 18,000 sub-surface points of information per seismic attribute per square-kilometre). All of this information should be integrated into the mine planning and development process to maximise the benefit-to-cost ratio of undertaking a 3D seismic survey. Strategies for effectively achieving this are presented below.

Reconciliation

Reconciliation, as defined here, is the process of comparing the seismic interpretation results with hard geological data from either validation drilling or underground mine mapping. It can be thought of as a calibration process, allowing the mine to understand the advantages and limitations of the seismic method in characterising faults (predicting fault throw, location, orientation) and identifying stratigraphic anomalies. The reconciliation process helps reduce ambiguity in the seismic interpretation results.

Ambiguity exists because the physical process of sound waves travelling through the earth limits the vertical and lateral resolving power of the seismic data. This can result in the inability to distinguish a small fault from a seam roll, or impede the accurate imaging of a complex faulted zone. Reconciliation focuses on determining the accuracy of fault throws and location, by comparing structures interpreted from 3D seismic data with those intersected during mining operations. Typical fault throw and location errors are ±1.2m and ±11m, respectively.

From the surface, reconciliation of seismic fault information typically involves drilling 3 boreholes about an interpreted fault, and comparing borehole information with seismic data to assess the accuracy of the seismic image. Note that, using surface drilling to test the seismic derived structure can produce inconclusive results. If mine development is taking place, underground maps and seam elevation collected by the mine geologist are more reliable for conducting reconciliation.

Our experiences suggest that mines who most effectively integrated 3D seismic into their mine planning and development are those who are proactive about reconciliation, both through drilling and during underground mapping. In this way the mine staff and seismic interpreter are constantly learning what information the seismic volume can bring to the mine planning and development process. This continues to take place throughout the working life of the mine.

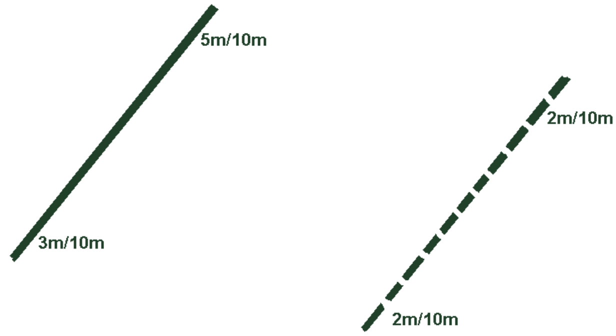

Figure 2a: Over simplified representation of fault information derived from the seismic data. Lines indicate fault position, the numbers which are annotated (e.g. 2m/10m) represent the throw and width in metres. Heavy Solid line = confident interpretation, Heavy dashed line = less confident

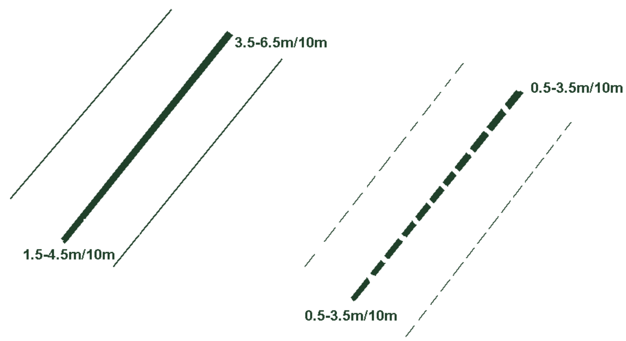

Figure 2b: A more effective way to represent fault information derived from seismic data. Secondary lines bound the fault centerline. The distance that these are offset from the fault centerline is regarded as the error in the spatial location (e.g. ±11m). In this case the fault throw is represented as a range of possible displacements rather than a single value. This range may be considered the error in the estimated displacement (e.g. 2m±1.2m).

Structural Information

Typically, accurate delineation of structure is the primary objective for a 3D seismic survey. Structural information derived from seismic data interpretation (e.g. fault throw & location) is delivered to the mine in ASCII or DXF format, which can be easily imported into most mine planning packages. Further, it is common that such interpreted structures are described with varying degrees of interpretation confidence (e.g. confident, less confident). While simply plotting these features onto mine plans conveys the basic seismic interpretation results, it is not using all available information effectively. As discussed above there is known ambiguity in seismic interpretation results. The mine planning team has to ensure that all mine-site staff understands the uncertainty in the seismic interpretation results by ensuring this information is included on all mine plans and team discussions.

Staff at one Bowen Basin mine-site have addressed this problem by incorporating secondary lines (representative of location error) and representing faults with a variable range of throws in their mine plans (Figure 2).

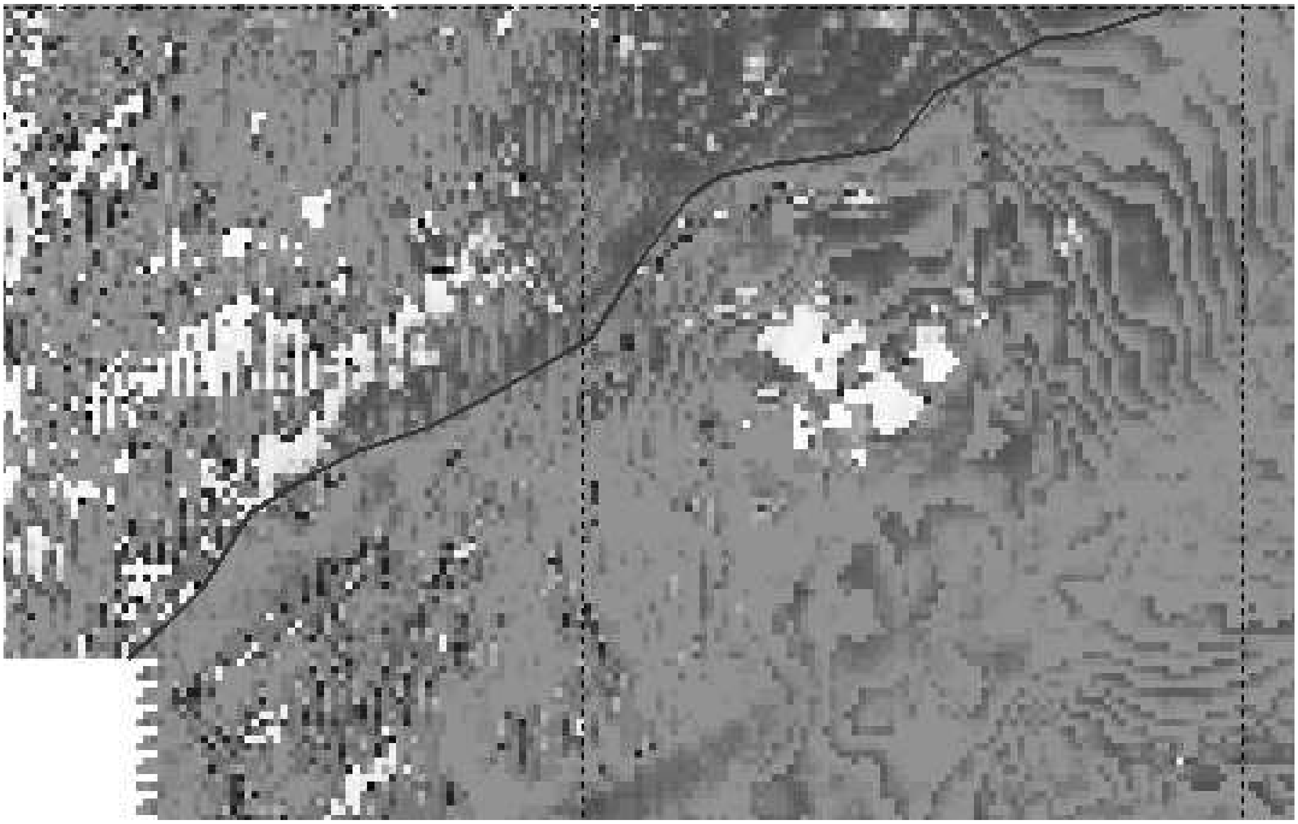

Figure 3: Instantaneous Frequency indicating seam split line. Line indicates interburden thickness or ~1.5m

As noted above these errors can be quantified through the process of reconciliation. Alternatively, draw on the experience of the seismic interpreter and adopt the suggested errors detailed in the technical report that accompanies the 3D interpretation results. Some attempt to convey errors of the interpreted results to the end-users, is better than nothing.

Stratigraphic Information

Recently there has been a growing desire to obtain more than just structural information from a 3D seismic volume. As noted above, there are complex seismic stratigraphic interpretation packages designed to recover information such as roof/floor rock properties, coal quality and gas content. However, here we will restrict our discussion to the type of stratigraphic information that is commonly presented to a mine as a result of conventional seismic interpretation methods.

Typically stratigraphic lineaments or zones will be delivered to the mine in ASCII or DXF format for incorporation into their mine planning software. As for fault information, the uncertainties in the absolute location of any stratigraphic anomaly should be marked on all maps that include the 3D seismic interpretation results. Additionally, there must be some supporting evidence of what the stratigraphic anomaly might be. Our experiences suggest that seam splitting and igneous intrusions (sills) are two of the most prevalent stratigraphic anomalies detected via conventional seismic interpretation. The following discussion is an example of how a mine might effectively incorporate a suspected seam-split seismic anomaly into their mine maps.

A stratigraphic anomaly (such as a seam split, or intrusive sill) will be detected by the seismic interpreter using a number of different seismic attribute maps (e.g. TWT gradient, seismic amplitude, instantaneous frequency). For the seam-split example being considered here, instantaneous frequency was a significantly useful seismic attribute (Figure 3). Mine geologists could correlate the seismic attribute anomaly with an expected seam split in the area.

However, reconciliation drilling was required to gain an understanding of what the anomaly represented in real physical terms. It was found that the anomaly actually marked the point at which the interburden thickness between the split and working section reached 1.5m. An effective way to present all the above information for mine-site staff is to import the ‘seismic split line’ into mine maps, but refer to it as the ‘1.5m interburden thickness line’. Further, importing the instantaneous frequency map and marking the zone over which the instantaneous frequency anomaly occurs, suggests to end-users that the ‘1.5m interburden thickness line’ has an inherent error in its lateral position.

If the rate at which the seam splits has geotechnical implications for the mine, further useful information could be extracted from the 3D seismic volume in the form of interburden thickness contours (coal ply to working seam thickness map) being overlaid onto the mine plan.

Depth Surfaces

Whilst elevation surfaces are highly valued by mine staff, it is important to keep in mind that absolute elevation derived

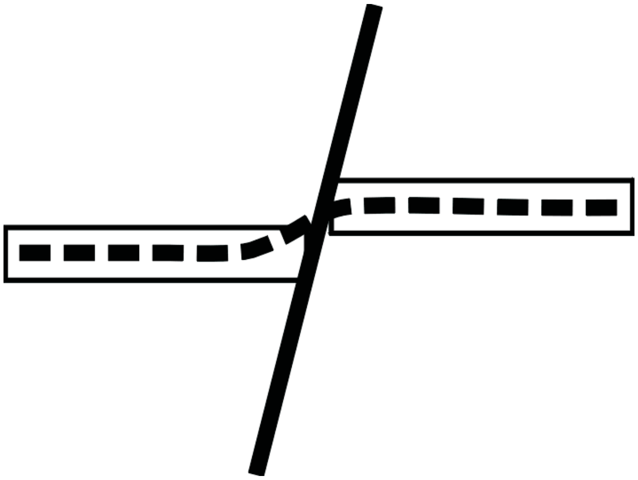

Figure 4: Example of how seismic derived depth information can be used by the mine. Flight plan indicating longwall cutting profile, Dashed line = representative long wall cutting height

from seismic can be erroneous. In contrast, experience suggests relative changes in seam elevation are quite reliable. These assumptions, however, should be tested by reconciliation prior to integrating the seismic-derived elevation into mine planning. Typically, this involves importing and comparing the seismic derived elevation data with both borehole seam picks and underground survey data.

Once the reliability of the elevation data is evaluated, the mine staff have a number of options for integrating the seismic data into their mine planning and development. Current examples include using seismic elevation data to assist with grout pattern design and flight plan design for longwall cutting profiles, and to guide inseam drilling for the purpose of gas drainage.

Figure 4 is an example of a flight plan designed to negotiate a structure with a full seam thickness throw. In this instance the seismic derived roof elevation data for the entire 3D survey area have been imported into the mine planning software. By subtracting the seam thickness (determined from boreholes) from the seismic roof elevation, a profile of the coal seam could be obtained for the entire mine area. This info was used to help plan longwall cutting profiles.

Note also, that if reconciliation determines that these elevation data are reliable, then coal seam structure maps may be used to directly derive estimates of fault throws.

CONCLUSION

A growing number of 3D seismic surveys are being acquired in conjunction with underground coal-mining operations. To maximise their benefit-cost-ratio, coal mines must ensure effective integration of this 3D seismic information into the mine planning and development process.

Mine staff should familiarise themselves with all data files that are produced from a 3D seismic interpretation project, and should have a basic understanding of the seismic method as well as working knowledge of the inherent advantages and limitations of 3D seismic. Many of these concepts are addressed in detail in the reports provided with the seismic interpretation results.

A proactive approach to reconciliation should be adopted. Information recovered from the reconciliation process, such as fault throw errors, lateral position errors or stratigraphic information, should always be included with the seismic interpretation results on any maps and/or presentations. Mines should also consider using seismic attribute maps directly in their mine-planning software to aid understanding of the strengths and weaknesses of the seismic interpretation results.

Mines must recognise that 3D seismic interpretation results are dynamic, and will need to be re-visited and updated as more geological information becomes available throughout the working life of the mine.

To date, mines will typically confine the use of 3D seismic interpretation results to two-dimensional space (i.e. plan view). However, 3D seismic data provides the opportunity to visualise 3D earth models. It is possible to combine fault, stratigraphic, seam elevation and borehole data into a 3D workspace, such that a mine planning team can immerse themselves in the 3D subsurface. We believe this will ultimately become the method of choice for successfully integrating 3D seismic into the mining process.

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