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Application of LiDAR for hydrocarbon exploration in logistically and geologically challenging environments: examples from the Papuan Fold and Thrust Belt, Papua New Guinea

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SUMMARY

The Papuan Fold and Thrust Belt (PFTB) in Papua New Guinea hosts the prolific Papuan Basin petroleum system yet remains underexplored compared with other fold and thrust belts worldwide. The underexplored nature of the PFTB results from its remoteness, inhospitable karst topography and thick tropical vegetation which combine to create an exceedingly difficult and expensive area to explore. There are, however, significant rewards awaiting those able to overcome these challenges.

The history of exploration success in the PFTB has been closely linked to technological advancements aimed at overcoming these challenges. The latest development is LiDAR (Light Detection and Ranging), a remote sensing technology that provides the ability to “see” through the thick tropical vegetation covering the PFTB, thus revealing previously obscured geological outcrops and revolutionising surface operation planning. LiDAR data are used to create very high-resolution digital elevation models of the earth’s surface that have a variety of exploration applications including geological mapping and 3D geological model building. LiDAR has facilitated a significant leap in our understanding of hydrocarbon trapping styles in the PFTB. In this paper we discuss some of the ways that LiDAR is being used to explore within one of the most challenging yet underexplored areas in the world.

Key words: LiDAR, remote sensing, hydrocarbon exploration, structure, Papuan Fold and Thrust Belt

INTRODUCTION

The Papuan Fold and Thrust Belt (PFTB) in Papua New Guinea (PNG) is one of the most remote and logistically-challenging environments in the world to explore for natural resources. It is characterised by inhospitable terrain and exceedingly complex geology that has resulted from a complicated geological and tectonic evolution throughout the Cenozoic between the obliquely-converging Australian and Pacific plates (e.g. Hill and Hall, 2003). Yet the folded and thrusted sediments of the early Mesozoic Papuan Basin host some large hydrocarbon accumulations (e.g., Buchanan *et al*., 2000), in addition to several world-class mineral deposits (e.g., Williamson and Hancock, 2005).

The history of petroleum exploration success in the PFTB has been closely linked to technological advancements aimed at overcoming these logistical and geological challenges. For example, prior to the 1980s exploration drilling was mostly restricted to the raft-accessible frontal structures of the fold belt and success was limited. In the 1980s, the advancement of heli-transportable drilling rigs—used to access highly-prospective structures within the interior PFTB—and the improvement of 2D seismic reflection acquisition approaches (e.g., Hill *et al*., 1996) facilitated the discovery of several large oil and gas fields, many of which are still being developed and/or produced today.

Exploration of the PFTB has since progressed, but the challenges remain. Field geological and seismic data acquisition is exceedingly expensive, and exploration has moved on to more cryptic petroleum plays (e.g. Hill and Wightman, 2015; Giddings *et al*., 2020) that demand a precise 3D understanding of the surface and sub-surface geology and structure of the fold belt. Modern technologies and tools are proving crucial to cut cost and to reduce geological uncertainty.

The most significant of these is LiDAR (Light Detection and Ranging), a relatively new remote sensing technology to the PFTB that has dramatically improved our operational and geological capabilities. LiDAR provides the ability to “see” through the thick tropical vegetation that characterises the PFTB, uncovering the rugged topography along with previously hidden and inaccessible geological outcrops (e.g. Mahoney et al., 2019; Burgin *et al*., 2020; Richards, 2020). LiDAR data and derivative products such as digital elevation models (DEMs) have facilitated significantly improved operational planning, and the ability to remotely observe surface geological trends and extract structural measurements which provide key constraint on sub-surface geological models. Regional-scale LiDAR surveys are providing an exciting stimulus for the identification and delineation of new hydrocarbon trapping styles throughout the PFTB. In this paper, we discuss some of the ways that LiDAR data are being used to explore within one of the most challenging environments in the world.

METHOD AND RESULTS

Regional airborne (fixed- and rotary-wing) LiDAR datasets acquired across the PFTB over the last decade comprise billions of three-dimensionally geospatially referenced elevation points that effectively provide a digital representation of the earth’s surface, including the ground, vegetation and man-made structures. Sophisticated point classification algorithms are used to classify each of these elements, which can therefore be controlled and isolated in GIS software to be independently visualised, analysed or used to produce a range of derivative products.

The ground points, or "ground returns" are of the most interest for geological and surface operational planning applications, as they allow for high-resolution DEMs and derivative terrain products to be produced (Figure 1). The resolution of these "bare-earth" DEMs depends on the density of ground returns, which is in turn determined by the thickness of the overlying canopy. The extensive thick tropical jungle covering the PFTB means that derivative DEMs mostly attain resolutions in the metre-scale, significantly lower than unvegetated terrain where high-performance sensors can achieve centimetre-scale resolutions. Despite this, LiDAR-derived DEMs are vastly superior to legacy satellite-derived DEMs which suffer from additional smoothing due to an inability to penetrate the thick canopy.

LiDAR-derived DEMs are commonly used to generate slope maps that further illuminate the geological outcrops and structural features cropping out beneath thick vegetation at the surface of the fold belt (Figures 1 and 2). High-resolution DEMs are best visualised and analysed in 3D and in combination with slope map overlays that emphasise geomorphic features which often reflect previously undetected stratigraphic variations or structures, thus providing key new constraints on both surface and sub-surface models (e.g. Figure 2). LiDAR DEMs provide a regionally-continuous dataset that can be integrated and visualised with high-value—but spatially limited—datasets such as field geological transects and 2D seismic reflection lines. This digital integration has significantly improved our 3D understanding of the geology, structure and hydrocarbon trapping styles of the PFTB, which has provided a stimulus for the identification of new exploration plays.

LiDAR-derived DEMs are also being utilised for field operations planning. The high spatial resolution and 'bare earth' characteristics provided by LiDAR-derived terrain models allows for detailed quantitative terrain analysis to be conducted. GIS based cost weighted distance algorithms applied to these datasets (e.g. LiDAR pathfinding) helps optimise field geological and seismic transects through strongly karst terrain, allowing for previously obscured terrain obstacles to be identified and avoided (Figure 3).

In LiDAR pathfinding, "cost" is equivalent to the amount of energy required to traverse a terrain feature, which for PFTB operations is closely linked to monetary cost. Cost weighted distance algorithms work by scanning though LiDAR-derived slope maps to identify the most cost-efficient path (e.g. the path with the least terrain obstacles). The cost weighting (the cost assigned to a given slope angle) is defined by the operator and depends on the task being undertaken. For instance, the cost of steeper slopes will be higher for a seismic drilling team than a field geological team, as the former has cumbersome drilling equipment to transport. LiDAR pathfinding is a powerful project planning tool that significantly improves the safety and cost-efficiency of data acquisition within the challenging terrain characterising the PFTB.

CONCLUSIONS

LiDAR is a relatively new technology to the PFTB but is already revolutionising the way we work within such a remote and inhospitable environment. In addition to the examples provided herein, many other applications are being developed, and applied, to improve the safety, cost-efficiency and geological certainty associated with exploration activities.

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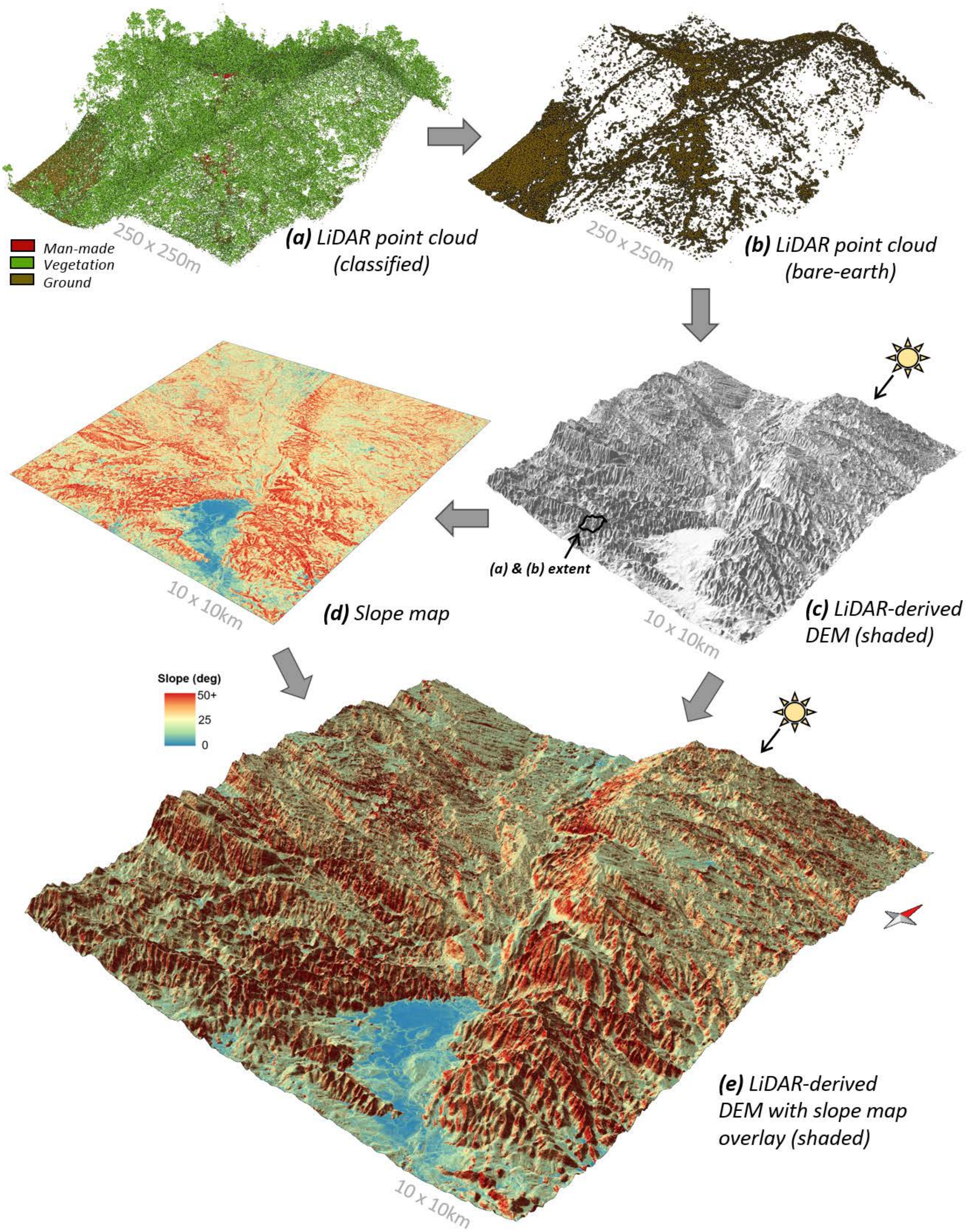

Figure 1. LiDAR workflow, example from typical PFTB terrain in the Hela Province: **(a)** Classified LiDAR point cloud containing ~2 million points, extent = 250m x 250m; **(b)** LiDAR bare-earth point cloud (ground-returns only), note the variable density of ground returns; **(c)** LiDAR-derived DEM (shaded), extent = 10km x 10km, **(d)** Slope map produced from LiDAR DEM; **(e)** LiDAR-derived DEM with slope map overlay (shaded). Note the increased definition of geological and topographic features. Data courtesy of the PPL 545 Joint Venture.

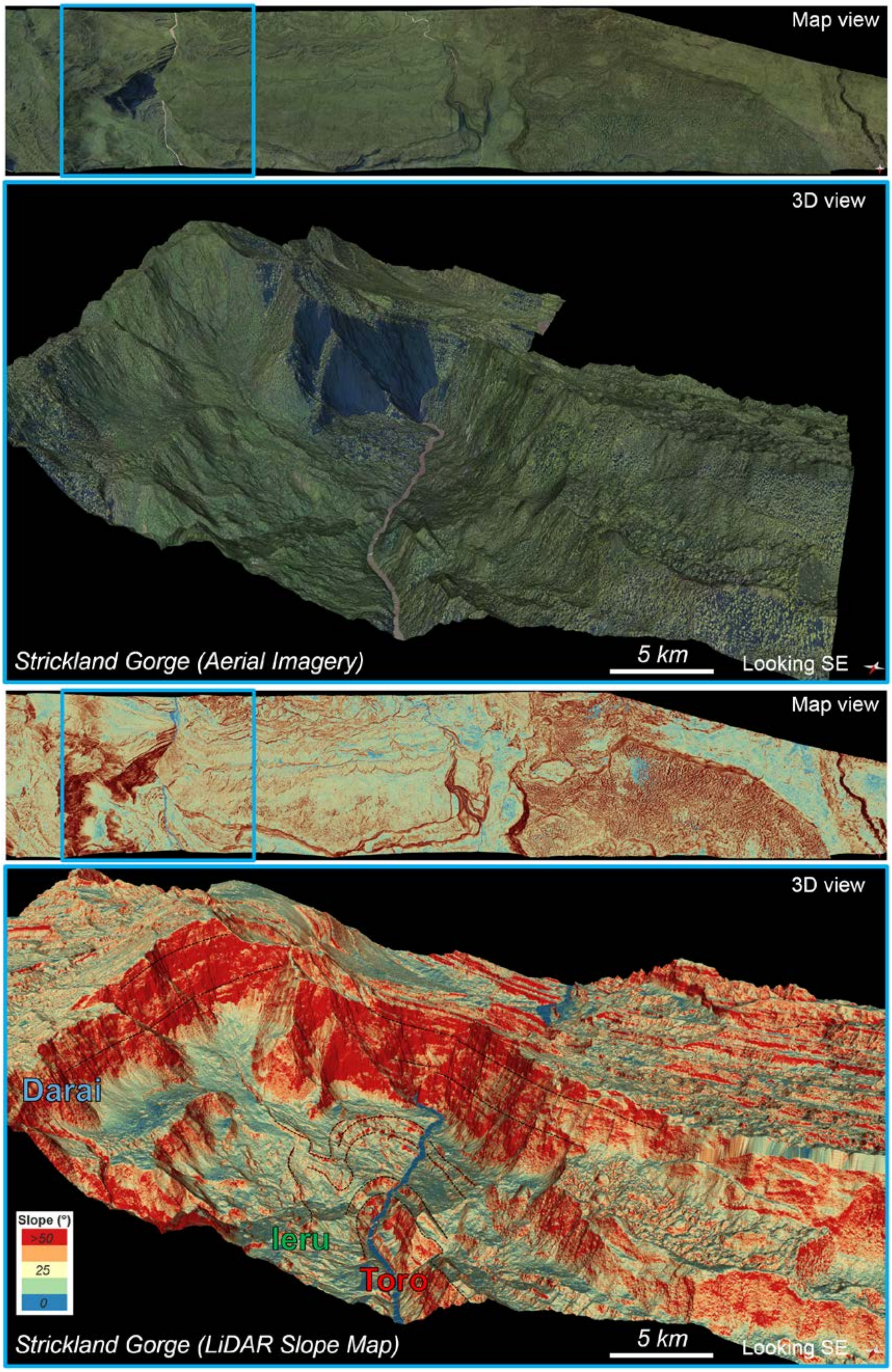

Figure 2. (top) DEM with aerial imagery overlay showing the unbroken forest canopy that characterises the PFTB; **(bottom)** LiDAR-derived DEM with slope map overlay. Note the rugged topography and geomorphic expression of the strongly folded and faulted Papuan Basin stratigraphy. Surface geological interpretation forms the basis for sub-surface mapping and 3D geological model building. Darai = Darai Limestone; Ieru = Ieru Formation (interbedded shales and sandstones), Toro = Toro Sandstone.

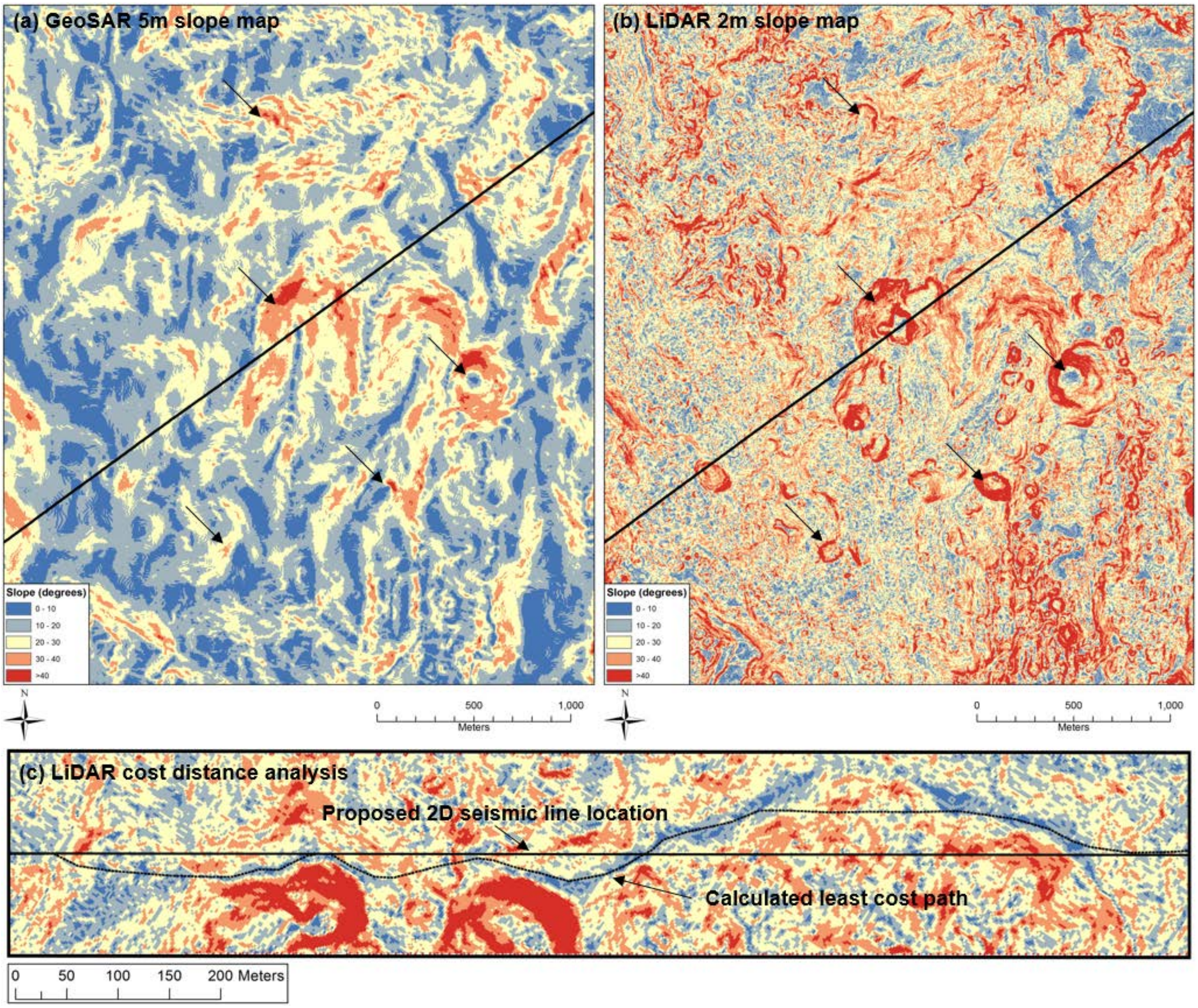

Figure 3. (a) 5 m GeoSAR slope map and **(b)** 2 m LiDAR terrain slope maps showing how LiDAR is considerably more effective in revealing terrain obstacles such as dolines/sinkholes as indicated by the black arrows. Black lines are legacy seismic lines acquired prior to the use of LiDAR pathfinding—note the large sinkhole which forms a major obstacle on the line. **(c)** The use of LiDAR-derived slope maps as inputs to cost distance path finding algorithms. Solid line is a proposed 2D seismic line and the dashed line shows the calculated least cost path. Path finding analysis is conducted using ESRI's ArcMap "Distance" tools which are available under the Spatial Analyst licence. The 'Cost Distance" and "Cost Path" algorithms are used to calculate least cost paths over LiDAR derived DEMs.