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3D Time-Lapse Imaging of Polygonal Patterned Ground in the McMurdo Dry Valleys of Antarctica.

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***Abstract* - We surveyed four sets of polygons at 0.5 m line spacing using 100 and 200 MHz antennas for 3D GPR imaging at two field locations in the McMurdo Dry Valleys of Antarctica, one in Victoria Valley and the other in Beacon Valley. The aim was to use 3D GPR and time-lapse 3D GPR to resolve subsurface structure and PPG process activity over the thaw season of polygonal patterned ground (PPG) in Antarctica.**

We applied migration and topographic corrections to the data sets before collating the data into 3D cubes. The subsurface structure can be analyzed using the processed profiles and resulting 3D data cubes. Signal was received down to 12 m (200 MHz) and 20 m (100 MHz) depth. Variations in salt concentrations, soil horizons and crack penetration may be interpreted using these data sets. The time-lapse images from Victoria Valley show reductions in signal through the season provisionally identified with changing quantities of free water and salts associated with PPG activity.

The results show that 3D GPR allows the collection of valuable information about the subsurface structure and processes of PPG and provides a way to monitor changes in these processes as climatic conditions evolve.

***Keywords* – polygonal patterned ground (PPG), GPR, 3D, time-lapse, permafrost, Antarctica, Dry Valleys.**

I. INTRODUCTION

The McMurdo Dry Valleys are found within the Royal Society ranges of the Transantarctic Mountains and with a total area of 4800 km^2, they are the largest ice free areas in Antarctica. Permafrost is classed as an earth material with annual average temperatures below 0.0 °C for more than 2 consecutive years. With mean annual air temperatures ranging from -14.8 °C to -30.0 °C and mean annual soil temperatures down to depths of 10 cm ranging from -16.6 °C to -26.1 °C ([1] measurements from 1986-2002), the Dry Valleys are a large expanse of continuous permafrost.

Permafrost environments often contain patterned ground phenomena that occur as a result of the ground thermal regime. These features include sorted circles, stripes, pingos and polygonal crack networks and are found in polar and high altitude areas. Lachenbruch [2] published a comprehensive evaluation of the theoretical mechanics of the development of polygonal patterned ground (PPG) and described the propagation of thermal contraction cracks to create the interlocking patterns known as PPG.

With each freeze-thaw season thermal contraction of soils results in laceworks of cracks as stress of the expanding and contracting soils is accommodated. Ice and soil and rock debris accumulate in open cracks during the freeze preventing closure over the thaw. Successive seasons reopen contraction cracks and expand them laterally, forcing crack propagation to depth, and deformation of soil stratigraphy. This expansion and contraction resulting in increased depth of the cracks constitutes part of the activity targeted in these surveys. Movement of salts and water as the thaw progresses are also part of PPG activity and influence ground penetrating radar (GPR) signal response in PPG. Debate still ensues whether some Antarctic PPG are still actively continuing to form, as they exhibit extreme topography and possible relationships between surface expression and underlying buried massive ice bodies.

The activity of polygonal patterned ground phenomena have been studied extensively in Arctic localities but the formation of PPG has been contentious in Antarctic Dry Valleys as the climatic conditions are different from the Arctic and the interpretation of a relic vs. active PPG surface has dramatic impacts on the derived glacial history of the area. Research on Antarctic PPG dates back to the early 1900’s with the discovery of the Dry Valleys and initial cataloguing of the PPG by Scott’s research parties in 1903 [3]. However, the research methods most commonly applied to permafrost in the Dry Valleys, such as surficial trenching and hand drill core samples, are limited to the near surface and are environmentally damaging.

Near surface geophysical methods have previously been applied in the Antarctic ice free regions on a variety of targets (e.g. [4], [5])and GPR is a common method for permafrost studies elsewhere in the world (e.g. [6], [7], [8]). The lower electrical conductivities of frozen ground means that signal penetration will be better in permafrost than in unfrozen equivalents and so GPR should be an effective tool in examining PPG activity [9] and has been explored in the Arctic (e.g.[10], [11], [12]) but has received less attention in the Antarctic. Previous GPR work in the Antarctic Dry Valleys has shown that subsurface structure can be resolved [13] but it has not been used as a tool specifically for evaluating PPG.

To examine further the questions of activity and subsurface structure, a range of high resolution near surface geophysical methods were employed at two field locations in the Dry Valleys, Victoria and Beacon Valleys, during the summer field season of 2006/2007. The objectives of this field season were: to determine subsurface structure at depth and possible relationships to buried massive ice, and activity of PPG over the thaw season, using 3D GPR methodology previously never used in Antarctica (for a Northern Hemisphere example refer [14] and [15]). Two sets of polygonal ground features were surveyed at each valley using GPR at 100 and 200 MHz, electromagnetic mapping (EM31) and electrical resistivity imaging. This paper focuses on the results of the GPR surveys.

II. FIELD AREA

2.1 Overview

Field camps were set up at two locations, first in Victoria Valley, and the second in Beacon Valley. At each location, two sets of polygonal ground were surveyed using a Sensors & Software pulseEKKO 100A system and 0.5 m spaced north-south lines. The area of these surveyed polygons ranged from 240 m^2 to 540 m^2. The PPG in these locations showed a range of forms from young newly forming low relief polygonal patterned ground to mature highly developed and high relief PPG.

2.2 Survey design

Two sets of PPG were surveyed at each field locality making a total of 4 PPG data sets. These sets provide a continuation from young underdeveloped PPG exhibiting low relief and limited central depressions through to mature PPG with high relief and a “doughnut” structure related to established ice wedge crack processes. The Victoria Valley polygons included a set of four “young” polygons with low relief and an intersection of four periphery cracks in the centre of the survey (Figure 1a.), and a moderately developed single polygon with surface relief up to 0.75 m high (Figure 1b.). For the purposes of this paper these polygons will be referred to as VVP1 and VVP2 respectively. The Beacon Valley sets included a polygon with moderate to high surface relief (0.5-1.2 m) and a depressed centre (Figure 1c.). The second set was a mature high relief (>1.5 m) circular, centrally depressed polygon displaying a doughnut geometry (see

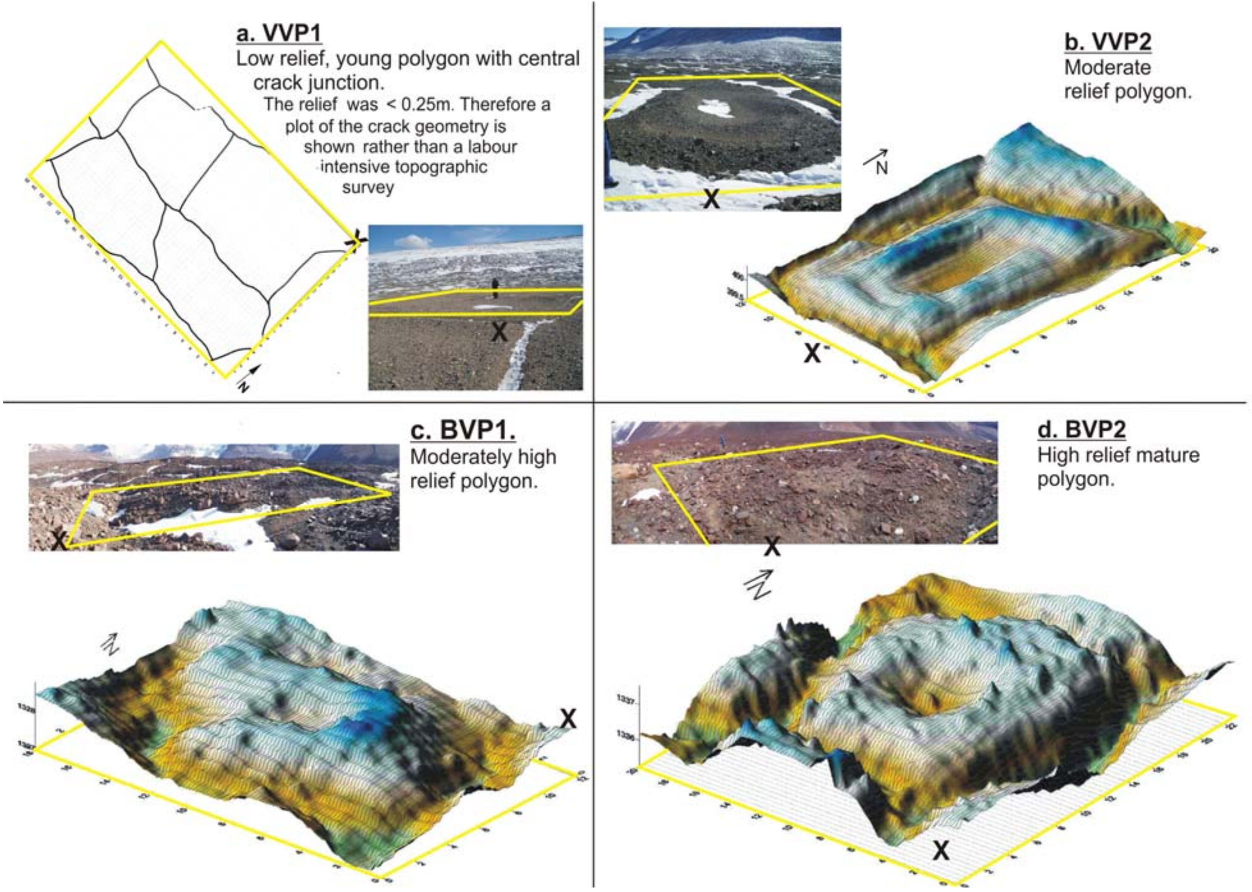

Figure 1. The four PPG areas surveyed. The topographic surfaces were derived from survey grids as described in the text. X marks where photographs of each polygon survey area were taken. Yellow boxes show the extent of each survey.

Figure 1d.). Both polygons in Beacon Valley were located along a long transect profile that crossed the valley to look at deeper features [16]. These polygon data sets will be referred to as BVP1 and BVP2 respectively. The survey grid was South to North along 0.5-m spaced lines, collected using 0.1 m step sizes. Topographic surveying, using an optical level and measuring staff, was completed on the survey grid spacing of 0.5 x 0.5 m on BVP1 and BVP2 and 0.5 x 0.25 m on VVP2.

Polygon VVP2 was surveyed with GPR multiple times during the thaw season to monitor seasonal change. During this thaw, surface snow disappeared and on calm days trickling water could be heard in the vicinity of the polygonal cracks.

III. GPR PROCESSING

The data sets were processed using pulseEKKO software version 4.3 and EKKO_3d. Topography was applied to whole data sets using batch file processing. Data sets were migrated using a velocity of 0.13 m/ns, as determined from common mid-point (CMP) survey data from the floor of Victoria Valley, and checked with diffraction-derived velocities. CMP data could not be collected from Beacon Valley sites due to the extreme topography. Data cubes were created using data sets with only topographic correction, and then with topographic correction and migration.

Automatic gain control (AGC) and spreading and exponential compensation (SEC) were applied to the data to emphasise different features [17], [18]. An AGC gain is inversely proportional to the signal strength [19] producing a profile where the weakest responses are not readily distinguishable in amplitude from the strongest responses. We used AGC gain to evaluate the continuity of reflector horizons, especially at depth which was particularly relevant for determining crack penetration. SEC gain strives to compensate for the decay of GPR signals from spherical spreading loss and exponential ohmic dissipation of energy [19]. Applying SEC gain produces a profile where relative signal strengths are maintained while applying a limited boost to the decaying signal of late responses.

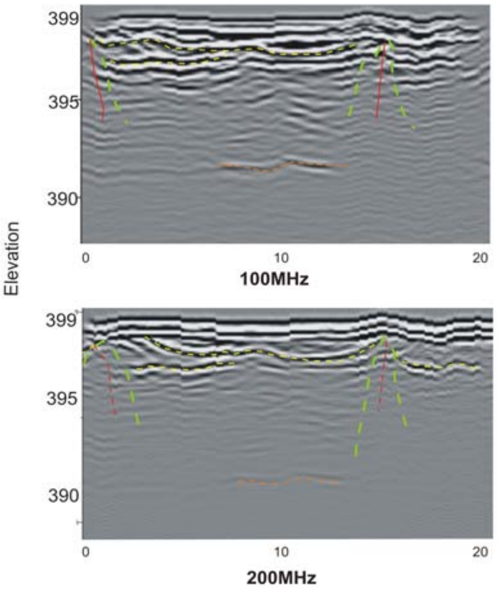

Figure 2. VVP2 profiles displayed using SEC gain, with maximum gain of 500 and attenuation of 1 dB/m. Line 12 (6m along east-west baseline from 0,0 corner). Yellow dashed lines are identified subsurface structure, red dashed lines are inferred polygonal cracks and green dashed areas represent zones of signal weakness.

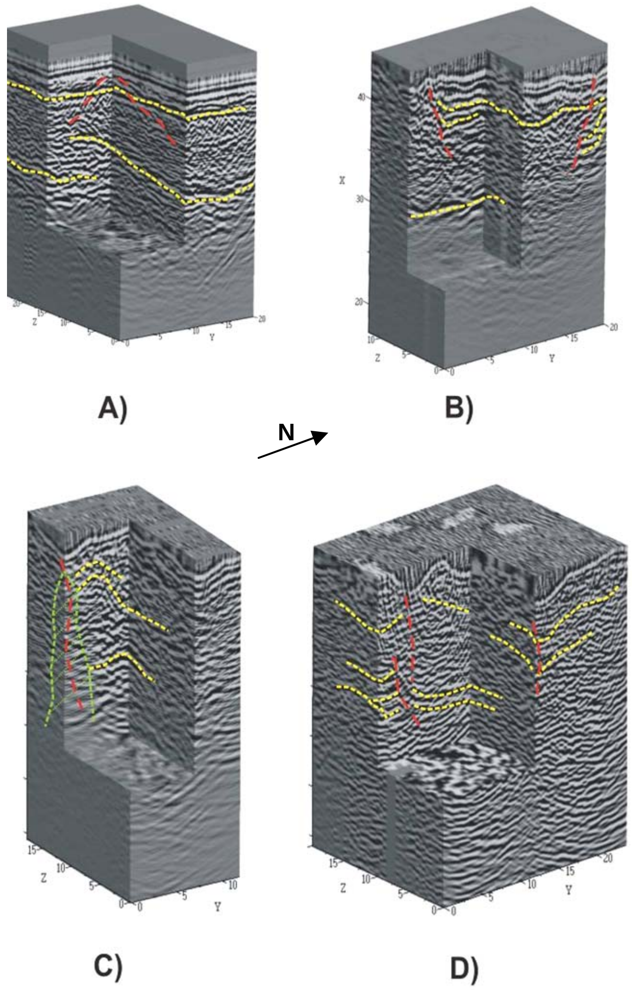

Figure 3. Northwest view from (0,0) corner of 3D cubes (AGC) for 200 MHz at A) VVP1 B) VVP2 C) BVP1 D) BVP2. See Figure 2 for colour line key.

IV. RESULTS

4.1 3D data cubes

Figure 2 shows individual profiles from the middle of VVP2, where subsurface horizons and zones of differing signal response can be seen. 3D analysis allows examination of the continuity and variation of these features over a volume rather than a single cross-sectional line. The 3D data cubes were examined from different angles, with the use of “cut-outs” that remove sections of data to view previously concealed aspects, and with slices taken progressively throughout the cube volume. The data cubes show significant reflections from subsurface features. Figure 3 shows topographically corrected and migrated GPR cubes from both valleys with a cut-out to show structure from the middle of each polygon. The coloured dashed lines show interpreted subsurface structures.

Clear reflectors from the subsurface are visible in the

Victoria Valley polygons. VVP1 shows strong continuous reflectors that are mostly linear with minor deflection into curves while VVP2 shows clear deflection of linear reflectors beneath the surface expression of contraction cracks (Figures 3A and 3B). Beacon Valley data contain more noise than Victoria Valley, probably as a result of the rougher topography and larger boulder composition of the soils. However, slices through the cubes still reveal horizontal linear reflectors becoming curved near zones of low signal or "ringing" signal (Figures 3C, 3D). Evaluation of signal quality and strength shows zones of low signal that are spatially related to the surface expression of thermal contraction cracks.

4.2 Time lapse analysis

Figure 4 shows the time transgressive 3D GPR data cubes with an enlarged section of the view. The evaluation of the time lapse images was focused on detecting changes from one cube to the next rather than specific subsurface features. Progressive signal loss through the season can be seen in Figure 4 as the 3D cubes progress from 1 (early in the thaw season at the end of November) to 4 (late in the thaw season at the end of December) As signal is lost throughout the majority of the cube, previously weaker reflectors become stronger and resolve into a single continuous feature by the end of the season (see Figure 4 details 1 through 4). Signal loss is shown again to be concentrated under the surface expression of the thermal contraction cracks. As the thaw season progresses the strongest remaining subsurface signal is best found beneath the core of the polygonal ring structure.

V. DISCUSSION

The subsurface structure shows consistent traceable reflectors and signal variations linked spatially with the surface expression of the targeted PPG. The curvature and deflection of reflectors in areas of crack propagation are consistent with deformation of bedding and stratification of soils due to lateral expansion of the thermal contraction cracks as they propagate to depth. Positive identification of crack geometry from direct reflection is less common than identification due to signal variations best seen in SEC gain profiles, or associated deflection of liner continuous reflectors. This may be the result of the possible irregular composition of the contraction crack fill material or signal effect such as "end-fire" vs. "broadside" signal responses from dipping reflectors [20]. Although Lachenbruch [2] described the mechanics of a perfect thermal contraction crack formation in permafrost it is unclear whether the polygonal ground crack geometries remain vertical with depth. Certainly with the irregular geological composition of most periglacial soils, which include grain sizes varying from fine sands to large boulders, the concept of deflection of the contraction crack with depth warrants further investigation. Consequently absolute crack depths are not easily defined. However a relative increase in depth of crack indicators can be seen as you move from low topography VVP1 data to high topography BVP2 data. Also, the deflection of horizontal subsurface structures becomes more pronounced with developing maturity of the polygons consistent with PPG formation theories [20].

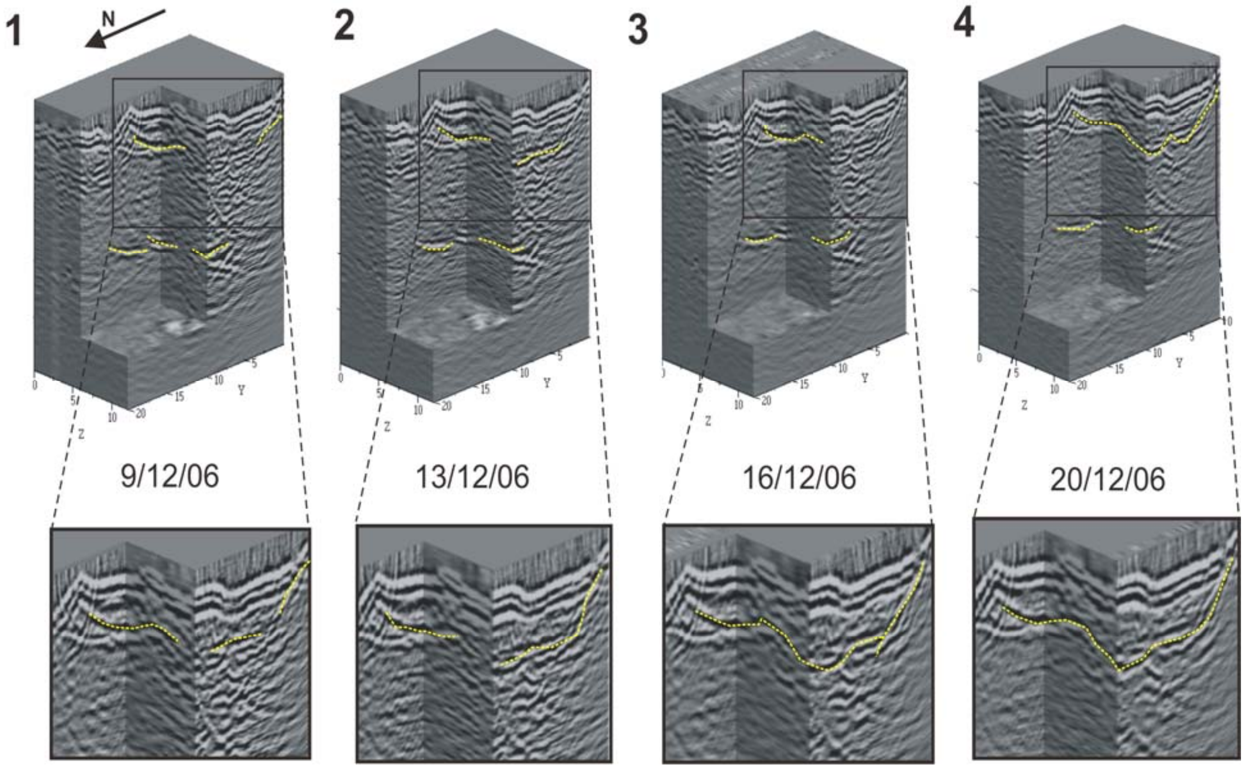

Figure 4. 200 MHz time-lapse GPR survey of VVP2. Surveys progress 1 through 4 as the thaw season progresses from late November to late December 2006. The associated details show the progression of signal loss and the subsequent resolution of a continuous subsurface reflector.

In VVP1 a strong reflection can be seen throughout the cubes at 8-10 m depth. (Figure 3A). The strength of this reflector indicates a significant change in physical properties at this boundary. The signal beneath this reflector exhibits curved cross-cutting relationships reminiscent of cross-beds. Further interpretation of this feature is limited without additional information. However, VVP1 was located in a zone of low relief relatively newly forming polygonal ground indicating a more recent exposure of this surface than the surrounding PPG. If this is the case the strong reflector seen under VVP1 may represent a relic surface covered by glacial lake deposits that remained in situ longer than in the surrounding area.

Within VVP2 data cubes a reflector at a depth of approximately 9 - 12 m can be consistently identified in each cube. This reflector does not vary with time and is provisionally identified as the top of a buried massive ice body. VVP2 lies within 10 m of a near surface geophysical transect [16] which identifies an area of probable buried massive ice in the vicinity of VVP2. The relationship between PPG formation and development, and underlying buried massive ice has been examined in Beacon Valley [22] and has potential implications for the interpretation of activity and processes from the surface expression of PPG. Significantly if GPR surveys on PPG can detect previously unknown underlying buried massive ice further evaluation of this relationship may be completed by examining lesser known buried massive ice bodies and the associated PPG.

The variation in signal through the progression of the thaw season indicates a change in subsurface physical properties with time. This is most likely related to the release of salts during the thaw which includes free water and the movement of salt concentrations. Since the activity of PPG is based on variation in the thermal regime between freeze and thaw these data shows the possibility of using GPR to pinpoint the subsurface thaw within whole PPG structures. The environment and ecosystem in the Dry Valleys is sensitive to climatic change [23] and continued concern about global temperatures has raised the issue of monitoring within this delicate environment. Due to the changing nature of our global climate and the sensitivity of PPG to global systems changes [24], the use of GPR to monitor the depth and timing of subsurface thaw could provide additional information for assessment of climate change in the Antarctic. Since the time-lapse imaging for this paper was limited to one site there is significant scope for future work at multiple locations to confirm the results seen here. Future work using time lapse surveying of PPG should attempt to operate on both seasonal and longer term (minimum 5 year) timescales to isolate changes in PPG processes due to climatic influences.

The resolution of PPG activity could be enhanced using GPR techniques applied at a higher frequency and smaller grid scale. Grasmueck et al. [25] discuss the need for higher density data collection for comprehensive use of 3D GPR techniques and suggests a grid of 0.1 – 0.2 m line spacing to prevent spatial aliasing. However, a grid of this density could not easily be carried out under Antarctic field conditions. Higher frequency antennas may provide significant information relevant to PPG processes in the Antarctic if scattering is not significant.

VI. CONCLUSIONS

GPR can be used in the McMurdo Dry Valleys to determine subsurface structure within polygonal patterned ground. Three dimensional surveys of polygonal systems in Beacon and Victoria Valleys show subsurface reflectors and variations in signal quality and response which can be used to identify the location and extent of contraction cracks in the subsurface. With the use of time-lapse GPR surveys variations in subsurface physical properties can be seen through loss of signal during the progression of the thaw.

Further research should be undertaken to expand on the results gathered here, such as future applications relating to buried massive ice and PPG relationships; thaw season timing and penetration; as well as greater use of GPR in the resolution of PPG subsurface structure. As shown in this paper subsurface activity seasonality may be detected with GPR. As the subsurface activity has not been resolved in detail from this research there is significant scope for further work expanding on this data using different GPR frequencies at multiple sites.

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