**Introduction:** Lunar mare basalts are made up of individual, compositionally and temporally, distinct lava flows [e.g. 1, 2]. Whilst the areal extent of these flows has often been remotely mapped [e.g. 1-5], determining their thickness and volume is more problematic. There are some depth estimates for the total basalt deposits [e.g. 6-8], but there are few such estimates for the individual lava flows [e.g. 9]. In this study we use Clementine multispectral reflectance data to identify conspicuous compositional signatures associated with the continuous ejecta of impact craters within an area of Oceanus Procellarum. These ejecta represent material excavated from older lava flows beneath that in which the craters are situated; their size can therefore be used to constrain the thicknesses of the surficial flows.

**Methods:** Clementine UV-Vis reflectance data were downloaded at full resolution (0.1 km/pixel) and in a simple cylindrical projection from the USGS Map-A-Planet website (www.mapaplanet.org) as radiometrically, geometrically and photometrically controlled .raw files [10]. The files were extracted and analysed using an in-house IDL (Interactive Data Language) code. These data were used to produce maps of the study area in Oceanus Procellarum (Fig. 1) for various parameters, including FeO and TiO₂ wt. % abundances (according to the algorithms of [11] and [12] respectively).

**Results:** The TiO₂ wt. % abundance map reveals a number of craters within a particular lava flow (‘P52’, as termed by [2]) that appear to be surrounded by haloes of material with a lower TiO₂ content than the surrounding lava flow (see Fig. 2), and which approximate the extent of their continuous ejecta blankets (i.e. ~1 crater radius beyond the rim: [13, 14]). We hypothesize that these haloes evidence material that has been excavated from a lithology beneath the surface lava flow (‘P52’), with a lower TiO₂ content. A candidate for this deeper lava flow is ‘P24’ (as termed by [2]), which is TiO₂-poorer (by ~3 wt. %), and stratigraphically older than ‘P52’.

Figure 3 is a plot of mean FeO and TiO₂ wt. % abundances for (i) the ejecta of the thirteen craters with TiO₂-poor haloes identified in lava flow ‘P52’ and (ii) the average lava flow compositions of ‘P52’ and ‘P24’. This figure illustrates that the ejecta of the thirteen haloed craters have a distinct composition from that of lava flow ‘P52’ in which they lie; the ejecta compositions are more similar to that of the proposed underlying lava flow, ‘P24’.

![Figure 1](image1.png)  
*Figure 1. A Clementine 750 nm image of the study area within Oceanus Procellarum, showing the major surface features and lava flow boundaries (as mapped in [2]); lava flows relevant to this work, ‘P24’ and ‘P52’, are marked.*

![Figure 2](image2.png)  
*Figure 2. Examples of impact craters within lava flow ‘P52’ displayed in terms of TiO₂ wt. % [12] and reflectance at 750 nm. The craters in (a) and (b) both possess the TiO₂-poor (blue) haloes, with (a) displaying bright ejecta and (b) not. The craters in (c) and (d) have no TiO₂-poor haloes, yet (c) has bright ejecta and (d) does not. The area between the solid (crater rim) and dashed (extent of continuous ejecta) lines in (a) is the region from which data for ejecta compositions were obtained. The ejecta limit does not always completely encompass the halo, but the arbitrary distance of 1 crater radius was chosen for the sake of consistency. The apparently low-TiO₂ crater interior (dark blue) is caused by the bright, non-space weathered material on the steep slopes; asymmetries are caused by variations in illumination due to topography. The scale for all the images is equal.*
We do not attribute the difference in TiO₂ wt. % values for ‘P52’ and the ejecta to an unresolved maturity (albedo) issue as craters both with and without surrounding bright ejecta may or may not display TiO₂-poor haloes (Fig. 2). Furthermore, on a plot of the 415/750 nm reflectance ratio vs. reflectance at 750 nm (Fig. 4), the ejecta of the haloed craters in lava flow ‘P52’ form a distinct group from the ejecta of a set of craters with no haloes in the same lava flow (the craters with haloes are predominantly larger than those without). The offset of these two groups follows a trend of increased TiO₂ content rather than one of increased maturity and therefore supports the notion that the haloes are indeed caused by lower TiO₂ wt. % contents than their immediate surroundings. Additionally, the two sets of craters display a clear distinction in TiO₂ wt. % values, but not in albedo (both as a function of crater diameter).

This evidence suggests that impact craters within lava flow ‘P52’ have indeed excavated material from a deeper, compositionally different lava flow (i.e. ‘P24’). As such, the diameter of the craters (between ~2 km and ~4 km) can be used estimate their maximum depth of excavation [15, 16], and therefore constrain the thickness of the surficial lava flow. Our results show that the lava flow ‘P24’ lies between ~100 m and ~300 m below the surface of ‘P52’ in this region. This estimate is consistent with previous ones for the total thickness of basalts in this area of ~500 - 1000 m [6-8]. Our estimate for the thickness of ‘P52’ suggests that the two flows, ‘P52’ and ‘P24’, each make up approximately half of the total thickness of basalt.

**Conclusion:** We have identified impact craters within Oceanus Procellarum that have excavated and brought to the surface material from deposits underly-