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Observations of Ruapehu Crater Lake (Te Wai ā-moe) and implications for lake dynamics and volcano monitoring

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Abstract

All historical eruptions at Ruapehu have occurred from its Crater Lake, Te Wai ā-moe. This study aims to better understand Crater Lake dynamics by using visible light and long wavelength infrared images of the lake. Over 10,000 images from 1902 – 2021 were analysed to produce a time-series of lake observations. Our results show that visible light observations reveal colour changes on the entire Crater Lake surface from blue to grey, and localised grey, yellow, and black discolourations. Grey discolourations are interpreted as localised upwellings of lake-floor sediment, and yellow and black material to comprise vent-hosted sulphur/sulphides, both transported by volcanic fluids from subaqueous vents to the surface. The locations of upwellings were used to identify five vent locations beneath Crater Lake, three more vents than were previously recognised. Upwellings appeared and disappeared in 10 min. Steam above the lake surface was controlled by both lake temperature and cloud conditions. Blue lakes were most common in summer and autumn, implying a relationship with ice or snow melt entering the lake. Grey lakes were observed in the month before 97% of eruptions, suggesting a correlation between a grey lake and eruption precursors.

Crater Lake processes are illustrated by three regimes. Regime 1, a vigorously convecting grey lake associated with steam, eruptions, and more frequently the high end of recorded lake temperatures (within the range of 7 – 69 °C). Regime 2, a blue lake to occasionally green that typically occurs in summer and autumn when ice or snow melt is significant and is associated with generally the low end of lake temperatures and reduced volcanic fluid input. Regime 3, a blue-grey lake, the most observed lake colour in this study and effectively a balance between volcanic and seasonal processes. We suggest that an array of cameras would be useful additions to the current volcano monitoring network at Ruapehu.

Keywords Ruapehu, Crater Lake, Upwelling, Sulphur, Vents, Volcanic fluids, Lake convection

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Introduction

Volcanic lakes are natural features found on volcanoes that increase volcanic hazard, making them important for volcano monitoring (Pasternack and Varekamp 1997). Crater lakes are the source of many natural hazards, including phreatic eruptions (e.g. Kilgour et al. 2010), limnic gas-turnover events (e.g. Kling et al. 1987), lahars (e.g. Massey et al. 2010), pyroclastic flows (e.g. Shepherd and Sigurdsson 1982), seiches (e.g. Moore et al. 1966), tsunamis (e.g. Simkin and Siebert 1994), base surges (e.g. Shepherd and Sigurdsson 1982), mud eruptions (e.g. Edwards et al. 2017), and seepage of acid lake-water into groundwater (e.g. Rowe et al. 1995). The interaction between a crater lake, magma, and volcanic fluids will determine how volcanic activity is manifested at the surface (Mora-Amador et al. 2019). The volume of a crater lake is determined by the following equilibrium equation shown below (Hurst et al. 1991; Rowe et al. 1992a; Ohba et al. 1994; Pasternack and Varekamp 1997; Rouwet and Tassi 2011; Rouwet et al. 2014):

$$\text{Volume} = (\text{volcanic water} + \text{meteoric water} + \text{groundwater}) - (\text{evaporation} + \text{outflow} + \text{seepage})$$

Ruapehu is an andesitic composite stratovolcano located in the central North Island of New Zealand (Hackett and Houghton 1989; Hales 2000; Tost and Cronin 2015; Townsend et al. 2017) with a crater lake, known as Te Wai ā-moe, on its southern summit area (Fig. 1). At present day, the Crater Lake is approximately 450 m × 550 m in diameter and has a maximum depth of 134 m (Christenson 1994; Oppenheimer 1997). The first recorded observation of Crater Lake was in the 1860's (Mead 1979; Scott 2013; Williams 2013), and it has been present since, except for brief disappearances due to eruptive activity in 1945, 1995, and 1996 (Christenson 2000; Wilson 2009). The lake froze over in 1886 and 1926 (Williams 2013).

The lake surface exhibits numerous temporal variations, including changes in colour, ephemeral dark grey 'upwellings' of sediment located above subaqueous vent areas, and sulphurous 'slicks' which comprise bubbles coated in sulphur that float on the surface (Giggenbach 1974; Christenson 1994). The lake surface temperature has a characteristic six to twelve-month cyclic pattern, with temperatures varying between 9 – 60 °C since 1960, but with 15 – 40 °C fluctuations being more common recently (Christenson 1994). Crater Lake temperature has been intermittently measured by handheld thermometer during volcano monitoring trips since 1960, with a permanent datalogger established in Crater Lake in 2016 that continuously monitors lake temperature and is calibrated by manual thermometer measurements taken approximately every month.

The first recorded eruption from Ruapehu Crater Lake was in 1861 (Crawford 1880; Gregg 1960; Latter 1985; Scott 2013). A large phreatomagmatic eruption followed in 1895 (Cowan 1927; Reed 1945; Gregg 1960; Latter 1985; Scott 2013; Sork 2021), and a lava dome formed in 1945 before being removed by large phreatomagmatic eruptions (Reed 1945; Gregg 1960; Johnston and Neall 1995; Johnston 1997a, 1997b). Vent locations evolved significantly in size and activity during the 1945 eruptive sequence (Beck 1951; Gregg 1960; Johnston and Neall 1995). Two large phreatomagmatic eruptions occurred in 1969 and 1975 (Paterson 1976; Healy et al. 1978; Nairn et al. 1979; Latter 1985; Scott 2013), and multiple large phreatomagmatic eruptions occurred in 1995 that partially emptied Crater Lake (Fig. 2a). Volcanic activity resumed in 1996 with eruptions fully removing Crater Lake (Bryan and Sherburn 2003; Scott 2003, 2013). Minor phreatic eruptions were observed from 1997 to 1999 (Keys 1998a, 1998b, 1999; Wilson 2009) and in 2006 (Scott 2013). In 2007 a moderate-sized eruption occurred that dispersed ash, ballistics, and lahar material across Ruapehu (Fig. 2b) (Kilgour et al. 2010). The last reported eruption was a minor phreatic eruption in July 2009 (Scott 2013). The quiescent period since 2009 is the longest quiescence since historical records of Ruapehu's eruptions began (Scott 2013).

Various studies have been undertaken at Ruapehu Crater Lake, including geochemical analysis of the lake waters (e.g. Takano et al. 1994; Christenson 2000), lake water convection and heat output (e.g. Christenson 1994; Hurst et al. 2012), eruption dynamics(e.g. Kilgour et al. 2010), numerical modelling (e.g. Morrissey et al. 2010), statistical analysis of eruption probabilities (Strehlow et al. 2017), analogue modelling (Vandemeulebrouck et al. 2005), gas emissions (e.g. Werner et al. 2006), and installation of a buoy to record lake temperature and meteorological data (Cole-Baker and Christenson 2010).

This paper will extend the existing body of literature by: (1) using images of Ruapehu Crater Lake to establish timescales of the observed visual fluctuations and understand the driving processes; (2) evaluating the benefits of visible light, multispectral, and infrared cameras for monitoring volcanic activity at Ruapehu; (3) using upwelling locations, bathymetry, and empty crater images to identify vents beneath Crater Lake; (4) interpreting important lake regimes to identify hazard and monitoring implications for Ruapehu and crater lakes elsewhere.

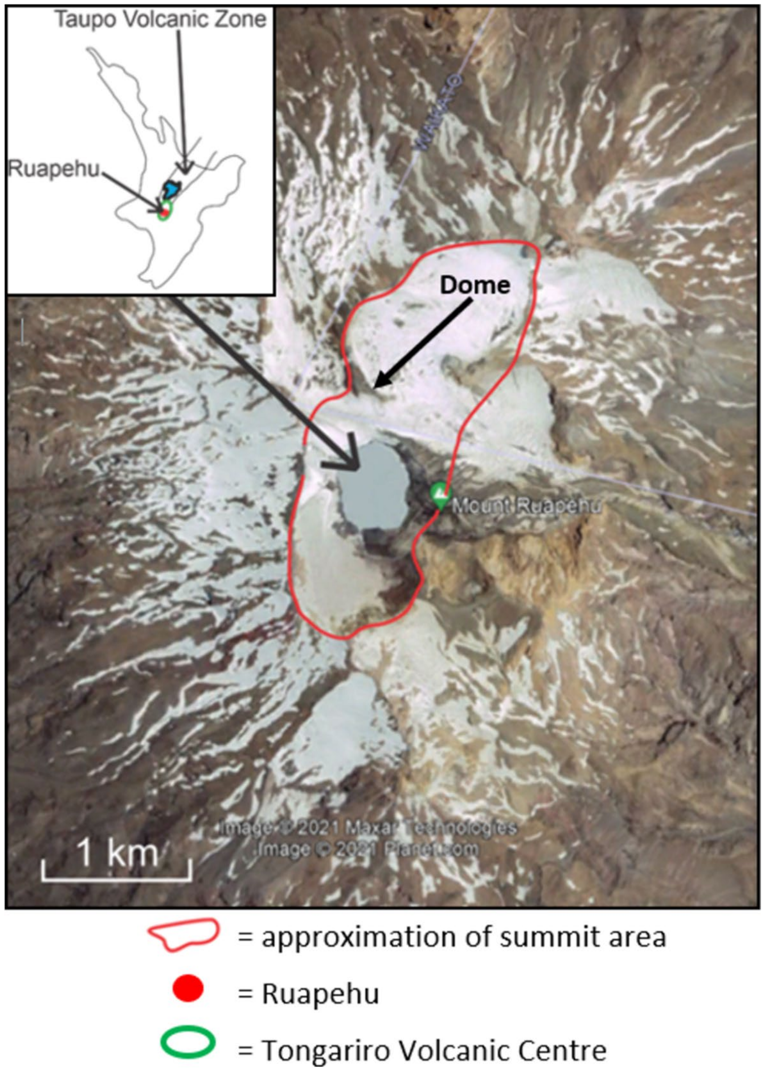

Fig. 1 Aerial image of Ruapehu showing the location of Crater Lake and Dome viewing area (Google Earth 2019). Inset: Map of the North Island of New Zealand, showing the location of Taupō Volcanic Zone (TVZ) and Ruapehu (modified from Cole 1990; Wilson et al. 1995; Conway et al. 2016; Leonard et al. 2021)

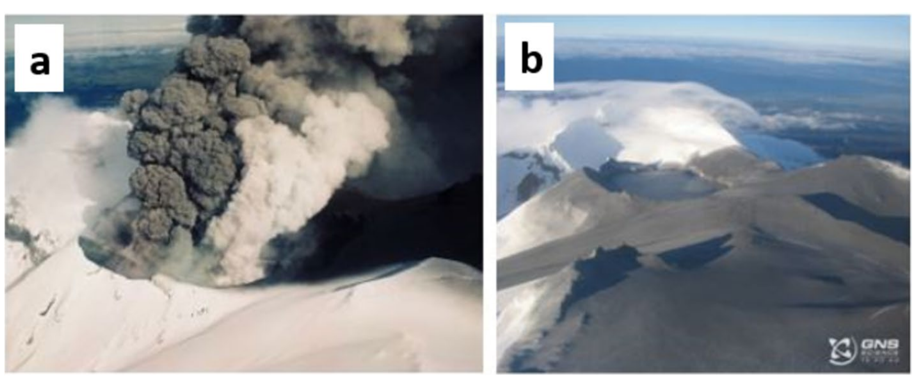

Fig. 2 **a** Eruption in 1995 (Photo: C. Wilson, GNS Science VML 175785), and **b** image taken after the 2007 eruption (Photo: G. Jolly, GNS Science VML 190925)

Methods

Fieldwork involved capturing thousands of images of Crater Lake from the Dome viewing area (Figs. 1 and 3), a natural vantage point overlooking Crater Lake. These images and observations allow a better understanding of the lake dynamics at timescales of seconds to minutes (e.g. how long it takes for upwellings to appear and disappear, and for the lake to change colour), and the processes driving these changes in the lake dynamics. A simultaneous image-capture with visible light, multispectral, and infrared cameras, allowed evaluation of the effectiveness of cameras for monitoring volcanic activity at Ruapehu.

Five different cameras were used to capture images of Crater Lake: (1) iPhone 6, (2) Nikon z7 visible light with polarised filter, (3) MicaSense RedEdge™ 3 multispectral, (4) infrared trail, and (5) Optris PI450 long wavelength infrared camera, taking images every 10 – 20 s for 2 – 4 h (Fig. 3). Camera specifications are summarised in Table 1, and full details are provided in the Supplementary material. The images were used to produce timelapse videos to visualise daily Crater Lake dynamics. Crater Lake images were collected from 31 January to 24 June 2021. To supplement these images and extend back the timeline of Crater Lake observations, other sources of Crater Lake images were also used, as shown in Table 2.

During field work, observations were systematically made of colour, the presence of upwelling fluids or sulphur slicks on the lake surface, and the presence of steam. A full spreadsheet of recorded observations is included in the Supplementary material. Reference images were chosen early in the study to compare Crater Lake colour across all images, ensuring colour descriptions were described consistently and providing confidence for further analysis. Crater Lake colour was described qualitatively as either blue, blue-green, green, blue-grey, or grey (Fig. 4).

We attempted to quantitatively describe the lake colour, but this was unsuccessful because the differing camera angles produced varying glare and 'false' colours. Similarly, the orientation of the sun altered the apparent lake colour (Fig. 5) and atmospheric effects such as significant cloud cover resulted in observed darker lake colours. Also, consistent identifiable referencing points were not available in each image so colour matching between images was not easily automated. For example, potential reference points (e.g. rocks) which could be used for images taken in summer were covered by snow in winter. In addition, different cameras and camera settings resulted in different lake colours.

Upwellings and sulphur slicks were described by their surface area, colour, and location on the lake surface. Upwelling size was described as large, moderate,

Fig. 3 Camera positions and types for newly acquired image data set for this study, (additional camera positions from DOC and GNS Science aerial imagery used not shown) (**a**) Nikon z7 visible light camera used during February fieldwork. **b** Nikon z7 visible light camera, MicaSense RedEdge™ 3 multispectral camera, and trail camera, all used during March 2021 fieldwork. **c** Optris PI450 infrared camera and Nikon z7 visible light camera used during June fieldwork (photo: Harry Keys). All cameras were set up on tripod(s) beside the GNSS monument at Dome

Table 1 Camera technical specifications summary

	Nikon z7 Visible Light Camera	Optris PI450 Long Wavelength Infrared Camera	RedEdge 3 Multispectral Camera
Optical Resolution	45.7 Megapixel (8256 × 5504 pixels)	382 × 288 pixels	1280 × 960 pixels
Spectral Range	380–700 nm	8 – 14 microns	Narrowband (Blue 465–485 nm, Green 550–570 nm, Red 663–673 nm, Red Edge 712–722 nm, Near IR 820–860 nm)
Frame Rate	N/A	80 Hz switchable to 27 Hz	1 Hz (e.g. 1 capture per second)
Temperature Accuracy	N/A	± 2°C or ± 2%, whichever is greater	Unknown
Weight	585 g	320 g (including lens)	150 g

Table 2 Image sources used in this studys and their characteristic camera locations, Crater Lake views, and overall image qualities. High quality images had relatively high pixel resolution and captured the entire lake surface, providing confidence that all lake observations were identified correctly. Medium quality images showed most of the lake, but had relatively low pixel resolution, resulting in a moderate possibility that lake observations were missed. Low quality images only showed small areas of the lake and had relatively low pixel resolution, and thus were generally not catalogued

Image source	Dates taken	Camera location(s)	View of Crater Lake	Image quality
This study	2021	Dome	Low angle	High
GNS Science gas flight	2003 – 2022	Fixed wing aircraft	Low angle	High
GNS Science sampling trip	1960 – 2022	Helicopter, Crater Lake outlet	High, and very low angle	High
Ngāti Rangi, a local Māori tribe	2014 – 2016	Dome	Low angle	Moderate
Department of Conservation (DOC)	1995 – 2018	Helicopter, Fixed wing aircraft, Dome, Crater Lake outlet	High, low, and very low angle	Moderate-high
Hikers	1902 – 2020	Tahurangi Peak, Dome, Crater Lake outlet and rim	Medium, low, and very low angle	Low–high
Literature	1926 – 2008	Helicopter, Fixed wing aircraft, Dome, Crater Lake outlet and rim	High, medium, and low angle	Low-medium

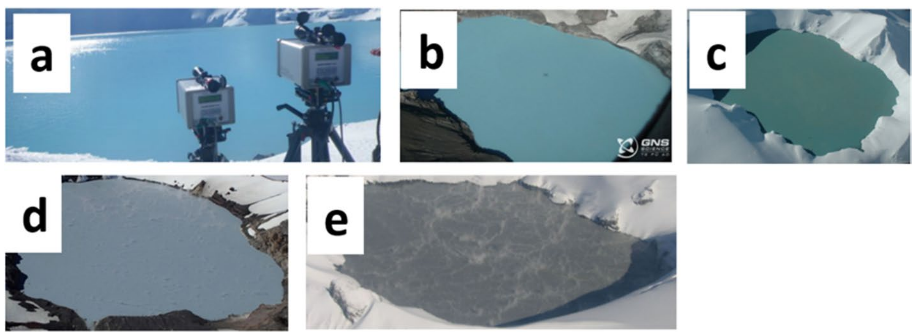

Fig. 4 The five main lake colours, **a** blue, **b** blue-green, **c** green, **d** blue-grey, **e** grey. **a** Photo: A. Mazot, GNS Science VML 120532. **b**-**e** Photos: Copyright GNS Science

Fig. 5 All three images of the Crater Lake (GNS Science Visual Media Library numbers (**a**) 253025, (**b**) 253019, and (**c**) 253035) are taken between 11:04am and 11:05am on 22 March 2021. This demonstrates how different image orientations can affect the apparent lake colour (Photos: K. Britten)

or small, and colour which depends on the amount of sediment in the upwelling, described as dark grey, light grey, or sediment-poor. The lake was divided into central, northern, western, eastern, and central-northern sectors to describe the location of each upwelling and sulphur slick. The amount of steam on Crater Lake was described as either none, weak, mild, vigorous, or very intense.

This study analysed > 10,000 images over 647 days from 1902 – 2021. The variability of colour, upwellings, sulphur slicks, steam, and eruption observations over time were compared to determine if specific observations commonly preceded eruptions or volcanic unrest. Between 1900 and 1959, only 14 images were recorded. The number of images increased between 1960 and 1999 but was limited by a lack of systematic observations and camera technology. Since 2000, lake observations have increased substantially due to the introduction of monthly volcano monitoring flights and technological advances resulting in increased camera use by hikers.

We positioned vent locations through identifying upwellings in 3D space using the photogrammetry software Agisoft Metashape. We then compared this with observed vent locations in 1995 – 1997 when Crater Lake was empty of water. During GNS monitoring visits high-angle aerial images of Crater Lake were captured using a handheld camera operated from a helicopter. These were input into the software to create a vertical orthomosaic image which had a view perpendicular to the lake surface, allowing upwellings and slicks to be accurately located. The 3D model was georeferenced using recognisable rock outcrops as control points surrounding the lake and their associated latitude and longitude coordinates obtained from Google Earth, resulting in sufficiently accurate measurements to estimate lake area, and upwelling and slick locations. These control points were not located using a manual GPS survey due to permit constraints associated to the sacred status of Te Wai ā-moe to local Māori tribes, and the steep dangerous terrain surrounding Crater Lake. The lake shoreline and upwelling locations were traced on each orthomosaic image to precisely identify upwelling locations. Low-angle images taken from Dome were also overlain onto the orthomosaic image.

There were two main limitations to using Agisoft Metashape to identify upwelling locations. First, the latitude and longitude coordinates obtained from Google Earth were not precise. The mean horizontal positional accuracy of co-ordinates used in Google Earth has been calculated to be 4.1 ± 5.8 m (2 S.D) (Paredes-Hernández et al. 2013), which is a notable but manageable error. Second, the original images became distorted in the process of creating the orthomosaic image. This resulted in slight inaccuracies when overlaying the traced lake outlines from Dome that only showed approximately two thirds of the lake shoreline, with the traced lake outlines of the entire lake created from aerial imagery. The error associated with image distortion using Agisoft Metashape was quantified using check point markers and control-point scale bars Check-point markers compare a known location with the same location on a previously georeferenced modelControl-point scale bars measure the distance between two known locations and compares that to the distance between the same two locations in the model. The average check-point error was 7.2 m, and the average control-point error was 2.3 m, which is sufficient to distinguish and estimate upwelling locations.

Results

Lake observations and eruptive activity

The lake colour is highly variable, as indicated by the time-series of lake colour observations from 1963 to 2021 shown in Fig. 6a. The most common lake colour is blue-grey, which was observed in 48% of images, while a grey lake was observed in 34% of images, and a green lake was only seen in less than 2% of images (Fig. 6b). Slight colour changes (e.g. grey to green) occur over days to weeks and major colour changes from blue to grey and vice versa occur over 1–2 months. Major colour changes to grey are associated with upwelling activity in the centre of the lake, while changes to a blue lake are spatially associated with glacial meltwater entering the lake from the western or northern lake edges and spreading across the entire lake surface.

Scott (2013) compiled a comprehensive record of eruptive activity at Ruapehu (Fig. 6c). We focus on observations since 1960 as earlier images are of low quality. From 1960 to 1999 there were numerous reports of eruptive activity with 317 days of documented activity (Scott 2013). Since 1999, there have only been three instances of eruptive activity, in 2006, 2007, and 2009. From 1960 – 1999, the lake was predominantly characterised as a grey lake with few upwellings (although grey upwellings can be hard to observe in a grey lake), and abundant sulphur slicks and steam. However, this set of characteristics is also common from 2000 – 2004 when no eruptions occurred. From 2009 – 2013 the lake transitioned to a blue or blue-green colour with more upwellings, and one small eruption. The lake has been mostly blue grey from 2014 – 2021, with many upwellings and no eruptions.

Observations before eruptions were analysed to decipher what the lake conditions were in the month prior to eruptive activity. A one-month period before eruptive activity was chosen because fieldwork in 2021 revealed that all lake observations can change (e.g. colour from blue to grey, upwellings, sulphur slicks, steam) over a one-month period (this also coincides with the typical frequency of volcano monitoring sampling campaigns). Combining Crater Lake observations from images and recorded lake observations, results in 98 incidents of eruptive activity from between 1969 and 2009 with observations of the lake colour within one month beforehand. During this period, there were a total of 321 observations of eruptive activity (we have observations of lake colour within a month before 30% of events). The average lake colour within one month before eruptive activity was grey 97% of the time, blue-grey 2% of the time and green 1% of the time (Fig. 6d). There is one eruption, which occurred on 1981–10-20, where the lake colour is green in the month before the eruption, and two eruptions where the lake colour is blue-grey before (2007–09-25 and 2009–07-13). All three eruptions occurred when the Crater Lake temperature was low, as shown in Fig. 7.

A Mann–Whitney U test, which is a non-parametric statistical test that is appropriate for non-normally

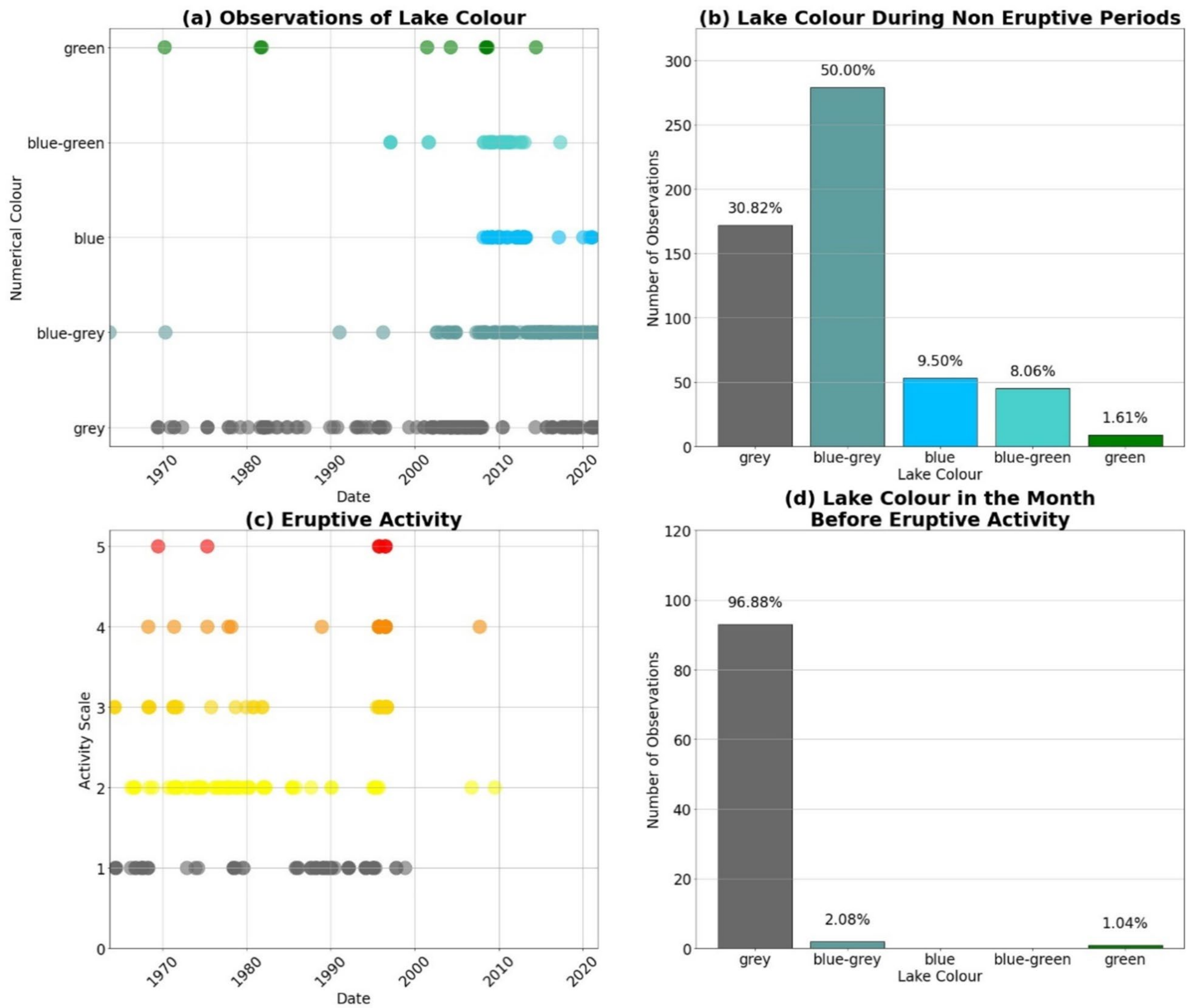

Fig. 6 Observation of lake colour and correlation with eruptive activity. **a** Observations of lake colour from 1963 to 2021. **b** Frequency of each lake colour during non-eruptive periods (defined as more than a month before an eruption). **c** Ruapehu eruptive activity from Scott (2013). The activity scale (which is different to Geonet's volcanic alert levels) ranges from 1 for small phreatic eruptions confined to the Crater Lake to 5 for large scale explosive eruptions displacing moderate volumes of the lake. **d** Average lake colour prior to eruption for all eruptions with images within a one-month period prior to the eruption

distributed data like the lake colour observations shown here, was used to assess statistical significance by comparing observations of lake colour during non-eruptive periods (defined as more than a month prior to eruption) with the lake colours observed in the month prior to eruptive activity. This resulted in a p-value of 7×10^{-29}, which is much less than 0.05 and hence indicates that the lake is more likely to be grey than any other colour in the month prior to eruption.

It can be challenging to distinguish between grey and blue-grey lakes, and potentially only possible for a trained observer. Noting this, we compare the frequency of grey and blue-grey lake observations through the whole observation period with observations in the month prior to eruptive activity. Grey/blue-grey lakes are observed 81% of the time whereas grey/blue-grey lakes are observed before 99% of eruptive activity. The two distributions are statistically significantly different with a p-value of 1×10^{-5}.

A similar analysis was performed on observations of upwellings, sulphur slicks, and steam. Of 60 eruptions where the presence of upwellings was documented in the month prior to eruption, upwellings were only observed prior to 2 of the eruptions (3%), which was statistically different to the whole data set. However, we note that grey upwellings are challenging to observe in a grey lake,

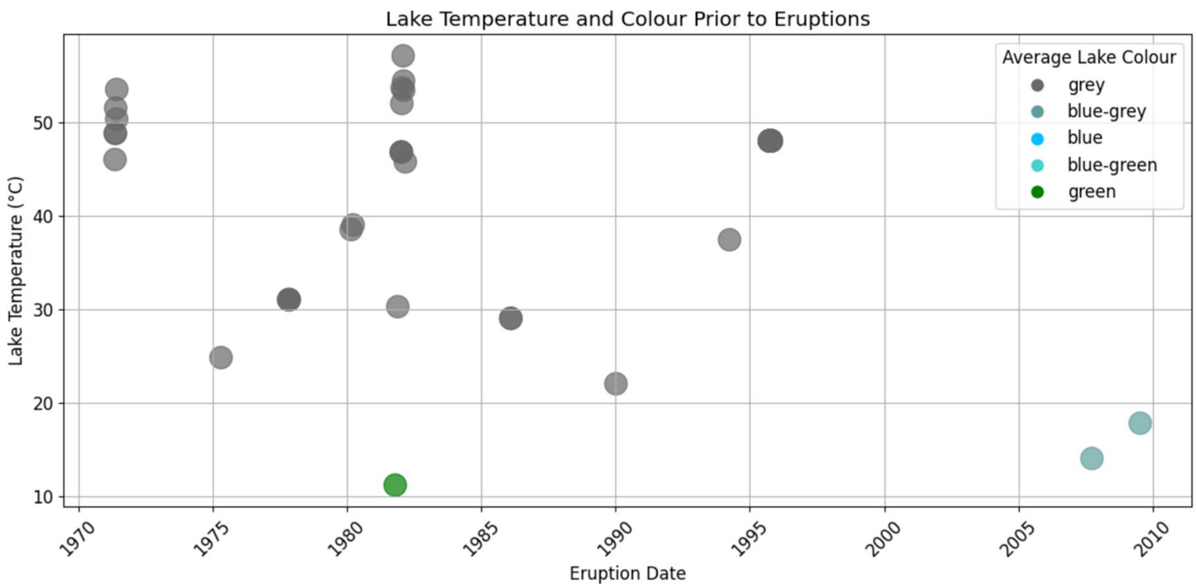

Fig. 7 Average lake temperature and lake colour for the 53 eruptions that have both temperature and colour observations in the month prior to eruption. Eruptions from a green or blue-grey lake occur at lower lake temperatures than eruptions from a grey lake

which may explain the lack of upwellings observed prior to eruptions. Observations of sulphur slicks prior to eruptions were not statistically significantly different to the overall observations of sulphur slicks across all dates. Steam was observed within a month before 97% of all eruptions, which was statistically different to the whole dataset. However, steam was only recorded if it obscured the lake (Scott 2013) and so the dataset may undercount observations of steam during non-eruptive periods.

To identify relationships between the different phenomena, we focused on 306 high quality images between 1981 and 2021 and computed the cross-correlation between lake colour, upwellings, sulphur slicks, and steam. The highest correlation was 0.28 between upwellings and sulphur with all other correlations less than ± 0.18 (see Supplementary material).

Upwellings

Upwellings are identified by circular grey patches or calm areas on the lake surface and are hugely variable both spatially and temporally (Fig. 8a). Observations from fieldwork indicate upwellings can appear and disappear in < 10 min, remain present for hours, and vary in size from metres to hundreds of metres. They can also appear in slightly different locations over time. Upwellings remained stationary while sulphur simultaneously moved across the surface, suggesting that wind or surface water currents do not substantially affect the upwelling location.

Sulphur slicks

Sulphur slicks are black or yellow patches commonly observed moving across the lake surface (Fig. 8b), rarely appearing as circular rings, and often associated with upwelling sediment. Sulphur slicks occasionally form an elongate chain (Fig. 8) and are moved by either surface currents or wind; they can disappear out of sight and re-appear minutes or hours later. The simultaneous movement of sulphur slicks in different directions suggests that variable surface currents are most likely moving the sulphur slicks across the lake, aided by observed localised swirling wind conditions. The residence time for sulphur slicks on the lake surface is difficult to estimate as they may adhere to the lake edge after they make contact or linger on the lake edge before being blown back into the lake. A rock or former sulphur slick was found at the lake outlet that was mostly yellow, highly vesicular, composed of many agglutinated spherical shapes, and smelled of sulphur (Fig. 9).

Sulphur slicks are interpreted to form due to degassing through a molten sulphur pool with temperatures between 116 and 160^{O}C. At temperatures above 160^{O}C, the viscosity of sulphur increases substantially, causing the trapping of rising gases (Scolamacchia and Cronin 2016). The presence of subaqueous pools of sulphur has been previously hypothesized (Giggenbach 1974; Hurst et al. 1991) at several volcanoes including Poas (Costa Rica) and Ruapehu (Bennett and Raccichini 1978; Scolamacchia and Cronin 2016) and similar yellow and black spheres have been observed in geysers (Shean 2006).

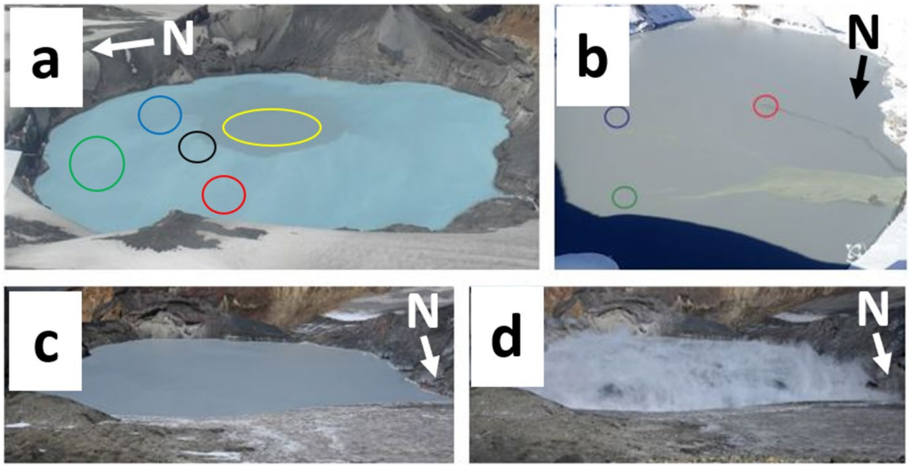

Fig. 8 Crater Lake images of (**a**) upwellings, **b** sulphur slicks, **c** no steam, **d** very intense steam. Figure 8a and b show the grouping of upwellings and slicks into central (yellow), western (red), central-northern (black), east (blue), and northern (green) lake locations. **a** Photo: Copyright GNS Science. **b** Photo: K. Britten, GNS Science VML 254648. **c**, **d** Images taken in this study

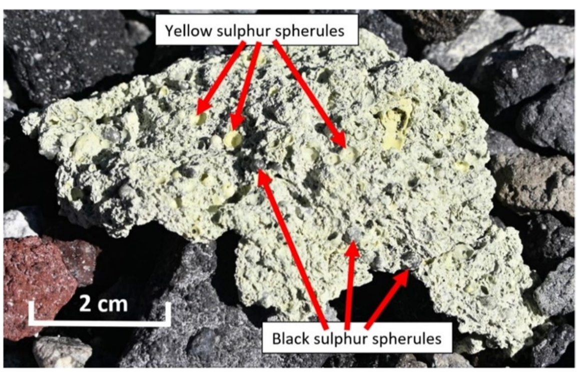

Fig. 9 A rock or former sulphur slick found at Crater Lake outlet

Condensed water vapour/steam

The amount of condensed water vapour, herein referred to as steam observed above the lake surface, was found to vary over minutes to hours. Vigorous or very intense steam obscures large regions of the lake surface (Fig. 8d), making observations of lake colour, upwellings, and sulphur slicks difficult. Increased steam is seen on cloudy days; however, the lake temperature needs to be moderate to high (> 30 °C) for vigorous or very intense steaming to be observed. Steam morphology also varies across the lake surface, occurring in circular or polygonal patterns during low winds, and as sheets of steam blown across the lake during high winds (Fig. 10). Hurst et al. (2012) previously observed small whirlwinds of steam caused by convection above the lake and termed the phenomenon "steam devils". We do not use that term here due to the wide range of steam morphology observed during this study.

Long-wavelength infrared imagery

Long-wavelength infrared images were compared with visible light images captured simultaneously, to test whether infrared imagery would be a useful tool for future monitoring of Crater Lake and crater lakes elsewhere. Discoloured areas were sometimes identified on visible light images (i.e. upwellings) but not in infrared images taken simultaneously, suggesting the discoloured area and the rest of the lake were the same temperature. However, infrared images also revealed some areas of the lake that were measured to be colder than others, while the lake surface appeared smooth and had no clear discolouration on the associated visible light imagery (Fig. 11a). Condensed water vapour (i.e. steam) that has risen many metres above the lake has cooled down and become colder than the lake water (appears blue on the infrared image in Fig. 11b). Therefore, steam inhibits observations of upwellings and sulphur slicks on both infrared and visible light images.

Lake temperature

When lake colour was plotted against lake temperature from 1963 to 2021, there was no correlation (Fig. 12). Multiple lake temperature fluctuations from 20 – 40 °C have occurred without any change in lake colour, with the lake being continuously grey from 2004 to 2008 (Figs. 12 and 13), except immediately prior to the September 2007 eruption when it was blue-grey (Fig. 7), and continuously blue from 2012 to 2013 (Fig. 12). The high lake temperatures from 1995 to 1997 with few lake colour observations was due to an active period of volcanism, with large eruptions emptying Crater Lake, and steam obscuring

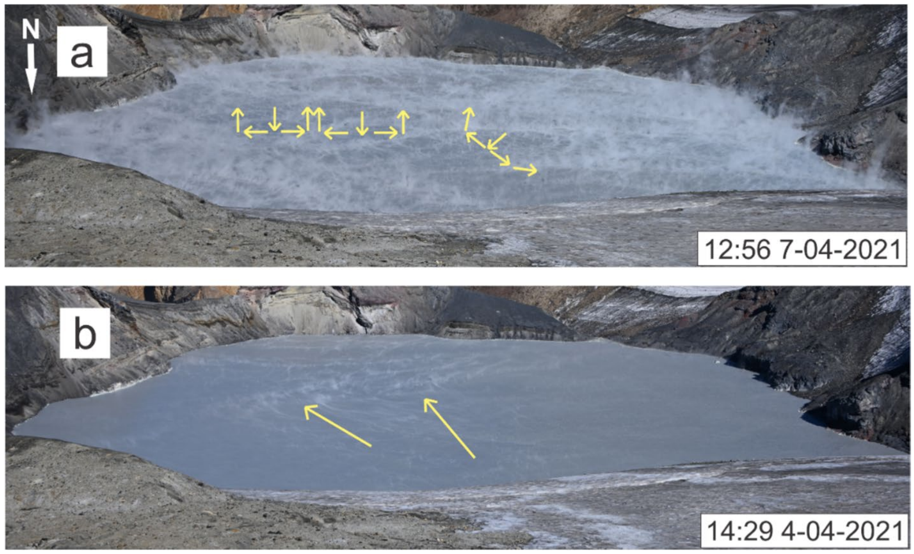

Fig. 10 **a** Convective hexagonal steam cells. **b** Laminar flow of steam across Crater Lake

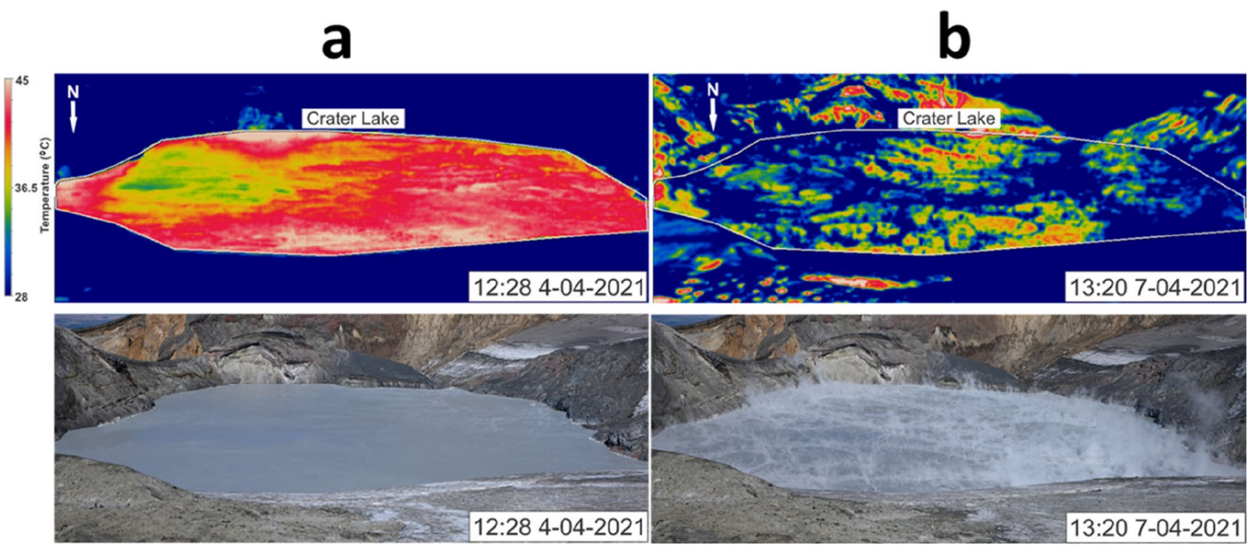

Fig. 11 Daytime infrared image of Crater Lake (top) and a visible light image (bottom) taken simultaneously. **a** The measured lower temperature green area in the infrared image correlates to a smooth lake surface with no clear discolouration in the visible light image. **b** Highlights the deleterious effect of steam on thermal imagery at Ruapehu Crater Lake

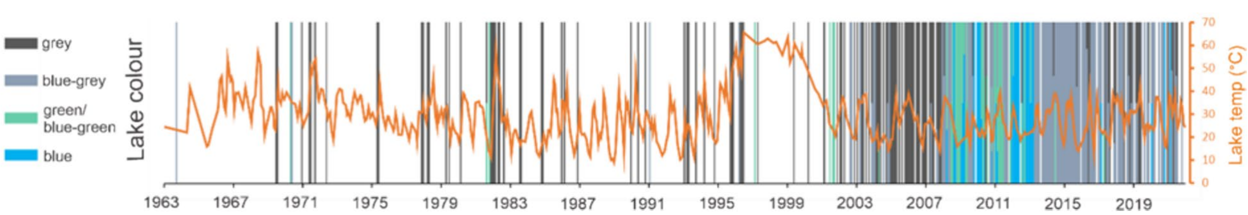

Fig. 12 Plot of lake colour against lake temperature from 1963 – 2021

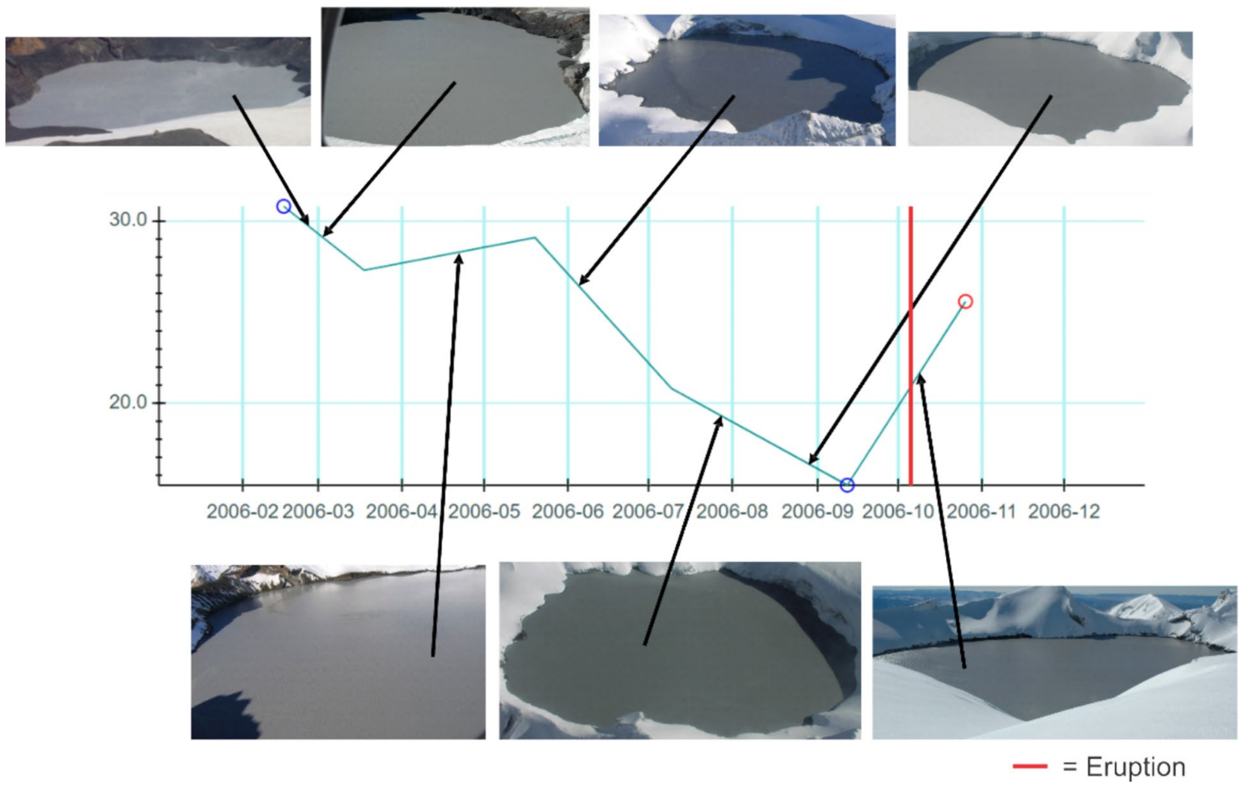

Fig. 13 Lake colour remaining grey throughout Crater Lake temperature fluctuations. Photos: Copyright GNS Science

most of the lake surface as the crater refilled with water. The influence of seasonal and volcanic processes on lake colour is explored further in the discussion.

Lake temperature data was collated into monthly intervals and average lake temperature was calculated for each month, using all available data. The lake temperature is slightly warmer in summer (30.8 ± 19.2 °C (2 S.D)) and autumn (32.3 ± 19 °C (2 S.D)) than winter (27.2 ± 20.6 °C (2 S.D)) and spring (27.7 ± 20.8 °C (2 S.D)). These differences in lake temperature are within two standard deviations so are not statistically significant but suggest a weak seasonal correlation between lake temperature and the seasons. The mean air temperatures measured at the Chateau (a hotel on the northern flank of Ruapehu at an elevation of 1097 m compared to the summit of Ruapehu with elevation of 2797 m) range from 12.4 °C in January to 3.1 °C in July (this is the 30-year climatology normal for NIWA station Mt Ruapehu, Chateau EWS from 1981 to 2010).

Lake colour plotted as averaged monthly observations reveals a seasonal variation (Fig. 14). Blue and blue-green lakes are observed mostly during summer and autumn and are rarely observed in winter and spring. Of all blue lake observations, 76% occurred during summer and autumn, and only 6% in winter. Grey and blue-grey lakes had no clear seasonal variation, with similar occurrences independent of the season (55% and 60%, respectively, in combined summer and autumn).

Summary of results

Abundant eruptions (> 300) occurred from 1963 to 1999 (Scott 2013) when Crater Lake was mainly grey with steam. A reduction in volcanic activity since 1999 has coincided with considerable variation in all lake surface observations. Analysis of lake observations and eruptions reveals that the lake was grey during the month before 97% of eruptions at Ruapehu when observations were made in the month prior to eruption. In contrast, a grey lake was identified 34% of the time during both eruptive and quiescent phases; thereby demonstrating a statistically significant difference in lake colours with eruptive activity,

Certain years appear to show a blue lake correlating with cooler lake temperatures and a grey lake with higher lake temperatures, however decadal time-series plots show no lake colour-temperature correlation. Short-term lake colour change to blue appears to correlate with seasonal changes, while short-term colour change to grey seems to relate to simultaneous lake temperature and water level increases, which are driven by volcanic processes.

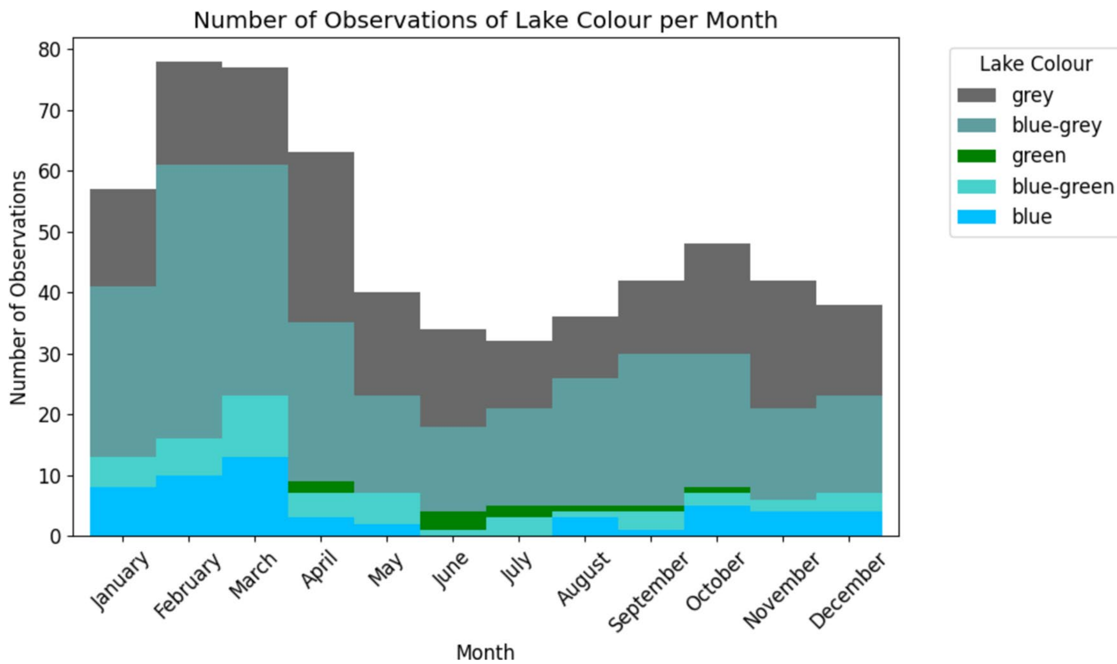

Fig. 14 Monthly plot of lake colour taken as an average of all 587 images from 1963 to 2021 revealing seasonal variation in the lake colours

Discussion

Crater lake colour

The colour of Ruapehu Crater Lake is a direct result of its chemical composition and varies due to the presence of suspended material (e.g. upwelling fluids and sediment, sulphur slicks, iron-oxide precipitates, glacial rock flour) and changes in the dissolved material (e.g. Fe^{2+}). No microbial life has been identified at Ruapehu Crater Lake, potentially due to its high acidity (Koshida 1991; Takano et al. 1994; Mapelli et al. 2015), although microbes have been identified in thermal pools with high acidity in Yellowstone National Park (USA) (Rowe et al. 2024).

Upwellings are interpreted to consist of volcanic fluids and lake-floor sediment emitted from vent(s) beneath the lake. They have been observed at Ruapehu, where Hurst and Dibble (1981) found thermochemical evidence of subaqueous fumarolic discharges, and observations from scientists who witnessed bubbles rising to the surface in these upwelling locations (Christenson 1994). Upwelling locations at Ruapehu have also been correlated to lake-floor vents that emit volcanic fluids (Christenson 1994), identified when the floor of the Crater Lake was visible, and from depressions visible in a 2010 bathymetric survey (Christenson 2010, unpublished). Upwellings have been recognised at other crater lakes, including Laguna Caliente (Brown et al. 1989), Kawah Ijen (Delmelle and Bernard 1994), Kelimutu (Murphy et al. 2017), and Copahue (Agusto et al. 2017). Laguna Caliente is often a grey colour due to upwelling volcanic fluids convectively mixing lake-floor sediment into the lake (Brantley et al. 1987; Brown et al. 1989; Mora-Amador 2010; Christenson et al. 2015; Rouwet et al. 2014). It is suggested that grey lake colour at Ruapehu is also a result of volcanic fluid convection stirring sediment throughout the lake waters due to voluminous central vent upwelling activity.

Sulphur slicks at Ruapehu are thought to form as volcanic gases rise through a liquid sulphur layer at the bottom of Crater Lake (Christenson 1994). Ascending gas bubbles become coated in liquid sulphur and coalesce. The sulphur coating solidifies as the gases rise to the surface and cool to form sulphur spherules (Giggenbach 1974). The coalesced sulphur spherules float on the surface, sometimes sticking together to form a sulphur-coated vesicular rock (Fig. 9) that is then transported to the lake shoreline by either water currents or wind. Floating elemental sulphur has been observed at many crater lakes globally (Rouwet et al. 2014). The appearance of black sulphur spherules and slicks (Figs. 8 and 9), suggests that sulphur slicks may be a composite of elemental sulphur and clay, sulphate, or sulphide minerals, which have been identified in ballistic deposits (Christenson et al. 2010).

Blue or blue-green lakes generally occur during low lake temperatures and reduced volcanic input, when glacial or snow-derived meltwater may affect lake colour. This explanation is reinforced by observations of meltwater changing the lake colour to blue, and meltwater more commonly being observed entering the lake during the summer and autumn months, predominantly December to March (Keys and Green 2008), when the air temperature is consistently above 0 °C and solar insolation is higher. During the summer, the average lake temperature is 30.8 °C whereas during the winter the average temperature is 27.2 °C, indicating a correlation between lake temperature and air temperature (although there is a lot of variation in the temperature observations, as discussed in Sect. 3.6). The blue colour is due to scattering of light from suspended particles. Glacial rock flour comprising plagioclase and pyroxene mineralogy has been studied to cause blue glacial lakes in Oregon, USA, a formerly glaciated volcanic terrain (Rampe et al. 2017). The primary mineralogy on Ruapehu is also dominated by plagioclase and pyroxene (Leonard et al. 2021), suggesting that glacial rock flour entering the Ruapehu Crater Lake may be causing the blue lakes seen mostly in summer and autumn. Another possible cause of blue or blue-green lake colour is < 0.45 μm sized colloidal sulphur particles in suspension, or colloidal silica derived from lake-floor sediment, as has occurred on the crater lakes of Kelimutu (Indonesia) and Mount Aso (Japan) (Pasternack and Varekamp 1994; Ohsawa et al. 2002; Murphy et al. 2017).

A green Crater Lake has been observed rarely at Ruapehu and can be explained by the presence of Fe^{2+} ions. Ruapehu Crater Lake water has a pH < 1, and in these acidic waters Fe^{2+} solubility dominates over Fe^{3+}, resulting in the majority of dissolved Fe in the lake being in the reduced form of Fe^{2+} (Christenson and Wood 1993). Elsewhere, the crater lakes of Kelimutu and Mount Aso also vary from green to blue-green, with a green colour caused by increased Fe^{2+} that is sourced from either wall rock dissolution or hydrothermal input (Pasternack and Varekamp 1994; Ohsawa et al. 2010; Murphy et al. 2017).

Condensed water vapour/steam

The amount of condensed water vapour (i.e. steam) is controlled by the difference between lake temperature and air temperature, and atmospheric moisture. Observed circular or polygonal steam patterns, previously termed "steam devils" by Hurst et al. (2012), are a result of heat being naturally and efficiently dissipated (Ma et al. 2019). Steam 'circles or polygons' form when central down-drafts of air push the steam sideways, and peripheral up-drafts of air carry steam upwards (Mancini and Maza 2004). As wind speeds increase on the lake surface, these circular or polygonal patterns transition to sheets of steam blowing across the lake as laminar flow develops.

Long wavelength infrared imagery

Ground-based infrared imagery captured at the Crater Lake of Kawah Ijen Volcano in Indonesia identified localised areas on the lake that were measured to be 4–7 °C colder than the rest of the lake, however in-situ temperature measurements showed no clear temperature difference from the rest of the lake waters (Lewicki et al. 2016). Infrared camera observations of Ruapehu Crater Lake also revealed central or eastern areas of the lake measured to be approximately 5 °C cooler than the rest of the lake, while a smooth lake surface with no discolouration was evident on the associated visible light imagery (see Fig. 11a). Similar infrared observations of an apparent cold spot on the lake surface have also been recorded by GNS scientists from Dome (N. Fournier, pers. comms 2024), which is counterintuitive to the hypothesis that this would be a region of 'hot' volcanic fluids ascending to the surface. These apparent 'cooler' areas on the lake surface are likely a false result produced by the oblique 14° low angle view of Ruapehu Crater Lake from Dome, resulting in reflections of the cooler surrounding rock heat signature or the colder sky heat signature, and/or evaporative cooling of the lake surface (Lewicki et al. 2016; B. Scott, pers. comms 2023).

Lake temperature

It has been hypothesized that an influx of volcanic fluids produces a grey lake. This theory is supported by the mean temperature of the lake being higher when it is grey and lower when it is blue, however the means are within two standard deviations of each other, so the difference is not statistically significant. This suggests that the influx of volcanic fluids (approximated by hotter lake temperatures) may influence lake colour under certain conditions, however, the effects from other processes such as meltwater entering the lake, will dominate lake colour during other conditions. A seasonal lake temperature relationship can be explained by higher air temperatures in summer and autumn increasing the lake temperature. However, the lake temperature-season correlation is weak because of volcanic fluid influx which occurs independently of the seasons producing cyclical temperature fluctuations. Grey and blue-grey lakes have similar occurrences independent of the season, suggesting that grey and blue-grey lakes are mainly governed by volcanic fluid influx. The lake is also influenced by convection and stratification processes, as detailed by Christenson (1994).

The mean lake temperature in the month before past eruptions is 39 ± 24 °C (2 S.D), while the overall mean lake temperature from all recorded data is 27 ± 14 °C (2 S.D). This indicates the lake temperature was typically higher before past eruptions, but as the mean for all Crater Lake temperature data and Crater Lake temperature before eruptions are within two standard deviations, the difference is not statistically significant. As the lake can be very dynamic, some changes occur over shorter periods than one month so averaging over one month may miss these subtle processes. Comparatively, Strehlow et al. (2017) chose two months for their analysis of eruption frequency associated with lake temperature, which found a bimodal eruption distribution at temperatures typically below 15 °C, or above 40 °C. From 1964 – 1999 there were > 300 eruptions, compared to only three eruptions since 1999 (Scott 2013). This reduction in volcanic activity since 1999 has resulted in other processes such as glacial or snow meltwater input having a greater effect on lake observations.

Crater Lake can undergo temperature cycles from 7 – 69 °C, but typically it varies between 15 – 40 °C over a 6 – 12-month period. Distinguishing between driving mechanisms for lake temperature cycles is beyond the scope of this paper, but previous authors have reported they may be due to: (1) inferred instabilities in the vent/heat pipe beneath the lake that are unrelated to changes in the underlying magma body (Vandemeulebrouck et al. 2005); (2) cyclic input of hot hydrothermal fluids due to movement of fresh magma (Rowe et al. 1992b); and (3) significant variations in viscosity of a liquid sulphur inferred boundary layer at the bottom of the lake (Hurst et al. 1991). (4) Blockage or sealing of the vent system caused by mineralisation of sulphur and other secondary minerals (Christenson 2000; Christenson et al. 2010).

Vent locations

The inferred locations of the vents on the bottom of Ruapehu Crater Lake are based on: (1) upwelling locations on the lake surface; (2) bathymetry from a survey completed in 2010; (3) images of the Ruapehu crater floor when Crater Lake had been evacuated by eruptions and vents were visible.

Observations of Crater Lake have indicated at least five upwelling locations (Fig. 15a). It is assumed that upwelling sediment is carried approximately vertically to the lake surface. However, observations during fieldwork in this study indicated slight variations in upwelling location, either caused by volcanic fluids ascending to the surface at an oblique angle, or minor variations in the source location of volcanic fluid output. Observations from GNS scientists suggest that wind or surface water currents may also have a minor effect on upwelling location and morphology.

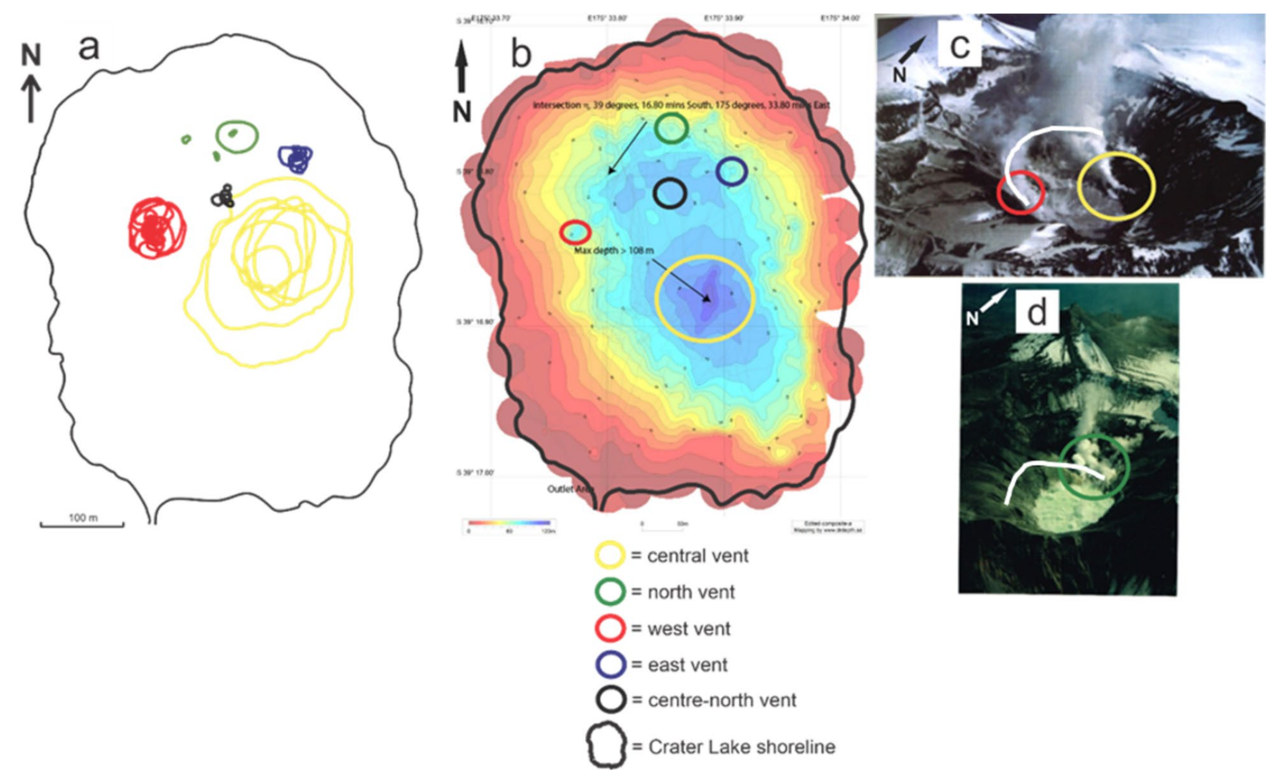

Fig. 15 Five vent locations interpreted using images of the exposed crater floor, upwelling locations, and lake bathymetry. **a** Upwellings traced using Agisoft Metashape photogrammetry-derived orthomosaic images, utilising 18 days of images taken during fieldwork in February – April 2021. **b** Bathymetry map created in 2010 (Christenson 2010, unpublished data). **c** Partly exposed crater in November 1995, photo: Harry Keys (Williams and Keys 2008). **d** Partly exposed crater in April 1997, photo: Harry Keys. **c**, **d** White linear features are ring faults as mapped in Beck (1951); Gregg (1960)

The size of the convective fluid upwellings is likely to indicate the strength of the fluid output. Colour is used as a proxy for the concentration of sediment transported from the lake floor to the surface by upwellings. However, if there is no sediment available on the lake floor because it is already in suspension within the lake, then strong fluid upwellings may occur without producing a dark colour at the surface. This is exemplified by a lack of upwellings observed in a grey lake during 1963 – 2000, either because no lake-floor sediment was available to be carried to the surface, or because upwellings could not be distinguished from the rest of the lake because they had similar sediment concentrations to the rest of the lake and were a similar colour. The lack of correlation between observed upwellings and Mg^{2+} (which is produced by interaction with fresh magma or hot rock), and the temperature of upwellings being cooler or similar to the lake water, indicates these are likely old batches of lake-floor precipitates and sediment being recycled from the lake floor. Central upwellings were significantly larger and darker than the other four upwelling locations, suggesting that the central lake floor emits more volcanic fluids than any other lake floor location. An alternative hypothesis is that the maximum lake depth is where more sediments precipitate during periods of quiescence, which means there is more material available to be entrained by upwelling fluid flux from the deeper central vent. In February 2021, upwellings were observed above the northern, western, and eastern parts of the lake when it was blue, however observations in March 2021 revealed a dark grey lake with a large dark grey central upwelling, suggesting that the central lake floor is the only area capable of convecting sediment throughout the entire lake and producing a grey Crater Lake.

Lake bathymetry can be used to identify morphological features (e.g. topographic highs and lows) on the Crater Lake-floor which may correlate with vent locations (Fig. 15b). Bathymetric depressions in the central, northern, western, and eastern lake floor correlate with observed upwelling locations, and the central, northern, and western depressions correlate with vents observed degassing from 1995 – 1997 when the crater was empty of water. A large 'central' depression with a depth of > 108 m is visible in the central eastern part of the lake (yellow circle), and minor depressions at approximately 70 m depth are found in the northern (green circle), western (red circle) and eastern (blue circle) areas of the lake. However, there is an upwelling that is not clearly associated with a bathymetric depression, and depressions that are not associated with upwellings. These relationships are common at other volcanoes where fumaroles may appear inside craters or on crater rims or plateaus (Kilgour et al. 2021).

Crater Lake was empty of water in 1945, 1995, and 1996 when large eruptions removed all water from the lake. Images taken from 1995 – 1997 show subaerial degassing at a highly active central vent, northern vent, and western vent (Fig. 15c, d).

Vent locations are most accurately determined when combining the above observations (Fig. 15). The central, northern, and western vents that were observed subaerially degassing from 1995 – 1997, correlate with upwelling locations on the lake surface, and localised depressions from the 2010 bathymetric survey. The eastern vent is interpreted from both upwelling locations and bathymetry data, and the centre-northern vent is inferred from observed upwellings. In 1945 when the crater was empty, a concentric ring fault scarp was indicated along the northern, western, eastern, and/or central-northern vents (Beck 1951; Gregg 1960). However, the ring fault cannot be georeferenced onto bathymetry or orthomosaic images because the lake shoreline was significantly different in 1945. Central vent upwellings were commonly found slightly north of the associated bathymetric depression, suggesting that either the vent is inclined northwards, fluids are emitted from an area north of the central bathymetric depression, or the lake-floor has changed since the 2010 bathymetry survey.

Since 1902 when images of Crater Lake have been captured, the central vent has consistently produced the most upwellings and sulphur slicks, with the central vent observed erupting in 1945 and first observed producing upwellings and sulphur slicks in 1963. The northern vent was first observed emitting slicks in 1969 after an eruption, the eastern vent initially produced an upwelling in 1977, a western vent upwelling was seen in 2007, and central-northern vent upwellings were observed in 2021. However, these central-northern vent upwellings may have occurred earlier and been misinterpreted as northern vent upwellings. These vents are likely to have been active before 1963, but the lack of images and poor image quality before then made identification of upwellings and therefore vent locations impossible.

Other features may affect vent locations on the floor of Crater Lake. There may be lava partially blocking the vent/conduit, structural control (i.e. faulting) controlling fluid pathways, or the boundary between crater breccia fill and solid rock wall may be acting as a permeable pathway for fluids to reach the lake-floor. Observations of the degassing from northern and western vents in 1995 – 1997 indicate that degassing occurred along linear features/ring fractures (white lines on Fig. 15c, d) suggesting that fluid emissions in these areas of the lake may be structurally controlled, which correlates with an arcuate ring fault observed when the crater was empty of water in

1945. An arcuate ring fault also developed on the NE side of the crater well above the 2530 m lake level during the 1995–96 eruption and was visible with steam and weak gas fumerole emission until 1999Bathymetric depressions that correlate with known vent and upwelling locations can be explained by cratering from eruptions, where loose breccia collapses into the top of the conduit (Kennedy et al. 2020; Kilgour et al. 2021), and pit cratering from subsidence of the roof of a magma reservoir (Holohan et al. 2011). The fine components of the loose fill are easily convected elsewhere in the lake, however much of the material may gradually descend into the vent system, producing a bathymetric depression. Pit cratering and the formation of small ring fractures evidenced in Fig. 15 results from magma or fluid withdrawal leading to subsidence of the crater floor above the conduit, with this process occurring during and after eruptions (Holohan et al. 2011). The central vent is the largest bathymetric depression because it has abundant loose breccia fill from considerable cratering in 1945 and 1995–96.

Conclusion and recommendations

The main findings of this study are that significant spatial and temporal variations occur at Crater Lake, over short-time periods. Lake colour typically varies from blue or blue-green to grey, with green rarely observed. Slight colour changes (e.g. blue-grey to grey) occur over days to weeks, and significant colour changes from blue to grey and vice versa occur over 1 – 2 months. Upwellings can appear and disappear in < 10 min, remain present for hours, and vary in size from metres to hundreds of metres.Upwellings can also appear in slightly different locations over time due to a) fluids ascending through the water column at an angle, b) variation in the vent position due to the formation of new fractures and fluid pathways, c) internal currents and circulation within the lake, or d) wind on the surface.. Sulphur slicks can appear as linear features often sourced from a point on Crater Lake surface, circular rings, or be associated with upwelling sediment. The residence time of sulphur slicks on the lake surface is difficult to interpret as they may adhere to the lake edge or be blown back into the lake. Future work could build upon the observations of sulphur slicks presented here to investigate the temporal variation in sulphur slicks and determine if they could be a useful monitoring tool. The amount of steam can vary over minutes to hours, with more steam seen on cloudy days, however Crater Lake temperature needs to be > 30 °C for vigorous or very intense steaming to be observed.

Our study of observations and historical monitoring data has been integrated to produce three 'regimes' which are important for understanding and monitoring Crater Lake. Regime 1 is a grey lake with steam. This correlates with past eruptions and contains upwelling(s) that are obscured in visible light imagery as the entire lake is grey from magmatically driven central vent convection stirring sediment throughout the lake (Fig. 16). Regime 2 is a surficial blue to occasionally green lake overlying blue-grey material at depth with minor or no upwellings or sulphur slicks or steam (Fig. 17). This typically correlates with seasonal non-volcanic processes such as increased glacial and/or snow meltwater input in summer and autumn and density-driven stratification of the lake (Christenson et al. 2010). Eruptions are much less common in regime 2, when compared to regime 1, however they have occurred, these rare eruptions from this regime have been interpreted to result from a sealed conduit where fluid and heat transfer was minimised during pressurisation (Christenson et al. 2010). Regime 3, the most common regime, is effectively a combination of regimes 1 and 2, as it comprises a blue-grey lake with upwellings and sulphur slicks and without steam. A balance between volcanic fluid input and meltwater input is responsible for producing regime 3.

When observations were made less than one month prior to an eruption, a grey lake was observed before 97% of eruptions at Ruapehu, suggesting regime 1 is the most volcanically active regime. Eruptions, which can be phreatic, magmatic, or phreatomagmatic, are more common in grey lakes than other lake colours because hot fluids are likely nearer the surface, emitting significant volumes of volcanic fluid and potentially interacting with lake water to produce explosive eruptions. Lake colour changes are the most easily identifiable Crater Lake observations, and are less dynamic than upwellings, suggesting that lake colour is the most useful observation parameter for identifying significant changes in magmatic activity. Although blue/blue-green lakes typically result from non-volcanic processes, observations of blue/blue-green lakes can occur when the vent area is sealed and there is a lack of volcanic input. Blocked vent conditions at low lake temperatures are uncommon but can result in hazardous unheralded eruptions, such as those in 1988 and 2007, which occurred during quiescent periods with lake temperatures < 20 °C (Christenson et al. 2010; Kilgour et al. 2010). Note that the 2007 eruption was preceded by minor volcano-tectonic earthquakes and tremor bursts which start 10 min before the eruption (Jolly et al. 2010). Therefore, no upwellings in a blue lake could indicate a potentially blocked vent system, although more data needs to be collected to support this hypothesis. A grey lake and central vent upwelling with sulphur slicks was observed in June 2021 during a low point in lake temperature, suggesting that the central vent remained open during this period of reduced volcanic

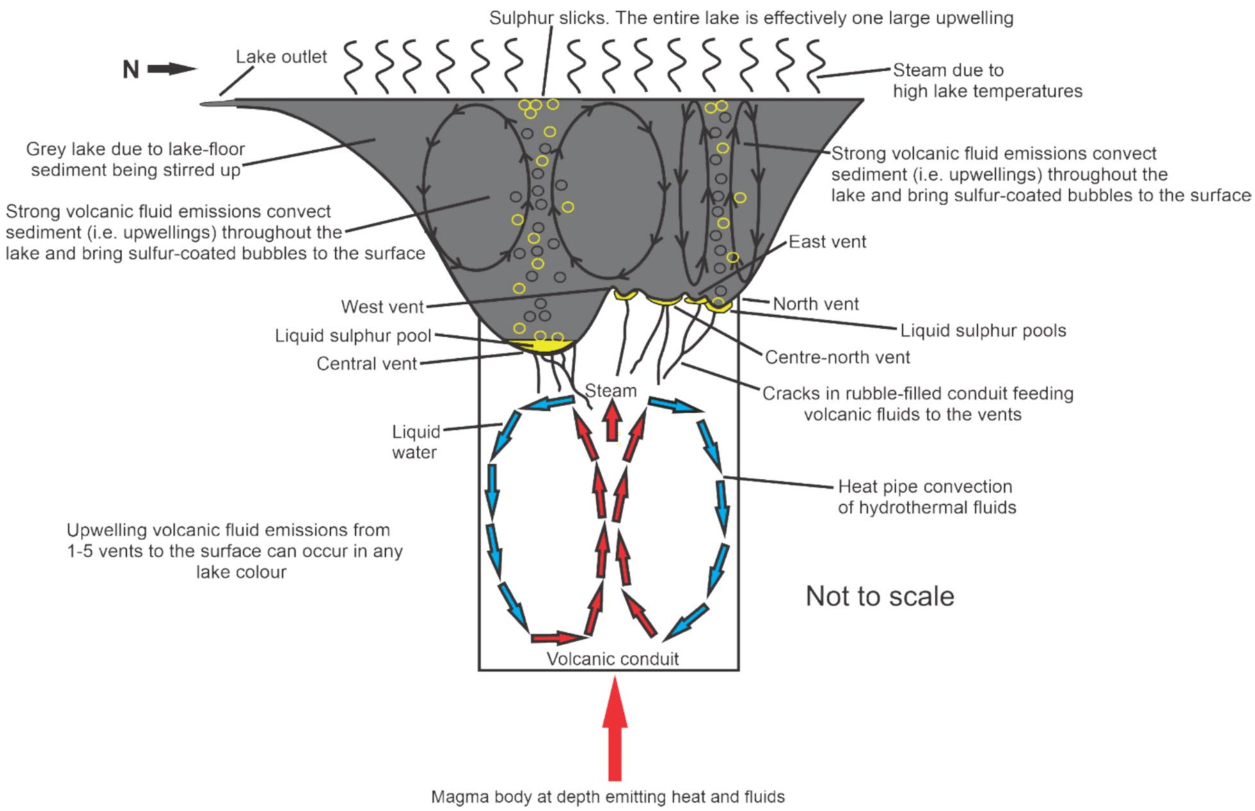

Fig. 16 Regime 1, a grey lake with steam and sulphur slicks

heat input and therefore the chances of an unheralded eruption occurring were reduced.

Crater Lake temperature before most eruptions is 39 ± 24 °C (2 S.D), which is typically higher than the average lake temperature of 27 ± 14 °C (2 S.D). There is also a minor difference in lake temperature when relating to lake colour, with grey lakes having a mean temperature of 31 ± 15 °C (2 S.D), while blue lakes had a mean temperature of 23 ± 9 °C (2 S.D). These temperature differences of 12 and 8 °C respectively, are likely due to volcanic fluid input which may occur prior to eruptions and/or alter the lake to a grey colour. However, the temperature differences are within 2 standard deviations of each other so are not statistically significant, and likely result from the complex interactions between volcanic and seasonal processes. Blue coloured lakes are much commoner in summer and autumn (76%) compared to winter (6%). This is likely caused by increased glacial and/or snow meltwater input due to higher air temperatures, and due to vertical stratification of the lake.

Vent locations have been mapped by comparing vent locations on images of the crater floor when no lake was present, with upwelling locations identified on images of the lake surface, and lake bathymetry. From this analysis five vents were found to be active in February – April 2021, compared to the identification of two vents previously. The vents are described as the central, northern, western, eastern, and central-northern vents, with the central and northern vents previously mapped. The earliest observations of eruptions, subaerial degassing, upwellings, or sulphur slicks, indicate the central vent has been active since at least 1945, the northern vent since at least 1969, the eastern vent since at least 1977, the western vent since at least 1995, and central-northern vent since at least 2021. The largest eruptions in the last 100 years at Ruapehu were in 1945, 1995, and 1996, with these eruptions observed to be from the central vent. Small phreatic eruptions have also been observed occurring above the central vent. The northern vent was observed emitting abundant sulphur slicks after the 1969 (Healy et al. 1978), and 2007 (Christenson et al. 2010) eruptions, suggesting that these eruptions were sourced from the northern vent (Kilgour et al. (2010). The western, eastern, and central-northern vents have not been observed erupting or emitting upwellings or slicks after eruptions, so it is unknown if eruptions have occurred from these three vents.

It is important to determine the locations of volcanic vents as they are the source of ballistic ejecta and other volcanic hazards (Edwards et al. 2017). This study has

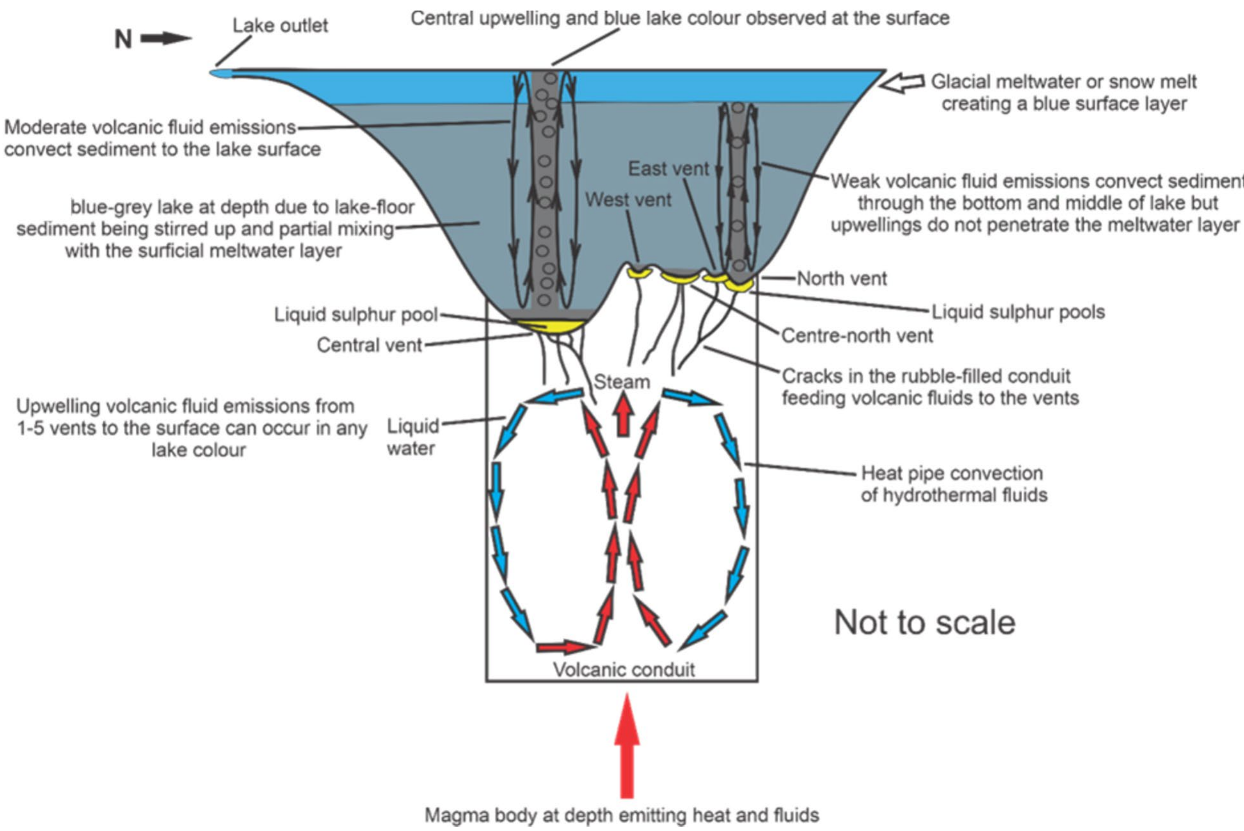

Fig. 17 Regime 2, a surficial blue lake with one visible upwelling, no sulphur slicks or steam

identified three more vents on the lake floor than previously recognised. All three vents are in the northern half of the lake, suggesting that land north of the lake is the most volcanically hazardous area on the mountain. However, the angle of the vents will also have a significant effect on the hazard of certain locations around the summit area, with previous studies showing the northern vent is inclined at an angle of between 45° and 60° (as measured from the horizontal) (Jolly et al. 2010; Kilgour et al. 2010). Comparisons between upwelling location and bathymetry suggest that the central vent is possibly inclined northwards. The hazardous area north of the lake unfortunately coincides with Dome, a natural viewpoint above the lake that is visited by thousands of tourists annually. Specifically, the volcanic hazard of viewing the lake from Dome should be communicated to hikers. Tahurangi Peak (the true summit of Ruapehu) is another vantage point used to view Crater Lake, however the mountaineering hazards associated with climbing to Tahurangi Peak from Tūroa ski field are greater than climbing to Dome from Whakapapa ski field, as the terrain is much steeper.

Visible light and infrared cameras both revealed changes to the surface of the lake. Infrared observations were inhibited by the presence of steam on the surface of the lake (Fig. 11b), and the reflection of infrared energy from surrounding rock or sky. Similar challenges were identified by the Yellowstone geothermal monitoring programme, where solar insolation could overwhelm the geothermal signal during the day. Instead, night-time infrared observations were preferable due to lower relative humidity and reduced steam. This suggests that night-time infrared imagery at Ruapehu Crater Lake may prove useful for monitoring purposes but future work is needed to investigate this. Visible light imagery allowed changes to the lake colour and any upwelling sediment and sulphur to be identified by a trained eye. Crucially, the ability to distinguish between blue-grey and grey lakes is essential to make lake observations useful for volcano monitoring. Steam and sulphur slicks were easily visible with infrared imagery, however these were also identifiable with the visible light camera. It is therefore recommended that a ground-based visible light camera is used to monitor Ruapehu Crater Lake. However, there are significant hurdles to overcome before permanent camera monitoring can occur, as Crater Lake is situated in a high-altitude environment that experiences rapid fluctuations in temperature and humidity. It is therefore suggested that semi-permanent camera deployments from January to April be undertaken when the weather is more stable and the lake is more accessible, with cameras being less likely to freeze over and batteries lasting longer. A frame rate of 1 – 5 min is recommended for future camera deployment, as upwellings can appear and disappear in < 10 min.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author's contributions
CC organised and undertook the fieldwork for this project with the aid of University of Canterbury Earth and Environment Technical Staff. CC also analysed the data and wrote the main manuscript text. BK, JC, and AN provided guidance throughout the entire project including suggestions for improvements to the methodology, analysis, and the manuscript. LW analysed the data and edited the manuscript. BC provided bathymetric data, expert knowledge, and assisted with interpreting the data. HK provided mountaineering expertise during fieldwork, facilitated communications with Department of Conservation and Ruapehu Alpine Lifts, and provided specific knowledge of the subject area. HG and JP helped define fieldwork methodology and gain permission from Ngāti Rangi to study Te Wai ā-moe, with HG supporting a DOC scholarship application. CA and KB helped undertake the fieldwork, including supplying a helicopter ride, and provided access to the GNS dataset of Crater Lake imagery. All authors have read, reviewed, and approved the final version.

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Data availability
Data supporting the conclusions of this paper can be found in the supporting material.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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