HYDROTHERMAL QUARTZ MICROTEXTURES AND DEPOSITIONAL PROCESSES REVEALED BY SEM-CL IMAGING

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SUMMARY – SEM-CL imaging of hydrothermal quartz from the Te Kopia geothermal field (New Zealand), complemented by fluid inclusion analysis, has revealed a complex history of crystal growth, dissolution and overprinting, unseen by other observational techniques. CL-dark quartz (characterised by euhedral growth zones) grew into fluid-filled space, at least 300-320 m below the present ground surface, in a $195 \pm 25°C$ reservoir. Movement on the Paeroa Fault provided pathways for fluids to move through the system, which resulted in further quartz precipitation, but SEM-CL evidence also shows that the quartz was partly dissolved, with later overprinting and void-filling by CL-bright quartz.

1. INTRODUCTION

Researchers have shown that mineral non-stoichiometry, poor crystallographic ordering, lattice defects or the incorporation of trace elements into a crystal structure can generate cathodoluminescence (CL; or luminescence of a material) of varying wavelength and intensity, which are useful for interpreting hydrothermal processes (Gotze *et al.* 2001). **As** such, CL may reveal microtextures (e.g. cryptic alteration, overprinting and microstructural evidence for crystallisation and/or deformation), which cannot be observed using other observational tools.

Interpretation of **quartz** textures seen by scanning electron microscopy-cathodoluminescence (SEM-CL), has enabled a range of geological problems to be resolved, such as: sedimentary provenance (e.g. Seyedolali *et al.* 1997), diagenetic and pressure solution processes (e.g. Schieber *et al.* 2000), nature of sandstone fracturing (e.g. Milliken and Laubach, 2000) and character of crystallization and deformation processes in granite (e.g. Muller et *al.*, 2002). SEM-CL is useful in alteration studies, by revealing CL-distinct hydrothermal quartz overprinting igneous quartz (e.g. Valley and Graham 1996), and vein formation chronology (Penniston-Dorland, 2001).

The Te Kopia geothermal field (New Zealand; Fig. 1) is located ~25 km **NNE** of Lake Taupo. Progressive uplift of parts of the geothermal system has exposed rocks that were once at least 300 m below the ground surface (Bignall and Browne, 1994). Textural and mineral overprinting in these rocks record thermal changes and information about fluid types within the former reservoir. We have used SEM-CL to characterise precipitation and overgrowth textures in hydrothermal **quartz** from the Te Kopia geothermal field. This work comprises part of a study being undertaken at Tohoku University to

understand quartz microfracturing (Hashida *et al.*, 2001) and chemical processes affecting rock permeability in deep-seated geothermal reservoirs (Tsuchiya *et al.,* 2001; Hirano *et al.*, 2002).

2. GEOLOGICAL SETTING

Surface manifestations at Te Kopia straddle the 220m scarp of the Paeroa Fault at the eastern margin of the Maroa Volcanic Centre (Fig. 2), from which several voluminous Quaternary ignimbrite sheets were erupted (now exposed at the surface, and encountered in the TK-1 and TK-2 geothermal wells). Bignall (1994) described the subsurface geology at Te Kopia, whilst
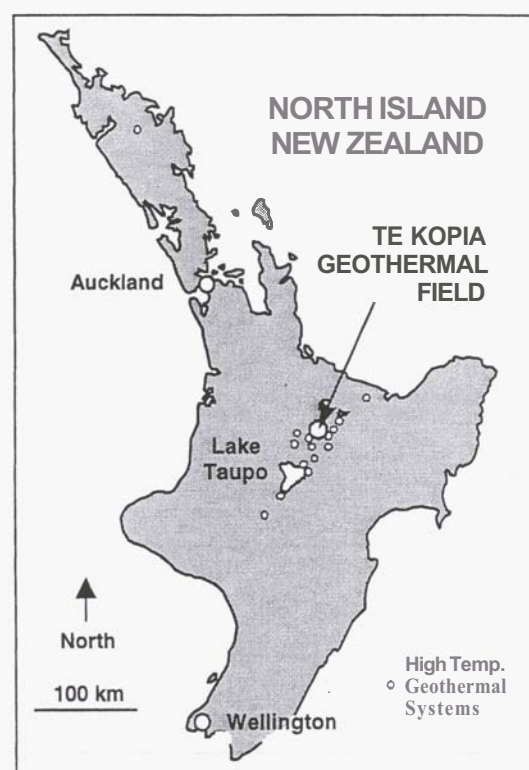

Figure 1: Location of Te Kopia geothermal field, North Island, New Zealand.

Bignall and Browne (1994), Browne *et al* (1994) and Martin *et al.* (2000) have documented thermal activity at the ground surface.

The Paeroa Fault is normal, and dips steeply to the west, with steam-heated pools, altered and steaming ground extending >2.5 **km** along its scarp. Nairn and Hull (1986) indicate the fault has moved during the last 1800 years, with the displacement rate over the last 75,000 years being –4 m/thousand years (Keall, 1987). Movement on the fault has clearly influenced the hydrology of the field, surface manifestations and hydrothermal alteration within the system (Browne *et al.*, 1994). The presence of in situ silica sinter shows that alkali chloride water discharged from hot pools (and/or geysers), possibly as recently as 1800 BP (Martin *et al.*, 2000).

Bignall (1994) reported overprinting of alteration minerals in rocks exposed on the Paeroa Fault scarp, with quartz-illite-adularia assemblages (from >250 m depth within the geothermal system) replaced by **quartz,** amorphous silica, kaolinite, cristobalite and/or alunite. Sub- to euhedral quartz crystals (up to 4.5 cm long) occur at two localities on the scarp (Fig. 2) and contain liquid-rich fluid inclusions that homogenize at 196 ± 11°C and 188 ± 15°C (<0.4 wt% NaCl equivalence). Bignall and Browne (1994) show one set of crystals (TKS-12; at 145 ± 5m RSL) grew at depths of >170 m below ground surface, and have been uplifted 315 m. The other set (TKS-10; at 180 ± 5m RSL) have ascended at least 300 m since their formation.
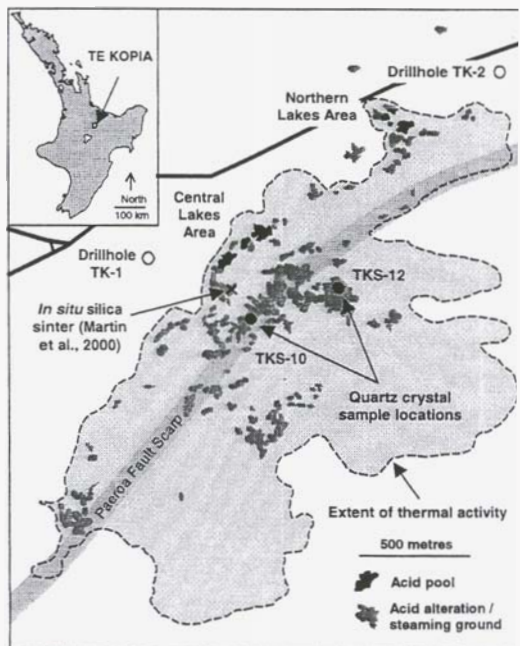

Figure **2:** Locality map, Te Kopia thermal area, showing exploratory geothermal drillholes, sinter and quartz crystal locations.

3. METHODOLOGY

Several **1–2** cm-long quartz crystals from TKS-12, on the Paeroa Fault scarp, were selected for SEM-CL imaging. Carbon coated, 100μm-thick, double polished sections were prepared: (i) through the centre of each crystal, perpendicular to the long (c-) axis and (ii) parallel to the c-axis Fig **3.**

SEM-CL images were observed using the Department of Geoscience and Technology's SEM-EDX Hitachi-S2460N scanning electron microscope, which is equipped with an Oxford Mini-CL detector and photomultiplier, and complemented by optical microscopy and fluid inclusion microthennometry (using our Linkham heating-freezing system).

The quartz thick-sections were analyzed at 15 kv with a beam current set from 10 to 30 nA (to obtain optimal contrast in observed luminosity). In **SEM-CL,** grey-scale images are produced, and apparent intensity of luminescence depends on
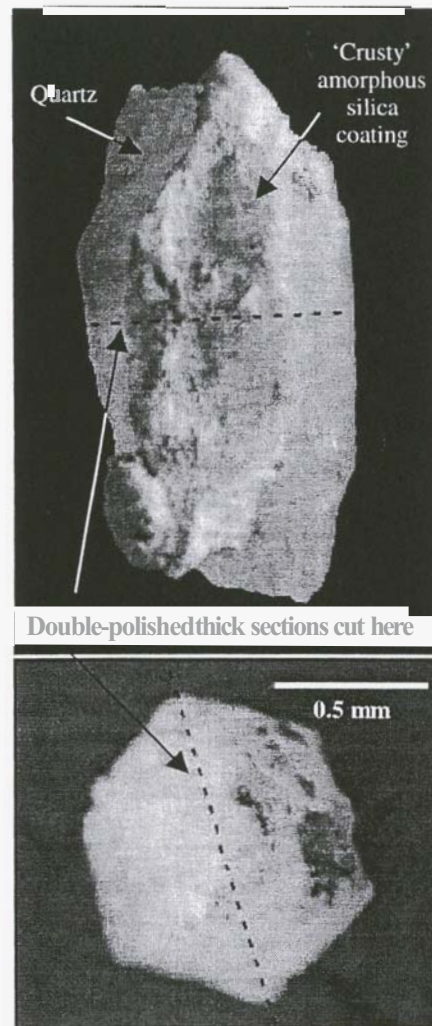

Figure 3: Two views of a quartz crystal, used for SEM-CL, from Te Kopia **(TKS-12;** see Fig. 2).
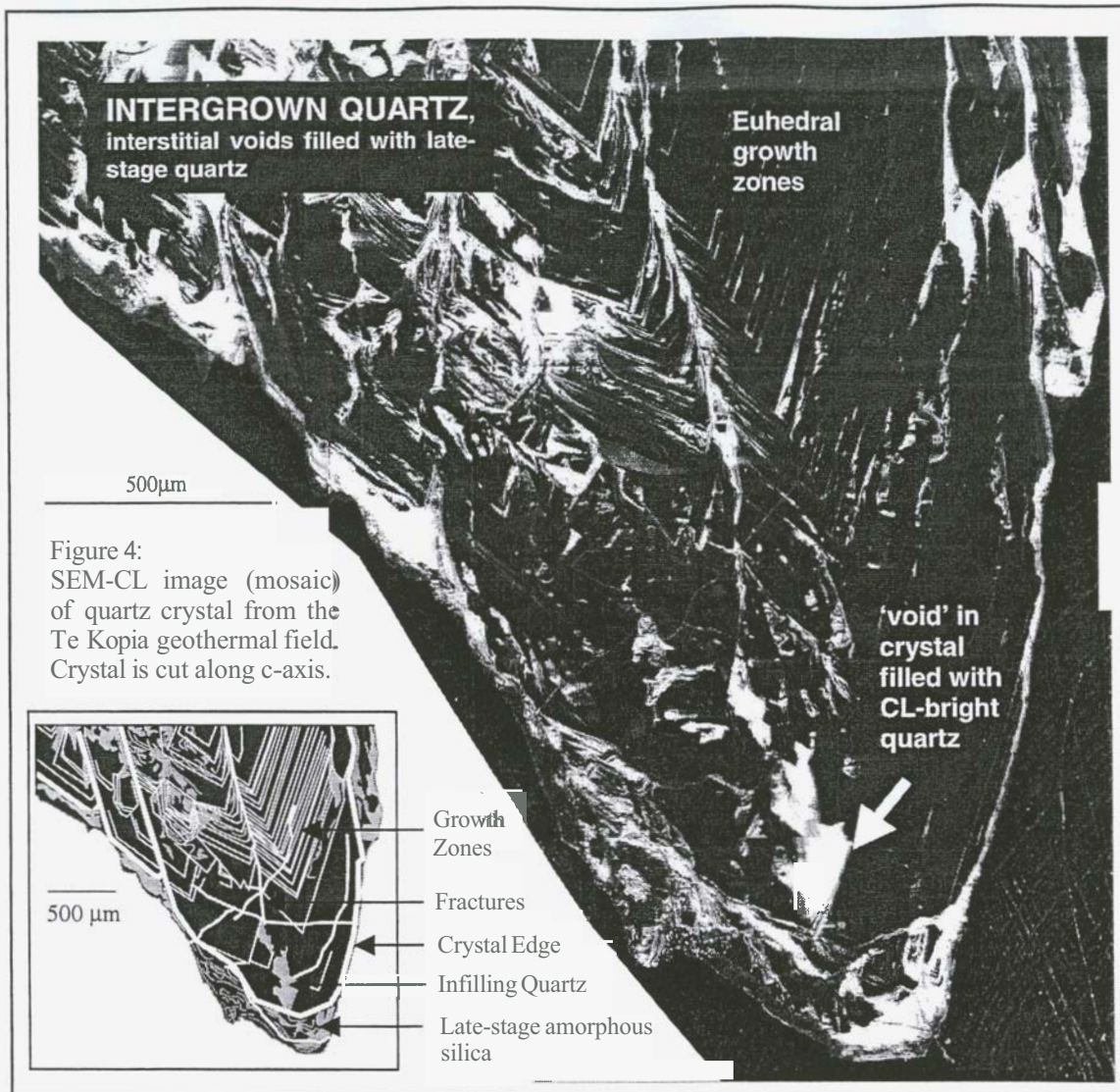
Figure 4:
SEM-CL image (mosaic) of quartz crystal from the Te Kopia geothermal field. Crystal is cut along c-axis.

the machine operating conditions, i.e. beam current, acceleration voltage, photomultiplier contrast and brightness, carbon coat thickness and sample-detector distance. Since absolute intensity is not readily quantifiable, we refer to CL luminescence intensity as "CL-dark", "CL-grey" or "CL-bright".

The SEM-CL technique is particularly suited for observing minerals with weak luminescence (e.g. quartz), due to its high spatial resolution and range of beam currents/acceleration voltages. Processed SEM-CL images may reveal growth textures, dissolution along crystal edges, and precipitation into open space, that aid interpretation of water-rock interactions in the geothermal setting.

4. SEM-CL IMAGING

Petrographic examination showed that Te Kopia quartz crystals are fractured, and partly covered by a crusty, amorphous "silica residue" coating. Transmitted light microscopy, however, reveals no other distinguishing features. SEM-CL, on the other hand, indicates that the quartz crystals have

a complex history of formation. SEM-CL imaging shows most of the quartz has low (CL-dark) intensity luminescence, but in places precipitated alternating CL-dark and CL-bright growth zones (Figs. 4 and 5). In addition, SEM-CL also shows that the crystals are fractured, partly dissolved (at the crystal edge and along fractures), and later precipitated CL-bright quartz into fracture/open spaces and CL-grey/bright amorphous silica residue onto the crystal surface.

Electron back-scattered and transmitted light images do not reveal the generations of quartz growth evident in SEM-CL, and instead the quartz appears to be crystallographically continuous.

The concentric growth zones seen in Figs. 4 and 5, have a euhedral form, comprising alternating bands of CL-dark and narrower CL-bright zones, of variable intensity. In addition, CL-bright quartz, of a later crystallisation phase infill open space in the CL-dark quartz. In places, the CL-dark quartz is enveloped by CL-bright quartz
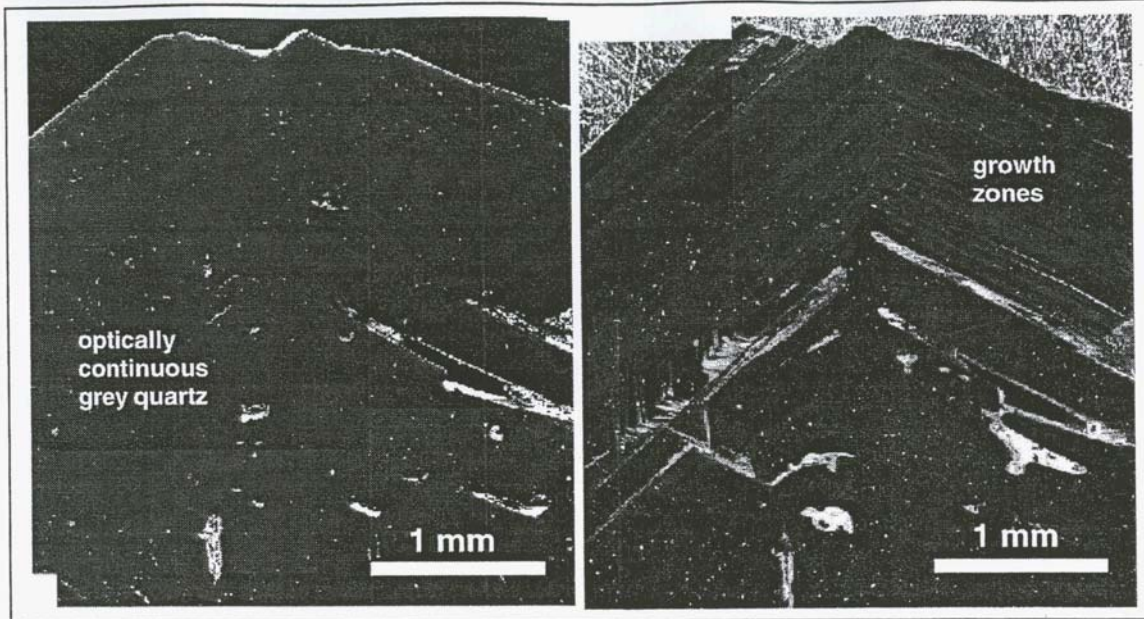
Figure 5: Back-scattered electron mosaic (a) and SEM-CL image (b) of a quartz crystal from the TKS-12 locality. Euhedral growth zones, containing fluid inclusions (Table 1) are only revealed by SEM-CL.

overgrowths. The textures indicate dissolution along fracture/grain boundaries and precipitation of late-stage quartz into open space.

Back-scattered electron and SEM-CL images of a quartz crystal, cut square to the c-crystal axis, are shown in Fig. **5**. The SEM-CL mosaic reveals microtextural evidence of two stages of crystal growth, which are likely to have occurred at different temperature-pressure conditions, whilst the back-scattered image is optically continuous. The central part of the crystal is composed of CL-dark quartz, and inferred to have grown under stable physico-chemical conditions within the Te Kopia geothermal reservoir. A **1.2** to 1.5 mm zone at the edge of the crystal is composed of alternating micron-scale bands of CL-dark and CL-bright quartz, which precipitated during a later period of crystal growth, possibly coinciding with uplift of the Paeroa Fault Block.

Textural relationships indicate that the quartz crystals precipitated into open space, and that they were later fractured and partially dissolved. Remobilisation of silica species, and subsequent quartz precipitation, resulted in CL-bright quartz overprinting the original CL-dark quartz (e.g. Fig. 8). In places, CL-dark and CL-bright quartz form **a** discontinuous pattern (e.g. Fig. 6), with irregular boundaries against the CL-grey zoned quartz, although their mode of formation is uncertain.

Recrystallization of quartz is indicated where CL-bright quartz is seen to overprint CL-dark quartz (Fig. 7). Change in luminescence intensity may result from element diffusion, in response to chemical gradients between the quartz and the hydrothermal fluid (Penniston-Dorland, 2001). Thin fractures, filled with CL-bright quartz,

irregularly cut the host quartz crystal, and post-date all other quartz generation phases (except the crusty, crystal-covering amorphous silica). The physical fracturing that took place underlines
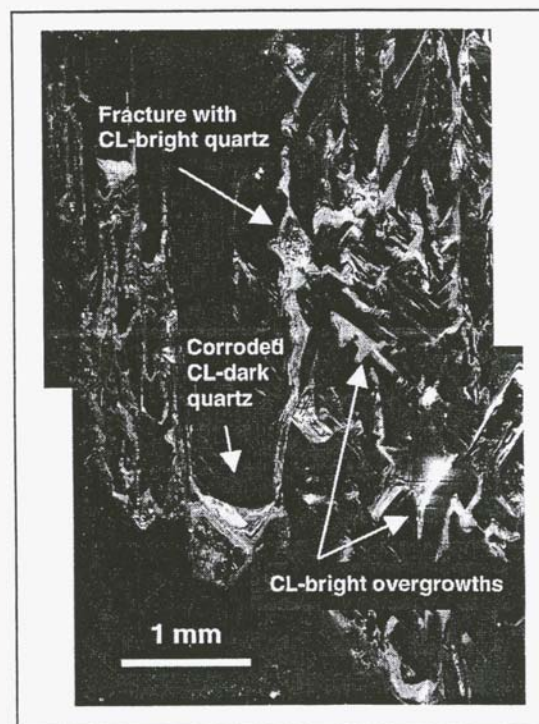

Figure 6: SEM-CL mosaic of Te Kopia quartz (from TKS-12), showing growth zoned, partly corroded CL-dark quartz, with CL-bright quartz overprinting (see also, Fig. 7), adjacent to a CL-bright quartz-filled fracture, and a zone of discontinuous, irregularly patterned CL-dark and CL-bright quartz.

the complex history of repeated microfracturing, and resealing (through quartz deposition) that occurred during crystal growth.

5. FLUID INCLUSION STUDY

Fluid inclusion data for quartz crystal samples from Te Kopia (Bignall, 1994; Bignall and Browne, 1994) has been re-assessed, in light of our SEM-CL imaging, and analysis of additional doubly polished, quartz thick-sections, with new results summarised in Table 1.

Table 1: Fluid inclusion microthermometric data for quartz crystal samples from Te Kopia (see Fig 2 for sample locations; Tohoku University (T.U.) analyses are from a crystal at TKS-12.

Sample	Range of T_m measurements (°C, mean)	Number of T_h measurements	Range of T_h measurements (°C, mean)
TKS-10	-0.2 to –0.1 (-0.1)	25	165 – 203 (188.6)
TKS-12	Not measured	14	185 – 205 (195.6)
T. U.* (core)	-0.1	13	209 – 247 (213)
T. U.* (growth zone)	Not measured	16	168 – 248 (210)
T. U.* (frac)	Not measured	5	194 – 209 (201)

* Previously unpublished data

Fluid inclusions analysed from TKS-10 and TKS-12 (Bignall, 1994) have a narrow range of T_h values (± 15°C), about 20°C lower than inclusions analysed during this study (from the core of the quartz crystal seen in Fig 3 - with the exception of one high T_h fluid inclusion). In contrast, fluid inclusions analysed from the 'growth zone' region have a wide (80°C) range of T_h values, although the mean T_h value is similar to data from the non-zoned crystal core. In other respects, the dilute, primary, liquid-type fluid inclusions (up to 150μm long), including some secondary inclusions from a crosscutting fracture, exhibit little variation.

6. DISCUSSION

Our SEM-CL study reveals microtextures in Te Kopia quartz that are unobservable by transmitted or reflected light microscopy, backscattered electron imaging or secondary electron imaging.

Integration of SEM-CL and petrographic studies aid the correlation of fluid inclusion populations (and their relative chronology) with specific hydrothermal events. SEM-CL may "fingerprint" the quartz; it is useful tool in relating fluid inclusions to a corresponding alteration stage, and

invaluable for understanding the temperature-pressure and chemical evolution of the hydrothermal system.

An inference, based on 1992-94 fluid inclusion data, that the eastern part of the Te Kopia thermal area had been uplifted at least 300 m since the quartz crystals formed (Bignall and Browne, 1994) is valid. However, the uplift history of the quartz is more complicated than envisaged, with distinct stages of mineral precipitation and dissolution now recognized (partly obscuring textural relations in the original quartz).

CL-dark quartz crystals initially grew into fluid-filled space, under hydrostatic conditions within the Te Kopia geothermal system, at least 300-320 m below the present ground surface, in a 195 ± 25°C liquid-reservoir. Repeated movement on the Paeroa Fault uplifted rocks hosting the quartz crystals and provided fluid pathways for pulses of hot reservoir fluids to move through the system, leading to further quartz precipitation (marked by euhedral growth zones, and fluid inclusions with a wide range of T_h values – but similar salinities), and infilling of open spaces, by CL-bright quartz. As well as crystal *growth* textures, **we** find SEM-CL evidence of partly *dissolved* CL-dark quartz (e.g. Fig. 7), with subrounded or corroded crystal edges, as a result of the quartz being out of chemical equilibrium with reservoir fluids, and
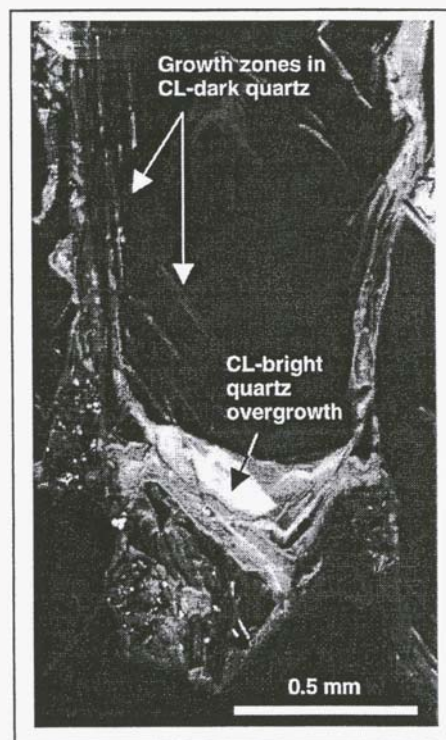

Figure 7: SEM-CL image of corroded, CL-dark quartz, with truncated euhedral growth zones, marked by CL-bright quartz overprinting.

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subsequent overprinting/replacement by CL-bright quartz, as the crystals were brought towards the surface. Low pH fluids in the near-surface setting have also acted to round the quartz crystals, and coat them with amorphous "silica residue"

7. CONCLUSIONS

SEM-cathodoluminescence (SEM-CL) is widely used by geoscientists to reveal microtextures in minerals that are not observable by any other method of observation. SEM-CL can reveal chronologic and physical relations in quartz that may have precipitated in a vein, and facilitate differentiation between multiple stages of hydrothermal alteration (or mineralization).

SEM-CL textures of quartz from Te Kopia has distinguished cryptic alteration, recrystallization, and fracturing, following initial crystal growth into fluid-filled space within the Te Kopia geothermal reservoir, and later uplift and exposure in the near surface/surface geothermal setting.

8. ACKNOWLEDGMENTS

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