Collapse structures of an eroded maar/diatreme volcanic field from Central Otago, New Zealand: The Crater as an example

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Abstract

The pyroclastic rocks of "The Crater", South Island, New Zealand belong to the Miocene, alkaline basaltic Dunedin Volcanic Group and represent an individual eruptive center with possible multiple vents. Three pyroclastic units have been separated at the study area based on textural and compositional features as well as their stratigraphic positions. The central part of The Crater comprises basal accidental lithic rich tuff breccias and unsorted, weakly bedded lapilli tuffs inferred to have been deposited by "en masse" deposition of fall back tephra and/or high concentration pyroclastic density currents from vent opening phreatomagmatic explosions, near vent. The unit subsequently subsided into the conduit. Above this unit, is a juvenile rich lapilli tuff deposited near vent by high-concentration pyroclastic density currents. These pyroclastic density currents were generated by phreatomagmatic explosions occurring at shallow levels, which did not excavate significant amounts of subsurface strata. In the western side of the area a large and complex crater rim sequence has collapsed into the vent. The rim exhibits a pyroclastic sequence developed by phreatomagmatic explosion generated pyroclastic density currents of decreasing energy and efficiency followed by magmatic explosion generated fall-out. Accidental lithic fragments in the pyroclastic beds are derived from pre-volcanic strata that are not now preserved in the vicinity of The Crater but which are inferred to have been present at the site at the time of eruption. be existing in the area during the volcanism. Calculating the total erosion since the volcanism an average of 30 m/My erosion rate is implied.

Introduction/geological setting

"The Crater", named for its circular tuff ramparts surrounded by schist, is an approximately 1 km long and 700 m wide depression, partially filled with pyroclastic rocks and cross-cutting dykes and/or sills, on the Otago Schist peneplain.

The pre-volcanic Cenozoic stratigraphy near the study area can be characterized by a series of non marine and marine clastic sediments (Youngson and Craw, 1996) deposited on an early Cretaceous erosional surface (LeMasurier and Landis, 1996) of a schist basement (Otago Schist). The oldest terrestrial clastic sediments deposited on the schist surface form the Hogburn Formation. Widespread marine transgression followed Late Cretaceous extension and separation of New Zealand from Gondwana (Carter, 1988) causing widespread marine clastic sedimentation in the area (Oligocene marine sequence). The area probably reemerged in the early Miocene in response to transpressional tectonics with the inception of the Alpine Fault (Cooper et al., 1987), with renewed terrestrial clastic deposition (fluvio-lacustrine) taking place (Dunstan Formation).

Most of the Cenozoic sedimentary sequence has eroded away especially in uplifted areas (LeMasurier and Landis, 1996). Volcanic eruptions took place in late Miocene time (Dunedin Volcanic Group: Coombs et al., 1986) along hydrologically active zones producing widespread phreatomagmatic maar/diatreme volcanism with extensive Strombolian scoria cone and lava flow forming eruptions. Most of the eruptive centers are strongly eroded to their root zones where downdropped sequences of pre-volcanic and former crater rim rocks can be identified. These entrapped blocks of pre-volcanic rocks in the conduits of eruptive centers provide important indications of the former lateral distribution of the pre-volcanic sedimentary units.

The lack of any Cenozoic sedimentary rocks cropping out around The Crater, together with the presence of Cenozoic sedimentary rocks as fragments in the pyroclastic rocks, suggests that 1) the Cenozoic cover either exists beneath the volcanics or 2) the fragments represent slide blocks and clasts from the former conduit wall of The Crater vent(s). Field observations presented in this paper eliminate the first possibility, since there is no reason for a small, sediment-filled, Cenozoic basin to exist on the surface of the schist basement. Support for the second possibility is presented in this paper based on characteristics of the pyroclastic lithofacies associations together with the calculated inferred erosion rate of the study area.

Volcanic units of The Crater

Lithic rich basal unit (LRU)

Description This unit is the lowermost in The Crater pyroclastic succession and it is composed of thick, weakly defined structureless beds of coarse-grained, accidental lithic rich lapilli tuff and tuff breccias. In lower levels of exposure, tuff breccias are common; they grade continuously upward into lapilli tuff beds. Individual beds are a few tens of centimetres thick. The beds are unsorted and non-graded with clasts from cm to dm size. Locally large (1.5 m long) elongate schist fragments are present. Rounded marine sandstone clasts up to 30 cm in diameter are common. Smaller (a few cm) schist fragments are angular and do not exhibit any preferred orientation; they seem to be dispersed homogeneously in a yellowish, quartzofeldspathic sand grain rich matrix inferred to be derived from the Tertiary marine deposits. Large juvenile fragments are rare, but a few scoriaceous and dense crystalline lava fragments are present. There are no impact sags under clasts. The dominant proportion, up to 60 % by visual estimate, of the total volume of rocks of this unit consists of accidental lithic clasts. Around 35 % of the total volume of the rocks are glass fragments, with a sideromelane to tachylite ratio of 7 to 3. The sideromelane glass shards are microvesicular with semirounded, spherical or slightly elongate shapes. Sideromelane glass shards are fresh, often with palagonitized rims.

Interpretation The unsorted, weakly or massive bedded, coarse-grained texture and the presence of angular volcanic glass fragments suggest a primary phreatomagmatic explosive origin for the unit. The presence of dominant sideromelane glass shards suggests magma/water interaction controlled the fragmentation of magma (Heiken, 1972; Heiken, 1974; Fisher and Schmincke, 1984). Abundance of accidental lithic clasts and their heterogeneous composition suggest that they were derived from the underlying strata by subsurface phreatomagmatic explosions, which efficiently fragmented the entrained country rock adjacent to sites of interaction. The massive lapilli tuff and tuff breccia most likely result from rapid deposition of a near-vent high concentration particulate pyroclastic density current generated by a collapsing hydromagmatic eruption column (Sohn and Chough, 1989; White, 1991). The absence of scouring or channeling indicates that the pyroclastic density currents were depositional (Sohn and Chough, 1989). LRU is a conduit filling pyroclastic unit formed by initial maar-forming, vent opening phreatomagmatic explosions that generated near vent high-concentration pyroclastic density currents and "en masse" fall back of tephra.

Bedded crater rim basal unit (BCR-a)

Description This unit is overlain by the BCR-b unit and crops out in the western and southern side of the study area. The unit consists of fine-grained, bedded, cross-bedded yellow tuff and lapilli tuff beds interbedded with coarse-grained, weakly-bedded to massive yellow lapilli tuff. The lapilli tuffs and tuffs consist of well-cemented, thin-bedded, ungraded or normally graded, laterally continuous beds. Low angle cross bedding and filled scours are common in the fine-grained part of the unit. The coarse grained part of the unit consists of thickly bedded, ungraded or weakly normal-graded lapilli tuff beds. Impact sags are not present. In general, both the fine and coarse grained beds of the unit are rich in accidental lithic clasts (up to 60 vol. % of total volume). Accidental lithic fragments are angular quartz grains, aggregates of quartz and mica derived from schist, and large amounts of rounded glaucony grains derived from Tertiary marine strata. Volcanic glass shards in each bed of the unit are predominantly angular, fresh sideromelane glass shards with rounded, slightly elongate microvesicles. Microlites in the glass shards are rare. Tachylite is not more than a few percent of the total volume of volcanic glass in the beds of this unit. Fossils are occasionally present, including foraminifera (Globigerinoides sp.), Echinoidea spicules, and Mollusc shell fragments.

Interpretation The thinly bedded tuff probably results from strong fragmentation of magma due to water magma interaction (Wohletz, 1986). The cross-laminated, fine-grained beds are indicative of deposition from low-concentration pyroclastic density currents rather than fall out. The thickly bedded, massive to weakly normal-graded lapilli tuff beds most likely result from rapid deposition from high-concentration pyroclastic density currents. The usual repeated couplets of coarse/massive - fine/bedded bed sets indicate deposition by passing pyroclastic density currents generated by repeated magma/water interaction. The relatively uniform westward dipping bedding suggest that this unit is part of a larger collapsed and inward subsided crater rim sequence. This unit represents an early stage of the development of tuff rampart around a maar/diatreme volcano which rim was subsequently collapsed into the conduit of a maar volcano.

Bedded crater rim capping unit (BCR-b)

Description This unit caps a larger, bedded, uniformly westward dipping pyroclastic sequence cropping out in the western side of the study area. This unit consists of a series of matrix-supported, spindle bomb rich lapilli tuff beds in the lower part and a more scoriaceous fragment-rich lapilli tuff in the upper part of the unit. The unit is underlain by accidental lithic rich lapilli tuff and tuff beds (BCR-a).

The lower part of BCR-b consists of well-cemented, weakly or thickly bedded ungraded lapilli tuffs with undulating, but laterally continuous upper and lower bed surfaces. The beds are moderately sorted and non-graded. Large clasts are fluidal shaped spindle bombs up to 1.5 m in diameter. Impact sags are not present. Weak low angle cross bedding in a bedded part of the unit is common, with scoriaceous scour fills. The matrix of the lapilli tuffs is dominantly (65 vol. %) volcanic glass, sideromelane (60 vol. %) and tachylite (40 vol. %). Accidental lithic clasts are dominantly schist derived quartz aggregates and mica, or rounded glaucony grains derived from Tertiary marine strata.

The upper part of the BCR-b consists of clast-supported, scoriaceous lapilli tuff beds. Elongate, irregularly shaped spindle bombs and ropy lava fragments in a red and black scoriaceous matrix give the dominant proportion of the individual beds. The beds are usually a few tens of centimetres thick, laterally continuous with sharp upper and lower bedding surfaces. Accidental lithic clasts are rare (max. 15 vol. %), and comprise inferred to be derived from schist or Tertiary marine strata.

Interpretation The matrix supported, thickly bedded, weakly cross bedded, non-graded, unsorted characteristics of the lower part of the unit with large spindle shape bombs suggest deposition in a near-vent position from a high concentration pyroclastic density current. The lack of impact sags even under large spindle shaped bombs suggests a high competence, highly viscous transporting current able to support large, probably originally ballistically delivered, bombs and clasts. The presence of angular sideromelane glass shards indicates magma/water interaction during fragmentation. The continuous transition of these beds into the upper, scoriaceous lapilli tuffs suggests either 1) a continuous drop of water supply to fuel magma/water interaction and/or 2) increasing magma flux, both leading to a Strombolian phase of eruption. This unit represents a late stage in the development of a tuff rampart around a maar-diatreme volcano; this rampart subsequently collapsed into the conduit of the maar.

Juvenile-rich central unit (JRU)

Description This unit is located in the central part of The Crater pyroclastic succession and overlies the basal lithic rich unit (LRU), but the contact is not exposed. The unit consists of well-cemented, weakly- and thickly bedded ungraded, coarse-grained, juvenile rich lapilli tuff interbedded with thin sets of fine-grained tuff. Bed thickness varies greatly, from a few cm to a few metres. Both the lapilli tuff and tuff beds are poorly to moderately sorted, non-graded or weakly normal graded, and consist predominantly of fresh, slightly microvesicular sideromelane and a small amount of tachylite glass shards. Clasts larger than 5 cm are rare, and are usually accidental lithic clasts (schist), up to 5 cm in the lower section, and large pyroxene megacrystals and mineral aggregates. Where bedding is well developed undulatory upper and lower bedding surfaces are present. In general, beds are laterally continuous, though their dip directions and values change greatly. Bedding is better developed in the lower section than in the top. Rare impact sags (1-5 cm deep) produced by 5-10 cm angular basaltic fragments are present in the lower section. Erosion surfaces, scour fillings and stringers of scoriaceous clasts are common features and more characteristic of the upper section. Spindle bombs are not present in this unit. Low angle cross bedding is characteristic and usually marked by undulatory tuff layers. The total juvenile fragment population varies between 60-80 vol. %. The juvenile fragments are predominantly sideromelane shards (75 vol. % of total juvenile fragments). Both the sideromelane and tachylite glass shards are angular. Highly fluidally shaped sideromelane glass shards are common. Accidental lithic clasts include abundant small polycrystalline, metamorphic quartz, broken feldspar and mica derived from underlying Otago schist. Rounded, shiny quartz pebbles are rare, and believed to be derived from the Hogburn Formation. Small bodies of finely dispersed silty mud give a slightly yellow appearance to the unit. Fragments of Tertiary marine sandstone are rare, but quartz sand grains and quartzofeldspathic silt form a significant amount of the matrix. Fossils are occasionally present, including foraminifera (Globigerinoides sp.). Large (mm scale) rounded glaucony grains derived from marine strata are common.

Interpretation The poor- to moderate sorting, the weakly to low angle cross bedding of the lapilli tuff and tuff with a dominantly angular sideromelane fragments is consistent with a primary, phreatomagmatic explosive origin for the unit. The angular, vesicle poor glass fragments are believed to originate by sudden chilling and fragmentation of magma upon contact with ground or surface water (Heiken, 1972; Heiken, 1974; Lorenz, 1975; Lorenz and Zimanowski, 1984). The variable shape of the sideromelane glass can indicate variable interaction of erupting magma with available water (White, 1996). The mix of tachylite and sideromelane pyroclasts with palagonitized pyroclasts suggests recycling (White, 1991; Houghton and Smith, 1993). The presence of accidental lithic clasts in beds suggests sub-surface explosion and excavation of the volcanic conduit (Lorenz, 1986). The relatively low ratio of accidental lithic clasts to total volume of the beds, in contrast to beds of LRU suggests a clearer and/or more stable state of the conduit walls, so that large blocks of pre-volcanic strata only occasionally collapsed into the "explosion chamber" and contributed a lesser amount to the ejected material.

The unsorted, massive or weakly bedded, scour-fill bedded, weakly normal graded beds of the unit suggest deposition by high concentration pyroclastic density currents, probably in a near vent position. The low angle cross-bedded tuffs with undulating upper and lower bed surfaces suggest deposition by low concentration pyroclastic density currents (e.g. Colella and Hiscott, 1997; Druitt, 1998). The entire unit is probably a part of a collapsed crater rim sequence which slid, after the BCR-a and BCR-b units into the conduit during formation of a maar volcano. This interpretation is based on the circular inward dip directions of the large blocks in the top-section of The Crater.

Conclusion

The 3 units of pyroclastic rocks at The Crater represent a complex history of phreatomagmatic to magmatic explosive eruptions and subsequent collapse and subsidence of bedded crater rim sequences (Figs 2 & 3). The BCR-a and BCR-b units represent a continuous sequence of crater rim deposits developed dominantly by pyroclastic density currents that formed due to subsurface magma/water interactions in the initial stage (BCR-a). The last stage of the eruption was characterized by increasing magmatic fragmentation resulted in scoriaceous capping beds (upper part of BCR-b). In the central part of the study area, a basal tuff breccia and lapilli tuff unit represents an early vent-opening stage of the eruption that formed accidental lithic rich, coarse-grained pyroclastic beds due to subsurface phreatomagmatic explosions (LRU). In the top section of the central part of the study area juvenile rich lapilli tuff beds indicate deposition by high-concentration pyroclastic density currents from subsurface phreatomagmatic explosions (JRU). The beds of this unit very likely represent late, inward subsided blocks of near-vent pyroclastic units (Figs 3 & 4). In general, the pyroclastic rocks of The Crater largely consist of different inward subsided former crater rim sequences (BCR-a, BCR-b and JRU) "mixed" with conduit filling "en masse" fall back tuff breccias (LRU). The presence of accidental lithic fragments from the Hogburn Formation and Tertiary marine strata indicate that the conduit of The Crater must have cut these sequences, thus they must have existed at the study area during volcanism (Fig 3).

In general, thickness of Hogburn formation varies greatly, between a few tens of metres up to few hundred metres in former valleys. Very likely the maximum thickness of this formation was no more than 100 m around the study area (J. Youngson pers. com 2000). Thickness of Tertiary marine units tends to be a few hundred metres. The study area is believed to have been covered with a no more than 200 m of marine strata (J. Youngson pers. com 2000). This indicates that at least 300 m of erosion has occurred at the study area. Considering that the diatreme already represents a relatively advanced stage of an erosion, exposing the middle section of a diatreme pipe with inward-subsided former crater rim sequences, it is inferred that at least a few tens of metres of schist have been eroded away as well (Figs 3 & 4). Assuming 100 m erosion of the schist since volcanism, a total of ~400 m of erosion is inferred at The Crater. Taking an age of 15 to 12 Ma for the volcanic rocks of The Crater (after assuming similar age of The Crater then other volcanic centers in Central Otago using available age data from other places then The Crater after e.g. Coombs et al., 1986) an average 30 m/My erosion rate is implied. This erosion rate is of the order expected for continental temperate climates (few tens of metres per My) (Walker, 1984; Karátson, 1996; Karátson, 1999; Németh and Martin, 1999;) but higher than previous calculation (8 m/My) for areas, which have a relatively mild climate (Wellman, 1984; Bishop, 1985).

References

Bishop P (1985) Southeast Australian late Mesozoic and Cenozoic denudation rates: a test for late Tertiary increases in continental denudation. Geology 13: 479-482.

Carter RM (1988) Post-breakup stratigraphy of the Kaikoura Synthem (Cretaceous-Cenozoic), continental margin, southeastern New Zealand. NZ J Geol Geophys 31: 405-429.

Colella A, Hiscott RN (1997) Pyroclastic surges of the Pleistocene Monte Guardia sequence (Lipari Island, Italy): depositional processes. Sedimentology 44: 47-66.

Coombs DS, Cas RA, Kawachi Y, Landis CA, McDonough WF, Reay A (1986) Cenozoic Volcanism in North, East and Central Otago. In: IEM Smith (Editor), Cenozoic Volcanism in New Zealand. Roy Soc NZ Bull pp. 278-312.

Cooper AF, Barreiri BA, Kimbrough DL, Mattinson JM (1987) Lamprophyre dyke intrusion and the age of the Alpine Fault, New Zealand. Geology 15: 941-944.

Druitt TH (1998) Pyroclastic density currents. In: Gilbert JS,Sparks RSJ (ed) The physics of explosive volcanic eruptions. London Geol Soc 145: 145-182.

Fisher RV, Schmincke H-U (1984) Pyroclastic Rocks. Springer, Heidelberg, 474 pp.

Heiken GH (1972) Morphology and petrography of volcanic ashes. Geol Soc Am Bull 83: 1961-1988.

Heiken GH (1974) An atlas of volcanic ash. Smithsonian Earth Science Contributions 12: 1-101.

Houghton BF, Smith RT (1993) Recycling of magmatic clasts during explosive eruptions: estimating the true juvenile content of phreatomagmatic volcanic deposits. Bull Volcanol 55: 414-420.

Karátson D (1996) Rates and factors of stratovolcano degradation in a continental climate: a complex morphometric analysis for nineteen Neogene/Quaternary crater remnants in the Carpathians. J Volcanol Geotherm Res 73: 65-78.

Karátson D (1999) Erosion of primary volcanic depressions in the Inner Carpathian Volcanic Chain. Z Geomorph 114 Suppl-Bd.: 49-62.

LeMasurier WE, Landis CA (1996) Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand. Geol Soc Am Bull 108(11): 1450-1466.

Lorenz V (1975) Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. Phys Chem Earth 9: 17-27.

Lorenz V (1986) On the growth of maars and diatremes and its relevance to the formation of tuff rings. Bull Volcanol 48: 265-274.

Lorenz V, Zimanowski B (1984) Fragmentation of alkali-basaltic magmas and wall-rocks by explosive volcanism. Annales Sci Uni Clermont-Fd.II 75: 15-25.

Németh K, Martin U (1999) Late Miocene paleo-geomorphology of the Bakony-Balaton Highland Volcanic Field (Hungary) using physical volcanology data. Z Geomorph N.F. 43(4): 417-438.

Sohn YK, Chough SK (1989) Depositional processes of the Suwulbong tuff ring, Cheju Island (Korea). Sedimentology 36: 837-855.

Walker GPL (1984) Downsag calderas, ring faults, caldera sizes, and incremental caldera growth. J Geophys Res 89(B10): 8407-8416.

Wellman HW (1984) The Alpine Fault, New Zealand, near Milford Sound and to the southwest. Geol Mag 121: 437-441.

White JDL (1991) Maar-diatreme phreatomagmatism at Hopi Buttes, Navajo Nation (Arizona), USA. Bull Volcanol 53: 239-258.

White JDL (1996) Impure coolants and interaction dynamics of phreatomagmatic eruptions. J

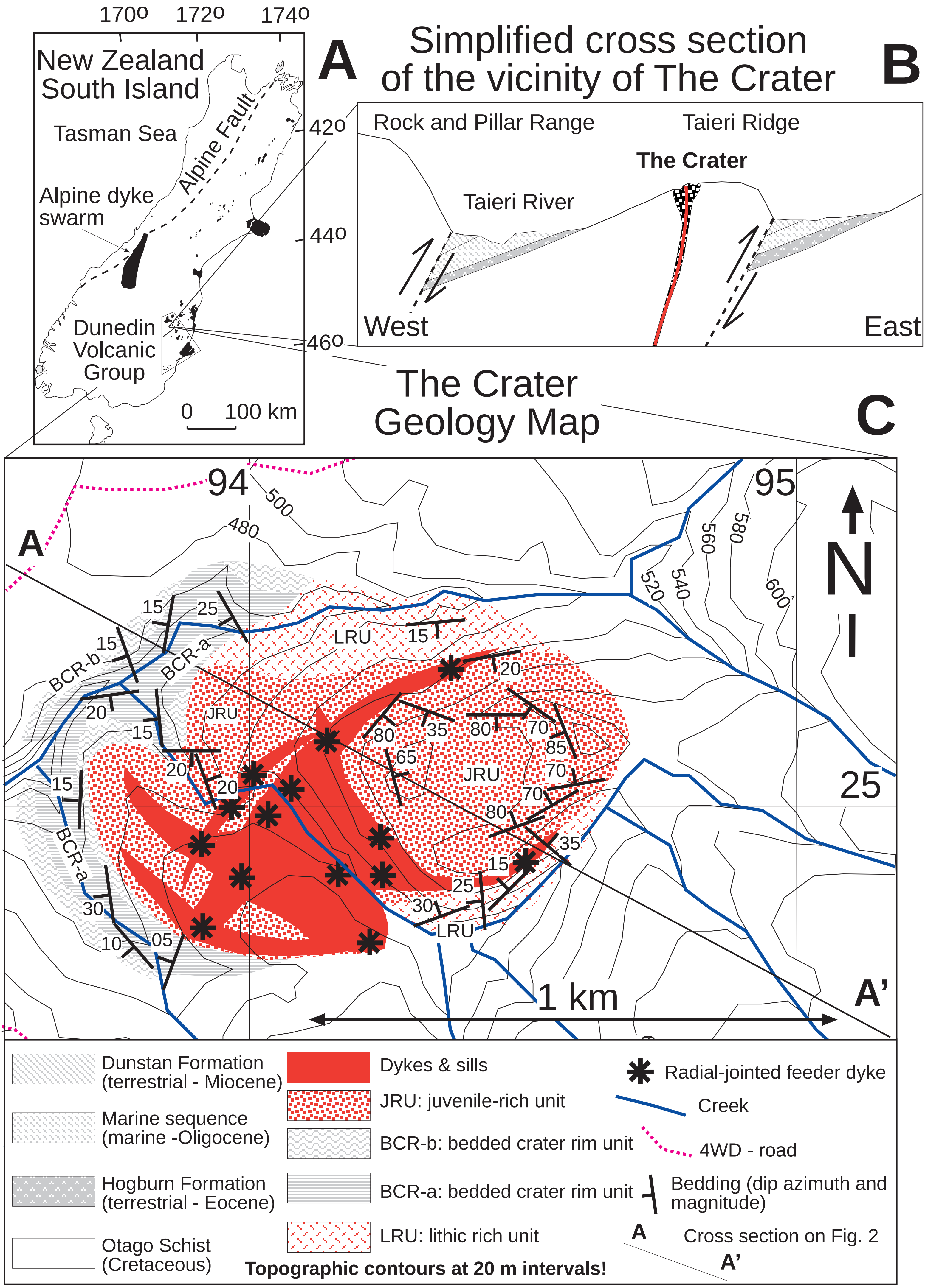
Volcanol Geotherm Res 65: 1-17.
Wohletz KH (1986) Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies. Bull Volcanol 48: 245 - 264.
Youngson JH, Craw D (1996) Recycling and chemical mobility of alluvial gold in Tertiary and Quaternary sediments, Central and East Otago, New Zealand. NZ J Geol Geophys 39: 493-508.

Figure 1 Geology map of The Crater. Coordinates are New Zealand Grid Reference numbers!

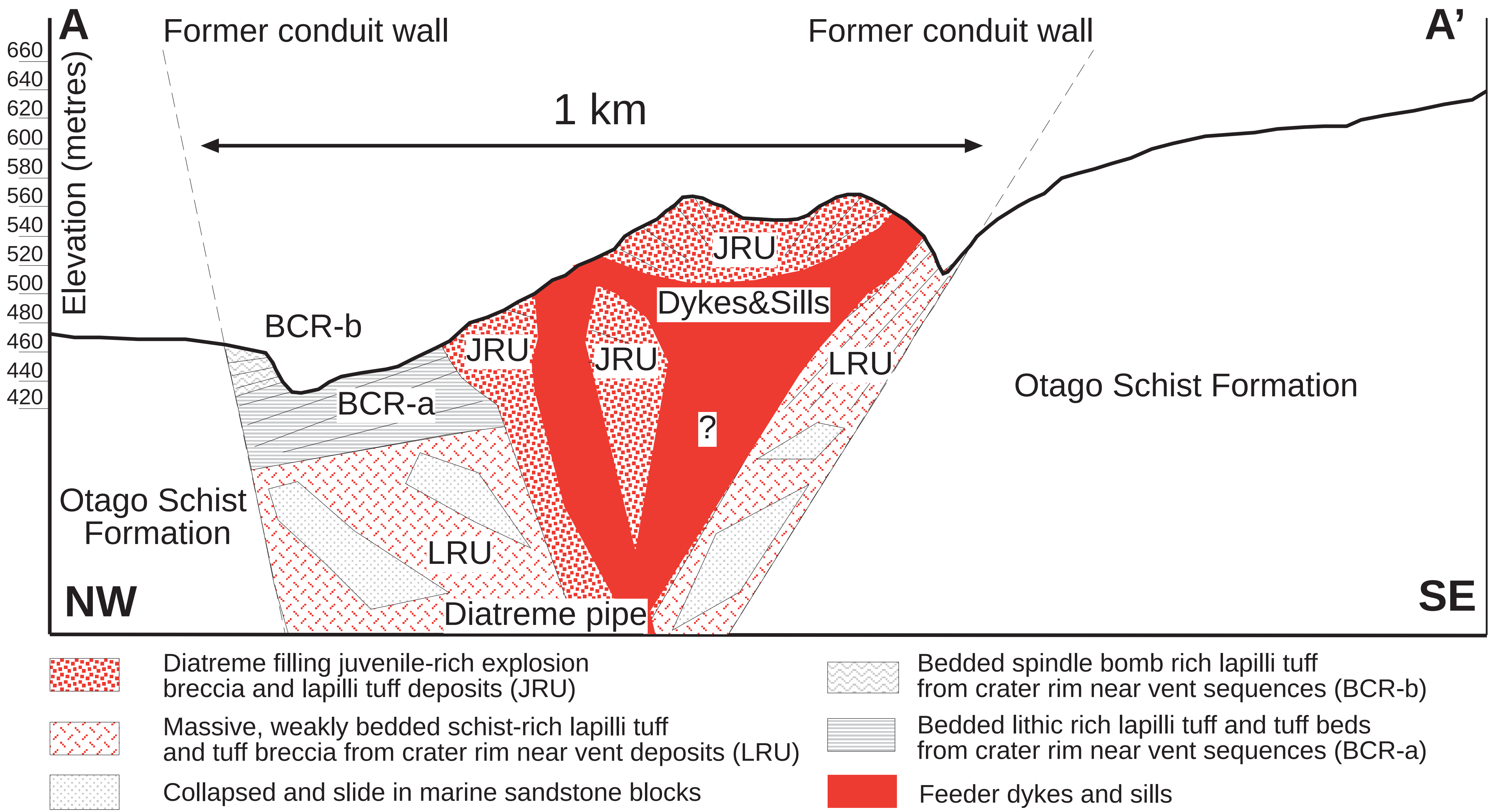
Figure 2 NW-SE cross-section of The Crater. The positions of subsided marine sandstone blocks are theoretic.

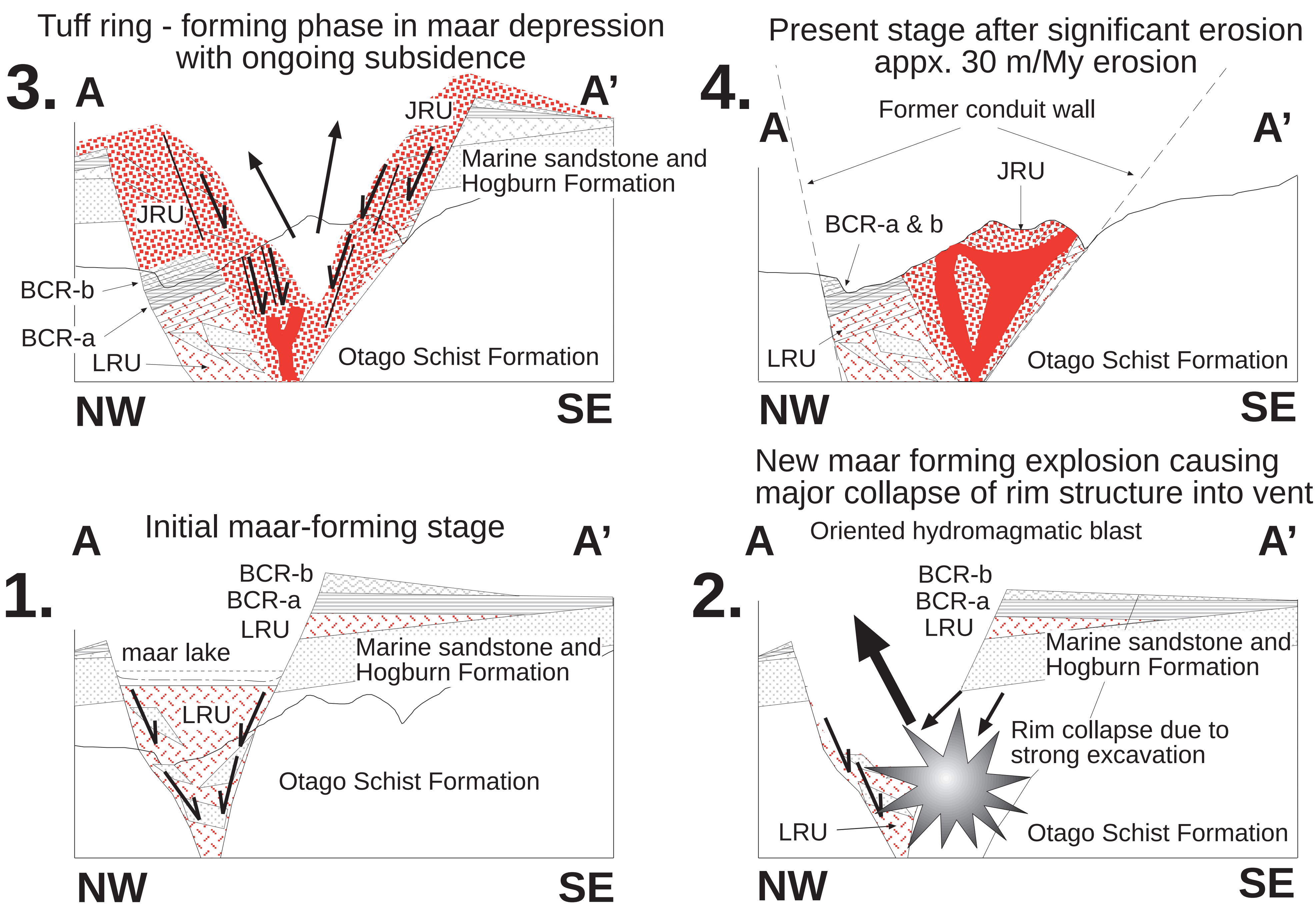
Figure 3 Evolution of The Crater. 1. stage represents initial maar forming with a development of deep maar basin undercut the pre-volcanic Cenozoic strata; 2. stage represents a subsurface phreatomagmatic explosion causing major collapse and subsidence of former crater rim beds; 3. stage represents a development of a tuff cone/scoria cone in the maar basin with possible ongoing subsidence of crater rim beds; 4. stage represents a present scenario after intrusion of dykes and erosion. Not to vertical scale!

Figure 4 Paleogeographic development of The Crater volcano. Compare to Fig. 3. Coordinates are New Zealand Grid Reference numbers!



170o
172o
174o
New Zealand
South Island
Tasman Sea
Alpine Fault
Alpine dyke
swarm
42o
44o
46o
Dunedin
Volcanic
Group
0
100 km
A
Simplified cross section
of the vicinity of The Crater
B
Rock and Pillar Range
Taieri Ridge
The Crater
Taieri River
West
East
The Crater
Geology Map
C
94
95
500
480
520
540
560
580
600
N
A
A’
25
LRU
JRU
BCR-b
BCR-a
1 km
Dunstan Formation
(terrestrial - Miocene)
Marine sequence
(marine -Oligocene)
Hogburn Formation
(terrestrial - Eocene)
Otago Schist
(Cretaceous)
Dykes & sills
JRU: juvenile-rich unit
BCR-b: bedded crater rim unit
BCR-a: bedded crater rim unit
LRU: lithic rich unit
Radial-jointed feeder dyke
Creek
4WD - road
Bedding (dip azimuth and
magnitude)
Cross section on Fig. 2
Topographic contours at 20 m intervals!


A
A'
Former conduit wall
Former conduit wall
1 km
Elevation (metres)
660
640
620
600
580
560
540
520
500
480
460
440
420
BCR-b
BCR-a
JRU
JRU
JRU
Dykes&Sills
?
LRU
LRU
Otago Schist Formation
Otago Schist Formation
Diatreme pipe
NW
SE
Diatreme filling juvenile-rich explosion breccia and lapilli tuff deposits (JRU)
Massive, weakly bedded schist-rich lapilli tuff and tuff breccia from crater rim near vent deposits (LRU)
Collapsed and slide in marine sandstone blocks
Bedded spindle bomb rich lapilli tuff from crater rim near vent sequences (BCR-b)
Bedded lithic rich lapilli tuff and tuff beds from crater rim near vent sequences (BCR-a)
Feeder dykes and sills


Tuff ring - forming phase in maar depression with ongoing subsidence
3.
A
A'
JRU
JRU
Marine sandstone and Hogburn Formation
BCR-b
BCR-a
LRU
Otago Schist Formation
NW
SE
Present stage after significant erosion appx. 30 m/My erosion
4.
A
A'
Former conduit wall
JRU
BCR-a & b
LRU
Otago Schist Formation
NW
SE
Initial maar-forming stage
1.
A
A'
BCR-b
BCR-a
LRU
maar lake
LRU
Marine sandstone and Hogburn Formation
Otago Schist Formation
NW
SE
New maar forming explosion causing major collapse of rim structure into vent
2.
A
A'
Oriented hydromagmatic blast
BCR-b
BCR-a
LRU
Marine sandstone and Hogburn Formation
Rim collapse due to strong excavation
LRU
Otago Schist Formation
NW
SE

The Crater (New Zealand) Paleogeography