Triassic–Jurassic granites on the Lord Howe Rise, northern Zealandia

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We present U–Pb zircon ages from a phosphate-cemented pebbly sandstone dredged from the central Lord Howe Rise and a 97 Ma rhyolite drilled on the southern Lord Howe Rise. Four granitoid pebbles from the sandstone give U–Pb ages in the range 216–183 Ma. Most detrital zircons in the bulk sandstone are also Late Triassic–Early Jurassic, but subordinate populations of Late Cretaceous and Precambrian zircons are present. The pebbly sandstone’s highly restricted Late Triassic–Early Jurassic zircon population indicates the nearby occurrence of underlying basement plutons that are the same age as parts of the I-type Darran Suite, Median Batholith of New Zealand and supports a continuation of the Early Mesozoic magmatic arc northwest from New Zealand. Zircon cores from the southern Lord Howe Rise rhyolite do not yield ages older than 97 Ma and thus provide no information about older basement.

KEY WORDS: Triassic, Jurassic, granite, Lord Howe Rise, dredge, Zealandia, sandstone.

INTRODUCTION

Zealandia, the Earth’s seventh largest geological continent, lies 94% submerged in the SW Pacific Ocean; its principal emergent parts are the islands of New Zealand and New Caledonia (Mortimer & Campbell 2014). The Pacific–Australian plate boundary transects Zealandia and divides it into northern and southern parts. Northern Zealandia is highly segmented into troughs and ridges of which the Lord Howe Rise is the main positive bathymetric feature.

Prior to Late Cretaceous sea floor spreading, Zealandia was contiguous with Australia and Antarctica, all three constituting the southern part of the Gondwana supercontinent. Parts of a Permian–Early Cretaceous continental magmatic arc can be recognised in eastern Australia, central Zealandia and West Antarctica (e.g. Muir et al. 1998; Pankhurst et al. 1998; Donchak et al. 2013). An important goal of Gondwana regional geology is to correlate and delineate geological provinces between and across the now-separated continents (e.g. Pankhurst et al. 1998; Mortimer et al. 2008; Higgins et al. 2011a; Tulloch et al. 2012). For the poorly sampled, wide continental shelves of Zealandia, especially northern Zealandia, this is not a trivial exercise. So far, only one sample of demonstrable pre-Late Cretaceous (pre-rift) basement has been obtained from the entire Lord Howe Rise (Mortimer et al. 2008). Therefore, any new offshore basement samples, in the form of dredges, drill core or xenoliths or xenocrysts from intraplate volcanoes are extremely useful.

This paper reports the results of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U–Pb dating of zircons from two rocks sampled from the Lord Howe Rise in order to help constrain the interpreted basement geology of northern Zealandia. One rock is a pebbly sandstone dredged from the central Lord Howe Rise during the 2006 AUSFAIR cruise (Colwell et al. 2006). Although the sandstone is part of the Late Cretaceous–Holocene sedimentary cover on the Lord Howe Rise, its restricted detrital zircon population provides information about local basement geology. The second rock is a Late Cretaceous syn-rift rhyolite drilled at Deep Sea Drilling Project site 207A (McDougall & van der Lingen 1974). This rhyolite has previously yielded a U–Pb zircon age of 97 Ma (Tulloch et al. 2009). In this paper, we date possible inherited zircon cores from the same sample as a probe of the underlying crust.

GEOLOGICAL SETTING

Seismic reflection studies (e.g. Bentz 1974; Collot et al. 2009; Bache et al. 2014) have shown that almost all of the Lord Howe Rise is covered by a 500–3000 m-thick blanket of Late Cretaceous to Holocene marine sedimentary rocks (part of Zealandia Megasequence of Mortimer et al. 2014). This makes sampling of Late Cretaceous syn-rift rocks and pre-Late Cretaceous basement rocks very difficult. The age of the oldest Tasman Sea floor adjacent to the Lord Howe Rise (Figure 1) ranges from older than...
83 Ma in the south to ca 67 Ma in the north (Gaina et al. 1998). To date, the only pre-Late Cretaceous basement rocks dredged or drilled from the entire 3 Mkm² submerged area of northern Zealandia (Figure 1) comprise Carboniferous granite dredged from the Challenger Plateau (Tulloch et al. 1991), Permian plutonic rocks dredged from the Dampier Ridge (McDougall et al. 1994), Early Triassic and Late Jurassic plutonic rocks dredged from the West Norfolk Ridge (Mortimer et al. 1997, 1998), and various plutonic and metasedimentary rocks drilled in Taranaki Basin (Mortimer et al. 1997). All of these rocks have correlative in onland New Zealand. A Neogene intra-plate basalt volcano near the Aotea Basin has yielded undated gabbro xenoliths (Mortimer 2004) and another volcano southeast of Lord Howe Island contains xenoliths of New England Orogen metasedimentary rocks (Mortimer et al. 2008). Occurrences of syn-rift Late Cretaceous volcanic rocks (i.e. from acoustic basement but not geological basement) have been obtained from a previously reported AUSFAIR dredge on the central Lord Howe Rise (Higgins et al. 2011b) and from the bottom of DSDP 207A on the southern Lord Howe Rise (McDougall & van der Lingen 1974). Late Cretaceous syn-rift sedimentary graben have been provisionally identified in several Lord Howe Rise seismic lines (Collot et al. 2009; Higgins et al. 2011a; Bache et al. 2014). This evidence for widespread intracontinental rifting indicates that, prior to sea floor spreading, the outcrop width of the Lord Howe Rise would have been somewhat less than it is today.

SAMPLE DATA

Central Lord Howe Rise

The 2006 AUSFAIR voyage carried out dredging at five sites, three of which were on the Lord Howe Rise (Colwell et al. 2006). Geochemical and petrographic data on Late Cretaceous volcanic rocks from dredge site MD153-DR03 were described by Higgins et al. (2011b). Our current paper describes a moderately hard, pebbly sandstone from MD153-DR01 (lat. 28°37.8'S, long. 163°03.8'E, water depth 1650 m). Dredge site DR01 is on a SW-facing fault scarp that exposes rare acoustic basement on the central Lord Howe Rise. Shipboard observation notes, deck photographs, a seismic reflection profile and multibeam bathymetry maps of all the AUSFAIR dredge sites, including DR01, were given in Higgins et al. (2011b) and are not repeated here. Higgins et al. (2011b) noted that, on the basis of seismic reflection interpretations, dredge DR01 was made with the prospect of recovering basement rocks and/or syn-rift strata. Apart from manganese oxide crusts, pebbly sandstone was the dominant lithology in MD153-DR01. A subsample of the DR01 sandstone was obtained by Mortimer from Geoscience Australia in May 2012 and given a GNS Science Petrol-ogy Collection number of P81390. The four largest visible granitoid pebbles (~5 g total weight) were sawn and chipped out of the sandstone, aggregated, and collectively given the sample number P81391. In order to improve zircon recovery, we used all of P81391 for zircon dating rather than try and obtain geochemistry as well. Sample and analytical data are lodged in Petlab, New Zealand’s rock and geoanalytical database (http://pet.gns.cri.nz).

In thin-section, P81390 is a poorly sorted pebbly sandstone with a phosphatic (collophane) cement (Figure 2; identification confirmed by X-ray diffraction). Possible
crude bedding, as variation in subrounded to subangular pebble percentage, is visible on some faces. The sandstone, aside from the pebble content, is medium grained (mode ~0.3 mm) and moderately sorted, and has sub-rounded grains. The finest clastic fraction is a very fine sand (~80 μm) size. Based on a visual estimate in stained thin-section, the sandstone size fraction comprises ~60% quartz, 15% volcanic lithics, 10% feldspar (mainly K-feldspar), 10% oxidised glauconite pellets and 5% sedimentary lithics. Subordinate grains of green-brown amphibole, zircon, apatite and titanite are present; all these mineral grains can be matched with minerals in the pebble population (see below).

The pebble (>2 mm) fraction comprises up to 10% of the clastic content of the sample. No thin-section was made of the P81391 pebbles, as all extracted clasts were used for dating. In thin-sections of P81390, pebbles are up to 10 mm in long dimension and subangular to well rounded. Pebble lithologies comprise ~40% varitextured mafic and felsic lavas, ~20% biotite granites (sensu stricto with abundant K-feldspar; some granophytic) and ~40% lithic sedimentary rocks. The sedimentary rocks mainly comprise mudstone–sandstone intraclasts but rare sericitised greywacke is also present. Some volcanic pebbles are plagioclase-phryic with a subtrachytic groundmass, others are olivine-phric, the olivine being completely altered to clay minerals, and still others are aphyric. A fourth volcanic pebble type is flow-foliated rhyolitic lava (possibly an ignimbrite). One lava clast has abundant secondary epidote. One metaquartzite/quartz vein clast was seen in thin-section. All pebbles are variably oxidised and altered to clay.

The pebbly sandstone lacks a clastic matrix but is cemented by authigenic collophane that comprises ~10% of the total rock. In places, collophane is interlayered with manganese oxides. Typically, the sand grains are completely enclosed by cement, and many of them are rimmed by vermiform-textured collophane. Minor porosity (<1%) is present. Diagenetic aspects of the sample are beyond the scope of this study, which focuses on the detrital origin of the pebbly sandstone.

Southern Lord Howe Rise

Deep Sea Drilling Project hole 207A bottomed in 156 m of vitrophyric rhyolite flows, some with feldspar phenocrysts. Naked eye and microscopic descriptions were given by McDougall & van der Lingen (1974) and are not repeated here. The same authors reported K–Ar and Ar–Ar ages of 93.7 ± 1.1 Ma (95.9 Ma using modern decay constants). Rhyolite from DSDP207A was reanalysed by Tulloch et al. (2009), who reported a high-precision U–Pb zircon TIMS age of 97.044 ± 0.045 Ma for P63855 and confirmed its intra-plate geochemical character. An εNd(97Ma) of –0.6 and a TDM of 1.03 Ga for the rhyolite suggested involvement of some older continental crust in its petrogenesis. It was on this basis that the zircon cores from P63855 were further analysed for the present study, in the hope that older age populations would match an identifiable terrane or igneous suite.

U–Pb Zircon Dating Methods

Mineral separation was undertaken at GNS Science using standard crushing, heavy liquid and magnetic separation techniques. After hand picking, cathodoluminescence images (e.g. Figure 3) were taken of zircon grains to detect composite core-overgrowth grains and to guide analysis site placement. Typical zircon grains were ~150 x 50 μm, but size varied considerably; some grains were too small to analyse with the standard 33 μm beam diameter.

Zircon dating was undertaken at the Centre for Trace Element Analysis, University of Otago by laser ablation inductively coupled mass spectrometry (LA-ICP-MS) on a Resonetics RESOlution M-50-LR laser ablation system incorporating a Coherent ComplexPro 102 193 nm ArF excimer laser and Laurin Technic two-volume sample cell. The laser was operated at 100 mJ and 12.5% transmission giving a typical fluence value of 4 J/cm², using a spot diameter of 33 μm and a 5 Hz repetition rate. Ablated material was carried by He gas (650–750 mL/min) from a two-volume sample cell, mixed with Ar (650–750 mL/min) and N2 (2–6 mL/min) and input to an Agilent 7500cs quadrupole ICP-MS. Gas flows were adjusted each day to achieve maximum sensitivity and

![Figure 3](image-url)
stability for $^{238}\text{U}$, constant $^{232}\text{Th}/^{238}\text{U}$ fractionation and minimum oxide production (<0.5%). Data for 18 mass peaks were collected in time-resolved mode with one point per peak. Integration times were 40 ms for $^{206}\text{Pb}$, $^{237}\text{Pb}$ and $^{208}\text{Pb}$; 25 ms for $^{207}\text{Th}$, $^{235}\text{U}$ and $^{238}\text{U}$; 5 ms for $^{28}\text{Si}$ and $^{91}\text{Zr}$; 10 ms for $^{31}\text{P}$, $^{81}\text{Y}$, $^{139}\text{La}$, $^{140}\text{Ce}$, $^{147}\text{Sm}$, $^{153}\text{Eu}$, $^{161}\text{Yb}$, $^{175}\text{Lu}$ and $^{177}\text{Hf}$; and 20 ms for $^{49}\text{Ti}$, giving a total scan time of 396 ms per analysis. Because of a high $^{204}\text{Hg}$ blank, $^{204}\text{Pb}$ was not included. Background data were acquired for 20 s followed by 40 s with the laser on, giving approximately 100 mass scans and a penetration depth of ~20 μm. A minimum purge time of 10 s was allowed between each spot analysis to permit a return to background signal levels. Correction factors were applied to each spot analysis to simultaneously correct for instrument mass bias and depth-related elemental fractionation. After laser triggering, several seconds were needed for a steady signal to be obtained, so the first 10 scans were routinely excluded from subsequent calculations. Depth related inter-element fractionation of Pb, Th and U were corrected by reference to the TEMORA-2 zircon standard (Black et al. 2004). TEMORA-2 (x2), R33 and DR/P73479 (secondary standards) and NIST glass 610 were measured at the beginning of each analytical session and then once every 15 unknown analyses. Measured $^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{235}\text{U}$ and $^{208}\text{Pb}/^{238}\text{U}$ ratios in the TEMORA-2 zircon standard and $^{232}\text{Th}/^{238}\text{U}$ ratios in NIST610 silicate glass were averaged and used to calculate correction factors based on published, accepted values (Pearce et al. 1997; Black et al. 2003). Data were reduced using Iolite software (Paton et al. 2011). Probability density plots and peak deconvolution were produced using Isoplot software (Ludwig 2003). All errors quoted are ±2σ and/or apply at the 95% confidence level.

Ages reported in the Supplementary Data File and used in Figures 4 and 5a are $^{206}\text{Pb}/^{238}\text{U}$ ages. One hundred and nineteen grains were analysed for sandstone P81390. Of these, 36 were discarded owing to spot MSWD >10 and/or >10% discordance of $^{207}\text{Pb}/^{235}\text{U}$ and $^{208}\text{Pb}/^{238}\text{U}$ ages. This left a total of 84 acceptable analyses which is short of 100 analyses to ensure that a source area population $>4\%$ would not be missed at the 95% confidence level (Vermeesch 2004). We acknowledge this limitation in our data. Of the 30 grains analysed from the P81390 granite pebbles P81390, 20 were acceptable by the above criteria. The P63855 rhyolite had 58 acceptable analyses out of 73 zircon spots analysed.

RESULTS

P81391 granite pebbles

Four separate granitic clasts were aggregated together for the purpose of obtaining adequate zircon for dating, although, with hindsight, it would have been better to process them separately, as the clasts were quite zircon productive. Cathodoluminescence images (not shown) reveal that the zircons are well shaped, are up to 200 μm in length and are texturally simple, showing oscillatory zoning with no identifiable inherited cores. The 20 analytically acceptable zircons gave individual ages ranging from 215.9 ± 6.3 Ma to 183.1 ± 6.1 Ma. The 20 zircons do not appear to be a single statistical population, e.g. related to a single igneous crystallisation event (Figure 4a). The 14 youngest zircon can be resolved into a 191 ± 2 Ma (95% confidence) population comprising most analyses, and an older, 214 Ma, population comprising just three grains. Speculatively, three of the pebbles...
MD153-DR03 at 97 Ma and 74 Ma (the DR03 site is 35 km NW of DR01). Thus, it is likely that some of the P81390 zircons (and trachyte pebbles; Figure 2) are from volcanic rocks similar in age and composition to those dredged at DR03.

Four zircons are appreciably older than the main Triassic–Jurassic cluster. These have individual ages of 2133 ± 43, 1967 ± 41, 842 ± 20 and 739 ± 16 Ma. Some are slightly more rounded than the Triassic–Cretaceous zircons, but not the 739 Ma one (Figure 3a). We speculate that the Precambrian zircons are derived from the same source as the sparse but conspicuous metagreywacke clasts noted in thin-sections of P81390. Interestingly, there are no zircons in the 600–500 Ma age range, which corresponds to dominant to prominent peaks in age spectra of metagreywackes of the Lachlan and New England orogens of Australia and Western and Eastern provinces of New Zealand. The ages of the four Precambrian zircons in P81390 are not diagnostic of any individual Australian or Zealandian terrane or orogen, but neither are they unusual or unrepresented in published reference datasets (e.g. Korsch et al. 2009; Adams et al. 2015).

P63855 rhyolite

Zircon grains from this sample are generally less than 100 μm in length, and cathodoluminescence images (Figure 3b) reveal both oscillatory and sector zoning. The centres of zircon grains were targeted for dating. All 58 acceptable analyses from this sample gave individual ages ranging from 99.7 ± 3.0 Ma to 84.4 ± 2.4 Ma (Figures 3b, 5; Supplementary Data File). Thus, despite our expectations on the basis of whole rock εNd, no evidence of older zircon cores was found. The Supplementary Data File shows that none of the unacceptable analyses (>10% discordant) were discordant because of possible inheritance. Our new data support, but do not improve on, the 97.044 ± 0.045 Ma U–Pb zircon age reported by Tulloch et al. (2009).

IMPLICATIONS FOR LORD HOWE RISE GEOLOGY

The total absence of pre-Late Cretaceous zircon cores in the P63855 DSDP207A rhyolite provides no new information on the basement geology of the southern Lord Howe Rise. The presence of four Late Cretaceous detrital zircons in P81390 confirms that the MD153-DR01 phosphate-cemented pebbly sandstone is part of the sedimentary cover of the central Lord Howe Rise. The presence of glauconite indicates a marine setting, and, considering its relatively high energy of deposition, the sample possibly correlates with either the syn-rift Momotu or the passive margin and transgressive Haerenga Supergroup of Mortimer et al. (2014), seismic Units 2 and 3 of Bache et al. (2014) and Syn-rift or Lower Sag of Higgins et al. (2011a).

Although the sandstone and pebble petrography indicate a mixed plutonic, volcanic and sedimentary provenance for the MD153-DR01 dredge (Figure 2), the dominance of Late Triassic and Early Jurassic zircons in both sandstone and granitoid pebbles (Figure 4) indicates restricted detrital zircon sources. The occurrence...
of Late Cretaceous zircons suggests that input from syn-
rift volcanic rocks and Precambrian zircons show that
there was a small detrital input from a nearby metagrey-
wacke terrane, but principally it was erosion from a
190–220 Ma plutonic terrane that contributed zircon in
sand and pebbles to be deposited in the Late Creta-
ceous–Paleogene at site MD153-DR01. This restricted
detrital zircon population is perhaps surprising for a
marine clastic sedimentary rock, as such rocks tend to
have a mixed provenance compared with fluviol and lit-
toral sandstones (Crittelli et al. 1997; Satkoski et al. 2013).
The restricted zircon ages make sense, however; given
the position of the dredge site in a possible syn-rift
sequence close to a basement high (Higgins et al. 2011b),
and are useful in terms of making inferences about the
geochemical nature of the basement high. While it is not
possible to be either accurate or precise about how
far the sand and pebbles might have been transported,
we tentatively infer there to be Late Triassic–Early
Jurassic plutonic basement perhaps within a few tens of
kilometres of MD153-DR01.

There are several potential along-strike correlatives of
the MD153-DR01 granites in onland New Zealand. Lacking
chemistry on the P81391 granite clasts, a corre-
lation is based solely on age. The Darran Suite of New
Zealand represents a major pulse of Early Triassic to
Early Cretaceous I-type calc-alkaline magmatism (Figure 3d; Muir et al. 1998; Mortimer et al. 2014) that
spans the 216–183 Ma age range of the MD153-DR01
granite pebbles. A subduction-related interpretation for
Darran Suite is reinforced by the presence to the east of
Early Mesozoic forearc basin and accretionary wedge
terranes. These latter terranes are also present in New
Caledonia (Figure 1; Aitchison et al. 1995). Darran Suite
rocks are principally plutonic, but some volcanic and
volcanoclastic lithologies are also present and help
define the full age range. As presently recognised, the
main pulse of Darran Suite magmatism was in the Late
Jurassic–early Early Cretaceous with a subordinate
pulse in the early Late Triassic (Figure 4d). As such, a
comparison of Figure 4c and d does not appear to pro-
vide a convincing match of the ages of the detrital zir-
cons from MD153-DR01 with the Darran Suite. However,
it must be remembered that the MD153-DR01 zircon ages
are highly restricted, and thus it is likely to be only a
very few, volumetrically minor latest Triassic to earliest
Jurassic Darran Suite plutons (e.g. Price et al. 2006) that
contributed detritus to the pebbly sandstone, rather
than the entire batholith-sized suite. In 100 Ma of Darran
Suite subduction-related igneous activity, there are
likely to have been pulses and lulls in magmatism at dif-
ferent places at different times.

In contrast to New Zealand, in coastal Queensland
there is a dearth of igneous rocks of 216–183 Ma age
(Cook et al. 2013; Donchak et al. 2013 and references therein). Cook et al. (2013) catalogue about two dozen
Late Triassic plutons whose (plausibly unreset) U–Pb,
K–Ar and Ar–Ar isotopic ages range from ca 232 to 215
Ma. The North Arm Volcanic Group and other Queens-
land correlatives give (plausibly unreset) isotopic ages
ranging from ca 291 to 217 Ma. A major Rhaetian (ca
208–201 Ma) unconformity separates these igneous
rocks from overlying quartzose and only rarely
volcaniclastic sandstones of the Bundamba Group. A
younger set of plutons in Queensland that intrude Bun-
damba Group are as old as 140 Ma (Cook et al. 2013).
Although these igneous rocks are traditionally treated as
‘post-orogenic’ (Cook et al. 2013), Tulloch et al. (2012) have
pointed out the match of Triassic and Cretaceous mag-
matic peaks and compositions with New Zealand’s Dar-
rann Suite, raising the possibility that the early Mesozoic magmatic arc passed through Queensland
(Figure 1). The proposition that the Early Mesozoic axis
does continue somewhere north of MD153-DR01 dredge
site is supported by Crowhurst et al. (2004), who
described 220 Ma igneous rocks in northern New Guinea
that they inferred to be a northern continuation of
Gondwana margin magmatism.

On the Lord Howe Rise, magnetic and gravity anom-
alies largely follow rift basin trends (Higgins et al. 2011a),
basement sample sites are few and widely spaced. How-
ever, at the scale of Figure 1, we feel able to provisionally
continue the axis of the inferred Early Mesozoic mag-
matic arc from its onland Darran Suite outcrop in north-
erth South Island, under Taranaki Basin where there are
many samples (Mortimer et al. 1997), out to the West Nor-
folk Ridge (Mortimer et al. 1998) and then to under or
near the MD153-DR01 dredge site. On Figure 1, we have
not attempted to correct or restore the position of the
magmatic axis for differential stretching across the New
Caledonia Trough. The position of the Early Mesozoic
magmatic axis north and west of the MD153-DR01 dredge
site is still unconstrained. On the one hand, the Mesozoic
accretionary wedge and forearc rocks of New Caledonia
suggest that it might strike north to the Fairway Ridge.
On the other hand, if the Triassic igneous rocks of SE
Queensland are subduction-related, the axis line might
strike more west (Figure 1). There is also the possibility
that the age range of subduction-related magmatism
would change over such long strike distances, and also
that the MD153-DR01 Late Triassic–Early Jurassic gran-
ite pebbles represent a new igneous suite that is unre-
related to the linear belt of Darran Suite magmatism.
Resolution of this issue must await acquisition of more
basement samples from northern Zealand.

CONCLUSIONS

A phosphatic pebbly sandstone was dredged from the
Lord Howe Rise at site MD153-DR01 on the 2006 AUSFAIR
cruise (Colwell et al. 2006; Higgins et al. 2011b), possibly
from the syn-rift sedimentary sequence. Zircons in gran-
ite pebbles and sandstone from MD153-DR01 yielded
exclusively 216 to 183 Ma and mainly 229 to 178 Ma ages,
respectively. On the basis of this restricted zircon popula-
tion, we infer the presence of Late Triassic to Early
Jurassic granitic basement near the MD153-DR01 dredge
site. On the basis of age and petrology, we tentatively cor-
relate these rocks with the Early Mesozoic Darran Suite
of New Zealand. This new sample doubles the known
number of pre-Late Cretaceous sample sites on the Lord
Howe Rise and suggests a provisional continuation of
the Early Mesozoic Gondwana magmatic arc northwest
from New Zealand and the West Norfolk Ridge across northern Zealandia.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

SUPPLEMENTAL DATA FILE

Raw U–Pb zircon data for P63855, P81390 and P81391.

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