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Primitive Layered Gabbros from Fast-Spreading Lower Oceanic Crust

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Three-quarters of the ocean crust formed at fast-spreading ridges is composed of plutonic rocks whose mineral assemblages, textures and compositions record the history of melt transport and crystallization between the mantle and the seafloor. Despite the significance of these rocks, sampling them *in situ* is extremely challenging due to the overlying dikes and lavas. This means that our models for understanding the formation of the lower crust are based largely on geophysical studies¹ and ancient analogues (ophiolites)²⁻⁵ that did not form at typical mid-ocean ridges. We report here the first significant cored intervals of primitive modally layered gabbroic rocks from the lower plutonic crust formed at a fast-spreading ridge, sampled by the Integrated Ocean Drilling Program (IODP) at the Hess Deep Rift (HDR). Spectacular cm-scale modally layered rocks, some of which have a strong layering parallel foliation, confirm a long held paradigm that such rocks are a key constituent of the lower ocean crust formed at fast-spreading ridges^{3,6}. Geochemical analysis of these primitive lower plutonics, in combination with previous geochemical data for shallow-level plutonics, sheeted dikes and lavas, provides the most completely constrained estimate of the bulk composition of the oceanic crust to date. Simple crystallization models using this bulk crustal composition as the parental melt accurately predict the composition of both the lavas and plutonics. However, the recovered plutonic rocks show early crystallization of orthopyroxene, which is not predicted by current models of melt extraction from the mantle⁷ and mid-ocean ridge basalt (MORB) differentiation^{8,9}.

This observation is most simply explained if compositionally diverse melts are extracted from the mantle and partially crystallize prior to mixing to produce the more homogeneous magmas that erupt.

The gabbroic rocks that make up the lowermost oceanic crust formed at fast-spreading ridges, such as the East Pacific Rise (EPR), have long been assumed to be modally layered and primitive in composition^{4,6,10,11}. Igneous layering, and a layering-parallel foliation, are nearly ubiquitous in the lower plutonic sections of many ophiolites^{3,5,10} and explaining the formation of these layered rocks has become central to models for the accretion of the plutonic crust at fast-spreading ridges^{2,4,5}. Accretion models have evolved from layers accumulating along the floors of large magma bodies^{3,6} to layers developing in sill-like magma bodies focused at the top of the crystal mush within axial magma chambers and/or distributed throughout the crustal mush zone^{2,4,5}. Until now, however, no significant cored intervals of layered gabbros have been recovered from the lower plutonic section at a modern fast-spreading ridge.

IODP Expedition 345 was conceived as a test of whether modern fast-spread crust shows layering similar to many ophiolites and to test models for the transport of parental melts into the crust and differentiation of these melts within the crust. In order to sample the generally inaccessible lower plutonic crust, the expedition took advantage of the tectonic window at the HDR in the equatorial Pacific^{11,12} (Fig. 1). This site is unique as it is the only place where the lower- to upper-crust have been extensively sampled by submersible or ROV¹¹⁻¹⁴ and drilling (ODP Leg 147)¹⁵, and that allows drilling on known seafloor exposures of lower plutonic rocks where previous studies have suggested that layering exists^{11,12}. At Site U1415, primitive olivine gabbros and troctolites were

recovered at one 35-m-deep hole (U1415I) and two ~110-m-deep holes (U1415J, U1415P), located within 100 m of each other (Extended Data Fig. 1). Sampling of primitive layered gabbro and troctolite series at Site U1415 thus provides the final part of the most complete composite section of fast-spreading East Pacific Rise crust to date.

Modally layered and banded rocks, collectively called the layered gabbro series, were recovered in all three drill holes, comprising >50% of the recovered core. The layered gabbro series in Holes U1415I and U1415J show modal layering, with or without concurrent grain size variations, on a scale of centimeters to decimeters (Fig. 2a, Extended Data Fig. 2). Layers include troctolite, olivine-gabbro, gabbro and gabbro-norite with local variations in texture (e.g., clinopyroxene oikocryst-bearing). Layering is reminiscent of so-called dynamic layering resulting from magmatic flow¹⁶ commonly found in layered mafic intrusions (LMI) and some ophiolites. A layering parallel foliation exists throughout these rocks that is commonly strong (Fig. 2c) and locally anastomoses around large oikocrysts. In contrast, the layered gabbro series in Hole U1415P displays irregular banding that is identified by modal and grain size variations, with all of the same lithologies present, but also includes rare anorthositic bands (Fig. 2b). Grain size variation is much more extreme and heterogeneous, bands can be discontinuous, and one lithology can enclose another. Additionally, the boundaries between bands are much less planar, show more abrupt changes in mineralogy leading to asymmetric distributions of distinct leucocratic and melanocratic bands (Fig. 2b), and mineral foliations are weak or absent. This banding is reminiscent of non-dynamic layering in LMI that is the result of varying rates of nucleation and growth, and post-cumulus processes^{17, 18}. The troctolite series at the base of Holes U1415J and U1415P contain melanocratic to leucocratic

troctolite with little or no layering or banding and a weak to moderate foliation (Extended Data Fig. 1). Evolved lithologies such as FeTi-oxide gabbros and felsic veins, prevalent in the upper gabbros, are strikingly absent throughout the cores indicating that evolved residual melt was efficiently extracted from the lower plutonic crust. Also absent are mantle rocks, suggesting the recovered lithologies are not part of the mantle transition zone.

The foliation and layering in the layered gabbro series provide important constraints on the processes of crustal accretion. There is little sub-solidus crystal plastic deformation meaning that the foliations were formed early while the rocks were still partially molten. In addition, olivine commonly exhibits skeletal morphologies, which limits the amount of grain-scale strain that some of the rocks may have experienced at low melt fractions. The abundance of layering in the material recovered from Site U1415, along with the absence of intermixed evolved lithologies, distinguishes the HDR lower gabbroic crust from crustal sections recovered from slow-spreading ridges (see, for example, ref. 19). This supports models that invoke a strong spreading rate/thermal control on magma chamber processes at mid-ocean ridges²⁰. Furthermore, the occurrence of layering that resembles both dynamic¹⁶ and non-dynamic¹⁷ layering in LMIs suggests multiple mechanisms of crustal accretion and melt differentiation. This variation in style of layering and banding, and the diversity of lithologies, differs from the MORB-like, southern portions of the Oman ophiolite that has been used as a fast-spreading ridge analogue^{3,5}.

The Site U1415 cores are much more primitive (high MgO, high Mg#) rocks than previously recovered in the overlying upper gabbros (Fig. 3). These new samples allow

estimation of the bulk composition of fast-spread ocean crust because the thickness of the crust and its component parts are known from field relationships determined from four previous submersible surveys^{11,13,14} and ODP Leg 147 drilling¹⁵ (details in Methods). The relative proportions of the upper crust (lavas and dikes: $22.5 \pm 4.5\%$ of the crust) and shallow-level gabbros ($32.5 \pm 7.5\%$ of the plutonics) constrain the plausible fraction of deeper gabbros. For these calculations we use the mean compositions of the upper crust (lavas and sheeted dikes) from the northern escarpment, the shallow-level gabbros from the northern escarpment and ODP Site 894 and the lower gabbros from IODP Site U1415 (see Fig. 1b for locations; Extended Data Table 1).

The calculated bulk composition of the HDR crust (Extended Data Table 1) contains 12.1 ± 1.0 wt% MgO, 7.7 ± 0.4 wt% FeO^{Total} with an Mg# of 74 ± 1 , falling at the Mg-rich end of the range of experimentally determined parental melts for mid-ocean ridge basalts²¹. The calculated liquidus temperature is ~ 1290 - 1300°C and fractional crystallization models follow the expected mid-ocean ridge basalt (MORB) sequence of olivine ($\sim\text{Fo}_{90-91}$) followed by plagioclase ($\sim\text{An}_{84-87}$) then clinopyroxene ($\sim\text{Mg}\#_{86-88}$) with orthopyroxene ($\sim\text{Mg}\#_{75-82}$) saturation at ~ 1165 - 1180°C ^{22,23} with 46-35% melt remaining^{22,23} (Fig. 3; details in Methods). The first olivine to be produced in these models has a similar Fo-content to the olivine in dunites and harzburgites recovered from Hess Deep by previous drilling ($\text{Fo}_{89.4-91.3}$ ^{24,25}); this is consistent with the bulk-crustal composition being representative of a primary mantle melt extracted either directly from the harzburgites or through dunite channels.

An unexpected finding is that cumulus orthopyroxene commonly occurs in primitive (bulk-rock $\text{Mg}\#_{80-85}$) plutonic rocks from the deep portion of the crust at the

HDR (Fig. 2d). Orthopyroxene is a common minor cumulus and early inter-cumulus phase (<5%) in olivine gabbro, gabbro, gabbro-norite and troctolite in the layered gabbro series. In contrast, the virtual absence of orthopyroxene as a phenocryst in MORB globally (including HDR), as well as experimental studies of MORB differentiation (see, for example, ref. 8) and modeling of the differentiation with our bulk-crustal composition (Fig. 3) all indicate that orthopyroxene should not be a liquidus phase until >50% crystallization has occurred with a substantial interval of clinopyroxene crystallization preceding orthopyroxene saturation. Such late stage orthopyroxene is commonly found in more evolved gabbros, including the shallow-level gabbros from the HDR¹⁵.

Orthopyroxene is ubiquitous in the upper mantle where its coexistence with olivine buffers the silica activity in primary mantle melts. The expected late crystallization of orthopyroxene in MORB is due to the generation of MORB via polybaric, near-fractional melting^{26,27}, with an average melting pressure of about 10 kbars²⁷. Decompression of melts aggregated from throughout the melting column leads to an expansion of the olivine stability field, and shrinking of the orthopyroxene stability field, leaving the low-pressure melt far from orthopyroxene saturation²⁸. Although several processes could explain the occurrence of orthopyroxene in the deep primitive gabbros at the HDR, most seem unlikely. For example, the parental magmas could be more oxidized than typical MORB. This would lead to less of the Fe in the melt being divalent and hence available to partition into mafic phases²⁹ and could also lead to early oxide saturation driving an increase in silica activity, both of which could lead to early orthopyroxene saturation. However, this model is difficult to reconcile with either the normal differentiation trends observed in the overlying lavas and dikes, including Fe-

enrichment trends³⁰, or the virtual absence of FeTi-oxides (typically ≤ 0.1 modal %) in the Site U1415 rocks. Another possibility is that orthopyroxene saturation is influenced by the addition and removal of H₂O from the system³¹. The low water content of primitive MORB³² and the observation that the Site U1415 cumulates contain almost no magmatic amphibole, suggest very limited H₂O in the system making this an unlikely scenario. The most reasonable explanation is that orthopyroxene was precipitated from a primitive melt that had undergone little decompression since being in equilibrium with shallow mantle orthopyroxene. This can be explained if this melt was either generated by shallow mantle melting, or re-equilibrated with the shallow mantle as it was transported through it, and crystallized within the crust without first mixing with aggregated MORB melts in the crust³³. Re-equilibration of melt during shallow mantle transport is supported by the relatively high Sr content of the primitive cumulates which suggests that their parental melt was not depleted in incompatible elements. If this model is correct, it indicates that diverse melt compositions feed the crust, and the lower crust acts as an efficient filter for mixing these prior to the eruption of their homogenized and differentiated products.

Overall, our findings demonstrate that although the bulk oceanic crust at the HDR has a similar composition to that which has been predicted for parental MORB there is a greater diversity in parental melts added into the crust than expected. Partial crystallization of these diverse melts occurs prior to mixing, something that is not considered in models of MORB differentiation. However, such melts are not erupted indicating that melt transport through the lower crust acts as an efficient mechanism to homogenize the Moho-crossing melts. The heterogeneity in the lithologies, bulk

compositions, layering types and foliation strength observed within the Site U1415 core suggests complex melt differentiation and crustal accretion processes at fast-spreading ridges.

Methods Summary

The bulk composition of the EPR crust exposed at the HDR and its uncertainty were calculated using new and published compositions and relative mass fractions of the main crustal lithologies: lavas and dikes, shallow-level gabbros, and deep-level gabbros (Extended Data Table 1). The mass fractions of the crustal lithologies and their uncertainties are derived from field observations¹¹⁻¹⁴. A series of models^{22,23} were run to investigate whether differentiation of a parental melt with the composition of the bulk crust would produce cumulates and residual melts of similar composition to the observed plutonics and upper crustal rocks at the HDR. A fuller description is given in Methods.

Full Methods and any associated references are available in the online version of the paper.

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Author contributions. All authors were shipboard participants on IODP Expedition 345, contributed to the shipboard data collection, and discussed the results and their implications. KMG wrote the first draft of the manuscript, KMG and JES were co-chief scientists on the expedition, and AK was the staff scientist.

Author information. Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to K.M.G. (kgillis@uvic.ca).

Figure Captions.

Figure 1. Tectonic setting of the Hess Deep Rift and location of IODP Site U1415.

The Hess Deep Rift (HDR) formed by deep lithospheric extension in front of the westward propagation of the Cocos-Nazca spreading center exposing oceanic crust that formed at the fast-spreading (130 mm/y) East Pacific Rise. Upper crustal lavas and dikes are exposed along the northern and southern escarpments, shallow-level gabbros along the northern escarpment and the western intrarift ridge, and lower level gabbros along the southern slope of the intrarift ridge^{11,12,13}. a, Map of the Galapagos triple junction in the eastern equatorial Pacific Ocean showing major tectonic boundaries. EPR = East Pacific Rise, TJ = triple junction. White box indicates location of the map in b. b, Regional bathymetric map of the HDR showing key morphological features and locations of IODP Site U1415 and ODP Site 894. Maps show bathymetry derived from satellite altimetry data and archived multibeam bathymetry data available from the Global Multi-Resolution Topography Data Portal at Lamont-Doherty Earth Observatory.

Figure 2. Typical gabbroic rocks at Site U1415. a, Simple centimeter-scale modal

layers of alternating lithology (labeled to right of core); layer boundaries are sharp and planar and a layering parallel foliation is seen throughout (Hole U1415I, section 4R-1, 47-115 cm); additional examples are given in Extended Data Fig. 2. b, Orthopyroxene-bearing olivine gabbro showing steeply dipping leucocratic and melanocratic bands that range from distinct to weak. Banding is defined by modal, grain-size and textural variations. Also of note is an orthopyroxene-rich band (Hole

U1415P, section 8R-1, 86-144 cm). c, Photomicrograph of a troctolite in the layered gabbro series showing a strong magmatic foliation indicated by the red arrow, cross-polarized light (sample U1415I, section 4R-2, 0-4 cm, piece 2). d, Photomicrograph showing cumulus orthopyroxene in an orthopyroxene-bearing olivine gabbro, cross-polarized light (sample U1415P, section 4G-1, 5-7cm, piece 2). Abbreviations: Ol G = olivine gabbro, Tr = troctolite, GN = gabbronorite, Ol GN = olivine-bearing gabbronorite, Opx Ol G = orthopyroxene-bearing olivine gabbro, Ol = olivine, Opx = orthopyroxene, Pl = plagioclase.

Figure 3. Variations in whole-rock CaO (a) and Al₂O₃ (b) with MgO for the different parts of the crust at the HDR. The lower plutonics recovered from Site U1415 are much more primitive than the shallow plutonics. The compositions of the lower gabbro cumulates and lavas and dikes can be broadly explained using a simple fractional crystallization model (grey arrows) of the bulk-crustal composition but the shallow gabbros clearly contain substantial trapped melt in the bulk composition (i.e. are mixtures of cumulate and melt compositions). The uncertainties for the bulk crust and plutonic section compositions lie within the size of their symbols (Extended Data Table 1). Crystallization trends for the melt (light grey arrow) and cumulates (dark grey arrow) calculated using the PETROLOG program²³ encompass the range of models considered (details in Methods). The first appearance of each mineral modeled is shown for the cumulate crystallization trend: olivine is the liquidus phase, plagioclase appears after ~7% crystallization,

clinopyroxene appears after ~32 to 35%, and orthopyroxene appears after ~55 to 65%.

METHODS

Calculation of the bulk composition of the Hess Deep Rift crust

Calculation of the bulk composition of the crust requires knowledge of the compositions and relative mass fractions of the crustal lithologies. We divide the crust into three sections: (i) the upper crust (lavas and dikes), (ii) shallow-level gabbros and (iii) deep-level gabbros. Seismic velocity-depth models for undisrupted EPR crust north of the HDR indicate a crustal thicknesses of ~ 5.6 km (G. Christeson, pers. comm., 2013). Field relationships constrain the thickness of the upper crust to be $\sim 1.25 \pm 0.25$ km (1 s.d.)¹³, thus the subjacent plutonic sequence is 4.1 to 4.6 km thick.

The composition of the upper crust is based on an extensive sample suite collected by submersible along vertical transects through the lava and dike sections of the northern escarpment of the HDR between $101^{\circ}13.5'$ to $101^{\circ}28.5'$ (Fig. 1b). This representative dataset includes whole-rock lava and dike ($n=157$)³⁰ and glass ($n=18$)^{30,34} compositions. A series of test calculations were performed to assess how using either just the glasses or an average of the glass and whole-rock data impact the resulting bulk-crustal composition; minimal difference in bulk crust composition was found and thus, the mean of the two datasets was used to define the bulk-composition of the upper crust and its uncertainty. The bulk crust modeling assumes the upper crust comprises $\sim 22.5 \pm 4.5\%$ (1 s.d.) of the total crustal thickness.

The shallow-level gabbro compositions are also based on an extensive sample suite, collected by submersible along the northern escarpment where the upper 1 km of the plutonic section is well-exposed subjacent to the sheeted dike complex, across a horizontal distance of 3 km¹³, ODP Site 894 which recovered a 150-m-long section from

the upper 1 km of the plutonic sequence¹⁵, and samples collected by submersible from the western end of the intrarift ridge in the vicinity of ODP Site 894^{11,12}. The mean composition of the samples from the northern escarpment (n=56)^{35,36}, ODP Site 894 (n=76)^{15,37} and the western end of the intrarift ridge (n=7)³⁸ was used to define the bulk composition of the shallow-gabbros and its uncertainty. The proportion of the shallow-level gabbros in the plutonic section is estimated using field relationships from the HDR (see above) and the Oman ophiolite³⁹, which show them to comprise >20-25% and 20–50% of the plutonic section, respectively. The bulk crust modeling assumes that the shallow-level gabbros comprise $\sim 32.5 \pm 7.5\%$ (1 s.d.) of the plutonic sequence.

The lower-level gabbro compositions are calculated from the Site U1415 samples, using the compositions of the layered gabbro series (n=28) and troctolite series (n=15). The proportions of the layered gabbro and troctolite series are approximately equal at IODP Holes U1415J and U1415P (the two >100 m deep drill holes), thus we model their relative proportions when calculating the bulk crustal composition and its uncertainty as $50 \pm 20\%$.

The mean compositions of the different sections of the crust calculated as explained above are given in Extended Data Table 1, along with the calculated bulk crustal and bulk plutonic sequence compositions. The uncertainties on the mass fractions of each portion of the crust, along with the uncertainty in their average compositions, was propagated into the uncertainty on the bulk crustal composition using a Monte Carlo error propagation assuming all errors are Gaussian.

Modeling Melt Differentiation

A series of models was run to investigate whether differentiation of a parental melt with the composition of the bulk crust would produce cumulates and residual melts of similar composition to the observed plutonics and upper crustal rocks at the HDR. Both the MELTS²² and PETROLOG²³ models were used to test how sensitive the results are to the model calibration. The models all assumed perfect fractional crystallization at 1 kbar and oxygen fugacities between the quartz-magnetite-fayalite (QMF) buffer and one log unit below this buffer. While perfect fractional crystallization is unlikely in oceanic crust (see, for example, ref. 9 and references therein), comparison of these trends with observed compositions from the HDR provides a first-order test of whether the calculated bulk crust composition is an appropriate parental melt composition. While the model used has a small effect on the result, all models are broadly consistent in predicting a liquidus temperature of ~1300°C, a crystallization sequence of olivine => olivine + plagioclase => olivine + plagioclase + clinopyroxene, and that orthopyroxene is not saturated until after a substantial interval of cotectic olivine + plagioclase + clinopyroxene crystallization. The PETROLOG models used the model of Kress and Carmichael⁴⁰ to divide Fe into FeO and Fe₂O₃ based on the defined fO_2 , and various combinations of mineral models as follows: olivine: Ford et al.⁴¹ and Danyushevsky⁴²; plagioclase: Langmuir et al.²⁷ and Danyushevsky⁴²; clinopyroxene: Langmuir et al.²⁷ and Danyushevsky⁴² and orthopyroxene: Beattie⁴³ and Ariskin et al.⁴⁴. The model crystallization trends shown in Fig. 3 outline the compositional range for the melt and instantaneous cumulates with progressive fractional crystallization using these mineral models in various combinations.

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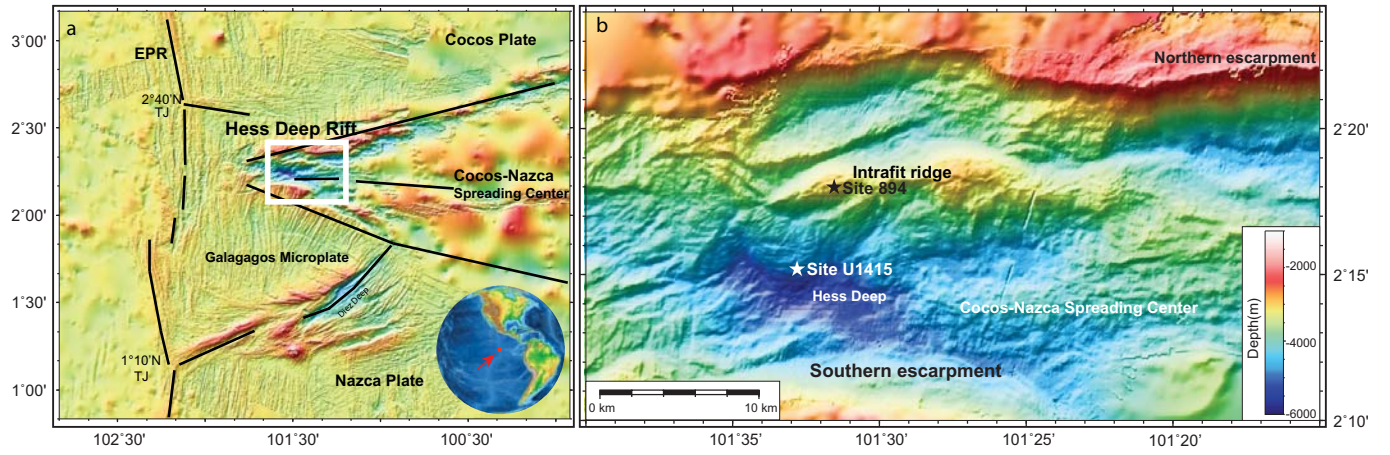


Figure 1 Gillis et al

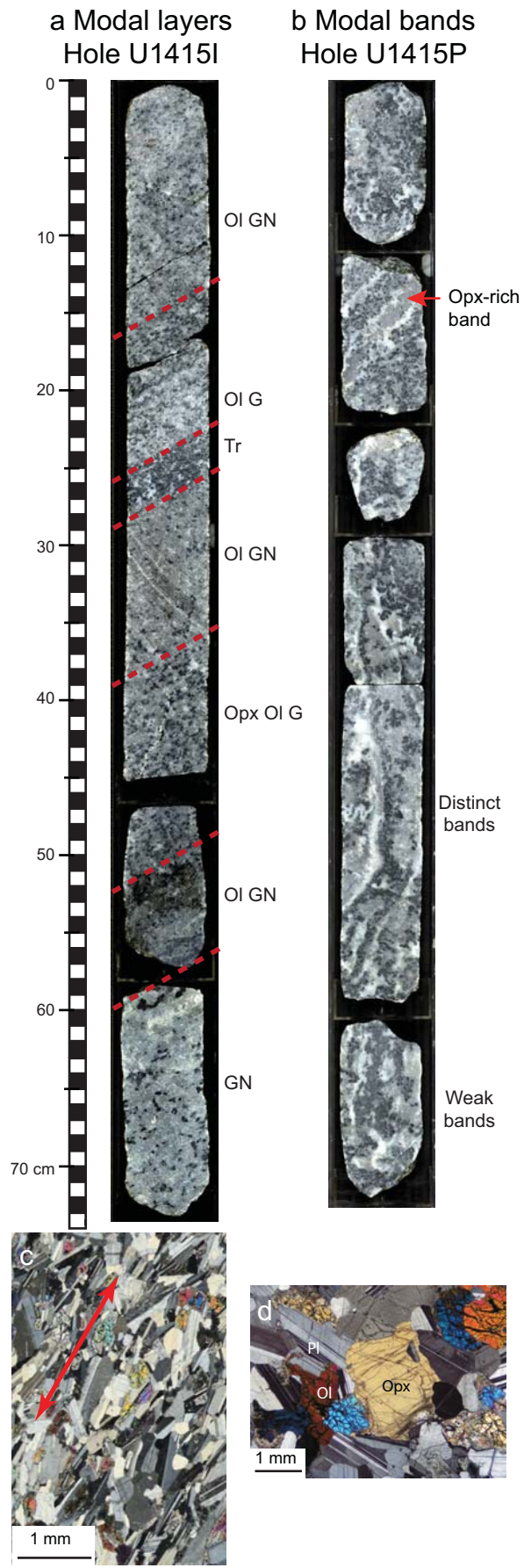


Figure 2. Gillis et al

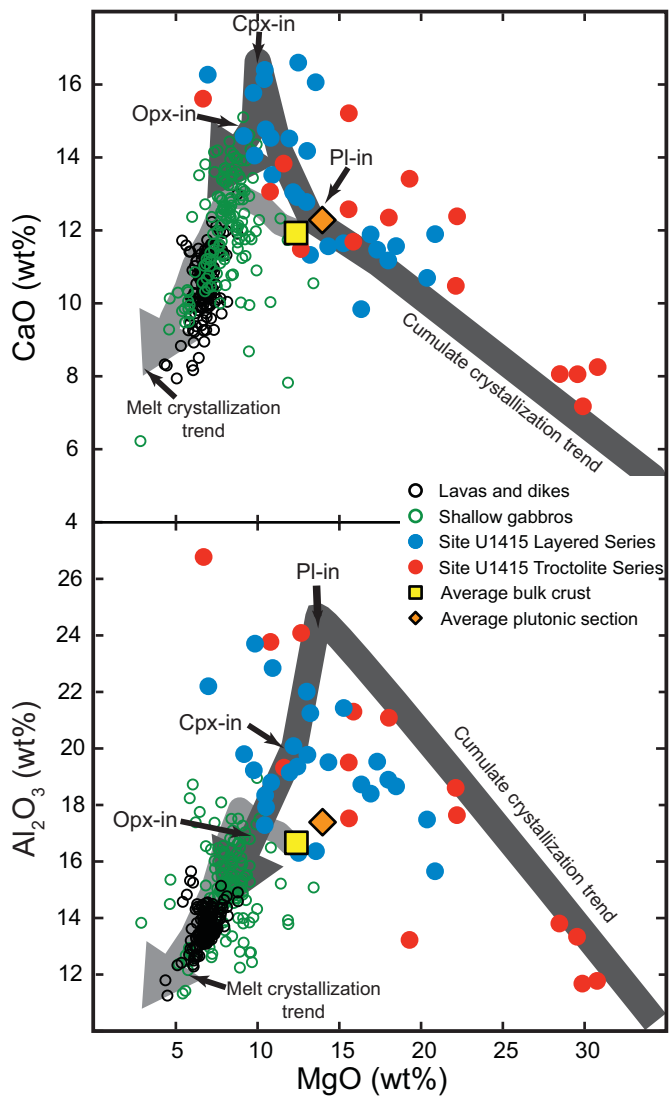


Figure 3 Gillis et al