

EARTH SCIENCES

High Mg# of the continental crust explained by calc-alkaline differentiation

Ming Tang^{1,*}, Xuanyu Liu¹ and Kang Chen²

ABSTRACT

We used compiled geochemical data to investigate the mechanisms that control Mg# (molar ratio of $Mg/(Mg + Fe_T)$) in andesitic arc lavas. We find that andesites from mature continental arcs with crustal thickness of >45 km have systematically higher Mg# than those from oceanic arcs with crustal thickness of <30 km. The elevated Mg# in continental arc lavas results from strong Fe depletion during high-pressure differentiation favored in thick crusts. This proposal is reinforced by our compiled melting/crystallization experiment data. We show that the Mg# characteristics of continental arc lavas match that of the continental crust. These findings suggest that the formation of many high-Mg# andesites and the continental crust may not require slab-melt/peridotite interactions. Instead, the high Mg# of the continental crust can be explained by intracrustal calc-alkaline differentiation processes in magmatic orogens.

Keywords: high-Mg# andesite, calc-alkaline differentiation, Fe depletion, slab melting, continental crust

INTRODUCTION

The classical model for the continental crust formation emphasizes oceanic arc magmatism, which produces voluminous felsic magmas necessary to account for the andesitic average composition of the continental crust [1,2]. But on the other hand, the continental crust possesses an Mg# of >0.5 , which is significantly higher than those of most andesites found in oceanic arcs. This discrepancy has led to a search of processes other than intracrustal arc differentiation to explain the composition of the continental crust [e.g. 3–5].

Over recent decades, much effort has been devoted to identifying slab-derived andesites as a potential high-Mg# candidate. Subducting slab may undergo dehydration and/or partial melting, depending on the P–T conditions of the slab surface [6,7]. We refer to slab-derived andesites specifically as those originating from slab melting; the resultant silicic melts would then interact with mantle peridotites and acquire high Mg# as they ascend through the overlying mantle [5,8–12]. These andesites may have sufficiently high Mg# (>0.5) and solve the Mg# problem of the continental crust if they constitute a significant component of the crust [e.g. 3,4,13–15]. If, indeed, this unusual type of andesite represents a

major building block of the continental crust, the formation of the continental crust would require very specific subduction settings that favor slab melting, which are rare on modern Earth [6].

Here we use compiled data to investigate how crustal thickness influences the Mg# of arc magmas as they differentiate in the crust. We emphasize the role of crustal thickness because crustal thickness dictates the pressure of intracrustal differentiation, which in turn exerts important controls on the composition of evolved arc magmas [16–21]. We then use our findings to revisit the question of whether intracrustal differentiation alone can generate felsic magmas with sufficiently high Mg# to match that of the continental crust.

DATA SOURCES

For arc lava samples, we took the compilation data set assembled by Ref. [22]. This data set contains 36 947 volcanic rock samples of Pleistocene to Holocene ages from global arcs. We divided the data into two groups. Group 1 includes samples from thin-crust arcs (10–30 km, crustal thickness converted from elevation), which are mostly oceanic arcs; Group 2 has samples from thick-crust arcs (45–80 km), which are manifested as mature continental

¹Key Laboratory of Orogenic Belt and Crustal Evolution, Ministry of Education; School of Earth and Space Sciences, Peking University, Beijing 100871, China and ²State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China

*Corresponding author. E-mail: mingtang@pku.edu.cn

Received 9 August 2022; Revised 10 November 2022; Accepted 10 November 2022

arcs. Groups 1 and 2 represent two endmembers of global arcs based on arc crustal thickness. This division of the data set is arbitrary. The purpose of this division is not to capture the entire compositional spectrum of all arcs, but to articulate the compositional differences between thin-crust and thick-crust arc endmembers.

We also compiled partial melting/crystallization experiment data. We did not separate partial melting and crystallization processes because they are chemically equivalent in general. We divided the experiment results into a low-pressure group (0–1.0 GPa) and a high-pressure group (1.0–2.0 GPa). To be consistent, we excluded experiments using alkali basalts as starting materials as they are unlikely to be the parental magmas or source rocks of most arc felsic magmas. Most of the experiments were conducted under oxygen fugacities > fayalite-magnetite-quartz buffer (FMQ) (Supplementary materials).

RESULTS AND DISCUSSION

Crustal thickness control on arc magma FeO_T content and $\text{Mg}\#$

$\text{Mg}\#$ is a function of both Mg and Fe contents, so an increase in magma $\text{Mg}\#$ can result from either Mg addition or Fe depletion. It is well known that arc magmas are on average depleted in Fe compared with those in mid-ocean ridges, but it is very underappreciated that the extent of Fe depletion varies significantly even within arcs. In particular, continental arc magmas are systematically more calc-alkaline and thus Fe-depleted than oceanic arc magmas [18,22–25].

One major difference between continental arcs and oceanic arcs is crustal thickness, with continental arcs having thicker crusts. The influence of crustal thickness reflects the effect of pressure on magmatic differentiation. In thin-crust arcs (10–30 km) or oceanic arcs, FeO_T content in magmas shows

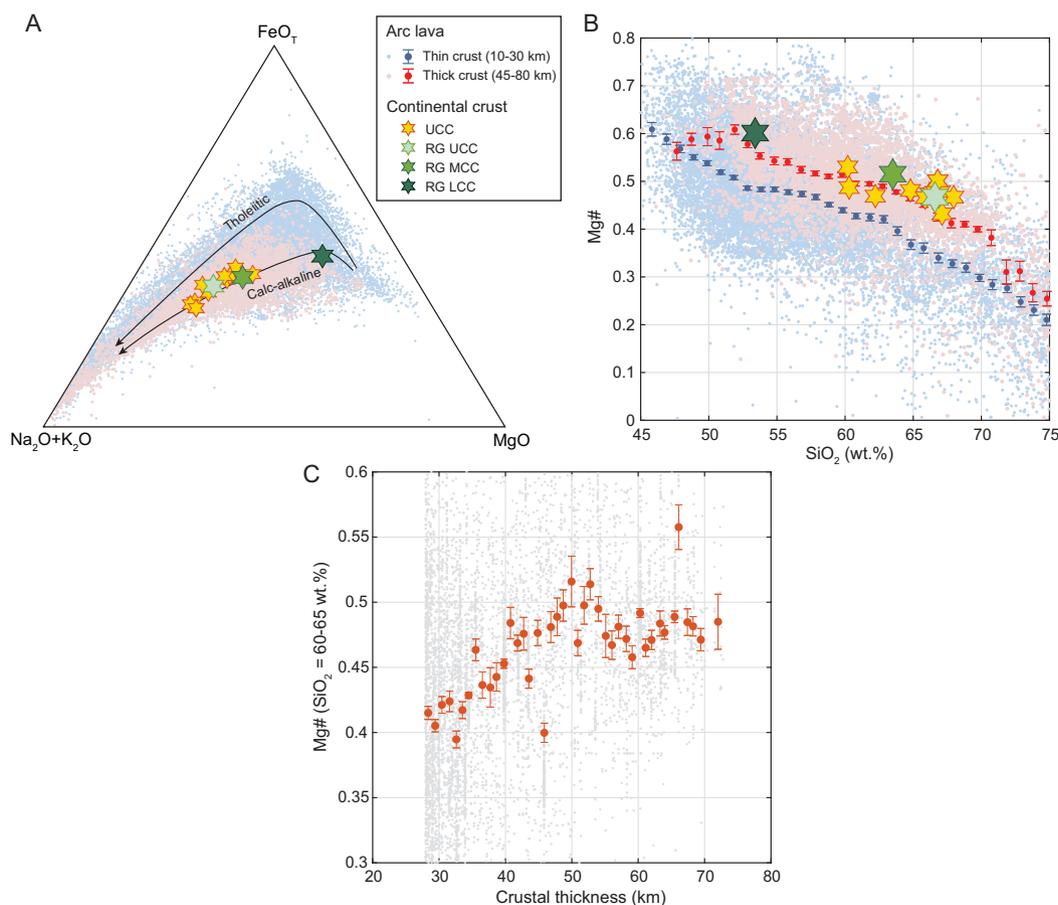


Figure 1. (A) AFM ($\text{K}_2\text{O}+\text{Na}_2\text{O}-\text{FeO}_T-\text{MgO}$) diagram showing the compositional evolution of lavas erupted in thin- and thick-crust arcs. (B) $\text{Mg}\#$ evolution of arc lavas. To show the systematic difference between thin- and thick-crust arc lavas, we also plot the binned averages with two standard errors. Bin width 1 wt% SiO_2 . For comparison, we plot the compositions of the upper, middle and lower continental crust estimated by Ref. [26] and various other estimates of the upper continental crust composition [27–37]. (C) Correlation of $\text{Mg}\#$ of arc lavas with $\text{SiO}_2 = 60\text{--}65$ wt% with crustal thickness. Bin width 1 km.

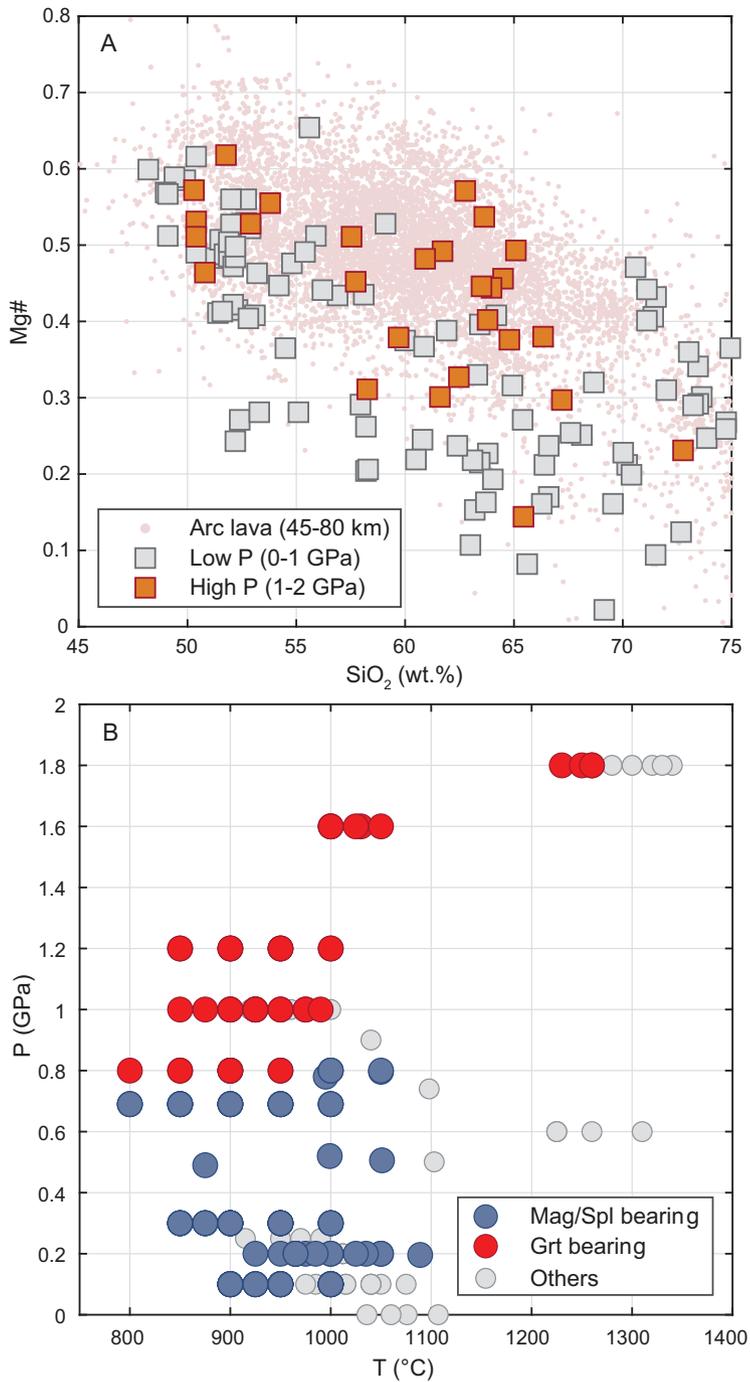


Figure 2. (A) Mg#–SiO₂ relationship for experimental melts generated under high and low pressures. We only plot experiments using basaltic starting materials in this panel. Natural samples from thick-crust arcs (45–80 km) are also plotted here for comparison. (B) Occurrences of magnetite/spinel (Mag/Spl) and garnet (Grt) in experiment products formed under various pressures and temperatures.

pronounced enrichment before declining in late stage (tholeiitic trend); in thick-crust arcs (45–80 km), or continental arcs, FeO_T content shows continuous depletion through nearly the entire differentiation range (calc-alkaline trend) (Fig. 1A).

What causes Fe depletion in arc magmas remains a contentious question. Many early studies suggested that Fe depletion in calc-alkaline differentiation results from early magnetite fractionation due to the oxidized and hydrous compositions of arc magmas [38–40]. However, this magnetite hypothesis cannot explain why Fe-depleting differentiation preferentially occurs in continental arcs. This is because high-pressure intracrustal differentiation in thick crusts strongly suppresses magnetite saturation as shown by both thermodynamic simulations [23] and experimental studies [41,42]. One additional difficulty with the magnetite hypothesis is that magnetite fractionation strongly depletes Fe³⁺ in the derivative melt and limits further magnetite fractionation. Thereby, a high initial oxygen fugacity typical of arc magmas is not enough; continuous magnetite fractionation requires a sustained influx of oxidants throughout magmatic differentiation, which is not supported by any observations so far.

An alternative hypothesis for Fe depletion argues for the role of Fe-rich silicate minerals, particularly garnet [18,43–45]. One major advantage of the garnet hypothesis is that garnet fractionation is favored at high pressures and high water contents. Although arc magma differentiation may involve complex interplay between crystal fractionation, assimilation and magma mixing, garnet (±amphibole) fractionation is critical and provides a straightforward explanation for the correlation between the extent of Fe depletion and crustal thickness. Recent work on Fe isotopes in andesites further supports the fractionation of garnet (±amphibole) as the primary driver of Fe depletion in arc magmas [46].

If one realizes the pressure effect on Fe, it becomes obvious that magmas formed in arcs of different crustal thicknesses should be treated separately when studying their Mg#. Our arbitrary division of the global arc lava data set shows that samples from thick-crust arcs have systematically higher Mg# than those from thin-crust arcs (Fig. 1B). The correlation of andesite Mg# with crustal thickness is further shown in Fig. 1C, in which andesite Mg# increases as crustal thickness increases from 30 to 50 km. Note that the average trend of thick-crust arc lavas overlaps with the compositions of the upper, middle and lower continental crust (Fig. 1B). This observation would suggest that high-pressure intracrustal differentiation, facilitated by synmagmatic crustal thickening, can generate felsic magmas with sufficiently high Mg# to match that of the continental crust.

The pressure effect on magma Mg# is also supported by crystallization/partial melting experiments. In Fig. 2A, we only plotted the results of experiments conducted using basalts (according to

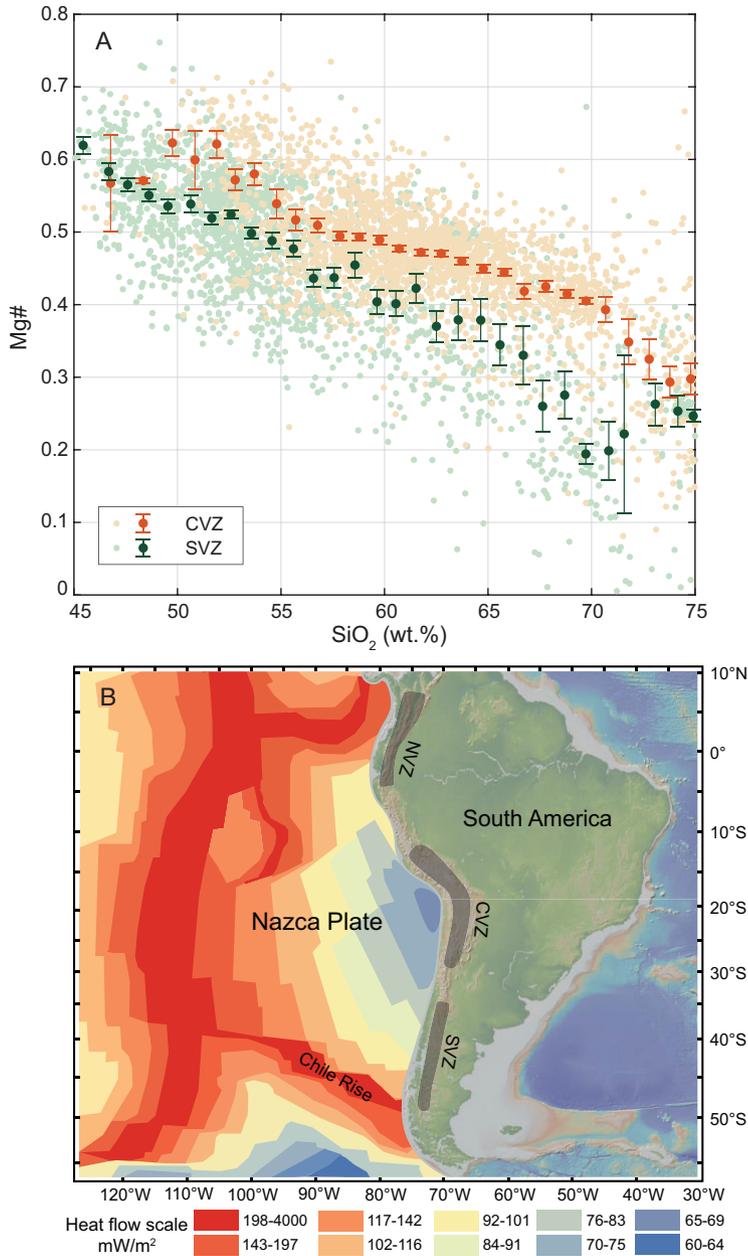


Figure 3. (A) Mg#–SiO₂ relationship for Central Volcanic Zone (CVZ) and Southern Volcanic Zone (SVZ) lavas in the Andean arc. Similar to Fig. 1B, the data are binned by SiO₂ content (bin width = 1 wt%) and the mean values and two standard errors are shown. (B) Map showing the locations of Northern Volcanic Zone (NVZ), CVZ and SVZ. Left half of the map is overlain by a heat flow map from Ref. [52].

the data sources) as starting materials. Experiments using differentiated starting materials may result in relatively low Mg# of the derivative melts. One such example is the study by [45]. The starting materials used by [45] have andesitic bulk compositions with Mg# of 0.40. This led to low Mg# of 0.15–0.42 of their derivative melts. The experiment data are somewhat scattered, possibly due to the compositional differences in starting materials, redox conditions and experimental/analytical artifacts.

Nevertheless, partial melts generated at high pressures (1–2 GPa) have systematically higher Mg# than those generated at low pressures (0–1 GPa) (Fig. 2A). Note that garnet is a common residual/crystallizing phase in high-pressure experiments, whereas magnetite is only present in experiments run under 1 GPa (Fig. 2B). These experiment data clearly show that high-pressure differentiation involving the fractionation of garnet, not magnetite, is efficient in increasing Mg# of the derivative melts. More importantly, the andesitic melts produced by high-pressure experiments broadly overlap with andesites from thick-crust arcs in this Mg#–SiO₂ plot.

Limited contributions from slab melting in continental arc lavas

What is the role of slab melting in generating the calc-alkaline lavas with high Mg# in continental arcs? Under appropriate conditions, subducted oceanic slabs may undergo partial melting in the mantle and produce silicic melts, which upon interaction with mantle peridotites may generate high-Mg# andesitic magmas [5,8–11,47]. Although high-pressure intracrustal differentiation is able to generate high-Mg# felsic magmas in continental arcs, is it possible that continental arc magmas also owe their high Mg# to significant inputs of slab melts equilibrated with peridotites? Insights to this question may come from the Andean arc.

The Central Andes, or the Central Volcanic Zone (CVZ), experienced substantial crustal thickening over the last ~25 Ma, reaching the modern thickness of 60–80 km [48]. The Southern Andes, or the Southern Volcanic Zone (SVZ), developed on a thinner continental crust of ~40 km [49]. The CVZ trend shows systematically higher Mg# than the SVZ trend (Fig. 3A). Slab melting requires hot geothermal gradients. In the Phanerozoic, such a condition is only met when the subducting slab is very young and thus warm [50,51]. If the elevated Mg# of the CVZ trend were due to the addition of peridotite-contaminated slab melts, one would expect the subducting plate beneath CVZ to be hotter. However, the opposite is true. The Nazca Plate currently subducting beneath CVZ exhibits a heat flow of 65–75 mW/m², which is significantly lower than that of the plate subducting beneath the SVZ (Fig. 3B). The hotter plate subducting beneath the SVZ is associated with the Chile Rise—a divergent plate boundary extending from the triple junction of the Nazca, Pacific and Antarctic plates to the Southern Andes. Because we only consider lavas of Pleistocene to Holocene ages here, we do not expect the slabs subducted in the last few million years to be significantly

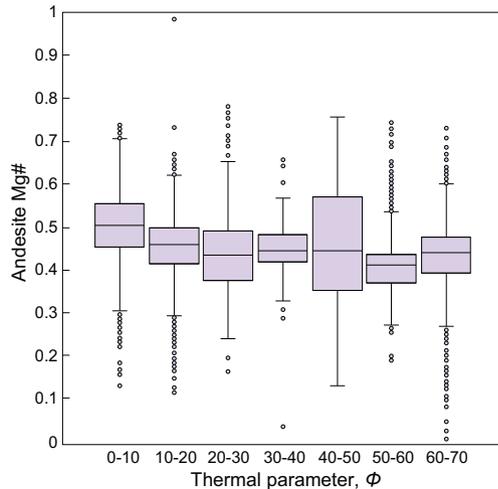


Figure 4. Box and whisker plot showing the relationship between andesite Mg# and subduction thermal parameter. The ends of the boxes show the upper and lower quartiles, and the ends of the whiskers show the 2.5 and 97.5 percentiles. Outliers are plotted as individual points.

different from those approaching the trenches today. These findings suggest that most high-Mg# andesites formed in continental arc settings are not associated with slab melting.

A survey of global andesite Mg# and slab temperature provides additional evidence to evaluate the role of slab melting in arc volcanism. The thermal parameter $\Phi = t^*v^*\sin\theta$, where t is age, v is slab subducting speed and θ is slab angle, has been frequently used as a proxy for the internal temperature of subducting slabs [53]. We find no clear correlation between andesite Mg# and subduction thermal parameter (Fig. 4). Because hot slabs are more likely to melt as they subduct, this lack of correlation suggests negligible contributions from slab melting to arc volcanism, at least on a global scale.

The Ni content of the continental crust has also been used to argue for slab-melt/peridotite interactions in the generation of the continental crust (e.g. [5,54]). Rudnick and Gao [26] estimated somewhat higher Ni contents in the continental crust, particularly the upper continental crust, than arc lavas of similar SiO₂ contents. However, unlike Mg#, the estimated Ni contents of the upper continental crust are highly variable and some are lower than in andesitic arc lavas (Fig. 5). This uncertainty compromises Ni as a useful tracer of slab-melt/peridotite interactions in continental crust formation based on current observations.

The role of magma mixing/recharge

Mixing between basaltic and granitic magmas can also generate andesites with high Mg#. This is shown by the apparent geochemical mixing trends and

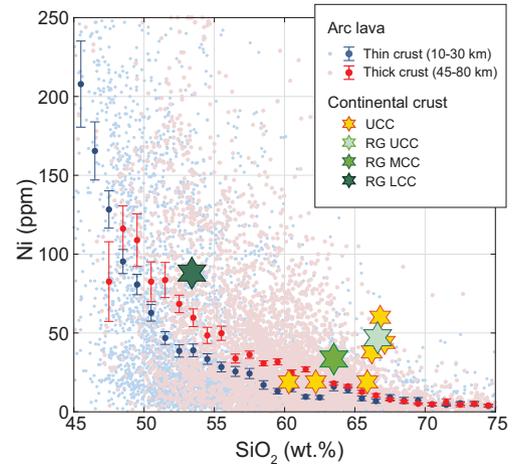


Figure 5. Ni-content evolution of arc lavas. Various estimates of Ni contents of the continental crust are plotted for comparison. These crustal composition estimates are from the same sources as those plotted in Fig. 1. Bin width 1 wt% SiO₂.

zoned phenocrysts found in high-Mg# andesites from several localities [55–57]. Nevertheless, the higher P₂O₅ contents in andesites than in most arc basalts and granites suggest that andesites cannot form by mixing basaltic and granitic magmas in most cases [58]. In fact, concave/convex trends are commonly seen in major and trace element Harker diagrams such as Ni–SiO₂ (Fig. 5), Al₂O₃–SiO₂ and FeO_T–MgO [59] for arc magma differentiation. These concave/convex differentiation trends are not consistent with magma mixing as the dominant process for arc magmas formation along the compositional spectrum because mixing would produce linear trends in element covariation diagrams.

More complex scenarios involving simultaneous magma recharge–fractionation have also been proposed to explain arc magma differentiation processes [60,61]. Extensive recharge tends to attenuate the depletions of compatible elements such as Mg and Fe²⁺ [60] and may fractionate Mg and Fe in evolved arc magmas if Mg and Fe have different compatibility. Magma recharge appears to be more efficient in thick-crust arcs [60,62], but Fe depletion becomes systematically enhanced with increasing crustal thickness [18,63], which is the opposite of what one would expect from magma recharge. This suggests that magma recharge alone cannot account for the behavior of compatible elements such as Mg and Fe in arc magma differentiation.

Implications for continental crust formation

The Mg# of the continental crust only appears high, or anomalous, if one compares it with magmas from

oceanic arcs. High-Mg# andesites form ubiquitously in continental arcs [64] and continental arc magmas have almost identical Mg# to the continental crust. This compositional difference between oceanic arc and continental arc magmas reflects the natural consequence of tholeiitic vs. calc-alkaline differentiation. In other words, the high Mg# of continental arc magmas and the continental crust results from Fe depletion instead of Mg addition.

Because calc-alkaline differentiation predominantly occurs in thick-crust arcs, synmagmatic crustal thickening appears to be key to continental crust formation [18,22,63]. Indeed, the upper continental crust has an average La/Yb of 15.4 [26], which is higher than that of average felsic magmas in oceanic arcs. The upper continental crust also has an elevated Dy/Yb ratio of ~2 compared with felsic oceanic arc lavas (average Dy/Yb ~1.6), which is a sign of garnet fractionation during continental crust formation. According to the empirical relationship between felsic rock La/Yb and crustal thickness from 16, the La/Yb of the upper continental crust indicates an average thickness of >50 km at the time of crust formation. While active arcs with crustal thickness of >50 km are less common today (mostly represented by the Northern and Central Andes), they are widely distributed in Earth's history. For example, Sierra Nevada, Kohistan, Gangdese, Coast Mountains and northern Mexican Cordillera were all once thickened to >50 km [16,65–67]. Today the preserved continental crust is ~34 km on average [68]. The contrasting thickness between the preserved crust and the crust at the time of formation suggests that extensive thinning must have taken place after the formation of the continental crust, possibly due to lower crust recycling or erosion [67,69–72].

There is no doubt that subducted materials contribute to arc magmatism [73]. In some places, there also appears to be irrefutable evidence for slab melting and generation of high-Mg# andesites in the mantle wedge [74]. However, our findings negate the need to invoke these processes as the dominant mechanism to explain the high Mg# of most continental arc magmas and the continental crust. The Mg# characteristics of the continental crust may be a natural consequence of intracrustal differentiation in thickened crust. On early Earth, hot subduction could have been more common [75,76], but even in the Archean, magmatic rocks show an average Mg#–SiO₂ trend almost identical to that of mature continental arcs today [77]. Thereby, the chemical consequences of the igneous differentiation processes that formed the continental crust may have been similar over Earth's history.

CONCLUSIONS

Magma Mg# differs between thick-crust continental arcs and thin-crust oceanic arcs. Andesites with Mg# of >0.5 are ubiquitous in continental arcs and continental arc magmas show an average Mg# similar to that of the continental crust. The pervasively high Mg# in continental arc magmas and the continental crust results from calc-alkaline intracrustal differentiation characterized by continuous Fe depletion. The comparable Mg# characteristics between the continental crust and continental arc magmas hint at synmagmatic crustal thickening as a critical process in the formation of the continental crust.

SUPPLEMENTARY DATA

Supplementary data are available at [NSR](https://doi.org/10.1093/nsr/nwac258) online.

ACKNOWLEDGEMENTS

We are grateful for the insightful discussions with Drs. Cin-Ty Lee, Yong-Fei Zheng, and Xianlei Geng. We thank Dr. Michael Farner for sharing the raw data from the [22] study. The constructive comments provided by Peter A. Cawood and two anonymous reviewers significantly improved the manuscript.

FUNDING

This work was financially supported by National Natural Science Foundation of China (42125302, 42073026, 41888101 and 42073024). M.T. is grateful for the support from the Explorer Prize.

AUTHOR CONTRIBUTIONS

M.T. initiated the idea and wrote the original manuscript. X.L. compiled the experiment data and made some of the figures. K.C. contributed to data interpretation. All authors took part in manuscript writing.

Conflict of interest statement. None declared.

REFERENCES

1. Taylor SR. The origin and growth of continents. *Tectonophysics* 1967; **4**: 17–34.
2. Taylor SR. Island arc models and the composition of the continental crust. *Island Arcs, Deep Sea Trenches and Back-Arc Basins* 1977; **1**: 325–35.
3. Kelemen P, Hanghøj K and Greene A. One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust. *Treatise on Geochemistry* 2003; **3**: 659.

4. Shimoda G, Tatsumi Y and Nohda S *et al.* Setouchi high-Mg andesites revisited: geochemical evidence for melting of subducting sediments. *Earth Planet Sci Lett* 1998; **160**: 479–92.
5. Kelemen PB. Genesis of high Mg# andesites and the continental crust. *Contrib Mineral Petrol* 1995; **120**: 1–19.
6. Martin H. Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas. *Geology* 1986; **14**: 753–6.
7. Zheng Y-F, Xia Q-X and Chen R-X *et al.* Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. *Earth-Sci Rev* 2011; **107**: 342–74.
8. Kay R. Aleutian magnesian andesites: melts from subducted Pacific Ocean crust. *J Volcanol Geotherm Res* 1978; **4**: 117–32.
9. Tsuchiya N, Suzuki S and Kimura J-I *et al.* Evidence for slab melt/mantle reaction: petrogenesis of Early Cretaceous and Eocene high-Mg andesites from the Kitakami Mountains, Japan. *Lithos* 2005; **79**: 179–206.
10. Yogodzinski G and Kelemen P. Slab melting in the Aleutians: implications of an ion probe study of clinopyroxene in primitive adakite and basalt. *Earth Planet Sci Lett* 1998; **158**: 53–65.
11. Chen L, Zheng Y-F and Xu Z *et al.* Generation of andesite through partial melting of basaltic metasomatites in the mantle wedge: insight from quantitative study of Andean andesites. *Geosci Front* 2021; **12**: 101124.
12. Straub SM, Gomez-Tuena A and Stuart FM *et al.* Formation of hybrid arc andesites beneath thick continental crust. *Earth Planet Sci Lett* 2011; **303**: 337–47.
13. Kelemen P, Yogodzinski G and Scholl D. Along-strike variation in lavas of the Aleutian island arc: implications for the genesis of high Mg# andesite and the continental crust. In: Eiler J (ed.). *Inside the Subduction Factory, Geophysical Monograph*. Washington DC: American Geophysical Union, 2003.
14. Lee C and King SD. Why are high-Mg# andesites widespread in the western Aleutians? A numerical model approach. *Geology* 2010; **38**: 583–6.
15. Tatsumi Y. High-Mg andesites in the Setouchi volcanic belt, southwestern Japan: analogy to Archean magmatism and continental crust formation? *Annu Rev Earth Planet Sci* 2006; **34**: 467–99.
16. Profeta L, Ducea MN and Chapman JB *et al.* Quantifying crustal thickness over time in magmatic arcs. *Sci Rep* 2015; **5**: 17786.
17. Chiaradia M. Crustal thickness control on Sr/Y signatures of recent arc magmas: an Earth scale perspective. *Sci Rep* 2015; **5**: 8115.
18. Tang M, Erdman M and Eldridge G *et al.* The redox ‘filter’ beneath magmatic orogens and the formation of continental crust. *Sci Adv* 2018; **4**: eaar4444.
19. Tang M, Lee C-TA and Ji W-Q *et al.* Crustal thickening and endogenic oxidation of magmatic sulfur. *Sci Adv* 2020; **6**: eaba6342.
20. Turner SJ and Langmuir CH. The global chemical systematics of arc front stratovolcanoes: evaluating the role of crustal processes. *Earth Planet Sci Lett* 2015; **422**: 182–93.
21. Chin EJ, Shimizu K and Bybee GM *et al.* On the development of the calc-alkaline and tholeiitic magma series: a deep crustal cumulate perspective. *Earth Planet Sci Lett* 2018; **482**: 277–87.
22. Farner MJ and Lee C-TA. Effects of crustal thickness on magmatic differentiation in subduction zone volcanism: a global study. *Earth Planet Sci Lett* 2017; **470**: 96–107.
23. Tang M, Lee C-TA and Costin G *et al.* Recycling reduced iron at the base of magmatic orogens. *Earth Planet Sci Lett* 2019; **528**: 115827.
24. Chiaradia M. Copper enrichment in arc magmas controlled by overriding plate thickness. *Nat Geosci* 2014; **7**: 43–6.
25. Zheng Y-F and Chen Y-X. Continental versus oceanic subduction zones. *Natl Sci Rev* 2016; **3**: 495–519.
26. Rudnick RL and Gao S. 4.1: Composition of the continental crust. In: Holland HD and Turekian KK (eds). *Treatise On Geochemistry*, 2nd edn. Oxford: Elsevier, 2014, 1–51.
27. Clarke FW. The relative abundance of the chemical elements. *Bulletin of the Philosophical Society of Washington* 1889; **11**: 135–43.
28. Clarke FW and Washington HS. *The Composition of the Earth’s Crust*. Washington DC: US Government Printing Office, 1924.
29. Fahrig W and Eade K. The chemical evolution of the Canadian Shield. *Can J Earth Sci* 1968; **5**: 1247–52.
30. Goldschmidt V. Grundlagen der quantitativen Geochemie. *Fortschr Mineral Krist Petrog* 1933; **17**: 112–56.
31. Ronov A and Yaroshevskiy A. A new model for the chemical structure of the Earth’s crust. *Geokhimiya* 1976; **12**: 1761–95.
32. Shaw D, Reilly G and Muysson J *et al.* An estimate of the chemical composition of the Canadian Precambrian Shield. *Can J Earth Sci* 1967; **4**: 829–53.
33. Taylor SR and McLennan SM. *The Continental Crust: Its Composition and Evolution*. Oxford: Blackwell, 1985.
34. Condie KC. Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. *Chem Geol* 1993; **104**: 1–37.
35. Gao S, Luo T-C and Zhang B-R *et al.* Chemical composition of the continental crust as revealed by studies in East China. *Geochim Cosmochim Acta* 1998; **62**: 1959–75.
36. Wedepohl KH. The composition of the continental crust. *Geochim Cosmochim Acta* 1995; **59**: 1217–32.
37. Borodin L. Estimated chemical composition and petrochemical evolution of the upper continental crust. *Geochem Int* 1999; **37**: 723–34.
38. Osborn EF. Role of oxygen pressure in the crystallization and differentiation of basaltic magma. *Am J Sci* 1959; **257**: 609–47.
39. Zimmer MM, Plank T and Hauri EH *et al.* The role of water in generating the Calc-alkaline trend: new volatile data for aleutian magmas and a new tholeiitic index. *J Petrol* 2010; **51**: 2411–44.
40. Sisson TW and Grove TL. Experimental investigations of the role of H₂O in calc-alkaline differentiation and subduction zone magmatism. *Contr Mineral and Petrol* 1993; **113**: 143–66.
41. Matjuschkin V, Blundy JD and Brooker RA. The effect of pressure on sulphur speciation in mid- to deep-crustal arc magmas and implications for the formation of porphyry copper deposits. *Contrib Mineral Petrol* 2016; **171**: 66.
42. Spulber SD and Rutherford MJ. The origin of rhyolite and plagiogranite in oceanic crust: an experimental study. *J Petrol* 1983; **24**: 1–25.
43. Green DH and Ringwood AE. The stability fields of aluminous pyroxene peridotite and garnet peridotite and their relevance in upper mantle structure. *Earth Planet Sci Lett* 1967; **3**: 151–60.
44. Green TH. Crystallization of calc-alkaline andesite under controlled high-pressure hydrous conditions. *Contr Mineral and Petrol* 1972; **34**: 150–66.
45. Alonso-Perez R, Müntener O and Ulmer P. Igneous garnet and amphibole fractionation in the roots of island arcs: experimental constraints on andesitic liquids. *Contrib Mineral Petrol* 2009; **157**: 541–58.
46. Du D-H, Tang M and Li W *et al.* What drives Fe depletion in calc-alkaline magma differentiation: insights from Fe isotopes. *Geology* 2022; **50**: 552–6.
47. Xu W, Gao S and Wang Q *et al.* Mesozoic crustal thickening of the eastern North China craton: evidence from eclogite xenoliths and petrologic implications. *Geology* 2006; **34**: 552–6.
48. Allmendinger RW, Jordan TE and Kay SM *et al.* The evolution of the Altiplano-Puna plateau of the Central Andes. *Annu Rev Earth Planet Sci* 1997; **25**: 139–74.

49. Bohm M, Lüth S and Echtler H *et al.* The Southern Andes between 36° and 40° S latitude: seismicity and average seismic velocities. *Tectonophysics* 2002; **356**: 275–89.
50. Sdrolias M and Müller RD. Controls on back-arc basin formation. *Geochem Geophys Geosyst* 2006; **7**: Q04016.
51. Syracuse EM and Abers GA. Global compilation of variations in slab depth beneath arc volcanoes and implications. *Geochem Geophys Geosyst* 2006; **7**: Q05017.
52. Davies JH. Global map of solid Earth surface heat flow. *Geochem Geophys Geosyst* 2013; **14**: 4608–22.
53. Kirby SH, Stein S and Okal EA *et al.* Metastable mantle phase transformations and deep earthquakes in subducting oceanic lithosphere. *Rev Geophys* 1996; **34**: 261–306.
54. Kelemen P. Origin of high Mg# andesite and the continental crust. *Mineral Mag* 1994; **58**: 464–5.
55. Conway CE, Chamberlain KJ and Harigane Y *et al.* Rapid assembly of high-Mg andesites and dacites by magma mixing at a continental arc stratovolcano. *Geology* 2020; **48**: 1033–7.
56. Geng X, Liu Y and Wang XC *et al.* The role of Earth's deep volatile cycling in the generation of intracontinental high-Mg andesites: implication for lithospheric thinning beneath the North China Craton. *J Geophys Res Solid Earth* 2019; **124**: 1305–23.
57. Streck MJ, Leeman WP and Chesley J. High-magnesian andesite from Mount Shasta: a product of magma mixing and contamination, not a primitive mantle melt. *Geology* 2007; **35**: 351–4.
58. Lee C-TA and Bachmann O. How important is the role of crystal fractionation in making intermediate magmas? Insights from Zr and P systematics. *Earth Planet Sci Lett* 2014; **393**: 266–74.
59. Keller CB, Schoene B and Barboni M *et al.* Volcanic-plutonic parity and the differentiation of the continental crust. *Nature* 2015; **523**: 301–7.
60. Lee C-TA, Lee TC and Wu C-T. Modeling the compositional evolution of recharging, evacuating, and fractionating (REFC) magma chambers: implications for differentiation of arc magmas. *Geochim Cosmochim Acta* 2014; **143**: 8–22.
61. O'Neill SC and Jenner FE. The global pattern of trace-element distributions in ocean floor basalts. *Nature* 2012; **491**: 698–704.
62. Hildreth W and Moorbath S. Crustal contributions to arc magmatism in the Andes of Central Chile. *Contrib Mineral and Petrol* 1988; **98**: 455–89.
63. Tang M. Composition of the Earth's crust. In: Alderton D and Elias SA (eds). *Encyclopedia of Geology*, 2nd edn. Oxford: Academic Press, 2021, 178–86.
64. Wang J, Dan W and Wang Q *et al.* High-Mg# adakitic rocks formed by lower-crustal magma differentiation: mineralogical and geochemical evidence from garnet-bearing diorite porphyries in central Tibet. *J Petrol* 2021; **62**: ega0099.
65. Chapman JB, Greig R and Haxel GB. Geochemical evidence for an orogenic plateau in the southern US and northern Mexican Cordillera during the Laramide orogeny. *Geology* 2020; **48**: 164–8.
66. Zhu D-C, Wang Q and Cawood PA *et al.* Raising the Gangdese Mountains in southern Tibet. *J Geophys Res Solid Earth* 2017; **122**: 214–23.
67. Jagoutz O and Schmidt MW. The composition of the foundered complement to the continental crust and a re-evaluation of fluxes in arcs. *Earth Planet Sci Lett* 2013; **371–2**: 177–90.
68. Huang Y, Chubakov V and Mantovani F *et al.* A reference Earth model for the heat-producing elements and associated geoneutrino flux. *Geochem Geophys Geosyst* 2013; **14**: 2003–29.
69. Ducea MN and Saleeby JB. The age and origin of a thick mafic–ultramafic keel from beneath the Sierra Nevada batholith. *Contrib Mineral Petrol* 1998; **133**: 169–85.
70. Lee CTA. 4.12: Physics and chemistry of deep continental crust recycling. In: Holland HD and Turekian KK (eds). *Treatise On Geochemistry*, 2nd edn. Oxford: Elsevier, 2014, 423–56.
71. Tang M, Rudnick RL and McDonough WF *et al.* Europium anomalies constrain the mass of recycled lower continental crust. *Geology* 2015; **43**: 703–6.
72. Lee C-TA, Morton DM and Little MG *et al.* Regulating continent growth and composition by chemical weathering. *Proc Natl Acad Sci USA* 2008; **105**: 4981–6.
73. Bebout GE. 4.20: Chemical and isotopic cycling in subduction zones. In: Holland HD and Turekian KK (eds). *Treatise on Geochemistry*, 2nd edn. Oxford: Elsevier, 2014, 703–47.
74. Drummond MS and Defant MJ. A model for Trondhjemite-Tonalite-Dacite Genesis and crustal growth via slab melting: Archean to modern comparisons. *J Geophys Res* 1990; **95**: 21503–21.
75. Cawood PA. Earth matters: a tempo to our planet's evolution. *Geology* 2020; **48**: 525–6.
76. Zheng Y-F and Zhao G. Two styles of plate tectonics in Earth's history. *Science Bulletin* 2020; **65**: 329–34.
77. Tang M, Lee C-TA and Rudnick RL *et al.* Rapid mantle convection drove massive crustal thickening in the late Archean. *Geochim Cosmochim Acta* 2020; **278**: 6–15.