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Petrochronology applied into evaluating the tectono-metamorphic context from rocks of the Turvo-Cajati Formation, Curitiba Terrane, and its influence in the Ribeira Belt Evolution, Cajati, SP

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COMISSÃO JULGADORA

Dr. Renato de Moraes

Dr. Maurício Pavan Silva

Dra. Kathryn Ann Cutts

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Orientador: Prof. Dr. Renato de Moraes

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À Mª Estela,

(in memoriam)

você é a luz que me guia e protege

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"It is a journey of evolution, adaptation. The journey we all take. The journey that unites each and every one of us"

Charlie Kaufman, Adaptation

RESUMO

Orógenos acrescionários antigos occrem em todo o globo e sua reconstrução apresenta desafios uma vez que grande parte de informação foi perdida. A Faixa Ribeira, SE do Brasil, é um exemplo de um orógeno acrescionário formado durante a amalgamação do Gondwana, no neoproterozoico. O entendimento da sua evolução tectonometamórfica é um trabalho em contínuo progresso. Nesse estudo, nós focamos em sua porção sul, especificamente no Terreno Curitiba. Diferentes técnicas são usadas para entender os ambientes de sedimentação e metamorfismo para uma unidade metassedimentar, a Formação Turvo-Cajati (TCF). Para avaliar o ambiente de sedimentação, zircão detrítico e gráficos de densidade de probabilidade são apresentados. Para entender o metamorfismo, geocronologia de alta resolução *in-situ* acoplada com modelagem termodinâmica sistemática para obter as trajetórias *P-T*-t que algumas rochas experimentaram. Um mapa de distribuição de isógradas também é apresentado baseado em trabalho de campo e petrografia. Nessa unidade, xistos e paragneisses de diferentes condições metamórficas afloram e assume-se que pertencem à mesma unidade (TCF). A unidade é dividida em três sub-unidades baseadas no seu grau metamórfico, a Low-TCF na zona da granada, a Medium-TCF na zona da sillimanita e a High-TCF na zona do feldspato potássico-cianita/sillimanita com fusão parcial. Zircão detrítico indica que as amostras da Low/Medium-TCF guarda assinaturas de uma bacia de retroarco e a High-TCF de prisma acrescionário. Ele também indica idade máxima de deposição entre 650-630 Ma. O metamorfismo foi delimitado usando petrografia, modelagem de pseudosseções nos sistemas MnKCKFMASHTO e NCKFMASHTO com o software Perplex. A idade do metamorfismo foi obtida através de datação isotópica e química. Diagramas de fase *P-T* são modelados para um grande conjunto de amostras tanto considerando fracionamento de diferentes estágios de crescimento de granada quanto composição de rocha total convencional. Cada amostra foi modelada para obter as condições *P-T* de diferentes estágios metamórficos e trajetórias *P-T*-t foram obtidas. Elas indicam uma evolução complexa, mesmo em rochas da mesma zona metamórfica. As idades de monazita indicam metamorfismo compartilhado na High-TCF e na Medium-TCF com crescimento de monazita entre 620-580 Ma, mas duas amostras recordam idades mais velhas (~640 Ma). Esse período entre 640-600 Ma antecipa o entendimento atual da duração do metamorfismo, que se sobrepõe parcialmente com os estágios finais de deposição. Comparando os gradientes metamórficos de campo e as trajetórias *P-T*-t na High-TCF e na Low/Medium-TCF, a relação dos eventos metamórficos pode ser melhor entendida. Razões termobáricas e regimes de pressão bimodais são observados ao interpretar um conjunto extenso de amostras. Portanto, é proposto um microcontinente tipo-Japão onde a Low/Medium-TCF estaria na bacia de retroarco e o a High-TCF no prisma acrescionário. Esse microcontinente também envolve os ortognaisses riacianos do Complexo Atuba como embasamento e o Arco Magmático Piên como resultado de um ambiente de subducção-a-colisão. Esse cenário evoluiu surante pelo menos 60 Ma (640-580 Ma) onde a colisão com o microcontinente Luis Alves causaria a maior parte do metamorfismo e a exumação dessas rochas. Finalmente, em algum momento por volta de 580 Ma, a instauração de zonas de cisalhamento de larga escala e granitos tipo A da Província Graciosa marca o fim desses eventos.

Palavras-chave: orógeno acrescionário, evolução metamórfica, datação de monazita, petrocronologia, Faixa Ribeira

SUMMARY

LIST OF FIGURES

Figures and Tables are listed per chapter:

CHAPTER 2

CHAPTER 3

LIST OF TABLES

Figures and Tables are listed per chapter:

CHAPTER 2

CHAPTER 3

CHAPTER 1 - INTRODUCTION

The Ribeira Belt is a major tectonic segment in SE-Brazil. It occurs between Brazilians states of Espírito Santo and Santa Catarina. It is composed of units with different tectonic origins such as Archean-Paleoproterozoic basement, Proterozoic metasedimentary units and late-Ediacaran igneous provinces (e.g., Heilbron et al., 2000, 2017, Meira et al., 2019). It can be divided in Northern, Central and Southern parts and several studies have been made on the last decades on all of them from different research groups in Brazil and abroad (e.g. Cordani et al., 1973, Almeida et al., 1981, Heilbron et al., 2017 and references there in, and more recently Campanha et al., 2019, Malta et al., 2020, Ribeiro et al., 2019, Meira et al., 2015, Cavalcante et al., 2018; Ricardo et al., 2020).

This study is focused on the Southern Ribeira Belt that comprises four tectonic domains: the Embu, Apiaí, Curitiba and Costeiro/Paranaguá Terranes (Basei et al., 1992; Faleiros et al., 2011; Passarelli et al., 2018). They have been interpreted as tectonic segments with distinct evolutionary histories that collided in the Neoproterozoic. This collision involved the São-Francisco, Paranapanema, Luís Alves and Rio de la Plata Plates with the closure of the Adamastor Ocean and resulted in the formation of Western Gondwana (Brito Neves et al., 1999).

This theory was recently questioned. Recent studies suggest another context where the Ribeira Belt would be an intracontinental orogen, formed at ~620 Ma, when metamorphic events of intermediate *P* happened (Meira et al., 2019). According to the authors, this event was followed by an extensional and wrench tectonics low-P event associated with orogenic collapse. This event occurred ~575 Ma and can be related to strike-slip shear zones and voluminous peraluminous magmatism (Meira et al., 2019). This study is made on the Embu Terrane, Central Ribeira belt but the authors suggest the tectonic context can be expanded to the Southern Ribeira Belt as a whole.

Even though lots of studies are being conducted on the Southern Ribeira Belt (e.g. Faleiros et al., 2011, 2016, Passarelli et al., 2018, 2019, Campanha & Sadowiski, 1999, Campanha et al., 2015) just a few of them had the Curitiba Terrane as the main object of study. This lack of recent studies is even greater in the metasedimentary units that composes the terrane, the Turvo-Cajati (TCF) and Capiru Formations. From the first we highlight Faleiros et al., (2011, 2016) and from Capiru Formation, Guimarães et al., (2002) and Santos et al., (2018). Nevertheless, the studies conducted on the TCF only focus on gneiss and migmatitic rocks, even though lower *P-T* conditions rocks were already described on literature for this unit (e.g. Faleiros & Pavan, 2013).

The Curitiba Terrain occurs between a Mesoproterozoic Terrane (Apiaí Terrane) and an Archean/Paleoproterozoic craton (Luis Alves Terrane). This makes the understanding of the Curitiba Terrane an important piece on the Ribeira Belt tectonic puzzle. Therefore, this study is focused on the never studied metapelitic schists and phyllites from the TCF. It aims to have a better picture on both the metamorphic and sedimentary events that affected the unit and correlate them with other units forming the Curitiba Terrane.

1. Methods

The main goal of this study is to obtain more detailed information about the metamorphic events that affected the Turvo-Cajati Formation. The methodology is based on field work, detailed and extensive petrography, chemical and isotopic analysis based on U-Pb method. The field work is used to understand the isograd distribution, structural geological control and sample collection. Petrography was performed not only on samples collected on field work, but also in material from the Brazilian Geological Survey (CPRM). Some samples were selected for more detailed studies such as mineral chemistry on EPMA (electron probe micro-analyzer), thermodynamic modeling and U-Pb/trace element on monazite dating.

The study then is divided in 2 complementary approaches. The first one aimed to have a broad understanding on the metamorphism and to complement this information, the sedimentary provenance from the TCF is also studied. Samples were selected to chemical studies on the EPMA, followed by a classical, less detailed approach on thermodynamic modeling. It was complemented with detrital zircon information to produce a preliminary tectonic model. This part of the study was published in May 2020 in *Precambrian Research.* The paper is entitled '*Tectonic implications of juxtaposed high- and low-pressure metamorphic field gradient rocks in the Turvo-Cajati Formation, Curitiba Terrane, Ribeira Belt, Brazil*' and can be found on **CHAPTER 2** of this dissertation.

The second part of the study aimed to detail the metamorphic *P-T*-t paths that different rocks from the TCF passed through and its tectonic implications to the TCF evolution. To obtain this, systematic thermodynamic modeling was implemented considering both local equilibrium and how it is affected by process such as elements imprisoned during garnet growth. Therefore, more than one pseudosection is modeled to garnet-bearing samples considering the best *P-T* estimative for each stage of garnet growth. The timing-scale is obtained by monazite U-Pb dating. Two methods were implemented: chemical dating on EPMA and isotopic dating and trace element composition obtained with LA-ICP-MS technique. A paper for this part of the research is being developed and will be submitted to acceptance in a petrological journal such as the *Journal of Metamorphic Geology*, *Lithos* or similar. A draft of the article containing the results and preliminary interpretation can be found on this dissertation on **CHAPTER 3**.

Combining all the information collected during the MSc research, discussions about the evolution of the TCF are also presented in **CHAPTER 4**. A discussion of the implications of this study on the Curitiba Terrane picture is also presented. Finally, it is expected that this MSc can contribute not only to the Ribeira Belt research, but also to evaluate the importance of using detailed studies and petrochronology to evaluate *P-T*-t evolution of metapelites even though some challenges may appear while applying such techniques. More detailed information about each methodology can be found in each article's respective Material and Methods sections.

CHAPTER 4 - DISCUSSIONS

Detailed metamorphic studies were previously conducted in the TCF (Faleiros et al., 2011, 2016). Nevertheless, the authors focused the investigation on the high-grade rocks with evidence of partial melting. Faleiros et al. (2011) present the most important contribution to the area detailing the metamorphic conditions to rocks from two different metamorphic zones in the TCF: the Kyanite-K-feldspar Zone and the Sillimanite-K-feldspar Zone. The authors used conventional geothermobarometry compiled with thermodynamic modelling to obtain the *P-T* peak conditions and the Gibbs method to constrain *P-T* paths. They obtained *P-T* conditions between 670-810 °C and 9.5-12 kbar as the metamorphic peaks to the rocks from the High-TCF. As for the trajectories they obtained, they interpret that the rocks from the Kyanite-K-feldspar zone as a near isobaric heating and the rocks from the Sillimanite-K-feldspar zone as a near isothermal decompression. They also obtained U-Pb chemical dating of monazite to constrain the metamorphic events in the area. They obtained 589 ± 12 Ma as the metamorphic peak followed by a greenschist facies overprint at 579 ± 8 Ma that they interpret to be related to the instauration of regional shear zones (Faleiros et al., 2011). Faleiros et al. (2016) also studied the High-TCF but from a different front. The authors present the first detrital zircon results to the area to one sample from the Kyanite-K-felspar Zone. They indicate that the maximum depositional age for the unit is between 650-630 Ma.

In this MSc dissertation, we investigated samples on the TCF that were not studied before. Metapelites from the garnet, staurolite and sillimanite zones crop out in the area and they were not investigated before. The MSc aimed to evaluate the tectonic evolution of those rocks and compare them to previous studies in the High-TCF. Some contributions to both the methodology and the tectonic understanding of the area will be addressed below.

To have a better understanding on the evolution of the unit, two fronts were approached. The first to collect data about the sedimentation conditions of the previous basin that originated the current TCF. Therefore, in Ricardo et al. (2020) (**section 2.0** in this manuscript) new and greater detrital zircon analysis are compiled and compared. Data from four new samples are presented and compared to the sample presented by Faleiros et al. (2016). Probability density plots are presented for samples from the Low-TCF (FS-21, DR-39), Medium-TCF (FM-426 and BR116-32) and sample 129A from the High-TCF from Faleiros et al. (2016). They indicate a shared source of detrital zircon with common peaks at 2300-1950 Ma, 1850-1700 Ma, 1550-1400 Ma and 1300-1100 Ma. Nevertheless, the youngest and highest peak is dislocated when samples from the Medium/High-TCF are compared to the Low-TCF. High/Medium-TCF have a higher peak at ~680-660 Ma and samples from the Low-TCF at ~800 Ma. Nevertheless, they also record younger ages with less prominence. The interpretation to this difference is the distance to the source. Low-TCF is interpret as more distal to the source than Medium/High-TCF.

The other shared age peaks indicate that the sub-units share source areas, therefore they are at least, neighbor basins. The older peak at 2300-1950 Ma is compatible with the main age population of the Atuba Complex (2200-2100 Ma, Sato et al., 2003, 2009). Therefore, the Atuba Complex is a potential detrital source to TCF, and possibly the basement to the TCF basin. Interpreting the probability density plots (pdp) and comparing to the tectonic setting proposed by Cawood et al. (2012), the pdp obtained to the Low and Medium-TCF present curves similar to back-arc basin setting, i.e. higher amount of older detrital zircons from the adjoining craton and greater younger peak. On the other hand, the High-TCF present a pdp plot similar to an accretionary wedge setting proposed by Cawood et al. (2012), i.e. faster deposition on the peak reflected by smaller number of analysis and lower contribution of older detrital zircon/basement.

To evaluate the metamorphism that affected those rocks, the initial approach was to have a general constrain on the *P-T* peak conditions that affected the rocks in the area. By compiling field work, data from previous studies and petrography, it was possible to evaluate the isograd distribution of the sub-units. It becomes clear that the sillimanite zone is the main zone in the Medium-TCF. This already indicates that rocks from this sub-unit passed through metamorphism below 6 kbar in the sillimanite stability field. Thermodynamic modelling was then implemented to constrain the *P-T* peak for some samples. Two samples were selected from the garnet zone in the Low-TCF (DR39 and DR206) and one sample from the sillimanite-staurolite zone (DR151). Pseudosection modelling indicates that metamorphic peak to these samples were reached at 530-560 °C, 6.0-7.0 kbar (DR39), 550-580 °C, 7.0-7.6 kbar (DR206) and 640-670 °C, 5.9-7.0 kbar (DR151).

This pressure regime (6.0-7.5 kbar) contrasts with the pressure conditions obtained to the High-TCF (~10-12 kbar). They also indicate different metamorphic field gradients when comparing the Low/Medium-TCF *P-T* peak conditions and the High-TCF. Faleiros et al. (2011) studying the High-TCF obtained these 10-12 kbar pressures and trajectories of quick exhumation associated with isothermal decompression. They already interpret that this could be a subduction-related metamorphic setting, probably in the accretionary wedge. The pressure regime (6.0-7.5 kbar) on the Low/Medium-TCF, on the other hand indicates a low-*P* regime that could be related to the metamorphism on the back-arc setting with an increase in temperature caused by an asthenospheric upwelling due to extension. This metamorphic contrast between a high-*P* (High-TCF) and low-*P* (Low/Medium-TCF) metamorphic setting associated is interpret as a paired metamorphic belt in a Japan-like microcontinent (Brown, 2006, Brown &. Johnson, 2018).

Based on the sedimentation setting and the metamorphic *P-T* peaks obtained for all TCF sub-units, a modeled is proposed for the evolution of the area and is presented in Ricardo et al. (2020) and in the session 3 of this dissertation. In this model, we interpret that rocks from the TCF developed in related but different settings. Both the sedimentation and the metamorphic data indicate that the Low and Medium-TCF would be in the back-arc setting. On the other hand, the High-TCF sedimentation and metamorphic setting indicate that the unit would be in the accretionary wedge. Those basins are correlated with a shared micro-continent that would be both the basement and detrital source to both basins. Based on the detrital zircon record, we interpret that the Atuba Complex could be this basement, forming this Japan-like microcontinent, the proto-Curitiba Terrane Microplate. The subduction of part of the Adamastor Ocean would cause the development of a magmatic arc, the Piên Magmatic Arc. This arc is the main source for those younger detrital grains in both TCF basins in the back-arc and the accretionary wedge. The development of this magmatic arc is long-lived and between 630-610 Ma, it would reach its final stages before the final collision with the Luis Alves Microcontinent. This collision at 600-585 Ma would have caused the main metamorphism in the back-arc (Low/Medium-TCF), also in the accretionary wedge (High-TCF) and exhumation of this sub-unit.

Nevertheless, the evaluation of the metamorphic conditions was made without considering the fractionation that occurs within garnet grains that affects the reactive bulk composition (Cutts et al., 2009, 2010). Therefore, more detail and systematic thermodynamic modelling was made to obtain the *P-T*-t paths that the rocks passed by and the possible implications on the tectonic evolution model. Metamorphic temporal data was also collected with petrochronology of monazite with both isotopic and chemical dating, with LA-ICP-MS and EPMA techniques, respectively. The results of this approach are discussed in the section 4 of this dissertation.

Phase diagrams were modeled in the MnNCKFMASHTO chemical system considering the evolution of the effective bulk composition to three samples from the Medium-TCF (BR04, DR352 and DR378). A *P-T* path is also proposed to each sample based on the *P-T* conditions constrained with isopleths of mineral compositions. Sample DR378 is in the staurolite zone, the *P-T* conditions calculated to the growth of garnet core is 520-530 °C and ~8.2 kbar and for the garnet rim 550-620 °C and 7.5-8.0 kbar. The trajectory indicates small increase in temperature within the same pressure conditions. Sample DR352 has mineral assemblage in the sillimanite zone, the *P-T* conditions obtained to the garnet growth are ~520 °C and ~8.2 kbar to the core and 650-700 °C and 6.0-7.0 kbar to the rim. Sample BR04 is a sample from the sillimanite zone, the *P-T* conditions obtained to the growth of the garnet core and rim are ~520 °C and ~6.8 kbar and 660-720 °C and 6.5-8.0 kbar and the *P-T* trajectory is interpreted as a near isobaric heating.

Monazite U-Th-Pb dating is also presented to understand the temporal scale of those events. Both techniques of isotopic and chemical dating were used duo to the characteristics of each sample. The isotopic dating was made with the LA-ICP-MS equipment combing the U-Th-Pb isotopic ages with trace element chemistry. Some correlations can be made between monazite growth and other minerals such as garnet, allanite, apatite and K-feldspar following their chemistry. Four samples were analyzed, DR352 and DR378 from Medium-TCF and DR298 and 129 from the High-TCF. Different populations were evaluated in each one of the samples but due to the conditions of the method, they overlap within uncertainties. The metamorphic ages range varies from 620-580 Ma in the samples DR352 and 129 and from 640-580 Ma in samples DR378 and DR298. Chemical dating was made in samples DR378, DR352, BR04, BR07 and BR18 from the Medium-TCF and 129 from the High-TCF. Chemical ages record a high value of uncertainties in each analyzes, therefore the range is bigger. Two populations were identified based on their age, an older which gives an average of 600 ± 5 Ma and the younger 543 ± 14 Ma. Nevertheless, no chemical control was used in these calculations, the grains record some Y and Th zoning that was not considered due to the small set of analysis from each domain. The average, therefore, considers all the collected data, not possible different domains.

Finally, collecting all the metamorphic data, *P-T*-t paths are proposed, and they indicate different evolution for each sample. With more detailed studies on the metamorphism, it becomes clear that the area presents high complexity. For instance, two samples studied here and located close to each other (BR4 and DR352) present similar mineralogy, on the sillimanite zone and similar temporal interval. Nevertheless, the pressure regime registered in both samples varies from near isobaric heating in sample BR04 and heating associated with decompression in sample DR352. Sample DR378 records metamorphism with monazite production for 60 Ma (630-570 Ma).

Samples from the High-TCF also records differences in both their *P-T* paths as already proposed by Faleiros et al. (2011) but in the timescale of this metamorphism. Sample DR298 from the Sillimanite-K-feldspar zones also records a long-lived (50 Ma, from 630-580 Ma) process of monazite growth related to partial melting. On the other hand, sample 129 from the Kyanite-K-feldspar zone records a shorter history (610-570 Ma).

Nevertheless, when comparing the *P-T* peak conditions to all samples presented here, a bimodal tectonic setting still seems to be the best option to explain this origin. Some samples record thermobaric ratios (definition from Brown and Johnson, 2019) and in the intermediate-*P* (775 °C/Ga) and others in the low-P (1500°C/Ga). Therefore, the model proposed by Ricardo et al. (2020) and in the session 3 of this dissertation still seems to be valid. The evolution is probably more complex than the model, with rocks within the same tectonic setting, i.e. the back-arc or the accretionary wedge, recording slightly different *P-T*-t paths. But Low/Medium-TCF and High-TCF still records distinct pressure regimes that could be explained by paired metamorphic belts. This petrochronological approach revealed that some samples with low-grade association (i.e. garnet or staurolite zone) may record high *T/P* ratios. Therefore, the distribution of the sub-units based only on the mineral assemblage is an oversimplification. The Low-TCF could not be dated duo to the absence of monazite grains, we suggest that the unit should be dated in the future with a different technique.

CHAPTER 5 - CONCLUSIONS

Understanding the tectonic evolution of a metasedimentary unit in an accretionary wedge setting can be challenging. Millions of years of tectonic events such as collisions, subduction and lateral displacement may rearrange the original geographic distribution (Cawood et al., 2012). Nevertheless, implementing the investigation of both the sedimentation and the metamorphic setting can be good approach to decipher not only the setting but the tectonic evolution. Systematic thermodynamic modelling coupled with petrochronology in older rocks is a crucial tool to evaluate the evolution of metamorphic trajectories, not only the *P-T* peak of some samples.

As for the evolution of the Turvo-Cajati Formation, it is proposed that the unit can be divided in three different sub-units: the Low, Medium and High-TCF. Low/Medium-TCF have a depositional setting in a back-arc setting and High-TCF in the accretionary wedge. The maximum depositional age obtained in this study is between 650-630 Ma. The metamorphism history is more complex, different samples share part of their histories but more in a complementary way. What is clear is that samples record a bimodal pressure regime with Low/Medium-TCF rocks with metamorphism between 6.0-7.0 kbar and High-TCF with pressure regime between 10.0-12.0 kbar. Metamorphic ages also indicate different time-scale processes. All studied samples record metamorphic ages from 620-580 Ma. This anticipates our understanding of the metamorphic events in at least 20 Ma from previous studies. Nevertheless, two samples record an even older metamorphic history, from 640-580 Ma. This period of metamorphism overlaps the sedimentation ages. We interpret this as a corroboration of the proposed tectonic setting of a subduction-to-collision orogeny in a Japan-like microcontinent. A good approach to have a more robust control on the history of the sample would be to apply all those techniques in the same samples. With this, the temporal and tectonic controls would be higher, therefore, lessening over and possible misinterpretation.

We propose the evolution of the TCF along with other units in the Curitiba Terrane as the following:

- 650-630 Ma – Maximum depositional age of TCF sediments marked on detrital zircon (Ricardo et al., 2020);
- 640-620 Ma – First records of metamorphic events associated to subduction of an oceanic crust on the active margin of the Curitiba Microcontinent. This subduction formed a magmatic arc in this microcontinent, the Piên Arc. This metamorphism produced monazite recorded in two samples from the TCF (DR378, DR298) possibly located in the accretionary wedge;
- 620-570 Ma – Metamorphic events recorded broadly in the TCF, i.e. all samples; somewhere in between this period, the collision with the Luis Alves Microcontinent would occur. Possibly around ~600 Ma where most monazites are recorded. The collision caused metamorphism in the back-arc and accretionary wedge basin and the exhumation of part of the High-TCF rocks;
- 580-570 Ma – Cease of metamorphism in the TCF. All samples stop recording monazite production related to the instauration of the transcurrent shear zones;
- 580 Ma - Intrusion of A-type granites dated on zircon grains by TIMS (Vlach et al., 2011);
- 580 – 530 Ma – Shear zones activation (Faleiros et al., 2011).
- ~540 Ma – Younger monazite grains recorded in some samples. More studies are recommended to address the origin of this process.

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