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The intellectual assets underpinning the modern knowledge economy are not normally associated with activities in the primary sector. This raises the question whether resource-based developing countries are eternally relegated to the Also-Runs in global competition or at least whether they need to disassociate themselves from their economic mainstay in order for catch-up to materialise. The answer to this question is of paramount importance to many developing countries, especially in Latin America and Africa. This analysis contributes to the discussion in two novel ways. The first is the focus on technological trajectories that start in or around resource-based activities and subsequently become more knowledge intensive. Hence the study shows the direct contribution resource-based activities make towards the development of a knowledge economy. The second is the attempt systematically to compare technological trajectories in Africa's most sophisticated economy with those in three Latin American countries at different stages of development. By contrast, this study concentrates on countries from continents that are customarily lumped together in the failure category. It analyses examples of technological learning and focuses on what works (not), and why, and whether insights from a collection of case studies can inform a broader policy discussion about how best to reconcile the demands of the knowledge economy with intensive resource endowments.

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1 Introduction

The intellectual assets underpinning the modern knowledge economy are not normally associated with activities in the primary sector. This raises the question whether resource-based developing countries are eternally relegated to the Also-Runs in global competition or at least whether they need to disassociate themselves from their economic mainstay in order for catch-up to materialise. The answer to this question is of paramount importance to many developing countries, especially in Latin America and Africa.

Economic history illustrates that resource intensity is not a guarantee for economic development and, in fact, can stifle technological upgrading. Economic theory suggests that what matters is how resource intensity is being exploited. This analysis contributes to the discussion in two novel ways. The first is the focus on technological trajectories that start in or around resource-based activities and subsequently become more knowledge intensive. Hence the study shows the direct contribution resource-based activities make towards the development of a knowledge economy. In other words, it analyses the *co-evolution* of resource- and knowledge-intensive modes of production. Much – though not all – of the relevant literature merely looks at the *co-existence* of the two.

The second is the attempt systematically to compare technological trajectories in Africa's most sophisticated economy with those in three Latin American countries at different stages of development. The similarities are obvious. In both regions, the rich natural resource endowments determine to this day what they export. Long episodes in their recent economic history have been marred by low growth in the presence of vast mineral and other riches. Much thinking has gone into probing the reasons for this. But while the Latin American experience has been subject to many comparative case studies, this is much less true for Africa. In addition, many analyses are subject to a bias that contrasts successful examples of catch-up (for example, many East Asian economies in the absence of resource endowments) with failures of underdevelopment (Latin America despite its incredible riches), or resource achievers (for example, Australia or Scandinavia) with resource underachievers (Argentina and Brazil).

By contrast, this study concentrates on countries from continents that are customarily lumped together in the failure category. It analyses examples of technological learning and focuses on what works (not), and why, and whether insights from a collection of case studies can inform a broader policy discussion about how best to reconcile the demands of the knowledge economy with intensive resource endowments.

Section 2 introduces the problems of resource-based development. It briefly surveys the relevant theoretical literature and combines it with select insights from the economic history of resource-based economies. It thus illustrates conceptually and empirically why the countries analysed here and many like them have had problems in reconciling resource exploitation with more knowledge-intensive, higher-growth activities. Section 3 discusses key tenets of technological learning, the role of foreign technology, linkages and interactions, and industrial policy that inform the analysis. Section 4 reviews five case studies and their technological trajectories. Analysis follows in Section 5 and Section 6 concludes with suggestions for further research.

2 Resource-based development: An update on the resource curse hypothesis

This section first reviews the crude case against resource-based development. It then introduces a more nuanced view based both on theory and historical examples.

According to the crude case, countries with abundant natural resources are afflicted by the "resource curse". The easy riches of, say, minerals prevent countries from investing into productive assets, including human capital. Once commodity booms are over, this leaves them with idle capacity, reduced export earnings, and the absence of alternative growth paths, all of which compromise their development prospects (Smith 1776, 562; Sachs and Warner 1995, see also UNIDO 2005).

Not everybody agrees with this assessment. One critic of the influential study by Sachs and Warner (1995) noted that since its observations fall into a period of debt crisis and structural adjustment that Latin Americans customarily refer to as their "lost decade", it is not obvious that resource intensity was the major culprit of low or negative growth, much less since a comprehensive understanding of what went wrong in Latin America would need to look at political economy issues that have nothing to do with resource intensity as such (Maloney 2002; for earlier statements to this effect see North 1955 and Viner 1952). Newer research (Martin and Mitra 2001) questions the interpretation of the very data that were the basis for Prebisch's (1959) famous indictment that secular declines in its terms of trade would militate against the emancipation of Latin America and cement its dependency on the core industrial countries. The argument is that while he may have been right for Latin America at that particular historical juncture, the generalisability of his view to all resource-intensive economies is doubtful.

The logic behind the resource curse is a combination of bad luck and bad policies. The geological make-up of the earth's land mass and the volatility of commodity prices are a case of bad luck.[2] It is worth pointing out the paradox of associating bad luck with possessing something of value. The resource curse only becomes a valid argument when the lure of easy riches from primary-sector activities leads to perverse incentives. This brings policy into the picture.

If in reaction to a commodity boom governments forego investments in education so that future generations can pursue more productive and less hazardous careers, they can be faulted for favouring short-term gains over long-term, sustainable development. Of course, the allure of the rentier economy lies exactly in the luxury of availing oneself of economic policies that in the absence of booming resources would never be sustainable in the first place (cf. Deaton 1999).

Among the better-known characteristics of the resource curse is the Dutch disease phenomenon. It kicks in when resource booms cause a real exchange rate appreciation that lowers the competitiveness of manufactures and other tradables. If the returns to manufacturing are higher than those available from resource exploitation, or if they *could* be higher insofar as technological upgrading may cause dynamic efficiencies, the concentration on commodities positively harms development prospects.

[2] Of course, it is possible to stabilise commodity prices but multilateral regimes to this effect, especially when run by developing countries, have largely fallen out of favour and been disbanded in the last two decades.

Nonetheless the resource curse is perplexing for development practice. Surely the solution to the dangers inherent in resource riches cannot be to ignore these endowments, especially if, as in large parts of Africa, they are for the time being the only comparative advantage countries possess (Deaton 1999). The good news is that over the last ten years or so – since Sachs' and Warner's (1995) paper rekindled the debate – theoretical advances and new empirical research significantly improved our understanding of how, and why, resource intensity impacts on economic development.

In short what counts for growth is not the relative abundance of natural resources in and of itself, but what one does with it (Gylfason 2001b). The often used comparison of resource-rich countries in Africa and Latin America with generally resource-poor but high-growth countries in Asia makes sense insofar as it highlights that countries without natural resources have no choice but to invest in human capital. By contrast, resource-rich countries can get away, at least for some time, without much education and training simply because they have a larger margin for error for unsustainable economic policies. This is clearly a blessing in disguise (cf. Gylfason 2001a).

It is important to differentiate between success stories and failures. Not all resource-intensive economies belong in the latter category. Transmission channels of the potentially negative effects of resource-based development play an important role. For example, natural resources seemingly do contribute positively to growth if one controls for bad governance, bad policies, and bad institutions (Papyrakis and Gerlagh 2004, see also Neumayer 2004). Put differently, the combination of natural resource abundance, sound macroeconomic policies, and economic policies aimed at generating high savings rates and productive investments, can work very well (Atkinson and Hamilton 2003).

It is certainly easier to explain the uncontroversial successes of resource-based industrialisation with this more open interpretative framework. Thus, the relatively more successful exploitation of mineral resources in the context of economic development in the US compared to Latin America had nothing to do with the quality of those resources that, if anything, were often better in Latin America. The key difference lay in the nature of the learning process that more or less promoted the economic potential of these resources (Wright 2001). What mattered was that the US applied its capabilities from exploration all the way to advanced utilisation in the mineral economy which is why the mineral sector became part of its knowledge economy. Latin America, by contrast, for a long time did not make much of its location-specific knowledge of the resource sector; in other words, it did not engage in much learning and upgrading (Wright and Czelusta 2004; see also de Ferranti et al. 2002, esp. Chapter 3).

In essence, therefore, in the past resource intensity was less than fortuitously matched with economic development in Latin America than in similarly endowed countries. But the recent history of Latin America produces a more differentiated picture. Next to well-known failures, there are very successful examples of economic development across a range of activities that include and go beyond traditional activities. Thus, countries exploited their natural resources as well as their locations making use of new technologies and knowledge to improve their production processes. Technology and knowledge may be embodied in foreign direct investment, but they will also be generated by domestic institutions and rely on investments in ICT infrastructure. Therefore, intelligent policies aided the transformation of natural-resource-based activities into knowledge-intensive assets (De Ferranti et al. 2002, Chapter 4).

In the 1990s resource-intensive economies from Sub-Saharan Africa and Latin America fared much worse in world trade than their resource-poor counterparts from Asia. More precisely, they exported relatively few products in which their world market share was rising and which simultaneously recorded above-average growth (Lawrence and Alves 2005). In the nuanced interpretative framework adopted here, this performance does not resuscitate the resource-curse hypothesis per se. But it shows that a high concentration of exports in primary and resource-intensive products was associated with a below-average export growth rate. This underlines the relevance of this analysis.

In sum, the literature suggests that, first, rich resource endowments may, but need not, slow growth. Second, like other (developing) countries, resource-rich economies must diversify their economies in order to obtain higher and sustainable growth. In this endeavour they face many of the same obstacles that bedevil resource-poor countries, namely the inherent risks and uncertainties of investments in innovative activities at the heart of restructuring and productivity growth. The rise of the knowledge economy tends to up the ante on risks and uncertainties. In short, technological, information, and coordination externalities militate against the pursuit of diversification through restructuring by individual entrepreneurs. This insight motivates interest in industrial policy in general (cf. Rodrik 2004), and more specifically has inspired reflections in Latin America on how to move from resource intensity to more knowledge-intensive activities (De Ferranti et al. 2002, Ramos 1998). The major difference between the literature reviewed here and the present study lies in the treatment of traditional factor endowments such as resources and new endowments such as human capital. Much of the literature looks at their co-existence. Perhaps it asks how gains from a resource-based activity can be invested to support the emergence of another activity.

But this is neither theoretically nor empirically satisfying. Restructuring and diversification in resource-rich economies are likely to take specific forms insofar as they at least in part happen on the back of related and input industries that supply resource-based sectors with goods and services. Although there is a global knowledge base for mining, agri- and acquaculture, or forestry, specific local circumstances will often ask for specific local solutions. This may mean that the local knowledge base around resource exploitation is deeper than in other parts of the economy. Everything else being equal, the depth of knowledge around – upstream and downstream – the resource economy is such that it may spur technological learning that starts in but does not stop with a resource-based activity. This insight motivates the interest in the co-evolution of resource- and knowledge-based activities through technological trajectories that link one with the other and, by implication, if and how industrial policy may complement it.

3 The determinants of knowledge intensification of resource-based activities

The literature on resource-based growth essentially draws on two different but complementary sources. The first is economic history. It explains, for example, how comprehensive mining innovation systems in the US or Australia led to vibrant manufacturing industries. The second is a growing body of economic theory that addresses growth and development as a function of a country’s ability to learn and build up capabilities through investments in human capital, good institutions, and infrastructure. The best work combines the two in theoretically informed, comparative historical analyses.

Knowledge intensification of resource-based activities can take three forms. The first is increasing knowledge intensity of the resource-based production process itself. The process need not necessarily become more complex, but the relevant actor must have the capability to influence the development of the core technology. Successively more complex foreign technologies would therefore per se not be associated with knowledge intensification in the host environment unless local capabilities allowed understanding and modifying these technologies, or developing alternatives. Examples include higher-yield or totally different mineral extraction technologies, new agricultural practices, and the like. The second form of knowledge intensification is downstream beneficiation, such as the development of biodegradable polymers from sugar cane described below. The third form is the development of upstream or downstream input industries that extends the degree of horizontal control over a resource-based value chain. It goes without saying that this, too, depends on the capability to understand and influence the development of the core technologies.

When the knowledge base of a resource sector and its associated capital goods and services sectors are applied in other sectors not linked to resource exploitation, additional development trajectories open up. We call this process “lateral migration”.[3] It occurs when the gradual and continuous accumulation of knowledge bridges the resource and the knowledge economy through linkages of human and other capital. Thus lateral migration presupposes the co-evolution – as opposed to the mere co-existence – of resource-based and knowledge-intensive activities. The case studies discussed below demonstrate how the resource economy can be part of the knowledge economy and vice versa. The strength of the linkages and the extent of transition to alternate technological trajectories depend on a series of factors that need systematic analysis.

In addition to the literature on the resource curse referred to above, four related bodies of knowledge inform our analysis – absorptive capacities or learning, technology transfer and diffusion, systems of innovation, and industrial policy. First, firms engaged in technological upgrading learn insofar they make use of external knowledge to modify existing or create new technologies. In both cases investments in R&D are important because they help generate new information and because they promote learning. In this perspective, learning is not *by-doing* but the outcome of a purposeful search for external knowledge to be selected, internalised, and exploited (Cohen and Levinthal 1989, 1990).

Spending on R&D will tend to relate to the characteristics of industry-specific technological and scientific knowledge. The more difficult to assimilate this knowledge, the more firms will spend on R&D. Likewise, the less overlap between a firm’s needs and outside knowledge, the more R&D is needed to compensate for the gap through in-house efforts. Absorptive capacities result not only from R&D (both current and the prior accumulated stock of knowledge) but also as a by-product of manufacturing operations (in the sense that involvement in the latter allows firms to recognise and exploit new information relevant to a product market). They further result from advanced technical training.

Absorptive capacities also influence the level of aspiration of an organisation. Firms with deep absorptive capacities are more likely to recognise emerging technological opportunities. Thus, absorptive capacities facilitate development of resource-based sectors and make possible technological transitions that lead to lateral migration. When the knowledge to be exploited is closely related to the firm’s existing knowledge base, absorptive capacities can be a by-product of routine activity. By contrast, when that is not the case, it must be created.

[3] The term was coined by Paul Jourdan of South Africa's Mineral Technology Research Council (MINTEK) and Miriam Altman of the HSRC.

Finally, absorptive capacities only become “realised” when the assimilated knowledge is commercialised – until then they are merely “potential” (Zahra and George 2002).

Second, insofar the relevant external knowledge is of foreign origin, the key question is how and to what extent technology import and indigenous investments complemented each other (Blomström and Kokko 1998, Lall 1993, Pack and Saggi 1997). On the one hand, with more capable buyers foreign firms have less need to internalise technology transfer through FDI. On the other hand, higher buyer capability also translates into a stronger competitive threat, thus increasing the need for control, especially over the foreign firm’s advanced technological assets. It is important to understand if the local firm had the option among a series of technology imports (e.g. license, JV, equity), and if and how it exercised its choice.

Third, learning is embedded in a knowledge infrastructure and takes place in interaction with consumers and producers of knowledge in the private and public sector, including those from outside the country (e.g. Bell and Pavitt 1993, Lall 1993). Thus, once the absorptive capacity of the firm from which the lateral migration technology originates and the nature of the external (foreign) technology input are understood, the focus turns to linkages between case firms and all other actors that matter, in industry, government, academia, and perhaps civil society. The study thus shares with the literature of the national systems of innovation (NSI) recognition of systemic dynamics and attention to linkages and interactions. But since this study moves from micro to macro, there is no need to describe all institutions that make up the national innovation system (cf. Edquist 1996, Lundvall 1992, Nelson 1993). Instead the focus is on those that matter directly or indirectly (i.e. through skill provision) to the technology at hand.

Finally, innovative activities are subject to externalities that governments may or may not alleviate (e.g. Rodrik 2004, UNIDO 2002). In this instance this refers to specific combinations of investments in science, technology, and innovation on the one hand and requisite policy frameworks on the other that drive innovation and the adoption of technologies. In addition to their role in the development of resource-based activities, by facilitating or impeding the transition of a technology to non-resource-based activities these policies and practices can be critical causes of lateral migration.

The reason for drawing on a relatively wide range of literature is to do justice to the complexity of these economic transitions, and more specifically the cumulative nature and systemic features of technological upgrading with resource-based activities as a point of departure, to knowledge-intensive activities that in turn influence the former, involving firms, universities and science institutions, and government agencies. Finally, the analysis of the attendant processes must be embedded in a description of the resource base – including the possible negative impacts it has – from which they took off.

4 Methodology and data

The research is based on five case studies from Latin America and Africa. Each addressed four sets of questions in semi-structured interviews. The questions drew on the literature discussed above so as to produce a common framework that allows for systematic comparability. The first set of questions confronted (organisational) absorptive capacities and learning. It focused on the scientific and technical discipline(s) in which the technologies originated and on the skills and organisational routines that allowed firms to internalise capabilities in these technologies.

The second set of questions explored the role of foreign technology transfer and diffusion. It examined the role of non-domestic knowledge systems and the incentives and disincentives for indigenous innovation created by foreign technologies. The third set investigated foreign and domestic linkages between producers and users of knowledge and interactions that developed around the relevant technologies. It also considered distributional dynamics of innovation – who participated and who benefited. The last set focused on the role of industrial policy as well as science and technology policy. It identified the extent of public interventions in the development of technologies and their transition toward more knowledge-intensive applications.

The remainder of this section summarises key features of the origins of the technologies in resource-based activities as well as their current and expected trajectories. A table communicates the relevant trajectory. The first column lists forms of knowledge intensification *i.e.* the resource-based production process itself, downstream beneficiation, upstream or downstream input industries, and lateral migration. The point of departure for knowledge intensification is highlighted. Finally, this is followed by an assessment of its present and future trajectories in the second and third columns on a six-point Likert scale. Lower values imply that the technology in question failed to extend its scale or scope, while higher values illustrate a successful graduation to ore knowledge-intensive or altogether new applications, or both (see Table 1).

Table 1 – Knowledge intensification and technological trajectories in the five cases

Form of knowledge intensification	Current trajectory	Likely future trajectory
1a – sugar cane-based plastic technology (Brazil)		
Resource production	0	0
Beneficiation*	4	4
Up-/downstream inputs	0	0
Lateral migration	0	0
1b – corn-based plastic technology (South Africa)		
Resource production	0	0
Beneficiation*	3	3
Up-/downstream inputs	0	0
Lateral migration	0	0
1c – optical sorting equipment (Costa Rica)		
Resource production	0	0
Beneficiation	0	0
Up-/downstream inputs*	5	5
Lateral migration	5	5
1d – hydro-hydraulic drilling equipment (South Africa)		
Resource production*	3	3
Beneficiation	0	0
Up-/downstream inputs	4	5
Lateral migration	3	2
1e – Bio-remediation technologies (Peru)		
Resource production*	1	1
Beneficiation	0	0
Up-/downstream inputs	0	0
Lateral migration	4	5

Note: 0 = not applied; 1 = application terminated; 2 = declining application; 3= static application; 4= increasing application; 5 = increasing and diversifying application; * = point of departure of technological trajectory toward higher knowledge intensity.

4.1 Sugar cane-based plastic in Brazil[4]

Brazil is the world's largest producer and exporter of sugar. In response to rising oil prices and depressed demand for sugar in the 1970s, Brazil began a programme producing sugar cane-based ethanol as an alternative to gasoline for vehicles. In conjunction with the increasing use of biofuel, the programme investigated a variety of technologies to improve sugar cane yields. Strong state support quickly led to a majority of ethanol-based automobiles. However, by the late-1980s decreasing oil prices and the discovery of substantial Brazilian oil reserves motivated the government to withdraw the ethanol incentives and reduce its R&D funding. As a result, a consortium of government, industry,

[4] For details of this case see Velho and Velho (2006).

and university research institutes with considerable expertise in ethanol began searching for alternative uses of sugar cane. That search led to the development of a sugar cane-based plastic (polymer) called polyhydroxybutyrate (PHB) in the mid-1990s.

The creation of PHB paralleled its ethanol predecessor in beneficiation of the Brazilian sugar cane industry (see Table 1a). PHB currently offers considerable promise for increasing and sustained beneficiation of the domestic sugar cane industry. However, two factors create some uncertainty around the future significance of PHB. First, a pilot plant to produce PHB was built in the late 1990s, but the first plant commercially manufacturing PHB only began production in 2004. By early 2006, the commercial PHB plant had still not reached a viable scale of output. The second factor critical to the future significance of PHB is its adoption by plastics converters in their production of intermediate and final goods. Thus, the future of PHB as a beneficiation technology is directly linked to its utility as a polymer.

In recognition of the interdependence of PHB's adoption by plastics converters and its potential as a beneficiation technology, as the pilot plant was developed collaboration began with established plastics converters into commercial applications. After the commercial plant came on stream, the development of PHB applications intensified and the department of materials engineering of a local university became another strategic partner in the consortium. To complement the consortium's own efforts and encourage adoption, samples of PHB are given to any interested party for testing. As a bio-plastic, PHB is well positioned to take advantage of increasing environmental regulation of petroleum-based plastics. In addition, PHB appears to have a greater range of applications than starch-based plastics which are currently the only other bio-plastics widely available.

4.2 Corn-based plastic in South Africa[5]

South African research and development into a corn-based plastic began in the 1990s when a leading domestic producer of corn starch looked to increase beneficiation. That search led to the eventual formation of a consortium by the corn starch producer, a national science council, and a local university. After initial challenges to secure funding, in 2002 the consortium began a three year collaborative research and development programme to produce a corn-based plastic (polymer), supported by government funds.

Building on related European work in starch-based plastics from raw materials like potatoes, the consortium made progress toward the production of a corn-based plastic. However, currently corn-based plastic is not yet produced, nor is there an immediate prospect for a pilot plant (see Table 1b). An important reason for this relative lack of success was that the corn starch producer lost its license for a high yield corn which was owned by a foreign producer. Without a high yield corn, the corn starch producer no longer considered the venture viable and withdrew from the consortium. In addition, costly anti-aging additives increased the costs of production and limited state support reduced the scope for lateral migration.

In parallel to Brazilian sugar cane-based plastics, success of the corn-based plastic beneficiation technology is dependent on its adoption by plastics converters. However, in contrast to sugar cane-based plastics, the scope for corn-based plastic is constrained by its properties as a polymer. Applications for the adoption by plastics converters were investigated along with the technology to produce corn-based plastic, but the properties of

[5] For details of this case see Walker and Farisani (2006).

this starch-based polymer are not as robust as the sugar cane-based plastics. In Europe these deficiencies are somewhat offset by environmental regulations promoting biodegradable polymers, but similar policies do not exist in South Africa and as a result it has been difficult to identify a competitive domestic market for corn-based plastic. Despite the lack of domestic regulatory support, the remaining members of the corn-based plastic research and development consortium continue efforts to promote commercial adoption because of the polymer's long-term environmental advantages.

4.3 Optical sorting equipment in Costa Rica[6]

Costa Rica is a large producer and exporter of coffee. In the early 1970s, as a result of deficiencies in imported bean sorting equipment for the local coffee industry, local entrepreneurs developed an alternative domestic technology. The firm established by those entrepreneurs has continuously improved its sorting technology, becoming an international market leader. Consequently, its sorting equipment is currently widely used by coffee growers domestically and internationally. The firm has also adopted its optical sorting technology to equipment for sorting a range of other agricultural products domestically and internationally, such as grains. The optical sorting technology that emerged around the domestic coffee industry has resulted in the development of a down-stream input industry with an international customer base that continues to evolve and develop (see Table 1c).

In the early 2000s, after decades of experience in agricultural products the firm began producing equipment that used its optical selection technology to sort plastic and emerald products marking thereby a lateral migration of the technology. In this measured move away from its traditional natural-resource based markets, the firm aims to enhance and entrench its international technical expertise in optical sorting.

4.4 Hydro-hydraulic technologies in South Africa[7]

South Africa remains the world's largest producer of gold, despite the majority of its deposits being several kilometres below the surface. In the late 1960s, the depth of gold deposits motivated the industry's co-operative research institute to undertake research and development of alternative technologies to extract the gold bearing host rock. With constant support from the gold mining industry, the institute oversaw the combining of several complementary technologies to produce in the late-1980s an integrated all water-based (hydro) hydraulic extraction technology. This innovation was new to the world and had several advantages over conventional oil-based technologies.

As a technology seemingly enhancing the efficiency of production, hydro-hydraulic technology held significant promise in deep underground mineral deposits like the majority of South Africa's gold and platinum mines. However, despite early adoption by a few South African gold and platinum houses, diffusion of the integrated hydro-hydraulic system has not significantly displaced established technologies (see Table 1d), except that some of the hydro-hydraulic technologies have found niche markets on mines in South Africa and internationally.

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[6] For details of this case see Giuliani (2006).
[7] For details of this case see Pogue and Rampa (2006).

While not realizing the large-scale adoption in mining initially envisioned, at least one South African hydro-hydraulic equipment manufacturer developed non-mining applications for the hydro-hydraulic technologies that took advantage of its utility as a hydraulic technology without the associated environmental hazards of oil. That movement into non-resource based industries marked the lateral migration of hydro-hydraulic technology. Nonetheless, the overwhelming focus of South Africa's hydro-hydraulic equipment producers is on mining applications. They are currently poorly positioned to compete in the significant and growing international market for environmentally friendly hydro-hydraulic technologies outside the resource base that emerged in the late 1990s.

Despite missing an opportunity to build on its early technological leadership to expand the lateral migration of hydro-hydraulic technology, there currently appears to be a re-emergence of hydro-hydraulic technology upstream in mining equipment. One of the firms that developed a hydro-hydraulic rock drill for the mines is now using the technology in conjunction with traditional pneumatic drills to create a hybrid-drill that combines technical advantages of hydro-hydraulics with the utility of traditional technologies. Building on initially promising performance and commercial adoption of the technology the firm envisions further hybrid-combinations of the technology for the mining and construction industries. If this promise is realized hydro-hydraulic technology may yet see significant lateral migration.

4.5 Bioremediation technologies in Peru[8]

Peru possesses large deposits of copper. In the early 1970s amidst nationalisation of the mines, Bolivia, Chile, Ecuador, Colombia, and Peru initiated collaborative research programmes into resource extraction technologies that would reduce technological dependency on foreign mining companies. By the mid-1970s, one of the state-owned Peruvian mining companies had developed a commercial heap-leach plant for the extraction of oxidized copper deposits. Despite the potential of this technology to reduce dependencies on foreign technologies associated with traditional, foreign concentration-based extraction technologies, it was only efficient in oxidized ores. Since the majority of Peruvian copper deposits are in non-oxidized ores, developing indigenous capabilities in extraction required development of other technologies besides heap-leaching. Thus, Peru began investigating bacterial leaching of its non-oxidized copper deposits. Despite promising results, financial constraints due to growing balance of payment difficulties led to the suspension of the programme in the late 1980s.

At the same time, international efforts continued and by the 1990s a foreign mining company had successfully commercialized a bacterial leaching process. The process was designed for large relatively homogeneous deposits, but in Peru a significant portion of its domestic mining industry are small and medium sized operations based on relatively complex heterogeneous deposits. Consequently in the late 1990s, a medium sized Peruvian mine initiated research and development on a bacterial leaching technology for smaller heterogeneous deposits that drew on international experience and Peru's previous research. Unfortunately, adequate economies of scale were not achieved, the mine closed in 2001, and the indigenous development of bacterial leaching once again was effectively suspended (see Table 1e).

[8] For details of this case see Kuramoto and Sagasti (2006).

However, the mine had partnered with a local university. Despite the mine's closure the research team at the university sought to keep the programme alive. Since no funding was available, the research team searched for alternative applications of their expertise and identified bio-remediation, where the bacteria are applied to contaminated soil to reduce or remove toxic substances. As an environmental technology, bio-remediation qualified for public support and allowed the research team to continue fostering its expertise. Thus, the original bio-leaching technology laterally migrated as it shifted to environmental applications. Currently, this promising bioremediation technology is undergoing field trials as its commercial viability is established.

5 Analysis

The five cases demonstrate that the co-evolution of the resource base and knowledge intensification originates in a variety of forms. The Peruvian bio-remediation and the South African hydro-hydraulic technologies both came from efforts to improve the efficiency of production in the resource base itself. Brazilian and South African bio-plastics originated as beneficiation technologies. Lastly, Costa Rican optical sorting technology originated as a down-stream processing technology.

The Costa Rican and Peruvian cases demonstrated that the systemic complexity of a technology in itself is not an indicator of a knowledge intensive domestic resource sector. In both cases, technological complexity was initially a barrier to meaningful domestic engagement but the associated dependencies on foreign technical expertise were critical incentives to the development of indigenous solutions obtained through technological learning and upgrading. This was critical to the subsequent co-evolution of resource-based and knowledge-intensive activities.

Despite the potential for dysfunctional dependencies, foreign technologies were generally important for the development of hoe-grown alternatives. For example in the case of South African corn-based plastic, European research into plastics from starches based on other raw materials directly contributed to the programme's ability rapidly to approach the technological frontier. The European research also highlighted the importance of state interventions in demand where biodegradable plastic legislation is driving development of starch based plastic.

Complementary domestic technological capabilities also played an important role. The difference between the Brazilian and South African bio-plastics cases are instructive. In Brazil, large and systematic research into sugar cane production created a resource-base with significant scope for domestic beneficiation. In contrast, when a foreign license for a variety of high-yield corn was lost the South African bio-plastic project was effectively suspended. While not certain, greater domestic capability in the production of high-yield corn would appear to offer greater opportunity for beneficiation in South Africa.

Systemic aspects mattered greatly as well. In the Brazilian and South African bio-plastics cases interdependencies of material development and application required the co-ordinated development of both the beneficiation technology as well as its adoption by plastics converters. Peruvian bio-remediation technology drew on absorptive capacities developed in the original technology, but co-ordination failures in its national system of innovation constrained their broader development. The South African hydro-hydraulic case was notable because the driving research organization explicitly undertook to develop absorptive capacity among the research consortium.

Innovation hinged on linkages. However, the nature of linkages varied significantly. Characterizing both the Brazilian and South African bio-plastic cases were deep linkages among industry, state research institutes, and local universities. In the South African hydro-hydraulic case deep domestic linkages between equipment supplier, research institutes, and producers were critical to co-ordinating the development of the technologies. The hydro-hydraulic case also illustrated the importance of linkages in creating technological complementarities between specialised technologies. Similarly, Costa Rican optical selection technology highlighted the major role played by specialized international expertise. While the specialized optical selection technology developed in Costa Rica has relatively limited linkages with other domestic firms and research institutes, it depends on skills generated by the local universities for its core technological competencies. Those competencies are then complemented by select foreign technologies to afford the firm's equipment its international competitiveness.

State policies similarly demonstrated an important but varied influence on the development of original technologies and their transition to other forms of knowledge intensification. At a macro-economic level, the Peruvian case illustrated the direct impact of reckless macro-economic policies constraining the pursuit of innovative activities. In contrast, the Costa Rican case indicated that fostering domestic capabilities under import substituting policies can create conditions that are favourable to the development of domestic technological capabilities.

Development of sugar cane-based plastic in Brazil highlighted a range of micro-economic interventions by the state that facilitated technological development. State support was critical to building a technological foundation for sugar cane-based plastic as well as directly fostering both the demand and supply of the technology. The benefits of that systemic support become clearer when contrasted with the case of South African corn-based plastic. While limited state support did facilitate initiation of the development of technologies, those supply incentives were not flexible to technological specificities nor complemented with direct interventions to increase demand for the technology.

6 Conclusion

This analysis has drawn attention to the importance of the co-evolution of resource-based and knowledge-intensive activities for economic development. It has also highlighted a path to resource diversification through the 'lateral migration' of technologies originally linked to the resource-base. Through the analysis of technologies developed in resource intensive economies, we have demonstrated that resource-based activities can form an effective platform for knowledge-intensive development.

There is considerable scope for further research. For example, the adoption, diffusion, and long-term acceptance of these technologies in their original applications are influenced by a variety of social and institutional factors besides technical performance, manufacturability, and cost-effectiveness. A wide range of factors also influence the scope for lateral migration. In its focus on the phenomenon of lateral migration, the present analysis has not expressly examined these influences on technological transition. Deepening understanding of these factors of success or failure thus represents an important area in need of further development.

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