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Knowledge intensification in resource-based economies

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A NUMBER OF QUESTIONS that are salient to economic development in Africa and South America motivate this volume, including:

- Does resource intensity hamper growth?
- Is it possible to reconcile resource intensity with the knowledge economy?
- What lessons do theory and history hold for economic policy in resource-based economies?

If the answers to these questions were, respectively, 'yes', 'no' and 'none', this study would be bad news indeed, but the answers offered in this book suggest no reason for concern. In short, high growth trajectories are possible in countries with intensive resource endowments. In addition, economies can excel contemporaneously in resource extraction as well as in the creation of the intellectual capital at the heart of the knowledge economy. Finally, new developments in our understanding of the determinants of technological learning, as well as the histories of countries as diverse as Argentina, Australia, Costa Rica, the United States or Sweden, bear lessons for resource-based countries today.

To be sure, resource intensity does not guarantee economic development. What matters is the way in which resource intensity is exploited. This study contributes to the discussion in two novel ways. Firstly, it focuses on technological trajectories that start in or around resource-based activities and subsequently become more knowledge intensive. The study therefore traces forward linkages and shows the direct contribution that resource-based activities make to the knowledge intensification of the economy at large. 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 considers the co-existence of the two.

Secondly, the study makes a systematic attempt to compare the technological trajectories of Africa's most advanced economy with those of several South American economies. The similarities are obvious. In both regions, rich natural resource endowments continue to determine what they export. Long episodes in their recent economic histories 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. While the South American experience has been the subject of many comparative case studies, this is far less true for Africa. Moreover, many analyses are subject to a didactic bias that contrasts successful examples of 'catch-up' (for example, many East Asian economies in the absence of resource endowments) with failures of underdevelopment (as in South America, despite its vast riches), or resource achievers (for example, Australia or Scandinavia) with resource under-achievers (such as Argentina and Brazil).

In contrast, this study concentrates on countries that are customarily grouped in the 'failure' category. It analyses examples of technological learning, not all of which had necessarily achieved success – in terms of their net present value – at the time of writing. Some cases are successful, others are not, while for some it is still too early to tell. A common characteristic of all the cases is that they exemplify technological learning. Since it is possible to learn from mistakes no less than from successes, this study therefore analyses what works, what does not, the reasons for success or failure, and whether insights from a collection of case studies can inform a broader policy discussion of how best to reconcile the demands of the knowledge economy with resource-intensive endowments.

This chapter (which is divided into seven sections) introduces, summarises and contextualises the book. The next section introduces the problems of resource-based development, briefly surveying the relevant theoretical literature in the light of selected insights from the economic history of resource-based economies. The third section presents data demonstrating that the four economies studied here – Brazil, Costa Rica, Peru and South Africa – have had problems in reconciling resource exploitation with more knowledge-intensive, higher-growth activities. Together, these two sections thus establish the relevance of this kind of research. The fourth section discusses key tenets of technological learning, the role of foreign technology, linkages and interactions, and industrial policy, which inform the analysis. The fifth section introduces five instances of technological learning from the four countries and presents the methodology. The analysis follows in the sixth section, and the seventh section concludes with suggestions for further research.

Resource-based development: the resource-curse hypothesis revisited

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

The crude case goes as follows. Countries with abundant natural resources are allegedly afflicted by the 'resource curse', namely, that sitting atop a mountain of, say, gold spoils one's character and, for a variety of reasons, stunts one's growth prospects. Adam Smith, for one, is on record for having warned his contemporaries against sinking their investments down mine shafts (1776: 562). In more recent times, a study by Sachs and Warner

(1995) attributed low growth performance to resource intensity. International organisations such as the United Nations Industrial Development Organisation (Unido) profess an explicit bias in favour of the secondary sector, because it allegedly offers higher productivity potential and income elasticities than anything the primary sector produces (Unido 2005).

Not everybody agrees with this assessment. Smith found his match in heavyweights such as Douglass North (1955) and Jacob Viner (1952), who disputed that there was anything intrinsically inferior in mining iron ore or growing apples as opposed to making toothbrushes. One of the critiques of the influential study by Sachs and Warner (1995) noted – given that their observations fall into a period of debt crisis and structural adjustment that South Americans customarily refer to as their 'lost decade' – that it is not obvious that resource intensity was the major culprit of low or negative growth, particularly since a comprehensive understanding of what went wrong in South America would have to take into account issues related to the political economy that have nothing to do with resource intensity as such (Maloney 2002). Recent research (Martin & Mitra 2001) questions the interpretation of the very data that formed the basis for Prebisch's (1959) old indictment that secular declines in its terms of trade would militate against the emancipation of South America and cement its dependence on the core industrial countries, many of which were – to add insult to injury – former colonial masters. Prebisch's analysis may have been accurate for South America at that particular historical juncture, but the generalisability of his view to all resource-intensive economies is doubtful.

Whatever people think about the significance of the resource curse, there is general agreement that the logic behind it is a combination of bad luck and poor policies. The geological composition of the earth's land mass and the volatility of commodity prices represent an instance of bad luck. By definition, bad luck falls outside the ambit of rational policy intervention, which is why all one can do is lament destiny's injustice for having been dealt a lousy hand of cards. It is worth pointing out the paradox of associating bad luck with possessing something of value. The resource curse becomes a valid argument only when the lure of, say, gemstones leads to perverse incentives. This brings policy into the picture.

If, in reaction to a mineral boom, more workers are sent underground to work in the mines and ruin their health instead of using the windfall to invest in education so that their children do not need to follow in their parents' footsteps and are able to pursue more productive and less hazardous careers, governments can be faulted for having made the wrong decision in favouring short-term gains over long-term, sustainable development. Of course, the allure of the *rentier* economy lies precisely in the luxury of availing oneself of economic policies that, in the absence of booming resources, would never be sustainable in the first place. To be sure, this is attractive only to the beneficiaries of a predatory state, Mobuto-style, but not to the majority of the population, which suffers the consequences of corruption, inequality and essentially a barren future (Deaton 1999).

Among the better-known facets of the resource curse is the 'Dutch disease' phenomenon, which manifests itself when resource booms cause a real exchange rate appreciation that lowers the competitiveness of manufactures and other tradeables. Of course, if human capital is absorbed into the resource sector, natural resources could have the effect of reducing the rate of growth (see Lederman & Maloney 2007). Then, 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 illusion that one can enjoy both alternatives positively harms development prospects.

Having said this, 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 currently the only comparative advantage that 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 have significantly improved our understanding of how, and why, resource intensity impacts on economic development.

In short – and this is as intuitive as the resource curse hypothesis was counter-intuitive – 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 frequent comparison of resource-rich countries in Africa and South 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. In contrast, education may seem a waste of time and money in well-endowed countries, even though a national effort in education is important in order to reap the potential benefits of natural resources for growth, as natural-resource endowment and education seem to be complementary (see Lederman & Maloney 2007). Resource-rich countries have a larger margin for error with respect to unsustainable economic policies. As countless examples from A (Argentina) to Z (Zaïre) illustrate, this is clearly a blessing in disguise (see Gylfason 2001a).

Although the rise in crude prices over the last few years is reason for concern as to whether or not oil-producing countries awash in cash have learnt lessons from history (see, for example, Shaxson 2005), it is important to differentiate between successes and failures. Not all countries with abundant riches have faltered. It is also important to analyse the transmission channels of the potentially negative effects of resource-based development. For example, natural resources – and this applies particularly to mining – seem to contribute positively to growth if one controls for the usual culprits of poor governance, poor policies and poor institutions (Lederman & Maloney 2007; Papyrakis & Gerlagh 2004; see also Neumayer 2004). Expressed differently, the combination of abundance in natural resources, sound macroeconomic policies, and economic policies aimed at generating high savings rates and productive investments can be very successful (Atkinson & 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 United States compared to South America had nothing to do with the quality of those resources, which, if anything, was often better in South America. The key difference lies in the nature of the learning process that promotes the economic potential of the resources to a greater or lesser extent (Wright 2001). What mattered was that the United States applied its capabilities from exploration all the way through to advanced utilisation in the mineral economy, and the mineral sector thus became part of its knowledge economy. South America, by way of contrast, for a long time failed to exploit its location-specific knowledge of the resource sector, which was thus not subject to learning and upgrading (Wright & Czelusta 2004).

National innovative capabilities were also important in the industrialisation of the resource-intensive economies of Sweden and Finland. In Sweden in the middle of the nineteenth century, networks of technical institutions, industry and government already existed. To this day, these networks ensure the production and dissemination of knowledge, and the transfer of skills from academic institutions to industry, which foster the international competitiveness of the Swedish forestry industry. One of the key insights of the Scandinavian experience is that the diversification of the economy did not take place *away from,* but *alongside,* the primary sectors such as forestry, which were crucial for take-off. Indeed, forestry, rather than pharmaceuticals or telecommunications, still accounts for the major share of Swedish exports (Blomström & Kokko 2007).

A comprehensive analysis of the reasons for the relative backwardness of many resource-rich economies in different parts of the world would require a historical treatment that is beyond the scope of this study (see Landes 1998). A commendable project undertaken by a group of researchers at the World Bank compared the relative failures of South American economies with the relative successes of similarly endowed countries such as Australia, Canada, the United States, Sweden and Finland (De Ferranti et al. 2002). In short, it blamed the Spanish and Portuguese colonisers for introducing an anti-progress bias in their dependencies, which meant that initial conditions were anything but ideal. While their contemporaries in other emerging economies were engaged in building industries, South Americans had not yet finished their task of building nations. Moreover, the highly inequitable distribution of wealth, land, financial capital and education militated against the establishment of dynamic, innovative societies. Since education was significantly less technically oriented than elsewhere, both active and passive technical capacities were severely compromised. Import-substituting industrialisation thus built on an incomplete and imperfect edifice. This resulted in sectors weaned on artificial monopoly rents rather than on the quasi-rents emanating from absorbing new technologies, which undermined the growth prospects of resource-intensive sectors. All these are important factors behind many of the spectacular failures on the South American continent (De Ferranti et al. 2002: Chapter 3; Maloney 2002).

In summary, in the past, resource intensity has been less fortuitously matched with economic development in South America than in similarly endowed countries. However, a more differentiated picture emerges from a consideration of the recent history of South America. To be certain, the region still has its fair share of unsuccessful economies, but it also has some eminently successful examples of economic development across a range of activities, which include and extend beyond traditional activities: fruit and salmon in Chile, electronics in Costa Rica and Mexico, or tourism in the Caribbean. According to the World Bank report (De Ferranti et al. 2002), the common factor in these experiences is that countries have 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 (FDI), but they will also be generated by domestic institutions and rely on investments in ICT infrastructure. Ultimately, intelligent policies aided the transformation of natural resource-based activities into knowledge-intensive assets (De Ferranti et al. 2002: Chapter 4). Intelligent policies are those that help build the endowments that underlie the knowledge economy – including education and training, support for R&D and innovation, accessible ICT infrastructure and generally sound institutions (De Ferranti et al. 2002: Chapter 1).

In summary, this brief review of the literature suggests, firstly, that rich resource endowments may, but need not, slow growth. Hence, for countries with this characteristic, there is no reason to sulk. Secondly, as with any 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 that lie behind restructuring and productivity growth. The rise of the knowledge economy tends to raise the stakes related to risks and uncertainties. In short, technological, information and coordination externalities militate against the pursuit of diversification through restructuring by lone entrepreneurs. This insight motivates interest in industrial policy in general (see Rodrik 2004) and more specifically has inspired reflections in South 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 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. That is why, in the Costa Rican case, we hear much about electronics but nothing about coffee – obviously there are no direct linkages between these two activities.

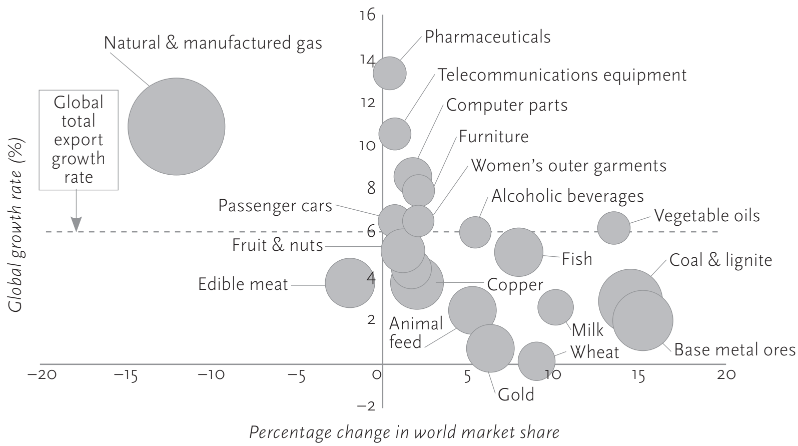
Restructuring and diversification in resource-rich economies are likely to take specific forms, however, insofar as they, at least in part, are supported by related and input industries that supply resource-based sectors with goods and services. Although there is a global knowledge base for mining, agriculture and aquaculture, or forestry, specific local circumstances will often require specific local solutions. This may mean that the local knowledge base around resource exploitation is deeper than in other parts of the economy. For example, a country with an important share of intensive animal husbandry in the economy would benefit from veterinarians that know how to keep large numbers of pigs relatively healthy, even though they may live in unnatural conditions, as opposed to veterinarians that specialise in the psyche of chihuahuas unable to cope outside the sheltered life that they lead with their owners. Everything else being equal, the depth of knowledge – both upstream and downstream – around the resource economy is such that it may spur technological learning that starts, but does not end, with a resource-based activity. This insight motivates interest in the co-evolution of resource- and knowledge-based activities through technological trajectories that link the one with the other, as well as a consideration of whether and, if so, how, industrial policy may complement it.

Resource intensity and knowledge: old and new economy

The previous section showed that resource intensity need not stifle growth and development. The case is theoretical, bolstered by insights from economic history. The question, then, is whether resource intensity is associated with low growth or stunted development in the countries under consideration. If it were not, there would not be much point in worrying about knowledge intensification of these activities. However, as will become clear, the data show unambiguously that the dynamism characterising some of their resource-poor competitors has largely eluded resource-intensive economies in the recent past. In the absence of China's demand for raw materials, this difference would be even more patent. In essence, this provides the rationale for probing the determinants of knowledge intensification of resource-based activities, which is taken up in the following section.

One way of considering the optimal positioning, or otherwise, of a country's exports in terms of global demand is to compare its share in those products that account for most of the dynamism in world trade. More precisely, a country is well positioned if its world market share in dynamic products is rising. Expressed differently, export specialisation in products with below-average growth rates suggests suboptimal positioning. Figure 1.1 shows that a group of countries consisting of 25 economies from sub-Saharan Africa and South America, as well as Australia, New Zealand, Indonesia, Morocco and Norway, exports relatively few products in which its world market share is rising and which simultaneously record above-average growth. In fact, the top right quadrant, which contains the world's most export-dynamic products, is relatively sparsely populated, while most exports take place in product groups located below the dotted line, for which world demand is falling (Edwards & Alves 2005).

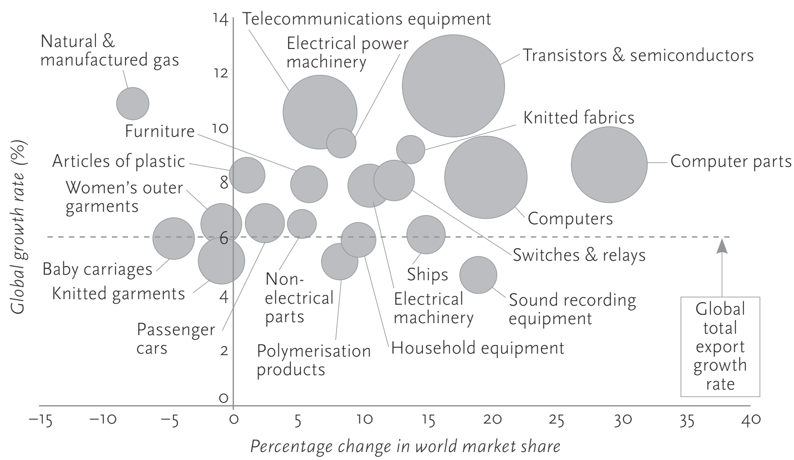
FIGURE 1.1 *Market positioning of the resource group's top 20 exports (2002)*



Note: The dotted line represents world growth for all products. Changes in world market share are expressed as percentage points.
Source: Edwards & Alves (2005: 19)

To varying degrees, the export specialisation of the four countries studied in the present volume reflects that of the larger resource group analysed by Edwards and Alves (2005). In 2005, Brazil's top 20 exports made up 40% of total exports. More than four-fifths consisted of resource-based goods, which thus dwarfed the share of more dynamic exports such as automobiles, mobile phone components and aircraft (Ministry of Industry and Trade 2006). Similarly, close to a quarter of exports from Costa Rica originated in fishing and agriculture (Procomer 2006). The fall in prices since the mid-1980s, especially for commodities such as coffee, led to an initially slow change in the composition of exports towards more dynamic products, notably in the electronics, medical device and textile industries, accelerated in the late 1990s by sizeable foreign investments in these areas. The problem in Costa Rica is the dualist nature of structural change. Sectors dominated by foreign multinationals are largely responsible for the

FIGURE 1.2 *Market positioning of East Asia's top 20 exports (2002)*



Note: The dotted line represents world growth for all products. Changes in world market share are expressed as percentage points.
Source: Edwards & Alves (2005: 19)

repositioning of exports towards areas of large and growing demand, while domestic producers continue to predominate in traditional commodities such as bananas and coffee, along with fresh fruit and basic processed food (Giuliani, with Ciarli 2005: Section 4).

In Peru, traditional exports, including mining, accounted for more than 70% of exports in the late 1980s. By 2005, this had not changed. The only products among the top 20 exports aimed at more dynamic markets were copper cathodes and T-shirts, making up 13% of the total (Ministerio de Economía y Finanzas 2006; Banco Central de Reserva del Perú n.d.).

Finally, South Africa's export composition is also primarily resource-based, and diversification into fast-growing export sectors is much less visible than in comparable countries. This is a problem insofar as the country's total export growth in the 1990s, at 2% per annum, lagged not only average world growth but also growth in similarly endowed countries. The main reason for this is the decline in exports of primary products. Consequently, South Africa's overall share of world exports fell from 0.89% in 1988 to 0.52% in 2002 (Edwards & Alves 2005). A similar trend was evident for aggregate manufacturing, in which South Africa's annual growth rate trailed that of developing countries in general and resource-intensive economies as well. This was particularly pronounced with respect to high-technology products.

In contrast, the performance of East Asia has been very different, which illustrates that East Asian economies have been the source of much of the dynamism in global trade in the last two decades (see Figure 1.2). This brief overview does not revive the resource-curse hypothesis in its crude form, but it does show that a high concentration of exports in primary and natural resource-based products was associated with a below-average export growth rate in the 1990s. This is among the factors that motivated the present study. The next section elaborates on how knowledge intensification might address this problem.

The determinants of knowledge intensification of resource-based activities

Towards co-evolution and lateral migration

The literature on resource-based growth essentially draws on two different but complementary sources. The first is economic history, which 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 explains growth and development as a function of a country's ability to learn and to build capabilities through investments in human capital, sound institutions and infrastructure. The best work combines the two in theoretically informed, comparative historical analyses.

This study considers instances of technology development, both failed and successful, and tries to identify their essential mechanisms. This leads to insights in their own right and contributes to the literature on knowledge industries based on natural resource-based activities. Insofar as this literature is still emerging, however, this study is also partially inductive. It formulates propositions that can be subjected to further scrutiny in future work. It is the combination of the two that allows recommendations to be made regarding the possible outcomes of particular policies. The study also suggests factors to be avoided in contributing to economic diversification based on, while at the same time moving away from, resource sectors.

The knowledge intensification of resource-based activities can take four possible forms, the first three of which are well known. The first is simply the improvement of the production process itself through technological upgrading. The second is downstream beneficiation. The third is the development of input industries, upstream or downstream. Finally, 'lateral migration' occurs when the knowledge, capital goods and services sector associated with a resource-based activity are applied in areas that are not linked to resource exploitation.[1] In other words, it occurs when knowledge accumulation bridges the resource and knowledge economies through linkages of human and other capital. Examples from South Africa include a low-dosage x-ray technology originally developed to control the loss of diamonds through theft from mines, which later found application in medical surgery (where it allowed total body scans of emergency patients in a few seconds), and cyclones originally designed to sort mine waste, the application of which in the food industry was subsequently explored (Corporate Strategy and Industrial Development Research Project 2004; Gostner 2004).

The original derivation of the idea of lateral migration was problematic, because it treated natural resources as a factor fixed by nature. While this is true in the very long run, it is, of course, not correct that natural wealth is fully exogenous. How much economically useful coal or oil a country has is itself a function of its ability to search for and then extract reserves. This ability, in turn, depends on the technological capability of the country, particularly the relevant sectors. In periods of high commodity prices, technological opportunities emerge that would not have been feasible under other circumstances. Expressed differently, the natural resources that a country has depend not only on what occurs underground or grows on trees but on how smartly the country sets about looking for and extracting value from such resources.

This should not detract from the important insight associated with lateral migration, however, namely that resource-based and knowledge-intensive activities may co-evolve. To underline the point, if a country were to tax certain old economic activities and provide incentives for perceived new economic activities, resource- and knowledge-intensity may co-exist, but there would be no linkages between the two. Although historical experience shows that some firms have indeed succeeded in creating certain competences *ex novo* – Nokia's advance into electronics from paper, tyres and cable is a prime example – it is obviously easier to think about, and steer, economic development in an evolutionary fashion, in which the accumulation of knowledge is gradual and continuous, and the challenge hence lies in

FIGURE 1.3A *Co-existence of resource and knowledge economies*

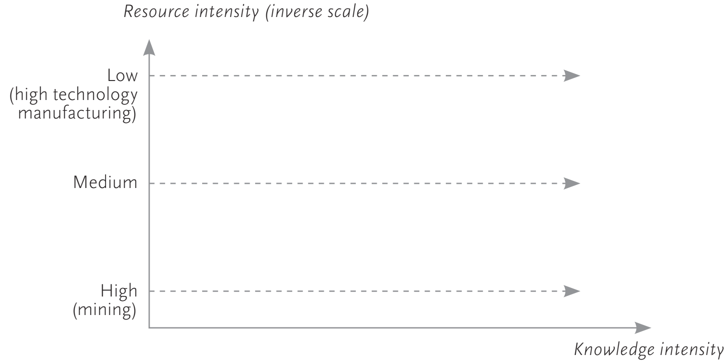
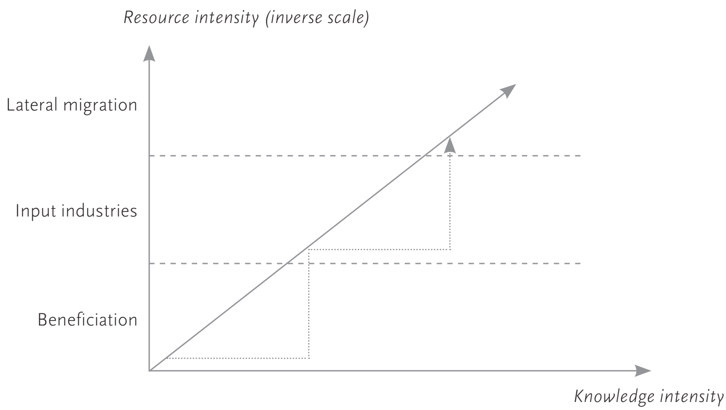


FIGURE 1.3B *Co-evolution of resource and knowledge economies*



creating and sustaining linkages that build bridges between the resource and the knowledge economy. Figures 1.3a and 1.3b illustrate in stylised fashion the various technological trajectories.

In Figure 1.3a, technological trajectories in more or less resource-intensive activities take place in parallel. Knowledge intensification may materialise, for example, through the adoption of superior mining technologies, but the knowledge base surrounding resource exploitation remains separate from non resource-intensive activities that, in turn, do not inform what happens in the traditional sector. In Figure 1.3b, the technological trajectory results from the interaction between resource- and knowledge-intensive activities. This relationship may take many forms and can go both ways – non-resource sectors can clearly increase the knowledge intensity of resource sectors. It is obviously unlikely to be linear; depending on the characteristics of the key technologies and the learning conditions in place, change might be stepwise in the sense that knowledge intensification in one activity must reach a certain threshold before the involvement of other sectors (including the full extent up to lateral migration) becomes feasible.

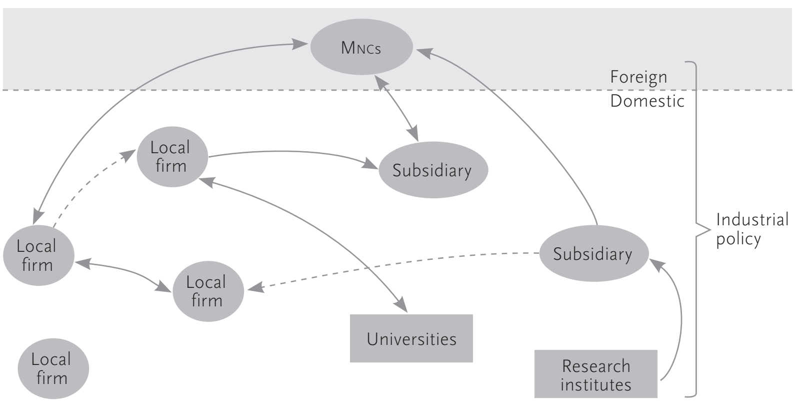
Not all the case studies in this report are examples of lateral migration. Some illustrate downstream beneficiation, while others more or less end with the development of input industries. Not all cases are successful, either, in the sense of realising fully commercialised technologies; a few are ongoing activities with relatively uncertain outcomes. However, they all exemplify co-evolution through linkages. They also demonstrate how the resource economy can form part of the knowledge economy and vice versa. The strength of the linkages and the relative success of the technological trajectories depend on a series of factors that require systematic analysis.

From firm learning to policy in support of lateral migration

In addition to the literature on the resource curse already referred to, four related bodies of knowledge inform this study: absorptive capacity and technological learning; technology transfer and diffusion of foreign knowledge; systemic linkages and interactions in the innovation system; and industrial or technology policy. In brief, the focus is on local firms and how they learn and upgrade. In this process, they entertain relationships with other firms, mainly as suppliers or customers, which are either domestic or subsidiaries of foreign multinationals. Knowledge flows between firms can be uni- or multidirectional and involve codified and tacit knowledge (see Figure 1.4). The exchange of knowledge can be intentional as in licence agreements, or work through spillovers (characterised by dotted arrows in Figure 1.4). Furthermore, some firms have relationships with knowledge producers such as universities or research institutes. The totality of these relationships can be more or less systemic or, in other words, more or less conducive to innovation. This depends in part on the policy framework, namely, whether firms operate in an environment in which they are well positioned to overcome information, coordination or network failures that might otherwise obstruct their quest to upgrade what they are doing, and how they go about it.

This deserves a fuller exposition. Firstly, firms engaged in technological upgrading learn insofar as they make use of external knowledge to modify existing technologies or to create new ones. In both cases, investments in R&D are important because they help generate new information and

FIGURE 1.4 *The flow of knowledge between local and international companies and research institutes in the context of industrial policy frameworks*



promote learning. This does not mean that learning occurs only in industries in which formal R&D is prominent (see Von Tunzelmann & Acha 2005), but merely that the role of R&D is crucial not only for the creation but also for the assimilation of new knowledge. In this perspective, learning does not take place simply by doing but is the outcome of a purposeful search for external knowledge to be selected, internalised and exploited (Cohen & Levinthal 1989, 1990).

Since the cases discussed in this book all involve R&D in one form or another, several more comments are in order. Firstly, spending on R&D will tend to relate to the characteristics of industry-specific technological and scientific knowledge. The more difficult it is to assimilate this knowledge, the more firms will spend on R&D. Likewise, the smaller the 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 (including both current knowledge and the previously 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). Such capacities also result from advanced technical training.

Absorptive capacities have the effect of influencing the level of aspiration in an organisation. Thus, firms with deep absorptive capacities are more likely to recognise emerging technological opportunities. When the knowledge to be exploited is closely related to the firm's existing knowledge base, absorptive capacities can be built as by-products of routine activity. In contrast, when that is not the case, such capacities must be created. Finally, absorptive capacities become 'realised' only when the assimilated knowledge is commercialised – until then they are merely 'potential' (Zahra & George 2002). Differences in knowledge bases and organisational structures could be the reason why a local firm with an otherwise high absorptive capacity potential fails to internalise knowledge embodied in foreign technology. In other words, firms learn more easily from some actors than from others (Lane & Lubatkin 1998).

The technological know-how of firms is augmented by the complementary assets and technologies required to bring the innovation to market (Teece 2006). Why do some firms succeed in capturing significant shares of the available profits from a particular innovation, while others fail to do so? The full answer to this question relies on the operation of the relevant innovation system, which will be further explored.

Secondly, insofar as the relevant external knowledge is of foreign origin, the key question is how technology imports and indigenous investments complement one another, and the extent to which this occurs (Blomström & Kokko 1998; Lall 1993; Pack & Saggi 1997). The relationship between FDI (the major channel of technology transfer) and indigenous technological development is not straightforward. The assimilation, adaptation and further development of imported knowledge require capabilities that not all firms in developing countries possess. At the national level, capability development is influenced by the respective trade and industry regime, human capital, information flows, infrastructure and supporting institutions. At the micro level, firms must undertake efforts to build new technological and organisational skills, have the ability to access (and generate) information, find a niche in which they can compete, and enable themselves to exploit linkages with relevant institutions both upstream and downstream. Systemic perspectives are therefore again important.

The scope for technology assimilation further depends on the transfer mode. Multinational corporations (MNCs) can externalise the transfer through minority joint ventures under the control of the host country, management contracts, subcontracting, and the like. Since this involves a certain degree of cooperation between foreign and local firms, spillovers may be greater. Alternatively, MNCs can retain control. Either way, FDI should intensify competition in the local market, which may in turn spur innovation. Even if it does not, however, it is likely to complement future technological ability by enhancing indigenous R&D productivity. From the perspective of the MNC, the internalisation choice depends on the nature of the technology in question, the strategy of the seller, the capabilities of the buyer, and the policy of the host government. The trade-off is between reduced rents from FDI due to heightened competition and a certain loss of proprietary information from licensing if the local firm uses the knowledge it gains by exploiting the licence to improve its R&D capability. For a local firm, the strongest incentive for innovation would result from licensing that would help it to increase its capability, followed by FDI with which it would then be better able to cope. In general, the more standardised and diffused the technology and the more capable the buyer, the more economic sense externalised modes would be expected to make (Pack & Saggi 1997).

Thirdly, the relationship between technology transfer and local capability building is both complementary and competitive. When local capabilities are weak, firms will find it more difficult and more costly to absorb and deploy foreign knowledge, which may negatively affect its impacts and quality. However, if domestic firms are able to reduce the technology gap through successful imitation of initial low-quality FDI, they can actually provide incentives for high-quality FDI (Glass & Saggi 1998). At the same time, as already noted, higher buyer capability also translates into a stronger competitive threat to the MNC, thus increasing the need for control, especially over its advanced technological assets. Nonetheless, it is only with high capabilities that host countries have the choice between alternative modes of technology import. For example, they might be able to design strategies that boost local R&D in conjunction with non-equity forms of technology transfer, instead of merely receiving the results of R&D performed elsewhere (Lall 1993). Thus, for the assessment of technological trajectories, it is important to understand whether a local firm was in a position to choose from a series of technology imports (for example, licence, joint venture or equity), and whether and in what manner it exercised its choice.

Fourthly, learning is embedded in a knowledge infrastructure and takes place in interaction with consumers and producers of knowledge in the private and public sectors, including those from outside the country (for example, Bell & Pavitt 1993; Lall 1993). There is, of course, a link between firm-level and national technological capabilities, though not in the simple sense that the former merely aggregate to the latter. Lall (2000) refers to this as an innovation system, by which he intends the externalities and synergies associated with the learning process, ways of doing business and competencies inherent in relevant institutions. At the macro level, technological achievement depends on the success with which policy addresses market failures emanating from the respective incentive regimes (the general policy environment, especially trade policy), factor markets (especially technical skills) and institutions (especially those that support industrial technology). Since market failures will vary by the type of technology and the nature of requisite complementary assets, policy support must often be selective (Lall 2000), about which more will follow.

In the classical formulations of the national system of innovation (NSI) approach, what matters most for technological upgrading is the functional (Lundvall 1992) or structural (Freeman 1988) linkages between the actors in the system. 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 study firms and all other actors that matter whether in industry, government, academia or even perhaps civil society. The study thus shares with the NSI literature a recognition of systemic dynamics and attention to linkages and interactions, but since this study moves from the micro to the macro level, there is no need to describe all the institutions that make up the NSI (see Edquist 1997; Lundvall 1992; Nelson 1993). Instead, the focus is on those that matter directly or indirectly (through skills provision, for instance) to the technology at hand.

Although the focus of the case studies in this volume is always on technological upgrading of individual firms, it is clear that in some cases, especially those of sugar in Brazil and mining in Peru and South Africa, these firms form part of sectoral systems in the sense that they share a knowledge base and require technological inputs. They are subject to specific learning processes and competencies and exhibit similar organisational structures and behaviours in their interactions with relevant institutions (Malerba 2002), but we do not specifically explore these interactions here.

However, the case studies do consider how institutions influence interactions between economic agents and how this affects economic activity. Recent work suggests that institutions matter in one of two ways: either they are a prerequisite to certain technological innovations being usefully exploited or, alternatively, institutional structures support technological innovation that would otherwise not take place. Putting the two together results in a view of economic growth as the co-evolution of physical and social technologies, firm and industry structures, and supporting and governing institutions (Nelson 2006).

None of this is easy. Firms do not have full information when confronted with choices about technological alternatives. Technological upgrading is a risky business, as the future is difficult or impossible to predict. Firms cope by developing routines that, in the best scenarios, are updated to incorporate new information. Of course, these routines may encourage safer options, rather than investments in risky activities with difficult technologies that provide specific technological and attendant social benefits. It is therefore incumbent upon governments to provide incentives for firms to undertake selected desirable activities across sectors in missing or underdeveloped markets. If the skills required for new technologies are highly specific and thus not easily available from the education and training system, interventions may have to be targeted to ensure the deployment of new technologies (Lall & Teubal 1998; see Blomström & Kokko 2007; Rodrik 2004; Unido 2002).

The reason for drawing on a relatively wide range of literature is to do justice to the complexity of technological transitions, especially insofar as they entail the considerable cognitive distance involved in lateral migration. In order to investigate whether there is a pattern to the knowledge intensification of resource-based industries, it is important to understand the internal resources and external knowledge that firms draw on, regardless of the purposeful or accidental nature of their technological enquiry. We must also understand the nature and the weight of the contribution of other actors and institutions in the system of innovation to which the firms belong. We must understand how they have individually or collectively overcome disincentives to innovation associated with market failures in technology, information and coordination. Finally, the analysis of the attendant processes must be embedded in a description of the resource base (including its possible negative impacts) from which they emerged.

Methodology and data

The research is based on five case studies from the two most resource-intensive developing regions in the world, namely South America and Africa. They were chosen both for pragmatic reasons – because the case researchers were experts in the respective areas and had had prior exposure to the relevant issues – as well as for substantial reasons. One such reason is that enough was known about the cases to embed the incidents of technological learning in the historical evolution of the respective national economies, the relevant sectors and government policy. Another reason is that the cases reflect enough variance in the four analytical dimensions – absorptive capacity and technological learning; technology transfer and diffusion of foreign knowledge; systemic linkages and interactions in the innovation system; and industrial or technology policy – as well as in the outcomes to allow for some comparison of the knowledge intensification of resource-based activities across the experiences of the five case studies.

Fieldwork took place in the second half of 2005. Each case study team was asked to address a core set of questions in semi-structured interviews (see Table 1.1). These questions are derived from the literature discussed and provide a common framework that allows for systematic comparability.

In the interests of analytical clarity, it is important to weigh these groups of questions carefully. A morphological account ending in a

TABLE 1.1 *Questions for semi-structured interviews*

Perspective	Questions
Absorptive capacities or firm learning	◆ What is the nature of the technology and the resource base from which it originated? ◆ What is the nature of the new application and industry into which the technology migrated? ◆ What were the determinants of cumulative and present absorptive capacities (role of R&D spending, share of R&D spending in turnover over time, advanced technical skills, manufacturing operations (if applicable)? ◆ What was the origin of the lateral-migration technology (including blue sky, reverse engineering, licensing, involvement in global knowledge flows through scientific or other forms of cooperation)? ◆ What were the problems with any of the above: nature and cause?
The role of foreign technology	Did foreign technology inflows: ◆ enhance incentives for innovation? ◆ diminish them because they obviated the need for indigenous generation of technology? ◆ matter only in terms of content or also with respect to the transfer mode? ◆ benefit from a strong/weak intellectual property rights (IPR) regime?
Linkages and interactions	◆ What is the nature of the embeddedness of the innovating firm in a system of innovation (including suppliers and customers, education and training providers, science institutes, sector associations, public authorities and standards bodies)? ◆ Which interactions with other firms and with the knowledge infrastructure mattered, and why?
Industrial policy	◆ What sort of market failures did the innovating firm encounter and how did it overcome them, or did it fail to overcome them? ◆ What was the role of industrial policy?

TABLE 1.2 *Profile of case studies*

Country	Resource base	Lateral migration	Key entities	Period	Results
Brazil	Agriculture	Sugar bagasse ▸ biodegradable plastics	Institute of Technological Research (IPT); Institute of Biomedical Sciences (ICB); Copersucar Technology Center (CTC); PHB Industrial SA (PHBISA); Department of Materials of the Federal University of São Carlos	1991–ongoing	Polyhydroxy-butyrate (PHB) biodegradable plastic production plant within a traditional sugar mill; functional but costly biodegradable thermoplastic
Costa Rica	Agriculture	Coffee beans ▸ specialised machinery for sorting by colour of coffee, grains, and seeds	Xeltron; AETEC	1974–ongoing	Sophisticated machinery using laser technology and artificial intelligence
Peru	Mining	Bioleaching for metal recovery ▸ bioremediation	Minera Lizandro Proaño SA (MLPSA); Repadre International Corporation (RIC); Global Environment Emerging Markets Fund (GEEMF); TECSUP; FIMA; Glencor; École de Mines d'Ales; Universidad Particular Cayetano Heredia	1997–ongoing	Successful conversion of a zinc and lead mine into a gold mine, but eventual commercial failure; advanced research in bioremediation

Country	Resource base	Lateral migration	Key entities	Period	Results
South Africa	Agriculture	Maize starch ▸ biodegradable plastics	Centre for Polymer Technology, CSIR; Institute of Applied Materials, University of Pretoria; African Products (Pty) Ltd; Xyris Technology CC	2002–ongoing	Prototypes for future commercial-isation: seedling trays and golf tees
South Africa	Mining	Hydro-hydraulic technologies in mining ▸ other sectors ▸ services	Chamber of Mines Research Organisation (COMRO); mining houses	Early 1980s–ongoing	Hydro-hydraulic technologies used for a variety of applications other than gold and platinum mining

Notes: AETIC is a subsidiary of a US multinational.

COMRO is part of the Chamber of Mines of South Africa (COMSA).

Copersucar is the Cooperative of Sugar and Alcohol Producers of the State of São Paolo, the world's largest exporter of sugar.

The CSIR (Council for Scientific and Industrial Research) is one of South Africa's nine statutory science councils.

FIMA is an equipment producer.

ICB hosts the Laboratory of Genetics of Micro-organisms and Biotechnology and is part of the University of São Paolo, Brazil's most prestigious university.

IPT is a public research institute of the State of São Paolo.

MLPSA is a family-owned mining firm.

PHBISA is a partnership between two of Brazil's strongest groups in the sugar and alcohol industry.

RIC and GEEMF are Canadian investment funds.

TECSUP is a mining training centre.

conclusion whereby everything is related to everything else would not serve the ultimate aim of this study, which is to determine whether there are any lessons from these experiences that suggest where and how governments might harness the positive aspects while minimising the negative. At a minimum, this calls for the differentiation of principal and marginal factors. It was important for case study researchers to construct counterfactual scenarios and have them assessed and triangulated by interviewees with different biases and perspectives with respect to the question at hand.

The case studies are profiled in Table 1.2. Three originate in agriculture and two in mining. All involve a private-sector firm, and many count firms and academic or scientific institutions among their key entities. Some are of rather recent vintage; others date back more than 30 years. Most of the projects have reached their narrower research objectives, but only half have managed to produce commercially viable goods or services. This does not imply that all the others are failures; some projects are ongoing and may yet manage to commercialise the object of their endeavours. The remainder of this section briefly summarises the key features of the five case studies.

Sugar-based plastic in Brazil

Brazil is the world's largest producer and exporter of sugar. In response to rising crude oil prices in the 1970s, Brazil started producing alcohol from sugarcane for use as a blend in car fuels. Since then, the country has also operated an R&D programme aimed at finding alternative sources of alcohol and increasing the efficiency of sugar production, and has built up considerable expertise in this area. From the late 1990s, a drop in world sugar prices, combined with lower demand for ethanol due to lower crude oil prices, as well as a gradual liberalisation of the Brazilian economy, led to much idle capacity in the industry. This provided the context within which the idea of producing biopolymers[2] was first considered. Biopolymers help reduce reliance on fossil fuels and diminish the production of industrial and household waste. They thus have several desirable features. Initial discussions involved the Copersucar Technology Centre (CTC) (Copersucar is the Cooperative of Sugar and Alcohol Producers of the State of São Paulo), the Institute for Technological Research (IPT), a state government-funded research institute, and the Institute of Biomedical Sciences (ICB) at the University of São Paolo. The partners had previously collaborated in sugar-related research (see Chapter 2 by Velho & Velho).

Funding was available partly through a loan from the World Bank's Science and Technology Reform Support Programme. The partners agreed to exploit biotechnology in order to produce biodegradable plastics from sugarcane and registered a patent on the process. Following successful trials, an established sugar mill, Usina da Pedra, agreed to build and run an intermediate-scale pilot unit in an existing mill and to underwrite the risk of failure. The conditions included full reimbursement of its costs and priority rights to the licence for five years should the project succeed.

In 2004, Usina da Pedra opened a commercial plant with an annual capacity of 2 000 tons. The product has been tested for a variety of applications, ranging from injection and extrusion technologies to packing materials, cups for seedlings and medical devices. New specialised research partners joined the consortium, including the Department of Materials of the Federal University of São Carlos, while the bioplastic is given to anyone who wants to test it, including multinational companies such as BASF. Although the consortium managed to produce what can be considered a consistent product with a relatively stable technical specification, bioplastics production is still not cost effective.

Knowledge intensification in this case refers to diversification in the use of an agricultural commodity for a variety of industrial applications outside the food-processing chain by means of downstream beneficiation. Thanks to a long tradition of researching alternative uses for sugar, this includes promising applications that move away from the environmentally undesirable use of fossil fuels.

Biodegradable plastics from maize starch in South Africa

A number of institutes and private companies pursued research on biopolymers in South Africa in the 1990s. This was in part a continuation of more general work on polymer technology and in part a response to emerging waste management problems due to the ever-increasing quantity of plastic bags. In addition, a manufacturer of maize starch was interested in exploring new downstream uses of its products. In the late 1990s, these players came together and formed a loose consortium that was able to obtain government funding from 2002 (see Chapter 3 by Walker). The research objective was to develop and commercialise a starch-based plastic without the use of significant amounts of synthetic polymers. This case is thus similar to the Brazilian case already described.

The consortium reached approximately 80% of its milestones in the third and final year of public co-funding of the project. Although it had failed to commercialise widely a suitable biodegradable plastic from maize starch at an acceptable price, it succeeded in producing two products – seedling trays and golf tees – that are commercially available.

This is a case of knowledge intensification, because it diversifies the use of an agricultural commodity – from maize as a staple food to starch for environmentally friendly plastics – in a wide range of industrial and household applications, using expertise accumulated from the downstream beneficiation of another commodity, namely oil.

Bioleaching and bioremediation in Peru

Peru is rich in mineral resources. Together with its Andean Pact neighbours (Bolivia, Colombia and Ecuador), the country was involved in attempts to use bacterial leaching to recover copper in the 1970s. Although successful, these attempts became the victims of a deep crisis afflicting the mining sector in the 1980s. Following the privatisation and liberalisation of the economy and subsequent inward direct investment by US mining houses, bioleaching took off again in the 1990s. Chapter 4 by Kuramoto and Sagasti describes the technologically proven but commercially unsuccessful indigenous development of a hydro-metallurgic method of gold leaching. A small, family-owned mining firm, Minera Lizandro Proaño SA (MLPSA) managed to obtain private international funding for a project to transform a lead and zinc mine into a gold mine. From 1999, gold was recovered through a cyanide-based technology in conjunction with the use of bacteria. Two other local actors were involved. A mining training centre (Tecsup) explored the feasibility of using the bacterial leaching technique to treat mining tailings. A domestic equipment producer (FIMA SA) was primarily responsible for the construction of the project.

The technology was essentially re-engineered from a process owned by the South African mining house, Gencor. When MLPSA first learned about the Gencor technology, it enquired about a licence. Since Gencor's asking price was unaffordable, it then decided to try to copy the process. After it had succeeded, it approached Gencor again because it was interested in the warranty that accompanied the licence. Gencor dropped its price considerably, and an agreement was concluded. Despite the technological advance, however, bottlenecks in mining output meant that the plant's demand for minerals could not be met, and the plant had to be closed after only a few years of operation. However, the process of gold and silver extraction *per se* was successful.

The scientists most closely associated with the experience used the insights gained into the behaviour of bacteria in metal extraction to conduct research on the use of bacteria for bioremediation. Contaminated soils can be remediated using bacteria either by extracting the toxic substances or by reducing their toxicity. Knowledge intensification thus took place in an input industry; a technology external to Peru was first adapted to local circumstances in mining (bioleaching) and then further pursued for applications that extend beyond mining (bioremediation). Since bioremediation can be applied outside of mining, this case therefore holds the potential for lateral migration.

Hydraulic technologies in South Africa's mining sector

South Africa has historically been a highly resource-intensive economy, particularly with respect to mineral deposits. Mining houses were interested in hydraulic technologies to increase labour productivity in the face of labour scarcity (although this was artificial), as well as increasingly deep, and thus more costly, mining operations from the mid-twentieth century.

After a long tradition of research in emulsion hydraulic technologies, the research arm of the Chamber of Mines, COMRO, began researching combined hydraulic power and cooling systems in the early 1980s. Hydraulic power systems are advantageous because they are more efficient than pneumatic drills and create far less mechanical and exhaust noise. In turn, water (in other words, pure) hydraulic systems are superior to emulsion (in other words, mixed) hydraulic drills, because, among other things, they do not leak oil into the environment.

By the early 1990s, a commercially viable hydro-hydraulic (HH) technology existed, making South Africa a world leader in this regard (see Chapter 5 by Pogue).

South Africa continues to develop water hydraulic technologies for the mining industry. Despite its pioneering work, however, the South African technology has largely missed the expanding market for non-resource-intensive applications.

Currently, international demand for water-hydraulic technology is growing as an environmentally friendly technology in construction, food processing, metal processing, fire fighting, industrial cleaning and a range of other industrial applications. Nonetheless, the technological trajectory of the South African technology has remained largely linear, with few linkages to non-resource-intensive applications. While the potential to lead rather than follow in this technology still exists, it would appear to risk falling by the wayside if greater support is not given to facilitate linkages outside the resource base.

Specialised sorting machinery in Costa Rica

Xeltron is a small, specialised, domestic machinery manufacturer, located in an export processing zone (EPZ) between the Costa Rican capital of San José and Cartago. Xeltron designs and produces machinery that sorts coffee, rice, beans, nuts and seeds in general by colour. Almost all Xeltron's output is exported. The origins of the company date back to the mid-1970s. At that time, coffee-sorting machinery was imported, and only maintenance and repair were carried out locally. Xeltron's founders have introduced a number of technological innovations over the years. First they improved existing colorimetric techniques by employing optical analysers that allowed for far more precise measurement of colour. Subsequent technological upgrades included the use of microprocessors and semiconductors and, finally, artificial intelligence. Xeltron holds five international patents on its innovations (see Chapter 6 by Giuliani).

This is the only pure case of successful lateral migration in this book. For the country as a whole, it occurred because Xeltron's machinery design took its point of departure from coffee crops, one of Costa Rica's traditional mainstays. For the company, lateral migration moved machinery that had been developed strictly for sorting coffee beans to other grains, and eventually even to the sorting of plastics and emerald products.

Analysis

The cases reviewed here tell stories – if not of blood, then definitely of much sweat and also of some tears – of the people behind these technological developments. Foreign knowledge was generally helpful to their pursuit, at least when it was actually available. The organisations that formed the subjects of the case studies entertained relationships with other actors that were fruitful more often than not, but the depths of the surrounding innovation systems are certainly not the same across the four countries or over time. Industrial policy was strongly supportive in some cases and largely absent in others. The degree of knowledge intensification of resource-based activities also differed, as did their commercial success. In seeking patterns that explain the observed technological trajectories, one must be sensitive to the similarities, but especially to the differences, in order to select the critical factors behind the observed outcomes.

In the area of firm learning, it is clear that knowledge is cumulative. In no case did the aspiring engineers and scientists arrive without precedent. Instead, they were always part of a longer tradition of seeking technological solutions, albeit not typically in the same application. Thus, a tradition of research formed the foundation for what many years later evolved into the activities discussed here. Knowledge intensification of resource-based activities therefore requires some stamina, certainly for those who actively pursue it, as opposed to those who merely adapt developments undertaken elsewhere. In either case, investment in the scientific and technological workforce is paramount.

More or less formal R&D was important for absorptive capacities and often yielded tangible benefits in the form of productivity increases, but the forums for learning differed between the countries. In Peru, it was essentially one firm that undertook strategically motivated research with dedicated staff, internal dissemination and organisational adaptation. More extremely, the Costa Rican firm, individually and independently, set itself the goal from the outset of reaching the global technological frontier. Its absorptive capacities were supported by advanced skills, many of which were acquired on the job. The firm was adept at controlling complementary assets by outsourcing the manufacture of components developed in-house so that it could focus on its core competence in the optical field.

In the Brazilian plastics and the South African drill cases, research was organised, and occasionally even undertaken, by sector associations. The retention of in-house capabilities alongside the outsourcing of R&D tasks to universities, science councils, equipment suppliers and so on suggests that such organisations did not believe in short cuts, but considered that the graduation from potential to realised absorptive capacities presupposed coopting knowledge-intensive partners with whom to seek solutions that they would not have been able to find alone. It is clear from the Brazilian case that the incentives for firm learning were extensively influenced by the alternative fuel programme, which allowed indigenous knowledge in a latecomer country to operate at the global frontier. In South Africa, in contrast, the depletion of essential engineering skills hampered the dissemination and absorption of new technology.

In all five instances, foreign knowledge had a role to play, but in different ways. The Brazilian researchers had initially merely to be aware of the results of international polymer research published in scientific journals. Foreign partners gained increased importance only *after* the successful process innovation, when commercial applications had to be explored in both domestic and international markets. The Peruvian case lies at the other extreme, in that it relied entirely on the donation of equipment from abroad. Although employees of foreign firms migrated to domestic firms and thus generated spillovers, Peruvian engineers were not even aware of cognate activities in a neighbouring country, thus underlining the importance not only of the availability and accessibility of knowledge, but of the very awareness of its existence – in short, absorptive capacities. The gap between these capacities and foreign technology also meant that the quest for lateral migration in Peru would experience potential problems with intellectual ownership, because the international licensors would be in a position to impose limits on how and where the technology in question could be exploited.

The other three cases lie between the examples of Brazil and Peru: foreign knowledge more or less intensely informed local research and increased innovation, but not necessarily with the domestic institutions as junior partners. Partnerships could also be between equals, or the latecomer firm could be the senior partner. The Costa Rican firm is the exception to the rule that FDI does not bring backward or forward linkages. Xeltron had no choice but to source technical knowledge abroad, because it was simply not available locally. The price for not being attuned to global networks would have been failure of the desired upgrading and innovation.

The technological trajectories reported in this volume evolved in very differently constituted innovation systems. In Peru and Costa Rica, to all intents and purposes, they did not exist. In Peru there was no history of university–industry linkages (UILs), or even of university research or teaching on the subject of leaching and hydrometallurgy. Even firms working at various times on the same technologies were not aware of one another's endeavours, which suggests that search capabilities were low or had little strategic importance. Despite the fact that people in the mining sector reportedly know one another, they do not seem to share information. The Tamboraque case of the convergence of all the factors necessary for success was ad hoc rather than systemic; the question is why this was so, given that in neighbouring Chile, systemic links seemed rather better developed.

The situation in Costa Rica is similar, except that Xeltron has far higher competencies. According to Xeltron, however, complementary assets were not available locally, and neither were UILs, despite the firm's attempts to approach universities. The lack of response by universities to the demands of industry represents a failure in the market for knowledge, which policy should correct. Similarly, the fear of knowledge leaks suggests that an appropriate IPR regime would go some way towards fostering UILs.

In contrast, UILs and other linkages existed in the other three cases. These were not just cosmetic; partners had complementary competencies and exploited them, thereby contributing to collective learning. Linkages were organised by principals, who linked actors in the pursuit of very specific technological objectives. On occasion, such linkages crossed borders, sometimes in highly informal, tacit ways, so much so that the 'national' in 'innovation systems' hardly seemed an appropriate qualifier. As some of the common interests that the national system of innovation (NSI) had held together became dissolved through globalisation, the coherence of the system suffered as a result.

The situation with respect to industrial policy somewhat mirrored that of the NSI. In Peru, a policy to alleviate information failures or to help firms overcome the risks and uncertainties associated with new technological developments was simply not available. Because of the lack of finance, the search for knowledge intensification was pursued in a rush, instead of preliminary feasibility studies first being undertaken. The lack of innovation funding also impeded the search for an alternative application of leaching and thus did not facilitate lateral migration. This was belatedly acknowledged through the recent elevation of mining as a priority sector in the Peruvian National Science and Technology Plan.

In Costa Rica, the lack of appropriately trained engineers and horizontal but rather generic policies in favour of EPZs implied that assets to complement Xeltron's competence in optical recognition were missing. In other words, coordination problems hampered the aggressive pursuit of lateral migration at a systemic level. In contrast, in the South African drilling case, the industry body effectively underwrote the risk for new technology development undertaken on its behalf by equipment manufacturers. Eventually, the diffusion of this technology was impeded by its very knowledge intensity; the absence of more stringent, mandatory health and environmental standards meant that the advanced drills did not compete on a level playing field with traditional technology, much as the lack of policy in support of linkages and lateral migration contributed to HH technologies remaining stuck in the sector in which they originated.

In the more recent South African biopolymer example, attention to resource-based industries and their links with the knowledge economy were incorporated in the National R&D Strategy, yet cost blocked more aggressive exploration of biopolymers because of concerns over the likelihood of commercial success, which is the very reason why the private sector is reluctant to accept the risk of investment in the first place. In turn, large-scale commercial feasibility would presuppose a fiscal regime that would penalise the use of non-renewables in favour of more sustainable inputs. It was therefore only in Brazil that a massive programme in favour of alcohol synthesis existed, replete with direct and indirect subsidies and policies in favour of human capital and systemic linkages. The targeted support for

TABLE 1.3 *Determinants of knowledge intensification in the five case studies*

	Absorptive capacity and technological learning	Technology transfer and diffusion of foreign knowledge	Systemic linkages and interactions in the innovation system	Industrial or technology policy
Brazil: bioplastics	High and rising, thanks to consistently high public–private investment in R&D.	Not a big role except in the advanced stage for testing purposes.	Intensive interaction between universities, technology centres and industry.	Government funding was key for ethanol from sugar and later for channelling World Bank funds to the bioplastics consortium.
Costa Rica: sorting machinery	High and rising, thanks to consistently high R&D investment and internal skills upgrading by firm.	Technical expertise-enhanced incentives for innovation. Intellectual property (IP) protection not important for market leadership.	Poor with domestic suppliers, customers and education institutions. Critical interaction with MNC subsidiary.	Market failures in infrastructure. Government support poor in R&D, trade and marketing. Export processing zones (EPZs) very bureaucratic.
Peru: bioleaching and bioremediation	Fragmented and discrete because of inconsistent investment in R&D.	Imports of capital equipment through development assistance-enhanced incentives for innovation.	Poor, especially with engineering departments in universities.	Andean Pact initiatives were set up in the 1970s but did not sustain a research programme. Strong financial constraints to further research.

	Absorptive capacity and technological learning	Technology transfer and diffusion of foreign knowledge	Systemic linkages and interactions in the innovation system	Industrial or technology policy
South Africa: biopolymers	High because of a strong tradition of polymer research. Rising, thanks to strategic search by science, universities and private sector. Skills upgrading through training in universities.	Technical expertise-enhanced incentives for innovation. Reliance on licence initially positive but then withdrawn.	Intense linkages between science sector, universities and private firms.	Strategic commitment at national level to resource beneficiation but public co-funding was small scale and relatively bureaucratic to access.
South Africa: hydro-hydraulic power and ventilation	High because of dedicated, long-term research programme. Potentially diminishing because of termination of main research vehicle and depleting skills in engineering.	Joint ventures and other partnerships with MNCs. Enhanced incentives for innovation. Control of potential abuse of IP protection important for technology diffusion.	Strong linkages within sector between research organisations and private firms; poor linkages with government policy.	Mission-oriented research historically important.

experimentation with alternative uses of sugar meant that finance, risk and uncertainty did not constitute insurmountable impediments to the search for new knowledge. As in South Africa, the absence of a regulatory regime that explicitly favours 'green' plastics means that the new technology is not yet cost competitive. At the same time, however, targeted support for high-end graduate training in biopolymers at several universities supported human resource development and knowledge dissemination, which might contribute to an eventual breakthrough in this technology.

The determinants of knowledge intensification are summarised in Table 1.3. The key insights are as follows. Firstly, the Costa Rican case shows that systemic linkages and targeted industrial policy are not strictly necessary for knowledge intensification, even though this case seems to be the exception to the rule. Secondly, foreign technology is generally conducive to innovation, but, as the Brazilian case shows, not strictly necessary in a major way. Thirdly – and this qualifies the previous two statements – a combination of unavailable or inaccessible foreign knowledge and the absence of industrial policy *is* a problem in the presence of weak absorptive capacities, as in Peru. Fourthly – and this is really the argument in reverse – the weaker the absorptive capacities, and/or the less accessible the foreign technology, and/or the more tenuous the systemic linkages, the more important the role of horizontal industrial policy becomes. In other words, absorptive capacities are critically important, and industrial policy must be a means to that end.

This is not to suggest that relatively poorer countries need industrial policy, and that richer ones do not. It merely means that a market failure in a poorer country constitutes a relatively stronger obstacle for firms to engage in the kinds of innovative activity that might give rise to the knowledge intensification of resource-based activities. What also matters is the level of aspiration behind the industrial policy. Brazil's Proalcool programme had the very ambitious objective of finding an alternative to fossil fuels, an enterprise that was clearly subject to immense risks and uncertainties. Nonetheless, with high capabilities and good access to resources, both financial and other, firms can be expected to be more willing to entertain risks that would be altogether unpalatable to those with less developed capabilities and more difficult access to complementary assets. Thus, although the ability of poorer countries to design and implement industrial policy will typically be more circumscribed than that of their richer counterparts, their need for such policy is no less pressing.

As regards the relationship within the case studies between knowledge intensification and the resource economy, there are two cases of downstream beneficiation (biopolymers); two cases of the development of input industries, each of which is involved in some lateral migration (leaching and hydro-hydraulic drills); and one case of actual lateral migration in which the original resource, coffee, is no longer necessary for the application of the technology. It is evident from the research that the Brazilian sugar beneficiation endeavour was more knowledge intensive than the starch beneficiation experience of South Africa. Likewise, the South African drill experience led to more lateral migration than the leaching experiment in Peru.

Conclusions

This study analysed five cases of knowledge intensification in resource-based activities, relating to and building on a sizeable body of work on resource-based growth. The study attempted to make an original contribution by accompanying its analysis of firm learning with attention to linkages between what many regard as virtually separate entities, namely the ‘old’ factor-based economy and the ‘new’ competence-based knowledge industries. For developing countries in particular, it is clearly more realistic to make use of prior accumulated knowledge to promote new competencies, as opposed to striving for blue-sky applications. Bridges between the old and the new are hence important. Expressed differently, it is primarily in the co-evolution of human capital, scientific pursuit, technological development and concomitant infrastructure investment around the linkages that resource-based economic activities can become more knowledge intensive and thus lead to higher growth.

The study confirms that knowledge intensification is a possible answer to the resource curse that potentially bedevils resource-intensive economies. It also shows that such a strategy is not easy. Much has been learned by comparing experiences of resource-based growth from around the world and at different periods of time. Most such comparative studies took their lead from instances of success and formulated their recommendations accordingly. This study took a more agnostic view, comparing successful cases with less successful ones. Reality is more nuanced than a simple dichotomy of success and failure and, in any event, learning can be based on insights into the reasons for failure as much as on the reasons for success in the more fortunate tales.

The crude version of the resource-curse hypothesis has been convincingly rebutted. This was the merit of comparative historical analyses of, say, Australia and Argentina. With determinism discredited, the challenge now lies now in systematically linking historical and theoretical insights – namely, the potential of resource-based growth and the importance of created assets such as human capital and knowledge infrastructure – with the empirical differentiation of local capabilities across developing countries in the present period. The case analysis not only confirms the expected differences between Peru and Brazil, in that the former was unable to marshal the collective resources required to identify, support and promote the search for a specific technology, but further illustrates differences between countries at comparable levels of development, namely Costa Rica and Brazil, on the one hand, and South Africa, on the other. Sugar-to-plastics in Brazil is a more successful story than starch-to-plastics in South Africa; likewise, the South African hydraulic-drill technology did not achieve anywhere near the export success of the Costa Rican grain-sorting machinery. Attempting to account for such variations warrants further study.

The process of knowledge intensification differs from sector to sector, and perhaps the rather more general attention to R&D subsidies, for example, should similarly be analysed to identify specifically what drives innovative activities across different sectors. There are, for instance, important differences in agriculture and mining to which this study paid little attention. In summary, a better understanding of the conditions under which knowledge intensification could be a successful strategy of industrial diversification requires a larger sample of cases from a more diverse set of developing countries.

Much heuristic benefit could be gained by raising the systematic requirements of the comparisons. For example, if knowledge intensity were properly measured both in terms of inputs (such as R&D investments) and outputs (such as knowledge assets embodied in the new technology), a better understanding could be gained of the efficiency and effectiveness of public policy in support of knowledge industries that originate in or otherwise relate to resource-based activities.

The following propositions are among those worth testing, but this list is by no means exhaustive. Firstly, absorptive capacities (of the relevant R&D entities) are the single most important determinant of lateral migration. Secondly, knowledge intensification can take place in the absence of foreign technology and with weak systemic interactions, but only from a certain level of economic development. In other words, there is a threshold value of absorptive capacities. Thirdly, the import of industrial policy is inversely proportionate to the level of development and proportionate to the level of ambition behind promoting knowledge industries. *Ceteris paribus*, at lower levels of economic development (of countries) or technological competence (of sectors), industrial policy must fulfil coordination roles without which the aggregated capabilities of firms are unlikely to reach the required threshold value of collective absorptive capacity. To this end, policy may have to secure access to external knowledge and will probably have to offer incentives for linkages and interactions. Likewise, the higher the ambition behind the policy, the more necessary it becomes to align the R&D endeavour with the requisite regulatory changes to facilitate the emergence of technological opportunities.

These, in essence, are the insights from this collection of case studies. As ever, the proof lies in the proverbial pudding, which is elegantly served in the chapters that follow.

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Notes

1 The term 'lateral migration' was coined by Paul Jourdan of South Africa's Mineral and Mining Technology Council (Mintek) and Miriam Altman of the Human Sciences Research Council (HSRC). It has only once been formally proposed in the literature (Walker & Jourdan 2003) and its use has remained limited to the South African policy community.

2 Biopolymers are plastics generated from renewable natural resources. They are often biodegradable and are less toxic to produce than conventional plastics.

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